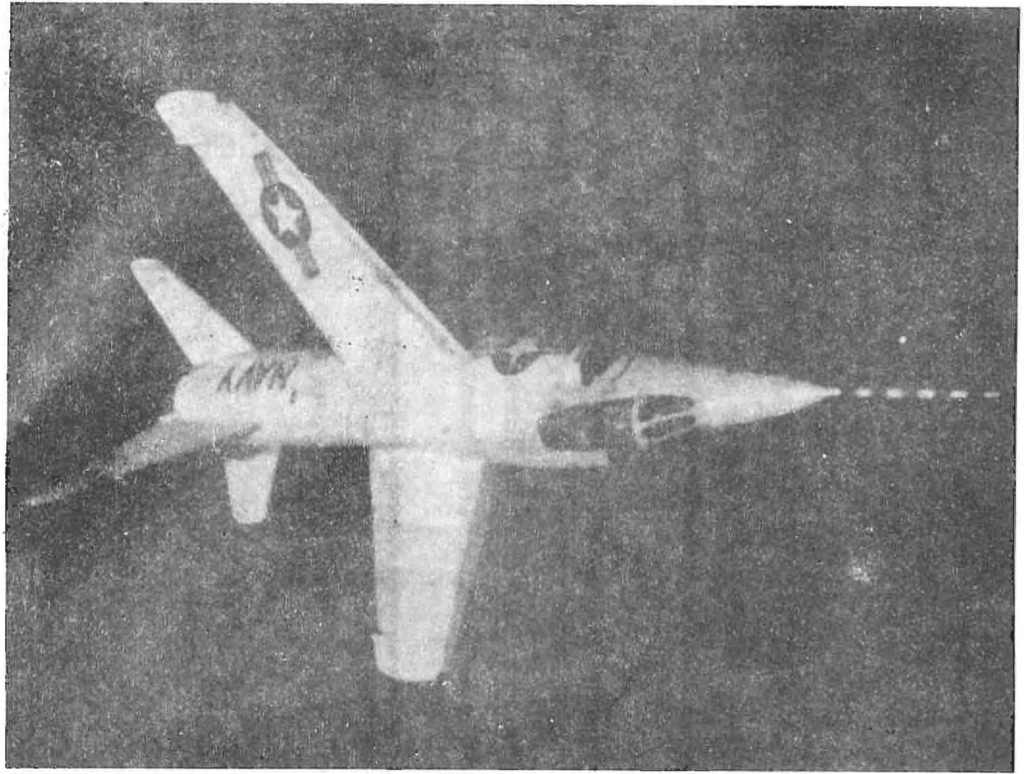
AIRCRAFT MATERIALS AND PROCESSES



Grumman Tiger- Navy Supersonic Fighter

Aircraft Materials and Processes

FIFTH EDITION

GEORGE F. TITTERTON

Assistant Chief Engineer, Grumman Aircraft Engineering Corporation
Formerly Faculty Lecturer, Graduate Division, College of Engineering,
New York University

HIMALAYAN BOOKS

Price Rs. 225

Published by
HIMALAYAN BOOKS
New Delhi- 110 013 (India)

Distributed by
THE ENGLISH BOOK STORE
17-L, Connaught circus
New Delhi- 110 001
Tel.: 2341-7126, 2341-5031 Fax: 2341-7731
E-mail: info@englishbookstore.net

Indian Reprint 2013 2015
By arrangement with Pitman Publishing Corporation

Printed at Thakur Enterprises, Delhi

PREFACE TO THE FIRST EDITION

The author's purpose in writing this book was to present in one coordinated volume the essential information on materials and processes used in the construction of aircraft. Unimportant details have been purposely omitted in the interest of brevity and readability. Within the aircraft field this volume is rather general in scope and should meet the needs of students, engineers, and designers, as well as practical shop men.

This book is based largely upon a series of lectures given by the author at New York University. Similar lectures were also given to a miscellaneous group composed of engineers, shop men, and purchasing department employees of a large aircraft manufacturing corporation. Both in these lectures and the book itself, the author has drawn freely on a fund of information obtained while employed as an engineer in the Naval Inspection Service. As a result, the latest materials and processes used in aircraft construction have been described from a utilitarian point of view. Numerous suggestions have been included on the choice of material for a particular job and on the best way of working, heat treating, and finishing materials for specific applications.

The technical data for a book of this type must, of necessity, be collected, from many sources. Government publications have been used to a large extent. These include Army, Navy, and Federal specifications as well as reports of the Forest Products Laboratory. The Handbook of the Society of Automotive Engineers has also been invaluable for reference purposes. The author is also indebted to many persons and companies for their cooperation in supplying data, and for proofreading portions of the text. The following named deserve special mention for their efforts along these lines:

Mr. Frederick C. Pyne of the Aluminum Company of America
Mr. Frank G. Flocke of the International Nickel Company
Mr. Harry A. Goslar of the Naval Inspection Service
The Dow Chemical Company

The author also wishes to thank those who so generously provided illustrations for the text. In so far as possible these contributions have been acknowledged in the title of the illustration.

It is, of course, improbable that a book such as this is wholly free of errors. The author will appreciate having errors brought to his attention to insure their correction in future revisions of this volume.

George F. Titterton

CONTENTS

ILLUSTRATIONS

TABLES

CHAPTER I

DEFINITIONS

PHYSICAL TERMS

TERMS used in describing the properties of materials should be clearly understood by the reader. Many of these terms have acquired popular meanings, which are not necessarily correct, while others are very hazy in the minds of a majority of people. It is the author's intention to define these terms in the following pages so that a firm foundation may be established before proceeding further.

Hardness. Hardness is the property of resisting penetration or permanent distortion. The hardness of a piece of metal can usually be increased by hammering, rolling, or otherwise working on it. In the case of steel, some aluminum alloys, and a few other metals, hardness can also be increased by a heat treatment. A modified heat treatment known as annealing will soften metals.

Increased hardness and strength go hand in hand. Testing apparatus has been developed for testing hardness rapidly without destroying or harming the tested metal or part. The principle usually employed in this type of apparatus is to sink a hardened steel ball under a definite load into the material being tested. The impression made by the ball is then measured and recorded; the smaller the impression, the harder the material. For each type of material there is a fairly definite relationship between the depth of penetration (which is represented by a Hardness Number for convenience) and the ultimate strength of the material. Tables have been worked up for different materials based on this relationship. By means of a simple hardness test and the use of such a table the approximate tensile strength of a piece of material or finished part can be obtained without cutting out tensile test specimens or mutilating the part.

Brittleness. Brittleness is the property of resisting a change in the relative position of molecules, or the tendency to fracture without change of shape. Brittleness and hardness are very closely associated. Hard material is invariably more brittle than soft material. In aircraft construction the use of too brittle material must be avoided or failure will be caused by the shock loads to which it will be subjected.

Malleability. Malleability is the property of metals which allows them to be bent or permanently distorted without rupture. It is this property that permits the manufacture of sheets, bar stock, forgings, and fabrication by bending and hammering. It is obviously the direct opposite of brittleness.

Ductility. Ductility is the property of metals which allows them to be drawn out without breaking. This property is essential in the manufacture of wire and tubing by drawing. It is very similar to malleability, and, in fact, is generally used in place of that term to describe any material that can be easily deformed without breaking. Thus in aircraft work a material is usually referred to as soft or hard, or else as ductile or brittle. Ductile material is greatly preferred because of its ease of forming and its resistance to failure under shock loads. In order to obtain the required strength it is often necessary, however, to use a hard material.

Elasticity. Elasticity is the property of returning to the original shape when the force causing the change of shape is removed. All aircraft structural design is based on this property, since it would not be desirable to have any member remain permanently distorted after it had been subjected to a load. Each material has a point known as the elastic limit beyond which it cannot be loaded without causing permanent distortion. In aircraft construction, members and parts are so designed that the maximum applied loads to which the airplane may be subjected will never stress them above their elastic limit.

Density. Density is the weight of a unit volume of the material. In aircraft work the actual weight of a material per cubic inch is preferred since this figure can be used in calculating the weight of a part before actual manufacture. The density of a material is an important consideration in deciding which material to use in the design of a part.

Fusibility. Fusibility is the property of being liquefied by heat. Metals are fused in welding. Steels fuse around 2500°F., aluminum alloys around 1100°F.

Conductivity. Conductivity is the property of transmitting heat or electricity. The conductivity of metals is of interest to the welder as it affects the amount of heat he must use and, to a certain extent, the design of his welding jig. Electrical conductivity is also important in connection with the bonding of airplanes to eliminate radio interference.

Contraction and Expansion. Contraction and expansion are caused by the cooling or heating of metals. These properties affect the design of welding jigs, castings, and the tolerances necessary for hot-rolled material.

HEAT-TREATMENT TERMS

Critical Range. Critical range, applied to steel, refers to the range of temperature between 1300°F. and 1600°F. When steel passes through this emperature range, its internal structure is altered. Rapid cooling of the metal hrough this range of temperature will prevent the normal change of the structure and unusual properties will be possessed by the material so treated. The heat treatment of steel is based on this phenomenon.

Annealing. Annealing is the process of heating steel above the critical range, holding it at that temperature until it is uniformly heated and the grain is refined, and then cooling it very slowly. Other materials do not possess critical ranges, but all are annealed by a similar heating process which permits rearrangement of the internal structure, followed by cooling (either slowly or quickly), depending on the material. The annealing process invariably softens the metal and relieves internal strains.

Normalizing. Normalizing is similar to annealing, but the steel is allowed to cool in still air—a method that is somewhat faster than annealing cooling. Normalizing applies only to steel. It relieves internal strains, softens the metal somewhat less than annealing, and at the same time increases the strength of the steel about 20% above that of annealed material.

Heat Treatment. Heat treatment consists of a series of operations which have as their aim the improvement of the physical properties of a material. In the case of steel these operations are hardening (which is composed of heating and quenching) and tempering.

Hardening. Hardening of steel is done by heating the metal to a temperature above the critical range and then quenching it. Aluminum alloys are hardened by heating to a temperature above 900°F. and quenching.

Quenching. Quenching is the immersion of the heated metal in a liquid, usually either oil or water, to accelerate its cooling.

Tempering. Tempering is the reheating of hardened steel to a temperature below the critical range, followed by cooling as desired. Tempering is sometimes referred to as "drawing."

Carburizing. Carburizing is the addition of carbon to steel by heating it at a high temperature while in contact with a carbonaceous material in either solid, liquid, or gaseous form. Carburizing is best performed on steels containing less than .25% carbon content.

Casehardening. Casehardening consists of carburizing, followed by suitable heat treatment to harden the metal.

PHYSICAL-TEST TERMS

Strain. Strain is the deformation of material caused by an applied load.

Stress. Stress is the load acting on a material. Internal stresses are the loads present in a material that has been strained by cold-working.

Tensile Strength. This is often referred to as the ultimate tensile strength (U.T.S.). It is the maximum tensile load per square inch which a material can withstand. It is computed by dividing the maximum load obtained in a tensile test by the original cross-sectional area of the test specimen. In this country it is usually recorded as pounds per square inch.

Elastic Limit. The elastic limit is the greatest load per square inch of original cross-sectional area which a material can withstand without a permanent deformation remaining upon complete release of the load. As stated under "elasticity," the aim in aircraft design is to keep the stress below this point.

Proportional Limit. The proportional limit is the load per square inch beyond which the increases in strain cease to be directly proportional to the increases in stress. The law of proportionality between stress and strain is known as Hooke's Law. The determination of the proportional limit can be more readily accomplished than that of the elastic limit, and since they are very nearly equivalent, the proportional limit is usually accepted in place of the elastic limit in test work.

Proof Stress. The proof stress is the load per square inch a material can withstand without resulting in a permanent elongation of more than 0.0001 inch per inch of gage length after complete release of stress. With standard 2-inch gage length the total permissible elongation would be 0.0002 inch.

Yield Strength. Yield strength is the load per square inch at which a material exhibits a specified limiting permanent set or a specified elongation under load. This load is fairly easily determined and is commonly used.

Yield Point. The yield point is the load per square inch at which there occurs a marked increase in deformation without an increase in load. Only a few materials have a definite yield point. Steel is one of these materials.

Elongation (Percentage). The percentage elongation is the difference in gage length before being subjected to any stress and after rupture, expressed in percentage of the original gage length. The length after rupture is obtained by removing the two pieces from the machine and piecing them together on a flat surface. The distance between the gage marks is then accurately measured.

Reduction of Area (Percentage). The percentage reduction of area is the difference between the original cross-sectional area and the least cross-sectional area after rupture, expressed as a percentage of the original cross-sectional area. This information is seldom used other than as an indication of ductility.

Modulus of Elasticity. The modulus of elasticity of a material is the ratio of stress to strain within the elastic limit. Thus $E =$ unit stress/unit strain.

CHAPTER II

TESTING AIRCRAFT MATERIALS

In aircraft construction it is essential that materials with a high strength/weight ratio be used. For this reason the designer tries to get the last ounce of strength out of each part. This procedure would be very dangerous if the exact strength of the basic material were not known. As a result, the materials entering into the construction of aircraft are probably more thoroughly tested than those employed in any other industry. In this chapter the test methods commonly used will be summarized for ready reference. Many of the tests are standard but are included for completeness.

TENSION TESTING

A tension test is probably the most valuable test that can be made to obtain the basic properties of a material. Besides the ultimate tensile strength it is possible to obtain the yield strength, the elongation, and the reduction of area. The yield strength is a definite indication of the maximum applied load that the material can withstand, and the elongation and reduction of area are a measure of its ductility and ease of working.

All tests should be made with a standard type of machine in good condition. All knife-edges should be sharp and free from oil or dirt. The testing machine should be sensitive to a variation of 1/250 of any registered load. It should also be accurate to within ±1½% throughout its range. These requirements are the minimum acceptable for material to be tested for government inspectors.

During the test the specimen must be held in true axial alignment by the grips. This requirement is particularly important with the relatively thin material used in aircraft construction. The speed of the testing machine crosshead should not exceed 1/16 inch per inch of gage length per minute up to the yield point, and it should not exceed ½ inch per inch of gage length per minute beyond the yield point up to rupture. For a 2-inch gage length these speeds would be 1/8 inch and 1 inch per minute, respectively. When using an extensometer to determine the elastic limit or the yield strength, the crosshead speed should not exceed 0.025 inch per inch of gage length per minute. The extensometer must be calibrated to read 0.0002 inch or less. It must be attached to the specimen only at the gage marks, and not to the shoulders of the specimen or any part of the testing machine.

Figures 1, 2, 3, 4, and 5 show the standard tension-test specimens. All specimens must be strictly straight and must be free from scratches. Test specimens should be subjected to the same treatment and processes as the material they represent in order to obtain a true indication of strength. When elastic properties are to be determined, the test specimen must not be bent, hammered, or straightened by any method involving cold-working of the part. In preparing a test specimen for bar or forging stock of uniform cross-section and less than 1½ inches thick, it should be machined concentrically from the stock. When the stock is over 1½ inches thick, the specimen should be taken from a point midway between the outer surface and the center. By this method the average strength of the material will be obtained. This average strength will be less than that for the hard surface and more than the soft center.

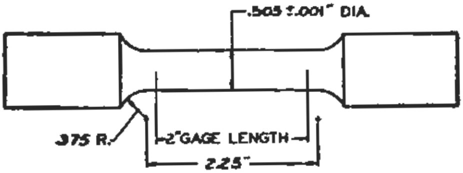


FIGURE 1. Round Tension-test Specimen

Figure 1 shows a tension-test specimen which is circular in cross-section and has a 2-inch gage length. The dimensions of the ends may be varied to suit the testing-machine grips to insure axial loading. It is permissible to taper the specimen inside the gage length toward the center to an amount not to exceed 0.003 inch. This taper will insure breaking between the gage marks. The diameter of the center must be 0.505 ± .001 as noted in Figure 1.

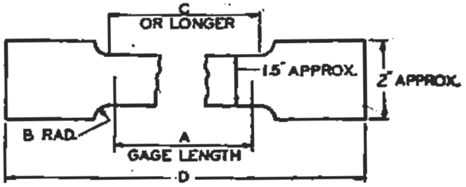


FIGURE 2. Flat Tension-test Specimen for Material over 3/8 Inch Thick

when A=2 in., B=0.25 in., C=2.25 in., D=9 in.
when A=8 in., B=1–3 in., C=9 in., D=18 in.

Figure 2 shows the dimensions of a tension-test specimen used for material over 3/8 inch thick. It is rectangular in cross-section and may be used with either a 2- or 8-inch gage length.

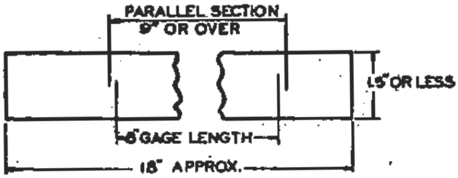


FIGURE 3. Flat Tension-test Specimen for Material over 3/8 Inch Thick and under 1½ Inches Wide

Figure 3 shows a specimen used for testing material over 3/8 inch thick when it is impractical to use a specimen of the type shown in Figure 2. The specimen of Figure 3 is not so wide as that shown in Figure 2.

Figure 4 shows a subsize specimen that may be substituted for the specimen of Figure 1. Like Figure 1 it is circular in cross-section, but its diameter and gage length are much smaller. It may also be tapered 0.003 inch toward the center to insure proper breaking.

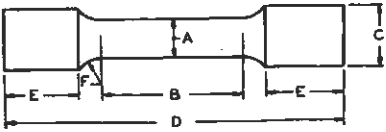


FIGURE 4. Subsize Round Tension-test Specimen

Dimension	Nominal diameter		
	0.357"	0.250"	0.125"
A, ± 0.001"	0.357"	0.252"	0.126"
B, gage length	1.4"	1.0"	0.5"
C, ±1/64"	0.5"	0.375"	0.25"
D, approximate	3.5"	3.0"	1.875"
E, approximate	0.75"	0.625"	0.375"
F, radius	0.375"	0.125"	0.375"

Figure 5 shows the type of specimen used for material not over 3/8 inch thick. It is rectangular in cross-section and requires a gage length of either 2 or 4 inches. The specimen may be reduced to the required width at the center of the gage length by draw-filing not more than 0.004 inch for a ½-inch width, or 0.006 inch for a ¾-inch width. This type of specimen with a 2-inch gage length is the one most commonly used in aircraft materials testing.

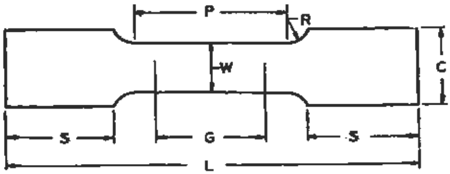


FIGURE 5. Flat Tension-test Specimen for Material 3/8 Inch Thick and under

Rods, bars, and shapes should be pulled in full size when practicable. This method eliminates a number of possible variables and gives the actual strength directly.

Dimension	Sheet thickness	
	Up to ¼ inch	¼ to 3/8 inch
C, maximum	1.13*W*	1.15*W*
G, gage length	2 or 4 inches	2 or 4 inches
L, approximate	9 or 11 inches	9 or 11 inches
P, minimum	1 1/8*G*	1 1/8 *G*
R, minimum	*W*	*W*
S, approximate	3	3
W	½ ± 0.010 inch	¾ ± 0.015 inch

Tubing is tested by putting solid plugs in each end, which permit gripping without crushing. It is standard practice to keep at least 6 inches of hollow tubing between the near ends of the plugs. If it is not practical to test the tubing in full section, a specimen (of the type shown in Figure 5) may be cut parallel to the axis of the tubing.

Elastic-limit Determination. The elastic limit of a material is the greatest stress that can be held without permanent deformation remaining upon complete release of the stress. In practical testing the elastic limit is considered to have been reached when a permanent set of 0.00003 inch per inch of gage length has been obtained. An accurate-reading extensometer must be used to read the permanent set. The method of testing is as follows: a load is applied until the stress is 20% of the expected elastic limit and the extensometer reading is recorded. The load is then increased to about 75% of the elastic limit, after which it is dropped to below 20% and then brought up to 20%, and then the extensometer read. If no permanent set has been obtained the extensometer should read identically the same as when the first 20% load was imposed. It is customary to refer back to 20% load rather than zero load to eliminate inaccuracies due to friction in the extensometer. After the 75% load, additional increments of load should be added and released as before to the 20% load, and the extensometer read. These increments should not exceed about 3% of the elastic limit as this point is approached. The elastic limit is calculated from the last load prior to the one that caused a permanent set of over 0.00003 inch per inch of gage length.

Proof-stress Determination. The proof stress of a material is the greatest stress it can withstand without resulting in a permanent set of over 0.0001 inch per inch of gage length after complete release of stress. For the standard 2-inch gage length this amounts to a permanent set of 0.0002 inch. The proof stress can be determined in the same manner as the elastic limit, or the load can be released to zero after each increment. The proof stress of a material is also referred to as its proportional limit.

Yield-strength Determination. The yield strength is the stress at which a material exhibits a specified elongation under load. The two commonly used methods for determining this stress are known as (1) *Set Method* and (2) *Extension under Load Method.* Either of these methods is easily applied and will give consistent results if an accurate testing machine and extensometer are employed.

1. *Set Method.* In this method the loads are applied and the extensometer readings taken for a number of loads. The loads usually selected are 20%, 75%, 90%, and several other loads just under and over the expected yield strength. A curve is then plotted, as shown in Figure 6, in which the applied loads are ordinates and the extensometer readings are abscissas. This curve

will be similar to the curve *OD* of Figure 6. It will be noted that the lower part of this curve is a straight line. The line *CD* is constructed parallel to the straight portion of line *OD* and at a distance to the right equal to the specified set. The point of intersection *D*, read as an ordinate, gives the applied load for the yield strength. The applied load divided by the original cross-sectional area is the yield strength.

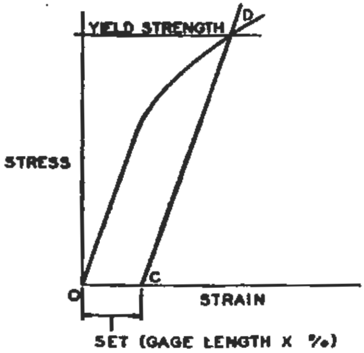


FIGURE 6. Set Method of Yield-strength Determination

This method of determination is used when the yield strength is specified in pounds per square inch for a given percent of set. For metals a set of 0.2% is usually specified. For the standard 2-inch gage length this set would be 0.004 inch. In this case the point *C* in Figure 6 would be at an abscissa of 0.004 inch. The principle of this method is based on the fact that if the load was released at *D*, the curve for the decreasing load would follow the line *DC*. *OC* would then represent the permanent set. The yield strength value obtained by the set method is arbitrary, but it is a measurable value of plastic yielding of the material below which the damaging effects are considered to be negligible.

The set method is frequently specified for determining the yield strength of aircraft materials. Steel, aluminum alloys, magnesium, and structural corrosion-resisting steel are metals whose yield strength is often determined as the point where a permanent set of 0.002 inch per inch of gage length is obtained. Very often there is a choice between the use of the set method and the extension under load method.

2. *Extension under Load Method.* This method is easier of application than the set method since no curve need be plotted, and it is frequently used. It is based on the same principle as the set method. The specified extension is made up of two parts: (a) the normal elongation based on the modulus of elasticity of the material and the expected yield strength, plus (b) a definite additional elongation which is usually 0.002 inch per inch of gage length, the same as that specified for the permanent set in the set method. The normal elongation must be computed for each material for the expected yield strength by the following formula:

$$\text{normal elongation} = \frac{\text{expected yield strength}}{\text{modulus of elasticity}}$$

In the case of heat-treated steel with a yield strength of 100,000 pounds per square inch and a modulus of elasticity taken as 30,000,000, the normal elongation would be 100,000/30,000,000=0.0033 inch per inch of gage length. Adding 0.002 inch to this makes the specified elongation 0.0053 inch per inch or 0.0106 inch for a 2-inch gage length. If, in testing, the yield strength obtained at this elongation is higher than 100,000, the material is better than anticipated.

This method is used generally for establishing the yield strength of aircraft materials. The modulus of elasticity used for the calculation of the normal elongation is as follows for the various metals:

Steel = 30,000,000 pounds per square inch
Aluminum alloys = 10,000,000 pounds per square inch
Magnesium = 6,500,000 pounds per square inch
Corrosion-resisting steel = 25,000,000 pounds per square inch

Yield-point Determination. The yield point of a material is the point at which there is a marked increase in elongation without increase in load. This phenomenon is found only in some materials, such as wrought iron and mild carbon steel. For these materials the stress-strain curve has a sharp break at the yield point. When the stress-strain curve of a material is smooth in this region, the material does not have a yield point. The yield point of a material can be determined by either of two methods: (1) *Divider Method* or (2) *Drop of Beam Method.*

1. *Divider Method.* In this method a pair of dividers is set to the exact distance between two gage marks. The load is then applied to the specimen with one arm of the dividers centered in one gage mark and the other arm held free above the other gage mark. At the instant visible stretch is noted between this latter gage mark and the dividers, the load should be noted. The yield-point stress is computed from this load.

2. *Drop of Beam Method.* In this method the load is applied uniformly and the recording beam kept balanced by the operator. At the yield-point load the beam will drop suddenly as the elongation increases rapidly at this point without increase in load. If the testing machine is equipped with a self-indicating load measuring device, the pointer will halt momentarily at the yield-point load. The yield-point stress is computed from this load.

HARDNESS TESTING

There is no positive assurance that a manufactured article has the same strength as developed by a test specimen. The test specimen has different dimensions and may have responded to heat treatment better, or it may have been taken from a different location, or it may not have been subjected to the same fabricating stresses as the manufactured article. It is apparent that some means is needed to check the comparative strength of manufactured articles without destroying or harming them in any way. The development of a hardness test has solved this problem.

There are four methods in general use for determining the hardness of metals: Brinell, Rockwell, Vickers, and Shore Scleroscope. These methods depend upon the impression made in the tested metal by a diamond cone or hardened steel ball, or the rebound of a small diamond-pointed hammer dropped from a fixed height. Each of these methods has its limitations and special uses which are described below. It is important in all cases, however, that the tested surface should be smooth and free from scratches, ridges, scales, or other unevennesses. The specimen must also be sufficiently thick so that the impression made by the testing apparatus does not bulge the opposite side and thereby give a false reading. Care must also be taken to see that there is sufficient edge distance to avoid any deflection due to the depression.

It has been found that hardness and tensile strength will correspond very closely for any particular material. By coordinating a large number of tensile and hardness tests made on the same specimens, it has been possible to construct a table from which the tensile strength can be obtained if the hardness is known. Manufactured articles need be subjected only to a simple hardness test to determine their approximate tensile strength.

This correlation does not apply to relatively soft materials such as aluminum alloys. Hardness-testing devices are not sufficiently sensitive, particularly on thin sheet aluminum alloy, to warrant even a reasonably accurate correlation between hardness and tensile properties. Hardness testing is accurate enough, however, to distinguish between annealed and heat-treated material of the same aluminum alloy.

Table 1 gives the equivalent tensile strength for hardness numbers obtained by any one of three commonly used methods. This table applies only to carbon and low-alloy steels and not to corrosion-resistant, magnet, valve, or tool steels. The strengths listed in the table correspond only approximately with the hardness numbers, due to the fact that no two hardness-testing machines, even of the same type, will read exactly alike. It is necessary to calibrate each machine periodically against standard specimens. Any process which affects the surface (such as buffing and plating) or the presence of decarburized or porous areas and hard spots will affect the hardness and the corresponding relation between hardness and tensile strength. The tensile, Brinell, Vickers, and Rockwell relationship is quite uniform for parts which are sufficiently large and rigid to permit obtaining a full depression on a flat surface without deflection of the piece. For cylindrical parts less than ½ inch in diameter, the Rockwell readings will be lower than those indicated in the table for the corresponding tensile strength.

TABLE 1. Approximate Correlation between Hardness and Tensile Strength of Carbon and Low-Alloy Steels (Federal Specification, QQ-M-151)

Rockwell[1]		Vickers[2] diamond pyramid	Brinell 10-mm. Ball		Tensile strength, 1000 p.s.i.	Rockwell[1]		Vickers[2] diamond pyramid	Brinell, 10-mm. Ball		Tensile strength, 1000 p.s.i.
C, 150 kg load	B, 100-kg load, 1/16" ball		Tungsten carbide ball[3]	Steel ball, 3,000-kg load		C, 150-kg. load	B, 100-kg. load, 1/16" ball		Tungsten carbide ball[3]	Steel ball, 3,000-kg. load	
67		918	820	717		37	110.4	367	356	347	165
66		884	796	701		36	109.7	357	346	337	160
65		852	774	686		35	109.1	348	337	327	155
64		822	753	671		34	108.5	339	329	318	150
63		793	732	656		33	107.8	330	319	309	147
62		765	711	642		32	107.1	321	310	301	142
61		740	693	628		31	106.4	312	302	294	139
60		717	675	613		30	105.7	304	293	286	136
59		694	657	600		29	105.0	296	286	279	132
58		672	639	584		28	104.3	288	278	272	129
57		650	621	574		27	103.7	281	271	265	126
56	121.3	630	604	561		26	102.9	274	264	259	123
55	120.8	611	588	548		25	102.2	267	258	253	120
54	120.2	592	571	536		24	101.5	261	252	247	118
53	119.6	573	554	524	283	23	100.8	255	246	241	115
52	119.1	556	538	512	273	22	100.2	250	241	235	112
51	118.5	539	523	500	264	21	99.5	245	236	230	110
50	117.9	523	508	488	256	20	98.9	240	231	225	107
49	117.4	508	494	476	246	19	98.1	235	226	220	104
48	116.8	493	479	464	237	18	97.5	231	222	215	103
47	116.2	479	465	453	231	17	96.9	227	218	210	102
46	115.6	465	452	442	221	16	96.2	223	214	206	100
45	115.0	452	440	430	215	15	95.5	219	210	201	99
44	114.4	440	427	419	208	14	94.9	215	206	197	97
43	113.8	428	415	408	201	13	94.1	211	202	193	95
42	113.3	417	405	398	194	12	93.4	207	199	190	93
41	112.7	406	394	387	188	11	92.6	203	195	186	91
40	112.1	396	385	377	181	10	91.8	199	191	183	90
39	111.5	386	375	367	176	9	91.2	196	187	180	89
38	110.9	376	365	357	170	8	90.3	192	184	177	88

Table 1. (Continued)

Rockwell[1]		Vickers[2] diamond pyramid	Brinell 10-mm. Ball		Tensile strength, 1000 p.s.i.	Rockwell[1]		Vickers[2] diamond pyramid	Brinell, 10-mm. Ball		Tensile strength, 1000 p.s.i.
C, 150 kg load	B, 100-kg load, 1/16" ball		Tungsten carbide ball[3]	Steel ball, 3,000-kg load		C, 150-kg. load	B, 100-kg. load, 1/16" ball		Tungsten carbide ball[3]	Steel ball, 3,000-kg. load	
7	89.7	189	180	174	87		68	120	111	108	58
6	89	186	177	171	85		66	116	107	104	56
5	88.3	183	174	168	84		64	112	104	100	54
4	87.5	179	171	165	83		61	108	100	96	52
3	87	177	169	162	82		58	104	95	92	50
2	86	173	165	160	81		55	99	91	87	48
1	85.5	171	163	158	80		51	95	86	83	46
0	84.5	167	159	154	78		47	91	83	79	44
	83.2	162	153	150	76		44	88	80	76	42
	82	157	148	145	74		39	84	76	72	40
	80.5	153	144	140	72		35	80	72	68	38
	79	149	140	136	70		30	76	67	64	36
	77.5	143	134	131	68		24	72	64	60	34
	76	139	130	127	66		20	69	61	57	32
	74	135	126	122	64		11	65	57	53	30
	72	129	120	117	62		0	62	54	50	28
	70	125	116	113	60						

[1] Rockwell C values below 20 and B values above 100 are not recommended for correlation; however, these values are sufficiently accurate to indicate the trend of relationship.

[2] Vickers values of 918 to 171 inclusive obtained with 50 kg. load; 167 to 95 inclusive obtained with 30 kg. load; 91 to 62 inclusive with 10 kg. load.

[3] Brinell tungsten carbide ball values 820 to 163 inclusive obtained with 3,000 kg. load; 159 to 86 inclusive with 1,500 kg. load; 83 to 54 inclusive with 500 kg. load.

Brinell Hardness. The Brinell test consists in pressing a hardened steel ball, under a known pressure, into a flat surface of the specimen to be tested. For testing steel a ball 10 millimeters in diameter under a pressure of 3000 kilograms (6600 pounds) is used. For softer metals, such as aluminum alloys and bronze, a 500-kilogram load is used. The load should be applied for at least 10 seconds before release.

The area of the impression made by the ball is measured by a calibrated microscope that reads accurately to 0.05 mm. The Brinell number is the load in kilograms divided by the area of the spherical surface of the impression in square millimeters. It is obvious that hard materials will have small impressions and consequently large Brinell numbers. A rough check of Table 1 will show that for steel the Brinell number is almost exactly twice the equivalent tensile strength throughout the whole scale. This is a useful relationship to keep in mind for occasions when a hardness table is not available.

For Brinell testing the surface should be free from scratches, and prepared by filing, grinding, machining, or polishing with emery paper. A smooth surface is essential to permit reading the small impression accurately.

Rockwell Hardness. Rockwell hardness is determined by measuring the penetration of a diamond cone or hardened steel ball under definite loads. The machine first applies a minor load of 10 kilograms, the direct reading dial is set to zero, and the major load is applied. This forces the penetrator into the metal, and after removal of the load, the Rockwell hardness can be read from the dial.

The dial of the machine has two sets of figures, one red and one black. The red figures are used with ball penetrators, and the black figures with the diamond-cone penetrator. To cover the wide range of hardness found in various metallic materials more than a dozen combinations of loads and penetrators are available with the Rockwell hardness tester. Ball penetrators up to ½-inch diameter and loads of 60, 100, and 150 kilograms are used. Each of these combinations is designated by a letter such as A, B, C, D. Only the B and C combinations or scales are commonly used in testing aircraft steels. These scales represent the following combination of load and penetrator:

Scale	Penetrator	Load (kilograms)	Dial
B	1/16-inch ball	100	red
C	diamond cone	150	black

The working range of the B scale is from B-0 to B-100. There is danger that the ball penetrator will be flattened if used on material harder than B-100. The useful range of the C scale is from C-20 upward. Inaccuracies in the manufacture of the diamond penetrator will be magnified and give inaccurate readings when used on material softer than C-20.

The accuracy of Rockwell hardness numbers depends, to a great extent, upon the surface condition of the specimen. Both sides of test surfaces should be free from scale and surface ridges caused by rough grinding or machining. The surface roughness must be much less than the depth of the impression.

A thickness of 0.027 inch or over is all that is necessary with hard steel to obtain a true hardness reading. For softer materials it is necessary to reduce the applied load and increase the penetrator diameter to obtain satisfactory readings if the material is thin. Penetrators as large as ½ inch in diameter, with a load of only 60 kilograms, are used on very thin aluminum. The results obtained by these means are purely relative and do not correspond to a set of tensile strengths.

The true hardness of curved surfaces with radii of 3/16 inch or greater can be obtained by the Rockwell tester. Smaller round surfaces must have a small flat spot filed on them if true readings are desired. The Rockwell apparatus is used very generally by aircraft manufacturing concerns because of its direct reading qualities, ease of operation, and reliability.

Diamond Pyramid (Vickers) Hardness. The Vickers hardness test is made with a diamond penetrator in the form of a square-base pyramid having an included angle of 136°. A normal loading of 30 kilograms is used for homogeneous material, and a 5-kilogram load for soft, thin, or surface-hardened material. It should be noted from the table that the Vickers hardness numbers are identical with the Brinell numbers for all but very hard material.

Shore Scleroscope Hardness. Shore scleroscope hardness testing consists of dropping a small diamond-pointed hammer from a fixed height and measuring and comparing the height of rebound with that from a standard test piece. It is an excellent means of obtaining comparative hardness of a large number of production parts. If absolute hardness is desired, it is essentia that the instrument be set level and rigidly fixed in position to prevent movement in any direction. If the slightest movement occurs, the rebound will be inaccurate. The rebound is measured directly on a vertical scale in one instrument, and in another it is registered on a recording dial.

The test specimen should be smooth and free from scratches. The average of five separate determinations is usually taken as the hardness of a part. By this means errors due to rebound or to a hard spot in the material are eliminated. The scleroscope hardness scale ranging from 0 to 120 is purely arbitrary.

BENDING TESTS

Most specifications for aircraft metals require them to pass a bending test. The usual test requires cold bending through an angle of 180°, over a pin equal to the diameter or thickness of the test specimen, without cracking. This type of test will give definite assurance that a metal is ductile and not inclined to brittleness. Although it is difficult to obtain the exact radius of bend specified even under laboratory conditions, this test can be readily applied in the shop to check doubtful material.

Bend-test specimens for sheet or strip stock are usually 1 inch wide by 6 inches long and the full thickness of the material. The edges of the specimen should be rounded with a file, making sure there are no rough spots or ragged edges where cracks can start. For heavy plate or shapes a specimen rectangular in cross-section is required. The corners of the cross-section may be just broken with a smooth file. The full thickness of the material and a width from 1 to 2½ inches with a suitable length should be used. Rods and bars are submitted to bend tests in their full section. Specimens of forging stock are machined to a section 1 by ½ inch in cross-section and at least 6 inches long. The edges of these specimens are rounded to a 1/16-inch radius. For heavy material, 1½ inches or over, these specimens must be taken from a point midway between the center and outer surface of the stock.

The actual bending may be accomplished either by a constant pressure or by blows from a hammer. The latter is somewhat more severe but represents an actual condition that exists in most shops in forming aircraft parts. Specifications usually require that bend-test specimens be taken both parallel to and across the grain. The high quality of aircraft material now available will permit bending in any direction relative to grain and still meet the rigid requirements of the specifications. For shop bending it is preferable, however, to make all bends across the grain. If this test is passed there is little likelihood of cracking in forming or in subsequent service due to fatigue stresses.

The severity of the bend test will be realized if the elongation necessary on the outer circumference of the bend is computed. This figure greatly exceeds the elongation value obtained from straight tension tests.

Reverse Bend Test. Round steel wire is usually subjected to a reverse bend test. In this test a specimen of wire at least 10 inches long is held in a vise or bend-testing machine and bent back and forth 90° each way through a total angle of 180°. The jaws of the vise are rounded to the required radius—3/16 inch for wire up to 3/16 inch in diameter and three times the diameter or thickness of the wire for heavier wire. Bending is done at a rate not exceeding 50 bends per minute, and slowly enough not to cause undue heating of the wire. In this test each 90° bend counts as one bend. Specification requirements vary from 50 bends for small wire to 7 bends for heavy wire.

Flattening Test. Flattening is a form of bending test applicable to tubing. A length of tubing equal to twice its diameter is flattened sideways and examined for cracks or other defects. When the test is applied to bronze tubing, the overall thickness of the flattened tube must not exceed three times the wall thickness.

IMPACT TESTS

Impact tests consist of notching a piece of material on one side and then fixing it in a machine so that it can be broken by means of a falling weight or a heavy swinging pendulum. The test has practically no absolute value, but can be used to compare two pieces of material of identical composition and tensile strength. Even two pieces of the same steel which have been subjected to different tempering treatments to obtain different tensile strengths will not give comparable impact values. The chief use of this test is to determine whether a batch of material has been subjected to the correct heat treatment. It does not indicate the shock resistance of a material, but it will show whether material is excessively brittle. Extremely ductile material cannot be impact-tested satisfactorily because it bends while breaking.

There are two standard impact tests: namely, the Izod and the Charpy tests.

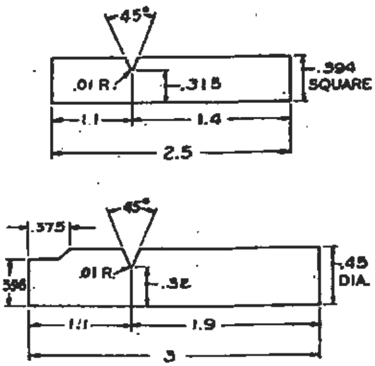
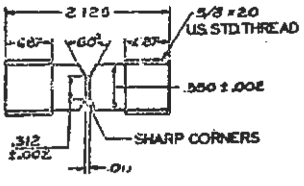


FIGURE 7. Izod Impact-test Specimen

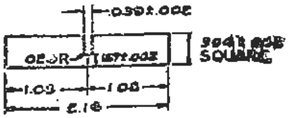
Izod Test. In this test a notched specimen is clamped in heavy jaws, with the notch level with the top of the jaws and facing a heavy pendulum. When the pendulum is released from a fixed height, it swings down and hits the specimen at the lowest point of its path. Breaking the specimen retards the pendulum and reduces its upswing. The height of the reduced upswing is measured on a quadrant calibrated in the foot-pounds absorbed in breaking the specimen. For comparable results the notch in the specimen must be held to close limits. Standard square and round Izod specimens are shown in Figure 7.

Charpy Test. In this test there are two types of specimens which may be broken under either a tensile or transverse load. These specimens are shown in Figure 8. The tensile specimen is threaded at both ends. One end is threaded into a swinging pendulum and a stop block is threaded on the other end. As the swinging pendulum reaches its lowest point, the stop block is brought to rest. This ruptures the specimen and reduces the swing of the pendulum. The energy absorbed in rupture is measured as in the Izod test.

In the transverse test the square Charpy specimen is placed in the machine so that it straddles two supports. The notch is at the exact center and facing away from the swinging pendulum. As before the pendulum ruptures the specimen at the lowest point of its arc and the absorbed energy is measured.



TENSILE CHARPY



SQUARE CHARPY

FIGURE 8. Charpy Impact Specimens

CRUSHING TESTS

Aircraft tubing is nearly always subjected to a crushing test. For this test a piece of tubing 1½ diameters long, with its ends machined normal to its axis. is used. This tube is compressed endwise under a gradually applied load until its outside diameter is increased on one zone by 25%, or until one complete fold is formed, or the specimen is reduced to two-thirds its original length. The tubing must stand this test without cracking. Tubing must be in the annealed condition when subjected to this test. It should not be in the normalized or heat-treated condition.

HYDROSTATIC TEST

Seamless tubing that is to carry pressure in service, or welded tubing such as the corrosion-resisting steel tubing used for exhaust collectors, is subjected to a hydrostatic pressure test. Welded exhaust tubing is subjected to an internal pressure sufficient to put the welded seam under a tensile stress of 10,000 p.s.i.

For tubing of any size or wall thickness the tensile stress along any seam can be computed from the following formula:

$$\text{tensile stress} = \frac{\text{internal hydrostatic pressure} \times \text{diameter}}{2 \times \text{wall thickness}}$$

It should be noted that extremely high internal pressures can be carried in small-diameter tubes without overstressing the material. It is common practice to carry oxygen under an 1,800 pound per square inch pressure through a 3/16-inch copper tube when conveying it from the storage tank to the regulator in aircraft oxygen apparatus.

TORSION TEST

Wire is always subjected to a torsion test. For wire over 0.033 inch in diameter the test specimen must be at least 10 inches long. It is held by two clamps 8 inches apart. One of these clamps is fixed and the other is rotatable. The movable clamp is rotated until the wire splits, at a uniform speed not exceeding 60 revolutions per minute or slower, if necessary, to prevent undue heating of the wire. The wire is under sufficient tension to prevent it from kinking during the test.

When wire of 0.033-inch diameter or less is to be tested a specimen 30 inches long must be used. The center of this length of wire is passed round a hook held in the movable clamp, and the loose ends are clamped together in the fixed clamp. The movable head is then rotated as for the heavier wire and the number of revolutions are counted before the wire splits.

FATIGUE TESTING

Materials subject to vibrational stresses have frequently failed at much smaller loads than anticipated. Investigation disclosed that each material has a fatigue stress beyond which it is not safe to load it repeatedly. The fatigue stress is defined as that stress which the material will endure without failure no matter how many times the stress be repeated. Testing for fatigue strength is so laborious that many materials have not yet been tested. For hard steels a 2,000,000-cycle test is necessary to definitely establish fatigue stress; for soft steels 10,000,000 cycles are necessary; for aluminum and magnesium alloys 500,000,000 cycles of completely reversed stress are required.

Many types of fatigue-testing apparatus have been developed. The most common are rotating-beam or rotating-cantilever tests. These rotating tests give a completely reversed stress in which the maximum unit tensile and compressive stresses in the surface of the specimen are equal. The speed of rotation varies in different machines but is usually of the order of 2000 r.p.m. or in high-speed work 12,000 r.p.m. Axial loading tests in which the specimen can be subjected to reversed stresses or from zero load up to a definite tensile load are also used.

Fatigue-test specimens are usually rolled- or forged-bar stock 1 inch in diameter. It must be remembered that these smooth, cylindrical test rods are free from holes, notches, or abrupt changes of cross-section and give maximum test results. The slightest corrosion or flaw will greatly reduce the fatigue limit of a part in service.

The fatigue limit of a material is half its fatigue range. In other words, it has the same limit for a plus or minus load. For steel the fatigue limit is about 0.5 of the ultimate tensile strength; for nonferrous metals it is about 0.3 to 0.4 of the tensile strength. An initial static stress in a part decreases the permissible dynamic stress. Heat-treated materials have higher tensile strengths and fatigue limits than annealed materials.

INSPECTION METHODS

It is essential that all parts of the airplane structure be free of cracks which in service might cause severe failures. Two methods are commonly used to detect minute surface or internal cracks in welded, forged, cast, or machined parts. These methods of inspection are known as radiography and magnaflux inspection.

Radiography. Radiography is a non-destructive method of locating cracks by means or X-rays or gamma-rays. A radiograph, or shadow picture, is obtained by passing X-rays or gamma-rays through the object being inspected. Cracks show up in the shadow picture as light spots. By taking pictures in two different places it is possible to locate the crack accurately and to determine its magnitude.

Exographs are radiographs, or shadow pictures, produced by passing X-rays through an object. X-rays are light rays having wave-lengths of the order of 10^{-6} to 10^{-9} centimeters. These X-rays emanate from a vacuum tube operated electrically. The shadow picture is recorded on a special X-ray film coated on both sides to increase the intensity of the reaction. X-rays are used efficiently for the inspection of steel parts up to 3 inches in thickness. It is possible to obtain exographs of less dense materials, such as aluminum, in much greater thicknesses. Exographs are frequently used in the inspection of castings of a new design.

Gammagraphs are radiographs, or shadow pictures, produced by passing gamma-rays through an object. Gamma-rays are light rays having wave lengths of about 10^{-11} centimeters. Gamma-rays are obtained from radium, usually in the form of radium sulfate, which is sealed in a small silver capsule. It is interesting to note that radium decays to one-half its original strength in 1580 years. Gamma-rays are more powerful than X-rays and it is possible to obtain a gammagraph of steel parts up to 8 inches thick.

Radiography gives a permanent record on a film but requires time and photography. Fluoroscopy has recently been developed to permit visual inspection of metal parts by passing X-rays through them on to a screen. Parts under inspection can be rotated and all defects located immediately. This process requires much higher voltages than radiography, since instantaneous images are created. A new development permits photographing this image on a 35-millimeter film in connection with a timing device that insures proper exposure.

Magnaflux. Magnaflux is an inspection process for magnetic materials and parts which indicates cracks, seams, laps, and nonmetallic inclusions. The process consists of magnetizing the part and then sprinkling it with magnetized powder. If a crack is present the distribution of the magnetic lines of force will be disturbed and opposite poles will exist on either side of the crack. The magnetized powder forms a pattern in the magnetic field between the opposite poles and thus indicates the location and shape of defects which are frequently invisible to the eye. With proper equipment internal defects can be located.

To locate a defect it is essential that the magnetic lines of force pass approximately perpendicular to the defect. It is necessary therefore to induce magnetic flux in several directions. Circular magnetization is the inducing of a magnetic field consisting of concentric circles of force about and within a part by passing a high amperage current through the part. This type of magnetization will locate defects running approximately parallel to the axis of the part. Bipolar (longitudinal) magnetization is the inducing of a magnetic field within a part whose lines of force are parallel to the axis of the part. A high-amperage current passed through a coil wrapped around the part, or placing the part between the poles of electromagnets will induce bipolar magnetization which will indicate defects perpendicular to the axis of the part. Equipment now available will induce circular and longitudinal magnetization simultaneously and can be continuously in operation while the magnetic powder is applied. This so-called "continuous method" of testing in which the current is kept on throughout the inspection operation induces an intensified magnetic field and gives better results. Rectified alternating or direct current can be used to magnetize parts.

Magnetic powder (black iron oxide, Fe_3O_4) can be sprinkled on the work dry or applied wet. In the wet method the powder is suspended in a liquid such as kerosene. The wet method has better sensitivity than the dry-powder method and is more generally used.

After inspection the part must be demagnetized before installation in the airplane. Demagnetization is accomplished by passing the part through a coil carrying alternating current. The part must be withdrawn about 18 inches from the coil so as to obtain the effect of a progressively weaker current. Another method of demagnetization is to leave the part in the coil and gradually reduce the current to zero. It is extremely important that all parts be demagnetized to as great an extent as possible to prevent interference with the airplane's compass.

SUPERSONIC TESTING

The supersonic method of testing aircraft materials affords a means for examining hand-forged billets; bar stock, thick extrusions, die forgings and blocker type forgings.

Using the piezo electric effect of a quartz crystal, high frequency sound (2 ¼ up to 15 megacycles) is projected into the material being tested and any reflections of this sound are analyzed by an electric circuit. If the material is homogeneous, the only reflection of sound will occur when the sound strikes the bottom face of the material. If any internal defects are present, these defects will reflect sound waves back to the crystal. These reflections can be viewed on an oscilloscope, and the size and depth of the defect can be approximated. By proper correlation with known defects, the strength reduction effect can be calculated.

The same principle of sound reflection is used in thickness measuring devices. These devices are valuable for measuring the thicknesses of such aircraft parts as tapered wing skins, hollow tubes, and integrally milled stabilizer skins.

CHAPTER III

STEEL AND ITS ALLOYS

The basis of all steel is iron which, when combined with carbon and other elements in varying amounts, gives a wide range of physical properties. Exact control of the alloying elements is essential to obtain a high-grade steel for aircraft use. Each element contributes definite characteristics which depend upon the amount of the element present in any particular steel. Due to the large number of elements that will combine with iron, an infinite number of steels is obtainable. In order to classify the better-grade steels used in automotive and aircraft work, the Society of Automotive Engineers has formulated a numerical index system which is generally used. This system has the great advantage of partially describing the steel insofar as the approximate percentage of the two most important elements is concerned.

The Navy Department and the Army Air Service each issue their own specifications covering all types and forms of material used in the construction of military aircraft. These two types of specifications are gradually being coordinated as *AN Aeronautical Specifications* (see p. 30). Copies of such specifications can be obtained from the Government Printing Office, Washington, D.C., for a nominal charge. To insure receiving the exact grade and quality of steel and other materials ordered, it is advisable to require conformance with one of these specifications.

PLAIN CARBON STEELS

By far the most important element in steel is carbon. In fact the classification of iron and steel is based on the percentage of carbon present. The generally accepted classification is as follows:

Wrought iron	Trace to 0.08%
Low carbon steel	0.10% to 0.30%
Medium carbon steel	0.30% to 0.70%
High carbon steel	0.70% to 2.2%
Cast iron	2.2% to 4.5%

An interesting fact in connection with the above percentages is that all carbon above 2.2% is uncombined with the iron and is present in the form of graphite. This graphite forms planes of easy cleavage, which accounts for the easy breakage of cast iron.

Besides iron and carbon the plain carbon steels normally contain small amounts of silicon, sulfur, phosphorus, and manganese. Silicon and manganese are beneficial elements; sulfur and phosphorus are harmful impurities which cannot be wholly eliminated but are kept as low as possible.

ALLOY STEELS

The addition of a metallic alloying element to plain carbon steels results in the formation of a new alloy steel with wholly different properties. The carbon content of alloy steels is of prime importance but varying properties can be obtained by adding an alloy. The metals commonly used as alloys in steel are nickel, chromium, molybdenum, vanadium, and tungsten. Small amounts of titanium and columbium are also used, particularly in the corrosion-resisting steels. In some alloy steels two alloying elements are present, such as chromium-nickel and chromium-molybdenum. One alloy steel which is commonly used for propeller hubs contains chromium-nickel-molybdenum.

Silicon and manganese are also used as alloying elements but in much larger amounts than are usually present in the plain carbon steels.

EFFECT OF INDIVIDUAL ELEMENTS

The development of alloy steels in the past has been largely a result of trial and error. It is practically impossible to predict, with any degree of certainty, the exact properties that can be obtained by a given combination of elements. In a general way, the effect of adding a specific alloying element is known. This information is useful to the designer in deciding which material possesses just the right properties for the proposed design. The constituents of plain and alloy steels are discussed in detail in the following paragraphs, emphasis being placed on those properties that have a bearing on aircraft use.

Carbon. Carbon is by far the most important constituent of steel. It combines readily with iron to form iron carbide (Fe_3C), which is a compound known as cementite. It is largely due to the quantity and behavior of this compound that steels can be heat-treated to various degrees of strength and toughness. This fact is equally true of both plain carbon and alloy steels. Within certain limitations, the higher the carbon content of steel is, the greater will be the ultimate strength, the hardness, and the range through which it can be heat-treated. At the same time, the ductility, malleability, toughness, impact resistance, and the weldability will be reduced as the carbon increases. In selecting a steel for a given design, the carbon content must be considered: a low-carbon steel is necessary if deep drawing or excessive mechanical working are required without excessive strength, and a high-carbon steel is necessary where great hardness is required and ductility is not important. In general, low-carbon steels are used for formed fittings and welded parts, and high-carbon steels for springs. The medium-carbon steels are used for forged fittings and tie-rods where good strength, combined with ductility, is required.

Manganese. Next to carbon, manganese is the most important ingredient in steel. Its primary purpose is to deoxidize and desulfurize the steel to produce a clean, tough metal. It deoxidizes by eliminating ferrous oxide, which is a harmful impurity; and it combines with sulfur to form manganese sulfide, which is harmless in small amounts. Sufficient manganese is added to the steel to leave an excess of no more than 1% in the metal. This excess magnitude exists as manganese carbide (Mn_3C), which has characteristics in hardening and toughening the steel similar to those of cementite (Fe_3C), although not to as great an extent. Manganese does possess the property known as "penetration hardness" which means that in heat treatment of large sections, the hardness is not merely on the surface but penetrates to the core as well. In addition, the presence of manganese will greatly improve the forging qualities of the steel by reducing brittleness at forging and rolling temperatures.

An excess of more than 1% of manganese will increase the brittleness of the metal. There is, however, a manganese steel containing approximately 13% manganese that is exceptionally hard and ductile; but it is too hard to cut and must be forged, rolled, or cast to practically the finished shape. Some finishing may be done by grinding. This material was used at one time for tail-skid shoes on aeroplanes, which were cast to size. Commercially it is used for rock-crusher jaws and railroad curves. It has the interesting property of being nonmagnetic.

Silicon. Only a very small amount, not exceeding 0.3% of silicon, is present in steel. It is an excellent deoxidizer, but it also has the property of combining with iron more readily than carbon. Therefore it must be limited. A small amount of silicon improves the ductility of the metal. Its main purpose, however, is to produce a sound metal.

Silicon and manganese in large amounts are used as alloying elements in the formation of silico-manganese steels. These steels have good impact resistance.

Sulfur. Sulfur is a very undesirable impurity which must be limited in amount to not more than 0.06%. The maximum permissible sulfur content is always specified in the chemical specification for any particular steel. The presence of sulfur renders steel brittle at rolling or forging temperatures. In this condition the steel is said to be "hot short." As stated previously, manganese combines with the sulfur to form manganese sulfide, which is harmless in small amounts. When too much sulfur is present, an iron sulfide is formed which, because of its lower melting point, is in liquid form at the forging temperature of the steel. This liquid ingredient breaks up the cohesion of the crystals of the metal, hence cracking and breaking result. With a minimum of 0.30% manganese present (as usually specified) and not more than 0.06% sulfur, all the sulfur will be in the form of manganese sulfide, which is harmless in such small quantities.

Phosphorus. Phosphorus, like sulfur, is an undesirable impurity limited in amount to not more than 0.05%. The maximum permissible content is always specified. Phosphorus is believed responsible for "cold shortness" or brittleness when the metal is cold. Below the 0.05% specified there is little, if any, brittleness in the steel. There is some evidence that very small amounts of phosphorus increase the strength slightly.

Nickel. Nickel is a white metal almost as bright as silver. In the pure state it is malleable, ductile, and weldable. It does not corrode quickly, as attested by its use in nickel plating. Nickel dissolves in all proportions in molten steel. The commonly used nickel steels contain from 3% to 5% nickel. The addition of nickel to steels increases the strength, yield point, and hardness without materially affecting the ductility. In heat treatment the presence of nickel in the steel slows down the critical rate of hardening which, in turn, increases the depth of hardening and produces a finer grain structure. There is also less warpage and scaling of heat-treated nickel-steel parts. Nickel increases the corrosion resistance of the steel. It is one of the principal constituents of the so-called "stainless" or corrosion-resisting steels.

Chromium. Chromium is a hard gray metal with a high melting point. Chromium imparts hardness, strength, wear resistance, and corrosion resistance to steel. It also improves the magnetic qualities to such an extent that chromium steel is used for magnets. Chromium possesses excellent "penetration hardness" characteristics and its alloys heat-treat well. The main use of chromium in alloys is in conjunction with nickel, molybdenum, and vanadium. About 1% of chromium is present in these alloys, which are strong, hard, and have fair ductility. These alloys are also resistant to shock loads. It is possible to heat-treat nickel-chromium alloys to an ultimate tensile strength as high as 250,000 p.s.i. and still retain ductility.

Corrosion-resisting steels contain large amounts of chromium. The most common of these steels is 18-8 steel—approximately 18% chromium and 8% nickel. This metal is very corrosion resistant. At the same time, it is practically nonmagnetic although some chromium steels are used for magnets and nickel in its pure state is magnetic. This material furnishes an excellent example of the fact that the alloy does not necessarily retain the properties of the constituents.

Some chromium alloys are used where great wear resistance is required. Thus a chrome-vanadium alloy is used for ball bearings, and a tungsten-chromium alloy for high-speed cutting tools.

Molybdenum. Molybdenum is a very effective alloying element. A small percentage has as much effect as much larger amounts of other alloying elements. It improves the homogeneity of the metal and reduces the grain size. It also increases the elastic limit, the impact value, wear resistance, and fatigue strength. An exceptionally important property from the aircraft viewpoint is the improvement in the air-hardening properties of steel containing molybdenum. This property is particularly useful where the steel has been subjected to a welding process, as is very common with chrome-molybdenum steel in airplane construction. In general it may be said that while molybdenum is one of the most recently used alloying elements, it shows great promise and without doubt will find many new applications in the near future. The molybdenum steels are readily heat-treated, forged, and machined.

Vanadium. Vanadium is the most expensive of the alloying elements. It is seldom used in amounts over 0.20%, but it is an intensive deoxidizing agent and improves the grain structure and fatigue strength. Vanadium also increases the ultimate strength, yield point, toughness, and resistance to impact, vibration, and stress reversal. These latter qualities are identical with fatigue strength and are the basis for using vanadium alloys for propeller hubs and engine bolts. The vanadium alloys, as used generally, contain about 1% chromium and are called chrome-vanadium steel. These steels have good ductility, along with high strength.

Tungsten. Tungsten steels have no direct application in aircraft construction, but they possess an interesting property known as "red hardness." "High-speed steel" is a tungsten-chromium steel used for tools which will retain their cutting edge even when heated to dull redness by working. This tool steel contains from 14% to 18% tungsten, and 2% to 4% chromium.

Titanium. Titanium is often added in small quantities to 18-8 corrosion-resisting steel to reduce the embrittlement at the operating temperatures of exhaust stacks and collectors.

S.A.E. STEEL NUMBERING SYSTEM

In the United States the Society of Automotive Engineers Numbering System is commonly used to designate the steels used in aircraft and automotive construction. By means of a simple numerical system the composition of the steel is partially identified. Unfortunately, only the major alloying element is so identified, but no additional information could be included without destroying the simplicity of the scheme now in use. As explained by the S.A.E., the system is as follows:

A numeral index system is used to identify the compositions of the S.A.E. steels, which makes possible to use numerals on shop drawings and blueprints that are partially descriptive of the composition of material covered by such numbers. The first digit indicates the type to which the steel belongs; thus "1-" indicates a carbon steel; "2-" a nickel steel; and "3-" a nickel-chromium steel. In the case of the simple alloy steels the second digit generally indicates the approximate percentage of the predominant alloying element. Usually the last two or three digits indicate the average carbon content in "points" or hundredths of 1%. Thus "2340" indicates a nickel steel of approximately 3% nickel (3.25 to 3.75) and 0.40 per cent carbon (0.38 to 0.43).

TABLE 2. S.A.E. Steel Numbering System

Type of Steel	*Numerals (and Digits)*
Carbon steels	1xxx
Plain carbon	10xx
Free cutting (screw stock)	11xx
Manganese steels	13xx
Nickel steels	2xxx
3.50% nickel	23xx
5.00% nickel	25xx
Nickel-chromium steels	3xxx
1.25% nickel; 0.60% chromium	31xx
1.75% nickel; 1.00% chromium	32xx
3.50% nickel; 1.50% chromium	33xx
Corrosion- and heat-resisting steels	30xxx
Molybdenum steels	4xxx
Carbon molybdenum	40xx
Chromium molybdenum	41xx
Chromium-nickel molybdenum	43xx
Nickel molybdenum; 1.75% nickel	46xx
Nickel molybdenum; 3.50% nickel	48xx
Chromium steels	5xxx
Low chromium	51xx
Medium chromium	52xxx
Corrosion- and heat-resisting	51xxx
Chromium-vanadium steels	6xxx
1% chromium	61xx
Nickel-chromium-molybdenum steels	8xxx
0.55% nickel; 0.50% chromium: 0.20% molybdenum	86xx
0.55% nickel; 0.50% chromium; 0.25% molybdenum	87xx
Silicon-manganese steels	9xxx
2% silicon	92xx

NOTE: The prefix X was used in the past of denote variations in the range of manganese, sulfur, or chromium. In the interest of simplification prefixes have been eliminated and variations of a standard composition are given a different number.

In some instances, in order to avoid confusion, it has been found necessary to depart from this system of identifying the approximate alloy composition of a steel by varying the second and third digits of the number. An instance of such departure is the steel numbers selected for several of the corrosion- and heat-resisting alloys

AIR FORCE-NAVY AERONAUTICAL SPECIFICATIONS

AN Aeronautical Specifications are prepared by the Permanent Working Committee of the Aeronautical Board. These specifications supersede the individual Army and Navy specifications. AN aero specifications have not yet been issued for all aircraft materials but have been listed in the following pages insofar as possible. The nomenclature of these specifications originally was the same as Federal specifications with AN prefixed. Thus we have

AN-QQ-S-689-Steel; Chrome-Molybdenum 2330 bar

where AN— indicates "Army-Navy (Aeronautical) Standard."
QQ— indicates the Federal Standard Stock Catalogue group for procurement.
S— indicates first letter of first word in specification title, which in this case is "Steel."
689— is a serial number determined by order of issue.

Current issues of AN Aeronautical Specifications omit the Federal Standard Catalogue letters. Thus we have

AN-A-12—Aluminum Alloy 2024 Plate, Sheet, and Strip

MILITARY SPECIFICATIONS

Military Specifications (MIL) are developed jointly by the technical services of the Army, Navy, and Air Force, and are issued by the Munitions Board Standards Agency. MIL specifications are identified by a symbol which is divided into three parts. Thus we have

MIL-R-5674—Rivets, Aluminum & Aluminum Alloy

where MIL— indicates Military Specification
R— indicates first letter of first word in title, which in this case is "Rivet"
5674— is a serial number

Military specifications are gradually superseding all others for military use.

CHAPTER IV

AIRCRAFT STEELS
PROPERTIES AND USES

Up until a few years ago mild carbon steel was about the only steel used in aircraft construction. It was used for fittings, fuselages, brace struts for landing gears and wings, and wherever else a piece of metal was required. As airplane construction developed and became more complex, other steels with higher strengths and specialized properties were made available and utilized. There are now some twenty different kinds of steel regularly used in aircraft construction. In order to select the proper steel for a given purpose, the designer must know the capabilities of all available steels. This chapter will be devoted to describing the commonly used steels in as much detail as possible.

In selecting a type of steel for use, the designer must first assure himself that it possesses the requisite mechanical properties to withstand the loads and service conditions it will be subjected to. The steel chosen must also be capable of ready fabrication into the desired shape. Other important considerations are the availability and the cost of the material. These latter points can be quickly determined through the company's purchasing agent or the nearest supply house.

It is common practice in aircraft construction to heat-treat or case-harden steel to obtain desirable properties. Whenever there is a choice of two materials, it is advisable to select the one requiring the less severe treatment in order to avoid as much distortion or cracking as possible. Detailed descriptions of the heat-treating and surface hardening of steel are given in later chapters.

Table 3 summarizes the steels used in aircraft construction. This table lists the S.A.E. number, the AN Aeronautical, the Navy, and the Army Specification by which the various steels are designated. It also gives the standard forms in which the material is available and the general use of each material.

For simplicity the steels will hereafter be designated only by their S.A.E. number. The description of each steel will include its specific uses, general characteristics as regards machining, forming and welding, and physical properties.

Table 4 gives the chemical composition of the steels as specified by the S.A.E. Individual metallurgists and government specifications often limit the

TABLE 3. Summary of Aircraft Steels

S.A.E. Number	Shape	Specifications	General Use
1045	Wire	QQ-W-461	Tie rods
1095	Bar	AN-S-5a	Drill rod
	Sheet	AN-QQ-S-666	Flat sheet springs
	Wire	QQ-W-474a (Comp C)	Small springs
		QQ-W-470 (Cl B)	Small springs
2317	Bar	QQ-S-624	Casehardened parts
2330	Bar	AN-QQ-S –689a	Machined parts, bolts
2515	Bar	QQ-S-24	Casehardened parts
3115	Bar	QQ-S-624	Casehardened parts
3140	Bar	AN-QQ-S-690	Machined parts
3150	Bar	QQ-S-624	Gears and spline
3310	Bar	QQ-S-624	Casehardened parts
4037	Bar	AN-S-9a	Bolts
4130	Bar	MIL-S-6758	Structural fittings
	Sheet	MIL-S-18729	Structural sheet fittings
	Tubing, seamless	MIL-T-6736	Structural tubing
	Tubing, welded	MIL-T-6731	Structural tubing
4135	Tubing	MIL-T-6735	Structural tubing
4140	Bar	MIL-S-5626	Structural fittings
4340	Bar	MIL-S-5000a	Structural fittings, etc.
4615	Bar	QQ-S-624	Casehardened parts
6135	Bar	MIL-S-5694	Forged parts, propeller hubs
6150	Bar	AN-QQ-S-687	Propeller cones, snap rings
	Wire	AN-S-58	Springs
6195	Bar	AN-QQ-S-688a	Ball bearings
8620	Bar	AN-S-13-B	Casehardened parts
8630	Bar	MIL-S-6050	Structural fittings
	Sheet	MIL-S-18728	Structural fittings
	Tubing, seamless	MIL-T-6732	Structural tubing
	Tubing, welded	MIL-T-6734	Structural tubing
8735	Bar	MIL-S-6098	Structural fittings
	Sheet	MIL-S-18730	Structural fittings
	Tubing	MIL-T-6733	Structural tubing
8740	Bar	MIL-S-6049	Structural fittings
9260	Wire	QQ-S-474a (Comp E)	Springs
Silicon-chromium	Rod	46-S-31	Springs
Nitriding Steel	Forgings	MIL-S-6709	Nitrided parts
HY-TUF	Bar Forgings	AMS-6418 MIL-S-7108	Landing gear parts and structural fittings
4330 Modified	Bar	MIL-S-8699	Structural fittings
	Forgings	AMS-6427	Structural fittings

TABLE 4. Chemical Composition of Aircraft Steels

S.A.E. number	Carbon (%)	Manganese (%)	Phosphorus (%, max)	Sulfur (% max.)	Nickel (%)	Chromium (%)	Molybdenum (%)	Vanadium (%)	Silicon (%)
1015	.13–.18	.30–.60	.045	.055					
1020	.18–.23	.30–.50	.040	.050					
1025	.22–.28	.30–.50	.040	.050					
1035	.32–.38	.60–.90	.040	.050					
1045	.40–.50	.60–.90	.045	.055					
1095	.90–1.05	.25–.50	.040	.055					
2317	.15–.20	.30–.60	.040	.050	3.25–3.75				
2330	.28–.33	.60–.80	.040	.040	3.25–3.75				
2515	.10–.20	.30–.60	.040	.050	4.75–5.25				
3115	.10–.20	.30–.60	.040	.050	1.00–1.50	.45–.75			
3140	.35–.45	.60–.90	.040	.050	1.00–1.50	.45–.75			
3250	.45–.55	.30–.60	.040	.050	1.50–2.00	.90–1.25			
3312	.17 max.	.30–.60	.040	.050	3.25–3.75	1.25–1.75			
4037	.35–.40	.40.–60	.040	.050			.15–.25		
4130	.35–.40	.75–1.00	.040	.040		.80–1.10	.20–.30		.20–.35
4135	.30–.40	.40–.70	.040	.050		.80–1.10	.15–.25		
4140	.35–.42	.60–.90	.040	.050		.80–1.10	.15–.25		
4340	.35–.45	.60–.80	.040	.050	1.65–2.00	.60–.90			
4615	.10–.20	.40–.70	.040	.050	1.65–2.00		.20–.30		
6115	.10–.20	.30–.60	.040	.050		.80–1.10		.15–.20	
6135	.30–.40	.50–.80	.040	.045		.80–1.10		.15–.25	
6150	.48–.55	.60–.90	.040	.040		.80–1.10		.15–.20	.20–.35
6195	.90–1.05	.20–.45	.030	.035		.80–1.10		.15–.20	
8620	.18–.23	.70–.90	.040	.040	0.40–0.70	.40–.60	.15–.25		.20–.35
8630	.27–.33	.70–.90	.040	.040	0.40–0.70	.40–.60	.15–.25		.20–.35
8735	.33–.38	.75–1.00	.040	.040	0.40–0.70	.40–.60	.20–.30		.20–.35
8740	.38–.43	.75–1.00	.040	.040	0.40–0.70	.40–.60	.20–.30		.20–.35
9260	.55–.65	.70–.90	.040	.040					1.80–2.20
silicon-chromium	.45–.50	.70–.90	.040	.040		.25–.35		.18 min	3.00–3.50
					Selenium %			Aluminum %	
nitriding steels	.38–.45	.40–.70	.040	.050		1.40–1.80	.30–.45	.85–1.20	.20–.40
	.30–.40	.50–1.00	.040	.060	0.15–0.35	1.00–1.50	.15–.25	.85–1.20	.20–.40
Austentic manganese steel	1.00–1.40	10.0 min.	.100	.050					
HY–TUF	.23–.28	1.20–1.50	.04	.04	1.65–2.00	.20–.40	.35–.45		1.30–1.70
4330 modified	.28–.33	.80–1.00	.04	.04	1.65–2.00	.75–.95	.35–.50	.05–.10	.20–.35

phosphorus and sulfur content to less than that listed, but in other respects the specifications are about the same.

CARBON STEELS

S.A.E. 1015. A galvanized (zinc-coated) steel wire is made from this material. It is used as a locking wire on nuts and turn-buckles and for serving nonflexible cable splices. This wire has a maximum tensile strength of 75,000 p.s.i. and a minimum elongation of 8 to 10%.

S.A.E. 1020. This steel is used for casehardened parts. In this form it is often used for bushings that must resist abrasion. It is also employed in the fabrication of stamping dies that require a hard, wear-resisting surface. When casehardened, this steel has a core strength of 60,000 p.s.i. and good ductility. In its normal state it has an ultimate tensile strength of 55,000 p.s.i., a yield strength of 36,000 p.s.i., and an elongation of 22%. This steel machines well. It can be brazed or welded.

S.A.E. 1025. This steel is commonly referred to as mild carbon steel or cold-rolled stock. For aircraft purposes the sheet is always purchased cold rolled to accurate dimensions. Bar stock is either cold rolled or cold drawn. For most purposes this steel has been superseded by chrome-molybdenum steel, S.A.E. 4130. It is still used for aircraft nuts and similar standard parts, however, and also for nonstructural clamps requiring a lot of bending.

In all its forms this steel has an ultimate tensile strength of 55,000 p.s.i., a yield strength of 36,000 p.s.i., and an elongation of 22%. When used for aircraft nuts, it is heat-treated and develops a minimum strength of 70,000 p.s.i.

In sheet form this material can be bent through 180° without cracking over a diameter equal to the thickness of the test section. The same thing can be done with bar stock over a diameter equal to twice the thickness of the test section.

This material machines fairly well. It can be brazed or welded.

S.A.E. 1045. This steel, obtainable as cold-drawn wire, is used for the fabrication of aircraft tie-rods. It is also procured as annealed bar for general machining and forging purposes in the manufacture of parts requiring greater strength than S.A.E. 1035 steel. Parts fabricated from the bar stock cannot be bent cold and must be heat-treated after fabrication.

PHYSICAL PROPERTIES

	Cold-drawn wire	*Heat-treated bar*
Ultimate tensile strength (p.s.i.)	140,000	100,000
Yield strength (p.s.i.)		70,000

The cold-drawn wire must withstand a reverse bend test in which it is bent back and forth 90° each way over a round surface with a radius three times the thickness of the wire. It must withstand seven of these 90° bends without failure. The cold-drawn wire may be cold-swaged or cold-drawn as required in the manufacture of tie-rods.

The bar stock machines well. It also has good surface hardness and wears well after heat treatment. Chain sprockets, hubs, and crankshafts are made from it.

S.A.E. 1095. This high-carbon steel is obtainable in all of the following forms:

Spring steel (sheet or strip) annealed is used for flat springs which are heat-treated after forming. As purchased the strip is cold-rolled and uniformly annealed. The annealed material can be bent flat over a diameter equal to its thickness. It is universally used for flat springs in aircraft work.

MIL-W-6101 spring steel (wire) heat-treated is a standard grade of music wire and is used in the fabrication of small springs. It is obtainable from 0.005- to 0.180-inch diameter, with a variation in tensile strength of 350,000 to 225,000 p.s.i., respectively, for these two extreme sizes. It is purchased in the heat-treated state and can be coiled into springs as received. After coiling the spring should be strain-relieved by heating for approximately one hour at a temperature of 325 to 375°F.

QQ-W-465 steel wire, high strength is a cold-drawn zinc-coated wire from 0.032- to 0.306-inch diameter, with a tensile strength varying from 308,000 to 209,000 p.s.i. for these two diameters. This wire is particularly good for hinge pins and in other locations where music wire is ordinarily used.

Bar stock is used for parts subject to high shear or wear if casehardening is not desirable. It is sometimes referred to as drill rod since it is employed in the manufacture of drills, taps, and dies. Bar stock is purchased in the annealed state when it is to be machined and then heat-treated. Drill rod is used for hard pins, keys, etc.

NICKEL STEELS

S.A.E. 2317. This is a carburizing steel with a moderately strong core. Its case has excellent wear- and fatigue-resisting characteristics, and its relatively low quenching temperature results in less distortion. Quenching in oil also reduces the distortion and gives a file-hard case. Thin sections should not be manufactured from this steel because of its strong core. It is used to produce bushings, trunnions for mounting machine guns, and other parts requiring a wear-resisting surface combined with a shock-resistant core of moderate strength. The normal core strength is 80,000 p.s.i.

This steel machines very well. It must, of course, be machined before casehardening. After casehardening it is ground to the finished dimensions.

S.A.E. 2330. This is the standard nickel steel and possesses good strength and great toughness. It can be purchased as bar stock in the forged, rolled, annealed, normalized and annealed, or heat-treated condition. If not purchased in the heat-treated condition it is heat-treated after fabrication. It is used for high-grade machined parts, such as aircraft bolts, turnbuckle eyes and forks, and tie-rod terminals. When heat-treated to 125,000 p.s.i. and 150,000 p.s.i. respectively, it has the following physical properties:

Ultimate tensile strength (p.s.i.)	125,000	150,000
Yield strength (p.s.i.)	100,000	120,000
Elongation (%)	17	15

Aircraft bolts are heat-treated to 125,000 p.s.i. ultimate strength.

This steel can be bent flat over a diameter equal to its thickness. It also has very good machining properties.

S.A.E. 2515. This is a carburizing steel with an extremely high-strength core. The case is not as hard as that obtained with other carburizing steels. If extreme core toughness is desired, S.A.E. 2512 steel should be used. In this steel the carbon content is limited to 0.17% maximum. It is used for engine gears, knuckle pins, and other applications requiring high-strength core and good wearing qualities. By proper heat treatment, a core strength of 120,000 to 160,000 p.s.i. is obtainable.

This steel machines fairly well but not as good as S.A.E. 2320.

NICKEL-CHROMIUM STEELS

S.A.E. 3115. This is a carburizing steel with an exceedingly hard wear-resisting surface and a tough core. Generally, it is used in engine construction for gear pins, piston pins, cam rings, push rod ends, and rollers. It has a core strength of 85,000 p.s.i.

This steel machines well.

S.A.E. 3140. This steel heat-treats exceptionally well and, consequently, is used for many structural parts requiring high strength and good fatigue qualities. It also has good creep resistance up to 1000°F.

Wing-hinge fittings, lift-wire trunnions, engine bolts and studs are its chief uses. For these applications it is usually heat-treated to 125,000 or 150,000 p.s.i.

Ultimate tensile strength (p.s.i.)	125,000	150,000	180,000
Yield strength (p.s.i.)	100,000	120,000	150,000
Elongation (%)	19	17	12

This steel machines well at heat treatments up to 150,000 p.s.i.

S.A.E. 3250. This is a high-carbon chrome-nickel steel used for high-strength machined or forged parts subject to severe wear. But casehardened steels are employed to a large extent instead of this steel, because they wear better and crack less in heat treatment. S.A.E. 3250 is used. however, for axle shafts, gears, spline shafts, and other parts for heavy-duty work. It has high strength and is very hard, and can be heat-treated to a tensile strength as high as 220,000 p.s.i. with a yield strength of 200,000 p.s.i.

S.A.E. 3312. This is a carburizing steel with a strong, tough core similar to S.A.E. 2512. It is used for wrist pins, starter jaws, timing gears, rear axles and transmission gears for heavy-duty trucks.

Its core strength is 100,000 p.s.i.

MOLYBDENUM STEELS

S.A.E. 4037. This is a molybdenum steel that has been used as a substitute for 2330 nickel steel in the manufacture of bolts, terminals, clevises, pins, and similar parts. It is normally heat-treated to an ultimate tensile strength of 125,000 p.s.i., a yield strength of 100,000 p.s.i., and an elongation of 17%.

S.A.E. 4130. This is chrome-molybdenum steel which has been generally adopted in aircraft construction for practically all parts made of sheet and tubing. Bar stock of this material is also used for small forgings under ½ inch in thickness. The general use of this steel is due to its excellent welding characteristics, its ease of forming, its response to heat treatment, and its availability in all sizes of sheet and seamless drawn tubing. The standard sizes of round and streamline tubing are given in the Appendix.

It is customary to specify this steel for all parts of an airplane fabricated from steel unless some special property possessed by one of the other steels is required. Chrome-molybdenum steel is used for all welded assemblies, for sheet fittings, and for landing-gear axles. Fuselages and landing gears are common examples of welded assemblies made of chrome-molybdenum steel. Sheet metal fittings can be readily fabricated from it because of its excellent forming characteristics. The landing-gear axles are formed from chrome-molybdenum tubing heat-treated to 180,000 p.s.i.

Sheet and tubing are usually purchased in the normalized state. In this condition the following physical properties can be expected:

SHEET

Ultimate tensile strength (p.s.i.)	90,000
Yield strength (p.s.i.)	70,000
Elongations: over 3/16-inch thick (%)	20
1/8 to 3/16-inch	15
1/16 to 1/8-inch	12
less than 1/16-inch	10

TUBING

Property	Wall thickness		
	Up to 0.035"	0.036" to 0.186"	Over 0.186"
Ultimate tensile strength (p.s.i.)	95,000	95,000	90,000
Yield strength (p.s.i.)	75,000	75,000	70,000
Elongation: full tube (%)	10	12	15
strip (%)	5	7	10

When heat-treated this material has the following physical properties:

U.t.s.	Yield strength	Shear	Bearing
125,000	100,000	80,000	175,000
150,000	125,000	100,000	190,000
175,000	140,000	115,000	200,000
200,000	150,000	125,000	210,000

Only 80% of these values should be taken if the part has been welded.

The following tabulation gives the minimum acceptable elongation for heat-treated chrome-molybdenum steel of various thicknesses:

MINIMUM ELONGATION IN 2 INCHES (%)

Diameter or thickness, inches	Ultimate tensile strength			
	125,000	150,000	175,000	200,000
Up to .028	2.0	1.5	1.0	1.0
.029–.067	4.0	2.5	1.5	1.0
.068–.124	6.5	5.0	3.0	2.0
.125-.254	9.0	7.0	5.0	4.0
Over .254	10.5	8.5	5.5	4.5

An examination of the elongation table will show that material .065 inch thick or less has a very low elongation when heat-treated above 150,000 p.s.i. This low elongation is a mark of brittleness. For this reason it is a good rule never to heat-treat material .065 inch or less in thickness above 150,000. Parts subject to vibration, such as control-system parts, should not be heat-treated above 125,000. If heat-treated above this value, under constant vibration any small flaws in the material will develop into cracks. It is customary to treat wing-hinge fittings to 150,000 p.s.i.; landing gear parts are heat-treated to 165,000 p.s.i.

Chrome-molybdenum welds readily with the oxyacetylene flame, and it may also be electric arc-welded when over 1/16 inch thick. Heat-treated parts, however, cannot be welded without destroying the heat treatment. Welding will reduce the strength of normalized metal in the region adjacent to the

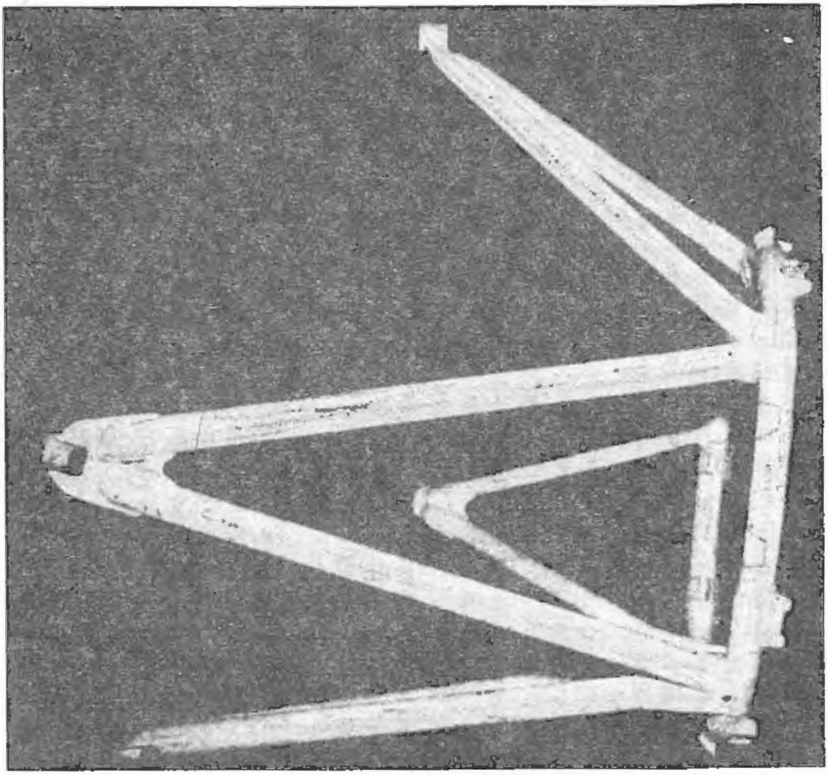


FIGURE 9. Engine Mount: Chrome-molybdenum Sheet, Tubing, and Forgings

weld that was heated to a temperature just below the critical range of the steel. It is desirable to normalize all welded parts after fabrication to regain the loss in strength and to relieve the internal stresses set up by the welding. These stresses are due to the fact that welding shrinks the metal. Rigid jigs must be used in welding up sheet or tubular assemblies to keep this shrinkage under control.

Chrome-molybdenum sheet may be bent cold through an angle of 180° over a diameter equal to its own thickness. The government specifications require this steel to pass this bend test either across or parallel to the grain of the metal. In fabricating fittings, however, bends should always be made across the grain, and the direction of greatest stress should be along the grain. If this is done, there is less likelihood of cracking or failure of the fitting in fabrication or due to fatigue stresses in service. When the fabrication processes involve severe forming, it is advisable to anneal the steel and then normalize or heat-treat the finished assembly.

Chrome-molybdenum can be brazed, but this process is seldom used nowadays in aircraft construction.

S.A.E. 4135. This is a chrome-molybdenum steel with a higher carbon content than the standard 4130 steel. Due to this higher carbon content it can be heat-treated to higher strengths. In aircraft work it is used primarily for heavy wall tubing requiring high strength. To avoid welding cracks this type of material should be preheated before welding.

This material can be heat-treated to an ultimate tensile strength of 200,000 p.s.i., a yield strength of 165,000 p.s.i., and an elongation of 7%. On thicknesses over 3/16 inch it may be necessary to water-quench to obtain high heat-treat properties.

S.A.E. 4140. This is a chrome-molybdenum steel containing a higher carbon and manganese content than 4130 steel. The higher carbon and manganese content improves the heat-treating properties of the steel and enables great strength and hardness to be obtained with thick sections. This steel is used for structural machined and forged parts over ½ inch in thickness, and is obtainable as bar stock in any one of the following conditions: forged, rolled, normalized or heat-treated. It is, however, usually purchased in the normalized condition, machined to shape, and then heat-treated. Forgings are always normalized or heat-treated after fabrication.

S.A.E. 4140 is used for wing-hinge fittings, flying-wire trunnions, and other similar fittings in aircraft requiring great strength. Forgings of this steel are very commonly used. The physical properties of this material are the same as those given for S.A.E. 4130 sheet stock. Bars 1½ inch thick or over in the normalized condition have slightly less strength—ultimate tensile strength is 85,000 p.s.i. and yield strength is 65,000 p.s.i. It is generally heat-treated to 180,000 p.s.i.

This steel machines without difficulty at heat treatments up to 150,000 p.s.i. It is seldom welded but can be if necessary, although its high manganese and carbon content makes welding more difficult than is the case with 4130 steel.

S.A.E. 4340. This is a nickel-chromium-molybdenum steel with excellent properties. It has very good depth-hardening qualities, which make it ideal for large forgings requiring high strength and hardness throughout, and also has good impact and fatigue resistance at high strengths. It is machinable in the heat-treated state up to 180,000 p.s.i. Propeller hubs, crankshafts, and other large forgings are made from this material. It is the ideal material for highly stressed aircraft parts requiring good hardenability. It is also used interchangeably with S.A.E. 3140.

As ordinarily employed this material has a tensile strength of 180,000 p.s.i., a yield strength of 160,000 p.s.i., and an elongation of 16%. It is sometimes heat-treated as high as 280,000 p.s.i. ultimate strength.

S.A.E. 4615. This is one of the best of the carburizing steels. It has a very fine grain, and usually requires only one quench to develop satisfactory properties. Due to the single quenching operation it distorts less than other carburizing steels. It also machines nicely. Because of its good machining qualities it is used commercially for automatic machine production. It has a file-hard case for resisting wear and is excellent for use in bushings, rollers, and other locations requiring wear resistance and accurate dimensions. A core strength of 80,000 to 100,000 p.s.i. is obtainable with S.A.E. 4615. It has high fatigue resistance in addition to its other good properties.

CHROME-VANADIUM STEELS

S.A.E. 6115. This is a carburizing steel with a core strength of 90,000 p.s.i. It is fine-grained and may be used interchangeably with other carburizing steels.

S.A.E. 6135. This steel is strong and tough, and has high fatigue resistance. It is used for propeller hubs, welded steel propeller blades, and engine bolts and nuts. All these applications require a high fatigue resistance. This steel also machines well. Its physical properties as used in the manufacture of propeller hubs are: ultimate tensile strength, 135,000 p.s.i.; yield strength, 115,000 p.s.i.; elongation, 15%.

S.A.E. 6150. This steel has high strength and fatigue properties. It is used for all important coil springs in aircraft and engine valve springs and is available in rod form from 0.180 to 0.500 inch in diameter. It is purchased in the annealed condition and heat-treated after forming. In bar form this steel is used for propeller cones and snap rings which require good fatigue and machining properties.

Rod for helical springs can be heat-treated to develop the following properties: ultimate tensile strength, 220,000 p.s.i.; yield strength, 200,000 p.s.i., elongation, 6%.

Bar stock is normally heat-treated to develop an ultimate strength of 180,000 p.s.i., yield strength of 170,000 p.s.i., and elongation of 14%.

S.A.E. 6195. This is a high-carbon chrome-vanadium steel which is used for parts subject to high-bearing loads and requiring maximum hardness. Ball bearings, roller bearings, and races are made from it.

S.A.E. 8620. This is a National Emergency (NE) steel which has excellent carburizing properties and is now established as a standard steel. It is comparable to 4615.

S.A.E. 8630. This is an NE steel which is used as an alternate for 4130 chrome-molybdenum steel. It has essentially the same physical properties and processing characteristics and is used interchangeably with 4130 in aircraft construction.

S.A.E. 8735. This is a chrome-nickel-molybdenum NE steel with somewhat better heat-treating characteristics than 8630. It is used for parts requiring somewhat higher strength than that obtainable with 8630 or 4130 and is more comparable with 4140. It can be welded if proper precautions are taken to avoid cracking.

S.A.E. 8740. This is a chrome-nickel-molybdenum NE steel with a higher carbon content than 8735 and is used as an alternate for 4140 in the manufacture of parts requiring high heat-treat strength.

S.A.E. 9260. This is a silicon NE steel that has been used as an alternate for 6150 in the manufacture of heavy-duty springs.

SPECIAL STEELS

Silicon-Chromium Steel. Important springs are manufactured from this high-strength steel which may be obtained in rod form. For this purpose it is interchangeable with 6150 steel. It can be heat-treated to an ultimate tensile strength of 200,000 p.s.i., a yield strength of 180,000 p.s.i. and an elongation of 6%.

Nitriding Steel. This is a special steel used only for nitrided parts. In the chapter on Surface Hardening its properties are discussed in detail. It is used for bushings and gears requiring great surface hardness and wear resistance.

Austenitic Manganese Steel. This material is also known as Hadfield's manganese steel. It has exceptional resistance to wear and abrasion and is extremely tough. It is almost impossible to machine and should be cast to size and finished by grinding when necessary. This material has been used for tail skids and for arresting-hook toes.

Hy-Tuf. Hy-Tuf is the trade name for a steel used in the high-tensile strength range of 220,000-240,000 p.s.i. This steel has found wide use in aircraft landing-gear components, arresting hooks, catapult hooks, and structural fittings.

The mechanical properties of Hy-Tuf after being hardened and tempered are:

Ultimate tensile strength (p.s.i.)	230,000
Tensile yield strength (p.s.i.)	194,000
Elongation (in 2 inch gage length)	14%

When steels are specified for aircraft parts requiring high strengths, care should be taken to make all radii as generous as possible. If the processing of high-strength steels is not precisely controlled, premature failure can result. All high-strength steels are very susceptible to failure if poor processing techniques are used. Surface finish, decarburizing, straightening, grinding, plating, and heat treatment all can cause premature failure if not closely controlled. Hy-Tuf is covered by specification AMS 6418. The fatigue strength of Hy-Tuf is shown in Figure 10.

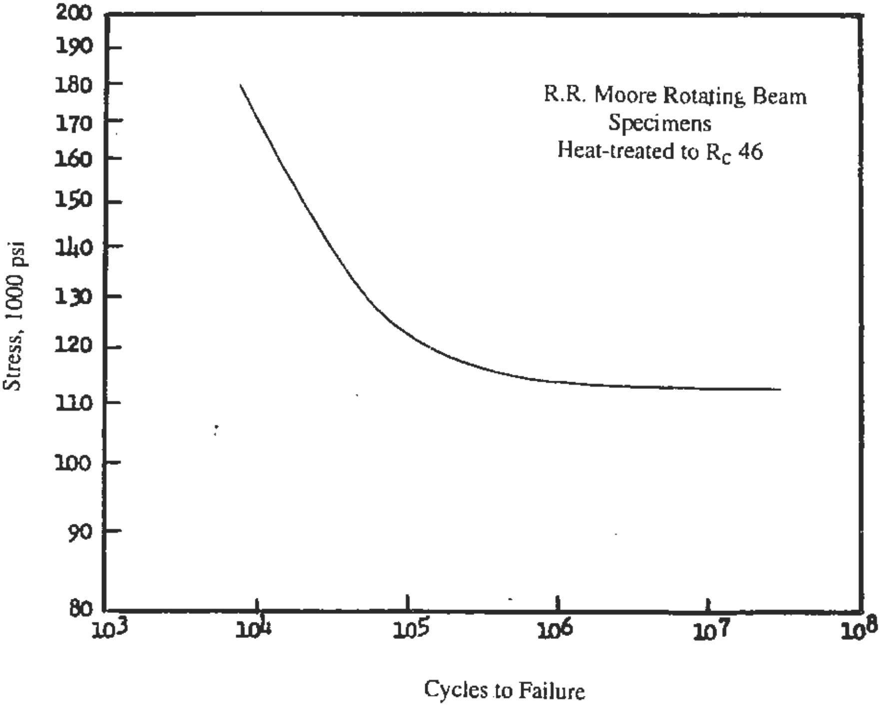


FIGURE 10. Fatigue Properties of Hy-Tuf

S.A.E. 4330 (Vanadium Modified). Vanadium-modified S.A.E. 4330 is another steel which was developed for use at a tensile range of 220,000–240,000 p.s.i. This steel is available in all standard mill forms and should be handled in the machine shop in a similar manner to S.A.E. 4340. Specification AMS 6427 covers this material which is finding wide use for landing gear components, tail bumpers, structural fittings, arresting hooks, and many other parts. AMS 6427 steel can be flash-welded or pressure-welded with resultant weld strengths approximately equal to the parent metal strength.

The specified mechanical properties for AMS 6427 are:

Ultimate tensile strength (p.s.i.)	220,000
Tensile yield strength (p.s.i.)	190,000
Elongation in 4D	10%

This steel is also susceptible to failure if the processing is not carried out in exacting detail. When specifying steel of this type, the following maximum section thicknesses should not be exceeded.

Shape	*Maximum Thickness*
Bar round	2 in.
Bar square	2 in.
Bar rectangular	1.5 in.
Plate	1.5 in.
Tubing	750 in.*

* Dimensions apply to wall thicknesses. When tubes have minimum I.D. of 1 inch and are fully open at both ends, to permit quenching on the inside, the dimension may be doubled.

CHAPTER V

HEAT TREATMENT OF STEEL

IT HAS long been known that a great variation in the properties of steel could be obtained by heating the metal to a high temperature and quenching quickly in a liquid, such as brine, water, or oil. Unfortunately, each alloy required a different treatment, and since the actual effects were not understood, the whole science of heat treatment was a hit-or-miss affair. Recently a new science known as "metallography" has been developed; it deals with the internal structure of metals and the principles underlying changes in structure. By means of etching and microscopic examination the internal structure of steel in all its various states has been studied. Due to these studies and the work of numerous investigators heat treatment is today an exact science.

Heat treatment of steel is based upon the fact that the metal has a crystalline structure which assumes different forms at various temperatures. The change in structure as the temperature decreases is normally slow, and it has been found that by rapid cooling, such as dropping the hot metal in a cold liquid, the normal structure at high temperatures can be retained at atmospheric temperatures. This new structure has totally different physical properties from the normal atmospheric-temperature structure. Numerous variations are possible, depending upon the temperature from which the metal is quenched and the speed of quenching. The practical terms which describe the heat treatments normally used are: annealing, normalizing, hardening, drawing. In addition to these we have special treatments called carburizing, cyaniding, and nitriding. To develop the desired properties all aircraft steels are subjected to one or more of these operations. This chapter will be devoted to the theory and practical applications of heat-treating.

CRITICAL RANGE

Materials are said to be allotropic when they possess the property that permits them to exist in various forms without a change in chemical composition. Carbon, which exists as diamond, graphite, and charcoal, is a common allotropic substance. Pure iron is also allotropic, existing in three states: namely, *alpha*, *beta*, and *gamma* iron. In this case each of these states is stable only between very definite temperature limits—alpha iron up to 1400°F., beta iron from 1400°F. to 1652°F., and gamma iron above the latter temperature.

When molten iron solidifies and is permitted to cool at a uniform rate, it is found that at 1652°F. the cooling stops momentarily. At this point a change in the structure of the iron has taken place, in which gamma iron has been transformed into beta iron. This rearrangement of the structure has resulted in the evolution of heat, which accounts for the retardation of the cooling. This point is designated by the symbol Ar_3 and is called the *upper critical point*. As the cooling continues, it is found that a second retardation occurs at 1400°F. Obviously this is caused by the transformation of beta into alpha iron with the resultant evolution of heat. This point is indicated by Ar_2, the *second critical point.*

In the heating of pure iron similar points occur in which heat is absorbed without a rise in the metal temperature. These points are designated Ac_2 and Ac_3. These heat-absorption points are some 20°F. higher than the respective Ar_2 and Ar_3 points. The critical range is the range of temperature between the lower and upper critical points.

Carbon steels have definite critical points and a critical range. The exact temperature at which these points occur and the number of points depend upon the carbon content of the steel. Low-carbon steels have three critical points. In addition to the preceding two points described for iron, when a small amount of carbon is added to the iron another point designated as Ar_1 occurs at 1274°F. There is, of course, a similar point on a rising heat designated Ac_1. The point Ar_1 is called the *lowest critical point* or the *recalescent point* because the intense evolution of heat causes the metal to glow.

The "*r*" in the symbol *Ar* is derived from the French word *refroidissement,* which means cooling. Similarly, the "*c*" in the symbol *Ac* is the first letter of *chauffage*—heating.

Referring to Figure 11 it can be seen that the number of critical points and the scope of the critical range depend upon the carbon content. There are three critical points up to a little over 0.4% carbon. In this region the two upper critical points merge, forming a single point, Ar_{3-2}. At 0.85% carbon all the critical points unite, and we have one point, Ar_{3-2-1}. Above 0.85% carbon a new point designated Ar_{cm} extends above the Ar_{3-2-1} point.

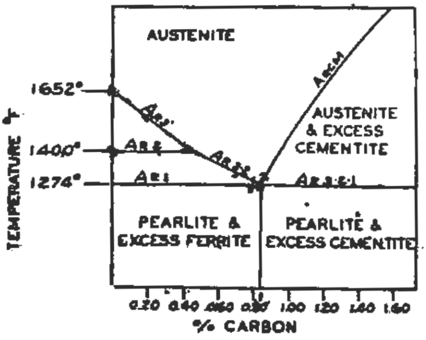


FIGURE 11. Critical Points of Steel

Alloy steels possess similar critical points, but they occur at different temperatures for each steel. Nickel and manganese have the property of materially lowering the critical range. In fact, the 13% manganese steel has a critical range below atmospheric temperatures.

INTERNAL STRUCTURE OF STEEL

The internal structure of steel is almost wholly dependent upon the exact relationship of the iron and carbon. The carbon is in chemical combination with the iron as iron carbide (Fe_3C), called *cementite.* In steels containing 0.85% carbon, the cementite forms a perfect mixture with the pure iron (called ferrite) present. This mixture is called *pearlite* because of its resemblance in appearance to mother-of-pearl. Pearlite is a mechanical mixture of six parts of ferrite to one part of cementite. Steels with less than 0.85% carbon are composed of pearlite and excess ferrite. Practically all aircraft steels are of this type. On the other hand, tool steels which contain more than 0.85% carbon are composed of pearlite and excess cementite.

In metallurgy the name *eutectic alloy* is given to that alloy of two substances which has the lowest fusing point. In every alloy there is one percentage combination of the two elements that will fuse at the lowest temperature. Variation of the percentage composition of either element, up or down, will increase the temperature of fusion. A similar condition exists in steel in the critical range, although here we are dealing with a solid solution. You will note in Figure 11 that the lowest temperature for the upper critical point occurs at 0.85% carbon content. This alloy has been named the *eutectoid.* Steel with less than 0.85% carbon is called *hypo-eutectoid* and with more than 0.85% *hyper-eutectoid.* Steels with excess ferrite are hypo-eutectoid, and steels with excess cementite are hyper-eutectoid.

Pearlite is normally a laminated structure consisting of alternate layers of ferrite and cementite. In some cases pearlite has a granulated appearance and is called granular pearlite. If steel is cooled very slowly through the critical range, laminated pearlite, which is the most stable form, will result. Pearlite is relatively strong, hard, and ductile. It has a tensile strength of over 100,000 p.s.i., an elongation of approximately 10%, and maximum hardening power. This latter point is extremely significant. It means that the greatest hardness from heat treatment is obtained by steel containing 0.85% carbon. It is also true that starting with low-carbon steel, greater hardness is obtainable as the carbon content increases and approaches 0.85%. This point is important when selecting a steel to give great strength and hardness after heat treatment.

Ferrite is pure alpha iron in carbon steels. In alloy steels containing nickel. molybdenum, or vanadium these alloying elements are in solid solution in the ferrite. Ferrite is very ductile and has a tensile strength of about 40,000 p.s.i.

It should be noted that it imparts these properties to low-carbon steels of which it is the major constituent. Ferrite does not have any hardening properties.

Cementitie is iron carbide (Fe_3C). It is very hard and brittle and produces a hardening quality on steels of which it is a part.

Austenite, the name given to steel when it is heated above the critical range, consists of a solid-solution of cementite in gamma iron. It is stable only when maintained at a temperature above the critical range. It will, however, attain perfect homogeneity if sufficient time is allowed. The grain size of steel, it has been found, is smallest just above the critical range, and it is a known fact that the smallest grain size will give the strongest and best metal. For this reason, when steel is heated for subsequent hardening or working, its temperature is kept just above the upper critical point for the time necessary to insure thorough heating of the material.

THEORY OF HEAT TREATMENT

When molten steel solidifies, austenite is formed. As further cooling takes place, the critical range is reached and the austenite goes through a transition until at the lower critical limit the familiar pearlite with excess ferrite or cementite, depending upon the carbon content, is formed. The transition from austenite to pearlite through the critical range is normally a slow operation. It has been found that the transition can be arrested if this operation is speeded up by such means as dropping austenitic steel just above the critical range in cold water or oil. By this means a structure can be produced at atmospheric temperature with physical characteristics different from those which normally would be obtained with slow cooling. This operation is so severe that an extremely hard, brittle material with shrinkage strains is obtained. By reheating the metal below the critical range the normal transition in the critical range is allowed to proceed a little further and shrinkage strains are reduced, thus creating a useful condition of moderate hardness and strength.

Hardening is the name given to the first operation described in the preceding paragraph. It consists in heating steel to just above the critical range, holding the metal at that temperature until thoroughly heated (called soaking), and then rapidly cooling (or quenching) by immersing the hot steel in cold water or oil.

Drawing, or *tempering* as it is sometimes called, consists in reheating of the hardened steel to a temperature well below the critical range, followed by soaking and quenching.

Martensite is the main constituent of hardened steel. It is an intermediate form of the cementite in alpha iron obtained when the transition from austenite to pearlite is arrested. Martensite is the hardest structure obtained in steel.

Troostite is another intermediate form, similar to martensite, which is often present in hardened steels. Troostite is also present in drawn or tempered steels whereas martensite is not.

Sorbite is the third intermediate form between austenite and pearlite. It is the main constituent of drawn steel and gives that type of steel maximum strength and ductility.

Hardened steel consists almost entirely of martensite with some troostite. When the steel is reheated, as in drawing, the martensitic structure breaks down and sorbite, with a small amount of troostite, remains. By varying the drawing temperature, different amounts of troostite and sorbite can be retained, and consequently a variation in physical properties is obtainable.

Heating through the critical range is absolutely necessary to obtain the best refinement of the grain. Fine-grain steel has the best physical properties. As steel is heated above the critical range, the grain becomes coarser. There is a narrow limit of temperature just above the critical range within which steel must be heated if it is to retain its fine-grain structure after quenching. It should be noted that a fine-grain structure is obtained just above the critical range only on a rising heat. If liquid steel is solidified and cooled the finest grain is obtained on solidification and becomes coarser as cooling progresses.

As you will note by referring to Figure 10, it is absolutely necessary to know the chemical content of the steel to establish the critical range and the heat-treatment temperature. Each steel, both carbon and alloy, has its individual critical range which must be definitely known if the best results are to be obtained from heat treatment.

The effects of heating to various temperatures and cooling at different rates may be summarized as follows:

1. When a piece of steel is heated to the upper critical point, Ac_3, it becomes as fine grained as possible no matter how coarse or distorted the grain was previously.
2. After it has been heated to Ac_3, if the steel is allowed to cool slowly, it retains the fine-grained structure and is also soft and ductile.
3. After it has been heated to Ac_3, if the steel is cooled rapidly, as by quenching in cold water, it retains the fine-grained structure and is fully hardened.
4. If steel is heated above Ac_3, permitted to cool to Ac_3, and then quenched, it will be fully hardened but more coarse grained than if it had only been heated to Ac_3 originally.
5. The higher the temperature above Ac_3 from which the steel is cooled, either slowly or rapidly, the coarser the grain. In this case slower cooling will result in coarser grain.
6. When a piece of hardened steel (which has been previously heated to Ac_3 or above, soaked, and quenched) is again heated to somewhere below Ac_1, it is softened but without change in grain size. The softening is greater as the temperature increases up to Ac_1.

Annealing. Annealing of steal is effected by heating the metal to just above Ac_3, soaking at that temperature for a definite time and cooling very slowly in the furnace itself. This treatment corresponds to number 2 just above. The time of soaking is about one hour per inch thickness of material to make certain that all of the material is brought up to temperature. Slow cooling is usually obtained by shutting off the heat and allowing the furnace and metal to cool together down to 900°F. or lower, at which time the steel may be removed from the furnace and cooled in air. An alternate method to restrict the rate of cooling is to bury the heated steel in ashes or lime.

Annealed steel is fine grained, soft, ductile, and without internal stresses or strains. It is readily machinable and workable. In the annealed state steel has its lowest strength. For that reason it is often given a subsequent heat treatment so as to increase the strength after all machining and mechanical work are complete. The ductility of annealed steel is utilized in tube and wire drawing and in rolling sheet. After the steel has passed through the dies or rolls several times, re-annealing is necessary to relieve the stresses induced by the cold work and to prevent cracking.

There are several modifications of the full annealing treatment used when all of the effects are not essential, and speed and economy are important.

Process annealing consists in heating below Ac_1 in the region between 1020° and 1200°F. This treatment is commonly used in the sheet and wire industries to restore ductility.

Spheroidizing is a form of annealing applied particularly to high-carbon steels to improve their machinability. As indicated by the name, a globular cementite structure is obtained. In this form the cementite can be pushed aside by the cutting tool instead of offering great resistance as when present in the laminated form. The operation of spheroidizing consists in prolonged heating just slightly below the critical range, followed by slow cooling.

Shop annealing is the term used to describe the practice of heating steel with a welding torch to 900° to 1000°F. and dropping it into a pail of ashes or lime to restrict the cooling rate. This treatment will relieve internal strains. It is never used in aircraft work unless it is to be followed by a regular heat treatment.

In all annealing processes, due to prolonged heating at high temperatures and slow cooling from these temperatures, the surface of metal is prone to scale. The scale on steel is iron oxide. Whenever possible, annealing should be done in closed receptacles to exclude air from the metal. The receptacle should not be opened until it has cooled almost to room temperature. In the case of high-carbon steels the prevention of scale formation is particularly important. Oxidation of the carbon at the surface will occur if not guarded against. This decarburization is injurious to the metal and must be avoided. When steel parts have not been annealed in a receptacle, the scale must be removed by a cleaning or pickling treatment. This treatment is described in the chapter on Corrosion.

Normalizing. Normalizing is a form of annealing which consists in heating the steel above Ac_3 and then cooling in still air. Due to the more rapid quenching, obtained by air-cooling as compared to furnace-cooling, the steel is harder and stronger but less ductile than annealed material. Normalizing is required whenever it is desired to obtain material of uniform physical characteristics. Forgings are generally normalized to relieve all internal stresses. Normalizing, too, will relieve stresses, refine grain, and make steel more uniform just as annealing will, but, at the same time, improved physical properties are obtained. Because of the better physical properties, aircraft steels are often used in the normalized condition but seldom if ever in the annealed state. If annealed steel is used in fabrication for ease of working, it is subsequently normalized or heat-treated to a higher strength.

Welded parts are frequently used in airplane construction. Welding causes strains to be set up in the adjacent material. In addition, the weld itself is a cast structure as opposed to the wrought structure of the rest of the material. These two types of structure have different grain sizes, and to relieve the internal stresses and refine the grain, all welded parts should be normalized after fabrication. Such treatment will reduce the possibility of cracks and fatigue failures in service. Normalizing of welded parts is considered so important by one government department that it even requires this treatment for engine mounts. In many cases where large furnaces are not available, or the basic design of mount will not permit normalizing without too much warping, it is necessary to design an assembled mount made up of small sections. The sections can be normalized individually and bolted or riveted together.

Low-carbon steels are often normalized to improve the machining qualities and. to reduce distortion in subsequent heat-treating operations. In actual practice the aircraft manufacturer buys tubing, sheet, and bar in the normalized condition, performs the necessary machining or welding operations, and then normalizes or heat-treats the finished article. In connection with the purchase of normalized material it is often necessary to specify the maximum tensile strength that is acceptable. This is particularly true of thin sheet which, when quenched in still air, will cool far more readily than heavier material. As a result, thin sheet will be composed of sorbite as well as pearlite—the usual constituent of normalized steel. The sorbite makes the steel stronger but also more brittle. Chrome-molybdenum sheet steel, as purchased in the normalized state, will often run from 110,000 to 125,000 p.s.i. ultimate tensile strength.

Figure 12 Grumman Retractable Landing Gear Heat-treated Chrome molybdenum Tubing

Where severe bending is to be done, the purchase order should specify a maximum of 95,000 p.s.i., which is the accepted strength for normalized chrome-molybdenum steel.

Medium- and high-carbon steels should be normalized and then annealed before machining or fabrication. This sequence of operations is sometimes called double annealing. The resultant structure is similar to that obtained by spheroidizing, as described previously. In aircraft work the machining done is usually small and the annealing is often omitted.

Some alloy steels cannot be satisfactorily hardened without first being normalized. This is especially true of alloys containing chromium.

Hardening. Hardening is the first of two operations required for the development of high-strength steels by heat treatment. Hardening consists of heating above Ac_3, soaking at that temperature until the mass is uniformly heated, and then quenching in brine, water, or oil. This treatment produces a fine grain, maximum hardness and tensile strength, minimum ductility and internal strains. In this condition the material is too hard and brittle for practical use.

Heating is conducted as little above Ac_3 as is practical, in order to reduce warping and the possibility of cracking when the material is quenched. On the other hand, large objects are heated to the upper limit of the hardening range in order to assure thorough heating. For the materials and sections used in aircraft work, quenching in oil is invariably the method employed. The heat absorption of oil is slower than that of water or brine, and consequently the cooling operation is more gentle. Less warping and cracking occurs and sufficient hardness is obtained.

Quench cracking is a result of non-uniform or too rapid cooling of the steel. The transition from austenite to martensite results in an increase of volume. When a piece is quenched, the external surface will cool rapidly and become a hard, brittle martensitic shell. As the internal austenite cools and becomes martensite it increases in volume and internal stresses are set up which may crack the earlier-formed outer shell.

Drawing (Tempering). Drawing (sometimes called tempering) is the second operation required to develop high-strength, heat-treated steel. It consists of heating hardened steel to a temperature well below Ac_1, soaking at that temperature, and then quenching in oil or air. This treatment relieves the strains in hardened steel, decreases the brittleness, and restores ductility.

In addition, the strength and hardness are somewhat reduced. The strength, hardness, and ductility obtained depend upon the temperature to which the steel was reheated. The higher the temperature the lower the strength and hardness but the greater the ductility. By decreasing the brittleness of hardened steel, tempered steel is made tough and still retains adequate strength. Tempered steels, as used in aircraft work, have from 125,000 to 200,000 p.s.i. ultimate tensile strength.

When hardened steel is reheated as in tempering, the transition from austenite to pearlite is continued further, and the martensite is converted to troostite and then sorbite. Tempered steel is composed largely of sorbite, which gives it toughness. Hardened steel, reheated to a low temperature and quenched, is composed of troostite and sorbite, and is still very hard and strong but more ductile than hardened steel; hardened steel reheated to a higher temperature and quenched is composed of sorbite and some pearlite and is tougher and more ductile but still retains considerable strength and hardness.

PRACTICAL HEAT TREATMENT

The first important consideration in the heat treatment of a piece of steel is to know its chemical composition which, in turn, determines its critical range. When the critical temperature is known the next consideration is the rate of heating and cooling to be employed to insure completion of transition or retardation of transition, as the case may be. The carrying out of these operations is beset with practical problems. These involve the use of furnaces for uniform heating, pyrometers for controlling temperatures, handling of hot metal, and quenching in suitable mediums. Some notes on the more vital considerations in heating, soaking, and quenching are given below.

Heating. The aim in heating is to transform pearlite to austenite as the critical range is passed through. This transition takes time; so a relatively slow rate of heating is employed. It is customary to insert the cold steel in the furnace when it is from 300° to 500°F. below the hardening temperature. In this way too rapid heating of the cold steel through the critical range is prevented. It is cheaper to keep a furnace up to the hardening temperature and remove heated steel and insert new cold steel periodically without permitting the temperature to drop several hundred degrees before inserting the new cold work. This is sometimes done where the work is not extremely important, but it does not guarantee complete and thorough transition to austenite. There is also the possibility of cracking, depending on the shape of the material, due to rapid heating and expansion.

In reheating for tempering, the furnace should not be above 800° to 1000°F. when the work is inserted and, in any case, not above the temperature of the steel which is being treated. If the tempering temperature is too high, the transition from martensite to sorbite will be accelerated beyond control of the heat-treater.

Several types of furnace are employed in heating. The common type is a "dry heat" furnace and is fired by oil, gas, or electricity. A uniform temperature must be maintained throughout the furnace, and the work must be properly placed to insure uniform heating. The work must not be placed too close to the wall of the furnace; otherwise radiated heat from the wall will heat one face of the work beyond the rest, with resultant uneven heating. In a dry furnace it is desirable to maintain a neutral atmosphere, so that the heated steel will neither oxidize nor decarburize. Practically, however, this condition is difficult to realize, and considerable scaling of the work results. In this respect the electric furnace is the most satisfactory because only a slight amount of scaling takes place. An atmosphere free of oxygen is maintained in one type of electric furnace by feeding a carbon vapor into it during heating operations. The carbon vapor is generated by "cracking" an oil in a smaller subsidiary furnace. There is practically no scaling of the work in this type of furnace. Special paint coatings, such as "Galvo Anti-scale," are sometimes used to minimize scaling during the heating operation when atmospheric control is not available.

A "liquid heat" furnace is frequently used for parts which have been finished-machined before heat treatment. In this type of furnace, parts are heated in a molten salt bath. Here there are several advantages, the most important being the complete elimination of scaling. In addition, better temperature regulation and more uniform heating are attainable. For production work where speed is essential, faster heating is possible with the liquid bath than with dry heat. Numerous other advantages are claimed for the liquid bath, but those just given are the most important.

Soaking. During the soaking period the temperature of the furnace must be held constant. It is in this period that the rearrangement of the internal structure is completed. The time of soaking depends upon the nature of the steel and the size of the part. Heavier parts require longer soaking to insure equal heating throughout. In specifying hardening temperatures, it is customary to give a range of from 50° to 75°F. within which the material must be soaked. Light parts are soaked in the lower part of this range and heavy parts in the upper part of the range. For the steels and sizes normally used in aircraft construction a soaking period of from 30 to 45 minutes is sufficient. During the tempering operation the steel is soaked from 30 minutes to one hour, depending on the thickness of the material.

Quenching. The rate of cooling through the critical range determines the form that the steel will retain. In annealing, the heated steel must be furnace-cooled to 900°F.; then it may be air-cooled to room temperature. Exceptionally slow cooling to 900°F., which is below the critical range, provides sufficient time for complete transition from austenite to pearlite, which is the normal, stable condition of steel at atmospheric temperatures. In normalizing, the heated steel is removed from the furnace and allowed to cool in still air. The cooling is more rapid than in annealing, and complete transition to pearlite is not attained. Some sorbite remains in normalized steel, which accounts for the improvement in physical properties over annealed material. Air-cooling is a very mild form of quench.

In order to harden steels, it is necessary to use a more rapid quenching medium. There are three mediums commonly used—brine, water, and oil. Brine is the most severe quenching medium, water is next, and oil the least severe. In other words, oil does not cool the heated steel through the critical range as rapidly as water or brine. However, oil does cool rapidly enough to develop sufficient hardness for all practical purposes. In aircraft work high-carbon and alloy steels are oil-quenched. Medium-carbon steel is water-quenched and mild-carbon steel (S.A.E. 1025) is quenched in either brine or water. A severe quench is required for steels with relatively low carbon content in order to develop the required hardness. This observation agrees with the comments previously made in the paragraphs under Internal Structure of Steel relative to the importance of the carbon content on the hardening properties of steel.

Oil quenching is preferred to water or brine when sufficient hardness is obtainable because of the reduced strain, warpage, and cracking of the steel when cooled more slowly. When the structure changes from austenite to martensite, the volume is increased; and if the change is too sudden, cracking will occur. Cracking occurs particularly in the lower temperature ranges when the steel is no longer plastic enough to readjust itself to expansion and contraction. The shape of a part is extremely important if excessive warping and cracks are to be avoided. Thin flanges on heavy sections are especially bad. When tubular parts are quenched, they should be immersed with the long axis vertical to reduce warpage.

Small parts when quenched cool more rapidly than large parts, and harden more uniformly throughout. In large parts the inside core is usually softer and weaker than the rest of the material. This fact must be given consideration in design in calculating the cross-sectional strength. Values obtained from heat-treated parts of small sections cannot be applied directly to larger sections. Strength values normally quoted are based on heat-treated sections 1 to 1½ inches in diameter. As explained in the chapter on Steel and Its Alloys, many alloys possess the property known as penetration hardness. These alloys harden quite uniformly throughout when heat-treated and quenched, and no allowance need be made for a soft core unless the section is excessively large. Such sections are seldom used in aircraft work.

The quenching oil is normally maintained between 80° and 150°F., but if water is used as the quenching medium it is held at a temperature below 65°F. This control involves a large reservoir of liquid and some method of providing circulation and cooling. The rate of cooling through the critical range is governed by the temperature maintained in the quenching medium. Inasmuch as variations in this temperature have an appreciable effect on the rate of cooling, it is obvious that the quenching-medium temperature must be held within limits if consistent results are to be obtained.

After steel is reheated and soaked for tempering, it is quenched in either air or oil. Chrome-nickel steels, however, must be quenched in oil—not air—after tempering in order to avoid "temper brittleness" to which this particular group of steels is subject if air-quenched.

HEAT TREATMENTS FOR AIRCRAFT STEELS

As previously explained, each type of steel has different hardening qualities which are governed by its composition. For this reason the practical heat treatments of various steels differ somewhat as to heating temperatures, soaking periods, and quenching methods. In the following pages an effort has been made to describe the heat-treatment operations commonly used on aircraft steels. Since these data are presented purely for the general information of the reader, and not as a reference for the practical heat-treater, there has been no hesitancy to discuss an interesting point right in the body of the description. For more specific information on the steels listed, or on others not listed, the steel manufacturer should be consulted and he will gladly furnish the required data.

The heat treatments listed in the following pages do not conform wholly to the Army or Navy specifications or S.A.E. recommendations but are an average of the three. Due to slight variations in the chemical composition of steel made by different manufacturers, in heat-treating equipment, in the size of average parts, and in the technique of heat-treaters—a definite, narrow range for hardening and tempering temperatures cannot be laid down. The figures given will satisfy average conditions, but the individual heat-treater may have to vary them a little to obtain satisfactory results.

The range of hardness numbers for a given tensile strength is also an average figure. Each factory should establish its own correlation between tensile strength and hardness numbers by heat-treating tensile test specimens, recording their hardness, and then testing to determine their ultimate tensile strength. For important work tension specimens should be heat-treated along with the work and tested. Absolute faith should not be placed in hardness readings alone.

It will be noted under Item 4 of S.A.E. 2330 steel that there is a discussion of the relationship between the tempering temperature to be used and the actual hardness of the steel after the hardness operation. Use of the suggested proportion on material above or below average may save time and labor, particularly where too soft tempered material would otherwise be obtained, thus requiring both re-hardening and re-tempering.

The lower part of the heating ranges should be used for material less than ¼ inch thick. A majority of airplane parts fall in this category. Prolonged heating of this material should also be avoided to prevent grain growth.

S.A.E. 1025—MILD-CARBON STEEL

Normalizing

1. The temperature of the furnace should not exceed 1100°F. when the work is inserted.

2. The temperature should be increased to 1625–1675°F. gradually and held at that temperature for 30 to 45 minutes depending on the thickness of the part.

3. The parts should be removed from the furnace and allowed to cool in still air.

Final hardness should be as follows: Rockwell B-62 to B-74, Brinell 105 to 130.

Ultimate tensile strength: 55,000 to 67,000 p.s.i.

Heat Treatment

1. The temperature of the furnace should not exceed 1650°F. when the work is inserted.

2. The temperature should be held from 1575 to 1650°F. for 15 minutes or longer, if required, to insure uniform heating.

3. The parts should be removed from the furnace and quenched in water at 65°F.

4. The hardened parts should then be inserted in a furnace whose temperature is not over 1150°F.

5. The furnace temperature should then be increased to 1150–1200°F. (the temperature will have dropped when the parts were inserted) and held for 30 minutes to one hour, depending on the thickness of the material.

6. The parts should then be removed from the furnace and allowed to cool in still air.

Final hardness should be as follows: Rockwell B-77 to B-85, Brinell 140 to 165.

Ultimate tensile strength: 70,000 to 82,000 p.s.i.

This heat treatment is used for S.A.E. 1025 steel when used in the manufacture of nuts. AN Standard steel nuts, which are used exclusively in aircraft construction, fall in this category.

S.A.E. 1045—MEDIUM-CARBON STEEL

Heat Treatment. (Technique similar to that described for S.A.E. 1035. Temperatures differ.)

1. Hardening temperature 1500–1550°F.
2. Quench in oil.
3. Tempering temperature 1000°F.
4. Cooled in still air.

Final hardness should be as follows: Rockwell B-92 to B-102, Brinell 193 to 259.

Ultimate tensile strength: 95,000 to 124,000 p.s.i.

S.A.E. 1095—HIGH-CARBON STEEL

Heat Treatment. (Technique similar to that described for Mild-carbon Steel).

1. Hardening temperature 1450–1500°F.
2. Quench in oil. (High-carbon steels are sometimes quenched in water until they have cooled to the temperature of boiling water when they are transferred to oil at 75°F. This method results in rapid cooling through the critical range and slower cooling at low temperatures where cracking occurs.)
3. Tempering temperature 800–850°F.
4. Cooled in still air.

Final hardness should be as follows: Rockwell C-42 to C-45, Brinell 400 to 430.

Ultimate tensile strength: 195,000 to 213,000 p.s.i.

This heat treatment is applied to S.A.E. 1095 steel when it is to he used for structural parts or springs. Leaf springs made from this material are commonly used in aircraft construction.

S.A.E. 2330—NICKEL STEEL

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the work is inserted.
2. The temperature should be increased gradually to 1450–1500°F. and held for 20 minutes.
3. The parts should be removed from the furnace and quenched in oil or water.

4. At this stage the Brinell hardness should be checked to ascertain that it is approximately 500. If it is over 500 the tempering temperatures given below should be increased somewhat; if below 500 the tempering temperatures should be reduced somewhat. The tempering temperatures should be increased or decreased about in the same proportion that the actual Brinell number bears to 500.

5. As previously explained in the paragraphs under Tempering, the final ultimate tensile strength and hardness of a piece of steel depends on the temperature to which hardened steel is reheated and drawn. Thus different tempering temperatures must be used if different strength values are to be obtained for the same type of steel. S.A.E. 2330 steel is commonly used in two different strengths; the tempering temperatures to obtain these conditions are:

Ultimate tensile strength	*Tempering temperature*
125,000 p.s.i.	950°F.
150,000 p.s.i.	800°F.

Parts should be held at the tempering temperature for a minimum of 30 minutes.

6. Parts should then be removed from the furnace and allowed to cool in still air. Final hardness should be as follows:

Ultimate tensile strength (p.s.i.)	125,000	150,000
Rockwell hardness, C scale	25 to 32.	33 to 37
Brinell hardness	250 to 300	310 to 360

S.A.E. 2330 steel heat-treated to 125,000 p.s.i. is used for a great many AN Standard parts, particularly aircraft bolts.

S.A.E. 3140—CHROME-NICKEL STEEL

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the work is inserted.

2. The temperature should be increased gradually to 1475–1525°F. and held for 15 minutes or longer, if necessary, to insure uniform heating.

3. The parts should be removed from the furnace and quenched in oil.

4. The furnace temperature should not exceed 800°F. when parts are inserted for tempering.

5. The temperature should be raised to the required value for the strength desired and held for 30 minutes to one hour, depending on the thickness of the material.

Ultimate tensile strength	*Tempering temperature*
125,000 p.s.i.	1050°F.
150,000 p.s.i.	950°F.
180.000 p.s.i.	800°F.

6. Parts should be removed from the furnace and cooled by quenching in oil. An oil quench is mandatory for chrome-nickel steels to avoid temper brittleness.

Final hardness should be as follows:

U.t.s. (p.s.i.)	Rockwell	Brinell
125,000	C-25 to C-32	250 to 300
150,000	C-33 to C-37	310 to 360
180,000	C-38 to C-42	360 to 400

S.A.E. 4037—MOLYBDENUM STEEL

Heat Treatment

1. Hardening temperature 1525–1575°F.

2. Quench in oil or water.

3. Tempering temperature 1100°F. for 125,000 p.s.i. ultimate tensile strength.

4. Cool in still air.

S.A.E. 4037 with heat treatment has been used as substitute for S.A.E. 2330 in the manufacture of aircraft bolts.

S.A.E. 4130—CHROME-MOLYBDENUM STEEL

Annealing

1. The temperature of the furnace should not exceed 1100°F. when the work is inserted.

2. The temperature should be increased gradually to 1525–1575°F. and held at that temperature for 15 minutes or longer to insure uniform heating throughout.

3. The furnace should then be shut down and the work and the furnace allowed to cool slowly to at least 900°F. at which point the work may be removed and allowed to cool in still air.

Ultimate tensile strength: approximately 78,000 p.s.i.

Normalizing

1. and 2. Identical with annealing process except that temperature range of 1600–1700°F. is used.

3. The work should be removed from the furnace and allowed to cool slowly in still air.

Final hardness should be as follows: Rockwell B-89 to B-99, Brinell 180 to 240.

Ultimate tensile strength: 90,000 to 110,000 p.s.i.

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the

work is inserted.

2. The temperature should be gradually increased to 1550–1650°F. and held for 15 minutes or longer, if necessary, for thorough heating. For sections under ¼ inch thickness the lower part of the temperature range should be used.

3. The parts should be removed from the furnace and quenched in oil. Bars or forgings can be quenched in water.

4. The hardened parts should be inserted in a furnace whose temperature is not above the desired tempering temperature and in no case above 800°F.

5. The temperature of the furnace should then be raised to the tempering temperature required to obtain the desired physical condition. These temperatures for the tensile strength used in aircraft construction are as follows:

Ultimate tensile strength	*Tempering temperature*
125,000 p.s.i.	1075°F.
150,000 p.s.i.	900°F.
180,000 p.s.i.	700°F.
200,000 p.s.i.	575°F.

Parts should be held at the tempering temperature for 30 minutes to one hour, depending on the thickness.

6. Parts should be removed from the furnace and allowed to cool in still air.

Final hardness should be as follows:

U.t.s. (p.s.i.)	Rockwell	Brinell
125,000	C-25 to C-32	250 to 300
150,000	C-33 to C-37	310 to 360
180,000	C-38 to C-42	360 to 400
200,000	C-42 to C-46	400 to 440

S.A.E. 4140—CHROME-MOLYBDENUM STEEL (HIGH CARBON)

Due to its higher carbon content this steel responds to heat treatment better than 4130 steel. For heavy parts machined from bar or forging stock it has replaced 4130 steel entirely. The heat-treatment process is practically identical with that given for 4130 steel, excepting that the hardening range is 25°F. lower, making it 1525–1625°F. This change is due, of course, to the higher carbon content. Tempering temperatures are approximately 100°F. higher than those for 4130.

S.A.E. 4340—CHROME-NICKEL-MOLYBDENUM STEEL

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the parts are inserted.

2. The temperature should be increased gradually to 1475–1525°F. and held for 15 minutes or longer, if necessary, to insure thorough heating.

3. The parts should be removed from the furnace and quenched in oil.

4. The hardened parts should be inserted in a furnace whose temperature is not above the desired tempering temperature and in no case above 1000°F.

5. The temperature of the furnace should then be raised to the tempering temperature required to develop the desired physical properties.

Ultimate tensile strength	*Tempering temperature*
125,000 p.s.i	1200°F.
150,000 p.s.i.	1050°F.
180,000 p.s.i.	950°F.
200,000 p.s.i.	850°F.

Parts should be held at the tempering temperature for 30 minutes to one hour, depending on the thickness.

6. Parts should be removed from the furnace and quenched in oil.

Final hardness should be the same as recorded for 4130—chrome-molybdenum steel—for equivalent tensile strengths.

It should be noted that this steel is one of the chrome-nickel series and must be quenched in oil after tempering to avoid temper brittleness.

S.A.E. 6135—CHROME-VANADIUM STEEL (MEDIUM CARBON)

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the work is inserted.

2. The temperature should be increased gradually to 1575–1625°F. and held for 15 minutes or longer, if necessary, to insure thorough heating.

3. The parts should be removed from the furnace and quenched in oil.

4. The hardened parts should be inserted in a furnace whose temperature is not above 800°F.

5. The temperature of the furnace should then be raised to the required tempering temperature, which depends on the tensile strength desired in the finished part.

Ultimate tensile strength	*Tempering temperature*
125,000 p.s.i.	1050°F.
150,000 p.s.i.	925°F.

Parts should be held at the tempering temperature for 30 minutes to one hour, depending on the thickness.

6. Parts should be cooled in still air.

Final hardness should be as follows:

U.t.s. (p.s.i.)	Rockwell	Brinell
125,000	C-25 to C-32	250 to 300
150,000	C-33 to C-37	310 to 360

S.A.E. 6150—CHROME-VANADIUM STEEL (SPRINGS)

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the parts are inserted.

2. The temperature should be increased gradually to 1550–1625°F. and held for 15 minutes or longer, if necessary, to insure thorough heating.

3. The parts should be removed from the furnace and quenched in oil.

4. The hardened parts should be inserted in a furnace whose temperature is not above 700°F.

5. The temperature of the furnace should then be raised to 700–850°F. and held for 30 minutes to one hour, depending on the diameter of the spring material.

6. Parts should be allowed to cool in still air.

Final hardness should be as follows: Rockwell C-42 to C-47, Brinell 400 to 444.

Ultimate tensile strength: approximately 200,000 p.s.i.

S.A.E. 8630, 8735, 8740

These NE steels which are now established as standard steels are heat-treated the same as S.A.E. 4130 or S.A.E. 4140 steels.

SPECIAL STEELS—HY-TUF (AMS 6418, MIL-S-7108)

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the parts are inserted.

2. The temperature should be increased gradually to 1600°F. ±25°F and held at this temperature for a minimum of one hour per inch of thickness.

3. The parts should be removed from the furnace after the proper soaking time and then quenched in agitated oil (75°F.–140°F.).

4. The parts should then be placed in the tempering furnace and slowly heated to 600°F ±25°F. for a period of two hours per inch of thickness.

5. After any finishing operations such as grinding, cutting, etc., a second draw is required to relieve any residual stresses. This second draw is a repeat of step 4.

Hy-Tuf was developed to make available a steel which has good toughness at a tensile strength of 230,000 p.s.i. If other strength levels are required, the tempering temperature should be changed as shown below.

HY-TUF (*Heat Treated at 1600°F.—Oil Quenched—Tempered*)

Tempering temperature °F.	Ultimate strength K.S.I.	Yield strength K.S.I.	Elongation %	Reduction of area %	Hardness Rc	Izod at 70°F. ft. lb.
400	239	183	14.3	46.6	48	33
500	235	191	13.9	49.7	47	33
600	230	194	14.0	51.7	46	29
700	222	193	14.2	53.3	45	24
800	201	180	13.6	50.6	43	23
900	181	162	16.3	54.4	39.5	36
1050	158	142	18.0	56.5	36	51

VANADIUM MODIFIED 4330 (AMS 6427, MIL-S 8699)

Normalizing

1. Insert the parts in a furnace with a temperature not exceeding 1100°F.

2. Slowly increase the temperature to 1650°F. ± 25°F. and hold the parts at this temperature for a minimum of one hour per inch of thickness. The parts should then be removed from the furnace and cooled in still air.

3. If any straightening is performed on the normalized part, it is advisable to stress-relive the straightened parts at a temperature of 1225°F. for a minimum of three hours.

Heat Treatment

1. The temperature of the furnace should not exceed 1100°F. when the parts are inserted.

2. The temperature should be gradually increased to 1575°F. ±25°F. and held for a minimum of one hour per inch of thickness.

3. The parts should be removed from the furnace and quenched in agitated oil (75–140°F.).

4. The hardened parts should then be placed in a tempering furnace whose temperature is not above 600°F., and soaked at this temperature (600° ±25°F.) for a minimum of two hours per inch of thickness.

5. After any finish machining, grinding, etc., it is advisable to repeat step 4 for an additional temper, to reduce residual stresses.

INTERRUPTED QUENCHING

In the last five years commercial application of so-called interrupted-quenching procedures has been made to attain special characteristics or economies in the heat-treating of steel. These procedures are known as cycle annealing, austempering, and martempering. Cycle annealing gives better control of the final annealed structure and can be accomplished in a fraction of the time required for full annealing and spheroidizing operations.

Austempering is limited to small sizes and deep-hardening steels but greatly increases the toughness and ductility of steels heat-treated to high hardness. Martempering is applicable only to relatively small sizes of deep-hardening steels but minimizes distortion and cracking due to quenching, reduces internal stresses, and gives good physical properties.

The development of these processes is directly related to the TTT (time-temperature-transformation) or S curves which are now available for each of the commonly used steels. A typical S curve, similar to that for S.A.E. 4140 steel, is shown in Figure 13. The first of the diagrams of this type was published in 1930 but they are now available for a wide variety of steels. Each composition of steel has its own diagram, which may be obtained from the steel companies.

An S curve or isothermal transformation curve for a given steel is established as follows: Above the critical range austenite is the stable structure of steel; below the critical range austenite is unstable and will transform to another type of structure if held at a constant temperature for a period of time. The length of time before the transformation of the unstable austenite begins varies at different temperatures and is plotted as the left hand curve in Figure 13; the time required to complete the transformation also varies with the temperature and is plotted as the right-hand curve in Figure 13. The type of structure obtained by transformation depends on the temperature at which the isothermal transformation takes place. At the higher temperatures pearlite is formed (as found in annealed steel), while at lower temperatures a structure named bainite is formed. Bainite is equivalent to a tempered martensite and is a feathery, acicular constituent that makes a hard but ductile and tough material.

The *Ms* line at the bottom of the diagram represents the temperature below which transformation to martensite takes place. *Ms* is the abbreviation of "martensite start." The *Ms* temperature varies from 260°F. to 640°F. for different steels. For carbon tool steel it is 380°F.; for S.A.E. 4140 it is 590°F.; and for S.A.E. 4340 it is 530°F.

It will be noted in Figure 13 that time is plotted on a logarithmic scale in order to include the very short as well as the extremely long time intervals covered by this type of diagram. The time required for transformation to begin may vary from a fraction of a second to 30 minutes or more, while the time to complete transformation may vary from less than five seconds to several days.

An examination of Figure 13 will show that the S curve has a so-called "nose" or "knee" at a temperature around 900°F. The location of this "knee" along the time scale is of primary importance in determining the hardenability of a steel. The reason is that the steel being hardened must be cooled to a point below the "knee" within the time interval shown in the diagram or the martensitic structure desired will be diluted with other types of structure (referred to as "nose products" or "knee products") which are softer than martensite. The "knee" is moved to the right (thus increasing the time interval in which quenching can be completed to insure the formation of pure martensite) by the addition or increase of alloy content. Manganese, chromium, nickel, and molybdenum are very effective in accomplishing this movement of the "knee" to the right. These steels have good hardenability.

It should be understood that the entire mass, including the center of the part, must be below the "knee" temperature within the time interval shown on the S curve for any particular steel. The austempering and martempering processes are limited by this requirement to deep-hardening steels of relatively small cross-sections.

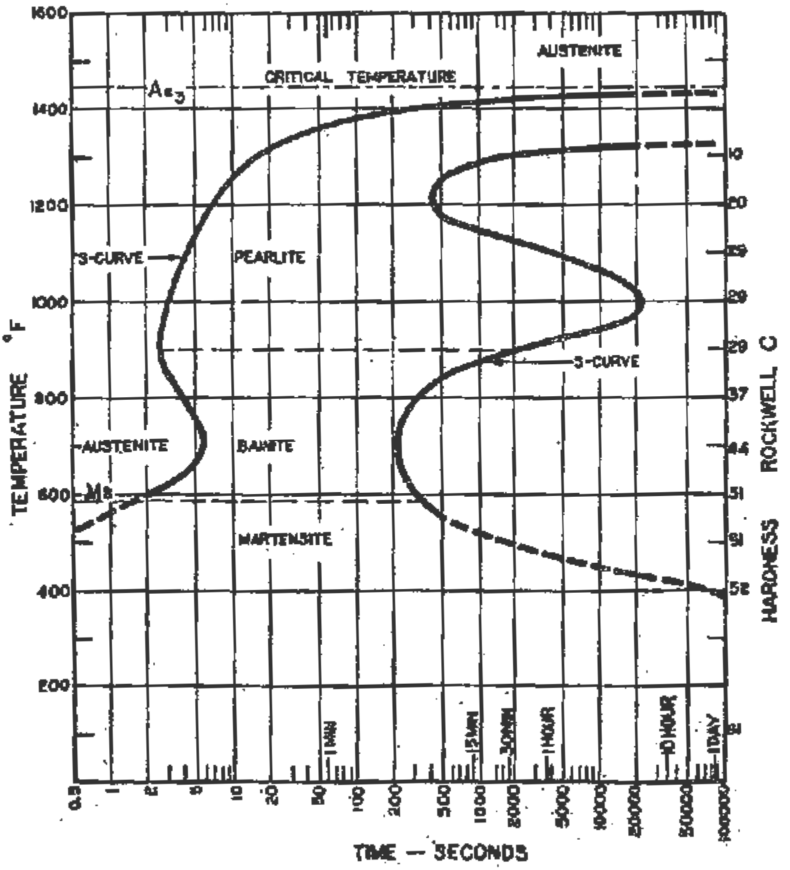


Figure 13. Typical Isothermal Transformation Diagram

Isothermal quenching must be done at temperatures above which brine, water, or oil are practical. A molten salt bath composed of half sodium nitrate and half potassium nitrate is frequently used for quenching. This salt bath can be operated from 350° to 1100°F. A molten salt bath around 400°F. has greater cooling power than ordinary quenching oil at room temperature—a characteristic advantageous in quenching steel adequately to below the "knee" temperature in the permissible time interval.

Cycle Annealing. This is a process in which austenite is transformed isothermally to pearlite at high temperatures, and this latter structure is retained when the work is cooled to room temperature. In actual practice the steel is austenitized (heated to a temperature above the critical temperature and soaked until a stable austenitic structure is formed throughout the part) at a temperature above but within 100°F. of the critical temperature. It is then quenched in a molten salt bath maintained at a temperature below the critical temperature but above the "knee" temperature. This temperature is usually held within 100°F. of the critical temperature unless the shape of the S curve is such that too long a period of time would be required to complete the transformation, in which case a somewhat lower temperature is used. After complete transformation is effected the work is cooled to room temperature by air or water without further changing the microstructure.

Sometimes the transformation is allowed to proceed only a certain amount before the work is removed from the quenching bath and allowed to air-cool. By this means a variation in properties is obtainable. Cycle annealing permits better control of the final structure and better reproducibility of a desired structure in a fraction of the time required for the full annealing and spheroidizing operation. Cycle annealing requires from 4 to 7 hours as compared with 18 to 30 hours for standard annealing.

Austempering. This is a process in which austenite is transformed isothermally to bainite at moderate temperatures. The material is austenitized and then quenched in a molten salt bath maintained at a temperature above the *Ms* but below the "knee" temperature. The work is held in the bath until the transformation to bainite is complete and then it is removed and cooled to room temperature by air or water. In some cases, to insure adequate cooling to below the "knee," it is necessary to quench in a bath maintained at a lower temperature than that required for the final hardness desired. In this case the bainite product is transferred for tempering to a second bath maintained at a higher temperature. This procedure permits the austempering of slightly larger sizes of material than would be possible by using only the second bath for quenching. The double operation is sometimes referred to as isothermal quenching.

Austempering is most useful when the steel is to be used in the hardness range of Rockwell C-48 to C-58. As compared to standard quench and temper steels of the same hardness, austempered steel has about 30% additional elongation, 100% greater reduction of area and impact strength, but slightly less yield strength. Spring products and other items requiring increased elasticity as well as hardness are obtainable by austempering. The finish of the part after austempering is the same as the initial material before heat treatment. The relative gentleness of the quench results in minimum distortion and cracking of the work.

As explained previously, a rapid-quenching or deep-hardening steel is required to get by the "knee" of the S curve. This requirement limits the austempering process to carbon steels above 0.55% carbon and to alloy steels. The maximum cross-sectional area of S.A.E. 1095 steel that can be austempered is the equivalent of a rod 0.148 inch in diameter; S.A.E. 4140 is limited to a 0.50-inch diameter; and a material like S.A.E. 4365 is limited to a 1.0-inch diameter.

Martempering. This is a process in which austenite is uniformly transformed to martensite at low temperatures by continuous cooling. In this process the work is austenitized and then quenched in a molten salt bath maintained at a temperature just above the *Ms* temperature of the steel being treated. The work is held at this temperature only a short period of time—long enough to permit all of the material to reach the same temperature, but not long enough for the transformation to bainite to begin. The work is then removed from the bath and allowed to air-cool. The transformation from austenite to martensite occurs during this air-cooling, at which time the difference in temperature between the outer skin and the center of the work is negligible. When room temperature is reached and the transformation to martensite is complete the work is subjected to a normal tempering operation to obtain the desired physical properties.

It should be noted that by quenching a part in the salt bath at a temperature above *Ms*, temperature uniformity throughout the part is obtained before any transformation or change in microstructure takes place. When the part is slowly cooled in air from this temperature the transformation occurs uniformly throughout. By this means nonuniform volume changes are reduced, high internal stresses are avoided, and warpage, cracking, and distortion are minimized. These are the particular advantages of martempering. Martempering is limited largely to high-alloy steel and small cross-sectional areas for the same reason that applies to austempering, namely, the necessity for getting by the "knee" of the S curve in quenching if the full advantage of the process is to be realized. S.A.E. 8630 steel can be martempered up to a cross-sectional area equivalent to a round of 1-inch diameter; S.A.E. 8740 can be processed up to a 1½-inch diameter.

HARDENABILITY

In recent years hardenability has come to the forefront as the primary basis for the selection of a particular type of steel. This criterion is logical since the physical properties normally required for a given application are directly related to the hardness of the material. Steels with equivalent hardening characteristics can be used interchangeably irrespective of their chemical compositions. In the future it is anticipated that most steel will be purchased under "H" steel specifications, which prescribe hardenability limits as well as overall chemical compositions. When steel is purchased under this type of specification the aircraft manufacturer's heat-treating problems will be simplified, as all material will come up to the required hardness when properly heat-treated. In the past, when material was purchased solely by chemical composition, there were many occasions when a sour lot of material would not respond to heat treatment for some unexplainable reason.

"H" steel specifications have been prepared for most of the commonly used steels. Steel in accordance with this type of specification is designated by adding an H to its numerical designation. Thus we have 4130H, 8740H, etc., to identify steels manufactured to hardenability-band limits. Tables and charts have been prepared for each type of steel to define its hardenability limits.

A Jominy or end-quenched hardenability test has been adopted as the standard method for determining hardenability limits in order to permit comparisons between different steels. This test is based on the concept that the hardening of steel by quenching is a function of heat extraction—rapid extraction resulting in high hardness and slow extraction resulting in low hardness.

The standard Jominy specimen is a round 1 inch in diameter by 4 inches long which has been machined after normalizing to remove all scale or decarburized surfaces. To insure uniformity the specimen is normalized at the temperature listed below for one hour, machined to finished dimensions, and then is held for 30 minutes at the austenitizing temperature listed below. The furnace should be at the austenitizing temperature when the specimen is inserted. A protective atmosphere furnace or other means is essential to protect the bottom end of the specimen from scale or decarburization.

Quenching of the specimen must start within 5 seconds after its removal from the furnace. The specimen is quenched by suspending it vertically with its bottom end ½ inch above a water orifice with a ½-inch opening which discharges water at a rate of approximately 1 gallon per minute. The water must be at a temperature between 40° and 85°F. and must impinge against only the bottom or quenched end of the specimen. Quenching in this manner is continued for 10 minutes.

Steel series	Maximum carbon content (%)	Normalizing temperature (°F.)	Austenitizing temperature (°F.)
1000			
3100			
4000	Up to 0.25 incl.	1700	1700
4100	0.26 to 0.36 incl.	1650	1600
4600	0.37 and over	1600	1550
8700			
6100	Up to 0.25 incl.	1750	1750
	0.26 to 0.36 incl.	1700	1650
	0.37 and over	1650	1600
2300			
2500	Up to 0.25 incl.	1700	1550
3300	0.26 to 0.36 incl.	1650	1500
4800	0.37 and over	1600	1475
9200			
9200	0.50 and over	1650	1600

A cooling rate of 600° per second is attained at the quenched end. The rate of cooling is slower as the distance from the quenched end increases and is only 4° per second at the opposite end. Since the cooling rate varies along the entire length some point will duplicate every quenching condition met with in practice from water to air quenching, and from the surface to the center of various sizes of material. For instance, the cooling of the specimen at 3/8, ¾, 1 1/16, and 1½ inches from the quenched end will result in hardness equivalent to that obtained at the center of 1-, 2-, 3-, and 4-inch rounds respectively when quenched in still oil. This type of result can be consistently correlated and therefore can be used to predict the attainable hardness for any shape from data supplied by the end-quench specimen.

To obtain the hardness readings of the end-quench specimen two flats 180° apart are carefully ground along the entire length of the specimen. Wet grinding is preferable, to avoid changing the quenched condition, and the flats should be at least 0.015 inch deep. Rockwell C hardness readings are then taken every 1/16 inch from the quenched end for 1 inch and at greater intervals for the remainder of the length. The Rockwell readings are then plotted on a standard chart in which the ordinates represent hardness and the abscissas represent distance from the quenched end. The chart applying to each steel is necessarily a band bounded by a maximum and a minimum curve. This spread is due to the variations permitted in the chemical compositions of a given steel.

In ordering "H" steel it is customary to specify two specific points of the desired hardenability band. In the preferred method, the distance from the quenched end where a specified Rockwell C hardness is desired is called for. Usually a minimum and maximum distance is given within which the desired hardness number must fall. In the alternate method, a minimum hardness number (or a range of hardness numbers which will be acceptable) at a specified distance from the quenched end is called for. In addition, in either of these methods, the minimum and maximum hardness 1/16 inch from the quenched end may be specified. The steel producer will list on the shipping papers the heat hardenability at the specified points or at 1/16, 1/8, ¼, ½ inches, etc., from the quenched end.

In order to understand more clearly the specifying of hardness requirements, consult the following hardenability chart for 8630H steel.

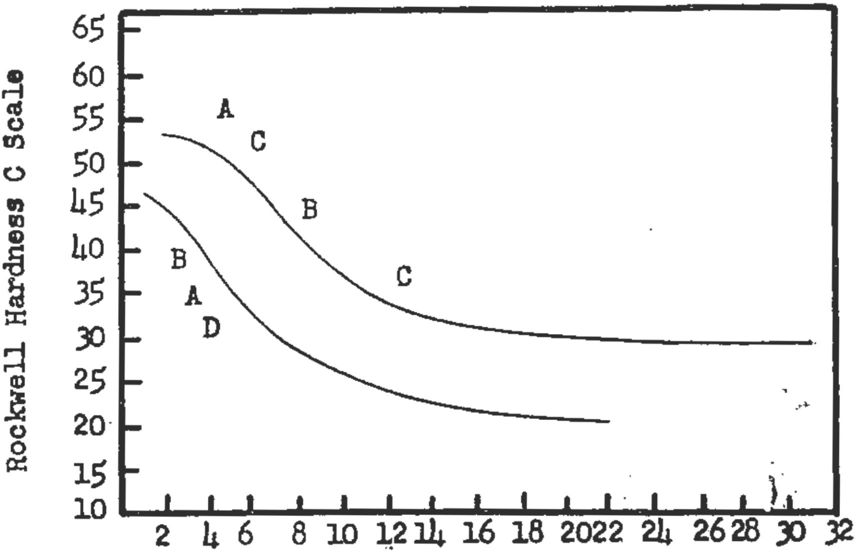


FIGURE 13A. Hardenability Band 8630H

Example illustrating alternate methods of specifying requirements. (Tabulating hardness values are used in ordering.)

Method	*Example*
A—Minimum and maximum hardness values at a desired distance	A–A J39/52 = 4/16 in.
B—A desired hardness value at minimum and maximum distances	B–B J42 = 3/16 in. to 8/16 in. (Minimum distance to Nearest 1/16 in. at left and maximum to nearest 1/16 in. at right)
C—Two maximum hardness values at two distances	C–C J50 = 5/16 in. max. J34 = 32/16 in. max
D—Two minimum hardness values at two desired distances	D–D J35 = 5/16 in. min. J 21= 16/16 in. min

CHAPTER VI

SURFACE HARDENING

FOR some design purposes it is necessary to have a hard, wear-resisting surface and a strong, tough core. This condition can be obtained in steel by a number of methods. Heat-treating alone, as discussed in the previous chapter, will give a uniform condition, either extremely hard and strong, or moderately hard and tough, throughout the entire cross-section of the metal. By the methods of surface hardening described in this chapter, it is possible to obtain a surface or case harder than the highest obtainable by heat treatment, combined with a tough core. Since any depth from a mere skin to over 1/8 inch can be produced, the case thickness can be varied to suit the design requirements. The hard case resists wear and abrasion, and the soft, tough core resists shock stresses. This combination of properties is essential in the design of gears, pinions, wrist pins, trunnions, and other parts subject to abrasion and shock loads.

The methods commonly used for surface hardening are known as carburizing, cyaniding, and nitriding. The combination of carburizing and the subsequent heat treatment which always follows this operation is called casehardening. Casehardening is used more often than the other methods in aircraft work.

CASEHARDENING

As commonly practiced, casehardening consists of carburizing a piece of steel, quenching either mildly or rapidly, reheating to refine the core, quenching rapidly, reheating again to refine and harden the case, quenching rapidly, tempering at a low temperature, and cooling slowly. For unimportant parts and with some steels one or more of these operations can be eliminated. A detailed discussion of the theory and practical application of each of these operations follows.

Carburizing. Carburizing steels may be either carbon or alloy steels but must be within the low-carbon range. The carburizing process consists in heating these steels in contact with a carbonaceous material. This material may be either solid, liquid, or gaseous. Above the critical range the iron carbide in steel passes into solution in the gamma iron, as explained under Heat Treatment. Low-carbon steels are weak solutions and will absorb free carbon. The carbon-rich carbonaceous materials when heated give off a gas containing carbon which diffuses into the steel surface. The depth of penetration depends upon the carbonaceous material, the temperature, and the time allowed.

The absorption of carbon at the surface will greatly increase the carbon content in this region. This carbon content will range from 0.80 to 1.25% at the surface and will taper off toward the center with the core remaining at the original content. Subsequent heat treatment will harden the case and toughen the core. This behavior is to be expected from the explanation made under Heat Treatment, where it was shown greater hardness could be obtained from high-carbon steels.

Solid Carburizing. The oldest and most commonly used method of carburizing is with a solid carbonaceous material. This material is usually bone, charred leather, wood charcoal, or coke. These materials are used singly or mixed together and usually contain an energizer to increase the formation of carburizing gases when heated.

The parts to be carburized are packed in a metal box (usually nichrome) with at least 2-inch legs, so that the furnace gases may circulate freely around the entire box. All surfaces of the parts must be covered with at least ½ inch of the carburizing material. The box must have a lid which can be sealed tight. A common seal is moist fire clay to which a little salt has been added to prevent cracking. When the box is properly packed and sealed it is ready for insertion in the furnace.

The furnace should be brought up to 1600–1700°F. as quickly as possible. The range of some carburizing steels is 1600–1650°F., others 1625–1675°F., and still others 1650–1700°F. All fall under 1700°F. More rapid penetration can be obtained at higher temperatures, but grain growth will increase rapidly and affect the quality of the steel. The temperature should be kept as close to the critical range as possible to avoid grain growth. It should be borne in mind, however, that due to the size of the box and the packing, the enclosed parts will lag about 100°F. behind the furnace when being heated. The furnace must be kept at the carburizing temperature somewhat longer to allow for this lag.

The carburizing temperature is held until the desired depth of case is obtained. The time required varies for the different carburizing steels. For S.A.E. 1020 carbon steel, which is often used for casehardened parts, the variation of depth of case with time at temperature is as follows:

Depth of case	*Time at 1650°F.*
1/64 inch	One hour
1/32 inch	Two hours
3/64 inch	Four hours
1/16 inch	Six hours
1/8 inch	Sixteen hours

In aircraft work a case depth of 1/64 or 1/32 inch is commonly used, since the abrasion is seldom great and shock resistance is important. Thick cases are liable to crack under shock loads.

After carburizing the box is removed from the furnace and allowed to cool in air, or the parts removed and quenched in oil from the carburizing temperature. The slower method of cooling is employed when warpage must be avoided. This cooling completes the carburizing process, and the parts are then ready for grain refinement, hardening, and tempering.

Liquid Carburizing. Carburizing in liquid salt bath has recently been successfully developed. This method is applicable to small parts where a depth of case not greater than 0.040 inch is satisfactory. Liquid carburizing has the advantage of forming a case uniform in depth and carbon content. In the use of solid carburizers it is often impossible to obtain uniform results on small parts packed in a box since temperatures near the sides differ from those in the center. Furthermore, liquid carburizing is faster than solid carburizing because laborious packing is eliminated.

A salt that melts several hundred degrees below the carburizing temperature is used as the liquid heat. An amorphous carbon is added to the bath to furnish the required carbon. Periodically, additional carbon is added to keep the bath saturated. A layer of carbon covers the top of the bath to reduce volatilization loss.

As with the solid material the depth of case obtained is dependent on the time and temperature. The following are typical figures for S.A.E. 1020 steel:

Depth of case, inches		*Time, hours*
1600°F.	*1675°F.*	
0.006	0.006	1/3
0.010	0.012	2/3
0.016	0.018	1
0.020	0.024	2
0.026	0.030	3
0.035	0.040	4

After carburizing, the parts may be quenched in water or oil. They are then ready for refinement, hardening, and tempering.

Gas Carburizing. Gas carburizing is becoming more generally used. One process consists in exposing small parts in a rotating retort to gas as a carburizing medium. Solid carburizer is sometimes added in the retort to enrich the carburizing atmosphere. Parts in the rotating retort are tumbled about, with resultant damage to corners and edges.

The latest improved process is done in the electric furnace with a carbon atmosphere as mentioned in the chapter on Heat Treatment. When carburizing, about twice as much carbon vapor is admitted to the furnace as when heat-treating. In this process the parts remain stationary.

Refining the Core. Due to the fact that the carburizing temperature is well above the critical range and is held for a long period of time, an excessive grain growth takes place in the steel. In order to obtain a fine, ductile grain in the core, it is necessary to reheat the steel to just above the upper critical point, soak until the metal is uniformly heated, and then quench in oil.

In actual practice the following typical procedure is used for S.A.E. 1020 steel. The furnace is preheated to 1200°F, and after the parts are inserted, it is brought up to 1600°F. in 45 to 60 minutes. A longer time is taken for complex parts. The parts are soaked for 10 minutes or longer. if necessary, and then quenched in oil.

Hardening the Case. Since the case of a carburized steel part has a high carbon content, the temperature required above to refine the low-carbon core is considerably above the critical range of the case. This high temperature results in grain growth and embrittlement of the case. It is, therefore, necessary to reheat the steel to just above the critical range of the high-carbon case and then quench in oil. This treatment refines the grain and hardens the case. The hardening temperature for the high-carbon case is well below the upper critical point for the low-carbon core. The only effect this reheating has on the core is a tempering action.

For S.A.E. 1020 steel the hardening procedure is as follows: The furnace is preheated to 1000°F., and after the parts are inserted, it is brought up to 1400–1430°F. fairly rapidly. The parts are soaked for ten minutes and then quenched immediately in oil.

Tempering. In order to relieve hardening strains, carburized steel parts are tempered by heating in the region of 300–400°F. This tempering should be done immediately after the hardening quench. The furnace or oil bath should be at the tempering temperature when the parts are inserted. The low part of the tempering range should be used if extreme hardness is desired since hardness decreases as the tempering temperature increases. The parts should be soaked until uniformly heated and then removed and cooled slowly in still air.

SELECTIVE CASEHARDENING

In many designs it is desired to harden only that portion of the part subject to severe wear. Methods have been evolved to protect the other portions of the part from carburizing. The best method is to copper-plate the sections to be left soft. A few thousandths of an inch of good dense copper plate will resist the penetration of carbon, providing too much energizer is not present in the carbonaceous material. Before copper-plating, the sections to be hardened are japanned to protect them from being plated. The japan is removed after plating but before carburizing.

It is customary to finish hardened carburized parts by grinding. In some cases, where soft sections are desired, sufficient material is left on in the original machining to allow for grinding. By this method the case is completely removed by grinding where a soft section is desired. This method is slow and expensive.

Sometimes a portion of a carburized part is threaded. It is essential that the threads be true and soft while the remainder of the part must be hard to resist wear. If the threads are cut and then carburized and hardened, the threads will be warped and thrown out of center with the hardened ground surface. To avoid this condition the following procedure is recommended:

1. Machine for carburizing, leaving ¼ inch of stock on the section to be threaded.
2. Carburize for the desired depth of case.
3. Turn off all but 1/64 inch of excess stock on the section to be threaded. All the high-carbon case will thus be removed from the threaded portion.
4. Heat-treat to refine the core and harden the case, and temper to remove strains.
5. Finish-grind the hardened surface, turn the threaded section to size true to the ground surface, and then thread. Machining operations are possible on the threaded section even after the hardening treatment because its low carbon content will not permit appreciable hardening.

Warpage and Cracking. Warpage of carburized parts is very common and is caused by improper packing or severe quenching. It is customary to finish-grind casehardened parts to reduce the distortion.

Cracking of parts occurs in the hardening quench. It is absolutely necessary to avoid all sharp corners, notches, or sudden changes of section in parts to be hardened. In some cases it is preferable to design a part in two or more pieces to avoid hardening cracks.

Some carburizing steels require a less severe quench than others and are not as subject to warping and cracking. Where absolute accuracy is necessary the proper steel should be selected with minimum distortion properties. S.A.E. 4615 is generally recommended.

Carburizing Steels. Carburizing steels are either plain carbon or alloy steels but are invariably in the low-carbon range. A low carbon content is necessary to retain a tough core after the heat treatment. In special cases steel with a carbon content as high as 0.55% has been successfully carburized. Normally, however, the carbon content is restricted to a maximum of 0.25%. For light parts requiring extremely tough cores, 0.18% carbon is the maximum that should be permitted. For heavy parts requiring strong cores, the carbon content of the steel should be 0.15 to 0.25%.

Since the carbon content is limited in these steels, an increase in strength cannot be obtained by merely using a higher carbon steel. In order to obtain greater strength without a decrease in toughness after heat treatment, it is necessary to use an alloy steel. The alloy steels commonly used are nickel,

nickel-chromium, and molybdenum steels. The greatest core strength is obtained by using a nickel steel, S.A.E. 2515.

A good case is also extremely important. The plain carbon steel S.A.E. 1020 gives a file-hard case that is slightly better than that obtained with the alloy steels. Alloys decrease the hardness of the case somewhat. An increase in the nickel content decreases the case hardness. S.A.E. 2515 steel has the softest case of the carburizing steels.

The following listed steels are used most frequently for carburized parts. Their core strengths are also given:

S.A.E. number	*Core strength (p.s.i.)*
1020	60,000
2320	80,000
2515	120,000–160,000
3115	85,000
3312	100,000
4615	80,000–100,000
6115	90,000

CYANIDING

Cyaniding is a surface hardening of steel obtained by heating it in contact with a cyanide salt, followed by quenching. Only a superficial casehardening is obtained by this method, and consequently it is seldom used in aircraft work. It has the advantage of speed and cheapness, however, and may be used to advantage on relatively unimportant parts.

The cyanide bath, which is usually sodium or potassium cyanide, is maintained at 1550–1600°F. The work to be hardened is preheated to 750°F. and then immersed in the bath for from 10 to 20 minutes. It is then withdrawn and quenched in water until cold. A superficial case of $^1/_{64}$-inch maximum depth is obtained. The case is hard but not homogeneous. Great care must be taken to remove all scale before cyaniding and to insure uniform cooling, or soft spots will be present in the case. Immersing the work for 20 minutes does not increase the case materially but results in high-carbon spots and brittleness.

In cyaniding it is also important to use a closed pot since the fumes are extremely poisonous.

The hard case obtained from cyaniding is not due wholly to a high carbon content; as a matter of fact, the carbon content is relatively low. Chemical analysis shows the presence of nitrogen in the form of iron nitride in the case. It is this constituent which imparts the hardness as well as brittleness to the case. It should be noted that the core is also hard and brittle after cyaniding, which is, of course, undesirable.

NITRIDING

Nitriding is the surface hardening of special alloy steels by heating the metal in contact with ammonia gas or other nitrogenous material. The process of nitriding has great possibilities, however, and should eventually supersede casehardening by carburizing on all important work. A harder case is obtainable by nitriding than by carburizing. In addition, there is no distortion or cracking associated with nitriding and the case obtained appears to be corrosion resistant in most mediums, including salt water.

Nitriding is applicable only to special steels, the most common of which are called nitralloys. A process has recently been developed for nitriding stainless steels to obtain an ultra-hard corrosion-resistant material. In aircraft work, steel in accordance with Military Specification MIL-S-6709 is normally used. This specification describes two types of nitralloy—composition A, which is a high-core strength steel, and composition B, which is a free-machining steel. The chemical and physical properties of these steels are as follows:

CHEMICAL COMPOSITION

	A (%)	*B* (%)
Carbon	0.38–0.43	0.30–0.40
Manganese	0.50–0.70	0.50–1.10
Phosphorus	0.040 max.	0.040 max.
Sulfur	0.040 max.	0.060 max.
Silicon	0.20–0.40	0.20–0.40
Chromium	1.40–1.80	1.00–1.50
Aluminum	0.90–1.35	0.85–1.20
Molybdenum	0.30–0.40	0.15–0.25
Selenium	—	0.15–0.35

PHYSICAL PROPERTIES

Composition	Thickness, inches	Tensile strength (p.s.i.)	Yield strength (p.s.i.)	Elongation (%)
A	1½ and less	135,000	100,000	16
	Over 1½ to 3	125,000	90,000	15
	Over 3 to 5	110,000	85,000	15
B	1½ and less	106,000	76,000	26
	Over 1½ to 3	102,000	74,000	28
	Over 3 to 5	95,000	70,000	30

The physical properties listed above are the minimum acceptable when subjected to the following heat treatments:

Composition A. Heat at 1725° to 1750°F., quench in oil (or water if diameter exceeds 2 inches), and draw at a temperature of 1100°F. or higher for 5 hours.

Composition B. Heat at 1700° to 1750°F., quench in oil, and draw at a temperature of 1050°F. or higher.

Before being given the nitriding operation the steel should be hardened and tempered to obtain a sorbitic structure. If annealed material is nitrided the nitrogen will penetrate the boundaries of the relatively large grains and cause a brittle, nonuniform casehardening. When no distortion is permissible in the nitrided part, it is necessary to normalize the steel prior to nitriding to remove all strains resulting from the forging, quenching, or machining.

The nitriding operation consists of heating the steel to 950°F. in the presence of ammonia gas for from 20 to 100 hours. The container in which the work and ammonia gas are brought in contact must be airtight and equipped with a fan to maintain good circulation and an even temperature throughout. The depth of the case obtained by nitriding is about 0.015 inch if heated for 50 hours, and the case has a Vickers Brinell hardness number over 950. The nitriding process does not affect the physical state of the core if the preceding tempering temperature (as is usual) was 950° or over.

The molybdenum present in nitriding steels imparts ductility to both case and core. In spite of this fact, however, the case is still very brittle. It is possible to improve its ductility by increasing the nitriding temperature to 1150°F. for a period of two hours at the end of the regular treatment. The increased ductility is gained at the expense of 100 points in hardness.

It should be noted that there is no quenching associated with the process of nitriding. As a result there is no distortion or cracking of the work, particularly of properly normalized material without internal strains, as explained above. Due to the brittleness of the case, care must be taken in the design to avoid sharp corners. The reason is that nitrides are formed on both sides as well as the edge, which makes a brittle corner or edge that is easily chipped.

No scaling of the work occurs during the nitriding operation. The slight oxide film formed is easily removed by buffing or by using emery paper.

Tinning of any surface will prevent it from being nitrided. This fact is utilized when a piece of work is to be partially treated only.

Nitrided surfaces can be reheated to 950°F. without losing any of their hardness. If heated above that temperature, they lose their hardness rapidly and cannot be retreated to regain the lost hardness.

Gas welding of nitriding steels is not practical since a large part of the aluminum is burnt away and the remaining metal will not nitride properly. Spot welding after nitriding has been successful.

Care must be taken to remove all the decarburized metal caused by preliminary heat treatment prior to nitriding. If the decarburized metal is not removed, the nitride case will flake. Nitriding steels decarburize more than other steels during heat treatment. They also are increased in size slightly by the nitriding process. This increase is of the order of 0.002 inch for a piece 12 inches in diameter.

As previously stated, nitrided steels are reputed to be corrosion resistant in fresh or salt water as well as under ordinary atmospheric conditions. The steel, however, has not been in use long enough to make a definite statement on its corrosion resistance.

INDUCTION HARDENING

Induction hardening is one application of induction heating which is finding numerous applications in aircraft and automotive work. Induction heating is the process of heating metallic substances by means of a powerful, rapidly alternating electromagnetic field. The current that produces this field is usually carried in a copper coil that encircles the work to be heated. Induction heating is a differential heating, that is, the surface of the work heats up first very rapidly and then the core of the material. When steel is used and the work is quenched immediately after the surface is heated to a high temperature, a casehardened surface is obtained without having affected the properties of the core material. The depth of the case and/or heat penetration varies with the frequency and intensity of the electromagnetic field and the length of time the current is on. Induction heating is used for surface hardening, and through-heating for heat treating, annealing, normalizing, brazing, soldering, forging, forming, or melting of metals. The required frequency, power, and heating time must be determined for each application.

Dielectric heating is similar to induction heating but is applicable only to nonconducting materials (dielectric materials) such as might be used for electric insulation. Plastics and compressed wood are typical applications. Dielectric heating is done by means of an electrodynamic field, the work being placed between two or more plates. Dielectric heating uniformly heats the material from the surface to the center as opposed to the differential heating of the induction-heating process.

There are four types of induction-heating equipment in common use. They are different in principle and in the current frequencies they can provide. The four types are as follows:

1. The first type uses the power-line frequency of 60 cycles per second and voltages up to 880. Transformers are used if required to attain the desired voltage. Current requirements range up to 1,500 amperes. This type of equipment is used for the preheating of joints to be welded, the stress-relieving of welds, and the heating of ingots for rolling or forging.
2. The motor-generator type of equipment converts 60-cycle power to frequencies from 1,000 to 12,000 cycles at capacities up to 1,000 kilowatts rated power. This type of induction-heating equipment is the most widely used. It is used for surface hardening

of crankshafts, gears, and similar parts, for brazing tool tips, for melting metals in large quantities, and for heating forging stock. This method of heating forging stock has the advantage of eliminating scale, uniformly heating the stock to the working temperature and saving considerable time and space normally required by furnace heating.

3. Spark-gap generator equipment produces a rapid reversal of the electromagnetic field at frequencies up to 400,000 cycles and 25 kilowatts output. It is used for the heat treatment of gears and precision gages and for the annealing of continuous strip for stamping and forging.

4. Vacuum-tube oscillator equipment is capable of producing frequencies from 100,000 to 10,000,000 cycles at capacities up to 400 kilowatts. This electronic induction-heating equipment consists of a transformer which raises the line voltage to that required for the oscillator-tube operation, a set of rectifier tubes which converts the alternating-current line power into direct current to supply the oscillator circuit, oscillator tubes of the high-frequency type, capacitors, and inductance coils which produce the high-frequency current to be delivered to the heater coil.

The heater coil is a separate unit which is designed to suit the size, shape, and material of the work to be heated. It may be a long cylinder of many turns or just a few turns, a flat pancake of only 1 or 2 turns, or a special shape to adapt it to the contour of the work. Copper tubing equipped with provisions for running cooling water through the inside is frequently used in the construction of heater coils. With this type of coil, high frequencies and current densities can be used to raise the surface temperature of a steel piece above its critical temperature in a fraction of a second.

The surface hardening of steel parts, usually referred to as induction hardening, is the primary application of induction heating in aircraft and automotive work. In this process the heat is applied so rapidly that the high temperatures are confined to the surface layers with the inner core remaining relatively cool and unaffected. When the current is shut off the rapid conduction of the surface heat to the cooler interior results in self-quenching of the hardened surface. For full hardness, however, a water quench is usually necessary.

When the current is applied the surface heat is transmitted by conduction almost instantaneously to the inner core of the material. To permit dissipation of this heat without raising the core temperature to a point where its structure is affected it is necessary to have adequate core material. A piece of tubing, for instance, must have a wall thickness at least twice the depth of the surface hardening. In induction hardening there is no sharp line of demarcation between the hard surface case and the inner core. There is a gradual transition from a hard case to the original properties of the core.

A normalized structure is desirable to obtain the best results from induction hardening. The short time during which the surface of the work is above its critical temperature requires a very rapid solution of the carbides as required to attain a hardened surface. This solution is assisted by starting with a sorbitic or fine pearlitic structure.

To permit uniform heating of the surface it is desirable that its cross-section be symmetrical. Variations in cross-sectional areas along the length of the work are all right. Symmetrical coils may be used for heating unsymmetrical objects, since the natural tendency of high-frequency currents is to follow the contour.

There is no distortion of the work due to induction hardening.

The selection of induction-heating equipment should be predicated on the thickness of the work to be heated or hardened. Frequencies above 100,000 cycles are required for ⅛-inch or thinner material; 9600 cycles or higher are required for ¼-inch material; and 1920 to 9600 for ½-inch material. The thinner the material, the higher the frequency required.

Induction-heating equipment is frequently used for soldering and brazing. In this operation the brazing material or solder is set in place at the joint and the work placed in or near a heating coil. A closely controlled heat is developed at the joint in both the brazing or soldering material and the adjacent portion of the work. Both the leading and trailing edge of hollow steel propeller blades are inside brazed. Beads of brazing material are laid along the inside edge and the propeller is moved edgewise through the coil. The brazing material melts and fuses with the steel to form an even, firm joint. The numerous wires leading into an electrical connector can be soldered simultaneously with a simple setup.

In dielectric heating, an alternating electric field of between 1,000,000 and 200,000,000 cycles per second is set up by means of a high-frequency vacuum-tube oscillator. This high frequency results in a uniform heating of the entire cross-section of the work. It is particularly adaptable for heating thick sections of nonconducting material which otherwise would take several hours of surface heating because of limited thermal conductivity. Material is heated between two or more plates from which the electrostatic current emanates. This type of heating is employed in curing impregnated materials, gluing, bonding, and preheating plastics prior to molding. A typical application is in the manufacture of compressed and impregnated wood-propellers which consist of wooden sheets, plastic impregnated, which are bonded together under high heat and pressure. Dielectric heating cures the assembly uniformly in a fraction of the time required by any other method.

SHOT PEENING

Shot peening is sometimes referred to as shot blasting. It should not, however, be confused with sand blasting or other surface-cleaning processes.

Shot peening is a recent development that improves the fatigue and abrasion resistance of metal parts. It is applicable to ferrous and nonferrous parts, but it is mostly used on steel surfaces. This process has been reported to increase the life of parts subject to repeated stresses (such as springs) from 3 to 13 times. The fatigue loads of shot-peened parts can be increased if an increase in the life of the part is not a consideration.

The shot-peening process consists of throwing hardened steel balls at the work to be peened. The steel balls, or shot, are thrown against the surface either by compressed air or by centrifugal force as the shot is fired from a rotating wheel. The intensity of the process can be varied by regulating the size of the shot, the hardness of the shot, the speed at which it is fired, and the length of time the work is exposed to the shot. If the shot-peening is too intense the work may be fractured internally, thereby undoing all the good expected from the peening. Saturation of the surface with the little indentations made by the shot is a quick visual method of inspecting the intensity of the shot-peening operation. It is desirable to run a sample piece to set up the conditions to be used in the production process.

Shot peening prestresses the surface of the work and adds to the fatigue and abrasion resistance. It leaves the surface with a countless number of shallow indentations where the hardened shot has struck. The surface of each of these indentations has been cold-worked by being stretched in every direction, and becomes harder, stronger, and less ductile than before. The net result is an increase in compressive stress in the skin, and an increase in tensile stress just below the surface. The compressive stress in the skin will counteract any tensile stress that normally might start a crack or fracture

Fractures usually start at a point of localized stress concentration. Sharp shoulders, tool marks, scratches, and notches should be avoided for this reason. The indentations made by the hardened steel balls are well rounded, and they are so numerous they dissipate any stress concentration over a wide area. Care must be taken to chamfer all sharp external corners before shot peening, however, or they will be worked out into sharp, finlike extensions which will induce early failures. Shot penning of relatively rough surfaces can be done considerably cheaper than polishing, and the fatigue strength of the peened surface equals or exceeds that of the polished surface.

Shot peening can be applied to irregular or complicated surfaces such as gear teeth, helical springs, universal joints, axles, rocker arms, bearings, propeller shanks and hubs. It has been applied to fillets and grooves to offset stress concentrations. When applied to gear teeth it produces a surface with increased resistance to wear and to pitting corrosion. Shot peening appears destined for more and more applications.

CHAPTER VII

SHAPING OF METAL

IN ORDER to fully utilize steel, or any structural material for that matter, it is essential that it be available in a usable shape. When newly made steel is removed from the furnace, it is in a molten condition. This molten steel is poured into a large ingot before being subjected to other processes required to obtain the necessary form. In rare cases the molten steel is poured directly into a mold of the shape of the finished piece. The steel ingot is reduced to material of the desired shape by one of several processes which have been developed. These processes may be classified broadly as mechanical treatment or casting. The mechanical treatment in turn may be subdivided into hot or cold working, and these in turn into rolling, forging, and drawing. This chapter will be devoted to describing these processes and the results obtained from each. In addition, the defects found in steel after fabrication, whether introduced in the furnace or during the working, will be described.

MECHANICAL TREATMENT

In determining whether a desired shape is to be cast or formed by mechanical working, several things must be considered. If the shape is very complicated, casting will be mandatory if expensive machining of mechanically formed parts is to be avoided. On the other hand, if strength and quality of material is the prime consideration of a given part, a casting will not be satisfactory. For this reason steel castings are seldom used in aircraft work.

As previously explained in the chapter on Heat Treatment of Steel, the grain size increases as molten steel solidifies and cools down to the critical temperature. When steel is worked mechanically above the critical range, the growth of the grain is prevented and a fine-grained, dense steel is the result. Gas cavities and blowholes are also eliminated by the pressure of mechanical working. The resultant steel is the best quality of steel obtainable from the physical viewpoint.

HOT WORKING

Almost all steel is hot-worked from the ingot into some intermediate form from which it is either hot- or cold-worked to the finished shape. When an ingot is stripped from its mold after about one hour of solidification, its surface is solid but the interior is still molten. The ingot is then placed in a soaking pit, which prevents loss of heat, and the molten interior of the ingot gradually solidifies while reheating the partially cooled surface. After about one hour of soaking, the temperature is equalized throughout the ingot, which is then reduced by rolling to intermediate sizes which may be more readily handled.

The rolled shape is called a *bloom* when its sectional dimension is 6 X 6 inches, or larger, and approximately square. The section is called a *billet* when it is approximately square and less than 6 X 6 inches. Rectangular sections in which the width is greater than twice the thickness are called *slabs*. Slabs are the intermediate shapes from which sheets are rolled.

Hot working is done either by rolling or forging. Simple sections required in large quantities are rolled; more complicated sections are forged. Because it is possible to control the pressure and temperature more closely in forging than in rolling, a forged part is of better quality than a rolled one. This difference is not marked, however.

Hot Rolling. Blooms, billets, or slabs are heated above the critical range and rolled into a variety of shapes of uniform cross-section. The more common of these rolled shapes are sheet, bar, channels, angles, I-beams, railroad rails, etc. In aircraft work we are especially interested in sheet, bar, and rod rolled from steel. It is extremely important that the rolling should end just above the critical range in order to obtain the finest-grained metal. If the rolling ends while the steel is well above the critical range, grain growth will occur until the critical range is reached; if rolling should continue below the critical range, the grain of the metal will be crushed and distorted. It is frequently necessary to reheat the steel between rolling operations when all the work cannot be done before the steel has cooled down to the critical range.

There are many types of rolling mills to serve different purposes but the principle of operation is the same. The section to be rolled is fed between two rollers which are somewhat closer together than the dimension of original section. By this means the cross-section is diminished. The operation is repeated until the desired thickness and shape is obtained. In the operation of rolling mills there is a strong temptation to keep the metal extremely hot and plastic to reduce the forces necessary for reduction of the cross-section. If this is done and the finishing temperature is far above the critical range, a very coarse-grained structure will result. Coarse grains lack the cohesion of fine grains, and consequently the metal is not strong. In hot rolling a scale is always formed on the surface of the metal, since it is impossible to keep oxygen away from the hot surface during the rolling operations. This scale may be removed by pickling in acid after completion of the rolling operations.

Steel shapes to be rolled are heated to approximately 2300°F. before rolling. Inasmuch as the rolling is finished somewhere above 1400°F., it is difficult to predict the exact thickness since contraction will occur during cooling. In addition, the surface scale must be removed, particularly in material intended for aircraft work. As will be explained later in this chapter, hot-rolled material is frequently finished by cold rolling or drawing to obtain accurate finish dimensions and a bright, smooth surface.

Forging. Complicated sections which cannot be rolled, or sections of which only a small quantity are required, are usually forged. In many cases in aircraft work the first parts for the experimental airplane are machined out of solid bar stock; although the intention is to forge the particular parts for production. The reason is the expense and delay involved in making the necessary die and obtaining the forging. Most parts are cheaper to machine out of bar stock if only a few are required. A comparison of costs should be made in every case before the decision is made to forge or machine a part. It should be borne in mind that the forged part will require some finish machining, and this expense should be included in the comparative cost of the forging. On the other hand, unless parts are machined out of forging stock, the machined parts will not be as good as the forgings insofar as the physical condition of the metal is concerned. The tendency at the present time is to forge as many parts as possible, thereby relieving the usually overworked machine department. Once a standard part is forged it is possible to use it on subsequent models without having to write off the cost of the die against the later contracts. There is a definite saving here.

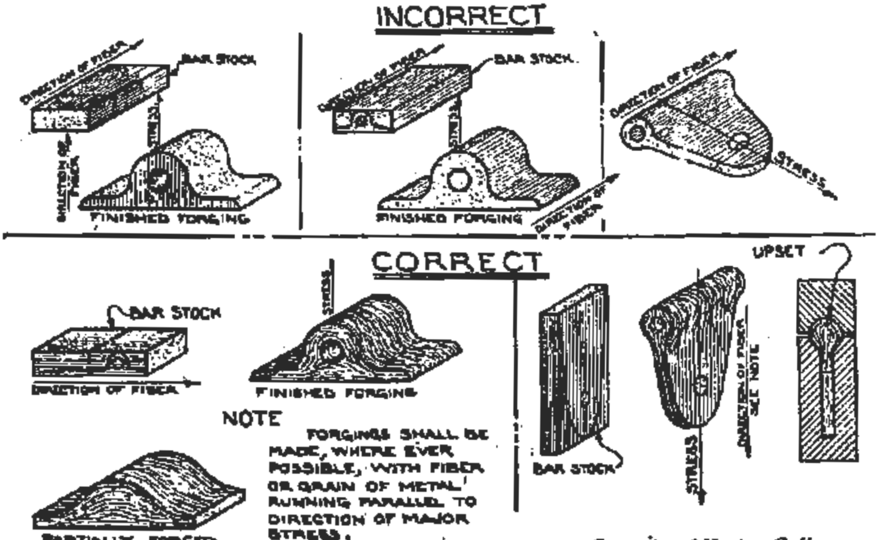
Forging of steel is a mechanical working above the critical range to shape the metal as desired. Due to the pressure exerted the grain of the metal is refined and the metal is made more dense and homogeneous. The best quality of metal is thus obtained. As previously explained, however, it is necessary to finish forging the steel just above the critical range in order to prevent grain growth or distortion. Working of the metal while hot breaks up the crystalline structure and prevents grain growth, so that the finest grain and best mechanical properties are procured if forging ends just above the critical range. Forging is done either by pressing or hammering the heated steel until the desired shape is obtained.

Pressing is used when the parts to be forged are large and heavy. It is also superseding hammering where high-grade steel is required. Since the press is slow acting, its force is transmitted uniformly to the center of the section, and thus the interior grain structure is affected as well as the exterior, giving the best possible structure throughout.

Hammering can only be used on relatively small pieces. Since the hammer transmits its force almost instantly, its effect is limited to a small depth. It is necessary to use a very heavy hammer or to subject the part to repeated beatings to insure complete working of the section. If the force applied has been insufficient to penetrate to the center, the finished forging surface will be concave. If the center has been properly worked, the surface of the forging will be convex or bulged. The advantage of hammering is that the operator has control over the amount of pressure applied and the finishing temperature, and is able to produce metal of the highest grade.

This type of forging is usually referred to as smith forging. Smith forging is extensively used when only a small number of parts are required. Considerable machining and material is saved when a part is smith-forged to approximately the finished shape.

Upsetting is a forging operation in which a hot piece of metal is increased in thickness and decreased in length by hammering on the end. This is the manner in which heads are put on bolts. An upset head is stronger than a machined head because the grain direction is ideal to resist pulling off stresses. In the case of the machined head the plane of cleavage would parallel the grain and would be weak. With the upset head the grain is perpendicular to the force and will resist shearing forces. The question of grain direction is extremely important in all metal fittings. In laying out forging, care must be taken to insure proper direction of grain relative to the major stress. Figure 14 shows the right and wrong methods of laying out forging from this viewpoint.



Courtesy of Horace C. Knerr

FIGURE 14. Correct and Incorrect Directions of Grain in Forgings

Swaging is a forging operation which may be done either hot or cold. It consists of reducing the cross-section and shaping a bar, rod, or tube. It is done by subjecting a revolving die, which shapes the work, to a large number of repeated blows.

Drop Forging. Drop forging is a modification of forging by hammering. Two dies are used, on of which is attached to the hammer and the other to the anvil. When these dies are brought together the shape inside them is that of the part required. At the intersection of the two dies there is a relieved section all around the edge to take care of surplus metal squeezed out when the dies are brought together. In the actual operation a heated billet is placed on the lower die and the hammer and upper die are dropped. The operation is repeated until the hot billet has assumed the shape of the dies. During the forging operation the dies are kept clean with a high-pressure steam or air hose to prevent scale being forged into the part. The surplus metal which has been squeezed out into the relieved section is called the *fin* or *flash*. This fin is trimmed off the finished part.

Drop forging is used for the production of individual pieces in large quantities. Fairly intricate sections can be made by this method. Aircraft fittings are drop-forged quite extensively. The fitting should be forged as close to finished dimensions as possible to save on machining. In some fittings only drilling and reaming of holes is necessary. Other fittings may require extensive machining if they are complex and cannot be forged to the finished shape. In laying out forging dies it is necessary to slope the inside faces from 3° to 7° to permit drawing out the finished part. This sloping of the sides is referred to as the *draft*.

Drop forgings are small relative to the hammer used and are satisfactorily worked throughout. Because of their small size and the indefinite time required for forming, it is difficult to obtain the proper finishing temperature. Practice and experience must be relied on in this instance.

Chrome-molybdenum and chrome-nickel-molybdenum steels are commonly used for aircraft forgings. Where corrosion resistance is important, 18-8 corrosion-resisting steel is used.

PRESSED POWDERED-METAL PARTS

The process of pressing powdered-metal parts is a method by which combinations of different metals, or of metals and nonmetals, that do not ordinarily alloy can be joined together. Two or more metal powders can be mixed to produce a new material which will retain the individual characteristics of each constituent in proportion to the quantity of each included in the final product.

Pressed powdered metal parts are formed on a press by placing a measured quantity of finely powdered metal in a die cavity and then applying pressure through a plunger to form a compact mass. This mass holds its shape when removed from the die by reason of the interlocking of the finely powdered particles. The formed parts are then sintered in a furnace at a temperature somewhat below the melting point of the material. This heat-treating operation welds together the surfaces of the particles that are in intimate contact. Highly accurate parts are then sized by pressing them in precision dies to correct for any expansion or shrinkage that occurred during sintering.

Dimensions parallel to the plunger travel can be held within tolerances of several thousandths of an inch, while dimensions at right angles can be held to less than 0.001 inch. Parts having an area as large as 10 square inches have been produced. The only size limitation depends on the capacity of the available equipment. The shape of powdered-metal pressings must be such that all particles of powder are subjected to the direct pressure of the plunger. Undercuts perpendicular to the axis of the part are not practical.

Parts of complicated shape requiring expensive machining to finish can usually be manufactured most cheaply as powdered-metal pressings. Tooling costs for pressings are very moderate since only one or at most two pressing operations are required.

The maximum tensile strength of a powdered-metal pressing may be as high as 80% of the tensile strength of the solid material. Porous pressings are, of course, somewhat weaker. Depending on the technique used, parts of varying degrees of porosity can be produced. Porous bearings containing graphite or free oil are very commonly used in locations not readily accessible for lubrication. Cemented carbide cutting tools, gears, odd-shaped parts, and many similar items are now manufactured as powdered-metal pressings.

COLD WORKING

Working of steel above the critical range as previously described is called hot working. Cold working of steel is done at atmospheric temperatures; it can be either cold rolling or cold drawing. Sheet steel and bars ¾ inch in diameter or larger are rolled; smaller bars, wire, and tubing are drawn to size.

Cold-worked material increases in strength, elastic limit, and hardness but loses its ductility. The increase in brittleness is very marked. A good surface finish is obtained by cold working, and the material can be held to accurate dimensions. These last two points are very important since hot-rolled material lacks both of these properties.

A more compact and better metal is obtained by cold working than by hot working. The crystals are broken into smaller masses and distorted along the direction of working to such an extent that their cleavage planes all but disappear. In order to relieve the internal strains set up by this condition, it is customary to anneal or normalize cold-worked material after fabrication.

Cold Rolling. Whenever bar or sheet with a smooth surface and accurate dimension is required, cold-rolled material should be ordered. The material is actually hot rolled to near the required size, pickled to remove the oxidized scale, and then passed through chilled finishing rolls to impart a smooth surface and reduce it to accurate dimensions.

The amount of cold work done in rolling is relatively little, so that no appreciable increase in strength is obtained. In the case of bar stock only the surface is hardened. It is advisable to purchase all material in the normalized state, however, to insure relief of all internal strains.

Cold Drawing. Wire is manufactured from hot-rolled rods of 1/8 to ¾ inch in diameter. These rods are pickled in acid to remove scale, then dipped in lime water, and finally dried in a steam-drying room where they remain until drawn. To reduce the cross-section of the rod, it is drawn cold through a die shaped as shown in Figure 15. The end of the rod is filed or hammered to fit through the die, where it is fastened to the drawing block which proceeds to pull the rest of the wire through. The force necessary is approximately 50% of the breaking strength of the wire. The rod cross-section is reduced gradually, and repeated drawings are necessary to attain the desired wire size. Each drawing reduces the ductility of the wire, so that after several drawings it is necessary to anneal the wire before further drawing. Wire annealing is done in a closed pot to prevent oxidation of the surface during the heating operation. The wire is not removed from the pot until near atmospheric temperature.

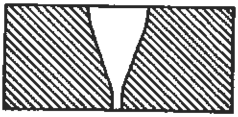


FIGURE 15. Wire-drawing Die

Cold drawing of wire increases the tensile strength tremendously but greatly reduces the ductility. Music wire is drawn to small diameters with a tensile strength of 300,000 p.s.i. By proper selection of the reduction to be made in each draw, and the number of draws to be made after annealing, it is possible to obtain wire of any strength desired. The reduction in cross-sectional area for each draw may be as high as 30%. When dead-soft wire is required, it is annealed after the final drawing operation.

In aircraft work large quantities of seamless steel tubing are used. This tubing must be accurate in outside diameter, and the thin wall must be uniform in thickness and free from defects. All aircraft tubing is finished to size by cold drawing. The operations required in the manufacture of seamless steel tubing are as follows.

1. A steel billet is hot-rolled to form a round bar of the necessary length and diameter.
2. The round bar is heated to 2200°F. and passed through the piercing rolls. These rolls spin the bar and force it forward over a conical shaped forged mandrel. The mandrel pierces a large hole longitudinally through the bar and at the same time lengthens it from two to four times its original length. The tube formed by this operation is not uniform in diameter and has a wavy surface.
3. The obtain a uniform diameter and the desired thickness of wall, the pierced tube, which is still hot, is passed through two grooved rolls of the desired diameter. As the tube is forced through the rolls, it also passes over a fixed mandrel of the required internal diameter. Several passes through the rolls over the fixed mandrel are usually necessary to reduce the outside diameter to the proper size.
4. After cooling, the tube is pickled to remove all scale. It is then cold-drawn through dies and over mandrels of varying sizes until reduced to the finished dimensions. The setup for this operation is shown in Figure 16. One end of the hot-rolled tube is hammered to a point, inserted through the die, and gripped by a pair of tongs. These tongs are attached to a traveling chain through which the drawing force is exerted. A mandrel is inserted through the open end of the tube and is positioned just between the faces of the die. As can be seen from the illustration, the outside and inside diameters and, necessarily, the wall thickness, are definitely fixed as the tube is drawn through the die and mandrel. The sectional area is reduced from 15% to 25% by each draw. It is necessary to anneal and pickle the tube after each draw in order to soften it sufficiently for the next draw. Sometimes as many as ten draws are required to obtain a tube of the desired diameter and wall thickness. Some tubing manufacturers have developed long, cylindrical, airtight retorts in which smaller-diameter tubing is enclosed during annealing. By this method pickling after each annealing operation is eliminated.

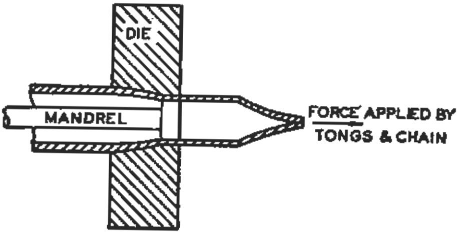


FIGURE 16. Cold Drawing of Tubing

Aircraft tubing is invariably purchased in the normalized condition. Tubing manufacturers are equipped for normalizing all tubing, so that all evidences of the cold-working may be removed.

It is obvious that the manufacture of dies and mandrels is an art in itself. Also, special lubricants must be used for all cold-drawing operations. These items are not within the scope of this book, but for those interested tubing manufacturers are only too glad to demonstrate how seamless tubing is made.

CASTING

Steel castings are being more generally used in aircraft construction as a result of improved quality and the development of high-strength heat treatments. Steel castings should not be used in place of forgings unless a definite advantage is gained thereby. This advantage might be the avoidance of excessive or difficult machining operations, the use of one casting to replace an assembly of forged-steel parts, or an attractive saving in cost if only small quantities are involved.

Castings do not have directional grain properties as do forgings and other wrought materials. This condition is advantageous if the properties of the castings are sufficiently high to exceed those obtained across the grain in wrought material. In general, forgings have better impact strength, fatigue resistance, and toughness. The ratio of fatigue to tensile strength is of the order of 0.5 for wrought steel, compared with a ratio of 0.4 for cast steel of equivalent composition. An increase in this ratio to approximately 0.45 can be obtained by shot peening the surface of the casting.

Steel castings are now manufactured from material of the same composition used in wrought steels. Similar heat-treatment techniques are used for both materials to obtain corresponding properties. Steel castings are usually divided into three classes, depending upon the heat treatment to which they are subjected:

1. Fully annealed castings having a minimum tensile strength of 75,000 to 85,000 p.s.i. and an elongation of over 22%.
2. Normalized, or normalized and drawn, castings having a minimum tensile strength of 85,000 to 100,000 p.s.i. and an elongation of over 18%.
3. Heat-treated castings which have been liquid-quenched, then tempered or drawn. These castings are obtainable with tensile strengths as high as 150,000 p.s.i., yield strengths of 125,000 p.s.i., and in a minimum elongation of 10%.

Steel castings have been used for tail-wheel forks, landing-gear axles, landing-gear yokes, turbosupercharger buckets, and miscellaneous aircraft fittings.

There are three commonly used methods for casting steel—static casting, centrifugal casting, and precision casting. The last two methods were greatly improved and expanded during the war years and are largely responsible for the increasing use of steel castings in aircraft construction. The three methods are described in the following pages.

Static Casting. This process has been used for many years as the standard method for manufacturing castings. It consists of the manufacture of a pattern which is a duplicate of the desired casting, the preparation of a mold from the pattern, the pouring of molten metal into the mold, and the removal and finishing of the casting after it has solidified in the mold. In this type of casting great care must be taken to eliminate internal voids and shrinkage cracks.

Patterns are made of wood or metal, depending upon the amount of service expected of them. Patterns are exact duplicates of the designed parts, except that their dimensions are somewhat greater to allow for the shrinkage of the molten metal as it cools. Steel castings will shrink ¼ inch per foot. To allow for this shrinkage the pattern-maker lays out the pattern with a shrink rule on which all the dimensions are expanded in the proportion of ¼ inch to the foot. Thus, although the rule reads 12 inches it is actually 12¼ inches long. By the use of a shrink rule the pattern-maker avoids the necessity of increasing each dimension with the attendant possibility of error. Sufficient metal should be allowed on the casting to permit finish machining if required. As cast, the surface will be quite rough. In order to remove the pattern from the mold it is customary to "rap" it to break it loose. Rapping slightly increases the size of the mold and will result in additional metal on the surface of the casting. If a definite, close-tolerance dimension must be held it will be necessary to machine off this additional metal.

Molds for steel castings are made with dry sand in iron containers. The surface of the mold is treated with a sticky substance to bind the sand and then sprinkled with ground quartz or similar material to make a highly refractory surface. The mold must be designed with the following considerations in mind:

1. The pattern must be readily removable. It is usually necessary to build the mold in two or more parts to permit the removal of the pattern. When the pattern is complicated it is often necessary to build it in several parts held together with dowel pins, so that it can be removed piecemeal without disturbing the mold.
2. An adequate number of gates of sufficient size must be provided for pouring the molten metal into the mold. Gates must be close enough, so that metal poured in adjacent gates will meet and blend together before either pouring has cooled. A surplus of molten metal must be kept in the gates to furnish metal to the casting as it cools and shrinks.
3. A riser must be provided leading from every high part of the mold. The risers allow the escape of air as the mold is filled, and also provide a place for loose sand and impurities to float clear of the casting proper. In addition the risers furnish a reservoir of hot metal to feed the casting as it shrinks.
4. Small vent holes are also provided for the escape of gases and steam.
5. The material of which the mold is built must resist burning by the molten metal and distortion due to the static pressure of the metal.

After cooling, the gate and risers are removed from the casting by sawing or burning off, and then filing smooth. In cooling castings, which are invariably composed of heavy and light sections, severe internal strains are set up due to the uneven cooling of the unequal thicknesses. To remove these strains all steel castings should be heat-treated. Steel castings are rarely used in aircraft except in the heat-treated state.

Many defects are found in castings if proper precautions are not taken; they are similar to the defects found in cast ingots and described in detail in this chapter. In many cases it is possible to repair cracks and small holes in castings by plugging or welding. If welding is resorted to it must be done before heat treatment.

Centrifugal Casting. This process has been devised as a method for applying pressure to the molten metal during the casting operation. In the static-casting process, only the pressure induced by the head of the molten metal is available. In centrifugal casting, pressure is obtained by whirling the mold. Any metal that can be cast in a sand mold can be centrifugally cast, but this process is mainly used for casting alloy steels in aircraft work.

There are three variations of the centrifugal-casting process in common use. Castings are classified according to the method by which they are fabricated. The three classifications are as follows:

1. *True centrifugal*, In this process only an external mold is used and it is spun around its own axis, The inside contour of the casting is formed by centrifugal force. Castings made by this process are limited in design to such shapes as air-cooled cylinder barrels, tubular sections, and landing-gear parts. Parts cast by this method are of the highest quality and can compete directly with wrought parts.
2. *Semicentrifugal*. In this process an inside core is used as well as an external mold. This arrangement permits more latitude in design and parts with irregularly shaped inside contours can be cast.
3. *Centrifuge*. In this process the work is rotated about an independent central axis around which the molds are grouped radially. The molds are connected by spruces to a central pouring chamber into which the molten metal is introduced. A wide variety of shapes can be cast by this method, but they are not as sound or strong as true centrifugal castings.

The technique used in centrifugal casting varies somewhat with the part being cast. In general, the average spinning speed is equivalent to 600 feet per minute at the surface. In some cases the mold is completely poured before spinning, while in other cases the molten metal is poured during spinning.

The advantages of centrifugal casting are very important considerations when the quality required for aircraft work is essential. Some of these advantages are as follows:

1. An improved surface appearance without cold shuts or wrinkles is obtained.
2. Good directional solidification is obtained because the molten metal flows immediately to the outside of the mold cavity where it chills first and gradually cools in towards the center. In static casting the metal cools simultaneously from the inside and outside surfaces, thus trapping impurities in the midsection. In centrifugal casting all impurities are inside at the axial surface where they can readily be eliminated or machined away. No dirt or flaws are trapped within the casting to be exposed later during inspection or machining.

3. A uniformly dense, fine-grained structure with a tendency towards slightly greater peripheral density is obtained.

After the proper technique is developed for a particular casting, a sound, satisfactory casting can be reproduced consistently. 100% radiographic inspection is unnecessary for this type casting. Magnaflux inspection is desirable for all castings just as with forgings or other steel parts.

Spinning metal molds have been used for many years in the manufacture of cast-iron pipe, and more recently in the manufacture of gun barrels. Steel car wheels, brake drums, and gears are also centrifugally cast without difficulty. In aircraft work the greatest application so far has been in the manufacture of almost a million air-cooled engine-cylinder barrels. Chrome-molybdenum S.A.E. 4140 steel was used for this purpose and had the following properties:

Tensile strength (p.s.i.)	140,000 to 150,000
Yield strength (p.s.i.)	125,000
Elongation (%)	12 to 15
Izod impact strength (ft. lb.)	30

Landing-gear axles for a bomber were also manufactured in large quantities. These were heat-treated to approximately 125,000 p.s.i. and had a 10% elongation.

Precision Casting. The precision or "lost wax" process of casting is used for intricate parts that must be held to high accuracy in size and shape at a reasonable cost. Jewelry and dental inlays have been cast by this process for some time. Practically any metal or alloy can be cast by this process. High-alloy steels and stainless steels which are difficult to machine can be cast by this process to exact contours, thus minimizing the machining required.

In precision casting the first step is the preparation of a master pattern which includes an allowance for the overall shrinkage of the process. This pattern is used to produce a mold of lead or other low-melting alloy. This mold in turn is used to make wax patterns. The wax pattern is given a ceramic coating which is then invested inside a thin metal cylinder by means of an air-setting silica mixture. After drying, the wax is melted from within, leaving a hardened ceramic mold. The ceramic mold is brought up to the casting temperature of between 1650° and 1920°F. and molten metal is forced into the cavity. Air pressure or centrifugal force is usually applied to the molten metal to force it into the cavity. After cooling, the mold is broken and the work removed.

Starting with a master pattern it takes from 2 to 3 hours to obtain the ceramic mold. For small experimental alterations the lead mold can be quickly modified and a sample casting made. The master pattern does not have to be changed until the final shape is determined.

This process is limited to relatively small castings, preferably of the order of a pound or two, though castings up to 15 pounds have been made satisfactorily. Large surfaces tend to collapse. Surfaces equivalent to a 4-inch cube are considered maximum.

The shrinkage in precision casting is indefinite and nonuniform. The number of operations and the use of heated molds makes it difficult for anyone not familiar with the process to make the proper shrinkage allowance. The casting manufacturer should be consulted before making the pattern drawing. Tolerances can be held to ±0.003 inch in dimensions up to ¼ inch, and to ±0.01 inch in dimensions up to 1 inch.

As in all casting practice, generous fillets and gradual changes in section are desirable. Since the mold is destroyed to remove the work, castings of irregular cross-sections and with projections can be made without the necessity for a mold involving numerous loose pieces. Fine details on the original pattern are reproduced precisely on the casting surface. Threads can also be cast. The surface finish is good and requires little or no machining.

The buckets on turbosuperchargers, with their varying contours, are good examples of work that can best be made by precision casting. Numerous small fittings and lugs used in aircraft work have also been precision-cast with complete satisfaction.

DEFECTS IN STEEL

In every stage of the manufacture or shaping of steel there is a possibility of defects creeping into the metal. These defects are the direct cause of many material failures. They seriously reduce the strength of the steel, particularly the fatigue strength, and destroy the reliability of the metal. In aircraft work, where one failure may cost several lives and cause expensive property loss, every precaution is taken to eliminate these defects. It is customary for aircraft manufacturers to maintain inspection staffs and special equipment to catch any flaws in material or workmanship. A short description of the most common defects found in steel follows.

Defects in Ingots. Gas cavities in the ingot, called blowholes, are caused by the trapping of dissolved or occluded gases as the ingot cools. Carbon monoxide gas is the most common cause of blowholes, which may be as large as 1 inch in diameter. In carbon steels, if blowholes are not oxidized they will weld when hot-worked and not cause any trouble. In alloy steels or when oxidized, they will not weld and will form internal cracks, seams, or hairlines when rolled. These are serious defects.

Impurities collect at the top of the ingot as it cools. These impurities are slag, oxides, and often particles of the furnace or ladle lining—all of which enter the steel during its manufacture. When the ingot has formed and been given a preliminary rolling, the top 15% to 30% is discarded or cropped. Cropping removes the impurities bodily.

Segregation is the concentration of many of the chemical compounds found in steel at the center of the ingot, thus destroying the homogeneity of the material. These compounds have solidification points that differ from the main portion of the ingot and collect at the hottest section of the ingot, which is the center. Segregation produces material which is not uniform in strength and quality.

Piping is the cavity formed at the upper center section of the ingot caused by contraction in cooling. The surface of the ingot cools and solidifies first, and as the interior cools, it is attracted to the already solid surface. This effect and gravity produce the pipe or cavity in the upper center section of the ingot. For this reason ingots are cast on end. The pipe is removed when the ingot is cropped.

Cracks are caused on the surface of the ingot if it is removed from the mold while very hot and exposed to chilly air. Cracks may also be caused by rupture of the thin solidified surface of the ingot just after pouring, due to internal pressure or a rough mold. If cracks are not numerous, they may be chipped out smoothly and all traces removed in rolling. But if they are not chipped out, rolling will close the crack but not weld it together.

Scabs or *cold shuts* are caused by molten metal splashing against the mold wall in pouring, and solidifying, and they either freeze there or drop into the molten metal. If not remelted because the molten metal is relatively cool, these drops of solidified metal remain separate. Should they appear on the surface, these scabs are not serious and may be chipped off before rolling.

Ingotism is the formation of large crystals caused by pouring the steel too hot and cooling it too slowly. Large crystals have poor cohesion and produce weak steel. The large crystallization may be broken up by reheating and hot-rolling the metal.

Defects Caused by Rolling. Small cracks known as seams are formed by the elongation of blowholes in rolling.

Hairlines are very minute seams caused by rolling small blowholes. They have no measurable depth and range in length up to ½ inch, but it is important to note that they may be the starting place of a fatigue failure.

Slivers are small pieces of metal that are rolled into the surface. These slivers may be scabs or cold shuts that were not removed from the ingot.

Laminations are produced by the failure of the metal to weld together because of piping, blowholes, slag, or the rolling of chilled metal into the surface.

Fins and *laps* are caused by improper rolling when a small amount of metal or fin is forced out between the rolls and is then rolled into the surface when the bar is rolled the next time, thus forming a lap.

Snakes are made by slag or chilled metal due to a delay in filling the ingot mold. They show as a mark across the surface of a rolled piece. Small surface cracks caused by rolling surface cracks in the ingot are also called snakes.

Hard spots are formed by segregated material or chilled metal striking the side of the ingot mold in pouring.

Pits and *scale marks* are caused by failure to keep the rolls or the rolled material clean during the rolling.

Defects in Cold-drawn Seamless Tubes. Thin fins of metal, called *laps*, are folded over the adjacent metal of the tube. They are formed in the piercing operation.

Pits are small depressions. They may be formed by rolling grit into the tube surface or by overpickling the tube when cleaning scale off preparatory to drawing.

Tears are ragged openings in the interior or exterior surface of the tube which are caused by the mandrel or die picking up hard or weak spots in the metal during drawing operations. Small tears are referred to as "checks."

Scratches are made by rough dies or mandrels, or by grit in the lubricant, or by insufficient lubrication.

Sinks are depressions or collars extending around the inside of the tube caused by a displaced mandrel, which permit drawing the tube to a smaller inside diameter than desired.

Rings are transverse corrugations in the wall of the tubing produced by insufficient lubrication and subsequent jumping of the tube during drawing.

Wall-thickness variation is brought about by inaccurate piercing or worn mandrels or dies. Government specifications permit a variation of wall thickness of 10% of the nominal wall thickness. Aircraft tubing as purchased readily meets this requirement.

CHAPTER VIII

CORROSION-RESISTING STEELS

CORROSION-RESISTING steels are often popularly called stainless steel. They were first developed about 1910 but were not commercially available until after the First World War. This delay was due to the fact that chromium, their main constituent, was restricted to wartime uses. Since then many hundreds of types of corrosion-resisting steels have been developed and many of these are available commercially. Slight variations of the chemical composition of these steels result in marked changes in properties. It is due to this sensitivity to change in chemical composition that so many types of corrosion-resisting steels have been developed. By the same taken, great care must be exercised in the selection and use of a given type to insure obtaining the desired physical properties.

Corrosion-resisting steels are normally classified into three groups:

Group 1. *Chrome-nickel Steel.* This group comprises those steels containing 0.20% carbon or less, 17% to 25% chromium, and 7% to 13% nickel. The well-known "18-8" corrosion-resisting steel is one of this group; in fact, this steel with minor modifications is most often used in aircraft construction. A distinctive property of this group is that the strength cannot be increased by heat treatment but only by cold working.

Group 2. Hardenable Chromium Steels. These steels contain from 12% to 18% chromium, with varying amounts of carbon up to as high as 1.00%. As indicated by the name, they are hardenable by heat treatment. This type of steel is commonly used for manufacture of cutlery, such as "stainless steel" knives and forks. It is also used in one form for the manufacture of aircraft bolts and fittings requiring good corrosion resistance.

Group 3. Nonhardenable Chromium Steels. These steels contain from 15% to 30% chromium and up to 35% carbon. They are not hardenable by heat treatment. They may be used for special applications, but as yet have not been used in aircraft construction.

For aircraft purposes no attention is paid to the above grouping. It is customary to think of the corrosion-resisting steels in relation to their uses in aircraft construction. The two main uses are: (1) nonstructural, such as the manufacture of exhaust collectors, which are dependent upon the excellent corrosion- and heat-resisting qualities of the steel; and (2) structural, which depend on the high strength and ease of fabrication, as well as the corrosion resistance. In the latter part of this chapter the corrosion-resisting steels commonly used in aircraft work are grouped and described under these headings. A further division of structural steels is made into general structure, such as sheet and tubing, machined parts produced from bar or forgings, and castings.

An ultimate tensile strength of 80,000 to 300,000 p.s.i. is obtainable, the lower value from annealed stock and the latter in cold-drawn wire. Structural sheet is procurable with a strength of 185,000 p.s.i. Round or streamline tubing may also be secured with this same strength value. As will be explained later, these great strengths are obtained by cold working—by rolling or drawing—and will be lost if heat is applied to the steel. This fact immediately eliminates the possibility of using heat in the fabrication or joining of this high-strength material and limits its use to a certain extent. Electric spot welding is used almost exclusively for joining this material.

CORROSION

Corrosion-resisting steels are not fully resistant to all corrosive agents. Their corrosion resistance depends upon their own physical state as well as the temperature and concentration of the particular corrosive agent. In aircraft design the most severe corrosive agent to be guarded against is salt water. Generally, the steels described in this chapter are resistant to salt-water corrosion but in varying degrees.

It is customary for aircraft specifications to require the material to pass a salt-spray test, which is a quick means of determining the relative corrosion resistance of a specimen. Specimens are rated A, B, C, or D—A representing the best resistance and D an unacceptable condition. A more detailed description of these ratings is given after the description of the salt-spray test.

The corrosion resistance of corrosion-resisting steels depends almost wholly on the surface condition of the metal. The formation of a tough, passive, invisible oxide film on the surface prevents further corrosion of the metal. It is important to have a clean surface free of impurities or particles of foreign matter, and this condition is obtained by either pickling or polishing, both of which are described in this chapter. When the surface is clean, it has been found advantageous to dip the metal in a solution of nitric acid to accelerate the formation of the protective oxide coating. This operation is called *passivating*.

Corrosion-resistant steels may be purchased in a variety of finishes, depending upon the use to which they will be put. It must be remembered, however, that any fabricating, and more particularly welding, will destroy the surface finish, which must be restored after completion.

INTERGRANULAR CORROSION

Intergranular corrosion is a phenomenon of 18-8 corrosion-resistant steels. It occurs when such steel is heated as in welding. It results in embrittlement

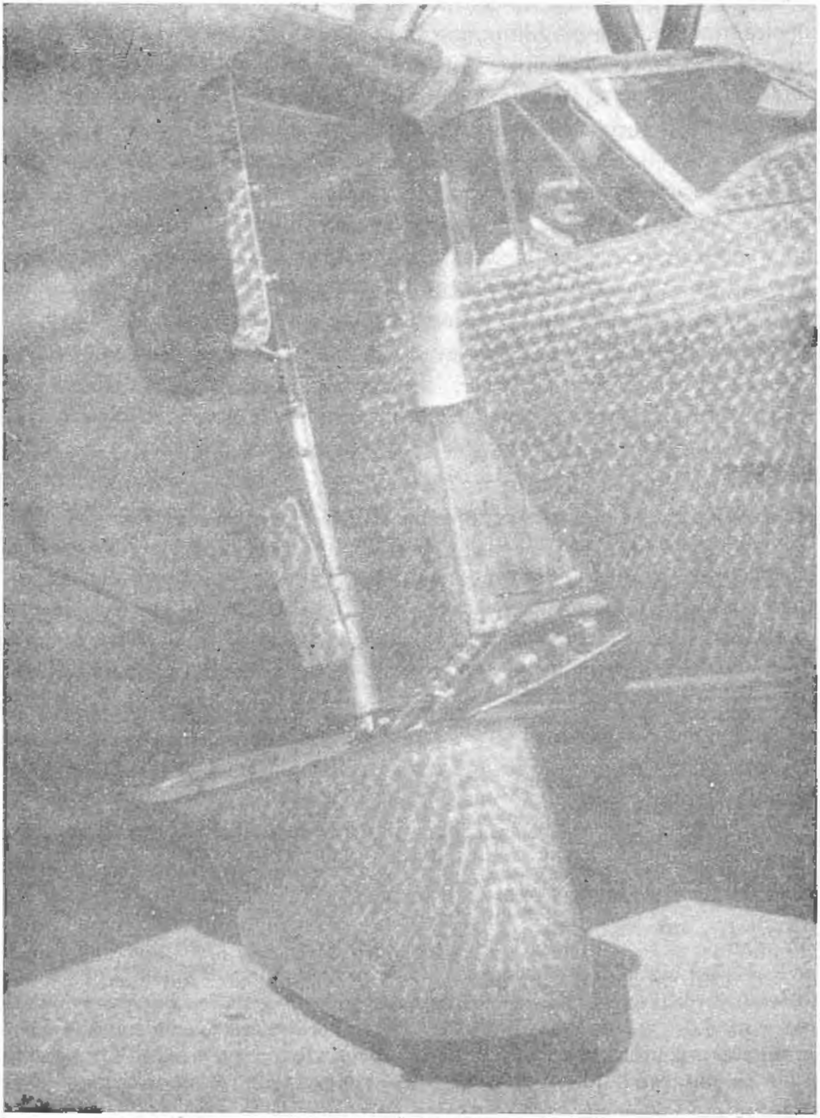


FIGURE 17. Hull and Body Covering; 18-8 Steel; Fleetwings Amphibian

and subsequent cracking of the steel in the vicinity of the weld. Since this type of steel is welded in the fabrication of exhaust collectors for aircraft, an understanding of the phenomenon and the means of avoiding it are necessary.

All 18-8 corrosion-resisting steels are austenitic in character. It will be remembered that standard steels are austenitic when heated above their critical range. In this state the constituents of the steel are in solid solution and the steel is nonmagnetic. At atmospheric temperatures, 18-8 corrosion-resisting steel is in this state. It is found, however, that when it is heated within the range of 1000–1550°F., carbides will be precipitated at the grain boundaries unless the carbon content is very low. These carbides are believed to be iron carbides or iron-chromium carbides. Carbide precipitation is not instantaneous but requires an interval of time in which to occur. During oxyacetylene-welding operations there is a zone just outboard of the weld that falls within the dangerous temperature zone, and carbides are precipitated.

The precipitated carbides do not cause failure until exposed to an active electrolytic agent (such as salt air, spray, or water in the case of the airplane). The electrolytic attack on the carbide zone results in extreme brittleness and subsequent cracking. Intergranular corrosion is not evident on the surface of the steel prior to failure.

In cases where 18-8 steel is to be welded it is customary to specify a maximum carbon content of 0.07% to reduce or prevent the precipitation of carbides. It has also been found that the addition of certain elements—titanium or columbium—will prevent the formation of chromium carbides. Such precipitation as does occur can be corrected by an annealing heat treatment when these special elements are present. In the case of steels containing titanium or columbium the heat treatment is referred to as a stabilizing treatment and is performed at a much lower temperature than the annealing treatment. Stabilizing is so called because it results in the formation of stable carbides which will not precipitate out of solid solution.

Embrittlement Test. In order to determine the extent of carbide precipitation and possible embrittlement, government specifications usually provide for an embrittlement test. In this test samples of the material are handled as follows:

The samples are heated for 2 hours at a temperature of 1200°F. and cooled in air. They are then boiled for 48 hours in a solution containing 10% H_2SO_4, 10% $CuSO_4$, and water. A reflux condenser (or similar device) must be used to prevent any change in the concentration of the solution. When removed from the solution, the samples must not crack when bent 180° over a diameter equal to twice the thickness of the material. In addition, the sample must ring when dropped on a hard surface.

Metallographic Examination. Government specifications require a metallographic examination to be made when the quality of the material is important. This examination is both macroscopic and microscopic.

The *macroscopic* examination is performed as follows:

The sample must be the full cross-section of the material to be examined. The surface must be either machined or ground smooth and flat. The samples are boiled for 60 minutes in an etching solution of 50% hydrochloric acid to secure a deep etch. They are then dipped in cold concentrated nitric acid, washed in running water, and scrubbed clean. Examination of the surface must show the material to be dense and sound and free from pipe, fissures, gas cavities, sponginess, abnormal inclusions or segregation or too many pinholes.

The *microscopic* examination is performed as follows.

The sample should be 3 inches long by ½ inch wide by ¹/8 inch thick. It is prepared for examination by subjecting it to an electrolytic etch. The electrolyte consists of 10 grams of sodium cyanide, containing not more than 0.20% chlorides, dissolved in 90 milliliters of water. The sample is the anode, and a piece of the same or similar material is the cathode. These electrodes are spaced about 1 inch apart. A 5- to 6-volt direct current is passed for 5 minutes or until the structure is well developed. The presence of precipitated carbides may then be determined.

HEAT TREATMENT

As previously stated, the strength or hardness of the 18-8 steels cannot be increased by heat treatment. It is practical, however, to anneal or stabilize these steels to eliminate carbide precipitation, or to remove strains due to cold working. In the case of the hardenable chromium steels it is possible to harden and temper the steel as is done with the standard steels. In the following descriptions the annealing and stabilizing operations apply to 18-8 steels, the hardening, to the chromium steel discussed in the latter part of this chapter.

Annealing. Corrosion-resisting steel is annealed to soften the metal, relieve fabricating strains, and reduce carbide precipitation. It is extremely important that the steel be heated and cooled rapidly through the carbide temperature range of 1000–1550°F. if further precipitation is to be avoided. Annealing is done at a temperature of 1940–1960°F. Unlike standard steels the quench from this temperature must be rapid. Heavy parts are water-quenched but light parts, such as are used in aircraft work, are air-quenched.

Stabilizing. Stabilizing treatment is a treatment used exclusively to dissolve precipitated carbides and prevent intergranular corrosion. It is applied only to 18-8 steels containing titanium or molybdenum as stabilizing agents. Columbium bearing 18-8 does not require stabilization if the columbium/carbon ratio is 10 or more. The treatment consists of heating the steel at 1575–1625°F. for from ½ to 1 hour and quenching as in annealing. This treatment is given exhaust collectors after they are completely fabricated and welded. Some metallurgists prefer the straight annealing treatment to this special stabilizing treatment. Either treatment will dissolve precipitated carbides.

Hardening. The chromium steel, in accordance with Army-Navy Specification AN-QQ-S-S-770 described later, is hardened by heating to 1875–1900°F., quenching in oil, and tempering to the desired strength. An ultimate tensile strength of 175,000 p.s.i. is commonly specified for this steel.

SALT-SPRAY CORROSION TEST

This test consists in subjecting a specimen of the material to prolonged exposure in an intense salt atmosphere in a closed box. After being cut the specimen is passivated and thoroughly cleaned by immersion in a suitable solvent, such as petrolic ether and alcohol. After drying, it is carefully suspended vertically from a glass rod in a closed box, about 3 feet long by 2 feet wide and 2 feet deep. This box must be constructed of a nonmetallic, neutral material such as glass, slate, or stone. By the use of compressed air and a nozzle arrangement with one end submerged in a salt-water solution, the box can be filled with spray. Baffles are installed to prevent direct impingement of the spray on the specimens, and the box is so designed that condensed liquid cannot drip on the specimens.

The salt concentration varies for different materials from 4% to 20%. The latter solution is becoming standard. It consists of 20 parts by weight of salt (sodium chloride) in 80 parts of distilled water. The specific gravity of this solution is 1.151 at 60°F. The salt should be a commercially pure grade, low in magnesium and calcium chloride content. The solution should be carefully filtered before using. The concentration of the salt solution should be checked every 24 hours and adjusted, as necessary, by the addition of salt or water.

The test is conducted at a temperature of 35°C. and as continuously as possible. Interruptions for regulation or adjustment are permitted. The duration of the test required for any particular material is set forth in the specification. It varies from 24 to 700 hours. The latter time applies to aircraft tie-rods.

Rating Salt-spray Test Specimens. After completion of the salt-spray test the specimens are carefully removed and washed in running tap water. They are then examined visually for evidences of corrosion and rated on the following basis:

A Rating—An ideal condition in which no pitting, or scaling, and little (if any) staining is present.

B Rating—A good condition with very little pitting, scaling or staining and practically no progressive corrosion.

C Rating—A fair condition without excessive pitting, scaling, or progressive corrosion.

D Rating—An unsatisfactory condition showing excessive progressive corrosion.

The strength of a material is adversely affected by corrosion. In comparing the strength of corroded material with that of the original, the average strength of not less than three corroded specimens should be compared with the strength of two or more of the original material.

PICKLING

When corrosion-resistant steel is annealed or welded a tenacious scale is formed on the surface which can only be removed by sandblasting or pickling. The usual practice is to sandblast the surface lightly and then complete removal of the scale by pickling. Pickling is the immersion of the material in an acid bath, usually for the purpose of cleaning the surface. The acid bath generally used to remove the scale from exhaust collectors which have been welded and then stabilized and quenched in air is a 50% solution by weight of hydrochloric acid at 130–140°F. Even when a light sandblast precedes this pickling, it is necessary to leave the material immersed in the bath about one hour to obtain satisfactory removal of the scale. The surface, however, will still be dark and dull looking.

A bright silvery finish may be obtained by pickling in a 10% nitric acid and 3% hydrochloric acid solution heated to 160°F. In extreme cases scale is removed by immersing the work in a solution made up of equal parts of nitric and hydrochloric acid. This solution is extremely powerful and will eat the metal away if immersed for more than a few minutes.

After immersion in the pickling solution the work must always be thoroughly rinsed in hot water to insure removal of the acid. When scale is particularly tenacious, the material is sometimes removed from the pickling solution, scrubbed with a wire brush to loosen the scale, and then repickled. By this method the danger of overpickling, which may result in hydrogen absorption and embrittlement of the metal, is avoided. All corrosion-resisting steel must be passivated after pickling. This operation will be described presently.

POLISHING

The best corrosion resistance may be obtained from 18-8 steel if the surface is highly polished. This operation is very slow and expensive. It is rarely required nowadays in aircraft construction since a sandblasted or pickled surface is found to possess satisfactory corrosion resistance.

Polishing is performed on surfaces which have been sandblasted lightly to remove the scale. A series of buffing operations, using cloth and cotton wheels and very fine buffing compounds, will gradually develop a highly polished surface. It is important that no steel or wire brushes be used, in order to avoid leaving steel particles imbedded in the surface of the polished metal.

PASSIVATING

Passivating is the final operation on corrosion-resisting steel after it has been sandblasted, pickled, or polished. It consists in immersing the material for 20 minutes in a solution containing from 15% to 20% nitric acid, at a temperature between 120 and 150°F. The material must then be washed thoroughly in warm water. Passivating does not affect the appearance of a polished surface. It is good practice to passivate corrosion-resisting steel after machining, fabrication, or severe handling, since it restores the corrosion resistance.

Corrosion-resisting steels owe that property to their alloy content, which aids in the formation of a tough, passive oxide film on the surface of the metal. The formation of this film is accelerated by the passivation treatment. Other than the formation of this film, nitric acid has little or no effect on corrosion-resisting steel. It will, however, remove any particles of foreign matter from the surface, thus eliminating a direct cause of corrosion due to the electric potential existing between dissimilar metals.

WORKING PROPERTIES

In general, corrosion-resisting steels are very difficult to forge or machine. Free-machining varieties of this steel have been developed by the addition of sulfur, but this element causes "red shortness" or brittleness at high temperatures and makes forging more difficult. Annealed sheet or tubing stock may be readily formed or drawn but work hardens rapidly. Intermediate anneals may be necessary to complete forming operations. Note the specific comments made about each operation.

Forging. The forging of corrosion-resisting steels requires pressures from two to three times as great as those used for forging ordinary steels. The temperature range is also higher and varies with slight changes in the constituents. For one standard grade of 18-8 steel the temperature range for forging is 2150–1800°F. Forging below 1800°F. might cause a cold check and result in the rejection of the part. Corrosion-resisting steel, in accordance with Military Specification MIL-S-7720 is normally used for forged parts in aircraft construction when corrosion resistance is essential. This MIL-S-7720 material is described in detail at the end of this chapter.

Forming and Drawing. The steels used in the manufacture of exhaust collectors are readily formed and drawn. This material is always bought in the annealed state and can be hammered and bent to the required shape without difficulty. In exceptional cases, where severe working of a part is necessary to obtain the required form, it is necessary to anneal the steel before completing the operation. This annealing should be done at a temperature of 1900–1950°F., followed by an air cool. Welded and seamless tubing are available for the manufacture of exhaust collectors. Welded tubing is usually considered satisfactory for this purpose, in view of all the welding that is going to be done anyway in the fabrication of the collector. The elbows of exhaust collectors have been bent around a radius equal to 2½ times the diameter of the tubing, although slightly greater radii are desirable. Special tube-bending machines are required to do this bending properly.

Structural corrosion-resisting steel sheet or tubing is cold rolled or drawn to the desired temper. A tensile strength of 185,000 p.s.i. is obtainable by full cold working. It is common practice to further draw or roll cold-rolled strip into U or other sections for rib capstrips (or for other structural purposes), particularly in connection with spot welding.

Machining. Corrosion-resisting steels are difficult to machine because the chips cling to the tip of the cutting tool, and the cut work hardens the surface, thus making the next cut more difficult. Free-machining varieties of corrosion-resisting steel have been developed by the addition of sulfur. This grade of steel is not quite as resistant to corrosion, however, as the standard grade of corrosion-resisting steel. When corrosion resistance is paramount, steel in accordance with composition MCR of Military Specification MIL-S-7720, in the annealed condition is used. This MIL-S-7720 steel is difficult to machine, but a satisfactory job can be done.

In drilling, only a very light center punch should be made, and the drill should not be allowed to ride on the metal without cutting. It is obvious that these precautions are necessary to prevent hardening of the metal by cold working. Similar precautions are necessary in milling and sawing.

In punching, this steel must be cut throughout its entire thickness. A close fit between punch and die is essential.

WELDING AND SOLDERING

Corrosion-resisting steels are commonly joined by one of three methods of welding: gas welding by means of oxyacetylene, electric arc welding, or electric spot welding. In aircraft work nonstructural steel, such as used in the fabrication of exhaust collectors, is usually gas-welded. Electric arc welding is not practical on material below 1/16 inch thick and for that reason is seldom used in aircraft work. Work-hardened structural steel can be spot-welded without affecting its physical properties. This method is commonly used to attach parts fabricated from sheet or strip.

These steels can also be soft-soldered or silver-soldered readily. Soldering is not used for structural purposes in aircraft, but may be used occasionally for sealing seams or in the preparation of cable terminals.

Gas Welding. In aircraft factories oxyacetylene welding equipment is always available for welding chrome-molybdenum steel. This same apparatus is used for welding nonstructural corrosion-resisting steel. A weld can be obtained by this method that can be bent flat on itself without cracking.

The type of welding flame used in gas welding corrosion-resisting steel is very important. If an excess of oxygen is used the metal will bubble and a porous weld will result. On the other hand, if a reducing flame (too much acetylene) is used, the metal will absorb carbon, the weld will be brittle, and

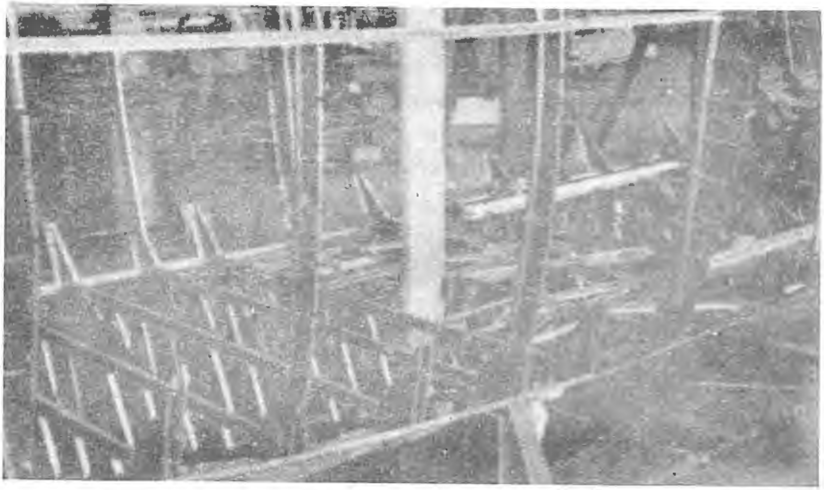


FIGURE 18. Hull Framing; 18-8 Steel

the corrosion resistance of the metal will be lowered. A neutral flame is therefore best, but because of the impracticability of maintaining this condition in practice, a slightly reducing flame is used to avoid porosity and oxidation. It has been determined that even a slightly reducing flame will increase the carbon content of the deposited weld metal about 15 points, whereas a full reducing flame will increase it 50 to 60 points.

There are many types of welding rods on the market for use with 18-8 steel. In general, the rod diameter should be the same as the thickness of the material being welded. The welding rod should also be of chemical composition similar to the welded material. Where the welded material will be subjected to high temperatures in service, as in exhaust collectors, it is advisable to use a welding rod containing columbium. A welding rod containing titanium is not practical, as most of the titanium is burnt away during the welding operation. A flux is universally used in conjunction with the above welding rod. The flux makes the metal flow more freely and aids in securing deeper penetration.

In the actual welding operation the flame is directed forward in order to preheat the metal ahead of the spot being welded. The torch is held close to the work, so as to push the flame down into the weld. The rod, on the other hand, is held just above the weld, so that it will melt and drop down in place as the work progresses. A relatively small tip is used on the torch to permit slow, careful welding without danger of obtaining a porous weld. Due to the fact that 18-8 steel expands about 50% more than ordinary steel when heated, but has only about one half the heat conductivity, there is great danger of warpage from welding. To avoid this warpage, it is necessary to clamp the parts to be welded in a rigid jig.

Electric Arc Welding. As stated above, it is not practical commercially to weld metal less than $^1/_{16}$ inch thick by the electric arc method. This method does give better welds than gas welding on heavier material. In aircraft construction the heaviest 18-8 steel welded is about 0.049 inch thick, so that metallic arc welding is not practical.

In electric arc welding the following practice is followed:

1. The material to be welded is made the negative electrode, the welding wire the positive. This method is just the opposite of that used in welding mild steel.
2. The material is thoroughly cleaned and freed of grease.
3. A flux-coated filler rod is used with a chemical composition similar to the material being welded. The flux must not contain any carbonaceous compound, in order to avoid increasing the carbon content of the weld.
4. The use of a short arc is recommended to enable the flux to function. The flux cleans the weld puddle and escapes to the surface, carrying with it the impurities in the weld. It then forms a glassy film over the top of the weld.
5. When a filler rod has been all used up, a small crater will mark the termination of the weld. Before proceeding with the next rod, it is necessary to clean the influx from the surface of the crater so as to avoid obtaining a porous spot.

Like gas-welded material, electric arc-welded material is subject to carbide precipitation and intercrystalline corrosion. It is desirable that welded material be annealed or stabilized after fabrication.

Spot Welding. Spot welding or shot welding, as it is sometimes called, consists essentially in holding two pieces of material in close contact between two electrodes and passing a low-voltage, high-amperage current through them for a very short period of time. Fusion immediately takes place between the two sheets. Corrosion-resisting steel is particularly adapted to spot welding because of its clean surface, its high electrical resistance, and its poor heat conductivity. The importance of these properties is explained in the following paragraph.

The heat energy generated in a weld is measured by

$$\text{resistance} \times (\text{current})^2 \times \text{time}.$$

The resistance is made up of three parts—namely:

1. The contact resistance between the sheets to be welded.
2. The contact resistance between the electrodes and the sheets to be welded.
3. The electrical resistance of the sheets themselves.

It is obvious that the first resistance is directly dependent upon a clean surface. The uniformity of the weld also depends upon accurate control of the electrode pressure upon which both the first and second resistances are dependent. If the third resistance, which is a property of the material and therefore constant, is large relative to the first and second resistance, then satisfactory welds can be obtained without perfect pressure control. For this reason thin 18-8 steel can be better welded than other metals. The relatively high electrical resistance of 18-8 steel also reduces the amount of current required to make a weld. Its poor heat conductivity aids in welding by preventing undue dissipation of the heat generated.

In studying the distribution of energy delivered to a weld, it has been found that only about 5% goes to produce fusion, while the remainder is dissipated through the surrounding cold metal and electrodes. It immediately becomes apparent that any small variation in the dissipated energy results in a large percentage variation in the fusion energy. Very accurate control of all elements entering into a weld is therefore essential. This fact has necessitated the development of precision machines and improved apparatus to guarantee uniform welds. The high initial cost of this apparatus has greatly retarded the use of spot welding in aircraft construction.

An extremely high heat is developed in spot welding at the instant of fusing, and this heat then dissipates rapidly. In the case of corrosion-resisting steels this rapid cooling or quenching leaves the weld soft and ductile. It is similar to the annealing process, previously described, wherein quenching is done in air or water. It is interesting to note that an effort was made to adapt spot welding to chrome-molybdenum steel but without success. With this steel the rapid cooling of the weld was a hardening process, which resulted in a very brittle weld that broke like glass. An attempt was made to overcome this trouble by normalizing after welding, but many of the welds failed during the heat treatment. These failures were probably due to expansion strains causing rupture before the normalizing temperature could be reached.

Due to the high temperature of spot welding, the surface along the weld will be turned blue by oxidation. This oxide will slowly turn brown, resembling rust, if exposed to the weather. The change, however, is a surface condition which affects only the original oxide. The oxide may be readily removed by pickling or polishing. Polished spot welds are as corrosion resistant as the original metal. In the occasional case where a spot weld has failed by corrosion (or for some other reason), it has been drilled out and a stainless steel machine screw inserted to fill the hole. This practice has been used, particularly in stainless steel seaplane floats, where watertightness was necessary. Very few spot welds failed in this application.

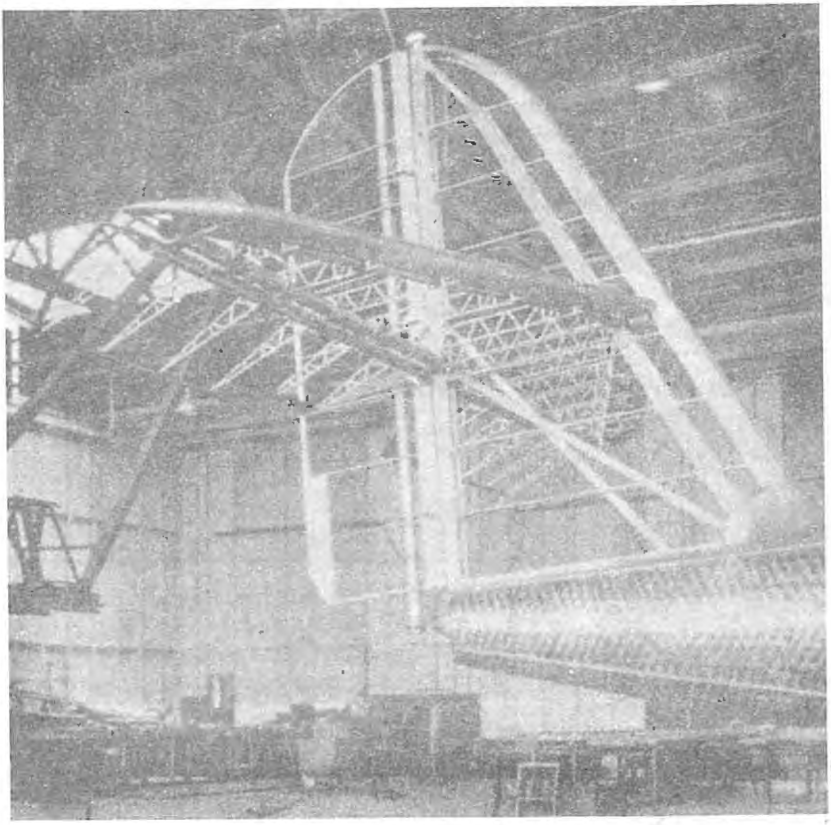


FIGURE 19. Skeleton Tail Assembly; 18-8 Steel Spot Welded

Spot welds may be placed at the rate of 960 per minute by means of roller electrodes. By the same means it is possible to seam-weld where watertightness is required. Seam welding is somewhat more difficult than spot welding since all traces of dirt must be removed between the contact surfaces if a satisfactory, continuous weld is to be obtained. The diameter of spot welds can be varied for different types of work, but in general a ⅛-inch spot is used. Spot welds may be spaced any desired distance apart. Automatic machines provide for spot spacing ranging from overlap up to ¾ inch.

Some of the numerous advantages claimed for spot welding are as follows:

Spot-welded joints can be designed to attain 100% of the strength of the material.

They are faster than riveting, since no layout and drilling of holes is necessary. Numerous spot welds can also be made in the time required to insert and head one rivet.

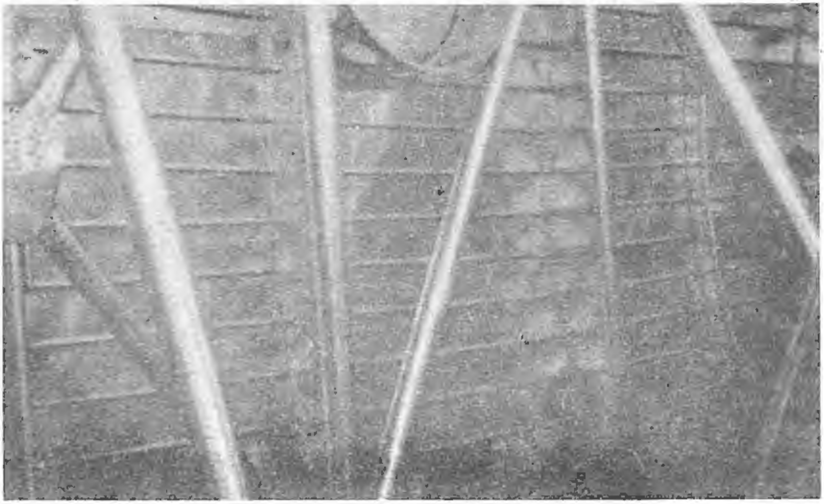


FIGURE 20. Body-panel Construction; 18-8 Steel Spot Welded

The pitch of spot welds may be much closer than rivets. In addition, only a small flange need be turned up for spot welding because the spot is small and little or no edge clearance is required.

Seam-welded watertight joints do not require the insertion of tape and a sealing compound. Thus weight and expense are saved.

The drag of rivet heads is eliminated in exterior covering.

Spot-welded stainless steel construction has already found many applications in aircraft and is constantly being put to new uses. A summary of structures in which corrosion-resisting steel was used wholly or partially is as follows: wing beams, wing ribs, wing covering, monocoque fuselage, seaplane floats, fuel and oil tanks, ailerons, tail surfaces. It is apparent that with the use of corrosion-resisting steel tubing and wire for controls, landing gear, and wing bracing, it is possible at the present stage of development to construct an entire airplane of corrosion-resisting steel. As a matter of fact such a plane has been built by Fleetwings, Incorporated. It is shown in Figure 21. Most of the illustrations in this chapter are taken from this plane.

Soldering. Corrosion-resisting steels are readily soldered with either soft or hard solder. Repairs to tanks can be made by soldering on a patching plate. Soldering corrosion-resisting steel will not cause carbide precipitation because of the low temperature employed, and consequently no heat treatment is required. The physical properties of cold-worked material will not be seriously affected by soldering either. Prior to the development of seam welding, joints were often spot-welded and then soldered to obtain tightness.

A silver brazing alloy reputed to have excellent properties has the following chemical composition: silver 50%, copper 15.5%, zinc 16.5%, cadmium 18%. Thus solder may be obtained in the form of strip, or wire, or granulated. Its melting point is 1175°F.

A soft solder containing 75% tin and 25% lead has been found satisfactory for use with 18-8 steel. Many other solders, both soft and hard, are also available.

The following practice is recommended for soldering 18-8 steel:

> Roughen the edges to be soldered with sandpaper, particularly when the surface is highly polished. Paint the edges with a soldering flux or fluid, which may be either plain hydrochloric acid or a prepared brand available on the market. Bring the metal to a heat sufficient to accept the solder in a liquid condition. This is done by heating the soldering iron well above the normal soldering temperature in order to compensate for the low heat conductivity of 18-8 steel. Sufficient heat must be maintained at all times to permit the solder to flow into the joint. Progress should be slow, to avoid the necessity of going over the joint a second time. In order to remove all traces of flux or acid from the joint or adjoining metal, the finished work is washed with a solution of 1 part nitric acid in 3 parts of water. After ten minutes this solution is washed off with clear water. This treatment removes all acid from the work and passivates it.

Brazing of 18-8 steel should be avoided because of the electrolytic corrosion set up due to dissimilar metals and also because of the reduced ductility and increased brittleness caused by penetration of the brazing alloy.

FIGURE 21. Fleetwings Amphibian

PROPERTIES OF CORROSION-RESISTING STEELS

In Table 5 the corrosion-resisting steels commonly used in aircraft construction have been grouped according to their use. The Army-Navy Specification number has been listed when applicable. Immediately following this table the properties of each group are given in detail. The properties of corrosion-resisting tie rods and cable are given in the Appendix.

TABLE 5. Summary of Corrosion-resisting Steels

General use	Form	Specification	
		AN & Military	A.I.S.I.*
Exhaust collectors	Sheet Tubing—seamless Tubing—welded	MIL-S-6721 MIL-T-8606 MIL-T-6737	321 and 347
Hydraulic systems	Tubing Tubing—annealed	MIL-T-6845 MIL-T-8504	
Structural	Sheet Tubing—round Tubing—streamline Wire Wire	MIL-S-5059 MIL-T-5695 MIL-T5695 AN-W-23 MIL-W-6713	304, 302, and 316
Machined parts	Bar Bar	MIL-S-7720 AN-QQ-S-770	302,303, 316, 431
Castings		46-S-27	
Tie-rods	Streamline Round or square	 MIL-T-5684	
Cable	Flexible, Preformed Non-flexible, Preformed	MIL-C-5424 MIL-C-5693	

* American Iron & Steel Institute.

CORROSION-RESISTING STEEL FOR EXHAUST COLLECTORS

Material for this purpose must have good forming qualities and be readily weldable. It must also be free from intergranular corrosion after welding, and for that reason a stabilized material containing titanium or columbium is used.

CHEMICAL COMPOSITION (A.I.S.I. 347)

Carbon (%)	0.10 max.	Nickel (%)	7.0–12.0
Manganese (%)	0.20–2.50	Silicon (%)	0.2–1.5
Phosphorus (%)	0.040 max.	Copper (%)	0.50 max.
Sulfur (%)	0.040 max.	Columbium*	8 X carbon content
Chromium (%)	17.0–20.0		

*Titanium may be substituted for columbium. Titanium = 4 X Carbon content. (A.I.S.I. 321.)

The maximum carbon limitation of 0.10% is very important if the material is to be welded, in order to reduce carbide precipitation to a minimum. The presence of a substantially larger amount of columbium or titanium than carbon reduces the danger of intergranular corrosion.

PHYSICAL PROPERTIES

Density	0.284 lb./cu.in.	Ultimate tensile strength	80,000 p.s.i.
Melting point	2550°F.	Yield point	35,000 p.s.i
Modulus of elasticity	28,000,000 p.s.i.	Elongation	40%

Heat Treatment. This material cannot be increased in strength by heat treatment. It is customary to stabilize it by holding it at 1550–1625°F. for 2 to 4 hours after severe forming or welding. Material below 1/16 inch in thickness as used in aircraft is quenched in air. Heavier material may be water-quenched.

Working Properties. All fabrication operations necessary for the manufacture of exhaust collectors can be done cold with this material. These operations consist of belling and bending tubing, and forming, cupping, or bending sheet. The material hardens as it is worked, but the operations are seldom severe enough to require intermediate annealing for softening the metal to permit further working.

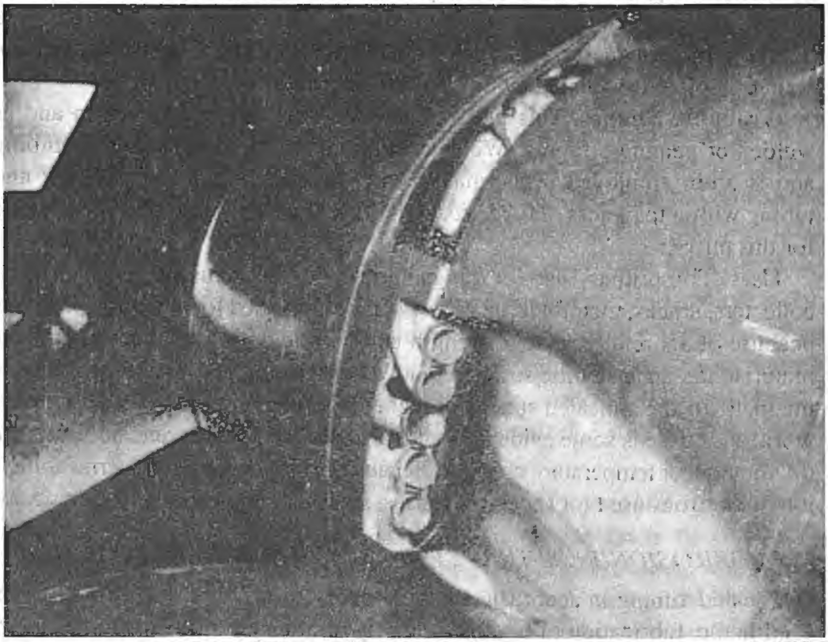


FIGURE 22. Exhaust Stacks; 18-8 Corrosion-resistant Steel

Sheet may be bent cold, without cracking, through an angle of 180° over a diameter equal to the sheet thickness. Government specifications require bend tests to demonstrate this property both across the grain and parallel to the grain. In shop work it is always preferable to bend sheet across the grain, since there is less tendency to crack when this is done, and slightly greater fatigue strength is obtained.

Tubing for exhaust collectors is usually from 2 to 4 inches in diameter and has a wall thickness of 0.035 to 0.049 inch. This tubing can be bent to an inside radius as small as two diameters, but a somewhat larger radius is preferable for ease of bending and to reduce the back-pressure of exhaust. Special bending jigs are necessary to obtain a smooth job. It is customary to sublet this job to a company that specializes in bending tubing.

Welding. This material is readily weldable with the oxyacetylene torch. A neutral to slightly reducing flame must be used to prevent a porous or carbonized weld. A welding rod containing columbium or molybdenum should be used. There are a number of fluxes on the market that will give satisfactory results.

Corrosion. A very tenacious scale is formed on the surface of this material by the welding or heat-treatment operation. This scale must be removed by sandblasting, pickling, or polishing to obtain full corrosion resistance. The quickest and cheapest method is to sandblast the surface lightly until clean. Exhaust collectors treated by this method are quite satisfactory.

Available Shapes. This material may be obtained in sheet form and as welded or seamless tubing. Welded tubing is cheaper than seamless tubing and is often employed in the manufacture of exhaust collectors. Sheet and tubing with a thickness of 0.035 to 0.049 inch have been found to be adequate for this purpose.

Uses. The primary use for this material is in the manufacture of exhaust collectors, stacks, manifolds, and firewalls. It is not used for structural purposes because of its relatively low strength and great elongation under load. This material has an austenitic structure and, as a consequence, is practically non-magnetic in the annealed state. Its magnetic permeability increases with cold work, and there is some evidence that it also increases in service, due possibly to vibration or temperature changes. Because of its low magnetic permeability, it is sometimes used for special purposes, such as in the vicinity of a compass.

CORROSION-RESISTING STEEL FOR HYDRAULIC SYSTEMS

Welded tubing in accordance with Military Specification MIL-T-8504 is used in the fabrication of high-pressure hydraulic systems. This tubing is an alternate to seamless tubing MIL-T-8606 or seamless tubing MIL-T-5695 and is obtainable in the same chemical compositions as these materials.

MIL-T-8504 tubing is only available in the annealed condition with a maximum tensile strength of 105,000 p.s.i., a yield strength of 30,000 p.s.i. minimum, and an elongation of 35%.

CORROSION-RESISTING STEEL FOR STRUCTURAL PURPOSES

This material has high-strength properties which are obtained by cold working. No heat can be applied to aid in forming this material without destroying its physical properties. Consequently, only spot welding, or riveting, can be used in joining this material. It is obtainable in a number of tempers which depend upon the amount of cold work done on it. These tempers are called ¼ hard, ½ hard, ¾ hard, and hard. Annealed material is also available but seldom used. When purchasing sheet material high or low ductility should be specified. The high-ductility material has double the elongation of the low-ductility material.

CHEMICAL COMPOSITION (A.I.S.I. 302)

Carbon (%)*	0.12 max.	Nickel (%)	7.0 min.
Manganese (%)	0.2–2.5	Silicon (%)	0.2–1.5
Phosphorus (%)	0.03 max.	Copper (%)	0.50 max.
Sulfur (%)	0.03 max.	Molybdenum (%)†	1.75–2.50
Chromium (%)	17.0 min.		

* Carbon content may be 0.15% max. up to and including 0.050 in.

† Molybdenum is added only when maximum corrosion resistance is desired. In this case, carbon content should be limited to 0.10% maximum (A.I.S.I. 316).

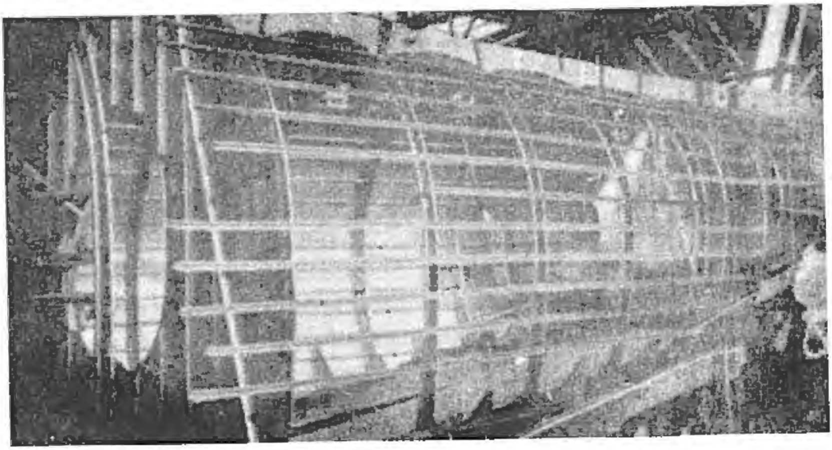


FIGURE 23. Skeleton Fuselage; 18-8 Steel

PHYSICAL PROPERTIES

Density	0.291 lb./cu. in.
Modulus of elasticity	28,000,000 p.s.i.

STRENGTH PROPERTIES

	Temper	Ultimate tensile strength (p.s.i.)	Yield strength (p.s.i.)	Elongation (%)	Bend diameter (X thickness)
Sheet and strip	A	75,000–110,000	30,000	40	1
	¼ H	125,000	75,000	25	1
	½ H	150,000	110,000	15	2
	¾ H	175,000	135,000	10	4
	H	185,000	140,000	8	6
Tubing—round or streamline	A	75,000–100,000	30,000	35	
	¼ H	120,000	75,000	15	
	½ H	150,000	110,000	7	
	¾ H	175,000	135,000	3	
	H	185,000	140,000	2	

STRENGTH PROPERTIES—WIRE

Condition	Diameter	Tensile strength (p.s.i.)	
		AN-W-23 Grade MCR	AN-W-24 Grade G
(A) Annealed	0.029–0.180	115,000 max.	115,000 max.
(B) Spring temper	0.026	210,000	280,000
	0.047	210,000	255,000
	0.080	195,000	230,000
	0.118	175,000	210,000
	0.146	170,000	200,000
	0.180	155,000	170,000

Heat Treatment. This material will not respond to heat treatment. Its properties are due wholly to cold working.

Working Properties. This material is regularly rolled, drawn, or bent to any number of structural forms. The most common of these sections is the simple U which is used in rib construction. Corrugated sheet is also readily formed and is used where stiffness is required. Forming of this material requires special technique due its "springiness" and low elongation.

The bend diameters for the various tempers of sheet are listed above under the Strength Properties. It will be noted that material above ½ hard temper requires a very generous bending radius. It is advisable to make all bends across the grain to reduce the possibility of cracking.

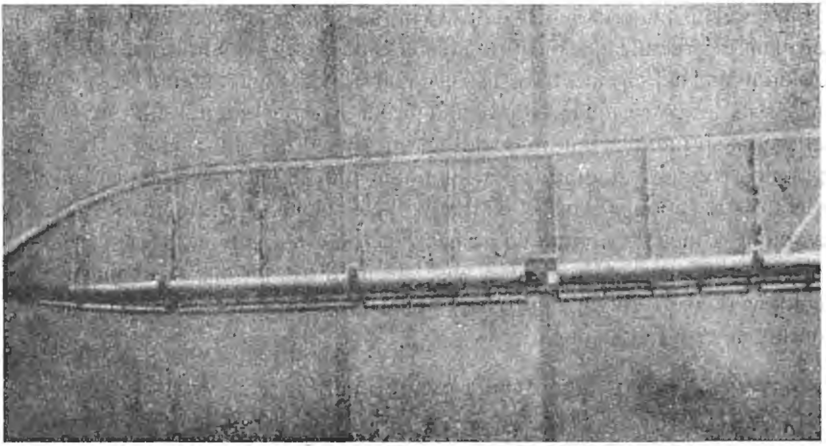


FIGURE 24. Aileron Construction; 18-8 Steel Spot Welded

Tubing of ½ hard temper has been successfully bent to a radius of five diameters, but the operation required special care and was expensive. This particular application was for the control stick of an airplane. Bending of this tubing is not recommended. It should be remembered that heat cannot be applied to aid the forming operation, without destroying the physical properties.

Drilling this material is very difficult due to its hardness and the increase in the surface hardness caused by the rotating drill.

Welding. Only spot welding is permissible with this material. Due to the rapidity with which the heat of spot welding is dissipated, there is no reduction in the physical properties of the metal. This material is almost invariably joined by spot welding.

Corrosion. The material has excellent corrosion-resisting properties if it has been pickled or polished. It is normally purchased in one of these conditions and does not require any further treatment by the purchaser.

AN-W-23, Grade MCR wire, has maximum corrosion resistance and should be used when avoidance of pitting is important. MIL-W-6713, Grade G wire, will pit if exposed to salt spray or salt water.

Available Shapes. This material is available commercially as sheet or strip, round or streamline tubing, and wire. It may be obtained in any desired temper, but ½ hard and hard are most often used. Sheet and strip may be obtained in thickness from 0.005 inch up to about 1/16 inch. The upper limit of thickness is determined by the impossibility of obtaining the harder tempers by cold rolling thick material.

Standard tubing sizes and gages are listed in the Appendix.

Uses. This material has been used in the construction of every part of an airplane's structure. Its most popular use has been as wing ribs and spars. Ailerons and tail surfaces have also been fabricated. Spot-welding facilities, the necessity for corrosion resistance and the strength/weight possibilities should all be taken into account in deciding whether to use this material. It is bad practice to employ it jointly with aluminum alloy in one assembly, because an electrolytic action will be set up that will eat away the aluminum alloy. Each assembly should be composed, as nearly as possible, of the same material.

AN-W-23 and MIL-W-6713 wire are used for springs. This material is cold worked to obtain its high physical properties and cannot be heated during or after fabrication.

CORROSION-RESISTING STEEL FOR MACHINED PARTS

There are several varieties of this steel. Slight differences in chemical composition result in different machining and forging properties. The specification numbers have been used for identification.

Chemical Composition. Three types of corrosion-resisting steel are covered by specification MIL-S-7720 with different chemical compositions.

Composition G—for general use.
Composition MCR—for use in applications requiring maximum corrosion resistance.
Composition FM—free machining.

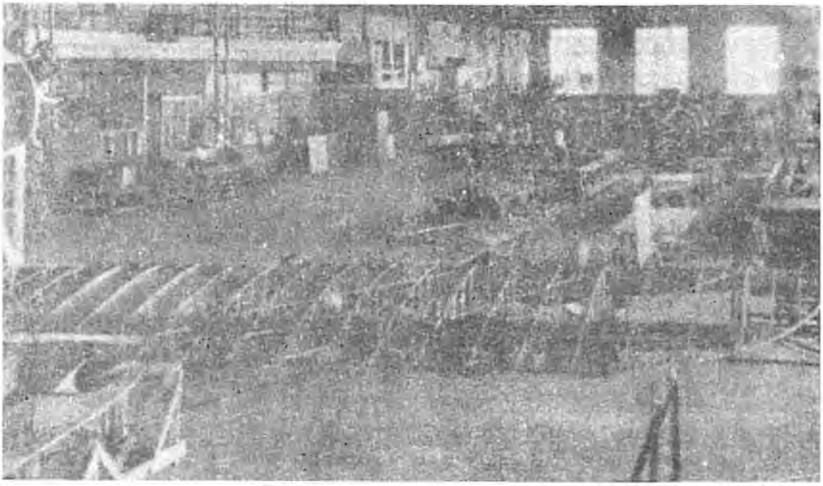


FIGURE 25. Wing Construction; 1 8 Steel Spot Welded

The following table gives the exact compositions of these three types.

CHEMICAL COMPOSITION OF CORROSION-RESISTING STEELS FOR MACHINED PARTS

Element	MIL-S-7720			AN-QQS-770
	Composition G (A.I.S.I. 302)	Composition MCR (A.I.S.I. 316)	Composition FM (A.I.S.I. 303)	(A.I.S.I. 431)
Carbon (max. %)	0.12	0.10	0.12	0.17
Manganese (%)	0.2–2.5	0.2–2.5	0.2–2.5	0.30–0.80
Phosphorus (max. %)	0.04	0.04	*	0.04
Sulfur (max. %)	0.04	0.04	*	0.04
Chromium (%)	17.0 min.	17.0 min.	17.0 min.	15.5–17.5
Nickel (%)	7.0 min.	7.0 min.	7.0 min.	1.5–2.5
Silicon (%)	0.2–1.5	0.2–1.5	02–1.5	0.20–0.60
Copper (max. %)	0.50	0.50	0.50	
Molybdenum (%)		1.75–2.50	0.75 max.	

* Phosphorus and sulfur may be any of the following:
(a) Sulfur 0.18 to 0.35%, phosphorus 0.06% max.
(b) Sulfur 0.10% max., phosphorus 0.12% to 0.17%, total must exceed 0.18.
(c) Sulfur 0.10% max., phosphorus 0.17% max., selenium 0.15% to 0.35%.

PHYSICAL PROPERTIES

Specification	Condition	Diameter or thickness (inches)	Tensile strength (p.s.i.)	Yield strength (p.s.i)	Elongation (%)
	annealed	All sizes	100,000 max.		35
MIL-S-7720	cold rolled or cold drawn	¾ and under	125,000	100,000	12
		Over ¾ to 1	115,000	80,000	15
		Over 1 to 1¼	105,000	65,000	20
		Over 1¼ to 1½	100,000	50,000	28
		Over 1½ to 3	95,000	45,000	28
		Over 3	80.000	35,000	28
AN-QQ-S-770	Class I		175,000	135,000	13
	Class II		115,000	90,000	15

MIL-S-7720 material is austenitic and will not respond to heat treatment other than a softening annealing treatment. Its physical properties can only be improved by cold working. Heating during fabrication will destroy physical properties induced by cold working. In the annealed condition this material is nonmagnetic.

AN-QQ-S-770 material is martensitic and can be heat-treated to obtain desirable physical properties.

Heat Treatment. All the steels listed above, except AN-QQ-S-770, are austenitic and cannot be heat-treated to improve their physical properties. They can be annealed as described earlier.

AN-QQ-S-770 material is heat-treated by soaking at 1875–1900°F. for ½ hour, quenching in oil, and then tempering to the desired properties. Class I material (175,000 p.s.i. u.t.s.) is obtained by drawing at 525°F., Class II material (115,000 p.s.i. u.t.s.) is obtained by drawing at 1200°F. Holding at these temperatures for two hours is recommended. This material should not be heat-treated to give strength values other than 175,000 or 115,000 p.s.i. because of the danger of obtaining poor impact strength and corrosion resistance.

Working Properties. The austenitic steels are all difficult to machine because of the tendency to harden when cold-worked. The addition of sulfur and selenium greatly improves the machinability. Composition FM, MIL-S-7720 is especially designed for free machining. AN-QQ-S-770 material machines readily.

Welding. These steels can be welded if necessary. This operation is not applicable to these materials when used as machined parts in aircraft construction. Welding, other than spot welding, will, of course, destroy the physical properties of all but the annealed material.

Corrosion. Other than composition FM, MIL-S-7720 material, all the steels listed above will merit an "A" rating if subject to a salt-spray test. AN-QQ-S-770 material must be heat-treated to develop this corrosion resistance. Composition FM material has a "B" rating in the salt-spray test.

Composition MCR is the most corrosion resistant of the materials under specification MIL-S-7720 and should be used where severe corrosion conditions will be met. This type of material is also free from intergranular corrosion even if welded and not subsequently annealed.

Available Shapes. This material may be obtained as bar or rod, or forged to any required shape.

Uses. Composition MCR, MIL-S-7720 material has the greatest corrosion resistance and is used for seaplane fittings, which are immersed in salt water a great deal. It is very difficult to forge and machine and is only selected when absolutely necessary for corrosion resistance.

Composition FM, MIL-S-7720 material is used for machine screws and nuts. The screws are either machined or upset. This material has nonseizing properties. Only one of a pair of mated parts need be made of this to prevent seizing.

AN-QQ-S-770 material is used for aircraft bolts, tie-rod terminals, and other parts requiring high strength and corrosion resistance. This material will seize if threaded to similar material, but not when threaded to MIL-S-7720 material (18-8).

PHYSICAL PROPERTIES

Ultimate tensile strength (p.s.i.)	70,000
Yield strength (p.s.i.)	32,000
Elongation (%)	30

Heat Treatment. All castings should be annealed at not less than 1800°F. and quenched rapidly in cold water.

Welding. Minor defects in the casting can be welded prior to the heat treatment. The defects must be thoroughly cleaned out to sound metal before welding.

Working Properties. Light finish machining can be done without difficulty. A bend-test specimen ½ inch thick can be bent cold through 150° over a ¾-inch pin.

Corrosion. This material will show practically no scaling, pitting, or staining after a 24-hour salt-spray test. It should be passivated after removal of the annealing scale by pickling or sandblasting.

CORROSION AND HEAT-RESISTANT STEEL FOR JET TAILPIPES

A material known as 19-9DL has good forming characteristics and good strength at elevated temperatures. It may be purchased under S.A.E. specifications as follows:

AMS5369—Castings, Sand
AMS5721—Bars (1" max.)
AMS5782—Wire, welding
AMS5526—Sheet & Strip
AMS5722—Bars, Forgings

CHEMICAL COMPOSITION (AMS5526)

Carbon (%)	0.28–0.35	Chromium (%)	18.00–21.00
Manganese (%)	0.75–1.50	Nickel (%)	8.00–11.00
Silicon (%)	0.30–0.80	Molybdenum (%)	1.00–1.75
Phosphorus (%)	0.040 max.	Tungsten (%)	1.00–1.75
Sulfur (%)	0.030 max.	Columbium & Tantalum (%)	0.25–0.60
Copper (%)	0.50 max.	Titanium (%)	0.10–0.35

PHYSICAL PROPERTIES

Ultimate tensile strength	95,000–120,000 p.s.i.
Yield strength	45,000 p.s.i. min.
Elongation (%)	30 min.

19-9DL can be formed and welded the same as 18-8 exhaust collector steel. It has high strength up to 1200°F. It is used for turbine nozzles, tailpipes, exhaust cones, etc.

CORROSION-RESISTING STEEL FOR SPRINGS

The material recommended for this purpose is a straight chromium steel, with a tensile strength of 200,000 p.s.i. after heat treatment and excellent corrosion resistance.

CHEMICAL COMPOSITION

Carbon (%)	0.35–0.40	Manganese (%)	0.30–0.50
Chromium	12.5–14.0	Silicon (%)	0.50 max.

PHYSICAL PROPERTIES

Modulus of elasticity (p.s.i.)	29,000,000	Elongation (%)	5
Ultimate tensile strength (p.s.i.)	200,000	Rockwell hardness	C-42
Yield point (p.s.i.)	175,000		

Heat Treatment. The physical properties listed above are obtained by heat-treating the material to 1825°F., followed by an oil quench, and then tempering at about 1100°F.

Working Properties. Material is purchased in the fully annealed condition and heat-treated after forming. In the annealed condition the material can be bent cold through an angle of 180°, without cracking, over a diameter equal to its own.

Corrosion. After heat treatment, pickling, and passivating, this material will withstand a 100-hour salt-spray test without pitting or corrosion.

Available Shapes. Material may be purchased as round bar up to 1-inch diameter.

Uses. This material is recommended for springs requiring good corrosion resistance.

CORROSION-RESISTING CASTINGS

Corrosion-resisting casting material has considerably less strength than forgings or bar stock but may be useful for special purposes where a complicated shape and corrosion resistance are the criteria.

CHEMICAL COMPOSITION

Carbon (%)*	0.20 max.	Chromium (%)	18.0 min.
Phosphorus (%)	0.05 max.	Nickel (%)	8.0 min.
Sulfur (%)	0.05 max.	Selenium (%)†	0.20–0.35

* Carbon up to 0.30% maximum is permissible if chromium is over 20.0% and nickel is over 10.0%.

† When selenium is added a better machining and nonseizing material is obtained.

CHAPTER IX

NICKEL ALLOYS

NICKEL is the chief constituent of a number of nonferrous alloys which are used in special applications in aircraft work. The main feature common to all of these alloys is their exceptionally good corrosion resistance. In this respect they are equal to or better than corrosion-resistant steel. These nickel alloys work fairly easily and are obtainable commercially in most of the standard forms. Their use is gradually increasing in aircraft construction, as more designers realize how well they fulfill specialized needs.

Three nickel alloys are of special interest to the aircraft designer: Inconel, Monel, and K Monel. *Inconel* is a nickel-chromium alloy with good corrosion resistance and strength at normal and elevated temperatures. These properties are ideal for airplane-engine exhaust collectors, which are frequently constructed of Inconel. *Monel* is a nickel-copper alloy with high corrosion resistance, reasonably good strength, and good working properties. *K Monel* is a nickel-copper-aluminum alloy with high corrosion resistance, exceptionally good strength (inherent as well as developed by heat treatment), and the property of being nonmagnetic. This latter property creates a use for this material as structural members in the vicinity of compasses.

The following pages describe these three alloys in as much detail as the aircraft designer is likely to require. There may be some occasional gaps in the data, due to the fact that two of these alloys are recent discoveries and have not yet been exhaustively tested.

INCONEL

Inconel is a nickel-chromium alloy classified as nonferrous because the iron content is negligible. The relatively small amounts of contained iron and carbon do not impart any of the characteristics of steel, such as transformation ranges and hardening by heat treatment. Inconel is a corrosion- and heat-resisting metal. In aircraft work it is used more especially for exhaust collectors but is rapidly acquiring new uses.

CHEMICAL PROPERTIES (Approximate composition)

Nickel	79.5%	Carbon	0.08%
Chromium	13.0	Copper	0.20
Iron	6.5	Silicon	0.25
Manganese	0.25		

Chromium is added in the form of ferrochrome, which also accounts for the iron present. The high nickel content gives the metal good workability and corrosion resistance, while the chromium contributes strength and a "stainless" or tarnish-resistant surface. An increase of iron up to approximately 20% has little effect on the properties, but above that percentage rusting occurs and the welding properties change. Inconel was selected from a series of experimental alloys (in which the constituent ranges had been varied and the properties investigated) as the alloy combining the best corrosion resistance, strength, and working properties.

PHYSICAL PROPERTIES

Density (grams per c.c.)	8.51
Weight per cubic foot	533.5 pounds
Weight per cubic inch	0.309 pounds
Melting point	2540°F. (1395°C.)
Modulus of elasticity (p.s.i.)	31,000,000 to 32,000,000
Modulus of torsion (p.s.i.)	10,000,000 to 11,000,000

STRENGTH PROPERTIES

Form and condition	Yield strength (0.20% offset) (1000 p.s.i.)	Tensile strength (1000 p.s.i.)	Elongation in 2 in. (%)
Rod and bar—cold-drawn:			
Annealed	25–50	80–100	50–35
As drawn	76–125	95–150	30–15
Rod and bar—hot-rolled:			
As rolled	35–90	85–120	45–30
Annealed	25–50	80–100	50–35
Rod and bar—forged	35–90	85–120	45–20
Wire—Cold-drawn:			
Annealed	25–50	80–105	50–25
Regular temper	115–165	130–175	12–3
Spring	150–175	165–185	10–2
Plate—hot-rolled:			
Annealed	30–60	80–110	50–35
As rolled	45–95	100–140	40–20
Sheet and strip—standard cold-rolled:			
Annealed	30–45	80–100	50–35
Hard sheet	90–125	125–150	15–2
Full-hard strip	120–160	145–170	10–2
Tubing—cold-drawn:			
Annealed	30–50	80–100	50–35
As drawn	65–140	110–160	20–2

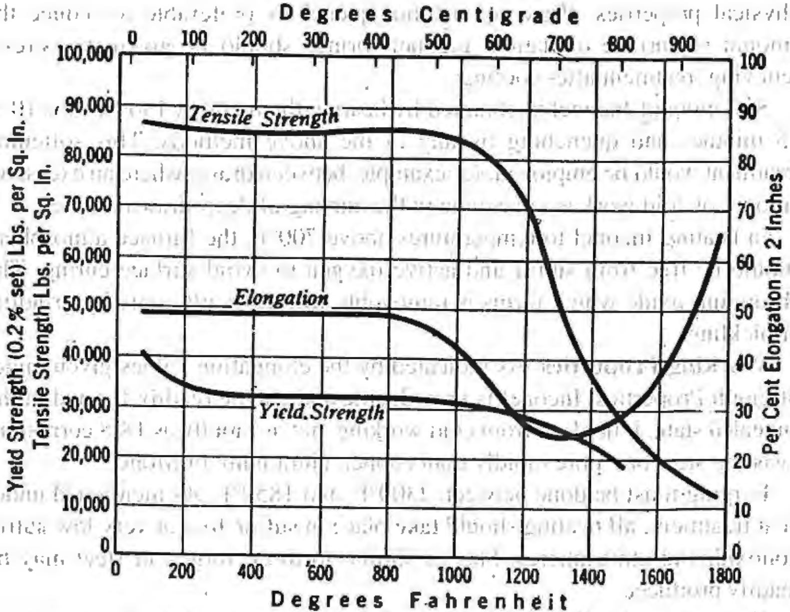


FIGURE 26. High-temperature Properties of Inconel

Inconel has the property of retaining high strength at elevated temperatures. This property is particularly important when the metal is used in heating systems or for exhaust collectors. The tensile properties of annealed Inconel at elevated temperatures are shown in Figure 26.

Impact toughness tests on a Charpy testing machine give an average reading of 200 foot-pounds without fracture of the specimen. Excellent toughness is indicated with a much higher value than steel and nonferrous alloys.

Wire up to 5/8-inch diameter can be cold-drawn and given spring temper. After coiling the springs should be treated at 800°F. to release coiling strains, a necessary treatment if springs are to operate at elevated temperatures up to 750°F. The torsional elastic limit of Inconel spring wire is 100,000 p.s.i.

Annealing and Stress Relieving. The heat treatment of Inconel consists only of annealing processes which will relive internal stresses due to cold working and for the purpose of softening the metal. Inconel cannot be hardened by treatment; it is only hardenable by cold working.

Internal stresses set up during cold rolling or during fabrication may be relieved without appreciable softening by heating the metal for 1 hour at 800–900°F. Cooling may be effected either by furnace cooling or quenching in air, water, or very dilute alcohol-water solution without changing the physical properties. Water or alcohol quench is preferable to reduce the amount of surface oxidation. Inconel springs should be given this stress-relieving treatment after cooling.

Softening of Inconel is obtained by heating the metal at 1800°F. for 10 to 15 minutes and quenching by any of the above methods. This softening treatment would be employed, for example, between draws where an excessive amount of cold work is to be done in the making of deep-drawn articles.

In heating Inconel to temperatures above 700°F. the furnace atmosphere should be free from sulfur and active oxygen to avoid surface curing. The chromium oxide which forms is removable with difficulty only by grinding or pickling.

Working Properties. As indicated by the elongation values given under Strength Properties, Inconel is very ductile and can be readily formed in the annealed state. It hardens from cold working, not as rapidly as 18-8 corrosion-resisting steel but more rapidly than copper, aluminum, or Monel.

Forging must be done between 2300°F. and 1850°F. As mentioned under heat treatment, all heating should take place in sulfur-free or very low sulfur nonoxidizing atmospheres. Shapes similar to those forged in steel may be readily produced.

Hot and cold rolling of sheets and strips is accomplished in a manner similar to that employed for steel. Rods are also hot-rolled or cold-drawn, and tubing—either welded or seamless—is cold-drawn. Steel practice is in general followed in these operations.

Inconel castings can be made but suffer from high shrinkage. The metal must be poured fast and at as low a temperature as will permit free running, and still completely fill the mold.

Machining of Inconel is difficult and must be done at low speeds with carefully treated and sharpened tools. Considerable heat is generated in machining. Inconel machines uniformly with sulfur base oils, and does not drag or stick badly.

Inconel bends readily. Government specifications require that test pieces must withstand cold bending, any direction of the sheet, without cracking, through an angle of 180°F on a diameter equal to the thickness of the test specimen. For shop work it would be advisable to call for bend radii equal to one thickness of the material.

Welding. Inconel welds readily and gives a strong, sound, ductile weld which resists corrosion. Welding may be done by electric arc, electric spot or seam (resistance welding), or with the oxyacetylene flame.

Oxyacetylene welding is used exclusively on engine exhaust manifold and collectors because of the lightness of the gage. In this type of welding an

Inconel rod coated with Inconel Gas-Welding Flux is recommended. The joint is also coated with a water paste of this flux on both surfaces to prevent oxidation. When a slightly reducing flame is used to avoid oxidation a uniform weld with excellent penetration is easily obtained. It is advisable when finishing off an Inconel gas weld to withdraw the flame slowly as this procedure permits slower freezing of the crater and so avoids any porosity at the finish of the weld.

Welded joints in the annealed metal develop the strength of the base metal. As evidence of ductility, welded sheet may be bent flat on itself, at right angles to the weld or along the welded seam, without the cracking of the weld.

There is no limitation on the thinness of sheet which can be welded with oxyacetylene other than the skill of the welder. It is also permissible to touch-up imperfection in a weld without affecting the general soundness.

Electric arc welding of material heavier than 18 gage (0.050 inch) is practical.

Welded tubing is produced from strip Inconel by automatic oxyacetylene and automatic atomic-hydrogen welding. This type of tubing approaches the soundness of seamless tubing (which is much more expensive) and can be annealed, drawn, swaged, and bent without failure. Welded tubing is superior to seamless tubing in uniformity of wall thickness, surface finish, and freedom from die scratches.

Welded joints in Inconel are not subject to intergranular deterioration, nor do they suffer any metallurgical change other than a normal very slight softening. They do not require heat treatment to improve their corrosion resistance.

Soldering and Brazing. Silver soldering and brazing are used where the strength of a welded joint is not required, or the heat of welding would cause buckling. Both operations are performed with the oxyacetylene torch, but because of the low flow points of silver solders (1175°F.), naturally a much smaller flame is required than for welding. In silver soldering Handy Flux and Handy & Harman's Easy-Flow Brazing Alloy are recommended. Silver solders must have a low flow point to avoid cracking of the Inconel, which is hot short around 1400°F. The recommended silver solder is of sufficiently low melting point to clear this range by an ample margin.

Soft soldering of Inconel is also possible, but care must be taken to insure a thorough bond with the metal. "Tinning" with an iron and the use of an active flux is recommended.

Corrosion Resistance. Inconel is practically corrosion resistant in normal atmosphere or in the presence of salt water. It is believed to be somewhat

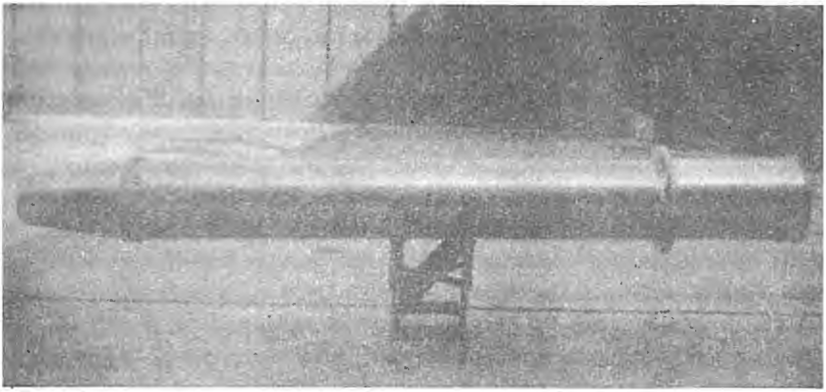


FIGURE 27. Jet Tail Pipe; Inconel

better than corrosion-resistant steel in this respect, but sufficient evidence is not at hand for a definite comparison.

Inconel welds are slightly more corrosion resistant than the parent metal. Due to the small amount of iron in Inconel, there is no trouble with carbide precipitation or intercrystalline corrosion as experienced with 18-8 corrosion-resistant steel after welding. Inconel welds should be cleaned after fabrication by immersing in a 50% (by weight) cold nitric acid solution for 5 to 10 minutes. This should be followed by a thorough water rinse.

Electrolytic corrosion or pitting of Inconel is almost negligible because o the high nickel content. Inconel is rated galvanically as a passive metal.

When heated above 700°F. in an oxidizing atmosphere chromium oxide is produced on the surface. This oxide can be removed only by grinding or pickling. For exhaust collectors there is no point in removing surface oxide as it will simply re-form as soon as the engine is run and the exhaust gets hot

Available Shapes. Inconel is available commercially in the following forms:

Sheet; Strip; Rod—hot rolled or cold drawn
Tube—cold drawn seamless; welded
Wire—cold drawn
Castings

Uses. Inconel is ideally suited for use in the construction of heat exchangers jet tail pipe, exhaust manifolds, and collectors. Its ease of forming and welding, combined with its strength at high temperatures and corrosion resistance, make a perfect combination of properties for this purpose. Its slightly greater weight, compared to corrosion-resistant steel is one disadvantage, but

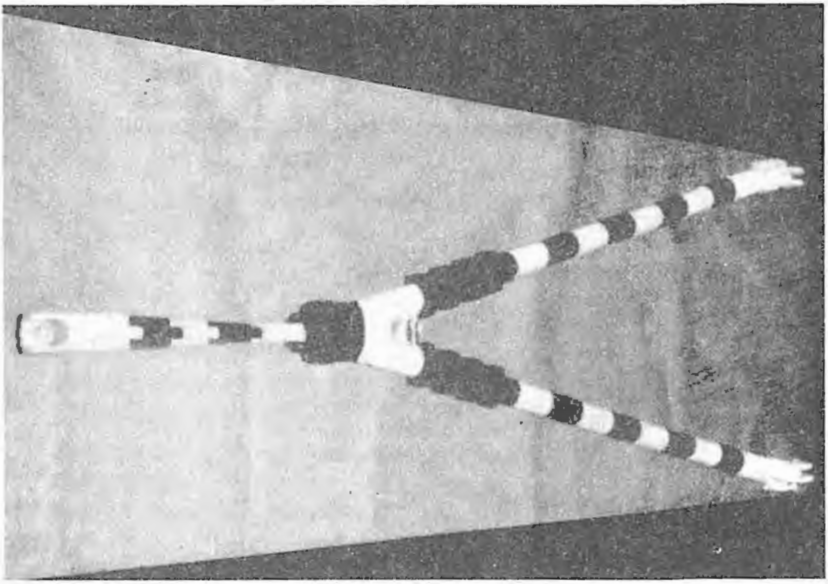


FIGURE 28. K Monel—Arresting Hook "A" Frame

this is compensated by the use of lighter material. Inconel exhaust collectors are usually made of 0.042-inch sheet and steel collectors of 0.049-inch sheet, which makes the weights about equal. A combined Inconel-asbestos packing is used for the sealing of exhaust joints.

Inconel springs are suitable for use at temperatures of 600° to 700°F. Inconel is also suited for locations requiring corrosion resistance or non-magnetic qualities. An example of the latter is windshield framework or ammunition chutes located within two feet of a compass. Aluminum alloy is not suitable for these locations because of the bulky joints required in the case of the windshield and the poor wearing qualities of the ammunition chute. No doubt other applications will be found for this relatively new material.

MONEL

Monel is a high nickel-copper alloy. It has an interesting combination of properties including high strength and excellent resistance to corrosion. Monel cannot be hardened by heat treatment, only by cold working. It is not used generally in aircraft construction but is used very generally for industrial and chemical applications.

Chemical Properties (Standard wrought Monel products)

Nickel	67%	Manganese	1.0
Copper	30	Silicon	0.1
Iron	1.4	Carbon	0.15

Spring wire has a higher manganese content up to 2.50% maximum. Castings have a higher silicon content up to 2.0% maximum.

Physical Properties

Density (gms per c.c.)—cast	8.80
Density—rolled	8.90
Melting point	2370–2460°F. (1300–1350°C.)
Modulus of elasticity tension	25,000,000–26,000,000
Modulus in torsion	9,000,000–9,500,000
Weight per cubic inch—cast	0.318 pound
Weight per cubic inch—rolled	0.323 pound

Strength Properties

Form and Condition	Yield strength (0.0% offset)* (1000 p.s.i.)	Yield strength (0.20% offset) (1000 p.s.i.)	Tensile strength (1000 p.s.i.)	Elongation in 2 in. (%)
Rod and bar—cold-drawn				
Annealed	20–30	25–40	70–85	50–35
As drawn	45–95	55–120	85–125	35–10
Rod and bar—hot-rolled	30–55	40–65	80–95	45–30
Rod and bar—forged	25–65	40–85	75–110	40–20
Wire—cold-drawn				
Annealed		25–40	70–85	50–30
Number 1 temper		50–85	85–110	20–5
Regular temper		85–130	110–140	15–4
Spring		130–160	140–170	10–2
Plate—hot-rolled				
Annealed	20–30	25–45	70–85	50–30
As rolled	25–70	40–90	80–110	45–20
Sheet and strip—special cold-rolled				
Annealed		25–45	70–85	50–30
Hard sheet		90–110	100–120	15–2
Full-hard strip		90–130	100–140	15–2
Number 35 sheet		45–65	78–85	40–20
Sheet—standard cold-rolled		25–45	70–85	50–30
Tubing—cold drawn				
Annealed		25–45	70–85	50–30
As drawn		60–120	90–125	20–10

* Proof Stress.

The magnetic transformation point of Monel is affected considerably by slight variations in composition and by mechanical and thermal treatment. Ordinarily a horseshoe magnet will attract Monel, but the pull of the magnet varies with temperatures and with the metal itself.

Annealing. Annealing for softening and the relief of cold-working strains is the only heat treatment for Monel metal. Hardening cannot be done by heat treatment, only by cold working.

Stress-equalizing annealing is accomplished by heating to 525-650°F., holding for one hour at temperature, and quenching in water containing 2% denatured alcohol. This alcohol-water quench will reduce the surface oxidation that takes place when the work is removed from the furnace. A silvery white surface results. A pink color after the quench indicates oxidation in the furnace, improper heating conditions, or delay in quenching which permits excessive oxidation.

Soft annealing of material is done by heating to 1700°F., holding for 3 to 7 minutes, depending on the severity of cold work that is to be performed, and quenching in alcohol-water solution.

Working Properties. Monel is similar to mild steel in its cold-working properties, such as cupping, drawing, bending, and forming. Due to its higher elastic limit, greater power is required than for steel; and for excessive working, it is necessary to anneal frequently.

Hot working, such as forging and hot rolling, must be done between 2150°F. and 1850°F. Heating for all high-nickel alloys should be done in sulfur-free atmospheres. These are obtainable by using gas or oil fuels, the latter carrying a specification of 0.5% (maximum) sulfur content. Coke or coal are not recommended because of their offending sulfur content. The combustion of the gases should be complete before these gases reach the surface of the metal. For that reason, combustion spaces must be large. Reducing atmospheres should be maintained. Cold-rolled or cold-drawn material is obtained by cold working hot-rolled material after pickling and annealing.

Sheet can be bent about a radius equal to one thickness of the material. The cold ductility of the metal is demonstrated in its ability to make sylphon-type bellows and corrugated flexible tubing.

Machining of Monel can be done without difficulty. For automatic-screw-machine work a machining-quality rod is available. Because of the great toughness of the metal, cutting speeds are slower and cuts are lighter than for mild steel. Tools should be of tough high-speed steel, ground with sharper angles than for steel, and honed. Sulfurized oil should be used abundantly as a lubricant for boring, drilling, and so on. It is preferred for all work, though water-soluble oils suffice for lathe work. R Monel is available for automatic machine work where high cutting speeds must be maintained.

Welding. Monel can be readily welded by any of the methods commonly used for steel, among them, oxyacetylene, carbon-arc and metallic-arc, spot, seam, butt, and flash welding. The method to use depends on the gage of material to be joined and the type of equipment to be made. Sound, strong, ductile welds are regularly made.

When oxyacetylene welding Monel, a slightly reducing flame neither harsh nor mild is maintained. A flux (Inco Gas-Welding & Brazing Flux) in the form of water paste is painted on parts to be welded and on the welding rod. The pool of weld metal should not be puddled or boiled, but kept quiet; otherwise the "life" of the metal may be burned out.

The metallic-arc welding of Monel is carried out by using a flux-coated Monel wire of the shielded-arc type capable of producing X-ray-perfect welds. Reversed polarity is used. Welds are made with single and multiple beads, but, of course, in the latter case the flux and slag must be removed before laying down subsequent beads.

Carbon-arc welding is similar to acetylene welding in that a source of heat in the form of an arc flame is used instead of an oxyacetylene flame. Small-diameter pointed carbons (⅛ to ¼ inch) are used, together with a lightly fluxed Monel filler wire.

Soldering. Soft soldering is a convenient easy means of joining where corrosion and contamination are not troublesome and where strength is not required. Soft solder is inherently weak and must not be used where finished equipment will be subjected to vibration or high stresses. Pre-tinning of the edges prior to forming is desirable. Either high- or low-tin solders are satisfactory; the 50-50 lead-tin is the more widely used with zinc chloride base fluxes.

Silver solders are also used for joining Monel, the procedure outlined under Inconel being applicable.

Uses. Monel has been used in the manufacture of oil coolers, stainers, and rivets for use with stainless steel.

K MONEL

K Monel is a nonferrous alloy composed mainly of nickel, copper, and aluminum. It is produced by the addition of a small amount of aluminum to Monel. It is corrosion resistant and can be hardened by heat treatment—two properties which are very important. K Monel has been successfully used for gears, chains, and structural members in aircraft subject to corrosive attack. K Monel being nonmagnetic is sometimes used for structural members in the vicinity of a compass.

CHEMICAL PROPERTIES (Approximate composition)

Nickel	66%	Iron	0.90
Copper	29	Manganese	0.85
Aluminum	2.75	Silicon	0.50
Carbon	0.15		

PHYSICAL PROPERTIES

Density (gms per c.c.)	8.47
Melting point	2400–2460°F. (1315–1350°C.)
Modulus of elasticity (tension) (p.s.i.)	25,000,000–26,000,000
Modulus of torsion (p.s.i.)	9,000,000–9,500,000
Weight per cubic inch	0.31 pound

STRENGTH PROPERTIES

Form and Condition	Yield strength (0.0% offset)* (1000 p.s.i.)	Yield strength (0.20% offset) (1000 p.s.i.)	Tensile strength (1000 p.s.i.)	Elongation in 2 in. (%)
Rod and bar:				
Cold-drawn				
Annealed		40–60	90–110	45–35
Annealed, age-hardened	70–100	90–110	130–150	30–20
As drawn		70–100	100–135	35–13
As drawn, age-hardened	80–125	100–130	140–170	30–15
Hot-rolled:				
As rolled		40–90	90–120	45–25
As rolled, age-hardened	80–110	100–120	140–160	30–20
Forged:				
As forged		40–90	90–120	40–25
As forged, age-hardened	80–115	100–125	140–165	30–20
Wire—cold-drawn:				
Annealed		40–60	90–110	45–30
Annealed, age-hardened		90–110	130–150	30–15
Spring		130–155	145–175	4–2
Spring, age-hardened		150–175	160–200	8–3
Strip—cold-rolled:				
Soft		50–65	90–105	45–25
Soft, age-hardened		90–110	130–150	25–10
Half-hard		85–105	125–145	20–5
Half-hard, age-hardened		110–130	150–180	15–3
Full-hard		105–120	145–165	8–2
Full-hard, age-hardened		125–145	170–200	10–2

* Proof Stress.

Cold-rolled, soft material is obtained by a softening heat treatment. It should be specified where great softness is necessary for fabricating operations. Structural parts made from this material should normally be hardened by heat treatment after fabrication. Secondary parts are often left in the soft state. It should be noted that the strength values given for the soft material are maximum values.

Cold-drawn material is the strongest grade that can be machined reasonably well. For this reason it is usually specified for machined parts that are to be used without further heat treatment.

The heat-treated materials are cold-worked and then given full heat treatment, which makes them hardest and strongest. These grades can be machined only with difficulty. They should be specified only for parts that can be purchased finished or can be finished by grinding.

Wire up to ¼ inch can be cold drawn and heat-treated to above 175,000 p.s.i. for use as springs. This is full-hard material. The wire must be in the cold-drawn condition when coiled if maximum strength is desired after heat treatment. If the spring is made from soft wire or formed hot, subsequent heat treatment will only develop intermediate properties. The reason for this action is explained under Heat Treatment, below.

K Monel is nonmagnetic at all normal temperatures. Its magnetic permeability is 1.0, which is the same as air. This property is extremely important for parts located in the vicinity of a compass.

Heat Treatment. Annealing or softening of K Monel is obtained by soaking at one of the following temperatures for the time specified:

1600°F.	5 to 10 min.
1800°F.	1 to 4 min.

Quenching must be done in water for sections over ½ inch thick, or in smaller sections. K Monel will not soften, if cooled in air, as it requires a rapid quench.

The maximum hardness that can be attained by heat treatment alone, if the hardness of soft material is increased by cold working and then heat-treated, the additional hardness developed by the heat treatment is superimposed on the cold-worked hardness. Thus, cold-worked metal with a Brinell hardness of about 250 can be further hardened by heat treatment, to 350–400 Brinell.

Hardening by heat treatment is obtained by following the procedure outlined below, depending on the initial hardness of material:

Material condition	Temperature (°F.)	Time at temperature
Soft: 140 to 180 Brinell	1200–1250 or 1080–1100	1 hr 16 hrs.
Moderately cold worked: 175 to 250 Brinell	1080–1100	8 to 16 hrs.
Fully cold worked: over 250 Brinell	980–1000	6 to 10 hrs.

The longest time should be used for the softest material. For best possible hardness, the material should be cooled not faster than 15°F. per hour to 900°F. Furnace cooling is essential.

K. Monel can be stress-relief annealed after cold working by heating to 525°F. and quenching. No softening occurs due to this treatment.

In heating K Monel the fuel should be free from sulfur and a reducing atmosphere maintained in the furnace to avoid excessive oxidation. K Monel should not be placed in a cold furnace and heated gradually, but should be charged into the hot furnace.

Working Properties. K Monel can be worked quite readily in the shop in the annealed form. Working above this grade is difficult, due to the greater hardness.

Hot working of K Monel should only be done between 2175°F. and 1700°F. The metal should be quenched in water from the finishing temperature above 1700°F. Annealed soft material will then be obtained.

Cold-drawn rod is produced from hot-rolled rod that is annealed, pickled, and cold drawn to size in two or more operations through chromium-plated hardened steel dies.

Cold-rolled strip or sheet is produced from hot-rolled material by annealing, pickling, and cold rolling to the desired hardness. The maximum hardness obtainable by cold rolling without subsequent heat treatment is known as the full-hard condition.

Wire is cold drawn in the same manner as rod but the percentage of cold reduction is greater. Spring wire is cold drawn to 25% of the original cross-sectional area. As noted under heat treatment, in order not to anneal out any of the effect of cold working this grade material is not heated as high as the softer materials. Heat treatment at 980–1000°F. will give a tensile strength of 175,000 to 200,000 p.s.i.

Hot-rolled or cold-drawn rod can be machined satisfactorily. Heat-treated material can only be machined with difficulty. A special free-machining grade, known as KR Monel, is available for high-production parts on screw machines, turrets, etc. The mechanical properties are slightly lower than for K Monel.

Welding. K Monel sheet has been successfully welded by oxyacetylene. A rod of the same material and a flux composed of half sodium fluoride and half Inco (a welding and brazing flux prepared by the International Nickel Company) mixed with water to form a paste can be used. Another satisfactory flux consists of 5 to 6 parts of chromalloy flux mixed with 1 part of fluorspar powder. A slightly reducing flame should be used. The weld will respond to heat treatment.

Electric arc welding of K Monel is readily accomplished. Spot, seam and flash welding can also be used.

Brazing. K Monel can be brazed readily and with good results by the use of Handy & Harman's Easy-Flo Brazing Alloy and Handy Flux. Care should be taken to have the edges of the sheets perfectly smooth or cracking will result because of hardness of the metal. The minimum amount of heat necessary to completely flow out the silver solder should be supplied to the joint.

Corrosion. K Monel is naturally corrosion resistant and does not rely upon a protective film, such as oxide formed on the surface. It is resistant to corrosion in normal atmospheres or in salt water.

Electrolytic corrosion does not affect K Monel since it is high in the galvanic series, but if coupled with steel or aluminum, it may cause corrosion of these metals.

As purchased, K Monel will usually be received in a nontarnished condition. If subsequent heat treatment is performed, the metal surface will oxidize. This oxide can be removed by pickling. The manufacturer will gladly furnish the proper pickling solution that should be used for any given set of conditions.

Available Shapes. K Monel is commercially available as strip, wire, rod, and forgings. Forged stock can be obtained to suit any possible requirements in aircraft work.

Uses. K Monel is used for instrument parts and for structural parts in the vicinity of compasses because of its nonmagnetic quality. The corrosion resistance and excellent strength qualities of this material make it practical for machined parts that are subject to corrosion. Specific examples of this use are gears and chains for operating retractable landing gears on amphibian planes.

SPECIFICATIONS

Inconel	QQ-W-390	Wire
	MIL-N-6710	Bars, forgings, and rods
	MIL-N-6840	Sheet and strip
	MIL-T-7840	Tubing, seamless, round
	MIL-T-7840	Tubing, welded, round
	MIL-R-5031	Welding rod
Monel	Federal QQ-N-281	Forgings, rods, sheet, wire
	Navy 44T38	Tubing
K Monel	Federal QQ-N-286	Forgings, rods, strip, wire

CHAPTER X

COPPER AND ITS ALLOYS

COPPER, brass, and bronze have a limited use in aircraft construction. They do have important specialized applications, however, such as bearings and fuel and oil lines. Copper wire is used throughout the electrical system. In general these metals are corrosion resistant, nonmagnetic, fairly strong, and good conductors of electricity.

COPPER

Copper Tubing. Copper tubing is very generally used for fuel and oil lines. The copper used in the manufacture of this tubing must contain at least 99.90% copper. The tubing is purchased in the soft annealed condition and it is seamless drawn. In the purchased condition or after annealing it has the following physical properties:

Ultimate tensile strength (p.s.i.)	32,000
Yield point (p.s.i.)	6,000
Elongation (%)	52%
Rockwell hardness	63 (B-1/8-100)

This tubing can be annealed by heating it in an air furnace at 1100–1200°F. and quenching it in water. To obtain the maximum softness and ductility the tubing should not be held at temperature longer than 5 minutes.

Copper tubing is available in sizes ranging from 1/8 to 1 1/8 inches outside diameter. A wall thickness of 0.035 inch is used up to 5/8-inch diameter and 0.049 inch for larger diameters. These sizes cover the standard requirements for aircraft fuel, oil, and water lines. For high-pressure oxygen lines a special high-pressure copper tubing is used.

Copper-Silicon-Bronze Tubing. This tubing is considerably stronger than pure copper tubing and has largely superseded it for fuel, oil, water, and air lines.

CHEMICAL COMPOSITION (%)

Silicon	1.00–5.00	Iron (max.)	2.50
Manganese (max.)	1.50	Impurities (max.)	.50
Zinc (max.)	2.50	Copper	remainder

This tubing has a tensile strength of 50,00 p.s.i. and an elongation of 35%. It is used in the following standard sizes: 1/8 X 0.035, 3/16 X 0.035, ¼ X 0.035, 5/16 X 0.035, 3/8 X 0.035, 7/16 X 0.035, ½ X 0.035, 5/8 X 0.035, ¾ X 0.049, 7/8 X 0.049, 1 X 0.049, 1 1/8 X 0.049.

This tubing can be annealed at a temperature of 1000–1000°F. if required after severe forming and bending.

Copper Wire. A soft copper wire is used as a locking wire in aircraft construction. It is drawn from pure copper and has a tensile strength approaching 40,000 p.s.i. and an elongation of 25%.

Beryllium-Copper. This material is a high-strength, heat-treatable nonmagnetic alloy available as bar, rod, sheet, strip, and wire. Its density is 0.298 lb./cu. in.

CHEMICAL COMPOSITION (%)

Beryllium	2.00–2.25
Elements added to obtain special properties	0.50 max.
Metals (impurities) other than above	0.50 max.
Copper	remainder

PHYSICAL PROPERTIES

	U.t.s. (p.s.i.)	Yield point (p.s.i.)	Elongation (%)
Bars, rods, forgings			
Annealed (over ¾")	80,000 max.		35
Cold-drawn (over ¾")	80,000 min.		5
Annealed (3/8 to ¾")	80,000 max.		35
Cold-drawn (3/8 to ¾")	95,000 min.		5
Annealed, heat-treated	150,000 min.	85,000	10
Cold-drawn, heat-treated	175,000 min.	88,000	3.5
Sheet and Strip (cold-rolled)			
Soft annealed	80,000 max.		35
Soft annealed, heat-treated	150,000 max.	90,000	7.5
¼ hard	80,000		10
¼ hard, heat-treated	160,000	92,000	5
½ hard	90,000		5
½ hard, heat-treated	170,000	93,000	2.5
Full hard	100,000		2
Full-hard, heat-treated	180,000	95,000	2
Wire			
Soft annealed	80,000 max.		35
Soft annealed, heat-treated	150,000		5
¼ hard	90,000		5
¼ hard, heat-treated	160,000		3
½ hard	100,000		2
½ hard, heat-treated	180,000		1.5

This material is annealed by heating at 1440° F. for ½ to 3 hours and quenching. Hardening is accomplished by holding at 525–575°F. up to 3 hours, depending on the properties required.

Heat-treated material is considered to have more stable and uniform properties and is preferred for aircraft work.

BRASS

Brass is a copper alloy consisting of a solid solution of zinc in copper. In addition to zinc and copper, brasses sometimes contain a small amount of aluminum, iron, lead, manganese, magnesium, nickel, phosphorus, or tin. Brass with a zinc content of 30% to 35% is very ductile, and with 45% zinc content it has a relatively high strength. Brasses with a zinc content up to 37% are in so-called "alpha solution," while above that percentage a "beta-solution" condition exists. It is the difference between these two conditions that accounts for the ductility of the low-zinc brass and the strength of the high-zinc brass. Alpha-solution brass can only be annealed, but beta-solution brass can be increased in strength by heat treatment.

Muntz Metal. Muntz metal is a brass composed of 60% copper and 40% zinc. It has excellent corrosion-resisting qualities in contact with salt water. It can be increased in strength by heat treatment. When heated to 1500°F. the beta solution absorbs the alpha solution. If quenched in water from this temperature the homogeneous beta condition is retained and the strength increased about 50%. If the heated metal is cooled slowly as in air, the absorbed alpha is reprecipitated and the properties of annealed material are obtained.

PHYSICAL PROPERTIES

	Heat treated	*Annealed*
Ultimate tensile strength (p.s.i.)	80,000	57,000
Yield point	60,000	20,000
Elongation (%)	9.5	48
Hardness (Brinell 10 mm., 500 kg.)	158	80
Weight (lb./cu. in)	0.303	0.303

As cast this metal has an ultimate tensile strength of 50,000 p.s.i. and an elongation of 18%. It is used in the manufacture of bolts and nuts, as well as parts in contact with salt water.

Manganese Bronze (Brass). Manganese bronze is really a high-zinc brass. It is exceptionally strong, tough, and corrosion resistant.

CHEMICAL COMPOSITION (%)

Copper	57–60	Manganese (max.)	0.50
Tin	0.5–1.5	Aluminum (max.)	0.25
Iron	0.8–2.0	Lead (max.)	0.20
Zinc	remainder	Impurities (max.)	1.10

PHYSICAL PROPERTIES OF WROUGHT MANGANESE BRONZE

	U.t.s. (p.s.i.)	Yield point (p.s.i.)	Elongation (%)
Rods and bars, half-hard	72,000	36,000	20
Rods and bars, hard	85,000	60,000	5
Shapes, soft	55,000	22,000	25
Plates, soft	57,000	22,000	20
Plates, half-hard	60,000	24,000	18

This metal can be forged, extruded, drawn, or rolled to any desired shape. It is generally used in rod form for machined parts when used at all in aircraft construction.

A casting variation of this alloy known as manganese-aluminum bronze has the following chemical composition:

CHEMICAL COMPOSITION (%)

Copper	60–68	Manganese	2.5–5.0
Tin (max.)	0.50	Aluminum	3.0–7.5
Iron	2.0–4.0	Lead (max.)	0.20
Zinc	remainder		

This type of casting has an ultimate tensile strength of 110,000 p.s.i., a yield strength of 60,000 p.s.i., and an elongation of 12%. This material can be sand-cast or centrifugally cast in permanent molds.

Hy-Ten-Sl-Bronze. This is the trade name of a very high-strength copper alloy resembling manganese bronze in chemical composition.

PHYSICAL PROPERTIES

	Sand cast	*Forged, rolled, extruded*
Ultimate tensile strength (p.s.i.)	115,000	120,000
Yield point (p.s.i.)	70,000	73,000
Elongation (%)	10	8
Weight (lb./cu. in.)	0.280	0.280

With lower strength but higher elongation this alloy is also available in four other grades. It is reputed to be extremely hard, wear resistant, noncorrosive, and readily machinable and is recommended for bearings or bushings subject to heavy loads.

Naval Brass (Tobin Bronze). Naval brass is often called Tobin bronze. It is not as strong as manganese bronze but has greater strength, toughness, and corrosion resistance than commercial brass. It is used for turnbuckle barrels, bolts, studs, nuts, and parts in contact with salt water.

CHEMICAL COMPOSITION (%)

Copper	59.0–62.0	Iron (max.)	.10
Tin	0.5–1.5	Lead (max.)	.20
Zinc	remainder	Impurities (max.)	.10

PHYSICAL PROPERTIES

	U.t.s. (p.s.i.)	Yield point (p.s.i.)	Elongation (%)
Rods and bars, soft	54,000	20,000	30
Rods and bars, half-hard	60,000	27,000	25
Rods and bars, hard	67,000	45,000	22
Shapes, soft	56,000	22,000	30
Plates. soft	52,000	20,000	30
Plates, half-hard	56,000	28,000	25
Sheets and strips, soft	50,000	20,000	20
Sheets and strips, half-hard	60,000	25,000	15
Castings	30,000		15
Tubing	67,000	45,000	15

Naval brass has excellent machining qualities and is used for screw machine parts. Turnbuckle barrels are made of this material, using either hard rod or tubing.

Red Brass. Red brass is sometimes classified as a bronze because of its tin content. Castings made from red brass are used in the manufacture of fuel- and oil-line fittings. It has good casting and finishing properties and machines freely.

CHEMICAL COMPOSITION (%)

Copper	84.0–86.0	Iron (max.)	0.25
Tin	4.0–6.0	Phosphorus (max.)	0.75
Lead	4.0–6.0	Antimony (max.)	0.25
Zinc	4.0–6.0	Impurities (max.)	0.15

Red brass castings have an ultimate tensile strength of 30,000 p.s.i., a yield point of 12,000 p.s.i., and an elongation of 20%.

BRONZE

Bronzes are copper alloys containing tin. Lead, zinc, and phosphorus are also present in some bronzes but do not total more than 15%. There is also an aluminum bronze in which aluminum is the major alloying element. The true bronzes have up to 25% tin, but those containing below 11% tin are the most useful. Bronzes have excellent bearing qualities due to the fact that the tin is in a hard delta solid solution in the copper. This hard delta solution distributed through the alpha metal gives ideal bearing properties. Delta solution is only present in bronzes with over 9% tin content. When less tin is present it is in alpha solution. It is possible to improve the strength of copper-tin bronzes through heat treatment. The exact response to heat treatment depends upon the state of solution of the tin. The bearing qualities are impaired if the delta solution is removed or changed by heat treatment.

Gun Metal. Gun metal is a hard bronze casting material. Its shrinkage is not great and it has fair machinability. It is recommended for use under severe working conditions and heavy pressures as in gears and bearings.

CHEMICAL COMPOSITION (%)

Copper	86.0–89.0	Lead (max.)	0.20
Tin	9.0–11.0	Iron (max.)	0.06
Zinc	1.0–3.0		

Gun-metal castings have an ultimate tensile strength of 30,000 p.s.i., a yield point of 15,000 p.s.i., and an elongation of 14%. It should not be used where the temperature will exceed 500°F. When used for bearings, it should not be annealed, or the hard delta eutectoid will be removed.

Phosphor Bronze. Phosphor bronze can be obtained in the following forms: rod, bar, sheet, strip, plate, and spring wire. It is used for the manufacture of bolts, valve disks, electric contacts, and small springs.

CHEMICAL COMPOSITION (%)

Copper (min.)	94.0	Lead (max.)	0.20
Tin (min.)	3.5	Iron (max.)	0.10
Phosphorus	0.05–0.50		

PHYSICAL PROPERTIES

	U.t.s. (p.s.i.)	Yield point (p.s.i.)	Elongation (%)
Rods and bars			
Up to ½ in.	80,000	60,000	12
Over ½ to 1 in.	60,000	40,000	20
Over 1 to 3 in.	55,000	30,000	25
Over 3 in.	50,000	25,000	25
Sheet and strip			
Spring temper, 0–8 in. wide	90,000	45,000	1
Spring temper, 8–12 in. wide	80,000	40,000	1
Half-hard, all sizes	50,000	25,000	25
Spring wire			
Up to .025 in	150,000		1.5
Over .025 to .0625 in.	135,000		1.5
Over .0625 to .125 in.	130,000		2
Over .125 to .250 in.	125,000		3.5
Over .250 to .375 in.	120,000		5
Over .375 to .500 in.	105,000		9

Phosphor Bronze Casting Alloy. This casting alloy is sometimes called a leaded phosphor bronze or leaded gun metal. It machines more easily than gun metal. It is used for bearings, bushings, gears, and other applications requiring good strength and resistance to salt-water corrosion.

CHEMICAL COMPOSITION (%)

Copper	86–89	Phosphorus (max.)	0.05
Tin	7.5–11.0	Iron (max.)	0.10
Zinc	1.5–4.5	Nickel (max.)	0.75
Lead	0–0.3		

This alloy has an ultimate tensile strength of 40,000 p.s.i. and an elongation of 20%.

Aluminum Bronze. Aluminum bronze possesses greater resistance to corrosion than manganese bronze, and hence may be used where greater strength and corrosion resistance is required. It has good bearing qualities as well as great strength. It may be readily forged. It is available commercially in the form of bars, rods, shapes, plates, and sheets.

Bar and rod can be purchased to specification MIL-B-6946. This material is frequently used for fluid connection fittings and coupling sleeves.

CHEMICAL COMPOSITION (%)

Aluminum	6.5–11.0	Iron (max.)	4.0
Manganese (max.)	2.0	*Nickel (max.)	5.5
Tin (max.)	0.60	*Silicon (max.)	2.25
Copper	remainder		

* If large amounts of either nickel or silicon are present the other element may not exceed 0.25% maximum.

PHYSICAL PROPERTIES

	U.t.s. (p.s.i.)	Yield point (p.s.i.)	Elongation (%)
Rods and bars			
Up to ½ in.	90,000	45,000	15
Over ½ to 1 in.	88,000	44,000	15
Over 1 in.	85,000	42,000	20
Shapes (all sizes)	75,000	35,000	20
Plates, sheets, strips			
Up to ½ in., under 30 in. wide	60,000	24,000	25
Up to ½ in., over 30 in. wide	55,000	22,000	25
Over ½ in., all widths	50,000	20,000	30

Aluminum Bronze Casting Alloy. This alloy is as hard as manganese bronze, and has great strength and resistance to corrosion, shock, and fatigue. It is used for worm gears, valve seats, bearings, and propeller hub cones.

Specification MIL-B-6947 describes this material.

CHEMICAL COMPOSITION (%)

Copper (min.)	78.0	Manganese (max.)	5.0
Aluminum	10.5–12.0	Nickel (max.)	5.0
Iron	2.0–5.0	Tin (max.)	0.20

This material after heat treatment has an ultimate tensile strength of 85,000 p.s.i. minimum, and a minimum elongation of 3%.

Bronze Cable. Extra-flexible bronze cable, 7 by 19 strands, is manufactured for aircraft use. The weight and breaking strength for each size of cable is as follows:

Diameter (inch)	*Weight 100 ft. (pounds)*	*Breaking strength (pounds)*
5/8	72.0	14,000
9/16	60.4	11,350
½	48.8	8,900
7/16	38.4	6,800
3/8	29.9	5,100
5/16	20.0	3,500
¼	13.5	2,500
7/32	10.7	2,000
3/16	7.3	1,500
5/32	5.0	1,000
1/8	3.3	700

SEASON CRACKING

Many of the brasses and bronzes are subject to a phenomenon called season cracking. These metals crack spontaneously after being in service for a period of time. It is believed this cracking is due to internal stresses left in the metal by cold working. A low-temperature anneal is usually sufficient to relieve these stresses and avoid season cracking.

Specifications generally require the following test for material subject to season cracking: the sample is thoroughly cleaned with nitric acid and then dipped into a mercurous nitrate solution for 15 minutes. This solution consists of 100 grams of mercurous nitrate and 13 cubic centimeters of nitric acid (specific gravity 1.42) dissolved in a liter of water. After removal from the solution, the sample is washed with water and then alcohol. The sample will crack visibly within 24 hours after this treatment if the material is subject to season cracking. This treatment is sometimes called a *strain test.*

CHAPTER XI

WROUGHT ALUMINUM ALLOYS

At the present time aluminum alloys are used almost exclusively in the construction of aircraft. Aside from fittings carrying high concentrated loads, or parts subject to severe wear, or special forms of corrosion—for which special steel alloys are used—the general structure of the airplane as built today is aluminum alloy. The ascendancy of this material is due to its light weight, high strength, ease of fabrication, and its availability in all standard forms. It is about one-third as heavy as steel and can be obtained with a minimum ultimate tensile strength as high as 78,000 p.s.i. It is available in many tempers and forms, so that just the proper material may be selected for any particular application. These applications vary from formed cowling requiring a very ductile material to highly stressed wing beams requiring great strength.

Aluminum is found in most clays, soils, and rocks, but the principal commercial source is the ore *bauxite*. Bauxite is largely aluminum oxide mixed with impurities. These impurities are removed by a chemical process leaving the pure aluminum oxide, *alumina*. An electrolytic process is used to obtain aluminum from the oxide. It was not until 1886 that a practical process was discovered to effect this separation on a commercial scale. In that year, Charles M. Hall in this country and P.L.T. Heroult in France, working independently, each discovered a practical process. The industrial development of aluminum began shortly after these discoveries.

The metallic aluminum obtained by the electrolytic process is cast into pig form. These pigs are later remelted to form the commercial ingots used in rolling, forging, extruding, and other fabricating processes. By the addition of other constituents during the remelting operations, many alloys of aluminum are obtained with varying properties. A great many structural shapes are wrought from the ingots by rolling, drawing, extruding. The common shapes used in aircraft construction are: sheet, tubing, wire, bar, angles, channels. Z-section, U-section, and so on. A number of the aluminum alloys are especially adapted for castings. Castings are regularly made in sand molds, permanent molds, or dies. As with other materials, castings do not have as great a strength as wrought material, but find numerous applications in aircraft.

NOMENCLATURE

The Aluminum Association has published a new alloy designation system for aluminum alloys. The new system has all the wrought aluminum alloys designated by a four-digit system. The first digit indicates an alloy group while the last two digits identify the aluminum alloy or aluminum purity. The second digit indicates modifications of the original alloy or impurity limits. The new system will help to eliminate some of the confusion which resulted when different aluminum producing companies produced alloys of practically the same chemistry but called them by different numbers.

The new Aluminum Association numbers for the more common alloys are as follows:

Old Commercial Designation	*A.A. Number*	*Old Commercial Designation*	*A.A. Number*
2S	1100	43S	4043
3S	3003	50S	5050
4S	3004	52S	5052
11S	2011	53S	6053
14S, R 301 Core	2014	56S	5056
17S	2017	61S	6061
A17S	2117	66S	6066
18S	2018	75S	7075
24S	2024	XA78S	X7178
25S	2025		

The system is arranged in order to divide the common alloy types into eight main groups:

A.A. Number	
1XXX	Aluminum—99.00% minus and greater
2XXX	Copper is the main alloying element
3XXX	Manganese is the main alloying element
4XXX	Silicon is the main alloying element
5XXX	Magnesium is the main alloying element
6XXX	Magnesium and silicon are the main alloying elements
7XXX	Zinc is the main alloying element
8XXX	Special element alloys
9XXX	Unused series

If new or experimental alloys are invented, they follow the same system but the four digits are preceded by an X.

The casting alloys were not changed because many ingot producers felt that the special trade names given to specific alloys were a form of advertising.

The temper designation system, in effect since December 31, 1947, continued without change. The temper designation follows the alloy designation

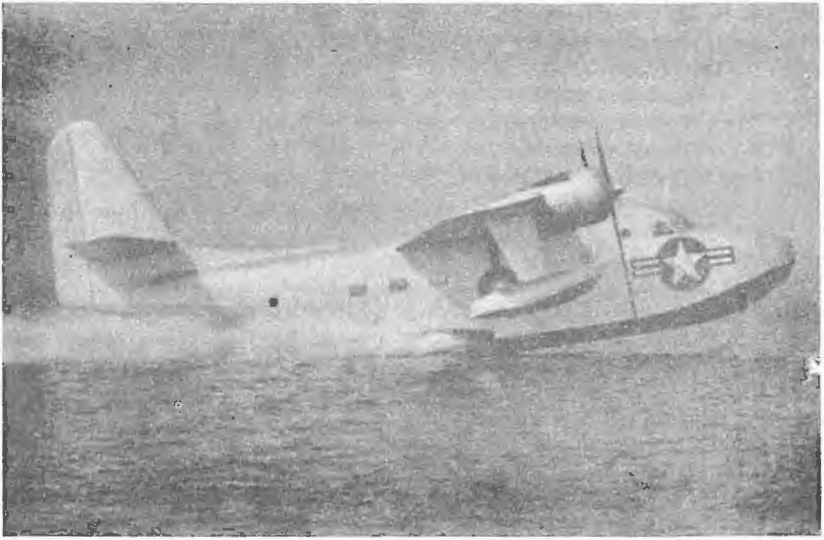


FIGURE 29. Grumman Amphibian; Aluminum-Alloy Construction

and is separated from it by a dash. Thus 3S-0 now becomes 3003-0, Alclad 24S-T81 is 2024-T81 and 75S-T6 is 7075-T6.

The wrought alloys can be manufactured in a number of different tempers. The temper designation consists of the letter O, F, H or T followed by a number. The temper designation O indicates annealed wrought material and F indicates the as-fabricated condition in which no effort has been made to control the mechanical properties.

The temper designation H is applied to those alloys that are strain-hardened by cold work. The commonly used alloys of this type are 3003-H12, 3003-H14, 3003-H16, 3003-H18, and 5052-H32, 5052-H34, 5052-H36 and 5052-H38. The second digit after the H represents the relative hardness and tensile strength where "2" is just above the annealed O temper and "8" is the hardest commercially practicable temper. When "1" is the first digit after H, temper has been produced by merely cold-working the material. When "2" is the first digit after H, the material has been cold-worked to a harder temper and then reduced to the desired temper by partial annealing. When "3" is the first digit after H, the material has been cold-worked and then stabilized by heating the material for a short time at a slightly elevated temperature. This treatment is applied to 3004, 5052 and 5056 alloys to prevent a decrease in the cold-worked strength which occurs when these alloys are held at room temperatures for a long time.

The basic temper designations for the heat-treatable alloys are as follows:

T2—Annealed castings
T3—Solution heat-treated and then cold-worked
T4—Solution heat-treated
T5—Artificially aged only
T6—Solution heat-treated and then artificially aged
T7—Solution heat-treated and then stabilized
T8—Solution heat-treated, cold-worked, and then artificially aged
T9—Solution heat-treated, artificially aged, and then cold-worked

If a modified heat treatment is used to obtain special physical properties, a second numeral is added to the basic designation. Thus we have 6061-T6 and 6061-T61.

Aluminum alloys are unstable for a period of time after solution heat treatment since age hardening begins immediately. This unstable temper is designated by W. The properties in the W condition vary with time as age hardening progresses. In the case of 7075 material, it is customary to indicate the time of age hardening as 7075-W (2 hr.) and 7075–W (2 mo.).

T3 temper is especially applicable to 2024 and Alclad 2024 flat sheet which has necessarily been cold-worked to obtain the degree of flatness required commercially. It has higher guaranteed properties than T4 temper.

T5 temper is used primarily in permanent-mold castings to increase mechanical properties, stabilize dimensions and relieve casting strains.

CLASSIFICATION OF WROUGHT ALLOYS

As indicated above under Nomenclature, the wrought aluminum alloys may be broadly classified under one of two groups as either *strain-hardened alloys or heat-treatable alloys.* In the first group the physical properties are improved solely by cold working, whereas in the heat-treatable group the properties are improved by heat treatment. Further improvement of the heat-treated group is obtainable by cold working slightly after heat treatment. The strain-hardened alloys do not respond to any heat treatment other than a softening, annealing treatment.

The two extreme tempers in which all strain-hardened alloys can be obtained are the soft-annealed temper and the full-hard temper. The latter temper is produced by cold-working the metal the maximum amount that is commercially practical. The intermediate tempers such as -H12, -H14 and -H16 are produced by varying the amounts of cold work after annealing. In the manufacture of sheet, tubing, or wire the cast alloy ingot is broken down while hot into slabs, tube blooms, or rods. The amount of reduction in area of these sections by cold working can be closely controlled by the setting of the

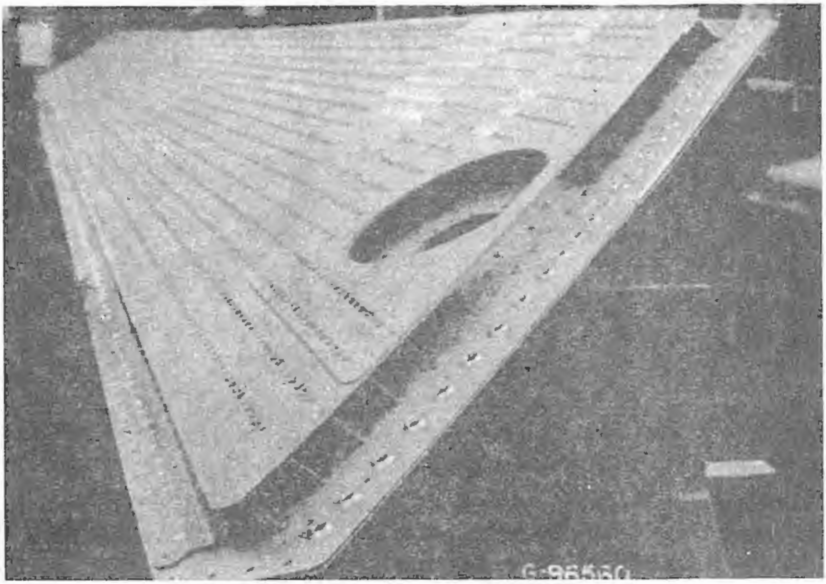


FIGURE 30. Corrugated Double Skin Construction—Alclad 2014-T6 and 7075-T6 Aluminum Alloys

rolls, or by the mandrel and die sizes. To obtain the intermediate tempers, it is only necessary to anneal the material at the proper size from which the remaining cold-finishing operations will give the desired temper.

The heat-treatable alloys can be obtained in the soft-annealed condition, the heat-treated condition, or the heat-treated and cold-worked condition. A few of the alloys also have an intermediate heat-treated condition. Greater strength is obtainable in the heat-treatable alloys than in the strain-hardened alloys. Consequently, they are used for structural purposes in aircraft in preference to the strain-hardened alloys.

CORROSION

Pure aluminum 1100 is very resistant to atmospheric corrosion but when alloying elements are added, the corrosion resistance is decreased. One strain-hardened alloy, 3003 and two heat-treatable alloys (6053 and 6061) are as corrosion-resistant as commercially pure aluminum, but all the other alloys are somewhat inferior. 5052 is more resistant to salt-water corrosion than 1100 but not atmospheric corrosion. It is customary in Naval aircraft work to protect all aluminum alloys with a coating of paint. A good protective coating is particularly important when the airplane will be subjected to severe corrosive conditions, as in the case of a seaplane.

One type of corrosion of aluminum alloys is the pitting of the surface, which is analogous to the rusting of iron. This eating away of the surface is accelerated in the presence of moisture, particularly salt water. If a dissimilar metal or impurities are also present, an electrical action is set up that eats away the aluminum alloy. All other metals used in aircraft except magnesium are above aluminum in the galvanic series, so that in any action set up the aluminum is the anode and will be attacked. Experience has shown that this type of corrosion occurs most often in parts of the structure that are poorly ventilated, and in inaccessible corners of internal joints.

Intercrystalline corrosion is a much more serious type of corrosion, since it greatly reduces the strength and destroys the ductility of the metal. This type of corrosion is apparently limited to aluminum alloys containing copper, such as 2017 and 2024. The resistance of these materials to this type of corrosion is lowered by incorrect heat treatment or by slow or delayed quenching. It is imperative that quenching of this type of material be done immediately in cold water, to avoid intercrystalline corrosion (Alclad 7075 may be given a slower quench without affecting corrosion). This type of corrosion gives practically no surface indication, but spreads through the interior of the metal along the grain boundaries. All types of corrosion must be guarded against in aircraft construction due to the light gage of material used.

ALCLAD ALUMINUM ALLOYS

"Alclad" is the name given to standard alloys, such as 2017 and 2024 when they have been coated with a thin layer of aluminum or another aluminum alloy which is alloyed to and integral with the base metal core. The name Alclad, a registered trademark, is usually reserved for products of the Aluminum Company of America. "Pureclad" was the equivalent name for material manufactured by the Reynolds Metal Company. Due to the fact that pure aluminum is highly resistant to corrosion, it protects the alloy sandwiched in between the two surface layers. The aluminum covering is electropositive to the underlying alloy and, consequently, also protects it by means of electrolytic action. This fact is important because the soft aluminum covering is easily scratched and the edges of the sheet are not coated with aluminum, so that corrosion might occur in these places if it were not for the electropositive aluminum coating. No painting of Alclad is necessary to protect it from corrosion unless it is subject to very severe service conditions such as underwater or bilge locations in seaplane construction. In such cases it is

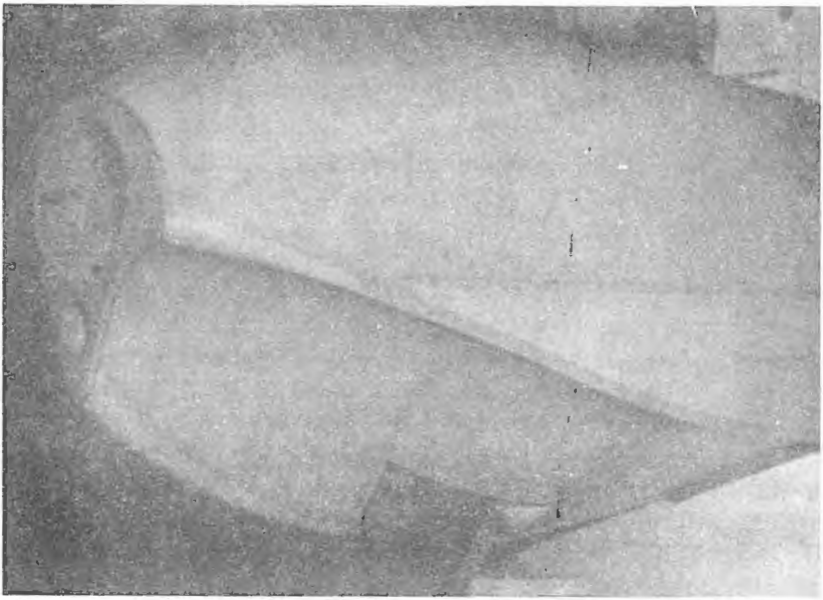


FIGURE 31. Bow of Mallard Hull; Alclad 2014

desirable to anodically treat the alloy before painting, in order to provide a good bond for the paint.

Alclad 2014 and 7075 are relatively new materials which are coated with corrosion-resistant aluminum alloy that is electropostive (anodic) to the base alloy. The cladding on Alclad 2014 is a magnesium-silicide of 6053 composition; the coating on Alclad 7075 is of a different composition, containing zinc, as shown later in the table of chemical compositions.

The average coating thickness per side for the various clad materials is as follows:

Alclad 2017 and Alclad 2024—5% under 0.064 inch thick; 2½% 0.064 inch and over.
Alclad 2014—10% under 0.040 inch; 5% 0.040 inch and over.
Alclad 7075—4% for all thicknesses.

A given thickness of clad material will not be as strong as the same thickness of the standard alloy. This reduction in strength is due to the strength of the coating being less than that of the base or core material. The exact strengths of clad and standard alloys are tabulated later in this chapter. Clad material has one great advantage, however, as regards strength, and that

FIGURE 32. Edo Seaplane Float; Alclad

is the fact that after years of service it sill retains most of its original strength. The standard alloys, even though protected by paint, may lose a great deal of their strength and nearly all of their ductility, due to corrosion. Corrosion in modern airplanes is usually localized to poorly drained spots but may have serious effects on the strength of the airplane. This retention of strength is particularly important in thin sections used in aircraft construction.

As explained later under Heat Treatment, it is important that Alclad be held only the minimum time at the soaking temperature. These precautions are necessary to prevent the diffusion of alloying constituent from the core to the cladding, thus reducing corrosion resistance.

EXTRUSIONS

In aircraft construction channels, angles, T-sections, Z-sections, and many other special structural shapes are required. These shapes are all obtainable in aluminum alloy by an extruding process. In this process a cylinder of aluminum alloy is heated between 750° and 850°F. and is then forced by a hydraulic ram through an aperture in a die. The aperture is the shape desired for the cross-section of the finished extrusion. Extruded material has performed satisfactorily but it does not have so fine a grain, nor is it so homogeneous as rolled or forged material.

Extruded shapes may be purchased in 2014-T6, 2017-T4, 2024-T4, 6053-T6, 6061-T6 and 7075-T6 material for aircraft purposes. The manufacturers have on hand a great many dies covering most of the commonly used sections. When a designer desires to use a new section, the manufacturer will make a new die for a very moderate cost and produce the necessary section. An

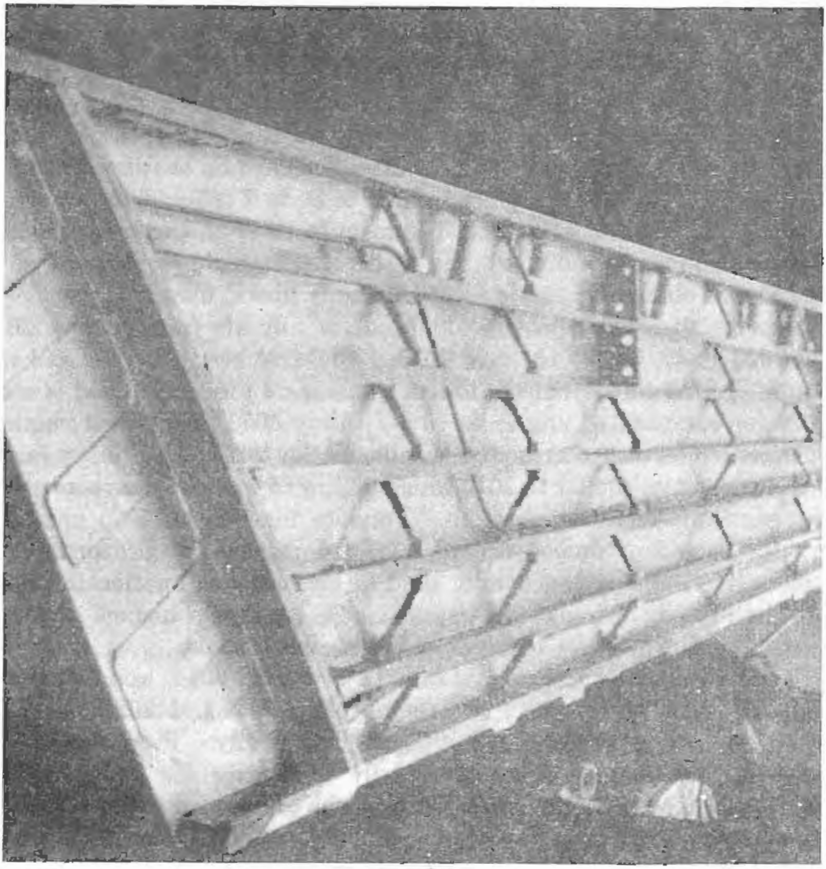


FIGURE 33. Modern Wing Construction—7075-T6 Machined Plate

extrusion pool has been established by a number of aircraft manufacturers and members are free to use any extrusion die in the pool by securing written permission from the aircraft manufacturer who purchased the die originally.

FORGINGS

Aluminum alloys may be forged to close limits to provide light, strong fittings, or other structural parts. These forgings have a uniform structure and are free from blowholes, hardspots, or cavities. Only a few thousandths of an inch need be allowed for finish-machining. In forging, the metal is heated to the proper forging temperature for the part in question and then hammered, pressed, drop-forged, or upset to shape. Pressed forgings have a fine finish and can be held to close tolerances.

The size limitation on pressed forgings was greatly increased during 1955 as a result of the initial operations of the Wyman Gordon 35,000-ton press and the Aluminum Co. of America's 50,000-ton press. Forgings in excess of several hundred pounds can now be fabricated. It must be remembered, however, that the 2014-T6 properties are reduced if the thickness of the forging is more than 4 inches, and also that 7075-T6 has thickness limitation of 3 inches.

At the temperatures used, the metal is not hot enough to flow easily so tremendous power is required to form it. A higher temperature cannot be used because the metal becomes hot-short and crumbly, and is ruined for future heat treatment. The power needed exceeds that used in forging steel. In laying out forgings a draft of 3° to 7° should be provided. The shrinkage allowance varies. The manufacturer should be advised of the finished dimensions desired. It is also important in forging design to avoid abrupt changes in section and to specify liberal fillets.

The aluminum alloys commonly used for aircraft forgings are 2014, 2017, 2025, 4032, 6053, 6151, and 7075. The most easily worked and the cheapest is 6151 but it has the lowest mechanical properties, and is used mostly for complicated engine forgings. Alloy 6053 has low mechanical properties, but is very corrosion-resistant. Alloy 2025 works fairly easily and has properties similar to 2017 which is hard to work but has somewhat better corrosion-resistant qualities. Forgings made from 2025 are used for aluminum-alloy propeller blades. Good mechanical properties are found in 2014, and it is generally used in aircraft construction in applications where high strength is required. 7075 has the highest physical properties and is ideal for highly loaded structural parts.

Because of their superior resistance to corrosion 2014 and 7075 are used in airplane structures. For engine parts 6151 and 2025 are used because the sections are heavy and frequently oily. Propellers made from 2025 have performed satisfactorily in service for years. Press (6053) forgings are ideal for tank flanges which are welded in place.

SPOT-WELDING ALUMINUM ALLOYS

Electric spot and seam welding of aluminum alloys has been generally adopted for joining nonstructural and semistructural parts. Spot welding has displaced riveting in many applications, due to its speed, lower cost, and elimination of projecting rivet heads. It has already been used successfully in

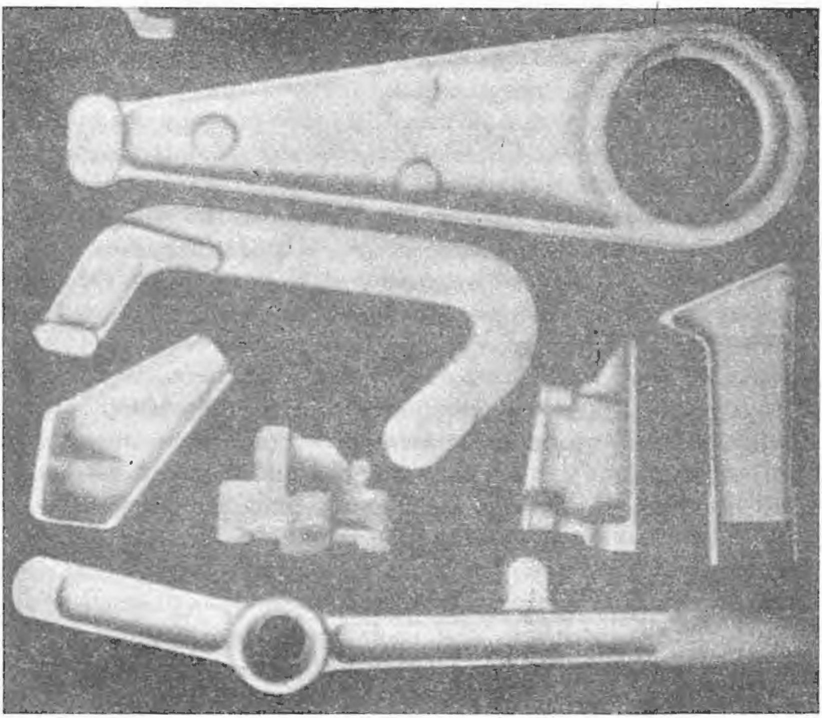


FIGURE 34. Aluminum-alloy Forgings

welding fuel tanks. Other common uses are the attachment of stiffeners to cowling, stringers to fuselage and wing skins, and in the assembly of brackets and shelves. Spot welding is generally used in the fabrication of primary structural parts of airplanes.

Spot-welding machines must have very accurate current, time, and pressure control. Machines in service at the present time have an amperage output of between 30,000 to 40,000 amperes and are capable of welding two 1/8-inch sheets. The throat of the machine may be as great as 72 inches. All four surfaces of the material to be welded must be absolutely clean. A wire brush hooked up to an air drill is one satisfactory method of cleaning such surfaces. The brush must not be so stiff, however, that it will remove the aluminum coating from Alclad. A fine grade of abrasive cloth, or fine steel wool may also be used. A hydrofluoric acid etching solution can also be prepared for this purpose.

Clad alloys and 5052 material are most satisfactory for spot welding. When resistance to corrosion is important and an extruded shape must be used, 6053 material should be selected if its physical properties are satisfactory. Clad material spot-welded to 2014, 2024, or 7075 extrusions has satisfactory corrosion resistance for aircraft use. Anodically treated material cannot be spot-welded. For this reason 2017 and 2024 must be spot-welded first and the assembly anodicaly treated. Adequate protection against corrosion cannot be obtained on the faying surfaces if this is done. For this reason clad material is preferred, particularly for forming structural assemblies that are to be spot-welded. More reliable welds are also obtained with clad materials.

It is possible to spot-weld through wet zinc chromate primer. When maximum corrosion resistance is necessary between the faying surfaces of 2017 or 2024 they should be coated with zinc chromate primer just prior to spot welding.

Spot welds should be put in shear only, since they are relatively weak in tension. They are usually spaced apart about 8 times the minimum sheet thickness and 4 times this thickness from the edge of the sheet. For maximum efficiency three rows of welds are necessary. With this arrangement it is believed an efficiency of 70% is obtainable with clad-sheet and 100% with 5052 materials. In either the soft or H-34 temper 5052 has been used for fuel tanks.

HEAT TREATMENT

There are two types of heat treatment applicable to aluminum alloys. One is called solution heat treatment, and the other is known as precipitation heat treatment. Some alloys, such as 2017 and 2024 develop their full properties as a result of solution heat treatment followed by about 4 days aging at room temperature. Other alloys, such as 2014 and 7075, require both heat treatments.

Solution heat treatment is so named because during this treatment the alloying constituents enter into solid solution in the aluminum. It has been found that these alloying elements which increase the strength and hardness are more soluble in solid aluminum at high temperatures than at low. After the metal is held at a high temperature for a sufficient time to complete the solution, it is quenched rapidly in cold water to retain this condition.

Precipitation heat treatment consists of *aging* material previously subjected to solution heat treatment by holding it at an elevated temperature for quite a long period of time. During this treatment a portion of the alloying constituents in solid solution precipitate out. This precipitation occurs at ordinary room temperatures in the case of 2017 and 2024 material. The precipitate is in the form of extremely fine particles which, due to their "keying" action, greatly increase the strength. The "natural aging" of 2017 and 2024 material at room temperatures is 90% to 98% complete after 24 hours, and fully complete

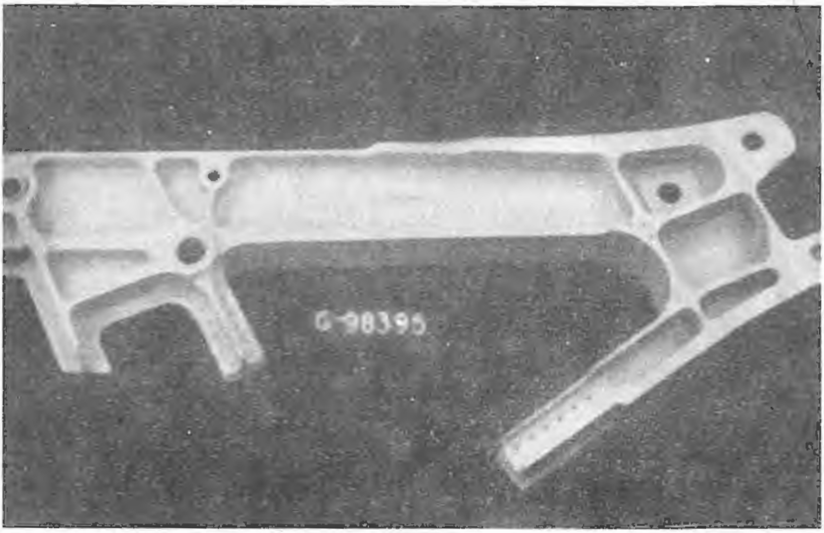


FIGURE 35. Large Aircraft Forging—7075-T6 Aluminum Alloy

after four days. Alloy 2024 develops greater strength than 2017 immediately after quenching, ages more rapidly, and is considerably less workable.

It has been found advisable to form aluminum alloys within one hour after solution heat treatment, before the aging has progressed too far. During this period the metal may be worked with ease and without danger of cracking, especially 2024 and 7075 alloys. It has been found that the aging of a heat-treatable alloy may be retarded for as much as 24 hours if it is kept at or below a temperature of 32°F. Aging can be retarded for longer periods if a lower temperature is maintained. In practice an ice-box containing dry ice or a refrigerating unit is used to hold rivets or small pieces of sheet until the shop is ready to work them.

In the solution heat treatment of aluminum alloys it is extremely important to hold the temperature within narrow limits. These limits are usually about 20°F., as in the case of 2014 material, when the heat-treatment range is 930–950°F. The heat-treatment range of 2024 material is 910–930°F. Exceeding the upper temperature limit may cause incipient melting of the eutectic and result in serious blistering. Alclad 2014 is an exception to this restriction and can be heat-treated 20–30°F. above the normal heat-treatment range of 930–950°F. without damage. But too high a temperature may cause eutectic melting. If the temperature is too low, complete solution will not take place, and the full properties of the material may not be developed. Solution heat

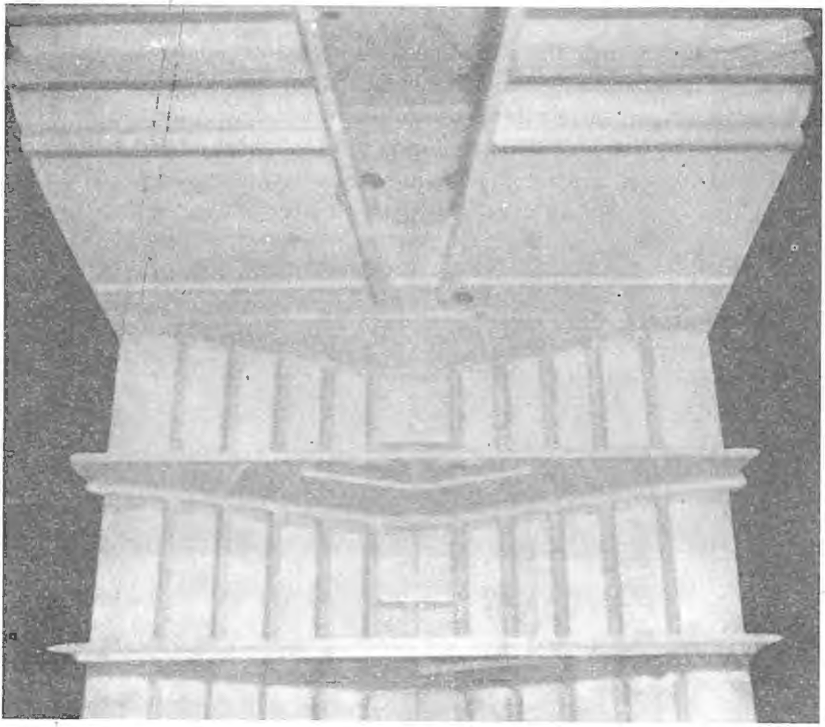


FIGURE 36. Hull Bulkhead and Bottom

treatment is usually done in a salt bath heated by gas, oil, or electricity, or in an electric air furnace. The salt bath is composed of fused sodium nitrate, or a mixture of 50% sodium nitrate and 50% potassium nitrate. The 50–50 solution must be used if the bath is also going to be used for annealing. The most important point in connection with the furnace selected is that it must maintain an even temperature throughout its interior. All parts of the work being treated must be subjected to the same temperature. It is common practice to raise and lower the load, always keeping it submerged in the salt bath, to obtain circulation of the liquid and assure a uniform temperature. In the electric air furnace provision should be incorporated for circulating the air.

The length of time that material must be soaked at the proper temperature depends upon the nature of the material, the prior heat treatment of the thickness of the material, and the type of heat-treating equipment. Heavier material requires a longer soaking period. When various thicknesses are treated at one time, the soaking time necessary for the heaviest material should be used. The lighter material will not be injured by a moderately long soaking. This is not true of clad material which must be heated as rapidly as possible and soaked for the shortest possible time; otherwise, the alloying elements of the base material will diffuse through the cladding and destroy the corrosion resistance. For this reason clad material should not be reheat-treated in thicknesses up to 0.049 inch, and not more than twice in thicknesses up to 1/8 inch. The standard alloys can be reheat-treated any number of times without affecting them.

Table 6 gives the time recommended for soaking wrought material, but these periods may vary slightly for different heating equipment. Soaking time begins when the temperature of the bath or furnace has reached the minimum heat-treatment temperature after inserting the load.

TABLE 6. Soaking Time for Solution Treatment—Wrought Aluminum Alloys

A. Wrought materials except forgings

Alloy	Time after load reaches minimum temperature (minutes)			
	Up to 0.032"	0.033–0.125"	0.126–0.250"	Over 0.250"
2014			30	60
Alclad 2014	7	15	25	45
2017	20	20	30	60
2024	30	30	40	60
Alclad 2024	20	30	40	60
6061	20	20	40	60
7075	25	30	40	60
Alclad 7075	20	30	40	60

B. Forgings

Alloy	Time (hours)	
	Up to 2" thick	Over 2" thick
2014	0.5–6.0	2–12
2025	3.0–6.0	4–12
4032	0.5–6.0	2–12
6151	0.5–6.0	2–12
7075	6.0	6

After soaking, the work is removed from the bath or furnace and quickly quenched in cold water. It is extremely important that not more than a few seconds elapse before quenching the hot material, or the resistance and strength will be seriously affected. In many plants a hood is placed over the work while transferring it from the furnace to the quenching bath, to prevent cooling. It is also important that the quenching bath be at a temperature below 85°F. when the hot work is immersed. The bath must be large enough to prevent the water temperature from rising above 100°F. while the work is

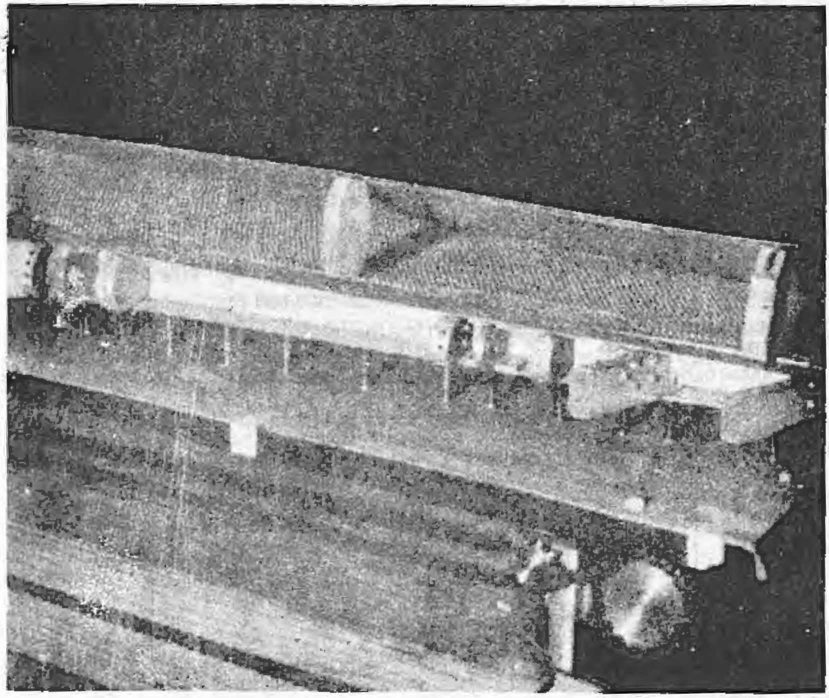


FIGURE 37. Honeycomb Cored Rudder Construction

cooling. If these conditions are met in the quenching bath, the corrosion resistance of the material will not be destroyed. It is advisable in the design of the quenching bath to provide for continuous running water and draining. These will aid in keeping the temperature of the bath low and will prevent the salting up of the bath caused by quenching material heat-treated in a salt bath.

Quenching may also be accomplished by the use of high-velocity and high-volume jets of cold water for thoroughly flushing the material. This method is particularly good for quenching massive objects in that it prevents the adherence of steam pockets.

When quenching in cold water will badly distort a finished part and it will not be subject to severe corrosion in service, it can be given a mild quench in oil or hot water, or quenched by water spray or air blast. This method should only be used for clad material and with the knowledge that the full physical properties will probably not be developed by the milder quench.

Forgings and castings are normally quenched by immersion in water at 150–212°F., unless their shape is such that cold water quenching will not cause cracking or excessive warpage.

Rivets must be quenched by dumping in cold water. Other small parts, such as spacers and washers, may be quenched in a tray or container designed to permit a free flow of quenching water.

Material heat-treated in salt baths must be rinsed after quenching to insure the removal of all the salt. Warm water is used for rinsing, but it must not exceed 150°F. The use of hot water for rinsing adversely affects corrosion resistance and accelerates aging of the material. This latter point is particularly important when it is desired to work and form material immediately after heat. In cases where severe forming must be done, it might be advisable to do it right after quenching, and rinse the material later. By this means it would be possible to work the material in the period before age-hardening sets in.

Precipitation heat treatment of aluminum alloys consists in heating the material for from 8 to 24 hours at a temperature around 300°F. In practice an oven heated by steam coils or an electric furnace is used for heating.

The heat treatments required to develop the full physical properties of various types of aluminum alloys used in aircraft construction are summarized in Table 7.

TABLE 7. Heat Treatment of Aluminum Alloys

Alloy	Solution heat treatment			Precipitation heat treatment		
	Temperature (°F.)	Quench	Temper	Temperature (°F.)	Aging time	Temper
2014	925–950	Cold water	2014-T4	345–355 355–365	8 hrs. 5 hrs.	2014-T6
2017	925–950	Cold water	—	Room	4 days	2014-T4
2024	910–930	Cold water	—	Room	4 days	2024-T4
2025	950–970	Cold water	2025-T4	335–345	8 hrs.	2025-T6
4032	940–970	Cold water	4032-T4	335–345	8 hrs.	4032-T6
6151	950–1010	Cold water	6152-T4	345–355	8 hrs.	6151-T6
6061	960–1010	Cold water	6061-T4	415–325 345–355	16 hrs. 8 hrs.	6161-T6 7075-T6
7075	860–880	Cold water	7075-T4	245–255*	24 hrs.	7075-T6
Alcad 7075	860–930	Cold water	Alclad 7075-T4	245–255*	24 hrs.	Alclad 7075-T6
Aclad 2014	925–950	Cold water	Alclad 2014-T4	310–330	18 hrs.	Alclad 2014-T6

*Other aging treatments known as interrupted and progressive aging treatments may be used. Interrupted aging consists of heating at 212°F. for 4 hours, cooling to room temperature, and then heating at 315°F. for 8 hours. Progressive aging consists of heating at 212°F. for 4 hours, increasing the temperature to 315°F., and holding it for 8 hours. Some of these treatments are patented.

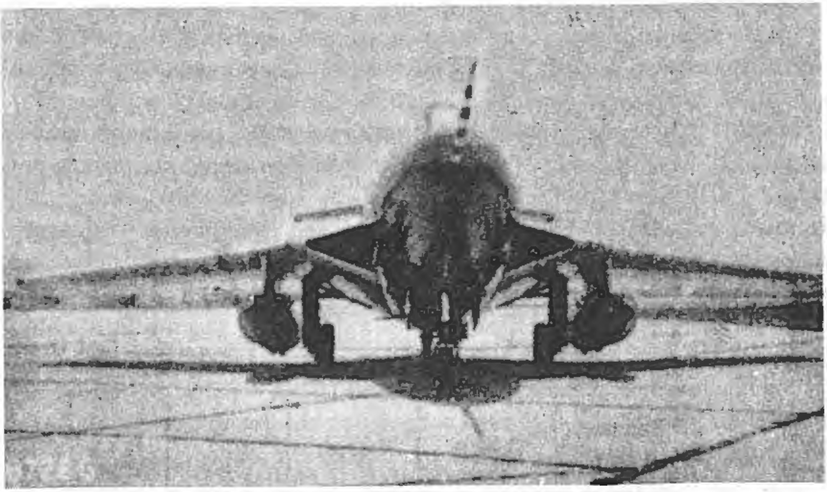


FIGURE 38. Fuel Tank—Droppable; 61SW Aluminum Alloy

Heat Treatment of Aluminum-Alloy Rivets. Rivets made from 2017 material are very commonly used in aircraft construction. These high-strength rivets may be identified by a small tit left on the head of the rivet. This identification is necessary to prevent substitution of weaker rivets made from 3003 material. From the strength viewpoint it is necessary that the 2017 rivets develop the full strength of the material in the 2017-T4 temper. It is difficult in diameters over 1/8 inch to drive a 2017-T4 rivet without cracking the head due to the hardness of the metal in this temper. But it has been found practical to heat-treat 2017 rivets and then drive them within one hour before they have age-hardened. Alloy 2024-T4 rivets age-harden within 20 minutes. It is necessary either to heat-treat small batches of rivets at frequent intervals to stay within the time limitation, or keep the rivets in an icebox to retard the aging. This latter method will keep the rivets soft for 48 hours and is very generally employed in the aircraft industry.

The actual heat-treatment operation for rivets is similar to that described above for structural material, but the technique employed is quite different because of the small size of rivets and the large quantities that must be treated. It is customary to use a steel tube (from 1 to 2 inches in diameter) with closed bottom and a loose fitting cap. A quantity of rivets is placed in this tube, the cap is placed on it, and the tube in immersed vertically in a salt bath. There it is held soaking at the heat-treating temperature for 40 minutes.

The top layer of rivets should be at least 4 inches below the surface of the salt bath and the cap should be tight enough to exclude the entrance of cold air. The cap must be removed while the tube is still submerged and the rivets poured into the quenching bath without delay. The rivets are poured into a wire basket in the quenching bath to facilitate their removal. No rinsing of the rivets is necessary since the steel tube container protects them from contact with the salt bath. As stated above, the heat-treated rivets must be used within one hour of quenching or placed in an icebox to retard aging. Rivets may be reheat-treated not more than 15 times.

In order to check the heat treatment and aging of the rivets, it is customary to check the hardness of a few rivets from each batch after they have aged for 24 hours. When subjected to a Rockwell test, using a 1/16-inch ball and a 60-kilogram load, the shank of the rivet must show the following minimum hardness:

Rivet diameter (inch)	*Rockwell hardness*
3/32	73
1/8	75
5/32	78
3/16	82
1/4	83

As explained in Chapter 2 under Hardness Testing, this test should not be considered too reliable.

Annealing. The heat-treatable alloys may be annealed to remove the strain-hardening effects of cold working or to soften heat-treated material that must be severely formed. Oftentimes the forming is too severe or will take too long to permit its being done within ½ hour after heat treatment, and in these cases the material must be annealed, formed, and then heat-treated. Annealing of heat-treatable alloys must be carried out with great care as regards the temperature and the rate of cooling. If the temperature is too high, the material will be partially heat-treated and will not attain its full softness. Under these conditions it is important to cool the material slowly to destroy as much of the heat-treating effect as possible.

To anneal material which was originally in the soft state and was strain-hardened by cold working, it is only necessary to heat it to a temperature of 640–670°F and cool it slowly in air. This operation would be necessary in a case where so much forming had to be done that the material would strain-harden and prevent further working before the job was done. This annealing treatment is satisfactory for all alloys except 7075, which can be strain-relieved by soaking it at 860–930°F from ½ to 2 hours and air cooling. Normally it is better to fully anneal 7075 as described in the last paragraph.

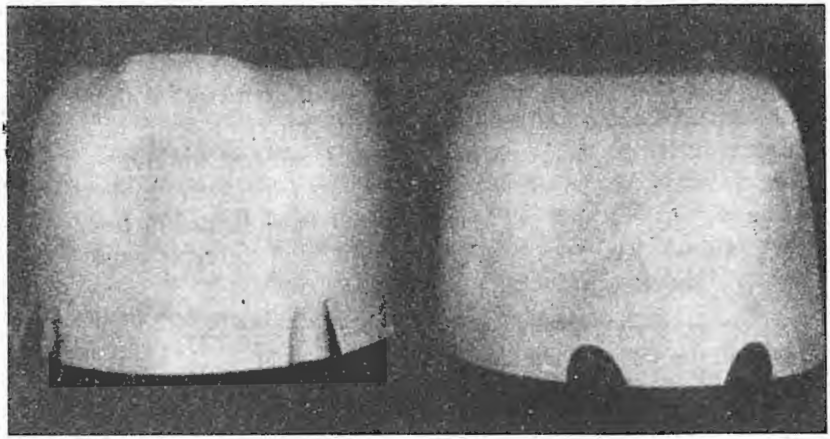


FIGURE 39. Engine Ring Cowl; Aluminum Alloy

To anneal material in the heat-treated temper when maximum softness is not required, the method described in the preceding paragraph may be used. This treatment will not remove all the effects of heat treatment, but it is usually satisfactory where only a moderate amount of forming is to be done.

To fully anneal heat-treated material and remove all effects of the prior heat treatment, the material must be heated to a temperature of 750–800°F. and soaked at this temperature for two hours. It must then be cooled at a slow rate (not exceeding 50°F. per hour) until it has reached 500°F., after which it may be air cooled. The rate of cooling is adjusted by leaving the material in the furnace and allowing the furnace to cool slowly. In the case of 7075 alloy the work must be held at 450°F. for at least one hour to stabilize it against age hardening, unless it will be formed within 5 hours after cooling. It is apparent that this method of annealing is costly due to the long soaking period and the tying-up of the furnace while the material is cooling. It is only necessary when severe forming is to be done. One such case is the flattening of the end of a tube. If the tube is flattened so that both faces touch each other and no radius exists at the flattened edges, it is likely that these edges will crack unless the tube has been given the full annealing treatment.

Heat-treatable alloys are never installed in the airplane in the annealed condition because of their poor corrosion resistance and strength in this condition. After forming they must always be heat-treated.

It is sometimes necessary to anneal strain-hardened alloys, such as 3003 and 5052 in order to complete forming operations. The method is described in the following section, Strain-Hardened Alloys.

STRAIN-HARDENED ALLOYS

The strain-hardened alloys which are commercially available are 1100, 3003, 5052 and 5056. All of these alloys are commonly used in aircraft construction, but they are not used for primary structural purposes because their strength is not as high as other available materials. However, they are readily bent, formed, and welded and, for these reasons, are used for tanks, cowling, and fairings. In tubular form these materials are used for electrical conduit and for fuel and oil lines.

Chemical Composition

	1100	*3003*	*5052*	*5056*
Aluminum (min.)	99.0%	97.0%	96.0%	remainder
Manganese		1.0–1.5		0.05–0.20
Magnesium			2.2–2.8	4.5–5.6
Chromium			0.15–0.35	0.05–0.20
Copper (max.)		0.2	0.07	0.10

Small amounts of impurities, particularly iron and silicon, are also present.

Table 8. Strain-Hardened Aluminum Alloys—Mechanical Properties

Alloy and temper	U.t.s. (p.s.i.)	Yield strength (p.s.i.)	[*] Elongation in 2 in. (%)	Brinell hardness (500 kg.-10 mm.)	Shearing strength (p.s.i.)	Fatigue[†] strength (p.s.i.)
1100-O	13,000	5,000	35	23	9,500	5,000
1100-H12	15,000	13,000	12	28	10,000	6,000
1100-H14	17,000	14,000	9	32	11,000	7,000
1100-H16	20,000	17,000	6	38	12,000	8,000
1100-H18	24,000	21,000	5	44	13,000	8,500
3003-O	16,000	6,000	30	28	11,000	7,000
3003-H12	18,000	15,000	10	35	12,000	8,000
3003-H14	21,000	18,000	8	40	14,000	9,000
3003-H16	25,000	21,000	5	47	15,000	9,500
3003-H18	29,000	25,000	4	55	16,000	10,000
5052-O	29,000	14,000	25	45	18,000	17,000
5052-H32	34,000	26,000	12	62	20,000	18,000
5052-H34	37,000	29,000	10	67	21,000	19,000
5052-H36	39,000	34,000	8	74	23,000	20,000
5052-H38	41,000	36,000	7	85	24,000	20,500
5056					24,000[‡]	

[*] Elongation values are for 1/16 inch sheet. Thinner sheets have less elongation.

[†] Based on 500,000,000 cycles of reversed stress, using R.R. Moore type of machine and specimen.

[‡] Cold-worked rivet stock.

Commercially pure aluminum 1100 has up to 1% of these impurities.

PHYSICAL PROPERTIES

	1100	*3003*	*5052*
Density (lb./cu. in.)	.098	099	096
Elect. conductivity (% of copper)	58	41	40
Modulus of elasticity	10,300,000 p.s.i.		

It will be noted from Table 8 that the tensile strength, yield strength, and fatigue strength increase with the temper or hardness of the material. There is also a distinct gradation of strength between the three materials. In selecting a material it is usually preferable to choose one that will give the required strength in the softest temper. Thus the material that can be most easily worked is obtained.

Annealing. The strain-hardened alloys cannot be heat-treated to improve their properties. Higher strengths are obtainable only by cold working. In fabrication or forming, these materials will harden too much if worked severely, and it is then necessary to soften them before further working. They can be softened by a simple annealing treatment which consists in heating the material to permit recrystallization. Softening due to recrystallization is practically instantaneous if the material is heated to a high enough temperature. For 1100 and 5052 material this temperature is 650°F., while for 3003 material it is 750°F. The metal should not be heated too much above this temperature. Annealing may also be done by heating the metal for a longer period of time at a lower temperature. In either case the rate of cooling is not important, provided it is not so rapid as to cause warpage.

It is common shop practice to anneal strain-hardened alloys locally when they become too hard by playing a welding torch on the part to bring it up to heat and then allowing it to cool. Care must be taken not to overheat or burn the metal.

Working Properties. When the proper temper is selected, all the strain-hardened alloys can be satisfactorily worked to the desired form for their aircraft use. The easiest to form by drawing, spinning, or stamping is 1100 material. Only slightly more difficult to form is 3003 material, and it has better physical properties. For this reason it has superseded 1100 material almost entirely in aircraft work. For spinning ring cowls 3003-O or 5052–O material is used. The material strain-hardens during the spinning and becomes equivalent to about 3003-H14 or 5052-H34 temper. Alloy 5052-H32 is generally used for engine cowling because of its ease of forming and greater tensile and fatigue strength. Wherever its forming properties are satisfactory for the purpose 5052 is rapidly displacing the other strain-hardened alloys. The high fatigue strength of this material is particularly important in reducing

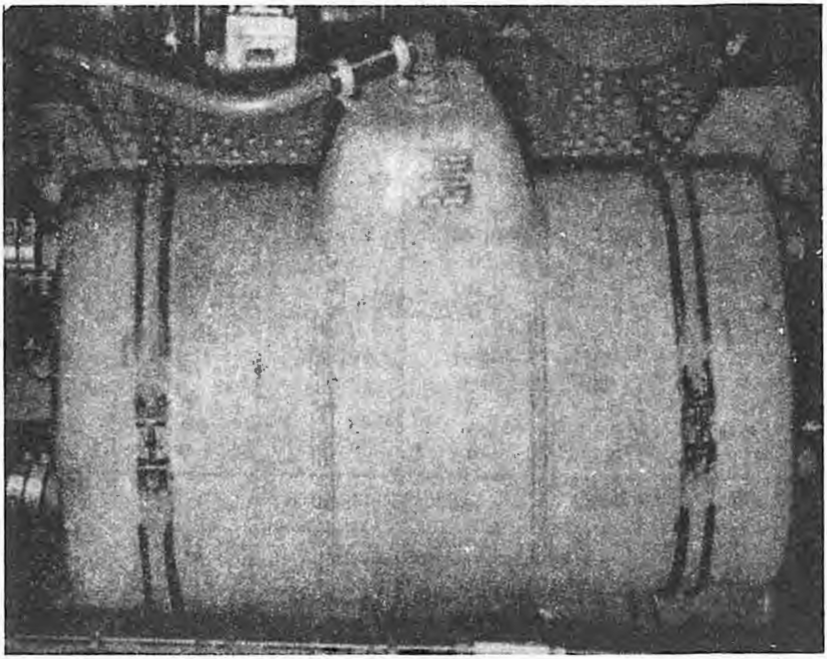


FIGURE 40. Oil Tank; 3S-H14 Aluminum Alloy

cowling cracks.

The following table gives the bending qualities of the strain-hardened alloys. These bend radii will vary somewhat with the tools used, the particular operation, and the technique employed.

It is difficult to predict in advance just which material and temper will work best in a new application. It is recommended that several possible samples be obtained and worked under the actual shop conditions before a final selection is made. It must be borne in mind that it is always difficult for a sheet-metal worker to get the most out of a new, unfamiliar material.

Welding. The strain-hardened alloys are normally joined by gas welding in aircraft work. Electric-arc welding is faster and causes less distortion, but the material must be at least 1/16 inch thick. This type welding is seldom used in aircraft constrction. Welding is done by either the oxyacetylene or the oxyhydrogen flame. Skilled aircraft welders can successfully weld 0.020 inch aluminum alloy with an oxyacetylene flame.

Most of the welding on strain-hardened aluminum alloys is done in the fabrication of fuel and oil tanks. These tanks are often subjected to a 15-hour vibration test after fabrication, to check the design, the welds, and the quality

APPROXIMATE RADII FOR 90° COLD BEND

Alloy	Approximate thickness (= *t*)				
	0.016 in.	0.032 in.	0.064 in.	0.128 in.	0.189 in.
1100-O	0	0	0	0	0
1100-H12	0	0	0	0	0–1*t*
1100-H14	0	0	0	0	0–1*t*
1100-H16	0	0	0–1*t*	½*t*–1½*t*	1*t*–2*t*
1100-H18	0–1*t*	½*t*–1½*t*	1*t*–2*t*	1½*t*–3*t*	2*t*-4*t*
3003-O	0	0	0	0	0
3003-H12	0	0	0	0	0-1*t*
3003-H14	0	0	0	0–1*t*	0–1*t*
3003-H16	0–1*t*	0–1*t*	½*t*–1½*t*	1*t*–2*t*	1½*t*–3*t*
3003-H18	½*t*–1½*t*	1*t*–2*t*	1½*t*–3*t*	2*t*–4*t*	3*t*–5*t*
5052-O	0	0	0	0	0
5052-H32	0	0	0	0-1*t*	0-1*t*
5052-H34	0	0	0–1*t*	½*t*–1½*t*	1*t*–2*t*
5052-H36	0–1*t*	½*t*–1½*t*	1*t*–2*t*	1½*t*–3*t*	2*t*–4*t*
5052-H38	½*t*–1½*t*	1t–2*t*	1½*t*–3*t*	2*t*–3*t*	3*t*–5*t*

of the material. Leaks caused by failure of welds or cracked material are cause for rejection. Seams to be welded are not butted directly together but are flanged slightly, the faces of the flanges butted together, and then the entire flange burnt down to the level of the sheet proper in the welding operation. By this method a continuous, sound, thorough weld is obtained.

A welding rod of pure aluminum, or of the same composition as the metal being welded, may be used. In aircraft welding a rod containing about 95% aluminum and 5% silicon is found to be best. Due to the formation of an oxide film on the surface, it is necessary to use a flux in welding aluminum alloys. It is sometimes necessary to weld two or more of the strain-hardened alloys together. This can be done satisfactorily if the 5% silicon welding rod is used.

After welding, the material on either side of the weld is in the annealed condition and the weld itself is a cast structure. The strength in the region of the weld is the same as the material in the soft temper. Unless welds are ground down, they will develop greater strength than the adjoining metal. Welds can be hammered to flatten them without reducing their strength. In fact, the working should improve it somewhat.

Corrosion. Aluminum 1100 is highly resistant to atmospheric corrosion. The addition of various elements to aluminum to form alloys changes the corrosion resistance characteristics.

Alloy 3003 is somewhat inferior to 1100 material in resisting atmospheric corrosion. Material 5052 will resist salt-water corrosion even better than 1100. It will retain its mechanical properties better, as well as its surface appearance. Aluminum-alloy rivets (5056) contain 5% magnesium and no copper and have practically no corrosive action on magnesium alloys.

In aircraft work it is considered good practice to protect all aluminum alloy with paints. It is essential that the material be given a surface treatment first. This treatment forms an oxide on the surface, which aids in protecting the surface, and also provides an excellent base for the paint. Painting usually consists of one coat of a good primer, followed by two coats of lacquer or enamel.

When tanks are fabricated by welding it is essential to remove all traces of the flux, which is corrosive towards aluminum alloys. This flux should be removed as soon as possible after completion of the welding. It may be removed by immersing the work in a tank containing a warm 5% solution of sulfuric acid, followed by a thorough rinsing in clear, warm water, and then drying. All accessible welds should be scrubbed with a stiff bristle brush before or during the water rinse. In the case of tanks, the rinsing water should be agitated in order to clean the interior welds that are not accessible for scrubbing.

Available Shapes. From time to time as the demand arises, the aluminum alloys are made available in new forms. At present it is possible to obtain the strain-hardened aluminum alloys in the forms listed below.

Standard Shapes—Strain-Hardened Alloys

Shape	*1100*	*3003*	*5052*	*5056*
Sheet	*	*	*	
Plate	*	*	*	
Rod and bar	*	*	*	
Wire	*	*	*	*
Extrusions		*		
Tubing		*	*	
Rivets	*			*

Sheet is 0.250 inch or less in thickness; plate is over 0.250 inch. Sheet can only be obtained up to 0.162 inch thick in the ¾ H temper and up to 0.128 inch thick in the full H temper.

Bar stock is similar to plate, but is obtainable only up to 10 inches in width.

Cold-finished rod is obtainable from 3/8 to 1½ inches in diameter. Rolled rod is obtainable up to 8 inches in diameter.

Wire can be obtained drawn anywhere from 36 gage up to 3/8 inch diameter. On special order, wire finer than 36 gage is obtainable.

Tubing can be obtained in practically all diameters and wall thicknesses.

Uses. As stated previously, strain-hardened alloys are commonly used in aircraft construction for cowling, fairings, tanks, electrical conduits, and fuel and oil lines. No one alloy excels the others for all purposes, but must be considered in connection with the particular application. The following alloys and tempers have been successfully used for the purposes described.

3003-H14 for welded fuel tanks, and for general engine cowling.

5052-O and 5052-H34 for cowling and fairings subject to severe vibration in service including ring cowl spinnings.

1100-H14 tubing for electrical conduit.

5052-O tubing for fuel and oil lines.

3003-O for ring cowls and other parts that are formed by spinning.

5056-H32 rivets are used almost exclusively in magnesium-alloy assemblies.

HEAT-TREATABLE ALLOYS

The heat-treatable aluminum alloys are used for aircraft structural purposes because of their relatively high strength and light weight. They are available in many structural forms and can be worked with production tools. The alloys commonly used in the manufacture of aircraft are 2014, Alclad 2014, 2017, 2024, 6061 and 7075. All of these are available in clad forms except 6061 which is very corrosion resistant without cladding.

Until recently 2017 and 2024 in both the bare and clad forms were used

TABLE 9. Heat-treatable Aluminum[*] Alloys—Chemical Composition (%)[†]

Alloy designation	Manganese	Magnesium	Chromium	Copper	Silicon	Zinc
2014	0.4–1.2	0.2–0.8	0.25	3.9–5.0	0.5–1.2	0.25
2014 (cladding)	0.75	0.8–1.5	0.35	0.10	0.35–1.0	0.20
2017	0.4–1.0	0.2–0.75		3.5–4.5		
2117		0.3		2.5		
2024	0.3–0.9	1.25–1.75		3.6–4.7		
2024 (cladding)	0.05			0.1		0.1
2025	0.4–1.2	0.02		3.9–5.0	0.5–1.2	
4032	0.2	0.8–1.3	0.10	0.5–1.3	11.5–13.5	0.25
6151	0.2	0.45–0.8	0.15–0.35	0.3	0.6–1.2	
6061		0.8–1.2	0.35		0.4–0.8	
7075	0.10–0.30	2.1–2.9	0.15–0.40	1.2–2.0	0.5	5.1–6.1
7075 (cladding)	0.10	0.10		0.10	0.7	0.75–1.25
Alclad 2014 (cladding) (Reynolds)	0.75	0.8–1.5	0.35	0.10	0.35–1.0	0.20

[*] Aluminum is remainder. Small amounts of iron and other impurities are also present.

[†] Element percentage is maximum except where indicated as a range.

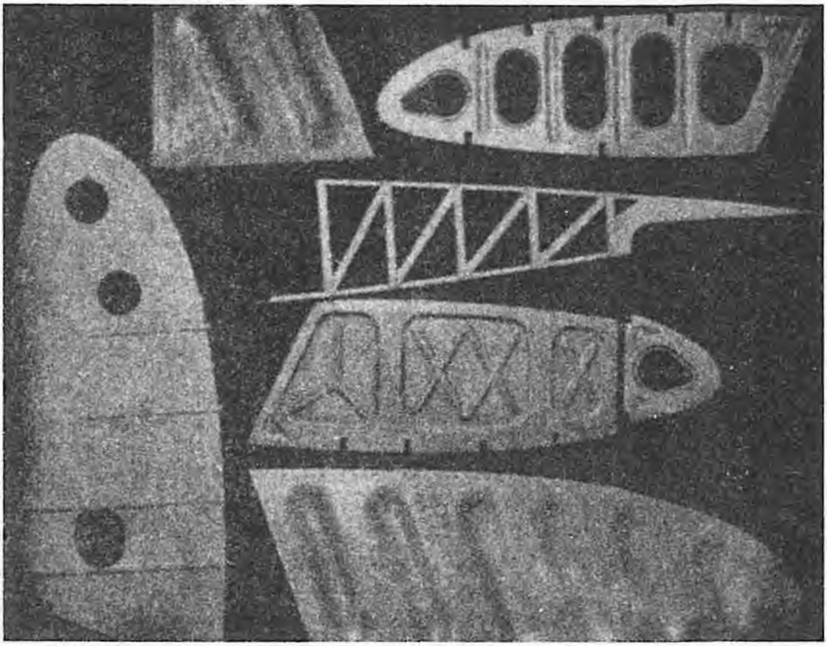


FIGURE 41. Wing Ribs

almost exclusively. The development of high-strength alloys, such as 2024 and 7075, and their commercial availability in standard forms have resulted in their widespread adoption in new designs. Alloy 7075 is available as clad or bare sheet, and in many other forms in the bare. It is the strongest of the aluminum alloys. Material 6061 has recently been quite generally adopted for severely formed parts which do not require extremely high strength such as cowling.

Chemical Composition. Table 9 gives the chemical composition of the heat-treatable aluminum alloys used in aircraft construction.

Physical Properties

Weight (lb./cu.in.) = 0.101
Modulus of elasticity = 10,3000,000 p.s.i.

Table 10 lists the mechanical properties of the heat-treatable alloys used in aircraft construction. It is recommended that this table be used only for reference purposes; ANC-5, Army-Navy specification, or the manufacturer of the material be consulted when a design must be based on the allowable

TABLE 10. Heat-treatable Aluminum Alloys—Mechanical Properties

Alloy and temper	Form and thickness of material	U.t.s. (p.s.i.)	Yield strength (p.s.i.)	Elongation in 2" (%)	Brinell hardness (500 kg–10 min.)	Shear strength (p.s.i.)	Fatigue strength (p.s.i.)
2014-O	Extrusion—1/8" and over	30,000*	18,000*	12			
2014-T4	Extrusion—1/8" and over	50,000	32,000	12			
2014-T6	Extrusion—1/8" and over	60,000	53,000	7			
Alclad 2014-T6	Forging	65,000	55,000	10	125	39,000	12,000
2014-O	Sheet	30,000*	14,000*	16			
Alclad 2014-T3	Sheet—0.039" & under	55,000	35,000	14		38,000	
Alclad 2014-T3	Sheet—0.040" & over	57,000	36,000	15		38,000	
Alclad 2014-T3	Same—reheat-treated	55,000	34,000	15		38,000	
Alclad 2014-T6	Sheet—0.039" & under	63,000	55,000	7		40,000	12,500
Alclad 2014-T6	Sheet—0.040" & over	64,000	57,000	8		40,000	12,500
2017-O	Bar	35,000*		16			
2017-T4	Bar	55,000	32,000	16	87	30,000	15,000
2017-T4	Rivet					30,000	
2017-T4	Rivet					25,000	
2117-T4	Bar—up to 5.5"	62,000	40,000	14	100	37,000	14,000
2024-T4	Extrusion—as received	57,000	42,000	12	96	34,000	14,000
2024-T4	Extrusion—reheat-treated	57,000	38,000				
2024-T4	Rivet					35,000	
2024-O	Bare sheet	32,000*	14,000*	12			
2024-T4	Bare sheet	62,000	40,000	15	100	37,000	14,000
Alclad 2024-T4	Sheet	58,000	37,000	15		34,000	
2024-T36	Bare sheet	69,000	52,000	11	110	39,000	
Alclad 2024-T36	Clad sheet	62,000	48,000	9		35,000	
2024-T3	Tubing—as received	64,000	42,000	12	100	37,000	14,000
2024-T4	Tubing—reheat-treated	64,000	40,000		100	37,000	14,000

Alclad 2024-T81	Sheet—0.063" & under	62,000	54,000	5			
Alclad 2024-T81	Sheet—0.064" & over	65,000	56,000	5			
Alclad 2024-T86	Sheer—0.063" & under	66,000	62,000	3			
Alclad 2024-T86	Sheet—0.064" & over	70,000	66,000	3			
2025-T6	Forging	55,000	30,000	16	90	35,000	12,000
4032-T6	Forging	52,000	40,000	5	115	38,000	
6151-T6	Forging	44,000	34,000	12	90	32,000	
6061-T6	Bar	42,000	35,000	10			
6061-T6	Extrusions	38,000	35,000	10			
6061-O	Sheet or tubing	22,000*	12,000*	16			
6061-T4	Sheet or tubing	30,000	16,000	16			
6061-T6	Sheet or tubing	42,000	35,000	10			
7075-O	Extrusions	40,000	24,000	6			
7075-T6	Extrusions	78,000	70,000	6		46,000	22,500
7075-T6	Forgings	75,000	64,000	10	135		
7075-O	Bare sheet	40,000*	21,000*	10			
Alclad 7075-O	Sheet	36,000*	20,000*	10			
7075-T6	Bare sheet—0.039" & under	76,000	65,000	7		46,000	22,500
7075-T6	Bare sheet—0.040" & over	77,000	66,000	8		46,000	22,500
Alclad 7075-T6	Sheet—0.039" & under	70,000	60,000	7		44,000	13,000
Alclad 7075-T6	Sheet—0.040" & over	72,000	62,000	8		44,000	13,000
7075-O	Tubing	40,000*	24,000*	10			
7075-T6	Tubing	78,000	70,000	10			
Alclad 2014 (Reynolds)	Clad Sheet	(Identical with 2014 sheet in physical properties and chemical composition)					

*All values for annealed material are maximum permissible.

strength. Manufacturers of materials will always furnish a minimum guaranteed strength for material in the form that is to be used.

Alclad 2024 is normally aged at room temperature. It has been found, however, that an artificial aging treatment at 365–380°F. for approximately 6½ hours will greatly improve the mechanical properties. When given this treatment the material is identified as Alclad 2024-T8 alloy. A second numeral is added after the 8 to indicate the percentage of cold work imposed on the material prior to the artificial aging treatment.

There are two commonly used tempers of this alloy, as follows:

Alclad 2024-T81. This temper is solution heat-treated, is straightened at the mill by stretching (cold working), and is artificially aged either at the mill or by the aircraft manufacturer. This temper is used for parts requiring moderate formability.

Alclad 2024-T86. This temper results from artificially aging Alclad 2024-T36 sheet or plate. It is used for wing skins and in similar locations requiring no forming.

Artificial aging is applicable to extruded 2024 as well as to clad sheet stock but the corrosion resistance is slightly reduced. Alclad 2024-T8 tempers have better corrosion resistance than bare 2024-T4 material aged at room temperature.

Heat Treatment. As the name implies, the heat-treatable alloys can be heat-treated to improve their physical properties. In aircraft work they are used only in the heat-treated state. As explained earlier in this chapter, the material is sometimes annealed to improve its forming qualities, but it is always heat-treated after forming.

The structure of many airplanes built nowadays consists of both Alclad 2014 and Alclad 2024 material. In heat-treating these materials it is advisable that they be done separately since their heat-treating temperatures are different. The temperature for 2014 material is 930–950°F., for 2024 material it is 910–930°F. If 2024 material is treated above 930°F., there is a possibility of surface blisters from overheating and also of extensive damage due to eutectic melting. The fabricating shop should definitely identify the type of aluminum alloy when it is sent to the heat-treating shop so that no errors are made.

Working Properties. Heat-treatable alloys are in general more difficult to fabricate into aircraft parts than the commonly used tempers of the strain-hardened alloys. They have much greater strength, however, and consequently are used where the best strength/weight ratio is required. Heat-treatable alloys are used for all primary structural members of aircraft.

New and stronger aluminum alloys are introduced into the commercial market every few years. They do not gain general acceptance as an aircraft structural material, however, until production fabrication techniques have been developed. The strongest material would be of no use if it could not be fabricated into useful shapes by production methods. Fortunately, there have been a succession of heat-treatable aluminum alloys over the past 20 years, each of which has had an improved strength/weight ratio and for which fabrication methods have been developed. Chronologically, these alloys have been 2017, 2024, 2014, and 7075. Fabrication methods are still being developed for 7075 aluminum alloy since it is the newest and most difficult to form of all these alloys.

In general, heat-treatable alloys are formed in the "O" or "-T4" condition before they have developed their full strength. They are subsequently heat-treated or aged to the maximum strength "-T6" condition before installation in the airplane. By this combination of processes, the advantage of forming in a soft condition is obtained without sacrificing the maximum obtainable strength/weight ratio.

Heat-treatable alloy 2024 either in standard or Alclad form is commonly used in aircraft construction. 2024 is slightly more difficult to form than 2017 (which was the standard aircraft structural material until recent years), but has superseded 2017 because of its higher yield point.

These alloys can be formed to any structural shape used in aircraft construction, or they can be bent, drawn, or rolled as necessary, provided the proper temper is selected. For severe forming operations requiring over 20 minutes for completion, it is necessary to use the material in the "O" temper. If the forming operation can be completed quickly, it is customary to heat-treat the work and form it within one hour before it has aged. The first 20 minutes of this hour is by far the best time to form the material. By this method heat treatment of the completed work is avoided. When work has been formed in the anneled state and heat-treated, it will distort badly. It must be straightened out before it can be used. The distortion is caused by the severe cold-water quench. Sheet alloy 2014-O (Alclad-O) can be formed in the same manner as 2024-O sheet. Difficult forming operations—stretching, deep drawing, etc. can be done, but the subsequent cold-water quench will distort the work and necessitate straightening. Freshly quenched 2014 or Alclad 2014 material has only slightly less formability than the annealed material. It can be stretched or drawn but must be worked within 1½ hours of quenching. In the "as received"-T3 condition, moderate forming can be done. The use of male and female steel dies is advisable in pressing material in this condition. Material 2014-T6 requires large radii for forming but dimples satisfactorily. When necessary to improve its formability in this temper, it can be heated to 350°F. for as long as 30 minutes without materially affecting its properties.

Material 7075-O, either bare or clad, can be stretched or rubber-formed in

FIGURE 42. Wing-tip Float and Bracing: Aluminum-alloy Sheet and Tubing

the hydraulic press but requires high pressures. It can be dimpled satisfactorily but distorts on quenching. Severe double-curvature forming is sometimes done partially in the "O" condition and finished in the freshly quenched -T4 condition. In this condition the material forms about as well as freshly quenched 2024. It should be worked within one hour of quenching but can be dimpled satisfactorily (using 2024-T4 tools) for several days after quenching. Due to its high yield strength 7075-T6 has very poor forming characteristics and is inferior to 2024-T4. It has a high notch sensitivity and deep scratches must be avoided. Cold dimpling of 7075-T6 has had only limited success on an experimental basis. Hot dimpling has been successful. In this method an electronic timer is used to apply dimpling pressure immediately after the area is heated electrically. Hot forming at temperatures up to 325°F. with less than 5% loss in strength and very little effect on elongation is practicable. Use of electrically heated forming dies, and heating the work and quickly forming it before the heat dissipates, have both been successfully used.

6061 in all its tempers has excellent formability. It is frequently purchased, formed, and used in the 6061-T4 condition. When this is done no heat treatment is involved.

The table below lists the bend radii for various thickneses and tempers of the heat-treatable alloys. The bend radii are a good criterion of the relative forming properties.

The heat-treatable alloys machine beautifully.

Welding. The heat-treatable alloys cannot be welded with the oxyacetylene

Approximate Radii for 90° Cold Bend

Alloy	Approximate thickness (=t)				
	0.016 in.	0.032 in.	0.064 in.	0.128 in.	0.189 in.
Alclad 2014-O 2014-T4	0	0	0	½t	½t
(Alclad 2014-T4)	1½t	2t	2½t	3t	3t
2014-T6 (Alclad 2014-T6)	2t	2t	3t	4t	4t
2024-O	0	0	0	0	0–1t
2024-T4	1½t–3t	2t–4t	3t–5t	4t–6t	4t–6t
2024-T36	2t–4	3t–5t	3t–5t	4t–6t	5t–7t
6061-O	0	0	0	0	0–1t
6061-T4	0–1t	0–1t	½t–1½t	1t–2t	1½t–3t
6061-T6	0–1t	½t–1½t	1t–2t	1½t–3t	2t–4t
Alclad 7075-T6	0	0	0–1t	½t-1½t	2t
Alclad 7075-T4	½t	½t–1t	1t–1½t	1½t–2t	2t
Alclad 7075-T6	3t	3½t	3½t–4t	4½t–5t	5t

Alclad 2024 can be bent over slightly smaller radii than the corresponding temper of the standard alloy.

Radii given for 2024-T4 are for the fully aged condition. Much smaller radii can be used if formed immediately after quenching.

Alclad 2014-T3 radii are for material as received. When such material is freshly quenched the values for 2014-O can be used.

Alclad 7075-T4 radii are for freshly quenched material. It is unstable in this condition and cannot be purchased.

torch without destroying their mechanical properties. Even if subsequently heat-treated after welding, the original mechanical properties cannot be restored. These alloys are difficult to weld in any event and are generally considered unweldable for aircraft purposes. 6061 is an exception; it welds readily with a silicon rod (4043) and is welded into ducts and cowling.

Prior to the introduction of electric spot welding these alloys were joined only by riveting or bolting. As described earlier in this chapter, electric spot welding is rapidly displacing riveting for nonstructural parts and is being extended to structural parts.

Riveting. Aluminum alloy rivets for structural parts may be grouped into two classifications: those requiring heat treatment just before driving, and those that can be driven as received. Heat treatment is required by 2017 and 2024 rivets, whereas 2117-T4 rivets can be driven as received.

On extremely important work where every pound of rivet strength is necessary 2017 and 2024 rivets are used. Because of their better heading qualities 2017 rivets are used more often even in 2024 structural assemblies. While 2017 rivets can be driven within one hour of heat treatment, 2024 rivets must be driven within 20 minutes of treatment. Aging of both these

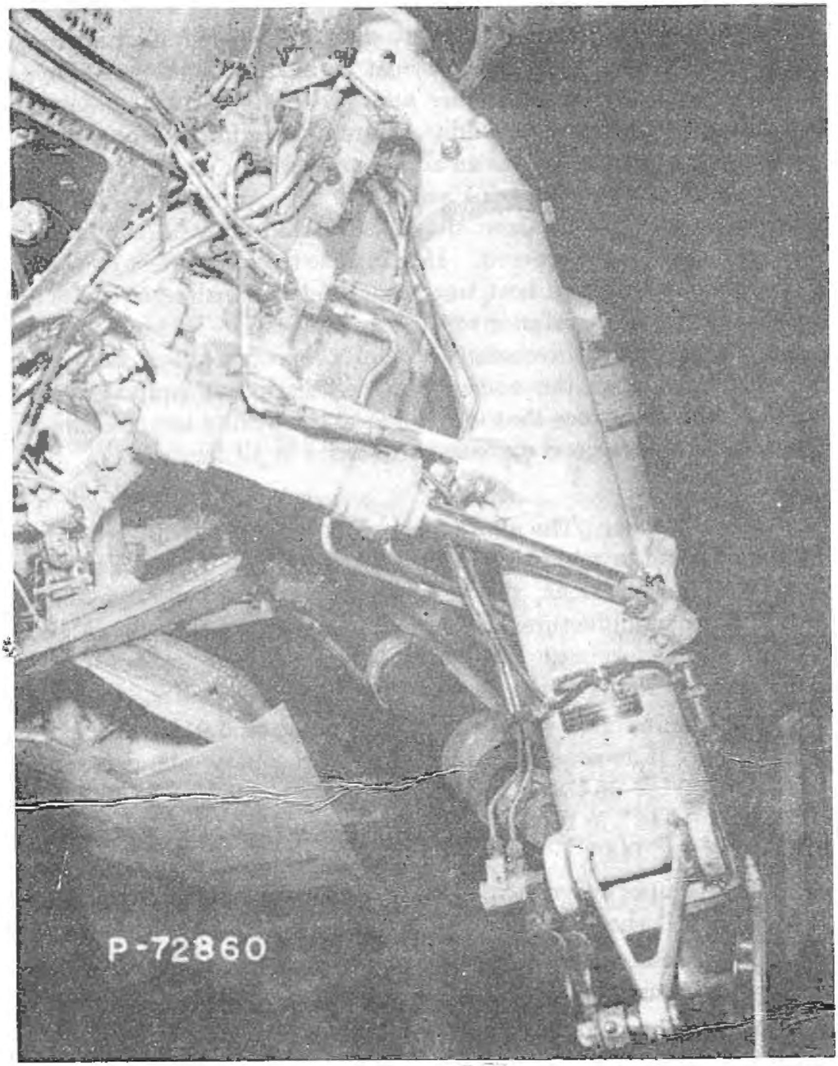


FIGURE 43. Retractable Landing Gear; 2014-T6 Aluminum-alloy Forging

types of rivets can be retarded by storing in an icebox. The 2017 rivets are identified by a small raised tit in the center of the head; 2014 rivets have two small radial dashes at the ends of a diameter on the periphery of the head.

The 2117-T4 rivets do not have as good strength as 2017 or 2024 rivets, but are very generally used even in structural assemblies, as metal-covered wings and fuselages. They are particularly good for field repairs since no heat treatment is necessary. The 2017-T4 rivets have a small dimple at the center of the head.

The strength properties (in pounds per square inch) of these rivets are as follows:

	2017-T4	*2024-T4*	*2117-T4*
U.t.s.	55,000	62,000	38,000
Yield strength	30,000	40,000	18,000
Shear strength	30,000	35,000	25,000
Bearing strength	75,000	90,000	60,000

Corrosion. Clad material should be used whenever severe corrosion conditions must be met in service. 6061 material has excellent corrosion resistance being comparable to pure aluminum, but its mechanical properties are not as high as those of the other heat-treatable alloys. Consequently, it is not practical to use 6061 if great strength is a primary requisite. The other heat-treatable alloys have about equal corrosion resistance, except 2025 which is somewhat inferior. Alclad 2014-T6 has less corrosion resistance than Alclad 2024-T4. The heat-treatable alloys do not have nearly such good corrosion resistance as the strain-hardened alloys.

It is standard practice in aircraft designed to operate under severe corrosive conditions to anodically treat or alodize aluminum alloys and then to apply one coat of primer and two coats of paint. Joints and fittings subject to corrosive conditions are often additionally coated with hot beeswax or paralketone as an added protection.

Alloys 2017-T4 and 2024-T4 are much more corrosion resistant than 2017-O and 2024-O. If these alloys are heated above 375°F. their corrosion resistance is also lowered. Heating has the same effect on the alloys that require precipitation heat treatment, and for this reason these alloys in the -T6 temper are inferior to the same alloys in -T4 temper. Baked enamel finishes are not recommended for aluminum alloys, because it is questionable whether the added paint protection is equivalent to the basic corrosion resistance that is lost due to the baking temperature.

Material 6061 has good corrosion resistance in all tempers.

Available Shapes. The alloys most often used in aircraft construction may be obtained in practically all standard forms. As explained in the paragraph on Extrusions, the designer may even specify the shape he wants and the manufacturer will supply it. Some of the other alloys are available only as forgings. The table below summarizes the standard commercial forms of the heat-treatable alloys.

STANDARD SHAPES—HEAT-TREATABLE ALLOYS

Shape	2014	Alclad 2014	2017	2117	2024	Alclad 2024	2025
Sheet		*			*	*	
Plate		*			*	*	
Rod and bar	*		*		*		
Wire			*		*		
Extrusions	*				*		
Tubing					*		
Rivets			*	*	*		
Forgings	*						*
Rolled shapes							

Shape	4032	6151	6061	7075	Alclad 7075	Alclad 2014
Sheet			*	*	*	*
Plate			*	*	*	*
Rod and bar			*	*		
Wire			*	*		
Extrusions			*	*		
Tubing			*			
Rivets			*			
Forgings	*	*		*		
Rolled shapes			*			

2014 extrusions are available only with section thickness of 1/8 inch and greater.

Sheet used in aircraft work usually falls between 0.014 and 0.120 inch in thickness. It is usually purchased in seven basic standard sizes as follows: 0.020" X 36" X 144", 0.025" X 36" X 144", 0.032" X 36" X 144", 0.032" X 48" X 144", 0.040" X 48" X 144", 0.051" X 48" X 144", 0.064" X 48" X 144".

Annealed-temper coiled strip is available at a considerable price saving compared to flat sheet.

Plate is purchased in much smaller pieces, usually 1 X 2 feet, since it is used for fabricating small fittings.

Rod can be obtained up to 8 inches diameter.

Bar can be rolled to a maximum cross-sectional size of 3 X 10 inches. Bar 10 inches wide is often used in place of plate for fittings.

Tubing is available in many round and streamline sizes. A table of standard tubing sizes used in aircraft construction is given in the Appendix.

Square tubing is also available and is often used.

Uses. The heat-treatable alloys are used for practically all structural purposes in aircraft. They are used only in the heat-treated temper but they are often formed in the annealed temper and then heat-treated.

2014 extrusions and forgings are used for primary structure requiring high strength.

Alclad 2014 sheet is used for structural sheet-metal parts, including wing and fuselage skins. 2014-T4 material is required for formed and double-curvature parts and skins, and may or may not be aged to 2014-T6—depending on the strength required.

Alloy 2017-T4 was the standard aircraft structural material up until about

TABLE 11. Aluminum-Alloy Specifications—Wrought

Alloy designation	Form	AN Aero specification	Federal specification
11	Bar		QQ-A11
	Sheet		QQ-A-561
3003	Sheet		QQ-A-359
	Tubing		WW-T-788
2014	Bar		QQ-A-266
	Extrusions		QQ-A-261,
	Forgings		QQ-A-367-C1.5
Alclad 2014	Sheet		QQ-A-255
2017	Bar		QQ-A-351
2117	Rivets	AN-R-19	
2024	Bar		QQ-A-267
	Sheet	AN-A-12	QQ-A-355
	Tubing		WW-T-785
Alclad 2024	Sheet	AN-A-13	QQ-A-362
2025	Forgings		QQ-A-3676C1.2
4032	Forgings		QQ-A-3676C1.6
6151	Forgings		QQ-A-367-CI.3
5052	Sheet		QQ-A-318
	Tubing		QWW-T-787
5056	Rivets	MIL-R-5674	
6061	Extrusions		QQ-A-325
	Sheet		QQ-A-327
	Tubing		WW-T-789
7075	Extrusions	AN-A-11	QQ-A-277
	Forgings		QQ-A-3676C1.10
	Sheet	AN-A-9	QQ-A-283
Alclad	Sheet	AN-A-10	QQ-A-287

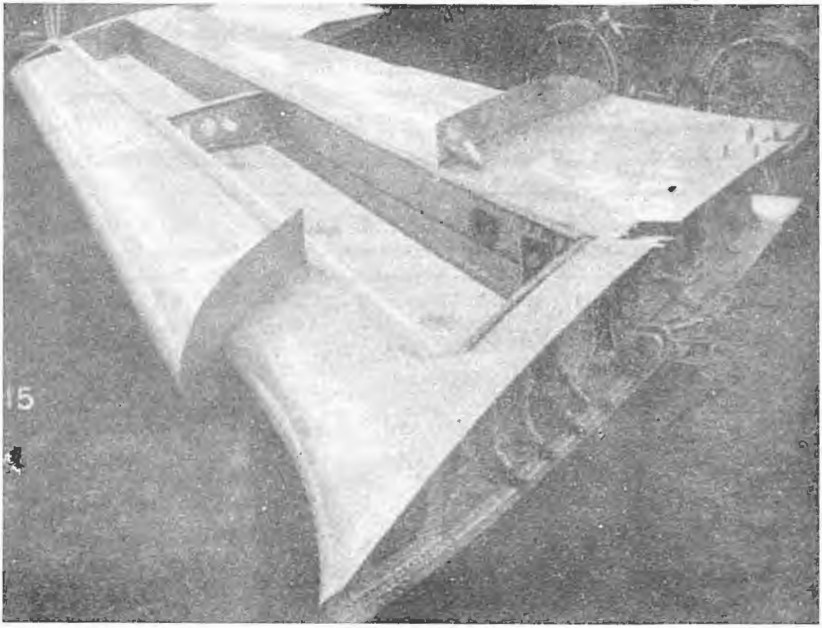


FIGURE 44. Jet-fighter Wing Showing Fuel Cell Cavity

ten years ago but is no longer produced in sheet, plate, or tubing forms. Rivets 2017 are still commonly used.

Alloy 2117-T4 rivets are frequently used to avoid the necessity for heat treatment. They are particularly useful in field repairs.

Alloy 2024–T4 has completely replaced 2017-T4 as the standard aircraft structural material but it is currently being displaced by 2014 and 7075 which have still higher physical properties. Alclad 2024 is frequently used when corrosion is important, as in covering seaplane floats and hulls.

Alclad 2014-T6 has satisfactory corrosion resistance for this application also.

2025-T6 forgings are used for propeller blades and engine parts.

4032-T6 forgings are used for aircraft-engine pistons and parts requiring good strength and hardness at elevated temperatures.

6151-T6 forgings are used for complicated engine parts and for aircraft fittings, where the mechanical properties of this alloy are adequate for the purpose.

Alloy 6061 is a relatively new material with good strength and excellent forming characteristics. It is rapidly finding favor for stamped and pressed sheet-metal parts. It should be fabricated in the -T6 condition wherever possible, to avoid the necessity for artificially aging the material from the -T4 temper. 6061-T4 is frequently used for cowling panels.

Material 7075 is the strongest aluminum alloy. It is ideal for wing-beam cap strips, fittings, and sheet parts not requiring much forming.

7079-T6

This aluminum forging alloy is a new material which should find wide use in the airframe industry. This alloy was produced in order to supply the industry with a die forging material which exhibits excellent cross-grained ductility, and has the ability to through-harden to thicknesses up to 6 inches. When alloys such as 2014 and 7075 are specified for large structural fittings it is often necessary to partially machine the fittings, then heat-treat to the T6 condition and then final-machine. This procedure is time consuming, expensive, and necessary since 7075- and 2014 do not have good through-hardening characteristics (4 in. maximum for 2014-T6 and 3 in. maximum for 7075-T6).

The chemistry of 7079 aluminum alloy is:

Element	*Percent*	*Element*	*Percent*
Zinc	3.8–4.8	Silicon	0.30 max.
Magnesium	2.9–3.7	Titanium	0.10 max.
Copper	0.40–0.80	Other impurities, each	0.05 max.
Manganese	0.10–0.30	Other impurities, other	0.15 max.
Chromium	0.10–0.25	Aluminum	remainder
Iron	0.40 max.		

Heat Treatment of 7079. Parts machined from hand forgings received in the "as forged" condition shall be heat-treated as per MIL-H-6088 in the following manner to obtain T6 condition.

Solution heat-treat for a minimum of 4 hours in a temperature range of 830°F. to 850°F. Quench in water at room temperature. Age naturally for 5 days at room temperature, followed by artificial aging in a 230°F.–250°F. range for 48 hours.

The following mechanical properties are to be expected after heat treatment to the T6 condition:

Grain direction	*Tensile strength p.s.i., min.*	*Yield strength at 0.2% offset p.s.i., min.*	*Elongation % in 4D. min.*
Longitudinal	72 000	62,000	9.0
Long transverse	70,000	59,000	6.0
Short transverse	65,000	54,000	4.0

7079 should be specified for structural fittings when:

1. They are over 4 in. thick.
2. When it is necessary to load the part in the short transverse direction.

CHAPTER XII

ALUMINUM-ALLOY CASTINGS

ALUMINUM-ALLOY castings are frequently used in aircraft construction. As is the case with all castings, their mechanical properties, shock resistance, and ductility are inferior to those obtainable with wrought alloys. It is a general rule that the casting must have a 100% margin of strength when used in aircraft. It is necessary to break down one typical casting of a given design under load to establish its strength. It is common practice in the aircraft industry to furnish the foundry with drawings that show the intensity, direction, and point of application of the principal loads on the casting. The casting technique is then adjusted to obtain the optimum strength. In the production of important castings it is customary to have the manufacturer X-ray enough castings to ascertain if there are any interior flaws. With these precautions, plus intelligent design, it is possible to use castings for many aircraft applications. Castings are particularly useful when the part is so complicated that an excessive amount of machining would be necessary to fashion it from bar stock. Another important application occurs on experimental planes when only a limited number of parts are required. In production these parts can be redesigned to obtain the greater strength and ductility of a forging. For limited production a casting is much cheaper than a forging.

There are a large number of casting alloys with varying properties available for use. In selecting the alloy to be used it is necessary to bear in mind the primary service requirement, which may be any one of the following: strength and ductility, strength at elevated temperatures, pressure tightness, corrosion resistance, ease of casting due to complicated shape, low cost.

There are three ways of casting aluminum alloys: (1) sand casting, (2) permanent-mold casting, and (3) die casting. *Sand casting* is the most common and is used for complicated shapes or where only a few parts are required. *Permanent-mold casting* is similar to sand casting, but a metal mold is used which permits the making of many parts with better accuracy than sand casting. *Die casting* is used when many small parts must be made and held to close tolerances.

The chemical composition of the aluminum-alloy casting materials that have found applications in aircraft construction is given below. Percent of alloying elements is given. Aluminum and impurities constitute remainder.

Alloy	Copper	Iron	Silicon	Magnesium	Nickel	Zinc
13			12.0			
43			5.0			
85	4.0		5.0			
122	10.0	1.2		0.2		
A132	0.8	0.8	12.0	1.0	2.5	
142	4.0			1.2	2.0	
195	4.5					
B195	4.5		2.8			
212	8.0	1.0	1.2			2.5 max.
214				3.75		
A214				3.75		2.0
218				8.0		
220				10.0		
355	1.25		5.0	0.5		
356			7.0	0.3		

Some of the above alloys are used both for sand- and permanent-mold casting. Others are used for only one type of casting, being developed especially for that purpose. Each type of casting will be described in detail and the physical properties obtainable with the different alloys tabulated. These values will vary with the type of casting even though the same alloy is used.

SAND CASTING

Sand casting of aluminum alloys is the method most frequently resorted to in obtaining castings for aircraft construction. The quantity of castings required is usually fairly small and would not warrant the manufacture of a permanent metal mold or die. The wooden patterns used for sand casting will stand up under the manufacture of several hundred castings unless they are abused or the casting is of unusual shape. Patterns made of white metal are sometimes substituted for wood. If more than several hundred castings are to be made, the unit cost of making a second pattern will be very small.

It is advisable to let the casting manufacturer also make the pattern from the designer's blueprint. When this is done there can be no question about obtaining the proper shrinkage and machining allowance. The shrinkage allowance for aluminum-alloy sand castings is $^{5}/_{32}$ inch per foot. If a machine finish is desired, $^{1}/_{16}$ inch should be allowed for machining, particularly on the upper surface of the casting where the impurities collect.

Aluminum-alloy sand castings cannot be manufactured with a wall thickness of less than $^{1}/_{8}$ inch. There is practically no limit to the size or core complexity of castings made by this method.

The following table gives the mechanical properties of sand-cast aluminum

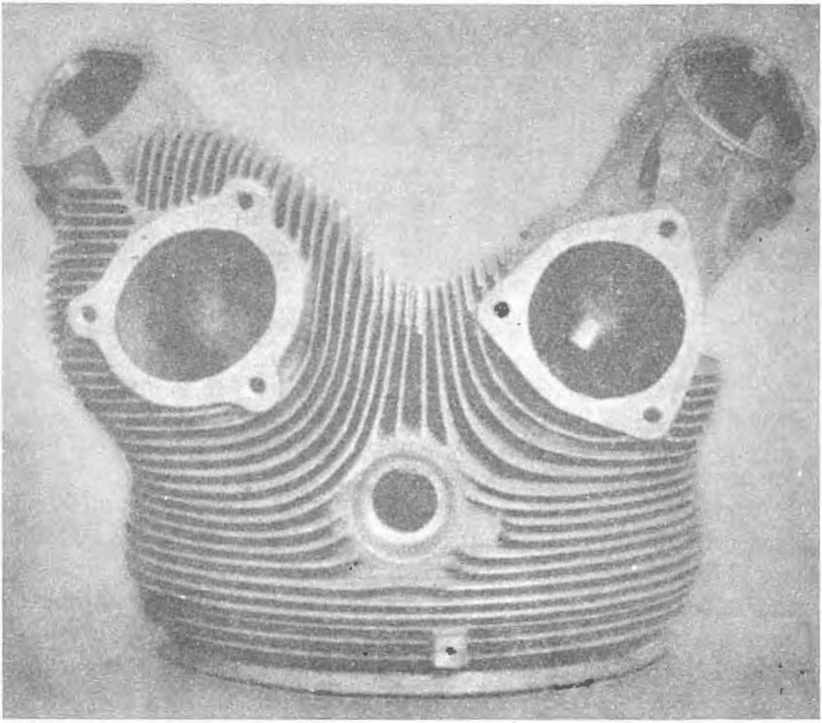


Figure 45. Sand-cast Cylinder Head; Aluminum Alloy

alloys used in aircraft construction:

Sand-Cast Aluminum Alloys

Alloy	U.t.s. (p.s.i.)	Elongation (%)	Brinell hardness	Density (lb./cu. in.)
43	19,000	4.0	40	0.096
195-T4*	31,000	8.0	65	0.100
195-T6	36,000	4.0	80	0.100
212	22,000	2.0	65	0.102
214	25,000	9.0	50	0.095
220-T4*	45,000	14.0	75	0.092
355-T6	35,000	3.5	80	0.097
356-T4*	28,000	6.0	55	0.095

*T4 will very nearly attain the properties of T6 if allowed to age at normal temperatures for six months.

Applications. Alloy No. 43 remains fluid down almost to the solidification point and for this reason can be used for complicated castings and thin-walled castings. It also makes a dense, leakproof casting with good corrosion resistance. It has been used for carburetors, hot-air scoops, fuel-line fittings, and fuel- and oil-tank flanges. In this latter application it can be readily welded to the sheet metal of the tank.

Alloy No. 195-T4 is largely used for structural aircraft castings. It has good strength and maximum shock resistance. It does not cast as well as No. 43 nor have as good corrosion resistance but it machines much better and has considerably greater strength.

Alloy No. 195-T6 is somewhat stronger than 195-T4 but has less elongation and shock resistance.

Alloy No. 212 has good casting properties and is used as a general-purpose alloy when high strength is not important.

Alloy No. 214 has maximum corrosion resistance. It is difficult to cast into intricate, leakproof castings.

Alloy No. 220-T4 has high tensile and yield strength as well as good impact and elongation values. It has good corrosion resistance and machines well. It is not pressure tight, requires special foundry technique, and uniform sections at least ¼ inch thick are desirable because of high solidification shrinkage.

Alloy No. 355-T6 has excellent casting qualities and retains its strength well at temperatures up to 400°F. Its leakproof and heat-resisting qualities have been utilized in the manufacture of water-cooled cylinder heads for engines.

Alloy No. 356-T4 can be substituted for 195-T4 when the casting is complicated. To some extent aging alone will improve the properties of this alloy without heat treatment. This fact is utilized in intricate castings that cannot withstand quenching stresses. This alloy has good corrosion resistance.

PERMANENT-MOLD CASTING

Permanent-mold casting is similar to sand casting except for the use of a metal mold. The manufacture of this mold is relatively expensive and is only justified when a large number of castings are required. Castings with complicated cores cannot be manufactured in metal molds. Sometimes cores are fabricated of sand in the metal mold. This process is called semi-permanent-mold casting. It utilizes the advantages of both sand and mold casting.

In mold casting the molten metal is fed into the mold by gravity. The mold is hot but chills the molten metal as it comes in contact with it. Chilling results in more rapid solidification and a finer grain. This finer grain makes permanent-mold castings more susceptible to heat treatment, and improves their corrosion resistance and physical properties.

Due to the metal mold a fairly smooth finish is obtained on the casting. If a machined finish is desired, it is only necessary to allow about 1/32 inch for machining. Permanent-mold castings can be produced with a wall thickness of 3/32 inch. It is possible to hold overall dimensions to a tolerance of ±0.01 inch.

The mechanical properties of several commonly used permanent-mold casting alloys are as follows:

Alloy	U.t.s. (p.s.i.)	Elongation (%)	Brinell hardness	Density (lb./cu. in.)
43	21,000	5.0	45–55	0.097
122–T65	40,000		125–150	0.104
A132-T61	34,000	1.0	90–120	0.097
142-T61	40,000		100–130	0.100
B195-T4	33,000	4.5	70–90	0.101
A214	21,000	2.5	50–65	0.096
355-T6	37,000	1.5	90	0.097
356-T4	33,000	5.0	60	0.095

There are also several other heat treatments which give properties different from those listed for Alloys Nos. 122, A132, 142, B195, 355, and 356.

Applications. Alloy No. 43 when cast in a permanent mold will have a better finish and can be held to closer dimensional tolerances than when sand cast. The cost of machining can thus be saved for some applications.

Alloys Nos. 122, A132, and 142 have been used for engine pistons. A132, in particular, has a very low coefficient of expansion and the lowest weight, both of which are important considerations for this use. These alloys have also been used for brake shoes and bearing caps. Sand-cast 142 is also used for cylinder heads of aircraft engines.

Alloy No. A214 has the same nontarnishing property as the sand-casting alloy 214.

Alloy No. 356 has excellent casting qualities, good corrosion resistance and good mechanical properties.

It should be noted that the permanent-mold alloys have slightly higher strengths than the equivalent sand-casting alloy. Due to the difficulties involved in permanent-mold casting, it is advisable to consult with the manufacturer before definitely selecting an alloy.

DIE CASTING

Die casting consists in forcing molten metal under pressure into water-cooled dies. The pressure imposed and the chilling of the molten metal result

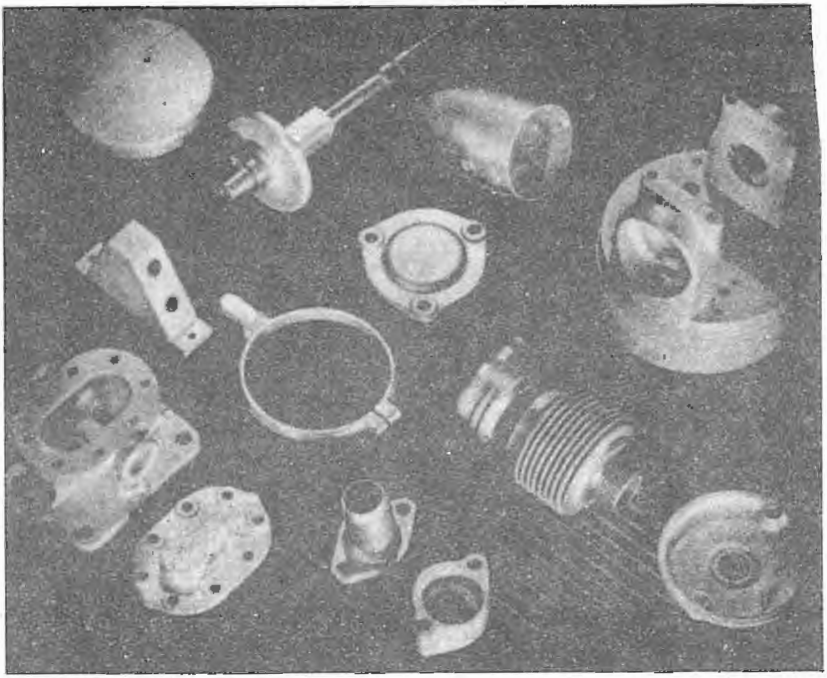


FIGURE 46. Aluminum-alloy Die Castings

in a homogeneous, fine-grained casting. The castings have an excellent finish and may be held to very accurate dimensions. A section tolerance of ±0.0025 inch can be held. It is also possible to produce sections as thin as 0.030 to 0.040 inch but 1/16 inch is preferred. Because of the dimensional accuracy and fine finish, little machining is necessary. Even holes are cored to size, ready for reaming or tapping.

Only small parts required in large quantities are die cast, owing to the high cost of the dies. There are many limitations to the process, so that it is almost mandatory to discuss the problem with the die caster before laying out the job or selecting the alloy. The casting properties of the alloy are sometimes more important than the mechanical properties. Three of the most commonly used die-casting alloys are Nos. 13, 85, and 218.

Alloy	U.t.s. (p.s.i.)	Yield strength (p.s.i.)	Elongation (%)
13	33,000	18,000	1.5
85	32,000	19,000	2.0
218	36,000	20,000	5.0

These alloys are used extensively for aircraft accessories. Alloy No. 13 has good corrosion resistance and excellent casting properties. Alloy No. 85 is a relatively cheap general-purpose alloy which is used for simple castings that do not have very thin walls and do not require maximum corrosion resistance. Alloy No. 218 presents the best combination of strength and ductility combined with good corrosion resistance. Alloy No. 218 is difficult to cast in complicated shapes.

DESIGN OF CASTINGS

The following precautions should be taken in the design of all castings:

1. High stress concentrations should be avoided.
2. Reentrant angles between surfaces with pockets and corners, where porosity or cracks may develop due to shrinkage and air bubbles, should be avoided.
3. Slender cantilever lugs, sharp corners, and abrupt changes in section should be avoided. Generous filleting is very important.
4. Eccentricities should be avoided.
5. Allow a reasonable margin between the design stress and the elastic limit of the casting. A 100% margin on the ultimate tensile strength is good.

Castings should not be used for the following purposes:

1. Main structural fittings whose failure would endanger the airplane.
2. Lugs attached to struts and wires exposed to the air stream, or to parts subject to vibration, such as the engine mount.
3. Castings should not be used to take even moderately high bending stresses.
4. Castings should not be used with lugs which may be subject to accidental bending stresses during assembly, disassembly, alignment, or ground handling. Many casting failures have occurred because of cracks started by careless mechanics performing one of these operations and imposing bending on lugs designed to take tension.
5. Castings should not be used for fittings subject to reversal of loads of high magnitude.

Heat-treated Castings. Casting alloys have been developed which when heat-treated possess superior mechanical properties as compared to castings which are not susceptible to heat treatment. Both types of castings are included in the preceding tabulation. For some purposes the common unheat-treated castings are more suitable than the higher-strength heat-treated castings.

There are several patented heat treatments applicable to heat-treatable castings. Starting with the same basic material, the mechanical properties are altered in different ways by the various heat treatments. The resulting product is denoted by adding a T and a number which designates the particular treatment to which it was subjected. Thus, 195-T4 and 195-T6 have quite different physical properties. Alloy No. 195 was given a T4 heat treatment in ne case and a T6 heat treatment in the other.

TABLE 12. Aluminum-alloy Specifications—Castings

Alloy designation	*Casting method*	*Specifications*
13	Die	QQ-A-591
43	Sand	QQ-A-601
43	Permanent mold	QQ-A-596
43	Die	QQ-A-591
85	Die	QQ-A-591
122	Permanent mold	QQ-A-591
A132	Permanent mold	QQ-A-596
142	Sand	QQ-A-601
142	Permanent mold	QQ-A-596
195	Sand	QQ-A-601
B195	Permanent mold	QQ-A-596
212	Sand	QQ-A-601
214	Sand	QQ-A-601
A214	Permanent mold	—
218	Die	AN-A-38
220	Sand	QQ-A-601
355	Permanent mold	QQ-A-596
356	Sand	QQ-A-601
356	Permanent mold	QQ-A-596

Alloy No. 195-T4 heat treatment consists of soaking in an electric air furnace for 12 hours at 941–977°F. A constant temperature of 970°F. is desirable. The part is then quenched in water above 125°F. If the casting is intricate or has abrupt changes in section the quenching water should be between 200° and 212°F. The final operation is the aging of the quenched casting for 2 hours in boiling water.

Military Specification MIL-H-6088 describes heat treatment for other casting alloys.

During the latter part of 1954 several large aluminum casting companies refined their casting processes by accurately controlling such variables as chemistry, pouring temperature, degassing, mold hardness, atmosphere control, foundry sands, and others. The result has been that it is now possible to purchase castings having guaranteed properties much higher than those in the past. It is now possible to obtain guaranteed mechanical properties of 38,000 p.s.i. ultimate, 28,000 p.s.i. yield, and 6% elongation in 2 inches in 356-T6 aluminum alloy. These values are obtained from test specimens actually cut from the casting. The future of the accurately controlled casting techniques looks very promising.

CHAPTER XIII

MAGNESIUM ALLOYS

MAGNESIUM is the lightest of the structural metals available for aircraft construction. Pure magnesium weighs only 65% as much as aluminum. It is a silvery white metal that is relatively soft, and does not have the strength or other properties required for structural use. In its pure state magnesium has been widely used for flashlight powder, and magnesium alloy was used for the cases of incendiary bombs. This latter use resulted in the construction and expansion of numerous magnesium plants during the war. A peak production of 21,000 tons of magnesium per month was reached early in 1944. This production rate was subsequently reduced when new types of bombs not using magnesium were developed. This enormous capacity was kept available in active or standby status, however, and may well be utilized in the near future as the structural applications of magnesium alloys increase.

Magnesium is commonly alloyed with aluminum, zinc, and manganese, to create usable structural materials. Magnesium alloys have a specific gravity of 1.8, as compared to 2.7 for aluminum and 7.9 for steel. The light weight and relatively high strength of magnesium alloys results in a strength/weight ratio that is very attractive in aircraft design. There are many places in aircraft construction, such as fairings, ducts, doors, brackets, bulkheads and partitions, and similar locations, where strength is secondary and a minimum thickness of material is all that is necessary. The use of magnesium alloys in these locations will effect an appreciable weight saving.

Magnesium alloys are nonsparking and nonmagnetic; this characteristic permits their use adjacent to magnetic compasses. These alloys machine very well, can be gas-, arc-, or spot-welded, and can be fabricated into many shapes, although special techniques are usually required.

Magnesium alloys are available as sand, permanent-mold, and die-castings; press and hammer forgings; extruded bar, rod, shapes, and tubing; and rolled sheet, plate, and strip. A number of alloys with varying characteristics are available in each form. These characteristics must be considered in choosing the best alloy for a specific application. In the following pages the important characteristics of the commonly used alloys and their typical applications are described.

At present there are three main fabricators of magnesium alloys in the United States: Magnesium Division of the Dow Chemical Company, American

Magnesium Corporation, a subsidiary of the Aluminum Company of America; Magnesium-Aluminum Division of Revere Copper and Brass Incorporated. Each of these companies manufactures similar alloys but each has its own method of designating them. Army-Navy aeronautical specifications have been issued describing the commonly used alloys. Since the designations of the fabricators have enjoyed widespread use up until this time, these designations as well as the AN aero specifications have been listed in the tables in this chapter. Table 13 has been prepared to indicate the specifications and designations of magnesium alloys of similar type. For completeness S.A.E. and A.S.T.M. specifications have been included.

PURE MAGNESIUM

Magnesium is never found in its native state. There are several common ore sources from which it is extracted, namely: magnesite (magnesium carbonate) which contains 500 pounds of magnesium per ton; dolomite (magnesium calcium carbonate) which contains 240 pounds of magnesium per ton; carnallite (magnesium and potassium chloride) which contains 160 pounds of magnesium per ton. These ores are found practically all over the world. Magnesium constitutes 2.24% of the earth's crust and is fifth in abundance of the metals in the earth, following silicon, aluminum, iron, and calcium in the order named.

In addition to that in the magnesium ores, there is an infinite supply of magnesium in ocean water. Magnesium chloride makes up about 11% of the total salt content and magnesium is about 0.125% by weight of ocean water. The Great Salt Lake in Utah contains 0.56% magnesium. One pound of metallic magnesium is recoverable from every 770 pounds of ocean water.

Production Methods. Magnesium was first produced in 1808 by Sir Humphrey Davy, who reduced magnesium from magnesium oxide with potassium vapor and also by the electrolysis of anhydrous magnesium chloride.

The first production of magnesium in this country on a commercial basis began in 1914. There are three basic methods used in this country at the present time for the reduction of magnesium from its source. These are the electrolytic process; the ferrosilicon process (Pidgeon); and the carbothermic process (Hansgirg).

The electrolytic process electrolyzes molten magnesium chloride which is obtained from brine, from sea water or from one of the ores. The pure magnesium collects at the cathode. Magnesium ingot produced by this method may, if required, have a minimum purity of 99.88%.

The ferrosilicon or Pidgeon process is a thermal reduction process in which temperatures as high as 2150°F. are used. This method was adopted

TABLE 13. Magnesium Alloys—Specifications and Uses

Form	Federal	S.A.E.		A.S.T.M.		American Magnesium	Dow, Revere	General use
		No.	A.S.M	Designation	Alloy			
Sand castings	QQ-M-56	50	4420 4422 4424	B80-53T	AZ63A	AM 265	H	General casting use
	QQ-M-56			B80-53T	M1B	AM 403	M	Weldable—tank flanges
	QM-M-56	500	4434	B80-53T	AZ92A	AM 260	C	Pressure-tight castings
Permanent mold castings	QQ-M-55	503	4484	B199-51T	AZ92A	AM 260	C	Strong—good corrosion characteristics
	QQ-M-55	502		B199-51T	AM100A	AM 240	G	Casts well—inferior corrosion
Die castings	QQ-M-38	501	4490	B94-52	AZ91A	AM 263	R	Housings, fittings, instrument parts
Extruded bar, rod, and shapes	QQ-M-31	52		B107-53T	AZ31B	AMC 52S	FS-1	Cold forming
	QQ M-31	520	4350	B107-53T	AZ61A	AMC 57S	J-1	General purposes—good strength
	QQ-M-31	522		B107-53T	M1A	AM 3S	M	Weldable—light stresses
	QQ-M-31	523		B107-53T	AZ80A	AMC 58S	O-1	Highest strength
Extruded tubing	WW-T-825	52		B217-53T	AZ31B	AMC 52S	FS-1	Medium strength—extrudes well
	WW-T-825	520	4350	B217-53T	AZ61A	AMC 57S	J-1	Best strength—high notch sensitivity
	WW-T-825	522		B217-53T	M1A	AM 3S	M	Welding—high resistance to salt water
Forgings	QQ-M-40	531	4358	B91-49T	AZ61A	AMC 57S	J-1	Intricate shapes—press forged
	QQ-M-40	532	4360	B91-49T	AZ80A	AMC 58S	O-1	High strength—difficult to forge
	QQ-M-40	533				AM 3S	M	Weldable—easily forged—low cost
				B91T-49T	AZ31B	AMC 52S	FS-1	Easily forged
Sheet	QQ-M-44	510	4375	B90-51T	AZ31A	AMC 52S	FS-1	Cold forming—welding—tough
	QQ-M-54	51	4370	B90-51T		AM 3S	M	Deep drawing—welding—low cost

S.A.E. is the abbreviation for Society of Automotive Engineers.
A.M.S. are S.A.E. Aeronautical Material Specifications.
A.S.T.M. is the abbreviation for American Society for Testing Materials.

for many of the new plants constructed during the war because it uses a minimum of electric power. The process consists of reducing magnesium oxide in a vacuum with heat by means of ferrosilicon (an alloy of iron and silicon containing about 75% silicon). The magnesium oxide is prepared by calcining magnesium carbonate obtained from dolomite. Magnesium produced by this process may have a minimum purity of 99.99%.

The carbothermic or Hansgirg process for the reduction of magnesium is also a thermal process. It consists of heating magnesium oxide (previously reduced from dolomite and sea water) in the presence of coke at high temperature. The products of reaction are magnesium and carbon monoxide. The magnesium vapor, at 3500–4000°F., is shock-chilled by cold natural gas, causing condensation of the magnesium as a very fine dust. Magnesium produced by this process may have a minimum purity of 99.99%.

Physical Properties. Pure magnesium has the following properties:

Specific gravity	1.74
Density	0.064 lb./cu. in.
Melting point	1204°F.
Flame temperature	8760°F.
Electrical conductivity:	
Volume basis	38% of copper
Mass basis	197% of copper
Mean coefficient of thermal expansion, per inch per °F.(32°–750°F.)	0.0000166 inches
Modulus of elasticity	6,500,000 p.s.i.

MAGNESIUM ALLOYS

The advantages of the use of magnesium alloys in aircraft construction have not yet been fully realized by aircraft designers. The increased availability of these alloys in a variety of forms, their excellent strength/weight ratio, and the improvement in protective systems against corrosion will soon result in their general use in aircraft design. These alloys have, however, certain disadvantages which the designer must allow for if failures are to be avoided. These alloys are very poor as regards toughness and notch sensitivity in fatigue, and some alloys are susceptible to stress-corrosion cracking. Suitable heat treatment, good design, and the proper choice of alloy for a given application will minimize these disadvantages.

The fabrication of wrought magnesium-alloy parts will require new shop tools and technique. The reason is that many forming operations can only be done at elevated temperatures of from 450° to 700°F. The close-packed hexagonal crystal structure of these alloys permits only a small amount of

Courtesy of Dow Chemical Company

FIGURE 47. Stratosphere Gondola; Magnesium-alloy Sheet

deformation at room temperatures. Zinc has a similar crystal structure. Copper and aluminum have what is known as face-centered cubic crystal structure and as a result are very ductile and easily worked at room temperature. As the temperature of magnesium alloys is raised above 450°F. they may be more severely worked than most other metals at room temperature. The use of heat also allows parts to be completely drawn or fabricated in one operation, whereas in other metals several anneals and redraws might be required. Springback is negligible in parts formed at high temperatures. In general, magnesium-alloy parts can be formed in more intricate shapes than aluminum-alloy parts if the shop is properly equipped.

The directional properties of magnesium-alloy sheet are very pronounced. This condition is often referred to as preferred orientation. It evidences itself by a difference in properties, such as tensile strength and elongation, in different directions. In magnesium alloys the tensile strength and elongation will be found at right angles to the direction of rolling, or across the grain as it is commonly called. In general, the poorest properties are parallel to the direction of rolling, or with the grain—except the yield strength of hard-rolled sheet, which is sometimes higher with the grain. The physical properties tabulated in this chapter are along the grain or the lower of the two directions. It should be noted that in magnesium alloys the maximum tensile strength and elongation always occur in the same direction, which is contrary to other alloys. Because of the greater elongation across the grain it is possible to make sharper bends when the bend line runs parallel with the grain. As would be expected, hard-rolled magnesium-alloy sheet has considerably greater differences in properties across and along the grain than annealed sheet has.

Chemical Composition. The chemical compositions of the commonly used magnesium alloys are given in Table 14. Since the same basic alloy is used in different forms such as forgings, extrusions, and sheet, all the specifications that apply have been listed opposite each alloy. Nominal percentages of each element have been listed; individual specifications should be consulted if detailed chemical compositions are desired.

TABLE 14. Magnesium Alloys—Chemical Composition (Nominal)

Specification			Aluminum	Manganese	Zinc	Tin	Magnesium
AN aero Federal	American Magnesium	Dow, Revere					
QQ-M-55 QQ-M-56 (AZ-92)	260	C	9.0	0.1	2.0		Remainder
QQ-M-44, AN-M-27, WW-T-825	C52S	FS-1	3.0	0.3	1.0		
QQ-M-55	240	G	10.0	0.1			
QQ-M-56 (AZ-63)	265	H	6.0	0.2	0.2		
QQ-M-40, WW-T-825	C57S	J-1	6.5	0.2	0.2		
QQ-M-56, (M1); QQ-M-54, QQ-M-40, WW-T825	403, 3S	M		1.5			
QQ-M-40, AN-M-25	C58S	O-1	8.5	0.2	0.5		
QQ-M-38	263	R	9.0	0.2	0.6		

Suffix -1 or prefix C on alloy indicates that iron and nickel impurities are reduced to lowest concentration (0.005% maximum).

The common impurities found in magnesium alloys are iron, nickel, and copper. These impurities affect the corrosion resistance of the alloy and must be held to a minimum.

MAGNESIUM-ALLOY CASTINGS

In recent years 80% of the magnesium alloy products have been castings. The excellent mechanical properties of these castings permit their substitution for aluminum-alloy castings on an equal-volume basis, with a resultant weight reduction of about one-third. In highly stressed castings, adding of fillets and increase of section may reduce saving to one-quarter. Patterns or dies designed for use with aluminum alloys can be used for magnesium. Magnesium alloys have good casting characteristics and may be cast in intricate shapes. Practical castings have been made that weigh hundreds of pounds, while others weigh only a few ounces. Magnesium alloys are available as sand, permanent-mold, and die castings. The type of casting chosen depends upon the quantity, size, intricacy, shape, strength, finish, or other requirements of the intended application. The three available types of castings are described in detail in the following pages.

Magnesium-alloy castings are used extensively in aircraft construction in such applications as wheels, brake pedals, control columns, bell cranks, instrument housings, engine housings, bomb-rack supports, gear-box housings, and other miscellaneous brackets. Their satisfactory service record in these applications will result in the increased use of magnesium alloy castings in the future.

These alloys are available in various chemical compositions and physical conditions. The choice of alloy depends upon the properties required for the intended application. The available casting alloys and their mechanical properties are listed in Table 16.

As mentioned above, aluminum-alloy casting patterns may generally be used for magnesium castings, since the shrinkage factors for these two metals are very similar. However, in magnesium-alloy castings subject to high stresses, larger fillets and radii should be used, stud bosses should be increased, and critical sections strengthened. Section changes should be gradual to reduce stress concentrations, and notches should be avoided. In general, the precautions in the design of castings outlined in the chapter on Aluminum-alloy Castings should be followed. The notch sensitivity of the magnesium alloys to fatigue is even greater than that of aluminum, and more care must be taken to avoid stress concentrations. In magnesium castings it is also desirable to use stud lengths of the order of 2½ to 3 times the diameter, and to use inserts for bolts or studs that must be frequently removed in service.

Heat Treatment of Castings. Magnesium-alloy castings can be stabilized, solution heat-treated, solution heat-treated and stabilized, or solution heat-treated and aged. All these heat treatments improve the properties of the casting in one way or another.

Solution heat treatment puts alloying ingredients into solid solution and increases the tensile strength and ductility.

Aging, after solution heat treatment, precipitates alloying ingredients and results in high yield strength and hardness. Aging also minimizes growth at elevated temperatures.

Stabilizing of cast material provides higher creep strength and less growth at elevated temperatures. In addition to these effects, the yield strength is increased when solution-treated material is stabilized. Stabilizing is really a high-temperature aging treatment that can be done more quickly than full aging.

The time and temperatures required for the various treatments are given in Table 15. Type II and III-a alloys require a pretreatment of not less than two hours' duration during which time the temperature of the furnace should be increased slowly from 640°F. to the heat treatment temperature. Heating slowly through this range avoids fusion of the lower melting eutectics in the alloy before they are absorbed into solid solution in the heat-treatment operation. The presence of small amounts of calcium in an alloy reduces the danger of partial fusion and pretreatment is unnecessary. Type III-b in Table 15 is such an alloy.

TABLE 15. Magnesium-alloy Castings—Heat Treatment

Alloy designations			Types heat-treat spec. MIL-H-6857	Solution (hours temperature)	Aging (hours at temperature)	Stabilizing (hours at temperture)
Federal specifications	American Magnesium	Dow				
QQ-M-55	AM240	G	I	18 at 780°F.	10 at 325°F.	
QQ-M-56 (AZ63)	AM265	H	II	(as cast—stabilized A.C.S.)		18 at 350°F. 4 at 500°F.
QQ-M-56 (AZ63)	AM265	H	II	10 at 730°F.;	14 at 420°F.; 18 at 350°F.	4 at 500°F.
QQ-M-56 (AZ92) —sand cast		C	III-a	18 at 770°F.	18 at 350°F.	4 at 500°F.
QQ-M-56 (AZ92) —sand cast	AM260		III-b	(as cast—stabilized A.C.S.)		8 at 325°F.
QQ-M-56 (AZ92) —sand cast	AM260		III-b	14 at 780°F.	12 at150°F. 20 at 350°F.	8 at 325°F.
QQ-M-55	AM260	C	III-c	(as cast—stabilized A.C.S.)		10 at 325°F.; 4 at 500°F.
QQ-M-55	AM260	C	III-c	18 at 770°F.	10 at 235°F. –350°F.	4 at 500°F.

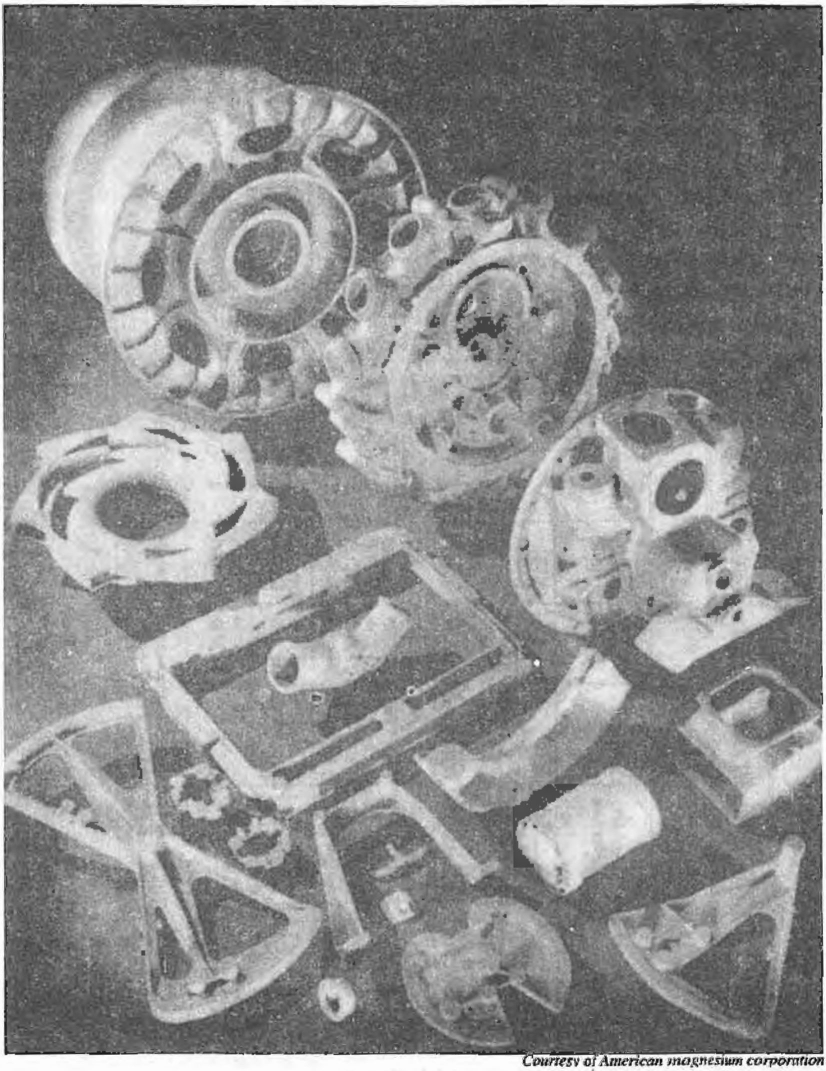
TABLE 16. Magnesium-alloy Castings—Mechanical Properties

Form	Specification					Tension			Compression yield (p.s.i.)	Brinell hardness (500 kg/ 10 mm.)	Shear (p.s.i.)	Fatigue (p.s.i.)	Impact Izod (ft./lb.)	Condition
	Federal			American Magnesium	Dow	U.t.s. (p.s.i.)	Yield (p.s.i.)	Elongation (%)						
Sand castings	QQ-M-56	AZ-63	-AC	AM265-C	H-AC	24,000	10,000	4	14,000	50	18,000	11,000	3	As cast
			-ACS	AM265-T51	H-ACS	24,000	10,000	2				11,000		As cast—stabilized
			-HT	AM265-T4	H-HT	34,000	10,000	7	14,000	55	19,000	14,000	5	Solution heat-treated
			-HTA	AM265- T6	H-HTA	34,000	16,000	3	19,000	73	20,000	13,000	2	Heat-treated—aged
			-HTS	AM265-T7	H-HTS	34,000	13,000	4		59		13,000		Heat-treated—stabilized
Permanent-mold castings QQ-M-55			M1-AC	AM-403	M-AC	12,000		3	4,500	33	11,000		9	As cast
		AZ-92	-AC	AM260-C	C-AC	20,000	10,000	1	14,000	65	18,000	11,000	1	As cast
			-ACS	AM260-T51	C-ACS	20,000	11,000					11,000		As cast—stabilized
			-HT	AM260-T4	C-HT	34,000	10,000	6	16,000	63	20,000	14,000	4	Solution heat-treated
			-HTA	AM260-T6	C-HTA	34,000	18,000	1	23,000	84	21,000	13,000	1	Heat-treated—aged
			-HTS	AM 260-T7	C-HTS	34,000	16,000	1		75		13,000		Heat-treated—stabilized
				AM240-C	G-AC	18,000	10,000	1	13,000	54	17,000	10,000	2	As cast
				AM240-T4	G-HT	34,000	10,000	6	12,000	52	19,000	12,000	4	Solution heat-treated
				AM240-T61	G-HTA	34,000	17,000		19,000	69	21,000	10,000	2	Heat-treated—aged
Die casting	QQ-M-38			AM263	R	30,000	20,000	2	20,000	60	20,000	14,000	2	As cast

Yield strength is defined as the stress at which the stress-strain curve deviates 0.2% from the modulus line.

Alloy C is used for both permanent-mold and sand castings.

Military Specification MIL-H-6857–Process for Heat Treatment of Magnesium-Alloy Castings describes acceptable furnace equipment and heat-treatment practice. For solution heat-treating an electrically heated air chamber with forced circulation is preferred. A 0.3% sulfur dioxide atmosphere should be maintained in the furnace. Aging and stabilizing may be of any type.



Courtesy of American magnesium corporation

FIGURE 48. Sand-cast Magnesium Parts

Sand Castings. The largest use of magnesium alloys is in sand castings. The design of this type of casting is essentially the same as for aluminum castings. It is very important, however, to provide generous filleting at intersections or where sections of different thicknesses blend together. Adequate filleting will minimize stress concentrations and will improve metal flow during the casting process, thus avoiding shrinkage cracks and porosity. Until experience is acquired in the design and application of magnesium castings it is desirable to consult with the casting producer for advice on pattern design, choice of alloy, heat treatment, and corrosion protection.

In the manufacturing of casting patterns it is necessary to use a shrink rule to allow for the contraction when the molten casting metal cools and solidifies. If the shape of the casting permits free contraction a shrinkage factor of $^{11}/_{64}$ inch per foot should be used for magnesium alloy castings, if free shrinkage is restrained by bosses, gates, risers, internal core, or casting shape a shrinkage factor of $^{1}/_{8}$ inch per foot is used.

In sand casting of magnesium alloys, a minimum wall thickness of $^{1}/_{8}$ inch is obtainable for small areas but $^{5}/_{32}$ inch is more practicable. A nominal tolerance of $\pm^{1}/_{32}$ inch on wall thickness or dimensions affected by core shift is customary.

Some magnesium casting alloys are subject to "growth" when used at elevated temperatures. This growth is an increase in dimensions slowly brought about at elevated temperatures by changes in the internal structure. It occurs particularly in casting alloys in the solution heat-treated condition, which grow slightly until the amount of precipitation corresponding to the temperature is in balance. These growth values do not exceed 0.00033 inch per inch and 0.00041 inch per inch respectively for casting-alloy types AZ63 and AZ92 of specification QQ-M-56. These alloys should not be used at temperatures above 200°F. in the solution heat-treated condition. A temperature of 350°F. is the maximum recommended when the alloys are stabilized or aged.

It is common practice in the design of magnesium castings to specify the use of steel or equivalent inserts for bushings, bearings, or threaded parts. Inserts such as these can be cast into place. Cadmium-plated steel inserts are preferable, as they minimize alloying action with the molten cast magnesium, and they do not contaminate the scrap when remelted. If brass, bronze, or other nonferrous inserts are used they should be chromium plated or sprayed with iron to reduce the alloying action.

Microporosity may occur in sections of magnesium-alloy castings. This porosity is caused by intergranular shrinkage voids. It is not visible on machined surfaces but excessive microporosity will impair strength and will permit leakage under pressure. Porous castings can be impregnated to eliminate leakage. Specification QQ-M-56 permits impregnation only if specifically approved and requires such castings to be stamped (IMP).

Local defects in magnesium-alloy castings can be repaired by welding if the flaw is in a nonstressed location. This type of repair should preferably be made before heat treatment. An X-ray of the defect before and after welding should be made to be sure no hidden flaws remain.

Federal Specification QQ-M-56 describes three types of magnesium-alloy sand castings, identified as compositions AZ63, M1, and AZ92. The mechanical properties of these casting alloys and the heat-treated conditions in which they may be purchased are listed in Table 16.

*Composition AZ*63 is a general casting alloy of high strength. This alloy is used in 75% of the production in the United States.

*Composition M*1 has good welding characteristics and corrosion resistance. It has low strength and should only be used for lightly stressed parts. It cannot be heat-treated to improve its strength. It is commonly used for such welded applications as tank fittings.

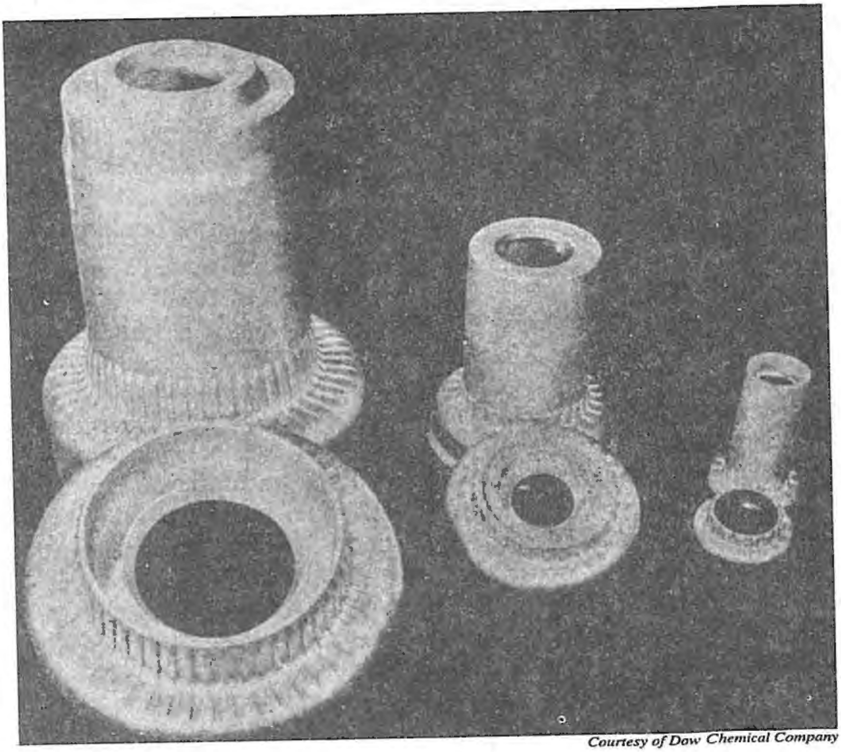
Composition AZ92 has good castability and is less subject to microporosity than alloy AZ63. It is used for pressure-tight castings.

Magnesium-alloy castings may be used in the as-cast (AC) condition for nonstructural parts requiring only moderate strength. For maximum ductility, elongation, and impact resistance the solution heat-treated (HT) condition should be specified. This condition should not be used if the castings are to be used at temperatures above 200°F. or the castings will grow. The solution heat-treated and aged (HTA) condition should be specified to minimize growth and to obtain maximum strength and hardness. Growth can also be inhibited by stabilizing treatments as previously explained under Heat Treatment of Castings.

Magnesium-alloy sand castings are widely used for aircraft landing wheels, instrument housings, control columns, and aircraft engine housings.

Permanent-mold Castings. Permanent-mold castings are being specified more and more as their advantages become better known. In this type of casting a metal mold made of cast iron or low-alloy die steel is used. These molds have long life and are thought of as permanent when compared to sand-casting molds. As opposed to die casting, in which high pressures are used, no external pressure is used in permanent-mold casting. In England this type of casting is called gravity die casting, which signifies the absence of external pressure. It is of interest to note that permanent-mold casting preceded sand casting. In ancient days tools and weapons were cast in stone molds.

The manufacture of metal permanent molds is an expensive proposition and consequently a minimum production of about 500 parts is required to



Courtesy of Dow Chemical Company

FIGURE 49. Permanent-mold Cast Magnesium Aircraft Wheels

justify this type of casting. The size of permanent-mold castings is also limited by the problems of mold manufacture. At the present time, however, permanent-mold castings up to 36 inches in length and 55 pounds in weight are being made successfully. The use of a metal mold instead of a sand mold permits closer control of dimensions and better surfaces, and the castings require less machining. The saving in machining time and cost should be considered when deciding on the type of casting to be specified.

Wall thicknesses of $^1/_8$ inch for small areas and $^5/_{32}$ inch for large areas may be obtained in permanent-mold castings. Dimensional tolerances as low as 0.01 inch can be held, but $\pm ^1/_{64}$ inch is more commonly specified.

Permanent-mold casting is particularly adaptable to simple castings with uniform wall sections. Uniform sections allow equalization of the rate of solidification and result in sounder castings. Undercuts on the outside face of the casting complicate the construction of the mold and are expensive. If undercuts or complicated coring are necessary it is common practice to use sand cores in combination with a metal mold. These are referred to as semipermanent molds.

The mechanical properties of permanent-mold castings are essentially the same as those of sand castings. These properties are listed in Table 16.

Federal specification QQ-M-55 covers permanent-mold castings. Dowmetal alloy C(AM260) and Dowmetal alloy G(AM240) are generally used for this type of casting, Dowmetal alloy C(AM260) is used most frequently because of its good casting qualities, mechanical properties, and corrosion resistance. Dowmetal alloy G(AM240) casts better than Dowmetal alloy C(AM260) but is inferior in other characteristics.

Permanent-mold castings are particularly adaptable for use in engine nose sections, landing wheels, wheel flanges, pistons, brackets, housings, and similar applications.

Die Castings. Magnesium alloys are well adapted to die casting. Die casting consists of forcing molten metal under high pressure into a metal mold or die. The high-pressure cold-chamber process of die casting is preferred for magnesium alloys. In this process molten metal is ladled into a receiving chamber in an injection cylinder. This receiving chamber is entirely separate from the melting pot or furnace and is referred to as a "cold chamber." The molten metal in the receiving chamber is immediately forced into the die by a hydraulically operated ram under high pressure. This pressure may run anywhere from 5000 to 35,000 p.s.i., depending on the type and size of casting and on the equipment. In this process a minimum of impurities is picked up in the molten metal since it is only momentarily in contact with the injection chamber and ram.

Dies and die-casting equipment are expensive and consequently high production of a part is necessary to reduce the cost per piece. In some cases as few as 500 pieces will justify die casting on an overall cost basis. Machining costs are greatly reduced because of the accurate dimensions that can be held and the excellent surface finish. The thin walls and sections that can be cast save much material. In large quantities, die castings cost less per piece than other types of casting. The size of die castings is limited by available die-casting equipment. Parts up to 5 pounds in weight and with a projected area of 250 square inches have been successfully die-cast.

Wall thicknesses of $^1/_{16}$ inch to $^3/_{16}$ inch are best both from casting considerations and to obtain maximum mechanical strength. Walls as thin as $^1/_{32}$ inch are possible for areas of 10 square inches or less. A maximum wall thickness of ½ inch should not be exceeded. This limitation is necessary because heavy sections do not die-cast well, owing to the fact that the die immediately chills the molten metal in contact with it, and section shrinkage porosity would result as the interior of the section cooled more slowly. Cored holes with a diameter as small as 0.062 inch may be die-cast.

Tolerances of 0.0015 inch per inch of length can be held. Normally a tolerance of ±0.005 inch for dimensions on any portion of the casting on the same side of the parting line is specified; for dimensions that cross the parting line a tolerance of ±0.010 inch is specified.

Draft allowances are very important in die-casting design to permit high production rates and to obtain a good surface finish. A minimum draft of 1° on outside surfaces at right angles to the parting line is necessary to allow for the ejection of the casting without galling. A draft of 5° will greatly improve the finish of cast surfaces. The tendency of the cooling metal to shrink around internal projections necessitates a 2° draft on these surfaces. Cored holes require a 1° draft per side. These holes must subsequently be drilled or reamed to size.

Die castings should be designed as simply as possible to avoid complication in production and increased cost. Undercuts in particular require loose die parts to permit removal of the casting. These loose parts must be replaced for each new casting, which operation reduces the production rate. Generous fillets and gradual changes in section are essential. Steel or nonferrous inserts may be cast in place, as previously described under sand casting. These inserts may serve as bearings or wear-resistant surfaces. External threads 16 per inch or coarser can be die-cast if the thread axis is in the parting plane. It is desirable to cast such threads from 0.005 to 0.010 inch oversize on the pitch diameter in order to allow sufficient stock for chasing the thread.

Specification QQ-M-38 describes the die-casting alloy that is used almost exclusively. This alloy has good casting characteristics and mechanical properties. It is used in the as-cast condition. The mechanical properties of this alloy are listed in Table 16.

Magnesium-alloy die castings are used for small engine parts, instrument parts and housings, small landing wheels, rudder and brake pedals, rocker-box covers, and similar applications.

WROUGHT MAGNESIUM ALLOYS

Magnesium alloys are commercially available in the form of extrusions, forgings, and sheet. Bars, rods, shapes, and tubing are fabricated by the extrusion process; both press and hammer forgings in a number of different alloys are available; and sheet, plate, and strip are procurable.

Magnesium alloys have the same ratio of modulus of elasticity to specific gravity as steel and aluminum. This agreement indicates there is a place in the structural field for wrought magnesium alloys. The limited applications thus far made in aircraft construction show that significant weight savings are attainable by the use of magnesium alloys. Such savings will not be as great as is the case for castings in which magnesium alloy can be directly substituted for a heavier material. The mechanical properties of wrought magnesium alloys are not directly comparable with those of aluminum or steel and some additional thickness is necessary if the magnesium-alloy part is to have equal strength. The relatively low modulus of elasticity ($E = 6{,}500{,}000$ p.s.i.) will result in greater deflections for the magnesium-alloy member if the dimensions of the member it is replacing must be held. In such a case it would also be necessary to increase the thickness and consequently the weight. For these reasons it is not possible merely to substitute magnesium alloy for aluminum alloy and realize a full one-third saving in weight.

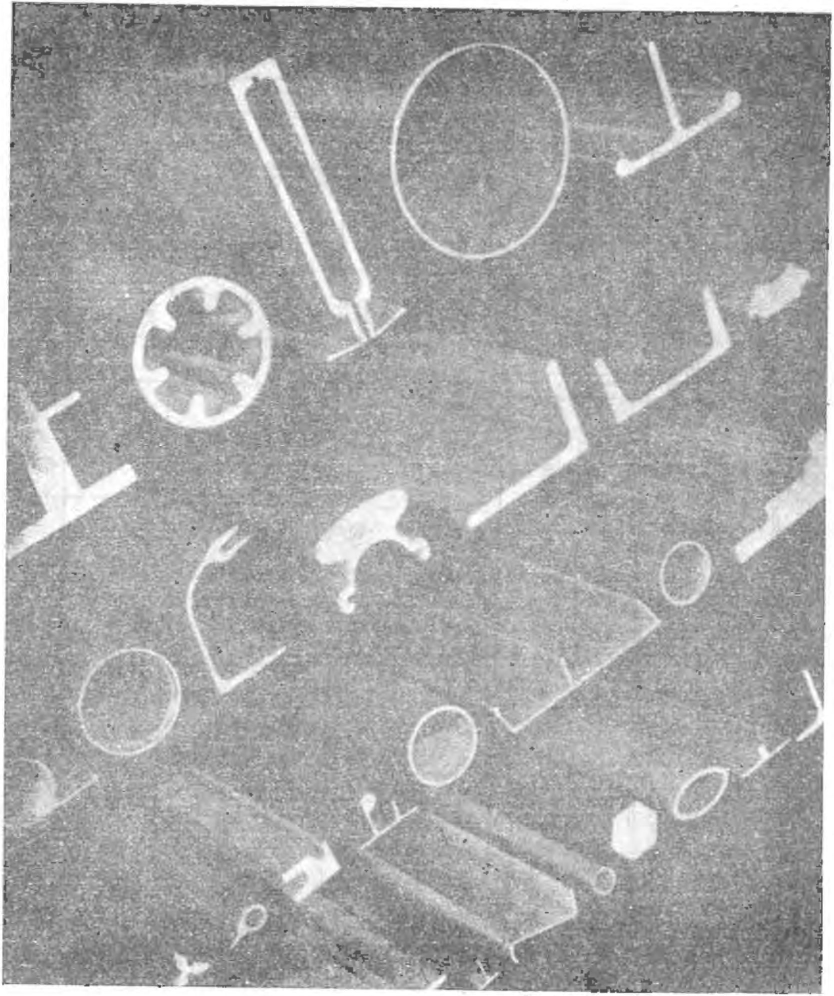
If a member is subject to bending stresses and its depth is not limited, the use of magnesium alloy will result in a substantial weight saving. The reason lies in the fact that in a beam the weight goes up as the first power of the depth, the beading strength increases as the square, and the stiffness as the cube.

If the diameter of a tube is not limited, magnesium alloy is most efficient as compared to aluminum or steel for medium or long tubes in compression. For geometrically similar tubes of the same weight and length, the increased section of the magnesium-alloy tube will result in a much smaller slenderness ratio. This will permit a higher allowable stress (comparative), which when multiplied by the greater cross-sectional area will give a total column load for the magnesium alloy, which exceeds that for the other materials.

In many applications a minimum thickness or bulk of material is needed for handling or for other reasons. In these cases the strength of the material is not critical. Fairings might be mentioned as one such application. The use of magnesium alloy under these circumstances would obviously result in saving weight.

Extrusions. Magnesium alloys can be readily extruded in a variety of forms, such as bars, rods, shapes, and tubing. Bars, structural shapes, and tubing are standard items and can be purchased from stock. Special shapes can be extruded to order but in this case the customer must bear the cost of the extrusion die. The cost of a die is quite inexpensive, however, usually not exceeding $50 for a reasonable shape.

Bars can be obtained round, square, rectangular, or hexagonal. Structural shapes such as angles, I beams, channels, and tees are obtainable in structural sections that are standard, except for larger radii which are used to minimize stress concentrations. Tubing is obtainable as square, oval, round, or other regular hollow sections. Round tubing only is standard.



Courtesy of American magnesium corporation

FIGURE 50. Miscellaneous Magnesium Extruded Shapes

Extrusion billets vary from 2 to 16 inches in diameter and from 12 to 32 inches in length. They are heated to around 700°F. and forced through the extrusion die by a ram pressure of 5000 p.s.i. Extrusions can be furnished up to 22 feet in length, and longer on special order. Tubing is limited to maximum ratios of diameter to wall thickness of 20/1 for J1 alloy (WW-T-825), and 30/1 for FS-1, and M alloys (WW-T-825). The tolerance on tubing wall thickness is ±10% with a minimum tolerance of 0.010 inch. The straightness of extrusions can be held to 1 in 1000, which is equivalent to $^1/_{16}$ inch in 5 feet.

TABLE 17. Magnesium-alloy Extrusion—Mechanical Properties

Form	Specification			Tension			Compression yield (p.s.i)	Brinell hardness (500 kg./10 mm.)	Shear (p.s.i)	Fatigue 500 X 10^6 cycles (p.s.i.)
	AN aero Federal	American Magnesium	Dow, Revere	U.t.s. (p.s.i)	Yield (p.s.i)	Elongation (%)				
Bars and Rods	AN-M-24	AM-C578	J-1	40,000	26,000	11	20,000	58	19,000	18,000
	AN-M-25	AM-C58S	O-1	43,000	28,000	9	22,000	55	20,000	19,000
	AN-M-25	AM-C58S-T5	O-1A	45,000	30,000	5	28,000	80	22,000	19,000
	AN-M-25		O-1HTA	48,000	33,000	4	30,000			
	AN-M-26	AM3S	M	30,000		3	14,000	42	16,000	9,000
	AN-M-27	AM-C52S	FS-1	35,000	22,000	10	17,000	49	19,000	14,000
Shapes	AN-M-24	AM-C57S	J-1	40,000	22,000	10	19,000	64		
	AN-M-25	AM-C58S	O-1	40,000	25,000	5	22,000	67		
	AN-M-25	AM-C58S-T5	O-1A	44,000	27,000	4	27,000	81		
	AN-M-25	—	O-1HTA	47,000	30,000	5	30,000			
	AN-M-26	AM3S	M	29,000		2	11,000	46		
	AN-M-27	AM-C52S	FS-1	34,000	20,000	10	15,000	50		
Tubing	WW-T-825	AM-C57S	J-1	36,000	16,000	7	15,000	50		
		AM-C52S	FS-1	34,000	16,000	8	15,000	46		
		AM3S	M	28,000		2	10,000	42		

The mechanical properties of magnesium-alloy extrusions are given in Table 17. Army–Navy aeronautical specifications have been issued covering all the extrusion alloys used in aircraft construction. The specific characteristics of these general-purpose alloys with good mechanical properties are as follows.

AN-M-24. This is a general-purpose alloy with good mechanical properties. It is susceptible to stress-corrosion cracking if severely formed or welded. This can be relieved by an annealing treatment at 400°F. for one hour. This alloy also has a high notch sensitivity.

AN-M-25. This alloy has the highest strength and would normally be selected for primary structural applications. In the aged and the heat-treated and aged conditions its compressive yield strength almost equals its tensile yield strength.

AN-M-26. This alloy has good weldability to material of the same composition. It is moderately strong and is the cheapest of the extrusions.

AN-M-27. This has the best cold-forming characteristics and elongation. It also has good corrosion resistance.

WW-T-825. This specification superseded AN-T-71(JI). AN-T-72(FS1) and AN-T-73(M) and covers extruded tubing.

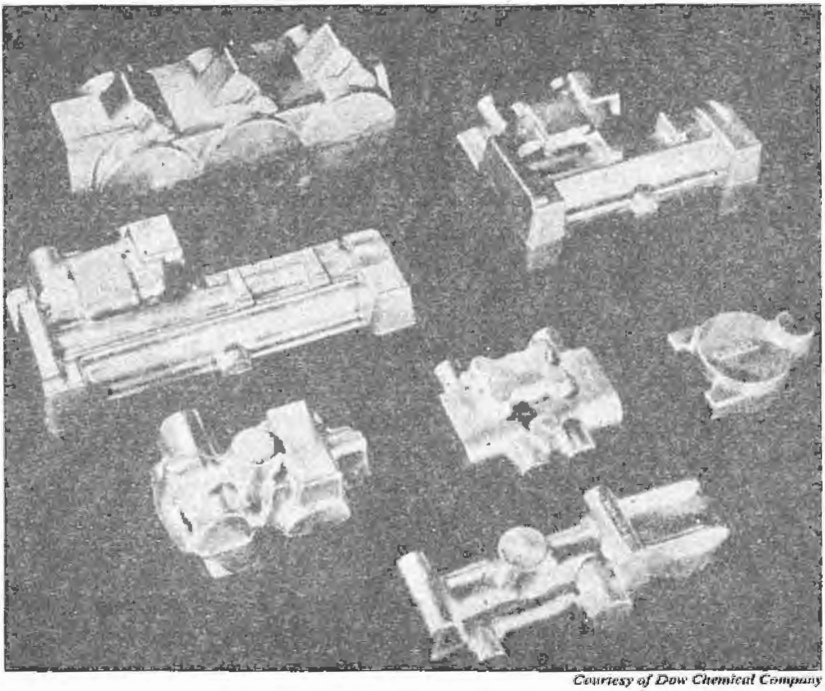
These extrusions are being used successfully for structural members, floor beams, moldings, stiffeners, seat framework, etc. Alloys AN-M-24 and AN-M-25 are ideal for screw stock.

Forgings. Magnesium-alloy forgings are sound, pressure tight, and light in weight. They are made from extruded stock which is a fine grained, partially worked, sound material. Forgings should be specified instead of castings if shock resistance, pressure tightness and great strength are required. The forging alloys are all weldable.

In the early days of the war this country used 5,000,000 pounds of magnesium castings in one year as compared to only 10,000 pounds of forgings. At about that same time the German ME-110 fighter and the JU-88 bomber were using about 100 pounds of magnesium-alloy forgings per plane. The JU-88 engine mount was a QQ-M-40 magnesium-alloy forging, 45 inches long, 14 inches wide, and with a projected area of 275 square inches.

Great progress in magnesium-forging practice and equipment has been made in this country in the last few years. Forgings up to 10 pounds in weight have been made for aircraft use, and a 17-pound forging has been made for other purposes. An 18,000-ton press standing 5 stories high and weighing over 5,000,000 pounds has been erected by the United States government in Worcester, Mass. This press is in the custody of the Wyman-Gordon Company and is available for production or research work by any company or agency with a large-forging problem.

In the design of forgings, sharp corners, notches, tool marks, and rapid changes of section should be avoided to minimize stress concentrations.



Courtesy of Dow Chemical Company

FIGURE 51. Press-forged Magnesium Hydraulic Parts

Generous fillets and radii of at least 1/8 inch should be provided. A 7° draft is required for hammer forgings but as low as 3° may be satisfactory for press forgings. Aluminum-forging dies are frequently usable for magnesium if the fillets and radii are generous.

A tolerance of 0.010 inch for dimensions under 2 inches ±0.003 inch for each additional inch can be held in width and length. For height dimensions across the parting line a tolerance of ±1/32 inch for small forgings and ±1/16 inch for large forgings is required.

The high-strength magnesium alloys must be press-forged, other alloys can be hammer-forged. Alloys J1 and O1 (QQ-M-40) are hot short when subjected to the rapid blows of a forging hammer. In press-forging these alloys it is sometimes necessary to apply top pressure for 1 minute to complete the metal flow. A press forge requires tremendous power as compared to a forging hammer: a 500-ton press is equivalent to a 1200-pound hammer. In many cases a forging is blocked out in the press and finish-forged in the hammer.

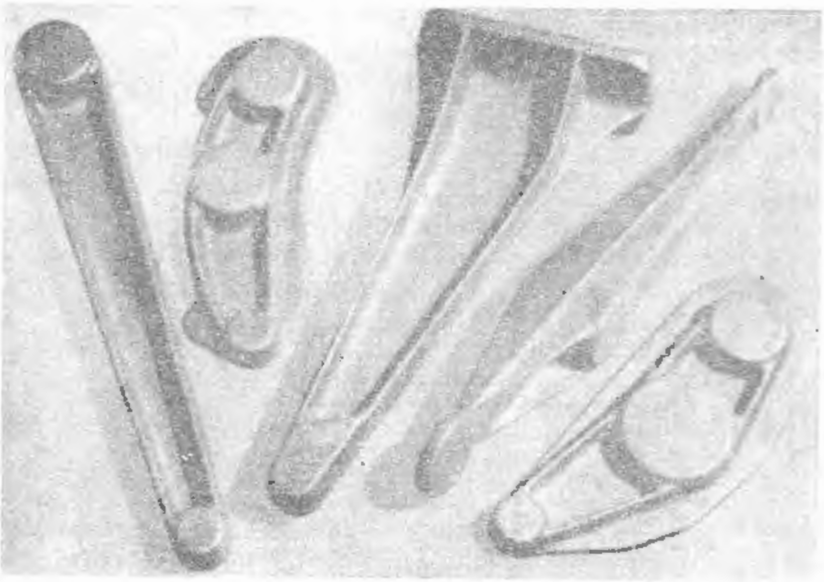


FIGURE 52. Hammer- and Press-forged Magnesium Control Parts

When this procedure is used it has been found desirable to finish the hammer forging when the part is at 400°F. At the start of forging the stock is at a temperature of between 600° and 775°F., depending on the alloy. The dies are heated to approximately the same temperature to prevent too rapid cooling of the forging stock.

The mechanical properties of the forging alloys are given in Table 18. Other properties are as follows:

J-1. This alloy has good formability and weldability. It can be forged into more intricate shapes than O-1.

O-1. This alloy is used when maximum strength is required. It is aged after forging for 16 hours at 325°F. to improve its strength but its elongation is reduced. To improve its creep resistance at elevated temperature the forged material can be treated for 2 hours at 700°F., water quenched, and then aged for 16 hours at 325°F. Crankcases have been forged of this material.

M-1. This alloy has the best formability and weldability but has relatively low strength.

D-1. This alloy is suitable for difficult designs, as it is easier to fabricate than J-1 or O-1, but does not have as good corrosion resistance or strength as those alloys.

Magnesium-alloy forgings have been used for aircraft-engine bearing caps, housings, rocker-arm supports, cargo-door and aileron hinges, hydraulic cylinders and valve bodies, levers, brackets, fittings, and crank cases.

TABLE 18. Magnesium-alloy Forgings—Mechanical Properties

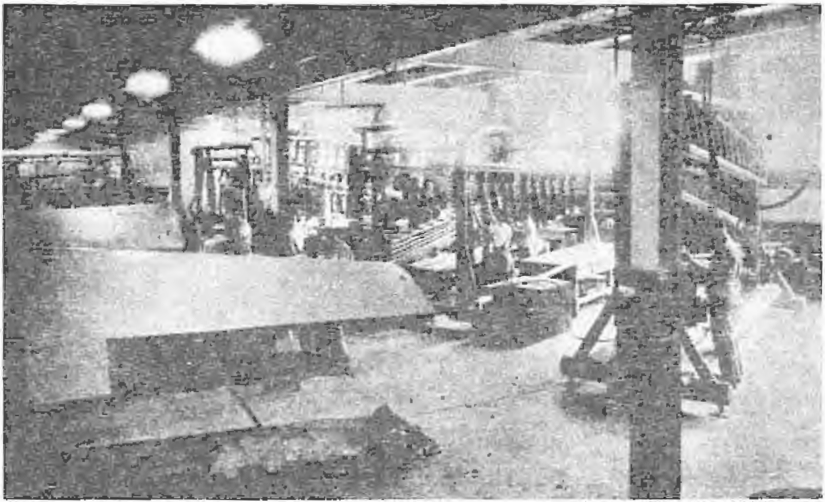
Specification			Tension			Compression yield (p.s.i.)	Brinell hardness (500 kg./10 mm.)	Fatigue, 500 X 10^6 cycles (p.s.i.)	Forging method
Federal	American Magnesium	Dow, Revere	U.t.s. (p.s.i)	Yield (p.s.i)	Elongation (%)				
	AM-C57S	J-1	38,000	22,000	6	14,000	55	16,000	Press
	AM-C58S	O-1	42,000	26,000	5	18,000	69	18,000	Press
	AM-C58S-T5	O-1A	42,000	28,000	2	20,000	72	16,000	Press
	—	O-1HTA	42,000	28,000	2	19,000	72	16,000	Press
QQ-M-40	AM3S	M-1	30,000	18,000	3		47		Hammer or press
	AM65S	D-1	36,000	22,000	7			10,000	Hammer
	AM-C52S	FS-1	35,000	22,000	10				Hammer or press

Letter A after alloy means forged and aged; letters HTA mean heat-treated and aged after forging; -T5 after alloy means forged and aged.

TABLE 19. Magnesium-alloy Sheet, Plate, Strip—Mechanical Properties

Specification			Tension			Compression yield (p.s.i.)	Brinell hardness (500 kg./10 mm.)	Shear (p.s.i.)	Fatigue, 500 X 10^6 cycles (p.s.i.)
Federal	American Magnesium	Dow, Revere	U.t.s. (p.s.i)	Yield (p.s.i)	Elongation (%)				
QQ-M-44	AN-C52S-O	FS-1a	32,000		12	16,000	56	21,000	12,000
QQ-M-44	AM-C52S-H	FS-1h	39,000	29,000	4	26,000	73	23,000	14,000
QQ-M-54	AM-3S-O	Ma	28,000		12	12,000	48	17,000	9,000
QQ-M-54	AM-3S-H	Mh	32,000	22,000	3	20,000	56	17,000	10,000

Letter a or O after alloy means annealed; letter h or H means hard rolled.



Courtesy of Dow Chemical Company

FIGURE 53. Assembly of Magnesium SNJ-2 Wings

Sheet, Plate, Strip. Three magnesium alloys are available in the form of sheet, plate, or strip stock. Each alloy is available in the annealed, as-rolled, or hard-rolled condition. The as-rolled condition is seldom specified. Sheet is material under 0.25 inch thick; plate is 0.25 inch or thicker; strip is material up to 8 inches in width and up to 0.125 inch thick. Strip may be coiled or as-sheared from sheet.

Sheet is available in thickness from 0.016 inch up. It can be obtained in lengths up to 144 inches and widths up to 48 inches. Strip is available in thickness from 0.016 to 0.051 inch in coils up to 125 feet long.

Due to the poor cold-working properties of magnesium alloys, sheets cannot be flattened by stretcher leveling. Rupture occurs in this process before the sheets are sufficiently stretched to lie flat. Sheet stock is flattened by placing it on a flat cast-iron surface and then superimposing additional cast-iron sheets to attain 300–450 p.s.i. pressure on the magnesium-alloy sheets. This assembly is then placed in a furnace. Annealed sheets require heating to 700°F. and cooling to 300°F., all under pressure; hard-rolled sheets require heating to 400°F. for QQ-M-54 alloy, and to 275°F. for QQ-M-44 alloys.

Magnesium alloy sheet can be drawn, spun, formed, and welded—either arc, gas or spot. Many of these operations have to be done at elevated temperatures because of the poor cold-forming characteristics of these alloys. These operations are described in detail later in this chapter.

The mechanical properties of magnesium-alloy sheet, plate, and strip are given in Table 19. Other properties are as follows:

QQ-M-44. Annealed sheet has the best cold formability but limited gas and arc weldability. Hard-rolled sheet has the best combination of fatigue and shear strength as well as toughness and low notch sensitivity.

QQ-M-54. Annealed sheet has the best gas weldability and hot formability. It is a low-cost alloy of moderate strength. Hard rolled sheet has the best resistance to creep at elevated temperatures but is seldom used.

Magnesium-alloy sheet is used in the construction of oil and fuel tanks, ducts, fairings, wing tips, flaps, ailerons, stabilizers, rudders, experimental wings, and other structural applications.

SHOP FABRICATION PROCESSES

The fabrication of magnesium alloys into finished articles may involve any number of the standard shop processes. Magnesium alloys can be machined, sheared, blanked, punched, routed, and formed by bending, drawing, spinning, pressing, or stretching. When these processes are applied to magnesium alloys the technique required differs somewhat from that used with other materials. The application of these processes to magnesium alloys will be described in the following pages.

Machining. Magnesium alloys have excellent machining characteristics. A smooth finish is obtained at extremely low cost. Surface grinding is seldom necessary. Machining can usually be done at the attainable speed of the machine. Light, medium, or heavy feeds can be used and the free cutting action of the material will produce well-broken chips which will not obstruct the cutting tool or machine. The power required for a given machining operation on magnesium alloys is approximately one-half that required for aluminum alloys and one-sixth that required for steel.

To take full advantage of the excellent machining qualities of magnesium, the machine equipment must permit operation at high speeds and feeds; sharp cutting tools of the correct design are necessary, and the part being machined must be rigidly supported. Due to lower cutting resistance, lower specific heat, lower modulus of elasticity, and the chemical properties of magnesium alloys, there are some essential differences in machining practice when compared with other metals. These differences may be summarized as follows:

1. Cutting edges must be kept sharp and tool faces polished to insure free cutting action and reduce the adherence of magnesium particles to the tool tip. Tools must be designed to allow for ample chip room, and tool clearances should be 10 to 15°. Large feeds are advantageous in reducing the frictional heat.

2. If the precautions of paragraph 1 are not taken the magnesium part being machined may distort, owing to excessive heat. This distortion is most likely to happen on thin sections, in which the heat will cause a large rise in temperature. Parts which tend to distort during machining can be stress-relieved by heating at 500°F., for 2 hours. If the part is stored for 2 or 3 days prior to finish-machining the same result is attained.

3. Magnesium cuts closer to size than aluminum or steel. Reamers should be specified several ten-thousandths oversize compared to those used on other metals; taps should be specified from several ten-thousandths to two thousandths oversize depending on the diameter.

4. Because of its lower modulus of elasticity, magnesium will spring more easily than aluminum or steel. Consequently it must be firmly chucked but the clamping pressure must not be great enough to cause distortion. Particular attention must be paid to light parts, which can easily be distorted by chucking or by heavy cuts.

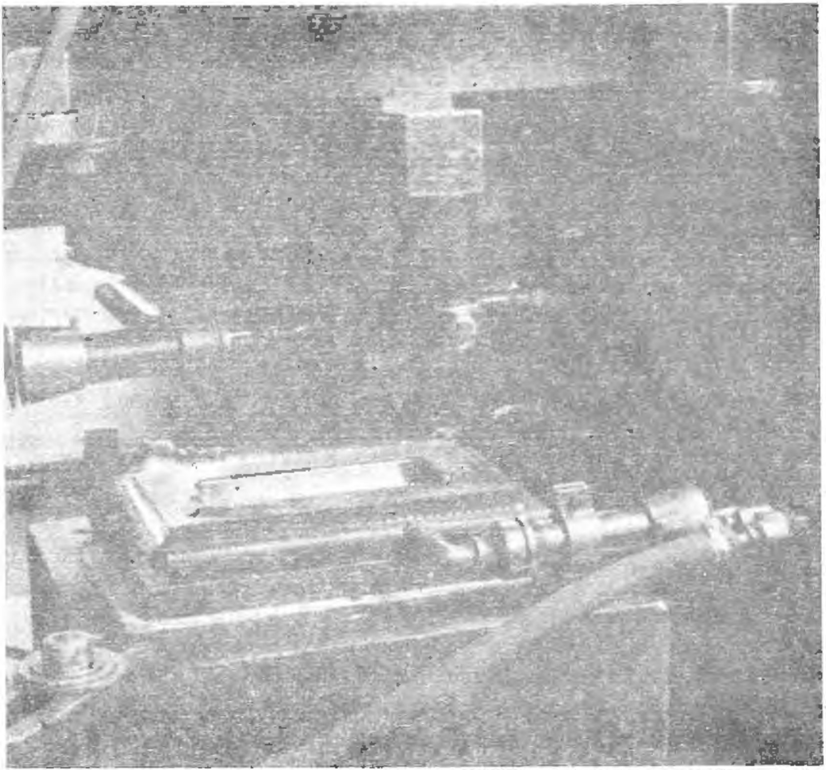
5. A cutting fluid* is used in reaming and in screw-machine work or when cutting speeds exceed 550 feet per minute. The cutting fluid is primarily a coolant. In all other operations magnesium can be machined dry with good results.

6. In grinding, a liquid coolant* should be used or the grinding dust should be exhausted and precipitated in water.

* Cutting fluids or coolants containing water should not be used without special precautions. Advice on machining practices can be obtained without charge from magnesium producers and fabricators.

Cutting tools designed for use with steel or brass can be used on magnesium but they must have a sharp cutting edge and good clearance. The basic principle in all cutting tools for magnesium alloys is to limit the friction to avoid the generation of heat and possible fire hazard. Carbon-steel tools can be used for reamers, drills, and taps, but high-speed steel is preferred and is most generally used. High-speed steel is also used for other types of cutting tools for magnesium, but cemented carbide tools have a much longer life and should be employed wherever possible.

Turning, shaping, and planing tools should be similar to those used for brass. Coarse-tooth milling cutters should be used, because the heavier cut obtained causes less frictional heat and consequent distortion. Ordinary twist drills and spiral reamers with about 6° relief behind the cutting edge give satisfactory results. Threading is readily done by means of taps, dies, or lathe turning. Roll threading is not satisfactory because it involves excessive cold working of the metal. Depths of tapped holes should be 2 or 3 times the diameter of the stud. Magnesium-alloy threaded parts will not seize when mated with other common metals or even with parts made from the same composition of alloy. Band or circular saws for cutting magnesium alloys should have from 4 to 7 teeth per inch and must be very sharp. Hand hacksaw blades should have 14 teeth per inch. Single-cut files are preferable for use with magnesium alloys.



Courtesy of American magnesium corporation

FIGURE 54. Hot Forming Magnesium Sheet—Gas Heating Dies

Precautions must be taken to reduce the fire hazard when machining magnesium alloys. Cutting tools must be sharp, and machines and floor must be kept clean. Scrap should be kept in covered metal containers. Lubricants should be used for automatic-machine work or when fine cuts are being made at high cutting speeds, to minimize the frictional heat. There is no serious danger from fire if care is exercised by the operator.

Shearing. In shearing magnesium sheet a rough, flaky fracture is obtained if the proper equipment is not used. The clearance between shearing blades should be on the order of 0.003 inch, and the upper shear blade should have a rake angle of around 45°. The sheared edge may be improved by a double shearing operation known as "shaving." This consists of removing an additional $^1/_{32}$ to $^1/_{16}$ inch by a second shearing. The maximum thicknesses recommended for cold shearing are 0.064 for hard-rolled sheet and 1/8 inch for annealed sheet. These thicknesses can be increased if shearing is done at an elevated temperature, but in any case sawing should be resorted to for cutting plate.

Blanking and Punching. These operations are practically the same as those used for other metals. A minimum clearance between the punch and the die is essential to obtain maximum edge smoothness. This clearance should not exceed 5% of the thickness of magnesium being worked. The punch and die are frequently made of materials of unequal hardness, so a sheared-in fit providing minimum clearance can be obtained. Magnesium alloys can be punched and blanked at room temperatures but better results are obtainable at elevated temperatures.

Routing. Routing magnesium alloys is a simple, straightforward operation. Dry routing can be done with little fire hazard if the router bit is sharp and the chips are thrown free. A low-viscosity mineral-oil coolant is frequently used as insurance against fire. Router bits of the single or double-flute type with polished flutes to provide good chip removal are used. Spiral-flute routers pull the chips from the work and have less tendency to load up.

Forming Magnesium Alloys. Magnesium-alloy sheet and extrusions, including tubing, can be processed with the same type of equipment used for other metals. One major difference is the necessity for heating the tools and the work since many of the forming operations must be done at elevated temperatures because of the close-packed hexagonal crystal structure of magnesium alloys. This crystal structure severely limits the amount of work that can be done at room temperatures without inducing a shear failure. At around 400°F. recrystallization occurs with a resultant decrease in tensile strength and increase in ductility. At about 440°F. a second set of cystallographic slip planes comes into action, with marked increase in capacity for plastic flow. As the temperature is further increased the ductility also increases and may reach a point as much as nine times the ductility at room temperatures.

The recommended forming- or working-temperature ranges are given in Table 20. In addition, the minimum bend radii are given for room temperature and for the reeommended working-temperature range.

It will be noted that the working-temperature range for hard-rolled parts is lower than for annealed material. Hard-rolled parts are stronger because of the cold working they received when rolled at the mill. If they are heated to a high temperature they will revert to the annealed condition and lose their strength. When hard-rolled sheet is specified, parts must be designed to permit forming at temperatures that will not anneal the material excessively.

The working of magnesium alloys at elevated temperatures involves the development of new shop techniques and methods of heating the equipment and work. There are several compensating advantages, however, in working at elevated temperatures. For one, parts can be formed in a single operation, without intermediate drawing dies. Secondly, springback is eliminated at the upper temperatures of the working range and is greatly reduced at the lower temperatures. Thirdly, by varying the temperature of the die it is possible to correct the size of parts which might be outside permissible tolerance limits due to errors in die construction or material variations.

TABLE 20. Magnesium Alloys—Forming Temperatures and Bend Radii

Alloy	Condition	Working temperature range (°F.)	Bend radii for 90° bends (material) up to 0.125 in. thick (t=thickness)	
			Working temperature	70°F.
QQ-M-44	Annealed	400–500	1–2t	5t
QQ-M-44	Hard rolled	275 or 300 (less than 15 min.)	5–6t	8t
QQ-M-54	Annealed	550-650	1–2t	6t
QQ-M-54	Hard rolled	400 max.	6–7t	9t

When magnesium alloys must be hot-formed it is desirable to preheat the sheet or extrusion to the working temperature. Gas or electric furnaces, immersion baths, or hot contact plates may be used. Preheating the work minimizes distortion due to internal stresses, keeps the dies at a uniform temperature, and increases the production rate.

In the following pages a short description of several common methods used in forming magnesium alloys will be presented: hand forming; bending of sheet, strip, extrusions, and tubes; drawing; pressing; sizing; spinning; roll forming and die drawing; stretch forming; drop hammering.

Hand Forming. In hand forming the material should be clamped in a soft-jawed vise or to a form block. A heat-resisting wood such as birch or a metal should be used for the form block. Metal form blocks made of magnesium alloy have the advantage of having the same thermal expansion as the work. The form block may be preheated in an oven or electrically heated. The work can be heated by conduction from the hot form block, it can be preheated, or it can be heated with a torch. If it is torch-heated, a contact pyrometer should be used to avoid overheating. A leather maul should be used for hammering. Hand forming should be used if the quantities are too small to justify the manufacture of dies, or if the part is very intricate.

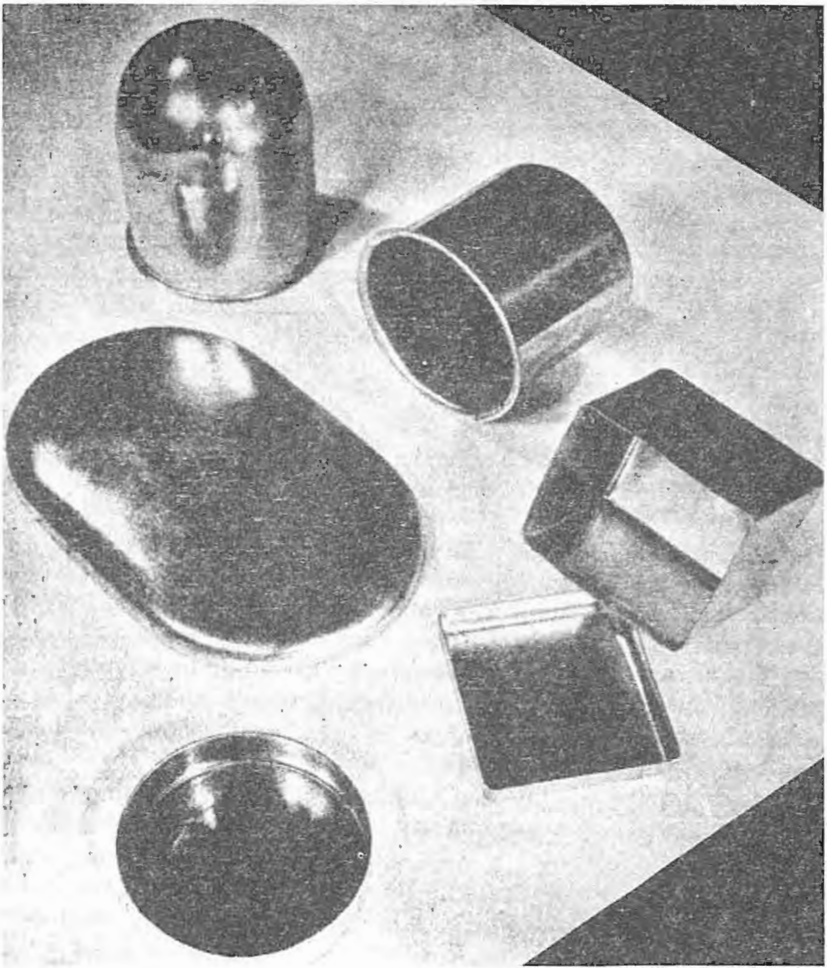
Bending. Machine-bending is frequently used for the manufacture of stringers, clips, and stiffeners made from sheet or strip. A press-type brake is used almost exclusively because of the ease with which it can be equipped with strip electric heaters on either side of the dies. Bends of the smallest possible radii are obtainable if a very slow press speed is used to finish the bend. When possible, both the dies and the work should be heated. If the dies alone are heated the work will absorb heat by contact and can be bent satisfactorily. If the work alone is heated, the bending operation must be rapid, before the dies dissipate the heat at the bend. Bends parallel to the grain direction are easier to make because of the greater elongation of magnesium alloys in the transverse direction.

Ordinary bending rolls are satisfactory for forming single-curvature sheet-metal parts. These can usually be formed cold, since the radius of the rolls is greater than the minimum permissible bending radius. The sheet is sometimes heated, however, to eliminate springback on small-radius bends.

Extrusion bending. Extrusions may be bent by hand, using a torch for heat and a contact pyrometer to avoid overheating. Production bending can be done with standard angle rolls, with mating dies, or on a stretch-forming machine. The work should be preheated if the working is severe, and the dies also if the operation is slow or the extruded section is large. Forming temperatures of 600°F. permit very severe working of all the extrusion alloys. Only alloy AN-M-25 is limited as to working temperature. If it is not to be aged after forming it can be worked at 600°F., the same as the other alloys. If this material is worked between 350° and 500°F. it will be partially aged, with a resultant increase in strength and reduction in ductility. Material in the aged or heat-treated and aged condition can be formed up to a temperature of 380°F. without change of properties. At this working temperature the alloy in these conditions can be bent about the same as the unaged alloy at room temperature.

Tube Bending. Standard pipe-bending machines using an internal mandrel can be used for bending magnesium-alloy tubing. Small-radius bends may require heating, as with other materials. If hot tubing is to be bent about a wood form it is advisable to metal-face the form. J-1 and FS-1 alloy can normally be bent at room temperature, while M is more likely to require heating.

Shallow Drawing and Pressing. In shallow drawing the parts are more pressed than drawn, since there is very little metal flow. Wing ribs, door-reinforcing panels, and fairings are typical examples of parts fabricated by this method. The Guerin patented process of using a rubber pad as the female die is most frequently used, although male and female metal dies would be justified for large quantities. In the Guerin process a rubber pad 6 to 10 inches thick is contained in a metal box and acts as the female die. A heated male die and work blank are placed on the platen of the press and the female rubber die brought in contact with them. A pressure of 1000 p.s.i. is exerted through the rubber and the blank assumes the shape of the male die. Synthetic



Courtesy of Dow Chemical Company

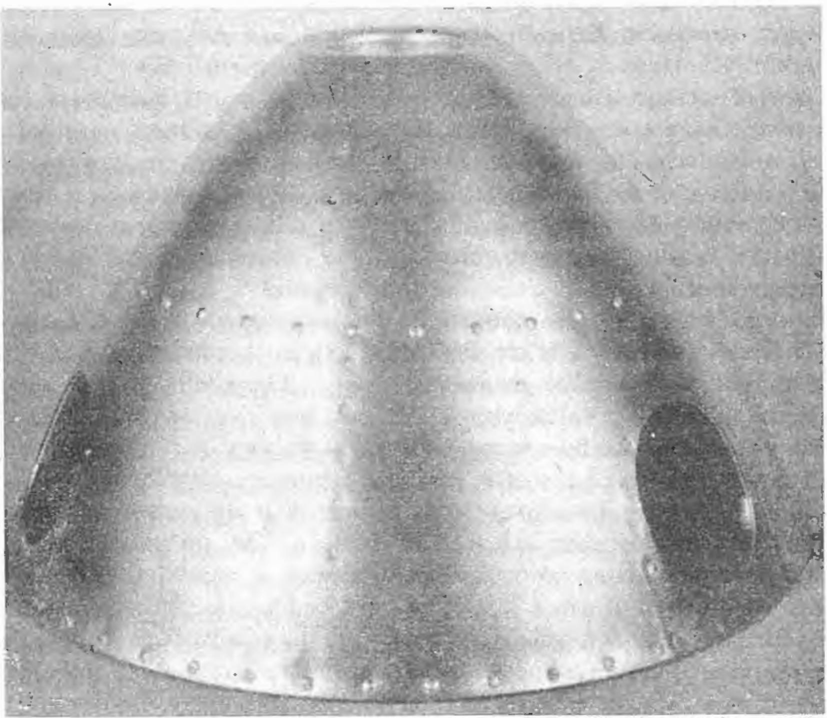
FIGURE 55. Drawn Magnesium Parts

rubbers or specially compounded natural rubbers are required for working temperatures up to 450°F. Ordinary rubber is satisfactory for temperatures up to 350°F. To prevent the rubber from sticking to the formed part, cornstarch or flaked mica is spread on the blank prior to pressing. Since in the Guerin process only a male die is needed it can be produced cheaply and revised when necessary without great difficulty. The male die is best made of magnesium to avoid differences in thermal expansion between the blank and the die. If aluminum is used it should be made approximately 1.002 oversize, if steel or iron approximately 1.004 oversize, to compensate for the differences in thermal expansion between these materials and the magnesium-alloy blank.

Deep Drawing. Oil-tank ends, nose spinners, wheel dust covers, and hub caps have been deep-drawn successfully. Cylindrical cups can be deep drawn to a depth 1½ times their diameter in a single draw—which is a reduction of 60% to 65%. Square junction boxes can be drawn to a depth equal to the side dimensions. Either a hydraulic or a mechanical press can be used for deep drawing. For maximum depth draws the clearance between the die and the punch should be from 0.25 to 0.35 of the stock thickness plus the stock. As explained above, dimensional allowances must be made for the differences in thermal expansion if the die material is other than magnesium alloy. The male die or punch can be magnesium alloy, cast steel, or cast iron. Dies of mild steel which has been stress-relieved have been used quite generally. Heat-resisting Meehanite cast iron gives promise of working out very well as die stock. Draw rings and pressure pads are made of mild steel which is highly polished and well lubricated. The pressure pad should impart sufficient pressure to the blank to prevent wrinkling but not too much to prevent it from being drawn through the clamping surfaces. Preheating the work blanks and heating the dies to working temperature are essential to insure proper drawing temperature and a uniform product. The blank should be lubricated on both sides as well as the die surfaces to prevent scoring or galling. Colloidal graphite suspended in a volatile carrier such as alcohol or naphtha may be sprayed on both sides of the blank; other commercial products can also be used. If colloidal graphite is to be used, sheet should be ordered with an oiled finish instead of the customary chrome-pickled finish. This specification is necessary because of the extreme difficulty of removing graphite from a chrome-pickled surface. For lubricating the dies, a mixture of 20% graphite in tallow applied by buffing with an asbestos cloth is satisfactory.

Sizing. Sizing is a cold operation employed to bring hot-drawn work closer to tolerance. When extremely accurate tolerances are required the part is normally drawn slightly oversize and then sized cold to finish dimensions. A cold-sizing die consists of a punch and a draw ring, both slightly undersize to allow for springback. The punch forces the part through the draw ring and the operation is completed.

Spinning. Spinning is used to fabricate circular articles such as propeller spinners and wheel caps. In this operation the blank is clamped against a maple or metal chuck which is shaped to the desired form. The chuck is then supported in the spinning lathe and rotated at the proper speed so that the



Courtesy of American magnesium corporation

FIGURE 56. Magnesium Propeller Spinner

part of the blank being worked on will move past the tool at from 1700 to 1900 feet per minute. The operator uses a wedge or a hardwood stick to force the blank against the chuck, whose shape it then assumes. Laundry soap or a mixture of 2 parts tallow and 1 part paraffin are satisfactory lubricants. Moderate spinning may be done at room temperatures. Normally, however, the blank should be heated to between 500° and 600°F. by a gas torch, a properly disposed ring of gas burners, or by conduction through a heated metal chuck. The area of original blank should be about the surface area of the finished part. The fact that material is thinned somewhat in spinning allows sufficient additional area for trimming.

Roll Forming and Die Drawing. This method of fabrication is used for the production of shapes with thin walls that cannot be extruded. It consists of drawing strip through a series of dies or rolls, each set of which changes the shape, somewhat nearer to the finished shape desired. Heated strip, adequate bend radii, lubrication, and gradual changes in shape are all necessary for this type of fabrication.

Stretch Forming. In stretch forming, the work is held in the jaws of two machines and pressure is applied between the blank and the die. Stretch forming is used primarily to obtain double curvature of a surface. It is essential that the die be heated and the blank should be preheated by conduction from the die. Temperatures of from 450° to 550°F. are normally used. If the magnesium-alloy sheet is held in the jaws of the stretching machine they should be lined with emery cloth rather than with serrations which would rupture the metal. Another method is to sandwich the magnesium blank between the die and a preformed mild carbon sheet which is held in the jaws of the machine. In this case the magnesium is not inserted in the jaws. Dies in this operation should be designed for some overforming to allow for springback and creepback during cooling.

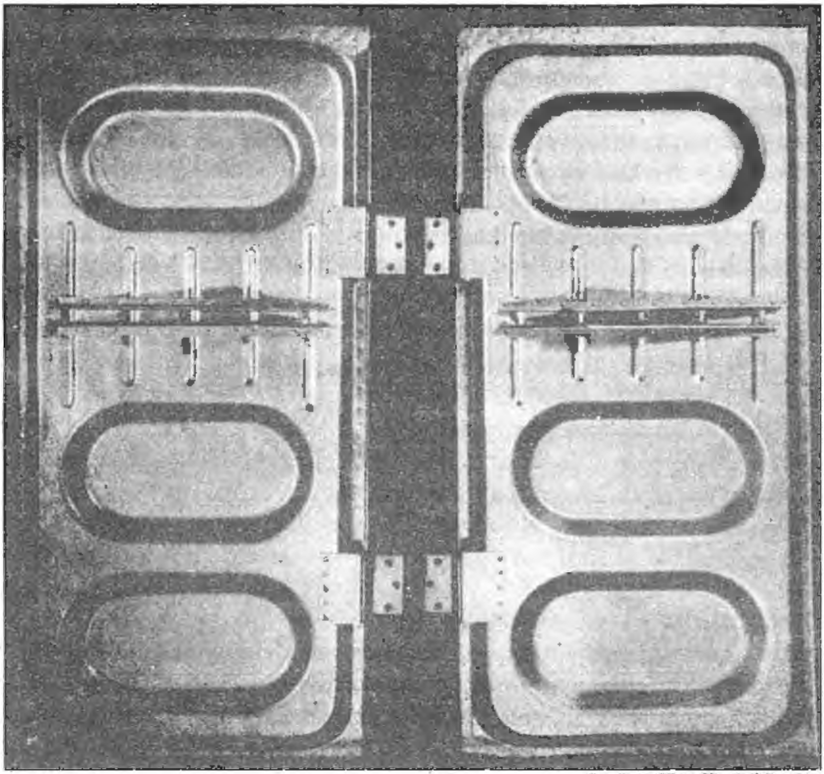
Drop Hammering. Drop hammering is not practical due to the difficulty in keeping the work heated long enough to complete the operation. Some drop-hammered parts have been made, but they required several reheatings of the material.

JOINING METHODS

Most of the standard methods of joining metals are adaptable for use with magnesium. Riveting, gas welding, arc welding, and spot welding are commonly used. The adaptations of these processes to magnesium alloy are described in the following pages.

Riveting. Riveting is the most commonly used method of assembling magnesium-alloy structures. Special consideration must be given to rivet selection, design of joints, driving technique, and corrosion protection of the assembly.

Magnesium-alloy rivets are not practical because they work-harden too rapidly when driven cold. Aluminum-alloy rivets of 1100, 2117, 2017, 2024, 5056-O, and 5056-H32 have all been used in assembling magnesium alloys. For aircraft work the use of 5056-H32 is recommended for all purposes except flush riveting in which case 5056-O rivets are used. Rivets 2117 can be used for field repairs but require assembly with wet zinc chromate primer and good paint protection to minimize corrosion. Rivets 5056 contain 5% magnesium and no copper and are less subject to galvanic corrosion than any of the other rivets listed above. The 5056-H32 rivets can be used as received, no heat-treating or quenching being required. They can be driven cold up to $^5/_{16}$-inch diameter. If it is necessary to drive rivets over this diameter they



Courtesy of Dow Chemical Company

FIGURE 57. Magnesium-alloy Aircraft Doors Assembled by Riveting and Spot Welding

should be heated to 650°F. The 5056-H32 rivets have a minimum ultimate shear strength of 24,000 p.s.i.; 2025 rivets have a strength of 25,000 p.s.i.

For well-balanced joints, rivet diameters should not exceed 3 times the thickness of the sheet, and should not be less than the thickness of the heaviest sheet being joined. For proper heading the rivet shank should produce from 1 to 1.25 rivet diameters; this protrusion will give a flat aircraft-type bucktail with a minimum height of 0.4 rivet diameter, and minimum diameter of 1.33 rivet diameter. An edge distance of 2½ times the rivet diameter is recommended to prevent cracking or bulging of the edge of the sheet. A rivet spacing of 4 times the rivet diameter is the minimum recommended.

Structural rivet holes should be drilled and not punched. Punching gives a hole with a flaky edge which is likely to crack under load. Nonstructural sheets up to 0.040 inch thick can be punched if desired. In drilling, the use of a drill with a 10° helix angle will give smooth, accurate holes. When parts are clamped or assembled prior to drilling they should be disassembled after drilling and the chips removed. If this is not practical an air hose should be used to clean the chips away.

Pneumatic hammers or squeeze riveters may be used, but excessive pressures and indentation of the magnesium should be avoided. The standard types of rivet heads may be used in assembling magnesium alloys. Up until recently it was necessary to use countersunk rivet heads with 120° included head angle, but now it is possible to satisfactorily dimple sheet for the standard 100° rivet heads. As stated above, 5056-O countersunk rivets must be used to minimize the cracking of the sheet under the riveting pressure.

Machine countersinking is limited to minimum sheet thicknesses for each diameter of rivet if efficient riveted joints are to be obtained. The recommended minimum are as follows:

Rivet diameter (inch)	*Minimum sheet thickness for countersinking (inch)*
$^3/_{32}$	0.040
$^1/_8$	0.051
$^5/_{32}$	0.064
$^3/_{16}$	0.081

When flush riveting is required for thinner sheets than those listed, it is necessary to pressure-countersink the sheet.

In pressure countersinking magnesium-alloy sheet, it is necessary to heat in the vicinity of the dimple. This heating is best done by using dies electrically heated to between 450° and 550°F. The work is heated locally by contact with the dies. By this method 15 to 30 dimples per minute can be made in production. A 5000-pound dimpling machine will make $^3/_{16}$-inch dimples satisfactorily in 0.072-inch sheet. Prior to dimpling, holes should be punched or drilled at least 15% smaller than the rivet diameter. After dimpling, the holes should be drilled or reamed to the correct size and burred. A sharp edge should not be left on the dimpled sheet against which the rivet head is to be formed, if cracking is to be avoided. This edge should be removed and a flat provided of about 1.33 times the rivet diameter.

The 5056 rivets do not require any particular corrosion-preventive methods when used for assembling magnesium alloys. Any other type of rivet should be set in wet zinc chromate primer. If it is necessary to use steel or brass rivets, bolts, or nuts, they should be cadmium or zinc chromate coated. All faying surfaces should be painted with two coats of zinc chromate primer before assembly.

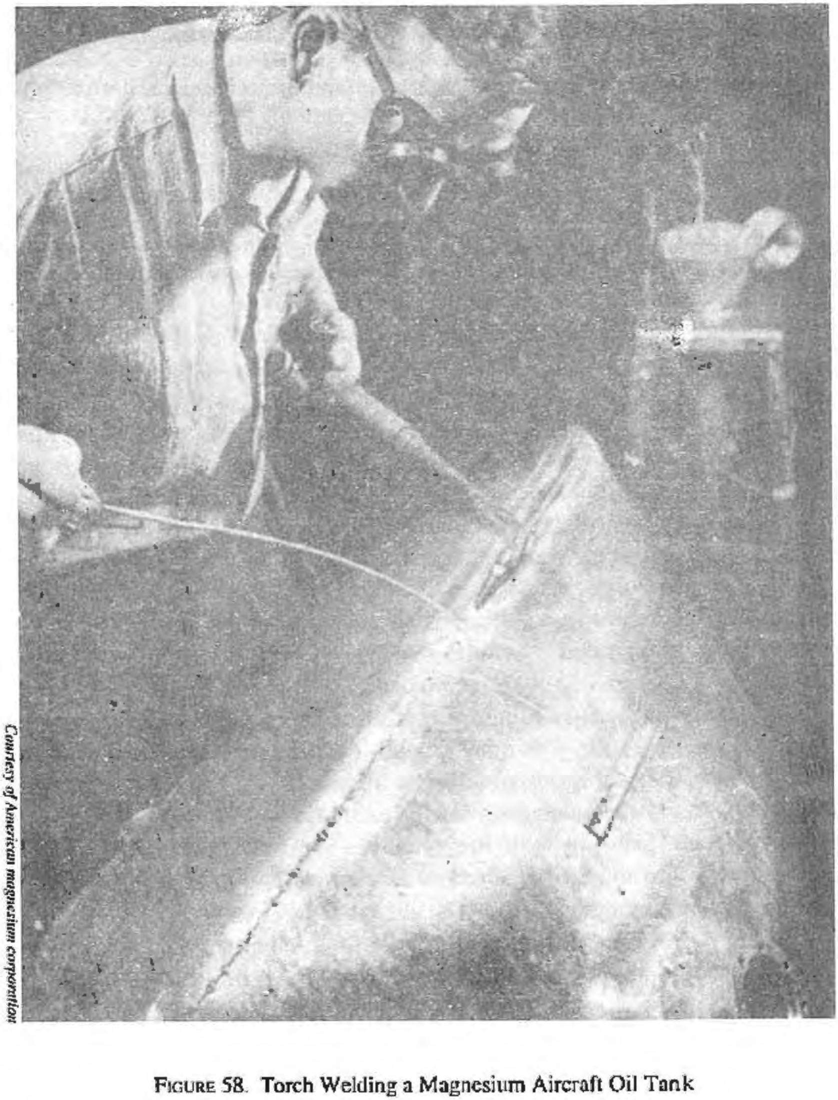
Gas Welding. Magnesium alloys can be gas-welded, using oxyactylene, oxyhydrogen, or oxycarbohydrogen gas. Oxycarbohydrogen gas is a mixture of hydrogen and methane. When using any of these gases a neutral or slightly reducing flame should be used. Oxyacetylene can only be used with difficulty on sheet thinner than 0.064 inch.

Standard welding equipment and torches are used for welding magnesium. A variety of tips from 0.035 to 0.081 inch should be available for use. An extruded filler rod of the same composition as the material being welded should be used. If two different alloys are being welded together the filler rod should match the alloy with the lower melting point. Filler rods melt between 1100° and 1200°F. Filler rods are available in diameters from 1/16 to ¼ inch. A 1/16-inch rod is satisfactory for welding 0.020-inch sheet, a 3/32-inch rod for intermediate thicknesses, and a 1/8-inch rod for 0.128-inch material. A flux must be used to coat the rod and either side of the edges to be welded, in order to prevent oxidation of the metal. Fluxes are usually purchased in the form of powder, which must be stored in tightly closed glass bottles because of its hygroscopic nature. The flux paste for use in welding is prepared by mixing 2 parts of powder with one part of water, by volume.

Only butt joints may be made in gas-welding magnesium alloys. In any other type of joint the hygroscopic, corrosive flux may be trapped in the joint with disastrous results. For the same reason, it is necessary to make welds with a single pass. This limits the material that can be welded to ¼-inch thickness. To allow for warpage and shrinkage a 1/16-inch or larger gap should be allowed between the mating edges to be welded. For thin material up to 0.040 inch thick this allowance is not essential, but the edges should be flanged up 1/16 to 1/8 inch. A gap up to 3/8 inch wide can be filled in when using thicker material. This fill is sometimes useful in making repairs. When material over 1/8 inch thick is to be welded, the top corners of the seam should be beveled before welding.

Before welding, all oil, grease, and dirt should be removed by means of gasoline or carbon tetrachloride. Any oxide or chemical coating should be removed from the edges to be welded by using steel wool, a wire brush, or a file. Welding on a chrome-pickled surface will result in weld porosity and impair the free flow of the material.

The work should be placed in a jig to hold it in alignment while being tack-welded. In tack welding the torch is held almost prependicular to the surface. Tack-welds are made from 1½ to 6 inches apart, depending on the thickness of the sheet and the nature of the part. Usually the work is then removed from the jig and finish-welded. In running the seam weld, the torch should be held at 45° to the work. The rod should be held in the outer flame until the base metal melts and forms a puddle, and then the rod should be dipped in the



Courtesy of American magnesium corporation

FIGURE 58. Torch Welding a Magnesium Aircraft Oil Tank

puddle intermittently. At the end of the seam the torch should be lifted slowly to prevent too rapid cooling and the formation of a crater. Leather or wooden hammers may be used for straightening buckled or warped seam welds. This hammering improves the strength of the weld. If large deformations must be straightened, the work should be reheated to 600° to 750°F.

Immediately after welding the following operations should be performed:

1. Wash in hot running water, and scrub with a stiff bristle brush until all traces of the flux are removed and the surface is clean.
2. Chrome-pickle the work by immersing it for one minute in the following solution: 1.5 pounds of sodium dichromate, 1.5 pints of concentrated nitric acid, enough water to make 1 gallon.
3. Wash in cold running water.
4. Boil for 1 to 2 hours in the following solution: 0.5 pound of sodium dichromate, enough water to make 1 gallon.
5. Rinse in cold water, followed by a dip in boiling water.

Magnesium-alloy welds may be inspected visually, by radiography, or by the fluorescent oil penetrant method.

Only the 1.5% manganese alloy gas welds readily. This alloy is available as sand castings (QQ-M-56), sheet (QQ-M-54), extrusions (AN-M-26), tubing (WW-T-825) and forgings (QQ-M-40). The other alloy which is available in sheet form, QQ-M-44, is limited to free welds only without any restriction. When sheet material is welded to castings or to forgings of heavier sections, the mating edge must be tapered or beveled to the sheet thickness. The heavy part should also be preheated to 600–700°F.

Arc Welding. In arc welding magnesium alloys there is no restriction on the type of joint used. An inert-gas shield is used to prevent oxidation in place of the corrosive flux that limits gas welding to butt joints. This inert-gas shield makes multipass welds possible and removes the limitation on the thickness of material that can be welded. There is less warpage with arc welding than with gas welding because the higher heat available is more localized and fuses the joint quickly with less diffusion of heat to adjacent areas. All wrought magnesium-alloy materials have good arc-weldability except QQ-M-44 sheet, which is limited to unrestrained welds if cracking is to be avoided. This is the same limitation this material has when gas welded and its strength with either type of weld is the same. Arc welds in QQ-M-54 material are stronger than the equivalent gas welds.

For arc welding magnesium alloys a direct-current or rectified-alternating-current machine of 100- to 200-ampere capacity is required. A machine with a stable arc equipped with a continuous amperage regulator to provide adequate current control is necessary. In arc welding magnesium, reversed polarity (electrode positive, work negative) is used. A tungsten electrode has been found to do the best job. The arc between the electrode and the work is enveloped in an inert-gas shield which excludes oxygen from the weld area and prevents oxidation. Either helium or argon may be used. The inert gas is fed from a cup about ½ inch in inside diameter which surrounds the electrode except for ¼ to 3/8 inch at the tip. A tungsten electrode diameter increases to

3/16 inch for 0.125-inch sheet.

In arc welding, a good rigid jig must be used to hold the work in position. The complete welding operation is done in the jig, and usually tack welding is not necessary if the jig is properly constructed. A good jig will reduce warpage and hold the joints tight. No gap between joints is permissible.

Good cleaning of the joints to be welded is a must, as previously described under Gas Welding. In the welding operation the torch should be held perpendicular to the work to provide the best shielding by the inert gas. The filler rod should be fed to the arc and not dipped in the molten puddle. The filler rod should preferably be of the same composition as the material being welded. A filler rod 1/16 inch in diameter should be used for 0.030-inch sheet, increasing to 1/8 inch diameter for 0.125-inch sheet.

After welding it is essential that the assembly be stress-relieved by heat treatment to release residual stresses that will otherwise cause stress-corrosion cracking. These internal stresses may run as high as 15,000 p.s.i. The heat treatment must be done with the work held in a jig to prevent warpage. For annealed material the relief treatment consists of heating the work at 500°F. for 15 minutes; for hard-rolled material it must be heated for one hour—at 265°F. for QQ-M-44 sheet, and at 400°F. for QQ-M-54 sheet. After heating the work should be cooled in still air.

Since no flux is used, the welds need only be wire-brushed. Inspection of the welds should be made for undercutting, cracks, porosity, craters, overlapping, or inclusions. Visual examination, radiography, or the fluorescent oil penetrant method may be used.

Spot Welding. Spot welding of magnesium alloys has been limited to low-stress applications, and to parts not subject to excessive vibration. Service experience on these secondary applications has been satisfactory thus far but additional experience will be required before spot welding can be generally adopted for primary aircraft structural use. All sheet and extrusion alloys can be spot-welded either to alloys of like composition or to the other alloys. The ease with which alloys of different composition can be spot-welded to each other is determined by the similarity of the alloying elements present in each. The spot welding of AN-M-24 composition material to QQ-M-54 is very difficult because of the great difference in their chemical composition. Two parts of unequal thickness can be spot-welded together if an electrode with a larger contact area is used against the thicker material.

Alternating-current or direct-current stored-energy spot-welding machines as used for aluminum alloys are satisfactory for use with magnesium alloys. Water-cooled electrodes with 2- to 8-inch dome tips are preferable.

Areas to be welded must be free of pickle coatings or oxidized surfaces. Material to be spot-welded should be purchased oiled instead of chrome-pickled to simplify the cleaning operation. Chemical cleaners are still in the experimental stage (immersion in a 20% chromic acid solution at 150°F. for 2 minutes appears to have promise), so wire brushing must be resorted to in order to clean the areas to be welded. Both sides of the sheet must be cleaned. A power-driven wire brush rotating at over 2500 feet per minute peripheral speed is used. The side of the sheet which the electrode will touch must then be finished with No. 3 steel wool or No. 160 to 240 aluminum oxide cloth. Small areas can be hand cleaned by using stainless steel wool or aluminum oxide abrasive cloth. Stainless steel wool is preferred for its nonmagnetic qualities.

The diameters of proper spot welds vary from 0.20 inch for 0.020-inch sheet to 0.375 inch for 0.10-inch sheet. Weld penetration should be from 30% to 80% into each of the parts being welded together. Weld penetration and diameter can be determined by cutting a cross-section through the weld, smoothing the surface with emery cloth, and etching for 10 seconds with a 10% to 50% solution of acetic or tartaric acid. The weld zone will darken and become quite visible.

Copper pick-up in the spots from the electrode will cause corrosion and must be avoided. The presence of copper will show up as a black discoloration after chrome pickling or etching with a 10% acetic acid solution. If copper is found, the welds should be cleaned up with steel wool or aluminum oxide cloth.

Spot welds can be made through faying surfaces freshly coated with zinc chromate primer. The primer must be well thinned so that it will squeeze out from under the spot when the pressure is applied and permit good metal-to-metal contact. Protective coatings for faying surfaces are adversely affected by the dichromate treatment finally given most magnesium-alloy assemblies. It is generally considered desirable to omit the faying-surface protection in favor of the dichromate treatment. This treatment is described in the chapter on Corrosion.

Inspection of the spots for cracks and porosity may be accomplished by microscopic examination or by radiography.

CORROSION RESISTANCE

Magnesium, in common with other metals, is subject to corrosion. In recent years its resistance to corrosion has been greatly improved and is now equal to or better than that of many commonly used metals. This advance in corrosion resistance is largely due to the introduction of the controlled-purity type of alloy. In these alloys impurities such as iron, nickel, and copper are limited to very small percentages. The use of chemical treatments that provide a passive surface layer and make a good paint base is also essential for aircraft use.

Military Specification MIL-M-3171 describes the following four protective treatments for use on magnesium alloys:

Type I—Chrome-pickle treatment. Used to protect parts in shipment, storage, or during machining.

Type II—Sealed chrome-pickle treatment. A modified chrome-pickle treatment adaptable to all magnesium alloys. It is an alternative finish to Types III and IV when a dimensional change is permissible.

Type III—Dichromate treatment. Provides maximum protection and paint adhesion and has no effect on dimensions of parts. Applicable to all alloys except the 1.5% manganese alloy as covered by QQ-M-54 for sheet material.

Type IV—Galvanic anodizing. This treatment is recommended for use on the 1.5% manganese type alloy. It is also applicable to the other alloys. No dimensional change.

These processes are described in detail in the chapter on Corrosion.

The corrosion of magnesium alloys may be caused by any one of the following circumstances:

1. *Environmental.* Salt atmospheres are much worse than inland exposures. In ordinary atmospheres bare magnesium alloy will form a protective coating of magnesium hydroxide, which is porous but subsequently is converted to hydrated carbonates and sulfates that are nonporous. This surface film cannot be relied on for general usage, however, and one of the protective treatments listed above plus paint protection is required to resist atmospheric corrosion.

2. *Galvanic Corrosion.* Metal-to-metal contact will create a galvanic cell when moisture is present, as is more fully described in the chapter on Corrosion. This condition is developed even when two magnesium alloys of different compositions are in contact, particularly QQ-M-54 material and one of the other magnesium alloys. A protective treatment and two coats of zinc chromate primer in the faying surfaces are required for protection. When two dissimilar metals are used, this protection plus the insertion of an insulating material between the faying surfaces is desirable. Magnesium is the least noble of all the structural metals and consequently is the one to suffer when galvanic corrosion is set up. Fortunately, 56S aluminum-alloy rivets and the magnesium alloys do not react on each other. These rivets exclusively should be used in assembling magnesium-alloy structures.

3. *Surface Contamination.* Metallic impurities in the surface resulting from wire brushing or similar operations should be removed by acid pickling or by chrome pickling. Welding flux resulting from gas welding should be removed by chrome pickling and boiling in a dichromate solution, as described under Gas Welding earlier in this chapter.

4. *Stress Corrosion.* This type of corrosion occurs when a part with internal residual stresses is subject to corrosive influences. It is evidenced by cracking or fracture without any prior evidence of surface corrosion. Stresses above 25% of the yield strength will cause this type of failure. Sheet material in accordance with QQ-MM-44 that has been arc-welded is particularly subject to this type of corrosion. The relief of stresses by heat treatment is essential. This operation has been described earlier in this chapter under Arc Welding.

CHAPTER XIV

METAL-JOINING PROCESSES

METALS may be joined by mechanical means (such as bolting or riveting) or by welding, brazing, soldering, or adhesive bonding. All of these methods are used in aircraft construction. There are three general types of welding: gas, electric arc, and electric resistance welding. Each of these types of welding has several variations which are used in aircraft construction and are described in the following pages. Copper-base alloy brazing, silver brazing, and aluminum brazing are all used in aircraft work. Soldering is never used for structural purposes but is frequently used in electrical work. Adhesive bounding by such processes as cycle welding has many applications in aircraft manufacture.

The processes mentioned above are described in the following pages. In many cases additional data applicable to a specific material have been presented in the chapter in which the material was described.

GAS WELDING

Aircraft fittings fabricated from chrome-molybdenum or mild carbon steel are often gas-welded. Engine mounts, landing gears, and entire fuselages constructed of steel tubing are also welded by this means. Aluminum-alloy parts made from strain-hardened alloys and from some heat-treatable alloys are also gas-welded. Such parts as fuel and oil tanks, air scoops, and cowling are in this category. There are two types of gas welding in common use: oxyacetylene and oxyhydrogen. Nearly all gas welding in aircraft construction is done with an oxyacetylene flame, although some manufacturers prefer an oxyhydrogen flame for welding aluminum alloys. The oxyacetylene flame is much hotter, but can be controlled by a skillful welder to give an excellent weld on aluminum sheet as thin as 0.020 inch.

The oxyacetylene flame is produced by the combustion of acetylene gas with oxygen. A heat of 6700°F. is produced at the tip of the torch. Acetylene is a hydrocarbon gas produced by the reaction of water on calcium carbide. The carbon in the carbide combines with the hydrogen of the water to form acetylene gas.

There are three types of flame possible with the oxyacetylene torch. The first is a neutral flame in which the amounts of acetylene and oxygen are just suited to each other, with no excess of either. This type of flame can be identified by the clear, well-defined, white cone at the tip of the torch. This flame is generally used for welding and gives a thoroughly fused weld, free from burned metal or hard spots. The second type of flame is called a *carbonizing* or *reducing flame*. It is produced when an excess of acetylene is burned and can be identified by a feathery edge on the white cone. This flame introduces carbon into the weld. Due to the difficulty of holding a perfect neutral flame, a slightly reducing flame is often used in welding corrosion-resisting steel to insure against having an oxidizing flame at any time. The *oxidizing flame* is the third type of flame. As the name implies, it is produced by an excess of oxygen. It is identified by its small pointed white cone and relatively short envelope of flame. An oxidizing flame will oxidize or burn the metal and result in a porous weld. It is used only in welding brass and bronze.

The oxyhydrogen flame may also be neutral, reducing, or oxidizing, depending upon whether the hydrogen supply is just right, in excess, or deficient. The neutral flame has a well-defined cone in the center of the large flame. The reducing flame is long and ragged and has no well-defined cone at the center. The oxidizing flame is small and has a very short cone at the tip of the torch. A neutral flame should be used to obtain a clean, sound weld.

In gas welding steel, no flux is necessary but a filler rod must be used. There are two types of welding rods generally used. A low-carbon rod containing a maximum of 0.06% carbon, 0.25% manganese (max.), and not over 0.04% of sulfur or phosphorus is used on parts that are not going to be heat-treated after welding. In welding chrome-molybdenum steel bar, sheet, or tubing that is going to be heat-treated after welding, a higher-carbon welding rod is used. This rod has from 0.10% to 0.20% carbon, 1.00% to 1.20% manganese, and a maximum of 0.04% sulfur or phosphorus. These rods are obtainable in the following sizes: $^1/_{16}$, $^3/_{32}$, $^1/_8$, $^5/_{32}$, $^3/_{16}$, $^1/_4$, $^5/_{16}$, and $^3/_8$ inch. A rod diameter of the approximate thickness of the material being welded should be used. A normalized piece of chrome-molybdenum tubing (95,000 p.s.i. ultimate tensile strength) when butt-welded with low-carbon welding rod will show a minimum strength of 80,000 p.s.i. without heat treatment. Based on this fact, welded steel tubes in tension are usually figured for 80% of their unwelded strength. In many cases chrome-molybdenum tubing butt-welded with high-carbon welding rod and heat-treated will break outside the weld, or at a strength equal to unwelded tubing given the same heat treatment. In other words, a welded joint after heat treatment can develop the strength of the unwelded material. This strength, of course, is partly due to the extra area of the weld metal. In structural analysis, however, it is customary to figure welded parts in tension of 80% of the heat-treatment strength.

Corrosion-resisting steel is welded by using a very slightly reducing flame to avoid any possibility of oxidizing the weld. A flux composed largely of borax is mixed with sodium silicate and water to obtain the desired consistency, and is painted on the rod and on both sides of the seam to be welded. This flux protects the metal against oxidation and floats impurities in the weld to the surface. A welding rod containing columbium or molybdenum is generally recommended for use with this metal. One such rod that has been found satisfactory has the following chemical composition: carbon, 0.07 max.; manganese, 0.20 to 0.70; nickel, 8.0 min.; chromium, 18.0 min.; columbium, 0.80 min.; silicon, 0.50 to 1.00; phosphorus and sulfur, 0.04 max. each; all figures are percents. The diameter of the rod used should be approximately equal to the thickness of the metal being welded. Diameters of rods most often used are 1/16, 6/32, and 1/8 inch. As explained in Chapter VIII on Corrosion-resisting Steels, it is usually necessary to stabilize this material after welding in order to protect it against intercrystalline corrosion. If properly welded, this material can be bent flat along the axis of the seam of a butt weld without cracking. Butt-welded joints in sheet will develop at least 80% of the strength of the unwelded sheet.

In welding aluminum or aluminum alloys, a flux is always used to remove the oxide film on the work to be welded. The flux is applied either to the seam or the welding rod prior to welding. An acceptable flux for aluminum welding is composed of sodium chloride, potassium chloride, lithium chloride, and sodium fluoride.

Either of two types of rod or wire may be used in welding aluminum alloys.

1100 wire (pure aluminum) should be used for welding 1100 or 3003 material. 4043 wire (3% silicon and remainder, aluminum and impurities) should be used for welding 5052 alloy or heat-treatable alloys 6151, 6053 or 6061, which are also weldable.

4043 wire should be used whenever parts are held tightly in jigs because its lower solidification shrinkage and melting point will dissipate contraction strains. It should also be used in other locations, as when welding fittings on tanks or in repairing welds, where it is advisable to reduce the strain on the weld when cooling.

On the other hand, 1100 wire gives a somewhat more ductile weld and is better adapted for butt and edge welds which are not subjected to severe cooling strains. In many shops 4043 welding wire is used exclusively with good results.

As with other materials, the diameter of the welding rod should approximate the thickness of the metal being welded. Standard rod diameters are 1/16, 1/8, and ¼ inch. All flux must be removed from the weld shortly after it has cooled, to prevent corrosion. The method of removal is described in Chapter

XV on Corrosion. The strength of welds in aluminum alloys is always greater than the strength of the annealed material just outboard of the weld. Calculations should, therefore, be based on annealed material.

Other metals besides the foregoing can also be welded with an oxyacetylene flame. Among these are Inconel, K Monel, and Monel, for which the process has been described in Chapter IX on Nickel Alloys. Brass, bronze, copper, nickel, iron, and cast iron can also be welded, but these metals have no welded application in aircraft construction.

ELECTRIC ARC WELDING

This process is based on the heat generated in an electric arc. Variations of the process are metallic arc welding, carbon arc welding, atomic-hydrogen welding, inert arc welding (heliarc), and multi-arc welding.

Metallic Arc Welding. In this process a metal electrode is used which furnishes the filler metal for the weld as it melts. To maintain the arc between the electrode and the work the metal electrode must be fed at a uniform rate or maintained at a constant distance from the work as it melts. The maintenance of a constant arc length requires an experienced welding operator. When the amount of work warrants its installation, automatic welding equipment will produce high-quality welds.

The metallic arc develops a temperature of approximately 6000°F. This heat is concentrated and causes less buckling and warping of the work than gas welding. This localization of the heat is used to advantage in welding up cracks without appreciably affecting the heat treatment of the part and in repair work in crowded places.

Metallic arc welding is applicable to carbon steel, to corrosion- and heat-resisting steel, and to aluminum. Carbon steel can be successfully welded in thicknesses as low as 0.032 inch, but corrosion-resisting steel and aluminum must be 0.064 inch or heavier.

Carbon Arc Welding. In this process a carbon electrode is used and a filler rod is held in the arc and fused into the joint. The carbon arc will develop a temperature of approximately 7000°F. The manual application of carbon arc welding is similar to oxyacetylene welding and the two processes can be used interchangeably in many instances. Automatic carbon arc welding is used commercially in welding such items as tanks, pipe, boilers, barrels, and ships.

Carbon arc welding is applicable to carbon steel, to corrosion-resisting steel, to aluminum, and to copper alloys. It is not used much in aircraft work.

Atomic-hydrogen Welding. In this process a stream of hydrogen is directed into an arc drawn between two tungsten electrodes. The intense heat of the arc dissociates the molecular hydrogen into atomic hydrogen. The atomic hydrogen is unstable and recombines to form molecular hydrogen, at the same time giving off the heat energy that was used in dissociating it in the tungsten arc. The temperature developed is between 6000° and 7000°F. Since the arc is formed between two electrodes in the welding torch it is possible to control the heated zone on the parts being welded by moving the torch toward or away from the weld. This gives some of the flexibility of gas welding.

Atomic-hydrogen welding is frequently used in welding aluminum and its alloys. Thicknesses from 1/32 to ¾ inch can be welded satisfactorily by this process. The joint must be coated with flux and a flux-coated filler rod is applied manually as in gas welding.

This process has also been used to weld corrosion- and heat-resisting steels as used in the manufacture of exhaust collectors. Smooth welds are obtainable in light-gage sheet up to 1/8 inch thick. In light-gage work no filler rod is necessary, and no flux is used at any time. There is reputedly less carbide precipitation with this type of welding than with oxyacetylene. Ordinary steel can also be welded by this process, as well as the copper and nickel alloys, but the process does not offer competitive advantages in the welding of these materials.

Inert-arc Welding (heliarc). In this process a tungsten or carbon electrode surrounded by helium or argon gas is used. The helium or argon gas are inert and exclude the oxygen and hydrogen present in air from the area being welded. This process is particularly adapted to the welding of magnesium. It is also used for welding aluminum and if argon is used for a shielding gas no flux is required. Dispensing with flux is a definite advantage since flux removal from aluminum welded joints is extremely important to avoid corrosion; many types of welded joints cannot be made when using welding methods that require fluxing. Corrosion-resisting steel as thin as 0.010 inch can be welded by this process. Steel and copper and other alloys can be readily welded by this process.

Multi-arc Welding. This process is new and has not yet had widespread use. It consists of a combination of alternating and direct current together with both metallic and carbon electrodes. A metal electrode is supplied with direct current and two carbon electrodes are supplied with alternating current. This arrangement results in the drawing of five arcs; three between the electrodes, one between the metal electrode and the work and one between one of the carbon electrodes and the work. This arrangement permits accurate control and concentration of the heat.

It is claimed that this process permits the butt welding of 0.016-inch aluminum sheet without shielding or back-up strips. The welding of the following materials is also claimed to be possible: aluminum 1100, 3003, 5052, 6061, 2024, Alclad 2024, 2014, 7075, Alclad 705; magnesium alloys; steel 1020, 4130, 8630 and many others; Everdur; brass; copper and the 18–8 types of corrosion-resistant steels.

ELECTRIC RESISTANCE WELDING

Electric resistance welding is based on the principle that heat is generated by the resistance offered by a conductor. The heat increases with an increase in resistance. Current is admitted to the work through large low-resistance copper electrodes. The low-voltage high-amperage current meets much greater resistance when it enters the work to be welded, and intense heat is generated. Three commonly used types of electric resistance welding are *butt, spot*, and *seam welding*.

Butt welding. Butt welding is very generally used commercially to weld together long sheets, bars, tubes, rods, or wires. It applies only to duplicate or production work because the welding machine is designed to handle only one particular type of joint. Butt welding is applicable to almost all metals, among them being steel and aluminum. Materials 1100, 3003, 6053 and 6061 aluminum are butt-welded commercially.

In butt welding the work to be welded is clamped in large copper jaws, which are also electrodes. One of the jaws is movable. At the proper time, pressure is applied to the movable jaw to bring the work in contact. This pressure amounts to approximately 2000 pounds per square inch of weld area in the case of aluminum, and 10,000 to 25,000 p.s.i. for steel. When the electric current is applied after the application of pressure it is called *upset butt welding*; in *flash butt welding* the edges are brought close enough together to start arcing and when they reach fusion temperature the current is turned off and the pressure is applied. The intense heat developed at the joint due to the resistance it offers to the current, combined with a high pressure results in a union of the two pieces. The heating of the joint starts at the center and works outward to the surface, so that a perfect weld is obtainable with complete fusion and contact along the entire seam.

But welding is used in aircraft work to weld terminals to control rods.

Spot Welding. Spot welding is frequently used in aircraft construction. It is the only welding method used for joining structural corrosion-resistant steel. This process is described in detail in Chapter VIII. The spot welding of aluminum alloys has been very generally adopted. At the present time it is approved for 1100, 3003, Alclad 2014, Alclad 2017, Alclad 7075 (over 0.032"), 7075, 5052, 6053, and 6061, which may be spot-welded themselves or to each other. Anodically treated surfaces cannot be spot-welded and, consequently, the faying surfaces of a spot-welded seam must be left unprotected either by anodic treatment or by paint. For this reason there is some doubt about the advisability of spot welding aluminum alloys other than 5052 or clad materials if the assemblies are subject to severe corrosion. It is possible to spot weld through wet zinc chromate primer placed in the faying surfaces, and then to apply a surface treatment to the assembled parts. For secondary work, such as cowling stiffeners, aluminum alloy is used and spot-welded in place. Corrosion of the faying surface should not be particularly serious in such locations.

In spot welding aluminum alloys there must be accurate control of the time, pressure, and current, as in all spot welding. Using a 60-cycle alternating current, a time of 5 cycles for 0.020-inch material, varying 12 cycles for 0.120-material, is generally satisfactory. A constant time of 10 cycles can be used successfully for all thicknesses of material if it is desired to eliminate this variable. The pressure varies from 300 pounds for 0.020-inch material to 1200 pounds for 0.120-inch material. For the same extremes of thickness the current varies approximately from 18,000 amperes to 35,000 amperes. All of the foregoing figures vary somewhat with the apparatus used, the technique of the welder, and the material being spot-welded. When unequal thicknesses are welded together, the time and pressure are determined by the thinner material. The amperage, however, varies with different combinations.

Stored-energy welders have largely superseded alternating-current spot welders in aluminum-alloy aircraft spot welding. This type of welder requires only one-tenth of the maximum power used in alternating-current spot welding, and gives a better surface finish.

Spot welds are weak in tension and should not be used to take this type of stress. The permissible shear strength values for design are listed in the table below.

Seam Welding. Seam welding is identical with spot welding, except for the use of power-driven rollers as electrodes. A continuous airtight weld can be obtained by this method. It is possible to seam-weld from 2 to 6 feet per minute when welding aluminum alloys.

WELDING CONSIDERATIONS

There are a number of general considerations that all designers should be familiar with in connection with the design of welded joints. The following comments on these points apply particularly to oxyacetylene welding or arc welding.

1. Straight tension welds should be avoided because of their weakening effect. When a weld must be in tension, a fish-mouth joint or finger patch should be used to increase the length of weld and to put part of it in shear.

2. A weld should never be made all around a tube in the same plane. A

Shear Strength of Aluminum-Alloy Spot Welds

Thickness of thinner sheet (inch)	1100	3003	5052, 6053, 6061 (except annealed)	Alclad 2014, 2017, 2024, 7075
.012	18	25	84	105
.016	40	55	120	140
.020	60	100	150	175
.025	90	140	170	225
.032	125	210	265	295
.040	170	280	365	420
.051	235	370	490	560
.064	300	545	665	770
.072	350	560	770	950
.081	405	595	910	1155
.091	455	665	1000	1295
.102	510	735	1155	1435
.114	545	770	1435	1575
.125	595	825	1680	1680

fish-mouth weld should be made. This situation arises frequently when attaching an end fitting to a strut.

3. Two welds should not be placed close together in thin material. Cracks will result because of the lack of metal to absorb shrinkage stresses.

4. Welds should not be made on both sides of a thin sheet.

5. Welds should not be made along bends, or cracks will develop in service.

6. Welded reinforcements should never end abruptly. The sudden change of section will result in failures by cracking when in service.

7. Aircraft bolts are made of 2330 nickel steel. They should never be welded in place because they cannot be satisfactorily welded to chrome-molybdenum steel. If such design is necessary, bolts should be machined from chrome-molybdenum steel and welded in place. It is possible to weld standard aircraft nuts in place, because they are made from 1025 carbon steel. Tack welding in three places is all that is usually necessary to position them. Complete welding weakens the material and distorts the nut.

8. All welded parts should be normalized or heat-treated after completion to refine the grain and relieve internal stresses caused by shrinkage. If welded parts are not normalized they will develop cracks in service, particularly if subject to vibrational stresses. This behavior is due to the fact that weld material is cast metal which does not have the strength, ductility, or shock resistance of wrought metal. The internal stresses are also seeking to adjust themselves. Sharp bends or corners, or rapid changes of section in the vicinity of welds, are especially liable to cracking.

BRAZING

Brazing refers to a group of metal-joining processes in which the filler metal is a nonferrous metal or alloy whose melting point is higher than 1000°F., but is lower than that of the metals or alloys being joined. In brazing there is no fusion (as in welding) of the metals being joined. In aircraft work three types of brazing are commonly used—copper brazing (usually referred to simply as brazing), silver brazing (also referred to as hard soldering), and aluminum brazing. The types of brazing are named after the metal whose alloy is used as the filler metal. In general, copper brazing is high-temperature brazing (above 1600°F.); and silver brazing is low-temperature brazing (1175–1600°F.)

Brazing (Copper). Copper brazing as applied to aircraft is the process of uniting metal parts by means of a molten brass filler. The brass filler when molten at high temperature has a surface alloying action with steel and other metals and forms a very strong bond. In the past, aircraft fittings were very commonly brazed. An allowable shear stress of 10,000 p.s.i. was used in figuring the strength of brazed parts. Welding has largely superseded brazing in recent years because it is free from the possibility of corrosion due to dissimilar metals being in contact.

The brazing filler used for aircraft work is a brass composed of 80% copper and 20% zinc. This filler starts melting at 1750°F. and is completely molten above 1830°F. The brazing operation is usually performed between 1830°F. and 1870°F. It is customary to heat-treat alloy-steel parts after brazing if the required heat-treatment temperature is not above 1650°F. Above this temperature the brazing filler begins to soften and causes a weakening of the joint. The heat treatment of brazed parts corrects the large grain structure caused by heating the material in the vicinity of 1850°F. for brazing.

A flux is necessary in brazing to clean the steel of oxide scale. The recommended flux consists of 2 parts of borax to 1 part of boric acid. But before brazing the parts must be thoroughly cleaned of all oil, grease, or paint by means of benzol or a hot caustic soda solution. Heavy scale should be removed by pickling, followed by a caustic dip to neutralize the acid.

Parts to be brazed must be securely fastened together to prevent any relative movement. This fastening can be done by riveting, electric spot welding, or tack welding with oxyacetylene. Tack welding causes scale formation, which requires another pickling operation for removal, and hence is not considered as satisfactory as the other methods. The strongest brazed joint is one in which the molten filler is drawn in by capillary action and therefore a close fit is advisable. The molten filler will penetrate into any joint no matter how tight.

In flame brazing, the parts are preheated slowly by means of a brazing temperature. An oxyacetylene flame can also be used for this operation. The joint should be liberally coated with flux during the heating operation. When the brazing temperature is reached, brass should be applied to the joint in the form of granules or wire. The brass will melt in contact with the hot steel and run into the joint by capillary action. When the brass comes out the opposite side of the joint, enough has been applied. The parts should then be cooled slowly as described below.

In dip brazing, the parts are heated to 1000°F. in furnace and soaked at this temperature for at least 20 minutes. They are then lowered slowly into a flux bath, maintained at about 1300°F., and left in it for five minutes. After this they are immersed in a second flux bath, maintained at about 1600°F., and left in this bath for five minutes. The parts are then transferred to the dip-brazing pot. The dip-brazing pot contains molten brass at a temperature of 1830°–1870°F. The molten brass is covered with a 2-inch layer of flux. The parts must be lowered very slowly into the brazing pot to avoid a rapid change of temperature with its attendant cracks. The parts should be left immersed for 2 to 3 minutes and should then be raised and lowered two or three times through the flux layer, after which they should be submerged for another minute or two.

After removal from the brazing pot or upon the completion of flame brazing, the parts must be cooled very slowly. They can either be buried in lime (or a similar insulating powder) or be placed in a cooling chamber maintained at 1000°F. After cooling to blackness, they can be cooled in air at room temperature. During the cooling operation the parts are protected by the flux coating from surface oxidation. After the cooling this flux is removed from the parts by immersing them for 30 minutes in a lye solution. This lye solution, which consists of one pound of lye per gallon of water, is maintained at 212°F.

The brass coating is removed from all surfaces except the joints by an electrolytic stripping operation. The joints are protected from the stripping action by coating them with paraffin. A solution containing 12 ounces of sodium nitrate to a gallon of water is used as the electrolyte. The brazed fittings are suspended from the positive bus bar of a 6-volt generator. The steel tank or steel electrodes are used as the negative bus bar. The brass can be removed in from 10 to 30 minutes by this method without appreciably affecting the steel fitting.

Silver Brazing. Silver brazing (hard soldering) like brazing and soft soldering, is based on the fact that practically any metal will surface-alloy with another metal that has a higher melting temperature. This latter metal must have a chemically clean surface and be heated to the melting temperature of the solder or filler. There are a number of hard solders, but in aircraft work this term refers almost exclusively to silver solders. These solders all contain some silver and melt around 1200°F. They can be used to solder metals that fuse at 1400°F. or above, such as copper, brass, bronze, iron, carbon-resistant steel, Inconel, Monel, nickel, and silver. This solder will make a strong joint. Its temperature range is intermediate between soft solder and copper brazing, and it should be used where strength without excessive heating is desired.

Before soldering, all surfaces must be thoroughly cleaned. A flux coating is then applied to the entire joint and to the solder to protect against oxidation and to aid the flow of the solder. Powdered borax mixed with water to form a thick paste is a good flux. For corrosion-resisting steels and other metals that form oxides hard to remove, a flux composed of borax, boracic acid, and zinc chloride solution is best. Silver-soldering fluxes are readily soluble in hot water and can be removed by dipping or scrubbing.

A silver-brazing alloy, as it is sometimes called, that is particularly suitable for use with carbon steel, corrosion-resisting steel, Inconel, and Monel has the following chemical composition: silver, 50%; copper, 15%; zinc, 16% cadmium, 18%. This solder melts at 1175°F. and is yellow-white in color.

Another alloy especially suitable for copper, brass, and other nonferrous alloys has the following chemical composition: copper, 80%; silver, 15%, phosphorus, 5%. This alloy has a melting point around 1300°F. It has a shearing strength of approximately 30,000 p.s.i. at 200°F. Its strength is about half this amount at 700°F.

Silver brazing can be accomplished by gas, dip, furnace, electric-resistance, or induction heating. A 50-kilowatt induction-heating machine in which the temperature is held at 1250°F. for 20 to 30 seconds has been very successfully used.

Aluminum Brazing. This process is applicable to 1100, 3003, 6053, 6061, and special brazing aluminum alloys. The special brazing sheets are duplex material with cores of 3003, or 6061, covered on one or both sides by a cladding of a brazing filler metal. When using special brazing sheet no filler is used. Wire 4043 is used as a filler for brazing 1100 and 3003 material.

Torch, furnace, and dip brazing are all used. In torch brazing an oxyacetylene or oxyhydrogen flame can be used. Both joint and filler should be covered with flux. In furnace brazing the flux and filler metal are applied to the assembled parts before placing them in the furnace. The furnace is held at 1160–1185°F. for 1100, 3003, and No. 1 and No. 2 brazing sheet; 1060–1090°F. for 6053 and 6061; 1090–1140°F. for No. 11 and No. 12 brazing sheet. The work must be left in the furnace from a few minutes for thin material up to 45 minutes for material ½ inch thick. In dip brazing, the assembled parts and filler are immersed in a molten flux bath held at the temperature stated above. In this method, heat transfer is more uniform and less distortion results.

When 1100 and 3003 material are brazed the high temperature anneals the material and eliminates any strain-hardened properties. Materials 6053 and 6061 can be water-quenched when removed from the brazing furnace and will become 6053W and 6061W. They can then be aged to the T condition. Material 3003 will develop a strength of 14,000 p.s.i. in tension; the heat-treatable alloys in the W condition will develop 24,000 p.s.i. and in the T condition 35,000 p.s.i.

Aluminum brazing is finding many uses in aircraft construction. It has been used in the manufacture of intercoolers, ducts, gasoline tanks for outboard motors, and in similar applications.

SOFT SOLDERING

Soft soldering is never used in aircraft work for joints requiring strength. It is used for making electrical connections, and to solder the wrapped or spliced ends of flexible aircraft control cables.

The standard soldering flux used for soft soldering is a paste composed of 75% mineral grease (petrolatum), wax, and resins, combined with 25% zinc chloride. This flux can be used generally except for the soldering of aluminum, which it will corrode seriously. It will also corrode other metals and must be removed as completely as possible after soldering. Rosin is frequently used as a flux in electrical and electronic soldering. It is noncorrosive and nonhygroscopic.

Common soft-soldering alloys are composed of tin and lead. A good grade generally used is composed of 50% tin and 50% lead. This alloy has a melting point of 421°F. and a solidification point of 361°F. A soldered joint should not be disturbed until it has cooled below the latter temperature. Solders containing more lead are cheaper, have higher melting points, and are not as strong. A "fine" solder containing two parts of tin to one part of lead is best for soldering steel, iron, copper, and brass. This alloy has a melting point of 370°F.

Another solder universally used in aircraft work is composed of 5–6% silver and the remainder lead. This solder has a melting point between 580°F. and 700°F. It will develop a shearing strength of 1500 p.s.i. at 350°F. When this solder is applied to hard-drawn brass or copper, the temperature should not exceed 850°F.

There are numerous aluminum solders on the market but they have little practical application in aircraft construction. If the heat-treatable alloys are soldered, the heat destroys their properties. One acceptable solder for use on aluminum alloy is composed of 75–79% tin, and 25–21% zinc. This material may be used for nonstructural applications such as attaching strainer screens to fuel- and oil-line fittings, and filling in abraded areas of cowling and other aluminum sheet assemblies.

ADHESIVE BONDING

During the past few years great strides in the development of metal to metal adhesives have been made. The quality and reliability of many adhesives enabled various aircraft producers to use bonded construction. The F7U swept-wing fighter, produced by Chance-Vought Aircraft Corporation, Dallas, Texas, has balsa wood core sandwich wing skins. The De-Havilland Jet Comet has a good portion of its primary structure bonded by good quality, high-strength adhesives. The Britannia Transport Plane also used metal-to-metal adhesives in many primary structural applications.

Basically two general types of laminating methods are used in guided-missile and aircraft construction. Metal-to-metal bonding is used to reduce the bad effects of rivets, spot welds, and other attachments which cause points-of-stress concentrations. Before any attempt to use this type of construction is made, careful testing of the adhesives, metal surface treatment, and types of joints is required. When designing structures which will be fastened by adhesives, care should be taken to:

1. Make the bond area as large as possible.
2. Stress the adhesive in the direction of its maximum strength.

Metal to metal, metal to wood, metal to plastics and metal bonded to other structural materials has been specified in aircraft and missile work. Bonding with the use of adhesives has many advantages over conventional fastening methods. Spot welding, bolting, riveting, and several other fastening methods cause points-of-stress concentration which must be overcome by using extra material, thereby reducing the stresses. The main advantage of using adhesive bonding is the large weight saving. This results from the elimination of the previously mentioned stress concentrations and fasteners. Weight savings of up to 20% have been recorded by the proper designing of bonded structures. Fatigue resistance, pressure tightness, aerodynamic efficiency, and cost reduction are other factors which are improved when adhesive bonding is specified. Along with the many advantages listed for adhesive bonding, there are several disadvantages—the main one being the lack of a good test method to insure 100% properly bonded area. Several methods under evaluation which appear promising at the present time are:

1. The reflected impedance measurement method.
2. The vacuum cup method.
3. The mechanical interferometer.

Of the there testing methods mentioned, the reflected-impedance method shows the most promise for nondestructive tests on structural adhesive bonds. The device measures the power used up when a piezo-electric crystal scans the surface of the skin of an adhesive bonded structure. Weak joints use more power than strong joints. If perfected, this device will enable more primary structure to be constructed using adhesive bonding.

Many types of adhesives are available for metal-to-metal bonding so no attempt will be made here to list the variety of adhesives. In general three types of adhesives are used.

Thermoplastic Adhesives. Thermoplastic adhesives can be softened or melted by heating and hardened by the lowering of the temperature. These types of adhesives are very poor for those applications where sustained loading at slightly elevated temperatures is concerned, since these thermoplastic adhesives become softer as the temperature is increased. Even the best of these materials loses strength very rapidly over 200°F. Several thermoplastic adhesives, and their typical uses, are listed below.

Polyvinyl Acetates—used for joining metal, glass, wood, cork and plastics.

Polyvinyl Alcohols—used mainly on cellulosic materials.

Acrylics—used to bond plastic materials usually where transparence of the adhesive is required.

Cellulose Nitrates—these adhesives are used to bond metal, glass, wood, cloth and thermoplastic resins.

Asphalts—used mainly for the bonding of flooring tiles (plastic, asphalt, cork, etc.). These adhesives are not strong.

Oleoresins—These adhesives are used for bonding plastic and metal tile to wood plaster and other materials.

Thermosetting Adhesives. This family of adhesives will soften temporarily with the application of heat but when curing starts the strength increases. After the curing reaction, they remain hard. These materials develop good shear and creep strengths. Characteristics and uses of several thermosetting adhesives are as follows:

Phenolics—used for bonding wood, metals, and glass. Bonds usually require pressure with the application of heat.

Resorcinols and Phenol-resorcinols—these adhesives (usually supplied in liquid form) are used to bond plywood, nylon, acrylic and phenolic plastics.

Epoxy—these adhesives show excellent adhesion to metals, ceramics, wood, and plastics. A good characteristic of the epoxy adhesives is that usually pressure is required for good bonding.

Urea-Formaldehyde—these are used for bonding wood products.,

Melamine Formaldehyde—these adhesives are finding increased use in the plywood industry. A curing temperature of 250°F. with pressures of approximately 150–250 p.s.i. is required.

Alkyl adhesives—used in the electrical industry to bond laminations in transformers.

Elastomeric Adhesives. The elastomeric adhesives are similar to thermoplastic resin adhesives since they soften with increasing temperature. However, they do not melt completely. The most widely used elastomers in adhesives are Buna N, Buna S or GR--S, neoprene, and polyisobutylene.

Silicones. These adhesives are used to bond polyethylene, teflon, and silicone rubbers. Many adhesive experts feel that silicone adhesives will be the answer to high-temperature problems.

When designing an adhesive-bonded joint, some general rules which should be followed are:

1. Design the joint which will minimize stresses in directions in which the adhesive is weakest.
2. Make as much of the adhesive work as is possible.
3. Stress the adhesive in the direction of its maximum strength.
4. Avoid cleavage stresses.
5. Avoid peel stresses.
6. If peel and cleavage cannot be avoided, use rivets or other reinforcements.

When adhesive bonded joints are specified, quality control is a prime requisite since a foolproof, nondestructive test is not available. Periodic specimens prepared along with actual parts should be statically tested in order to discover any manufacturing errors. It is also advisable to statically test a completed assembly periodically to see if the quality is up to specifications.

Some popular aircraft adhesives are pliobond, epon, cycleweld, plastilock, metlbond, and FM-47.

Shear strengths in excess of 4,000 p.s.i. at room temperature are obtainable in aluminum-to-aluminum joints. This strength is independent of metal thickness and equals or exceeds the strength of a typical sheet-stringer riveted joint. However, strength is temperature sensitive and inherent limitations of an adhesive must be taken into account.

The sandwich type of adhesive-bonded construction is finding the widest use on United States military and commercial airplanes. The original use of metal-faced honeycomb-core sandwich construction was limited to secondary structural applications such as floor doors, escape hatches, and decks. After a series of improvements in adhesive core materials and test methods, this type of construction is now used as primary structure in today's aircraft. For a complete description of honeycomb construction, the face materials, core materials, manufacturing techniques, and bonding will be discussed.

The following table show values for a popular structural vinyl-phenolic liquid adhesive (Bloomingdale FM-47)

		Average value
*	Shear strength at room temperature (p.s.i.)	4,200
	Shear strength at 180°F. (p.s.i.)	3,300
	Shear strength at –67°F. (p.s.i.)	2,700
**	Room temperature fatigue-strength or endurance limit (p.s.i.)	over 650
	Shear strength at 350°F. (p.s.i.)	1,000
	Impact strength at room temperature (ft. lb.)	over 20
	Shear strength after 30 days water immersion (p.s.i.)	5,000
	Shear strength after 7 days immersion in either ethylene glycol, anti-icing fluid, hydraulic, or hydrocarbon fluid (p.s.i.)	over 3,600

* The results were obtained from aluminum alloy lap-shear specimens cured for 25 minutes at 335°F., at a pressure of 200 p.s.i., after a one hour dry 150°F. and a 5 minute preheat at 335°F. without pressure application.

** Formulations are marketed which have more uniform, but lower room temperature tensile, properties over a temperature range of –100°F. to 400°F. (i.e. Epon 422—Shell Chemical Co.).

Facing Materials. It is possible to use any of the high-strength aluminum alloys such as 7075-T6, 2014-T6, or the alclad versions of these alloys for facing materials. Stainless steels of the 18-8 variety or the 12% chrome variety have been successfully used. Many other facing materials are being used in industries other than aircraft. These materials include steel, copper, magnesium, plastics, asbestos-cement board, and reinforced concrete. No matter which type of facing material is specified, it is mandatory that the surfaces to be bonded are properly cleaned and treated before application of the bonding material.

Exclusive tests by the United States Department of Agriculture indicate that a sulfuric acid-dichromate etch gave optimum results in preparing bare and alclad aluminum alloys. Moderately good bonds were obtained by processing the aluminum alloys with a sulfuric acid-anodizing treatment, but bonding over a chromic acid-anodized aluminum surface was poor. Tests on magnesium indicated that a hydrofluoric acid etch-dichromate seal (MIL-M-3171 Type 3) treatment enabled good bonds to be made. Alkaline degreasing of stainless steel resulted in bonds as good as those obtained with an acid-etch treatment.

Core Materials. Core materials which can be used in sandwich construction are numerous but an attempt will be made here to put emphasis on the materials generally used in aircraft sandwich construction. Balsa wood, which is the lightest of the commercial woods, makes an excellent core material because of its low specific gravity (approximately 0.2). Balsa-cored material was used in large quantities in the construction of the British Mosquito Bomber in World War II. Paper, impregnated with phenolic resin and formed into a hexagonal cell structure, has found wide use. The face sheets for this type of core are usually of wood or metal.

Foamed Core Materials. Foamed plastics and foamed rubber are used as core materials with many different types of facing materials. Most of the foamed core materials have a cellular structure produced by the release of a gas during the forming stage. The large expansion which takes place during forming helps to insure the filling of intricate shapes.

Metal Core Materials. The most commonly used metal core material is aluminum honeycomb which is manufactured from aluminum alloy foil. The aluminum foil from which honeycomb is manufactured can range in thickness from .001 in. to .006 in. 3003-H19 is often used although 5052 alloy is finding some use. The manufacturing of aluminum honeycomb is not complicated. The core is made by corrugating aluminum foil strips and bonding them into a honeycomb block. Since aluminum foil is available in many thicknesses, and since aluminum honeycomb can be manufactured in a variety of cell sizes, the following chart gives the nominal weights of aluminum core.

Core Material	Cell Size (in in.)	Average Density (in lb./cu. ft.)
0.0007 in. 3S-H19 Alum	1/8	3.1
0.0010 " "	1/8	4.5
0.0015 " "	1/8	6.1
0.0020 " "	1/8	8.1
0.0010 " "	3/16	3.1
0.0015 " "	3/16	4.4
0.0020 " "	3/16	5.7
0.0020 " "	¼	4.3
0.0030 " "	¼	6.1
0.0040 " "	¼	7.8
0.0050 " "	¼	9.6
0.0020 " "	3/8	3.0
0.0030 " "	3/8	4.2
0.0040 " "	3/8	5.4
0.0050 " "	3/8	6.5
60-lb. Kraft paper	7/16	1.8–2.1
End-grain balsa	—	7.5–8.5

The machining of aluminum honeycomb blocks is not difficult providing no double curvature is specified; if double curvature is required, the machining and bonding to the face plates becomes complicated. As a general rule, any structure which has double curvature should be given a thorough cost evaluation if honeycomb construction is specified. The tooling for bonding any parts which have double curvature is usually very expensive; often several times the cost of tooling for standard built-up structure.

Honeycomb structure is finding wide use for the following aircraft parts or assemblies:

1. Fuselage sections
2. Escape hatches
3. Tables
4. Bulkheads and partitions
5. Vertical stabilizer
6. Rudder
7. Elevator
8. Trailing edges
9. Trim tabs
10. Doors

CHAPTER XV

CORROSION AND ITS PREVENTION

ALL METALS are affected to some extent by the atmosphere. This effect, which is called corrosion, is especially important in aircraft due to the loss of strength it causes. Corrosion reduces the strength and ductility of metals to an alarming extent if not restrained. In the relatively thin sections used in aircraft construction even a small amount of corrosion is unsafe. For these reasons extensive study has been devoted to the protection of metals against corrosion. Metals have also been developed that are corrosion resistant in themselves, and they are very generally used when their other properties are suitable for the intended application. Such metals as Inconel, K Monel, Alclad, and corrosion-resisting steels are in this category. In general these metals are given a protective coating of paint only when it is desired to carry out some particular color scheme.

It has been generally established that corrosion is caused by the moisture in the air. A dry piece of metal in dry air will not corrode. This point is vividly brought out by the fact that sandblasted steel surface will oxidize in a few hours on Long Island if not painted, whereas in Wichita, Kansas, they can stand for days without painting. With this fact in mind it is obvious that all traps should be eliminated and plenty of drain holes provided in aircraft to drain off water or condensed moisture. In order to minimize the amount of condensation, it is necessary to adequately vent all the nooks and crannies, particularly inaccessible locations in seaplane hulls. Provision should be made for the inspection of all parts of an airplane when in service. Timely and thorough inspection will detect corrosion in its initial stages, when it can be easily arrested before becoming dangerous.

There are two distinct types of corrosion to which metals used in aircraft construction are subject. The first type is the eating away or pitting of the surface, as in the rusting of steel and iron. Practically all metals are subject to this type of corrosion when they oxidize in the presence of air. This type of corrosion is visible and can be prevented or retarded by protecting the surface with a plating or paint. The second type of corrosion is one that is not visible on the surface and is, therefore, very dangerous. It is called intergranular or intercrystalline corrosion, because it eats its way internally through the metal around the grain or crystal boundaries. This type of corrosion is found in some aluminum alloys and some corrosion-resisting steels. It has been described in detail in the chapters devoted to those metals. The resistance of materials to this type of corrosion is lowered by improper treatment of the metal and can be prevented by proper technique. Protective coatings have little or no influence on this type of corrosion.

CORROSION OF DISSIMILAR METALS

The corrosion of dissimilar metals in contact deserves special treatment. It has been found through sad experience, especially in naval airplanes, that when two dissimilar metals are in contact one of them will eat the other away. The fact that this phenomenon is more common in seaplanes indicates that the presence of moisture is a necessary condition. Every metal has an inherent electric potential. When it is set side by side with a metal of different potential and an electrolyte is present, such as moisture, an electric action is set up. It is found that this electric action causes pitting of the metal with the higher potential. When two metals of different potentials are compared, the one with the higher potential is said to be anodic to the other. The anodic metal is then the one that is destroyed by electrolytic corrosion, as it is called. When two metals have practically the same potential, there is very little interaction. The tabulation below lists the commonly used metals in the order of their potential magnitude. The anodic metals are on top. The metals grouped together do not have a strong tendency to corrode each other because of the slight differences in their electric potential.

Before really serious electrolytic or galvanic action can set in between any two of the above metals, it is necessary for the electrolyte present to be a solution in which one of the metals is susceptible to corrosion. Insofar as aircraft materials are concerned, namely aluminum and steel, moisture (particularly sea water or spray) fulfills this condition.

Before really serious electrolytic or galvanic action can set in between any two of the above metals, it is necessary for the electrolyte present to be a solution in which one of the metals is susceptible to corrosion. Insofar as aircraft materials are concerned, namely aluminum and steel, moisture (particularly sea water or spray) fulfills this condition.

Figure 59 shows graphically the action that takes place when two metals of different potentials are placed side by side. Current flows from the anodic metal to the cathodic metal of lower potential. The surface of the anodic metal is pitted by this action.

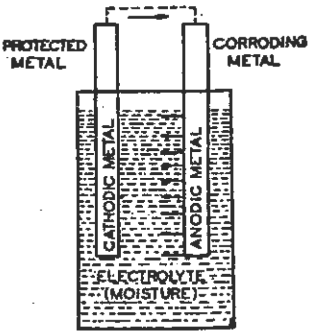


FIGURE 59. Galvanic-cell Action

Corroded end (anodic)
Magnesium
Aluminum

Zinc
Cadmium
Chromium

Iron
Chromium-iron (active)
Chromium-nickel-iron (active)

Solder
Tin
Lead

Nickel
Brass
Bronze
K Monel
Monel
Copper
Inconel
Titanium
Chromium-iron (passive)
Chromium-nickel-iron (passive)

Silver
Gold
Platinum
Protected end (cathodic)

To avoid electrolytic corrosion, joints between dissimilar metals should be avoided whenever possible. In aircraft work, aluminum alloys in particular should be kept away from steel, stainless steel, and copper-bearing alloys because of the great difference in potential. When joints must be made between two dissimilar metals the precautions set forth below should be taken to prevent corrosion. Threaded connections and press-fit bushings are of necessity excluded from the recommendations.

Carbon-steel and Aluminum-alloy joint. The steel surface should be cadmium plated or metallized with aluminum spray and then given two coats of primer before assembly. After anodic treatment the aluminum faying surface should also be given two coats of primer. All coats of primer should dry thoroughly before assembly. The faying surfaces should be insulated from each other by canton flannel or other fabric impregnated with bituminous paint, soya-bean-oil compound, or marine glue. An alternative insulator for nonwatertight joints is a pure aluminum sheet that has been anodically treated and primed. Aluminum foil, cellulose tape, synthetic rubber tape, plastic gaskets, and zinc chromate tape are other insulators that have been used successfully. The insulator should extend beyond the edge of the faying surfaces at least $^3/_{16}$ inch. This protruding insulator does not look very neat, but if trimmed close to the edge of the faying surfaces it will not do its job of insulating. This point should be impressed on shop personnel.

Stainless-steel and Aluminum-alloy joint. The stainless steel need not be plated, but in all other respects the joint should be the same as for carbon steel. Stainless steel has a much greater affinity for aluminum alloys than steel, so even greater care should be taken in insulating it.

CORROSION PROTECTION

Aircraft metal parts are almost always given special treatments to improve their resistance to corrosion. These treatments usually consist of a cleaning treatment such as sandblasting or pickling, which is followed by a plating process such as cadmium plating, chromium plating, or galvanizing, and finally by a paint job. Steel parts are subject to this whole sequence of operations. Aluminum-alloy parts are usually cleaned, anodically treated, and painted. Alclad parts, corrosion-resisting steel, Inconel, K Monel, Monel, and other corrosion-resistant materials are frequently left in their natural state without plating or paint unless it is desirable to match a color scheme.

The finishing operations will be described in detail in the order normally followed for steel parts. The anodic oxidation treatment of aluminum alloys will be described under the plating operations. There are many plating operations described but cadmium plating is generally used. There is a wide choice in paints and varnishes, but they all require an adequately prepared surface for satisfactory adherence.

CLEANING OPERATIONS

Sandblasting. Sandblasting is a general name applied to the process of cleaning parts by blowing abrasive particles against the surface. Sand, steel grit, and other abrasives are sometimes used. Steel parts that have been welded or heat-treated are normally sandblasted to remove the scale. The same applies to corrosion-resisting steel exhaust collectors which are subjected to both welding and heat-treatment operations. Aluminum-alloy parts are seldom sandblasted because of their softness, thinness, and loss of ductility after blasting. Occasionally aluminum alloy surfaces are sandblasted in the manner described below when it is necessary to remove abraded or corroded areas.

The sand used for blasting should pass through a No. 24 sieve and not through a No. 40 sieve. It should be at least 98% silica and free of salts, silt, dust, or other foreign matter. Steel grit used for blasting is called No. 50. It must be uniform and have sharp edges.

The actual blasting operation consists of blowing the grit through a nozzle by means of air pressure. The distance the nozzle is held from the surface, its angle relative to the surface, and the air pressure used are all dependent upon the type of work. In the case of thin aluminum alloy the nozzle must be held from 18 to 24 inches away from the work, and must not make an angle greater than 45° to the surface. Sand is used for blasting under an air pressure of 70 pounds per square inch or less. For heavier aluminum-alloy parts, such as castings, the blasting operation may be made more severe.

Sandblasted parts should not be handled with dirty or greasy hands, and they should be given a protective coating of paint as soon as possible. Sandblasted ferrous-metal parts will rust very quickly if allowed to stand in that condition for any length of time, particularly in damp locations—along the seaboard, for instance.

After sandblasting, parts must be cleaned by means of an air blast or by brushing to remove excess abrasive. If steel parts are to be electroplated after sandblasting, all imbedded particles must be removed by immersing the part in a dilute solution of hydrofluoric acid consisting of ½ pint of acid per gallon of solution. This treatment should not be used for aluminum-alloy parts.

Care must be taken in sandblasting not to eat away the metal and thus seriously reduce the strength. Sandblasting of a part should be limited to the minimum amount necessary to clean the surface. This caution applies particularly to parts of thin section or parts subject to high stresses in service. Parts requiring a ground or polished surface should not be sandblasted. These parts are usually heat-treated in a liquid bath to avoid scaling and do not require cleaning by blasting. Aluminum-alloy sheet should not be sandblasted unless absolutely necessary, because of the loss of ductility resulting from even a light sandblast.

Pickling Steel. Steel parts are pickled to remove scale, rust, and so on, particularly before plating them. The pickling solution may be either a sulfuric acid solution (5% to 10% of concentrated sulfuric acid, by weight) or a hydrochloric (muriatic) acid solution (15% to 25% of concentrated muriatic acid, by weight). The pickling solution, which is kept in a stoneware tank, is heated to 140–150°F. by means of a steam coil.

Paint, oil, grease, and the like are removed from the part before pickling by immersing it in a hot solution of lye. After a rinsing in running water, it is immersed in the pickling solution for the minimum length of time necessary to remove the scale or rust. This period varies from 5 to 15 minutes. If the scale is especially heavy, it is advisable to loosen it up by scrubbing with a wire brush to reduce the pickling time. All acids must be drained from the part, after which it should be thoroughly rinsed in cold running water. Parts to be electroplated should be transferred immediately to the plating bath after rinsing. All other parts should be immersed in a lime bath for 5 minutes to insure neutralization of any acid left on the part from the pickling solution. The lime bath is made by dissolving 20 pounds of quicklime in 100 gallons of water. After removal from the lime bath, the part should be drained, rinsed in clean hot water, and allowed to dry.

The pickling bath must be renewed occasionally, particularly if it turns brown. The lime bath will eventually become acid and must then be renewed. It should be tested periodically with a piece of blue litmus paper, which will turn red when the bath is too acid.

Pickling Aluminum Alloy. Aluminum-alloy parts that have been welded, such as fuel and oil tanks, are given a pickling treatment to remove all traces of the welding flux. The complete and prompt removal of welding flux is necessary to prevent serious corrosive attack. A 10% sulfuric acid bath at room temperature is used for this treatment. The solution is held in a wooden tank lined with lead or painted with asphalt paint. After removing as much flux from the part as possible by washing with water, it is immersed in the acid bath long enough to remove all traces of the flux. This may take up to one hour. It is necessary to renew the acid bath as soon as it loses its effectiveness. After removal from the acid, the part should be washed in fresh running water for ½ hour. This is best done by means of a rinsing tank with a continuous supply of fresh water and an overflow.

In preparing a sulfuric acid solution, the acid should be poured slowly into the water while stirring with a wooden paddle. The water should never be poured into the acid.

Pickling Corrosion-resisting Steel. Several methods and solutions for pickling corrosion-resisting steel are given in Chapter VIII.

PLATING OPERATIONS

Cadmium Plating. Cadmium plating is used more generally on aircraft parts than any other plating method. It is a general practice to cadmium-plate all steel parts small enough to fit in the bath, prior to painting. Welded tubular fuselages, engine mounts, and landing gears are not cadmium-plated because it is impractical. Steel parts are cadmium-plated to increase their corrosion resistance. Cadmium plating does not improve the paint adherence to the surface but resists corrosion itself. In fact, it is sometimes difficult to make paint stick to cadmium-plated surfaces unless they are kept exceptionally clean.

Parts made from copper or its alloys are frequently cadmium-plated in order to reduce the electric potential between these parts and adjacent steel or aluminum parts. Cadmium lies between iron and aluminum in the galvanic series; both of these, in turn, are far removed from copper.

Aluminum can also be cadmium-plated but such plating is seldom done because there is a better treatment available, known as the *anodic oxidation process* (which is discussed in the next section).

Cadmium plating is an electrical process carried out at a low voltage not exceeding 12 volts. The cadmium is deposited directly on the surface without the necessity of a preliminary coating of another metal. The cadmium deposit must be adherent, and without blisters, porosity, or other defects. A coating 0.0005 inch thick is usually specified except on threads, where a minimum coating 0.0002 inch thick is required. Parts plated in this manner will withstand 250-hour salt-spray test without showing evidence of corrosion of the base metal. It is customary to select cadmium-plated samples at random periodically and submit them to a salt-spray test to check the quality of the plating that is obtained in production.

Before putting parts in the cadmium-plating bath, they must be thoroughly cleaned by pickling or sandblasting. Pickling is preferable. Parts with more than 0.60% carbon should not be sandblasted. It is also essential to remove all particles of sand by immersing the part in a dilute solution of hydrofluoric acid. Copper, brass, and bronze parts must be pickled in a sulfuric acid solution prior to plating. All parts should be immersed for at least 30 seconds in a solution of sodium cyanide (2 ounces in 1 gallon of water) immediately before plating.

The plating solution consists of sodium cyanide, cadmium oxide, and caustic soda, dissolved in water at room temperatures. If a bright plating is desired, a brightener, such as hide glue or molasses, is added to the bath. The work to be plated is suspended by hooks or racks from the cathode bus bar and is completely immersed in the solution. Cadmium anodes are used. A voltage between 4 and 6 volts is required for this method of cadmium plating. Another method, called the "barrel plating" method, requires 8 to 12 volts. In this method the work to be plated is placed in a perforated barrel which revolves during the plating operation.

The thickness of the cadmium plating deposit is dependent upon the time and the current density. Increasing either the time or current will increase the thickness of the coating obtained. The physical character of the coating is also determined by the rate of formation as controlled by the current density. A coarse, soft deposit is obtained with a low current, while a stronger current produces a fine-grained, hard deposit. A high current results in a "burnt" deposit. The ideal time and current density for any particular set of conditions must be established to obtain the desired hardness and appearance. For a cadmium deposit of 0.0005 inch the following combinations of time and amperage may be used to obtain satisfactory results. The amperage given is per square foot of surface to be plated. It should be noted that the current is inversely proportional to the time.

Time (in minutes)	*Amperes per sq. ft.*
10	29.5
20	14.8
30	9.8
40	7.4

After completion of the plating operation the work should be removed from the bath and rinsed with clean, warm water. It should then be immersed for one to two minutes in a 3% to 5% solution of chromic acid and given a final rinse in warm or hot water. The chromic acid solution removes all traces of alkali remaining on the plated surfaces and also passivates the cadmium. This treatment improves adhesion of paint to cadmium plating.

Springs and other parts less than ¼ inch in thickness and containing more than 0.40% carbon must be given a strain-relief treatment after electroplating or after pickling if no subsequent electroplating is done. Internal stresses are set up in thin material of high carbon content by the pickling process. This phenomenon is a hydrogen embrittlement caused by the intermolecular penetration of the steel by nascent hydrogen in the pickling operation. The strain-relief treatment consists in baking the part at 350–400°F. for three hours after plating.

In shop practice the thickness of the cadmium coating is determined by measuring the part, before and after coating, with a good micrometer. The thickness of the coating can also be determined by applying eitber of the following methods to test specimens:

1. The specimen is first cleaned with alcohol and wiped dry with a clean cloth. It is then immersed in a stripping solution which removes the cadmium plating. This solution consists of the following ingredients:

Hydrochloric acid (37%)	73 c.c.
Water	27 c.c.
Antimony trioxide	2 grams

When immersed in this stripping solution the part gases until the cadmium is all removed. The length of time that gassing continues depends upon the thickness of the cadmium coating. For each 0.0001-inch thickness of cadmium, gassing will continue for 20 seconds from the time the part is immersed. Thus, 60 seconds of gassing indicates an average plating thickness of 0.0003 inch.

2. The second method depends upon accurately weighing a specimen of known area when plated and after removal of the plating. Cadmium plating weighs 0.072 ounce per square foot for 0.0001-inch thickness of plating. A 0.0003-inch-thick coating weights 0.216 ounce per square foot of surface. To remove the cadmium plating, the antimony trioxide solution described above may be used, or a solution consisting of one pound of ammonium nitrate per gallon of water. This latter solution will remove the cadmium coating in two to three minutes. Both solutions should be used at room temperature.

If the cadmium plating on a part is defective or soiled it can readily be removed by means of one of the above solutions and the part replated. All brazing and welding of parts should be done before cadmium plating or the plating will be destroyed. It is very important that plated parts be painted as soon after plating as possible to minimize the amount of dirt or grease that will settle on the plated surface if allowed to stand. The parts should be handled as little as possible between plating and priming. For example, it was found that in one shop paint would not adhere satisfactorily to cadmium-plated surfaces until the handling of the parts was cut in half by having inspection done in the paint shop itself. The chromic acid dip was also an aid in improving the paint adherence.

Galvanizing (Zinc Plating). Steel sheets are frequently galvanized for commercial work but seldom for aircraft. Before cadmium plating became common, it was the general practice to galvanize all steel aircraft fittings before painting. Galvanizing is not as effective as cadmium plating in resisting corrosion. Parts are galvanized by dipping them in molten zinc maintained at a temperature between 800–925°F. The parts remain in the zinc bath only a short time and are then removed and hung up until cool. Before dipping the parts in the bath, it is necessary to have them perfectly clean—an important requirement for all plating operations.

A zinc film can also be deposited on metal parts by an electroplating process similar to that described for cadmium plating. A solution of zinc sulfate and cyanide is used as the electrolyte and metallic zinc as the anode. A somewhat thicker plating is used than for cadmium plating to obtain equivalent corrosion resistance.

Sherardizing. Parts are sherardized by heating them in an atmosphere of zinc oxide. The zinc combines with the surface of the metal part, increasing its hardness, durability, and corrosion resistance. The process is carried out by heating the parts in a closed, rotating chamber containing zinc oxide, at a temperature of about 700°F. Sherardizing is not considered as effective as zinc or cadmium plating.

Parkerizing. Parkerizing consists in heating the parts to be treated in a bath of dilute iron phosphate. The bath is kept at about 190°F. by steam coils. When the work is immersed in the bath, a rapid stream of bubbles passes off for a period of 30 to 45 minutes. When the bubbles stop, the coating process is complete. The coating left on the treated part is a mixture of ferrous and ferric phosphate and black iron oxide. The surface is dull gray in color and of smooth texture. It furnishes an excellent base for painting. This process has the added advantage of coating the inside of tubular members, which cannot be done by any electroplating process. This property is particularly important for seaplanes, where moisture is frequently trapped in crevices or inside tubular members.

Bonderizing. Bonderizing is the same as parkerizing, except for the addition of the reagents to the bath which speed up the reaction. The process is completed in from 3 to 5 minutes by this method. After treatment the parts are removed from the bath and hot-rinsed and dried. Bonderizing has the same characteristics as parkerizing with reference to paint adherence and penetration in crevices. Neither of these coatings is very corrosion-resistant in itself but either is quite satisfactory when painted. These and similar processes are frequently referred to as compound phosphate rust-proofing.

Parco Lubrizing. Parco lubrizing is a chemical treatment applicable to iron and steel parts which converts the surface to a nonmetallic oil-absorptive phosphate coating. This is a modification of parkerizing that is primarily designed to reduce wear on moving parts. It has been successfully used in the automotive industry on camshafts, piston rings, valve tappets, generator pulleys, and similar parts. Application to hydraulic pistons in aircraft shows great promise.

The process consists of a precleaning treatment in which vapor degreasing, acid pickle, or spray emulsion is used, followed by a 15-minute dip in a solution prepared by adding 10% by volume of Parco Lubrite to water. This is followed by a water rinse and a dip in water-soluble oil. The phosphate surface soaks up oil and retains it.

This process increases the size of parts from 0.0003 to 0.001 inch on each surface. The exact amount of increase is dependent on the type of metal and the precleaning treatment used.

Coslettizing. Coslettizing is almost identical with parkerizing, except for the fact that the solution used consists of iron filings and phosphoric acid and is more dilute. This treatment gives a black nonrusting surface. It is used to some extent for engine parts.

Granodizing. Granodizing is an electroplating process by which zinc phosphate is deposited on the surfaces treated. The work to be coated is suspended from the cathode bar, which is insulated from the tank containing granodizing solution. The tank itself is the anode. An effort is made to coat the interior surfaces of tubing and remote corners by running anode mandrels inside them if possible. A current density of 36 amperes per square foot of surface is required for this treatment. A plating thickness of 0.005 inch is obtained in a period of about 3 minutes. The work is removed from the granodizing bath and immediately rinsed in cold water and dried. The coating is dull gray-black in color and is soft and velvety to the touch. It provides an excellent base for paint.

Metal Spraying. Metal spraying or metallizing, as it is sometimes called, is the surface application of molten metal on any solid base material. It is possible by this process to spray aluminum, cadmium, copper, nickel, steel, or any one of a dozen metals onto metal, wood, or any solid base. In aircraft work the process is used chiefly to spray a coat of pure aluminum on steel parts to improve their corrosion resistance and paint adherence. Another very useful application is the spraying of seams and crevices in fittings which might trap moisture and then corrode. Metallizing seals these crevices and prevents the entrance of moisture.

The sprayed metal relies purely on the roughness of the surface of the base material for its adherence. The base material must be sandblasted to obtain a rough surface, as well as a perfectly clean surface. The sandblasting of aluminum alloy parts should be done with caution to avoid eating away too much of the metal. In order to prevent soiling of the surface by handling or oxidation, metal spraying should be done as soon after sandblasting as possible.

Metal-spraying equipment consists of a supply of oxygen and acetylene piped to the spray gun and ending in a nozzle, at which point they can be ignited as in a welding torch. A supply of compressed air is also piped to the spray gun. This compressed air operates a feeding mechanism that draws the wire through the spray gun, and it also impels the molten wire onto the surface thus treated. The appropriate wire is led from a revolving reel through the rear of the spray gun, through the automatic feeding mechanism, and out through the nozzle. The wire is melted by the hot oxyacetylene flame and thrown against the surface by the compressed air. When the molten metal strikes the surface, it solidifies and cools fairly rapidly. If the surface is properly prepared, a perfect bond is formed between the metallized coating and the base material.

The spray gun is held from 4 to 6 inches away from the surface and as nearly perpendicular to the surface as possible. The nozzle must not be held at an angle less than 45° to the surface, otherwise the metal particles will glide off and not adhere. In metallizing aluminum alloys, the base metal must not be permitted to become hot or its resistance to intercrystalline corrosion will be lowered. The surface is gradually covered by passing the gun back and forth with as much overlap as necessary to insure covering the entire surface evenly. The gun should be moved at such speed as required to obtain a satisfactory thickness of coating. The surface is slightly rough and forms a good base for paint.

In naval aircraft construction, steel fittings in contact with aluminum alloy are metallized with pure aluminum and then painted. By this means corrosion due to dissimilar metals is eliminated. Whenever possible, steel structural parts which have been metallized with aluminum alloy should be boiled for

30 minutes in a 15% solution of potassium dichromate, rinsed in fresh water, and dried. This treatment will increase the resistance to corrosion.

The following metals in wire form have been successfully passed though the spray gun and deposited on a surface: aluminum, babbitt, brass, bronze, copper, high- and low-carbon steels, 18-8 corrosion-resisting steel, lead, monel, nickel, tin, zinc.

One of the major commercial uses of this operation is the building up of worn parts by spraying a thick coating of material on the worn surface. In the case of steel shafts this is done by revolving the worn shaft slowly in a lathe and spraying it until it is about 1/16 inch over the required size. It is then ground to size. A rough thread is cut in the worn surface before metallizing, to provide a good bond for the sprayed metal. A metallized surface that is almost file hard can be obtained by using a high-carbon steel wire.

Chromium Plating. Chromium plating is used particularly for its appearance, but it also makes a very hard surface which is exceptionally wear resistant—a property essential in the manufacture of chromium-plated brake drums and landing-gear oleo pistons. Successful experiments have also been made on chromium plating of worn shafts and wing hinge bolts, thus restoring them to their original dimension with a harder, more wear-resistant surface. The best results are obtained when the chromium is deposited in thick layers on the worn surfaces of fairly hard metal. In this process the chromium plating is deposited directly on the steel or other surfaces. This type of plating usually has a minimum thickness of 0.002 inch and is frequently deposited to a thickness of 0.015 inch. When it is applied to bolts or other close-tolerance parts, the parts are plated oversize and then ground to finished dimensions. When chromium plating for appearance and corrosion resistance, it is customary to copper- or nickel-plate the part first and then chromium-plate. A thin coat of chromium plating by itself is porous and will not prevent corrosion in outdoor service.

Chromium plating is an electroplating process utilizing a bath consisting of 20% to 30% of chromic acid (CrO_3), a very small amount of sulfates in the form of sulfuric acid (1% of the chromic acid content), and the remainder water. This bath must be kept between 122°F. and 140°F. during the plating operation. A current density of 150 to 200 amperes per square foot of surface will produce a bright deposit over polished surfaces. Too high a current will produce a burned or satin finish, while too low a current will give a bluish plate or insufficient covering.

Parts to be plated must be thoroughly cleaned by immersing in an alkali bath, rinsing, immersing in a hydrochloric acid bath, rinsing, and finally placing in the chromium bath while still wet. If a polished chromium surface is desired, the part must be polished and buffed before cleaning and immersion in the plating bath. It is difficult to chromium-plate in recesses, due to the poor throwing power of the solution. If it is necessary to plate recesses, the anodes must be shaped in a manner similar to the recess and located as far in as possible.

ANODIC OXIDATION PROCESS

This process, which is referred to as anodizing, is used exclusively for coating aluminum and aluminum-alloy surfaces. An aluminum hydroxide surface is produced on the work, which has good corrosion and provides an excellent bond for paint. This treatment is *not* a plating process. The anodized surface is soft and easily scratched, which necessitates giving the treated surface a coating of primer before handling it to any extent.

Government agencies require the anodic treatment of all aluminum or aluminum-alloy parts subject to severe corrosive conditions, except Alclad. If Alclad is to be left unpainted, no anodic treatment is necessary. If the Alclad is to be painted, however, it should be anodically treated or chromatized to provide a bond for the paint. Aluminum alloys containing over 5% copper cannot be anodically treated without destroying the electrolyte in a chromic acid bath and must, consequently, be anodized in a sulfuric acid bath. Castings are seldom anodically treated, because they already have an excellent rough surface for painting. In addition, castings usually have sufficient thickness of metal to minimize the danger from a little surface corrosion. Steel and copper parts cannot be treated by this process. All steel and copper parts must be left off assemblies to be anodically treated.

It is a general practice to anodically treat all parts prior to assembly. When subassemblies do not contain any dissimilar metals, fabric, or sealing compound, and are not subjected to contact with salt water, it is permissible to treat them as a unit. Such parts as wing ribs, built-up brackets, and shelves are in this classification. The anodic film will penetrate about one inch inside the edge of a riveted joint, but will not coat the metal immediately adjacent to the rivet inside the joint. It is important to do all cutting, drilling, and forming possible prior to anodic treatment in order not to break up the film. The rupture of the film after treatment permits local corrosion. To avoid even slight abrasion of the anodic film, all work is primed after treatment before assembling. This coat of primer also improves the corrosion resistance of the material between faying surfaces. It is sometimes impractical to do all drilling prior to anodizing (as in the construction of a monocoque fuselage or hull where it would be necessary to make a complete assembly, dismantle it, anodically treat the parts, and then reassemble permanently). In such cases it is permissible to drill holes on the assembly after anodizing. The screws of rivets inserted in these holes must be coated with wet primer when inserted to protect the raw edge exposed by the drilling.

The standard electrolyte used in the anodic oxidation process is a solution of chromic acid (CrO_3) in water. The chromic acid content varies from 5% to 10% in different baths. The chromic acid must be at least 99.5% pure and is limited in its sulfate and chloride content. The tank is made of steel and is equipped with iron pipe coils for heating and cooling purposes, as well as equipment for agitating the electrolyte. A direct-current generator permitting voltage control between 20 and 40 volts is used. In order to rinse the plated parts adequately and facilitate drying, a second tank containing water at 150°F. to 185°F. must be available.

Parts to be treated normally require no cleaning; but if they are coated with grease, oil, or paint they should be cleaned with thinner, solvent, or free-rinsing soap or cleaners. The parts to be treated are suspended in the electrolyte by means of wires, clamps, or perforated containers made of aluminum or aluminum alloy. These clamps or attachment parts must make a complete electrical contact to insure a free passage of electric current throughout the entire system. The parts are suspended from the anode connection; the steel tank is the cathode. If parts are too large to fit in the tank, they can be treated in sections by slightly overlapping adjacent films. During treatment the temperature of the electrolyte must be maintained between 91°F. and 99°F. The voltage is gradually built up to 40 volts and maintained at that figure as long as necessary. The length of time depends upon the percentage of chromic acid in the electrolyte. A minimum period of 30 minutes is required for a 10% chromic acid solution. A longer time is required with more dilute solutions. After treatment to accelerate drying the parts are washed in clean, fresh, hot water at a temperature between 150°F. and 185°F.

Because of the importance of a perfect anodic film all parts are inspected after treatment and before painting. Any discontinuity or damage to the film requires retreatment. If there is some doubt about an imperfection in the film, an indelible pencil or ethyl violet dye mark should be made on the spot and then rubbed off with a damp cloth. If the film is satisfactory, it will retain the indelible mark. This fact is made use of in stamping anodically treated surfaces. An inspection stamp is made on each part, using indelible ink. This inspection stamp will remain on the part even after the removal of paint that has been subsequently applied. The anodic film will also bring out small cracks in the metal that were invisible before treatment. All bends are particularly examined after anodic treatment for cracks. When inspecting anodically treated parts care must be taken to avoid soiling the surface, which would destroy the paint adherence. If inadvertently soiled, the anodic surface should be cleaned with carbon tetrachloride before painting. All anodically treated parts should be given at least one coat of primer before issuing to the shop for assembly purposes.

The effectiveness of the anodic bath should be checked monthly by selecting random samples anodized with routine production work and submitting them to a salt-spray test. The salt-spray test consists of exposing the sample to a 20% sodium chloride solution for 30 days. Its appearance is compared before and after exposure to this test. Any evidence of corrosion is cause for rejection. The physical properties of the corroded specimens are also checked by means of tensile tests on three samples, and compared to the results obtained on two samples prior to the salt-spray test. The maximum allowable decrease in strength is 5% and decrease in elongation 10%, of the original physical properties as established by the two tests prior to the salt-spray test.

Welded aluminum-alloy tanks can be anodically treated with success provided all the welding flux is removed by pickling, as previously described in this chapter. The anodic coating on the inside of the tank is inferior, however, unless an elaborate arrangement of cathodes is provided for the interior of the tank. Riveted tanks with a seam compound for sealing cannot be treated without destroying the seam compound. In this case the material should be treated before riveting. Rivets are anodically treated before heat treatment. Parts must not be heat-treated in a salt bath after anodic treatment, otherwise the film will be destroyed. All parts except rivets are anodically treated after heat treatment and forming are complete. When rivets are heat-treated in a tubular container, as described in the chapter on Wrought-aluminum Alloys, the anodic film is not injured.

There are several other solutions besides chromic acid for the anodic treatment of aluminum and its alloys. The most important of these is a sulfuric acid solution method which is patented in this country. It is used for aluminum-alloy parts containing over 5% copper. It cannot be used for anodizing subassemblies, however, since any sulfuric acid not removed from crevices will cause corrosion. This sulfuric acid anodize is called the Alumilite treatment.

Potassium dichromate has been found to be an effective inhibitor of corrosion of aluminum alloys. When applied to anodized surfaces the dichromate is absorbed in the anodic coating and greatly improves its corrosion resistance. The interiors of fuel tanks are protected by this means after anodizing. They are boiled in a 4% potassium dichromate solution for 30 minutes to seal the anodic coating. An alternate method is the location of small perforated cartridges filled with potassium dichromate at the lowest point of the fuel tank. This method is recommended for the protection of low points along the keel inside seaplane floats and hulls. Any moisture or salt water that collects at these points will leech out small quantities of potassium dichromate, which will inhibit corrosion. Potassium dichromate gives water a brownish color. When clear water is drained from a fuel tank it indicates the dichromate crystals are exhausted. In washing out the interior of hulls, it is believed the addition of a small amount of potassium dichromate to the rinsing water will prove beneficial. A mild solution of 0.5% by weight is generally recommended.

Chromatizing. This is a dip process which uses the same chromic acid bath as anodizing but without electric current. In chromatizing, the work should be immersed for 5 minutes in a chromic acid bath at a temperature of 120°F., rinsed in hot water, and air-dried. The film obtained by this process is not as heavy or as abrasion resistant as an anodic film, but is satisfactory for all but severe salt-air conditions.

An adaptation of this process is the swabbing with chromic acid of areas in which the anodic film has been damaged in service or repair work. This swabbing improves the corrosion and paint adherence of the affected area.

This chromic acid dip process may be used, in lieu of anodizing, on land planes with the following aluminum alloys: 1100, 3003, 5052, 6053, 6061, 2024, Alclad 2017, and Alclad 7075.

Alrok Process. This is a chemical dip process for the surface treatment of aluminum alloys which is almost as good as anodic treatment. For applications subject to severe corrosive conditions, such as hulls of floats, the anodic process is recommended over the Alrok treatment. It consists of oxidizing by immersion in a hot solution (212°F.) of sodium carbonate and potassium dichromate for about 30 minutes, followed by a sealing treatment in a hot 5% potassium dichromate solution.

The Aluminum Company of America licenses the use of this process for a nominal sum. It is approved for use by the Army.

Alodizing Process. This is a relatively new process developed by the American Chemical Paint Company of Ambler, Pennsylvania. It is approved by the military services for all applications of aluminum and aluminum alloys except the outside surfaces of seaplanes or amphibians. Because of its simplicity, it is rapidly replacing anodizing in aircraft work.

The alodizing process consists of the following operations:

Cleaning—An acidic or alkaline metal cleaner can be used to prepare the work. An alkaline cleaner is mandatory for 75S alloys. These cleaners may be applied by dip or spray.

Rinsing—Rinsing is extremely important especially if an alkaline cleaner was used. Thorough rinsing is assured by spraying the parts with fresh water under pressure for 10 to 15 seconds.

Alodine Treatment—This treatment is a simple chemical process using Alodine which increases the corrosion resistance and improves the paint bonding qualities. It can be applied by dipping, spraying, or brushing.

A thin, hard coating is obtained with ranges in color from light, bluish-green with a slight iridescence on copper-free alloys to an olive green on copper-bearing alloys.

The Alodine bath must be maintained between 100–120°F. The work is dipped for 1 to 2 minutes during which time there must be free circulation, and adjoining parts should not touch each other. The work is drained over the Alodine bath for 1 to 2 minutes and then transferred to the rinsing bath.

Rinsing—The first rinsing is done with clear, cold or warm (not over 120°F.) water for a period of 15 to 30 seconds. A second 10 to 15 second rinse is then given in a Deoxylyte bath maintained at 100–120°F. This is an acidulated rinse to counteract alkaline material in the rinse water and to make the alodyzed aluminum surface slightly acid on drying.

Drying—Drying may be accomplished in an oven with infrared lamps or in air at temperature below 150°F.

Painting—The alodyzed surface must be kept absolutely clean to insure good paint adherence. It is reasonably corrosion resistant and is sometimes left unpainted.

TREATMENTS FOR MAGNESIUM-ALLOY PARTS

Military Specification MIL-M-3171 describes in detail the approved processes for the corrosion protection of magnesium alloys. There are four processes in general use, each of which has its specific application. These processes are chemical treatments that cover the surface with a passive layer that resists corrosion and provides a bond for paint.

Thorough cleaning and pretreatment of magnesium-alloy surfaces are necessary to prepare the surfaces for the coating process. Oil and grease may be removed by the use of such organic solvents as petroleum spirits, alcohol, lacquer thinners, and chlorinated solvents. Final degreasing by alkaline cleaning is necessary, since it also removes previously applied chemical treatments such as the chrome-pickle treatment described hereafter, which is universally used to protect parts during shipment and storage. A satisfactory alkaline cleaning bath consists of 4 ounces of sodium carbonate, 4 ounces of trisodium phosphate, 0.1 ounce of soap, and water to make 1 gallon. This solution should be heated to 180–212°F. and the work immersed from 5 to 15 minutes.

Oxide films, dirt, and discolorations may be removed by sanding, wire brushing, steel wool, or blasting. These mechanical cleaning methods should be followed by pickling, particularly if metallic particles might remain in the surface. A commonly used nitric-sulfuric acid pickling solution consists of

90 parts of water, 8 parts of concentrated nitric acid, and 2 parts of concentrated sulfuric acid by volume. Work is dipped in this solution at room temperature for 10 seconds, then given a thorough rinsing. If the work has previously been blasted the dip time should be extended until 0.002 inch of the surface has been removed. The nitric-sulfuric acid and pickle should not be used on close-tolerance parts, since even the 10-second dip removes a sizeable amount of metal. For close-tolerance parts a hydrofluoric acid pickle is used. This consists of 1 part of 50% hydrofluoric acid and 2 parts of water by volume. The work is immersed in the solution at room temperature for 5 minutes and then given a thorough rinsing. A chromic and pickling solution consists of 1.5 pounds of chromic acid and water to make 1 gallon. The work is immersed for 1 to 15 minutes in the solution at a temperature of 190–212°F. This solution does not etch the material and is particularly good for removing drawing and forming lubricants.

Chrome-pickle Treatment. This treatment is used to protect the material during shipment, storage, machining, and for installed material requiring a good electrical bonding connection. It removes 0.001 to 0.002 inch of metal surface.

The chromic-pickle solution consists of 1.5 pounds of sodium dichromate, 1.5 pints of nitric acid (sp. gr. 1.42), and water to make 1 gallon. The work should be immersed in this solution at a temperature of 70 to 90°F. for ½ to 2 minutes until sufficiently etched, exposed to the air for at least 5 seconds while draining, thoroughly washed in cold running water, then given a dip washing in hot water. The chrome-pickle solution can be held in an earthenware, aluminum, or stainless-steel tank.

For parts such as tanks, which take a long time to fill and empty, the chrome-pickle solution should be diluted with an equal quantity of water. In treating cast alloys containing over 7% aluminum and all die castings, the addition of 2 ounces per gallon of either sodium, potassium, or ammonium bifluoride will prevent the formation of a dark-gray coating. An alternative treatment for die castings is to heat the basic chrome-pickle solution to 125–135°F. and immerse the work for only 10 seconds. Large parts may be treated by brushing on fresh solution for 1 minute and following with a thorough water washing.

Parts properly treated have yellow-red iridescent coatings.

Sealed Chrome-Pickle Treatment. This treatment is used for long-time protection for all magnesium alloys when close dimensional tolerances are required. The chrome-pickle treatment described above is applied first, and immediately after the work dries a sealing treatment is applied. The sealing treatment consists of immersing the work for 30 minutes in a boiling solution of 10–20% dichromate (potassium or sodium) and 0.25% magnesium or calcium fluoride by weight. The work is then rinsed thoroughly in cold running water and given a dip in hot water to facilitate drying. Paint should be applied immediately after the treated parts are dry.

Dichromate Treatment. This treatment provides good corrosion resistance for all magnesium alloys except Dowmetal M, AM3S material. It is applicable to work requiring close dimensional tolerances.

Just prior to the dichromate treatment the work must be cleaned by hydrofluoric acid pickling as described above. The work is then boiled for at least 45 minutes in the dichromate solution described in the paragraph above under Sealed Chrome-pickled Treatment. This solution can be prepared by dissolving technical sodium dichromate in water in the ratio of 1.0 pound per gallon. After the dichromate boil, the work must be rinsed thoroughly in cold running water and given a hot-water dip to facilitate drying.

Steel, brass, and bronze are unaffected by the dichromate treatment. Parts containing bearings, studs, or inserts of these materials can be treated. Aluminum is rapidly attacked during the hydrofluoric and pickling operation.

The color of properly applied dichromate coatings varies from dark brown to black.

Galvanic Anodizing Treatment. This treatment is particularly applicable to magnesium alloy Dowmetal M, AM3S when close dimensional tolerances are required. After being given the hydrofluoric acid pickling dip the work is immersed and galvanically anodized in a bath maintained at room temperature. This bath consists of 4 ounces of ammonium sulfate, 4 ounces of sodium dichromate, 1/3 fluid ounce of ammonia (sp. gr. 0.880), and water to make 1 gallon. The parts to be treated are connected electrically to the iron or steel tank or to metallic cathode plates if the tank is nonmetallic. A current density of 2 to 10 amperes per square foot is applied long enough to produce a uniform black coating. A minimum of 70 ampere-minutes per square foot is required and the maximum seldom exceeds 150 ampere-minutes. Increasing the temperature of the bath to 150°F. will shorten the time required. The work must be rinsed in cold running water and must then be dipped in hot water to facilitate drying, after removal from the bath.

Neither this treatment nor the dichromate treatment requires prior removal of the chrome-pickle coating found on practically all parts as received from the manufacturer.

PAINTS

The final finish operation on aircraft materials is painting. The sole purpose of most of the plating operations is to improve the bond between the paint and the surface of the part. The added corrosion resistance contributed by the plating is, of course, welcome, but it is subordinate to a good paint job. A satisfactory paint must be resistant to such corrosive mediums as salt water, must resist abrasion, must be elastic to prevent cracking, must have good adhesive qualities, and must give a smooth finish and good appearance. There are any number of paints on the market that will meet these requirements to a reasonable degree.

Painting consists of the application of a priming coat, followed by finishing coats of varnish, enamel, or lacquer. All of these have given satisfactory service on airplanes. For special locations, such as the interior of seaplane hulls, a bituminous paint is used. In the vicinity of storage batteries an acid-resisting paint is used. The various types of paint used will be described in the following pages.

Paint. Paint is a mechanical mixture of a vehicle and a pigment. The vehicle is a liquid that cements the pigment together and strengthens it after drying. The pigment gives solidity, color, and hardness to the paint.

The pigment selected for paint must be corrosion inhibitive and inert in order to protect the underlying surface. Since the pigment also contributes color to the paint, a variety of pigments are used in different colored paints. Among the commonly used pigments are: iron oxide, zinc chromate, titanium oxide, iron blue, lead chromate, carbon black, and chrome green.

The vehicles used for paint may be divided into two general classes:

1. *Solidifying oils* which, on exposure, dry and become tough, leathery solids. The most common of these oils used in aircraft paints is known as China wood oil, or tung oil. This oil dries quickly and is tough, durable, and free from cracks. Another common solidifying oil is linseed oil. It is not so good as China wood oil but does dry to a tough, elastic film. It can be obtained in the raw state, in which it is most effective, but it takes several days to dry. The addition of driers, such as lead or manganese oxides, will shorten the drying time appreciably by acting as catalysts and drawing oxygen from the air into the oil. Boiled linseed oil will also dry quickly but is not as effective as raw linseed oil.
2. *Volatile oils*, or spirits, which evaporate when exposed. These oils are used to dilute paint to the proper consistency and to dissolve varnish resins. The most common volatile vehicles are: alcohol, turpentine, benzine, benzole, toluene, ethyl acetate, and butyl acetate.

Ordinary paints, varnishes, and enamels are usually composed of a pigment and a mixture of both solidifying and volatile oils. Lacquer, which is noted for its rapid drying, is composed only of pigments, resins, and volatile oils.

Primer. A priming paint must have definite corrosion-inhibitive qualities since it is in direct contact with the surface of the metal. It must also have good adherence on the bare metal or plated surfaces, as well as furnishing a good base for the top coats of paint. In aircraft work it is customary to assemble parts after priming and apply the finish coats after assembly. Under these conditions the primer must be tough and durable to resist abrasion and scratching. There are two primers that are generally used on aircraft; namely, *red iron oxide* primer and *zinc chromate* primer. Zinc chromate primer has practically superseded red iron oxide primer.

Red iron oxide primer has brownish-red color. Its pigment is iron oxide and a small amount of zinc chromate. The nonvolatile vehicle is made of resin, China wood oil, and some linseed oil. About one-third of the primer is composed of volatile mineral spirits and turpentine. This primer spreads and adheres well and is very durable. It will dry to touch in 1½ hours, and completely in 6 hours. This primer is satisfactory for use on metals as a protective primer coating under oil enamels, but not under nitrocellulose lacquers or enamels. It should not be used on wood.

Zinc chromate primer has become the universal choice for aircraft work because of its general all-round qualities. This primer is greenish-yellow when applied. When the color is too yellow, it indicates too thick a coat. Its pigment is practically all zinc chromate with some magnesium silicate. The vehicle consists of resins, drying oils, and hydrocarbon solvents. The exact selection of the vehicle is left to the discretion of the paint manufacturer. This primer dries to touch in 5 minutes, and completely in 6 hours. This rapid drying to touch is a great aid in speeding up shop operations. Zinc chromate primer is satisfactory for use under oil enamels or nitrocellulose lacquers. It is also an excellent dope-proof paint. It can be painted over enamels to protect them from subsequent doping operations as on fabric covering of wings or fuselages.

The application of zinc chromate primer should be done by spraying because of its rapid drying qualities. It is thinned with toluene to obtain a suitable working viscosity. It can be applied rapidly by brush but the operation is difficult and undependable. Parts can also be dipped in this primer but should be withdrawn slowly enough to permit excess primer to run off.

Zinc chromate primer will adhere to cadmium-plated parts only if they have been given a chromic acid dip and are perfectly clean. If cadmium-plated parts are baked after priming, satisfactory adherence will also be obtained. Baking for 1½ hours at 160°F. is normally required.

The dope-proofing qualities of zinc chromate primer are excellent. For this purpose a heavy coating should be used, as indicated by a full yellow color. This primer can also be used in a similar capacity to seal an oil enamel finish to which a lacquer coating must be applied. Six hours should be allowed for drying before application of the lacquer.

Aluminum powder is frequently added to zinc chromate primer for use as an interior finish coat. This material is excellent except in locations subject to usage or handling.

Zinc chromate pigment has better corrosion-inhibiting properties than any other pigment. It is believed these properties are derived from the electrolytic depolarizing action of chromate ions which are liberated in the presence of water. This action makes zinc chromate primer very resistant to the starting or continuation of electrolytic corrosion.

Lacquer. A nitrocellulose lacquer is often used for the finishing coats on airplanes. These lacquers consist of cellulose nitrate, glycol sebacate, glyceryl phthalate resin, volatile spirits such as toluene, butyl acetate, butyl alcohol, and ethyl acetate, and pigment as necessary to give the correct color. Lacquers can be obtained in practically any color desired. They are lighter in weight than other airplane finishes and can be touched up readily in service. Lacquer dries almost instantly when applied. It may be used on fabric or metal surfaces. Lacquer does not have as good corrosion-resisting qualities as aluminum-pigmented varnish, but is wholly satisfactory for other than seaplane work.

Varnish. Varnish, unlike paints, is a solution and not a mixture. It consists of resins dissolved in oil or mineral spirits. Oil varnishes are those in which the oil dries and becomes part of the film after application.

Aircraft spar varnish is used for outside exposed surfaces of wood, metal, and doped fabric. It gives a clear, transparent, protective coating. It is also used as a vehicle for aluminum pigment, aircraft enamels, and primers. This varnish is a phenol formaldehyde varnish. It consists of resin, China wood oil, some linseed oil, driers, mineral spirits, turpentine, and dipentine. It can be brushed or sprayed successfully. It dries to touch in 1½ hours, and completely in 5 hours. This varnish is particularly good under conditions involving exposure to salt water, as in seaplane hulls.

Glyceryl phthalate spar varnish also gives a clear, transparent coating. It is used as a finishing coat on wood, metal, or primed surfaces, as well as a vehicle for aluminum pigment. The enamel formed by aluminum pigment and this varnish is very often used to finish airplanes. Glyceryl phthalate resin, modifying agents, and hydrocarbon solvents are the ingredients of this varnish. It can be brushed or sprayed. It dries to touch in 3 hours, and completely in 18 hours.

Enamel. Enamel is a mixture of a pigment and varnish. Varnish acts as the vehicle. Enamels are harder and more durable than paints. They are frequently used for the top coats in finishing airplanes. The color of enamels depends upon the pigment. Practically all aircraft enamels are made by mixing a pigment with spar varnish or glyceryl phthalate varnish, both of which are described just above.

Aluminum-pigmented varnishes are being rapidly adopted for general use because of their protective qualities. The spar-varnish mixture is believed to be somewhat better than the glyceryl phthalate varnish mixture as a protection against salt-water corrosion. For general work, however, aluminum-pigmented glyceryl phthalate varnish is more often used. The aluminum pigment is usually purchased in the form of a powder or paste and mixed with the varnish as needed. The aluminum pigment is made from commercially pure aluminum. An extra fine powder capable of passing through a No. 325 sieve is used for aircraft paints. This pigment mixes well with the varnishes described and gives a continuous, brilliant film. It is advisable to apply a final coat of clear varnish to fix the aluminum pigment, which otherwise adheres to any object that touches it, especially clothing.

Acid-resistant Paint. Acid-resistant paint is used to coat the insides of battery boxes and materials in the vicinity of such boxes. An asphalt varnish that is resistant to mineral acids is used for this purpose. This varnish is jet black in color and has good brushing qualities. It dries to touch in 5 hours, and completely in 24 hours. It is resistant to sulfuric acid, nitric acid, or hydrochloric acid.

Bituminous Paint. Bituminous paint is manufactured from a coal-tar derivative and suitable solvents. For aircraft purposes it is usually pigmented with aluminum powder. The unexposed parts of hulls, floats, wings, and tail surfaces on seaplanes are usually protected with two coats of aluminum bituminous paint. This paint will bleed through any other paint. Particular care must be taken when it is used under fabric covering to prevent it from staining the fabric. In this case all painted parts in contact with the fabric should be thoroughly covered with aluminum foil prior to covering. Generous lapping of the foil is necessary to protect the fabric.

Soya-bean-oil Compound. This compound is composed of nonvolatile raw soya-bean oil, ester gum, and China wood oil combined with a small amount of volatile turpentine. It is used as a seam compound for making metal hulls and floats watertight. This compound weighs 7.85 pounds per gallon. When completely exposed it takes over six days to dry hard.

Marine Glue. Marine glue contains rosin, pine tar, denatured alcohol, and a drying oil such as China wood oil, rosin oil, or linseed oil. It is used as a seam compound on either wood or metal hulls for water tightness. It is very adhesive and remains tacky.

Rust-preventive Compound. Rust-preventive compounds are applied to fittings, strut ends, and similar places over their regular protective finish to increase the corrosion protection. They are applied by brushing, dipping, or spraying at a temperature around 150°F. They are nondrying and form a continuous adherent, protective coating. They can be removed with kerosene.

Beeswax and Grease. A mixture of beeswax and grease applied hot is often used in place of rust-preventive compound. This mixture is very effective in resisting corrosion.

Paralketone. Paralketone is an all-purpose rust-preventive compound for use on both ferrous and nonferrous metals and for the lubrication and protection of cables. It has also been used to spray inaccessible parts of seaplanes over normal paint finish. It has displaced beeswax and grease and other rust-preventive compounds to a large extent.

FINISH OF DETAIL PARTS

In this section the author will endeavor to recommend a satisfactory finish for each of the parts that makes up an airplane. The recommendation will apply particularly to seaplanes, in which the most severe corrosion conditions are met. Many of the recommendations can be modified somewhat for less severe service conditions.

Control Cables. These cables should not be painted but will be satisfactory if dipped in paralketone prior to installation, and lightly coated with the same material after installation. The coating must be renewed periodically.

Oil tanks. Oil tanks constructed of aluminum alloy should be anodized and painted with two coats of primer on the outside surface. The inside is left unpainted. If the oil tank is visible and readily accessible, the painting may be replaced by a coating of rust-preventive compound.

Fuel tanks. Fuel tanks should be anodized and painted the same as inaccessible oil tanks. To protect the inside of the fuel tank, it should be boiled, after anodic treatment in a 4% potassium dichromate solution for 30 minutes.

Tank-supporting Straps. These straps should be given the regular finish of one coat of primer and two top coats. The padding for the tanks and straps should be immersed in castor oil until impregnated.

Storage-battery Boxes. The insides of battery boxes and surfaces within 12 inches of the battery, or other surfaces on which acid might be spilled, should be given the regular finish plus two coats of acid-proof paint followed by two coats of clear varnish.

Copper, Brass, Bronze. These parts do not require any treatment unless it is necessary to match a paint job, or for insulation between dissimilar metals such as steel or aluminum.

Magnesium-alloy Parts. These parts should be given a dichromate or a sealed chrome-pickle treatment, followed immediately by a coat of primer and three coats of the finish paint.

Faying Surfaces. Nonwatertight faying surfaces should be given two coats of primer, or one coat of primer and one coat of finish paint. The first coat should be thoroughly dry before applying the second. Watertight faying surfaces should be given the same treatment and should be assembled with zinc chromate tape or equivalent material or a strip of impregnated fabric of flannel between the joint. The fabric should be impregnated with a sealing compound, such as soya-bean-oil compound, marine glue, bituminous paint, or one of the patented compounds on the market.

Steel Tubular Members. The ends of these members should be sealed by welding to exclude the entrance of moisture. After completion of all fabrication operations, the inside of the tubing should be flushed with hot raw linseed oil or a rust-preventive compound such as paralketone. Oil at a temperature over 160°F. is forced through a small hole in one end of the tube under pressure. When the assembly comprises more than one tube, as in a welded fuselage, interconnecting holes are drilled between adjacent tubes. The presence of the hot oil in each tube must be checked by feeling it with the hand. The oil must remain in the tubes not less than two minutes, after which it is drained. All holes opened to the outside should then be filled with cadmium-plated self-tapping screws. These oil holes should be located in the region of lowest stress, and the drive screws should just fit the hole snugly without stretching, cracking, or splitting the surrounding metal. Serious failures have resulted from cracks started by driving self-tapping screws in highly stressed locations.

Aluminum Tubular Members. It is not practical to seal the ends of aluminum-alloy members by welding; so they should be left wide open at the end to permit drainage. The interior surfaces should be given the same finish as the outside surfaces. End fittings should be so designed that they do not form pockets to trap moisture.

Welded-steel Structures. Structures such as fuselages, landing gears, and engine mounts should be oiled or paralketoned internally, sandblasted, and painted.

Hull Interiors. The interiors of hulls and floats should be finished with three coats of zinc chromate primer.

Seaplane Finish. After being given their regular finish, all open-end struts should be dipped in a hot rust-preventive compound to a depth of 18 inches from the end. The strut should then be drained and wiped on the outside. All strut attachment fittings should be coated with rust-preventive compound after assembly. All other parts subject to spray should also be coated with this compound. An alternative to rust-preventive compound is a mixture of beeswax and grease, which can be applied in the same way.

Aside from the special treatments just described, all parts of the airplane should be finished with one coat of primer and two or more top coats. Inaccessible parts subject to severe corrosion should be given three coats of primer. All steel parts should be cadmium or zinc plated when possible prior to painting. Other steel parts should be sandblasted, parkerized, bonderized, or granodized. Aluminum-alloy parts should be anodically treated prior to painting. Careful preparation and care in painting will pay dividends in freedom from corrosion troubles.

CHAPTER XVI

WOOD AND GLUE

GENERAL USES OF WOOD

Wood in aircraft construction has been largely superseded by aluminum alloys and steel. It is still used extensively, however, in the construction of wing spars and ribs for small commercial airplanes. Wood propellers are still in common use and in some countries are preferred to metal propellers. Wood is also used with good effect for interior cabin trim and flooring. Due to its relative cheapness and the ease with which it can be worked to any desired shape, wood is ideal for the construction of the first experimental model of an airplane. The practice of using wood for this purpose will become more general, it is believed, when mass production of airplanes is a reality. Under these conditions the manufacture of jigs and dies will be too costly a gamble until a cheaply built experimental plane has been thoroughly test flown. In England and France it is common practice to construct entire airplanes of wood covered with plywood. The British Mosquito fighter-bomber is an all-wood airplane. Gliders have been constructed of wood almost exclusively.

Wood construction has very definite weight advantages when parts are lightly loaded, as in gliders or light airplanes. Wood has the advantage of large bulk for a given weight, combined with relatively great strength. The tensile strength of wood is exceptionally good. These properties make wood ideal for the manufacture of lightly stressed wing spars, such as are found in small civil aircraft. The ease of working is also important when only small quantities of planes are being built. Wood has excellent elastic properties which permit stressing almost to the breaking point without excessive permanent deformation. It also has the ability to resist a greater load for a short period of time than it is capable of carrying for a long period. This ability is very valuable in aircraft, in which peak loads are imposed only momentarily.

The nonhomogeneity of wood is its greatest disadvantage. The properties of wood vary even for two pieces taken from the same tree. The properties of a piece of wood are also dependent upon the moisture content. Moreover, the direction of the grain is of prime importance to the physical properties. Being the product of natural growth in the form of trees, wood is subjected to numerous experiences which leave their mark in the form of defects or flaws. A very careful inspection must be made of all wood before it can be accepted for aircraft use. This inspection limits the amount of wood available for aircraft and increases the cost. It is extremely difficult to obtain a long length of wood of moderate sectional dimensions for use as a wing spar. Before designing a wooden spar it is advisable to locate a reliable source of supply that can furnish wood of acceptable quality and of the desired dimensions.

Naming Wood. In purchasing wood it is essential that the botanical as well as the common name be given. The same wood frequently has many different common names. One species of pine has as many as thirty local names. On the other hand, the common name of cedar is often applied to several unrelated species.

The botanical name of a plant or tree is made up of terms denoting the genus and species. For example, Picea is the generic name that includes all the species of spruce, while sitchensis, rubens, and canadensis apply to particular species of the genus spruce. Picea sitchensis, Picea rubens, and Picea canadensis are complete botanical names for what are commonly called Sitka spruce, red spruce, and white spruce, respectively.

Classification of Trees and Woods. Trees are divided into general groups which are known as:

(1) *conifers*—softwoods, needleleaf, evergreen;

(2) *hardwoods*—deciduous, broadleaf, dicotyledons, nonconiferous.

Conifers is the most common name applied to the first group. The other names are not all applicable because some of the woods of this group are not soft, some do not have narrow leaves as indicated by "needleleaf," and others are not evergreens. Pines, firs, cedars, and spruces belong in this group. Coniferous trees cover large areas in parts of Canada and the United States. Their wood is comparatively light in weight, is easy to work, and is obtainable in large, straight pieces.

Hardwoods is the common name applied to the second group. Neither this name, nor the others applied to this group, are wholly true. Some of the woods of this group are soft; others are not deciduous but retain their leaves. Ash, birch, mahogany, maple, oak, poplar, and walnut belong in this classification. Hardwood trees grow in many parts of the world in natural forests and under cultivation. They are relatively heavy in weight, difficult to work because of their complicated cell structure and obtainable only in relatively small lengths.

There is also a third type of tree known as monocotyledons. This group includes the palm and bamboo trees. They have little or no structural value.

STRUCTURE OF WOOD

A tree trunk is composed of four distinct parts—a soft central core called the *pith*, concentric rings immediately surrounding the pith called the *heartwood,* which in turn is surrounded by the *sapwood*, followed by the *bark*.

The pith, or medulla as it is technically called, is evident in the sections of young tress for which it serves as a food storage place. In mature trees the pith is nothing but a point or a small cavity.

Heartwood or duramen is a modified sapwood. Each year as a new annular ring is added to the sapwood the heartwood also increases. It is formed from the adjacent sapwood, which dies, and takes a characteristic appearance by reason of the infiltration of coloring matter and other substances into the cell walls and cavities. Heartwood is heavier, tougher, and darker than sapwood. In the living tree the heartwood is subject to attack by fungi, but after cutting it is more resistant to insect attack, decay, stain, or mold than sapwood. The amount of heartwood present in a tree varies with the species from ½% to over 90% of the cross-section area.

Sapwood or alburnum is the younger, lighter colored, more porous wood located just under the bark of the tree. The cells of sapwood are alive and serve for the storage and translocation of food. Sapwood is more pliable than heartwood and is preferable when severe bending must be done. It is as strong as heartwood except in the case of very old trees, in which the sapwood is inferior.

Bark is the husk or outer cover that protects the tree. It does not serve any useful structural purpose.

Wood is composed of a great number of minute structural units or cells. These cells vary considerably in size and shape within a piece of wood and between species. The thickness of the cell walls and their arrangement, together with associated materials such as water, determine the physical properties of the wood. Due to its cellular structure wood has good bending strength and stiffness for a given weight, but it has low hardness.

The differences in physical properties of various species of wood are due to the cell size and wall thickness. For any particular wood the strength is proportional to its specific gravity.

Sawing Wood. All trees, except monocotyledons, grow annually by the addition of a concentric layer of wood around the outside surface of the sapwood. An examination of any tree trunk or log will show these concentric layers, which are called annual rings. In sawing logs into planks the wood can be sawed in either of two ways: along any of the radii of the annual rings, which will expose the radial or vertical-grain surface; or tangent to the annual rings. These two methods of sawing are shown

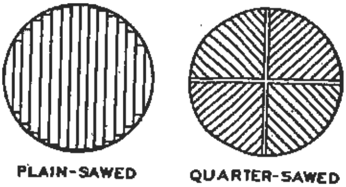


FIGURE 60. Methods of Sawing Logs

in Figure 60. There would be too much waste involved in sawing only along the radii; hence a modification, called *quarter-sawing*, is actually used. Even quarter-sawing wastes considerable material and is therefore more expensive than tangential sawing. Quarter-sawed lumber shrinks and swells less than tangential lumber, and develops fewer flaws in seasoning. Tangentially cut lumber is commonly called *plain-sawed* or *flat-grain surface.*

Government specifications for aircraft wood usually specify that either vertical-grain (quarter-sawed) or flat-grain material is acceptable, providing not more than 25% of any shipment is flat-grain material.

Grain. The grain of wood is determined by the direction of the fibers. It always runs along the length of a piece of lumber, but it is not always straight. The strength of a piece of wood without reasonable straight grain is greatly reduced. Aircraft wood specifications require that the grain shall not deviate more than 1 inch in 20 inches from a line parallel to the edge of the lumber. Even less deviation than this is desirable for the best strength properties. For parts whose failure will not endanger the airplane, a grain slope of 1 in 15 is usually acceptable.

Spiral grain is a defect often found in lumber. Spiral grain occurs when the fibers take a spiral course in the tree trunk as if the tree had been twisted. In examining for spiral grain, the edge of the board farthest from the center should be observed, since the slope of the spiral grain is greater in this location than it is at the center. An artificial spiral grain is produced if straight-grained stock is not cut parallel with the fibers as seen on the tangential face. All spiral grain is objectionable because of its weakening effects, the rough surface produced by planing against the grain, and its tendency to twist in seasoning. The slope of spiral grain should not exceed 1 to 20 for important members and 1 in 15 for other parts used in aircraft construction.

Diagonal grain, which is also objectionable, is produced when the direction of sawing is not parallel to the bark. It occurs when timber is sawed parallel to the center, or in sawing crooked logs. This type of grain also weakens the wood and produces a rough surface when planed against the grain. The same slope of grain is permissible as with spiral grain for aircraft work.

Interlocked grain occurs when adjacent layers of wood are spirally inclined in opposite directions. This condition is found mostly in hardwood trees, such as mahogany and sycamore. This type of grain causes warping and makes planing difficult. Interloked-grain lumber does not split so easily as straight-grained material. Mahogany used for aircraft propellers has interlocked grain, but does not warp seriously or offer much difficulty in planing.

Wavy and curly grain are the result of the wood fibers in a tree following a contorted course. The grain is always distorted when knots or wounds are grown over. These types of irregular grain weaken the wood and cause irregular shrinkage and rough surfacing when machined.

STRENGTH OF WOOD

The strength of wood depends upon a great many factors. The absence or limitation of defects is a primary consideration. The density of the wood as indicated by its specific gravity is a very definite indication of its quality and strength. Its moisture content has also been found to affect its strength probably more than any other one item. Still another important feature is the rate of growth of the tree as shown by the number of annual rings per inch. In some instances the strength of a piece of wood is dependent upon the locality in which it was grown. It is apparent that great care must be taken in selecting a piece of lumber for aircraft use when its strength is all-important.

Specific Gravity vs. Strength. The minimum acceptable specific gravities for aircraft woods are given in Table 21. The strength of a piece of wood varies almost directly in proportion to its specific gravity. It has been found that a 10% increase in the specific gravity will improve the following physical properties in the same proportion: compression parallel to the grain and modulus of elasticity in static bending. At the same time the shock resistance will be increased over 20%.

Because of the great variation in weight caused by different moisture contents, the specific gravity of wood must be determined for an oven-dry condition. The specific gravity of piece of wood can be readily established by the following method:

> Cut a sample of the wood about 1 inch in length along the grain for any desired cross-section. Place the sample in an oven and heat it for two to three days at a temperature of 212°F. until all its moisture is evaporated and its weight has become constant. The oven-dried specimen should be weighed while hot and the weight recorded in grams (1 ounce = 28.4 grams). The volume of the specimen should be calculated from accurate measurements of its dimensions. The accuracy of this calculation can be improved by selecting a smooth, regularly shaped specimen. The volume should be recorded in cubic centimeters (1 cubic inch = 16.4 cubic centimeters). The specific gravity may then be computed by dividing the oven-dry weight in grams by the volume in cubic centimeters. This, of course, is based on the fact that one cubic centimeter of water weighs one gram, and its specific gravity is 1.

Locality of Growth vs. Strength. Most woods have equal strength, providing their specific gravities are the same, irrespective of their locality—particularly Sitka spruce, black walnut, maple, and birch. Douglas fir grown in the Rocky Mountains has considerably less weight and strength than the same species grown on the Pacific Coast. Along with this difference in strength in the two localities it should be noted that there is also a similar difference in weight.

Rate of Growth vs. Strength. Hardwoods of very rapid growth are usually above the average in strength properties. An exception to this rule is swamp-grown ash, which grows very rapidly but is inferior in weight and strength. Aircraft specifications list this particular type of wood as unacceptable.

The conifers or softwoods, such as spruce, are below the average in strength when rapidly grown. It is customary to specify a minimum number of annual rings per inch for softwoods as a criterion of the rate of growth. For aircraft spruce the requirement is a minimum of six annual rings to each inch when measured in a radial direction on either end section through the zone of maximum growth.

Moisture Content vs. Strength. The strength of wood is very dependent upon its moisture content. Under natural service conditions it has been found that the moisture content of wood will stabilize at a maximum of 15% of the dry weight. Since it is not safe to figure on lower moisture contents with their greater strengths, all design calculations are based on figures for wood with 15% moisture content.

Moisture is present in wood as free water in the cell cavities and as hygroscopic moisture in the cell walls. The free water has no effect on the strength of the wood. When the moisture in the cell walls is decreased, the wood shrinks and increases in strength. The amount of moisture present in wood is regulated by a seasoning process. It will be noted in Table 21 that there is considerable shrinkage between green lumber and oven-dry lumber. It is essential that wood be seasoned to approximately the moisture content it will reach in service, in order to minimize the shrinkage and swelling of finished parts.

The strength of wood increases very rapidly with a decrease in the moisture content. Figure 61 shows this increase of strength for Sitka spruce that has been carefully dried. It will be noted that a considerable increase of strength is available in wood with less than the standard 15% moisture content. Tests have shown that it is not safe to count on this extra strength, however, since under normal conditions wood will stabilize at 12–15% moisture content, even though the wood is thoroughly protected with varnish. The varnish merely delays the absorption of the normal amount of moisture but does not prevent it.

The moisture content of a piece of wood can be determined by the following method:

> Cut a specimen from the wood to be checked that is at least 5 cubic inches in volume but as small in the direction along the grain as possible. It is desirable to have

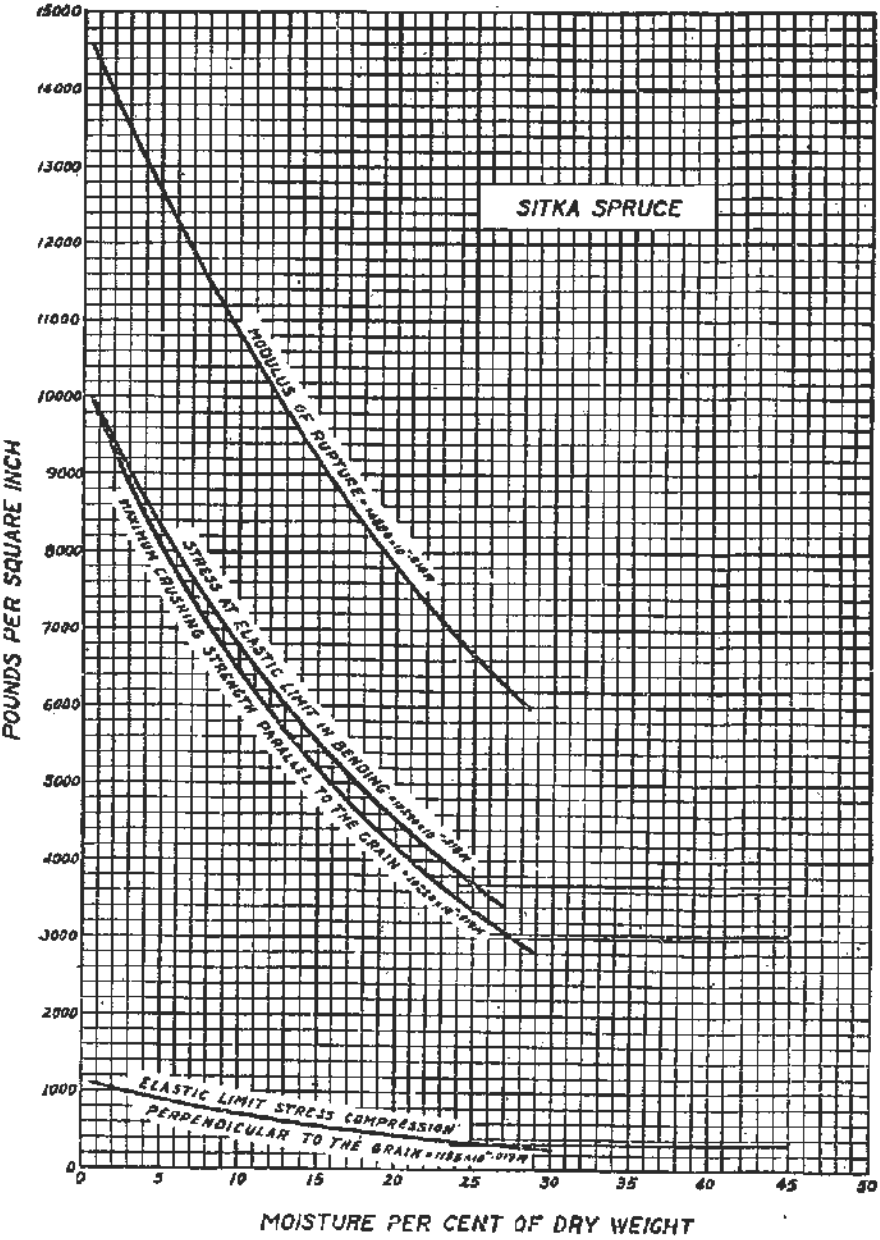


FIGURE 61. Relations between Strength and Moisture Content

the specimen about one inch long in the direction of the grain in order to shorten the time of drying. After cutting, the specimen should be smoothed up and weighed immediately in order to avoid any change in the moisture content. It should then be placed in a drying oven and dried for 2 to 3 days at 212°F. until the moisture is exhausted and the specimen has reached a constant weight. The dry weight of the specimen should then be determined immediately after removing from the oven. When the dry weight is subtracted from the original weight, the difference represents the weight of moisture in the original specimen. This difference divided by the oven-dry weight and multiplied by 100 is the percentage of moisture content of the specimen tested.

Defects vs. Strength. Defects in wood are very common and have a very bad effect on the strength. In purchasing wood for aircraft construction, the type and amount of defects that will be acceptable are always specified.

Sloping grain is the most common defect. This constitutes spiral, diagonal, wavy, curly, interlocked, or other distorted grain. The general rule is to specify that grain cannot have a slope of more than 1 in 20 for important lumber, such as that used for wing spars, and a slope of not more than 1 in 15 for lumber to be used for such items as boat frames, stringers, and interior-fitting supports. When a combination of types of sloping grain is present, such as spiral and diagonal grain, it is necessary to compute the combined slope. These two types of grain occur at right angles to each other, and, therefore, the combined slope can be computed by taking the square root of the sum of the squares of the two slopes. This is best done by converting the slope into decimals before squaring. Thus a spiral grain of 1/25 and a diagonal grain of 1/20 would be 0.04 and 0.05, respectively. Squaring these fractions, adding, and taking the square root will give 0.064, which is 1/15.6. The combined slope then is 1 in 15.6, which is unsatisfactory by the 1/20 criterion, although the individual slopes were good enough for first-class lumber. Experience has shown that wood with a large sloping grain not only has reduced strength but is very variable in other properties, and is unpredictable.

Knots reduce the strength of wood largely because the grain is distorted in their vicinity. Knots should not be permitted along the edge of a piece of wood or in the flange of a wing spar. An occasional knot is permissible in other locations, providing the grain distortion is not greater than 1 in 20 or 1 in 15 because of the presence of the knot. It is usual to restrict the size of knots to ¼ inch in important members and ½ inch in lesser members. The knots should be sound and tight. The weakening effect of knots, due to distorted grain which accompanies them, may be better appreciated when it is realized that the strength of wood along the grain is from 30 to 60 times stronger than across the grain.

Pitch pockets are lens-shaped openings between annual rings which contain resin. They vary from under one inch to several inches in length and are found only in such woods as pine, Douglas fir, and spruce. Pitch pockets are permitted in aircraft wood if they do not exceed 1½ inches in length and $^1/_8$ inch in width, and when not more than one is present in a 12-foot length of wood. Pitch pockets are not permitted in the edge of a member or in a wing spar flange, on the same basis on which knots are excluded.

Mineral streaks are dark brown streaks containing mineral matter and are found in such woods as maple, hickory, basswood, and yellow poplar. They extend for several inches to a foot along the grain and are from $^1/_8$ to 1 inch wide. Mineral streaks are frequently accompanied by decay. For this reason close inspection of wood containing them is essential. If decay has set in, the toughness of the wood will be greatly reduced.

Compression wood should never be used in aircraft parts. This name refers to the wide annual rings found on the lower side of leaning trees. It has a high specific gravity, very low strength, and abnormally high longitudinal shrinkage. It is subject to excessive warping and twisting. Compression wood is found frequently in conifers but not in hardwoods.

Decay in any form is not permissible in aircraft wood. Decay will reduce the shock-resisting qualities of wood in its early stages and seriously reduce all the strength properties as it develops. All stains and discolorations should be carefully inspected, for they may be the start of decay.

Checks, shakes, and splits in wood are causes for rejection. All of these defects weaken the wood, cause internal stress, and are generally unreliable, A *check* is a longitudinal crack in wood running across the annual rings and is usually caused by unequal shrinkage in seasoning; a shake is a longitudinal crack running between two annual rings; a *split* is a longitudinal crack in wood caused by rough handling or other artificial means.

Wood containing compression failures must not be used for strength members. These failures, which appear as fine wrinkles across the face of the wood, are caused by severe winds bending standing trees, felling trees on irregular ground, or other rough handling inducing high stresses in the wood. Compression failures seriously reduce the bending strength and shock resistance of wood parts. Compression failures are sometimes so small that the aid of a microscope is needed to detect them.

STRENGTH PROPERTIES

Table 21 gives the strength values of the various woods used in aircraft construction. Due to the variation in the strength of wood caused by many different factors, it was necessary to standardize a number of these factors in order to establish definite strength figures. The following notes explain the bases on which Table 21 is founded.

Table 21. Strength Values of Woods for Use in Airplane Design*

	Common and botanical names	Specific gravity (based on oven-dry vol. and wt.)		Weight at 15% moisture content (lb./cu.ft.)	Shrinkage from green to oven-dry condition		Static bending				Compression parallel to grain		Compression perpendicular to grain (p.s.i.)	Shearing strength parallel to grain (p.s.i.)	Hardness—load in pounds to imbed 0.444" ball ½ its diameter
		Average	Minimum permitted		Radial (%)	Tangential (%)	Stress at elastic limit (p.s.i.)	Modulus of rupture (p.s.i.)	Modulus of elasticity (1000 p.s.i.)	Work to maximum load, in lb./cu.in.	Stress at elastic limit (p.s.i.)	Max. crushing strength (p.s.i.)			
Hardwoods	Ash, commercial white (Fraxinus)	.62	.56	41	4.3	6.9	8,900	14,800	1460	14.2	5250	7000	1920	1380	1180
	Basswood (Tilia americana)	.40	.36	26	6.6	9.3	5,600	8,600	1250	6.6	3370	4500	530	720	370
	Beech (Fagus atropunicea)	.66	.60	44	4.8	10.6	8,200	14,200	1440	13.5	4880	6500	1430	1300	1060
	Birch (Betula)	.68	.58	44	7.0	8.5	9,500	15,500	1780	18.2	5480	7300	1300	1300	1100
	Cherry, black (Prunus serotina)	.53	.48	36	3.7	7.1	8,500	12,500	1330	11.7	5100	6800	1000	1180	900
	Elm, cork (Ulmus racemosa)	.66	.60	45	4.8	8.1	7,900	15,000	1340	19.3	5180	6900	1790	1360	1230
	Gum, red (Liquidambar styraciflua)	.53	.48	34	5.2	9.9	7,500	11,600	1290	10.9	4050	5400	1010	1100	650
	Hickory, true (Hicoria)	.79	.71	51			10,600	19,300	1860	27.5	6520	8700	2650	1440	
	Mahogany, African (Khaya species)	.47	.42	32	4.8	5.5	7,900	10,800	1280	8.0	4280	5700	1200	980	720
	Mahogany, true (Swietenia species)	.51	.46	34	3.4	4.7	8,800	11,600	1260	7.3	4880	6500	1510	860	790
	Maple, sugar (Acer saccharum)	.67	.60	44	4.8	9.2	9,500	15,000	1600	13.7	5620	7500	1850	1520	1270
	Oak, white (Quercus alba)	.69	.62	45	4.6	9.0	7,800	13,800	1490	13.6	4950	6600	1600	1300	1240
	Poplar, yellow (Liriodendron tulipifera)	.43	.38	28	4.0	7.1	6,000	9,100	1300	6.5	3750	5000	690	800	420
	Walnut, black (Juglans nigra)	.56	.52	39	5.2	7.1	10,200	15,100	1490	11.4	5700	7600	1480	1000	990
Conifers	Cedar, Port Orford (Cyamaecyparis lawsoniana)	.44	.40	30	4.6	6.9	7,400	11,000	1520	8.7	4880	6100	880	760	520
	Cypress, bald (Taxodium distichum)	.48	.43	32	3.9	6.1	7,100	10,500	1270	7.7	4960	6200	1050	720	480
	Douglas fir (Pseudotsuga taxifolia)	.51	.45	34	5.0	7.8	8,000	11,500	1700	8.1	5600	7000	1100	810	620
	Pine, white (Pinus strobus)	.38	.34	26	2.2	6.0	5,900	8,700	1140	6.3	3840	4800	670	640	380
	Spruce (Picea)	.40	.36	27	4.1	7.4	6,200	9,400	1300	7.8	4000	5000	720	750	440

* Table prepared by Forest Products Laboratory of the United States Department of Agriculture.

An extensive investigation of the moisture content of wood in various locations about the country and aboard battleships at sea showed the average moisture content to be between 12% and 13%. Some wood, however, had a content as high as 15%. Since the strength of wood with 15% moisture content is considerably less than that with only 12%, it was important to establish a standard value of strength that would cover the 15% wood. For this reason the strength values given in Table 21 are based on wood with 15% moisture content.

In testing wood specimens it was found that the strength values obtained varied considerably. It was at first thought that the arithmetical mean average of the values obtained should be computed and used as the standard value. However, it was discovered that considerably more specimens gave strength values below this average than above it. It was then decided to establish the standard value as the most probable value that would be obtained. From a number of tests on Sitka spruce, Douglas fir and white ash, the most probable strength value was found to be 94% of the average value. This factor was applied to the average strength to obtain the values given in the table for elastic limit and modulus of rupture in static bending, and elastic limit and maximum crushing strength in compression parallel to the grain.

Another factor has also been applied to the test results to arrive at the standard strength values for these stresses as given in the table. This is a factor based on the ability of wood to resist greater stresses for a short period of time than it can carry for an extended period. In view of the fact that aircraft loads are imposed only momentarily, as at the instant of pulling out from a dive or when hitting an air bump, it was decided to base the standard strength values on a 3-second duration of stress. It was found that a piece of wood could sustain a load 1.17 times the normal load sustained over a longer period. The most probable values were thus multiplied by 1.17 to obtain the figures listed in Table 21.

The modulus of elasticity values given in the table are only 92% of the average values of the apparent modulus of elasticity values (Ec) computed from the formula

$$Ec = Pl^3/48dI$$

(where P = load, l = length, d = depth, and I = *moment of inertia)*

when applied to a bending test of 2 X 2-inch beams of 28-inch span, centrally loaded. The use of the modulus of elasticity values given in the table in computing the deflection of ordinary beams of moderate length will give fairly accurate answers. For exactness in the computation of the deflection of I beams and box beams of short span, a formula that takes shear deformations into account should be used. Such a formula involves E_t (the true modulus of elasticity in bending) and F (the modulus of rigidity in shear). Values of E_t can be obtained by adding 10% to the modulus of elasticity values given in the table. If the I or box beam has the grain of the web parallel to the axis of the beam, or parallel and perpendicular thereto as in some plywood webs, the value of F is $E_t/16$. If the web is of plywood with the grain at 45° to the axis of the beam, F is $E_t/5$.

The values for work to maximum load in static bending represent the ability of the woods to absorb shock, after the elastic limit is passed, with a slight permanent deformation and some injury to the member. It is a measure of the combined strength and toughness of a material under bending stresses. It is of great importance to aircraft parts subject to shock loads or severe vibration. Material with a low value of work to maximum load is brittle (or brash, as it is called in wood) instead of tough, as is desirable.

The values in the table for the elastic limit in compression parallel to the grain were obtained by multiplying the values of maximum crushing strength in the next column by 0.80 for conifers and by 0.75 for hardwoods.

The values in the table for compression perpendicular to the grain are partly computed and partly test values. Wood will not exhibit a definite ultimate strength in compression, particularly when the load is applied over only a part of the surface as at fittings. Beyond the elastic limit the wood crushes and deforms while the load increases slowly. The values in the table were obtained by multiplying the average stress at elastic limit by $1^{1}/_{3}$. By this method design values were obtained which are comparable to the values for bending, compression parallel to the grain, and shear as listed in the table.

The values for shearing strength parallel to the grain were obtained by multiplying average values by 0.75. This factor was used because of the variability in strength and to make failure by shear less likely than by other means. The values listed are used for computing the resistance of beams to longitudinal shear. Tests have shown that by the use of a conservative shearing-strength value shearing deformations are limited and a better stress distribution occurs. This better stress distribution results in a maximum strength/weight ratio and a minimum variation in strength. These benefits will be realized if the shearing-strength values given in the table are used.

AIRCRAFT WOODS AND THEIR USES

The woods described in the following pages are the same as those listed in Table 21. It will be noted that only partial botanical names are given in the table for ash, birch, hickory, and spruce. In each of these cases the generic name is given but not the species. The reason for this is that there are several species of these woods with the same strength values as listed. The complete botanical name for each of these species will be given below.

Ash, White. The following species of ash which are ordinarily marketed under the name of "white ash" are satisfactory for aircraft use:

White ash (Fraxinus americana)
Green ash (Fraxinus lanceolata)
Blue ash (Fraxinus quadrangulata)
Biltmore ash (Fraxinus biltmoreana)

Ash is fairly heavy but is also hard, strong, and elastic. It resembles oak in many ways but is lighter, easier to work, tougher, and more elastic. A maximum of 16 annual rings per inch is desirable for the best grade of ash. Second growth ash is better than first growth.

Ash is used largely for bent parts. After steaming, the wood can be bent to a radius of twelve times the radial width of the member. Ash is sometimes used where toughness and solidity are necessary, as in door jambs and sills.

Basswood (Tilia americana). Basswood trees are known by many names—such as lime, linden, teil, bee, and bass. The wood is light, soft, easily worked, and tough, but not strong or durable when exposed to the weather. It receives nails without splitting better than most other woods.

Basswood is used extensively for webs and plywood cores.

Beech (Fagus atropunicea). This species of beech is also known as Fagus grandifolia. Beechwood is heavy, hard, strong, and tough, but not durable when exposed. It is liable to check during seasoning.

Beech is frequently used for facing plywood when hardness is desired. It will take a very fine polish.

Birch. The following species of birch are satisfactory for aircraft work:

Sweet birch (Betula lenta)
Yellow birch (Betula lutea)

Birchwood is heavy, hard, strong, tough, and fine-grained. It also takes an excellent finish. Due to its hardness and resistance to wear it is often used to protect other woods.

Birch is the best propeller wood among the native species and is also the best wood for facing plywood when a high-density wood is desired. Birch plywood is very commonly used in this country.

Cherry, Black (Prunus serotina). Black cherry wood is moderately heavy, hard, strong, easily worked, and fairly straight-grained. It is an excellent base for enamel paints.

Black cherry is sometimes used in manufacturing aircraft propellers.

Elm, Cork (Ulmus racemosa). Cork elm is also known as rock elm. It is heavy, hard, very strong, tough, elastic, and difficult to split. It will take a beautiful polish. It is low in stiffness but very resistant to shock, because of its tough qualities. It steam-bends well and is used as a substitute for ash. Elm suffers from interlocked grain, and will twist and warp badly if not properly dried.

Gum, Red (Liquidambar styraciflua). Red gum trees are also known as sweet gum. Gumwood is moderately heavy, soft, and suffers from interlocked grain which causes warping if not carefully seasoned. The wood glues and paints well, and also holds nails well.

Gum is used in the manufacture of plywood for semihard faces or cores. The heartwood is used for the faces of plywood.

Hickory. The following hickory trees, which are generally grouped as "true hickories," are satisfactory for use in aircraft:

Shagbark hickory (Hicoria ovata)
Bigleaf shagbark hickory (Hicoria laciniosa)
Mockernut hickory (Hicoria alba)
Cow oak (Quercus michauxii)

Wood of the true hickories is the heaviest and hardest wood listed in the table. It is also extremely tough.

Hickory is seldom used in aircraft construction because of its weight. Its excellent toughness and hardness are useful for special applications. Commercially it is used largely for axe handles.

Mahogany, African (Khaya senegalensis). African mahogany comprises a number of species. Another also commonly known is called Khaya grandifolia. African mahogany differs somewhat from true mahogany because it does not have well-defined annual rings. Mahogany works and glues well and is very durable. It shrinks and distorts very little after it is in place.

African mahogany is used for semihard plywood faces. It is also very decorative and responds well to stain and other finishing processes.

Mahogany, True (Swietenia mahagoni). True mahogany is also known as Honduran mahogany when it comes from that country. Similar mahoganies are obtained from Mexico and Cuba. True mahogany is strong and durable, but brittle. It glues and works well.

True mahogany is used in the manufacture of aircraft propellers and for the semihard faces of plywood.

Maple, Sugar (Acer saccharum). Sugar maple is also called hard maple. It is one of the principal hardwood trees of North America. It is heavy, hard, and stiff, and very difficult to cut across the grain. This wood has a very uniform texture and takes a fine finish. It wears evenly and is used as a protection against abrasion.

Sugar maple is used for hard faces in the manufacture of plywood and occasionally for aircraft propellers. A soft maple is sometimes used for semihard plywood faces.

Oak. The following species of oak are used for propeller construction or for bent parts in aircraft. They are classified as "white oaks."

White oak (Quercus alba)
Bur oak (Quercus macrocarpa)
Post oak (Quercus minor or Quercus stellata)
Cow oak (Quercus michauxii)

A number of red oaks are also used occasionally, but they are more subject to defects and decay, and are inferior to white oaks.

Oak is heavy, hard, strong, and tough. The radial shrinkage in oak is only about half the tangential shrinkage. This fact makes quarter-sawed oak excellent for propeller construction. Oak propellers are used for seaplanes, particularly because of their resistance to the abrasive action of water spray.

In addition to propeller construction, oak is used for members that must be bent. White oak can be bent to a radius of about 15 inches for finished sections up to 3 inches thick. Steaming before bending is, of course, necessary.

Poplar, Yellow (Liriodendron tulipifera). Yellow poplar is a hardwood whose properties qualify it as a substitute for spruce. It is sometimes called whitewood or tulip poplar. This wood is light, soft, moderately strong, but is brittle and has low shock resistance. It has good working properties, shrinks little, and is hard to split. Another characteristic is that it is free from such defects as checks and shakes. Poplar trees grow very large.

Poplar may be used as a substitute for spruce. It is also used as a core for plywood.

Walnut, Black (Juglans nigra). This wood is heavy, hard, strong, easily worked, and durable. It is difficult to season but holds its shape very well in service.

Black walnut is used in the manufacture of propellers. Next to birch it is rated as the best native propeller wood.

Cedar, Port Orford (Chamaecyparis lawsoniana). Port Orford cedar is one of a group known as white cedars. Its wood is light, strong, durable, and easily worked.

As a substitute for spruce it can be used in aircraft construction. It is also used for semihard faces of plywood.

Cypress, Bald (Taxodium distichum). Bald cypress is also known as southern cypress. Its wood is fairly light, soft, moderately strong, and durable. The living trees are subject to a fungus disease that causes cavities in the wood. When felled the disease stops, and the wood is very durable.

Cypress does not have any special application in aircraft construction.

Douglas Fir (Pseudotsuga taxifolia). This wood, also known as red fir and yellow fir, is not one of the true fir family. Douglas fir trees grow as high as 300 feet with a diameter of over 10 feet. Its wood is moderately heavy and strong, but splits easily and is rather difficult to work. It can be obtained in large pieces and is a good substitute for spruce.

In addition to substituting for spruce, Douglas fir is also used as a core for plywoods.

Pine, White (Pinus strobus). This is used commercially as a general-purpose wood. It is light, soft, rather weak, but durable. It works easily; nails without splitting; seasons well; and shrinks and warps less than other pines.

White pine can be used as a substitute for spruce and as a core for plywood.

Spruce. This is the standard structural wood for aircraft. All of the following species are satisfactory for this purpose:

Sitka spruce (Picea sitchensis)
White spruce (Picea glauca or Picea canadensis)
Red spruce (Picea rubra)

Spruce is a light, soft wood with a moderate strength. It has an excellent strength/weight ratio and has been obtainable in the past in the sizes required for aircraft construction. These two facts explain its general adoption for aircraft work. It works easily and seasons well.

Due to the extensive use of spruce in aircraft, it, has become increasingly difficult to procure lumber of the required quality. For this reason substitutes have been sought and used, as mentioned in the foregoing pages. Specifications for aircraft spruce require the average lengths of a shipment to be 26 feet, with none under 16 feet. Widths vary from 4 to 8 inches and over. It is difficult to obtain material for wing spars when a cross-section such as 3 X 3 inches is specified.

SEASONING OF WOOD

As noted previously, wood shrinks considerably as the moisture content is reduced. The percentage reduction in dimensions caused by drying green wood is given in Table 21. When wooden parts are manufactured, it is essential that their moisture content be approximately that which they will attain in service; otherwise they will not hold their shape. Freshly cut "green" lumber is saturated with moisture. It has been found that if this lumber is allowed to stand it will eventually dry to a much lower moisture content. The point at which the moisture content will be in equilibrium is determined by the humidity and temperature of the surrounding air. This point varies for different sections of the country but averages around 12% to 13% moisture content.

The natural drying of lumber by the weather is called air seasoning. However, air seasoning is seldom used for aircraft wood, because it takes from one to two years for completion and it cannot be controlled as accurately as artificial seasoning. A method of artificial seasoning known as *kiln drying* has been developed by which any desired moisture content can be obtained in less than one month.

Air Seasoning of Wood. The chief use of air seasoning is on surplus stocks of lumber which, while awaiting selection for manufacture, can be partly air-seasoned. This partial seasoning is an aid in obtaining good kiln drying of the lumber since its moisture differential is much less than green stock.

Air seasoning is performed by carefully piling the green lumber under a shed that will protect it from rain and snow, but will permit air to circulate through it. The foundation for the pile of lumber must be at least 18 inches high and have a slope of one inch per foot from front to rear. In piling the wood, good-sized air spaces must be provided to insure ventilation of all wood in the pile. To avoid checking of the ends of the lumber, caused by premature drying, the ends must be painted with a hardened gloss oil, paraffin, or pitch.

Figure 62 has been prepared by the Forest Products Laboratory of the United States Department of Agriculture to show the relationship between the moisture content of wood and the temperature and humidity of the surrounding air. As expected, the moisture content is high when the humidity is, but is reduced by an increase in temperature. Lumber stored in the open has a higher moisture content in winter than in summer because of the higher humidities and lower temperatures.

Kiln Drying of Wood. Kiln drying of wood is based upon the relationship between external air humidity and temperature and the moisture content of the wood. In the kiln-drying compartment these variables are closely regulated by means of heating coils and sprays. There is also a natural or forced system of ventilation through the carefully piled lumber. The temperature is gradually increased and the humidity lowered in the compartment as the moisture content of the lumber decreases. The exact procedure varies for different species of wood. In the case of spruce, drying starts with a temperature of 125°F. and 80% relative humidity when the moisture content is above 25%, but these figures are changed with each 5% reduction in moisture content until a temperature of 138°F. and relative humidity of 44% is reached for 15% moisture content. When the moisture content is down to 12%, the temperature is changed to 142°F. and the relative humidity to 38%. Careful adjustment of temperature and humidity is necessary as the drying progresses, to insure a steady, even drying and freedom from internal strains.

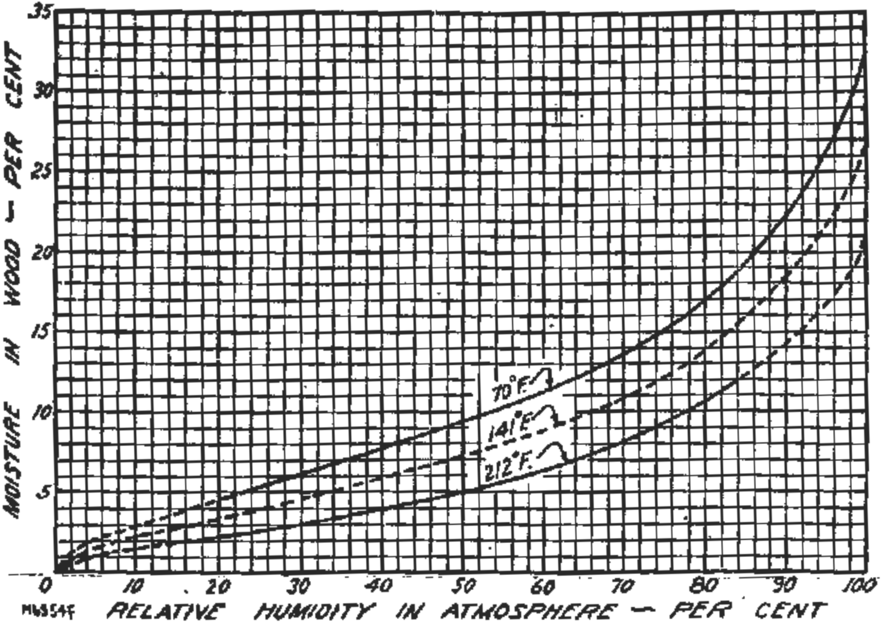


FIGURE 62. Atmospheric Humidity vs. Wood Moisture Content

In order to ascertain the moisture content at any point in the drying process, samples are inserted in the pile of lumber. These samples must represent the thickest, wettest, and slowest-drying material in the pile. It is customary to use three samples, placing one at average, one at slowest, and one at fastest drying locations. These samples are removed daily and weighed. Since the dry weight of the sample is known from a moisture content determination made on the green sample, the additional weight at any time represents the moisture content.

The kiln drying of spruce requires from 18 to 24 days. It is desirable to end up with a moisture content just under 12%. When this practice is followed there is no danger of warpage of finished parts due to a large absorption of moisture in service.

BENDING OF WOOD

Wooden parts can be bent either by steam bending or by laminating the member and gluing it in the desired shape. Steam bending can only be applied to hardwoods.

In steam bending the wood is steamed at 212°F. for a period of one hour per inch of thickness. The steamed wood is bent over a form and clamped in place until dry. Wood to be steam-bent should be finished approximately to size before steaming. When a piece is wider than it is deep, it is advisable to bend a piece double the required depth and cut it into two parts after it has dried.

Bending by lamination consists in gluing a number of layers of wood together. Each layer is fairly thin along the radius of the curve. Immediately after gluing, the member is clamped to the form and left there until the glue has set and the wood is dry. A variation of this method applicable to hardwoods is to use fairly heavy sections which have been steam-bent approximately to shape and thus reduce the number of laminations.

GLUES AND GLUING

In wooden aircraft construction glue plays a very prominent part. Many wood joints depend wholly upon the joining power of glue for their strength. It is necessary for aircraft glue to be absolutely reliable. It must retain its strength under adverse conditions (as when wet, hot, or attacked by fungus) and must not deteriorate rapidly with age. There are six types of glue commonly used in aircraft assembly operations which possess the necessary properties to a satisfactory extent. They are urea resin, resorcinol phenolic, alkaline phenolic, casein, blood albumin, and animal glues. Vegetable and liquid glues such as fish glue are not satisfactory for aircraft work. Phenol resin glue used in the construction of waterproof plywood is described later in this chapter under "Plywood." Table 22 lists the properties of the various types of aircraft glues. This table is based upon the use of the best quality of each type. There are many variations in the quality of these glues available on the market; hence care must be exercised in obtaining the proper grade for aircraft work.

Urea Formaldehyde Resin Glues. This glue is an excellent all-purpose glue for aircraft shop work. It is water and fungus resistant. It will cure at room temperature (70°F.) but is superior when cured at 140°F. under pressure for 4 to 8 hours. The pressure required is only that necessary to bring the parts into close contact, or to slightly compress the softer woods such as spruce. This glue has approximately a 3-hour life and can be used within that period after mixing. It will deteriorate if heated in water above 145°F. but is water resistant at normal temperatures.

Urea resin glue is now available as a dried powder under several trade names. When the powder is dissolved in cold water the resulting glue is ready for use.

Resorcinol Phenolic Glues. This glue is derived from resorcinol and formaldehyde and has the durability characteristics of the phenolic resin glue used in waterproof plywood combined with the working characteristics of the

TABLE 22. Properties of Aircraft Glues

Characteristics	Resorcinol phenolic	Alkaline phenolic	Urea resin	Casein	Blood albumin	Animal
Strength (dry)	Very high	Very high	Very high	Very high to high	High to low	Very high
Strength (wet after soaking in water 48 hours)	100% of dry strength	100% of dry strength	75–100% of dry strength	25–50% of dry strength	50 to nearly 100% of dry strength	Very low
Rate of setting	Rapid	Rapid	Rapid	Rapid	Very fast with heat	Rapid
Working life	3 hours	5 hours	4 hours	Few hours to a day	Few to many hours	4 hours
Temperature requirements	75°F. satisfactory	150°–180°F.	70°F. satisfactory; 140°F. ideal	Unimportant	Heat preferable	Control for glue, wood and room important
Dulling effect on tools	Negligible	Negligible	Negligible	Moderate to pronounced	Slight	Moderate
Tendency to stain wood	Slight	Slight	None	Pronounced with some woods	Dark glue may show through the veneers	None to very slight

urea glues. A resorcinol type glue consists of two parts—a water-soluble liquid resin and a separate powder which is added to the resin just prior to use. Individually the resin and powder are stable in storage. When mixed they have about the same working life, characteristics, and setting time as the urea glues.

Alkaline Phenolic Glues. This glue makes use of alkaline catalysts to insure curing of the glue in a reasonable time. Even so it is necessary to cure at an elevated temperature of between 150° and 180°F. This type of glue has excellent durability characteristics, and possesses much better resistance to adverse conditions of heat and moisture than urea and casein glues.

Casein Glues. Casein glue was the all-purpose glue in aircraft construction prior to the development of urea formaldehyde resin glue. Casein is obtained from curdled milk and is combined with other materials to form a glue. It is usually sold in powdered form, with detailed instructions from the maker on the method of preparing it. Generally, one part of casein glue powder is mixed with two parts of water by weight to form a liquid glue. To obtain the best results it is necessary to follow a definite mixing technique. The powdered glue is sprinkled or sifted into a container of water while a mixing paddle is turning about 100 revolutions per minute. When the powdered glue has all been added, the paddle speed is slowed down to 50 revolutions per minute and kept going for 20 to 30 minutes until a smooth mixture of even consistency is obtained. The speed of stirring is limited to avoid adding an excessive amount of air to the mixture.

Casein glue should be used only within four hours of its preparation. It is customary in most shops to prepare fresh batches each morning and afternoon. All mixing utensils must be thoroughly cleaned before preparing a new batch to prevent inclusion of old glue in the new mixture. The use of paper cups to hold a small supply for each man is one way of insuring purity. When casein glue is applied to wood, it should be clamped for at least five hours, preferably overnight, to permit thorough setting.

Blood Albumin Glues. Blood albumin glues are used in gluing standard plywood. They are very water resistant, exceeding even the best casein glue in this respect. These glues are made from an albuminous base from the blood of slaughtered animals, combined with chemicals, such as lime, caustic soda, or sodium silicate. The blood albumin is obtainable as powder, and the mixture is added to about twice as much water, more or less, depending upon the consistency desired. Blood albumin glues cannot be bought in the prepared state since they deteriorate rapidly if not used.

In the manufacture of plywood the water-resistant properties of the blood albumin glue are improved by pressing the plywood between two hot plates while glue is setting. Steam-heated plates are used which keep the glue at a temperature of about 160°F. up to 30 minutes, depending on the glue used.

Animal Glues. Animal glues were used extensively in gluing propellers. Urea resin or casein glue has replaced them somewhat because of better all-around qualities. Animal glues are manufactured from the hide, bones, or sinews of animals. These materials are boiled in water, and the extract concentrated and jellied by cooling. When desired for use the dry glue is thoroughly soaked in cold water for several hours and then heated in a closed retort at 140°F. to 150°F. The glue is kept at this temperature while being used. Glue which has been heated for over four hours must be discarded. One pound of dry glue should be mixed with 2¼ pounds of water in order to obtain the normal consistency.

Gluing Wood. Wood to be glued must be seasoned to the proper moisture content. Thin pieces of wood, such as laminations, should have a lower moisture content (5% to 10%) than thicker pieces (8% to 12%) in order to compensate for the relatively greater amount of moisture they absorb from the glue. The moisture content for propeller stock is usually specified as 8% to 10%.

Wood should be machined after seasoning when it is to be glued. The surface must be smooth and square. Surfacing should be done by machine, not by hand, to avoid irregularities. It is not necessary to scratch or sand the surfaces to be glued.

Glue must be spread uniformly on either or both surfaces of the work. Too thin a glue or not sufficient glue will result in a "starved" joint. An excess of glue is preferable although this may result in a "dried" joint if the glue lacks water. The glued surfaces must be clamped or pressed together with a uniform pressure of from 100 to 200 p.s.i. This pressure should be maintained for 5 hours or longer if possible. It is then necessary to allow the glued parts to condition themselves for 2 or more days before machining or finishing. During this conditioning period the glue moisture is absorbed uniformly throughout the wood.

PLYWOOD

Plywood is a material made by gluing a number of plies of thin wood together. Each sheet of thin wood is known as veneer. Veneer over 1/10 inch thick is seldom used in the manufacture of plywood. The grains of adjacent layer of veneer run at right angles to each other, which makes plywood equally strong in two directions. Except for a special 2-ply plywood, all plywood is manufactured with an odd number of plies to obtain symmetry. The center ply or plies are usually made of a softwood and are considerably thicker than the two face plies made of a hardwood. A hardwood is used for the face plies to resist abrasion, to furnish a better contact for washes and fittings, and to take a better finish.

Plywood is used in the construction of box spars for wings, webs of ribs, wing and fuselage covering, especially for the leading edge of the wing, as well as for flooring and interior cabin paneling. A plywood with a metal sheet cemented to one face to take excessive wear is often used for flooring.

The following woods are generally used in the manufacture of plywood:

Hard faces	*Semihard faces*	*Cores*
Birch	Mahogany	Basswood
Beech	Sycamore	Douglas fir
Maple (hard)	White elm	Fir
	Maple (soft)	Gum
	Red gum (heart)	Pine
	Port Orford cedar	Poplar
	Spruce	Redwood
		Spruce
		Port Orford cedar
		Western hemlock

Birch and mahogany plywood are most commonly used in aircraft construction. Basswood is the most common core material. The special 2-ply material mentioned above is made of spruce and is used almost exclusively for the webs of box spars. In this application the grains of the two plies are at right angles to each other and at 45° to the axis of the spar. Other plywoods vary from 3 to 15 plies, with 3 being most commonly used. When 9 plies or more are used the 2 outside plies on each side must be hardwood of the same species. Several different veneers are sometimes used in one plywood but any one layer must be all of the same material.

The veneers used in making plywood are either rotary cut, sliced, or sawed. Rotary-cut veneers are thin circumferential slices of wood cut from logs revolving in a lathe. Due to the slight taper of a tree trunk it is impractical to cut the veneers in an exact tangential plane, and consequently the grain is not absolutely parallel. Excessive cross grain is not permitted in aircraft plywood. Sliced or sawed veneers are cut tangential to the annual rings and are not as strong as rotary-cut veneer. The veneer for aircraft plywood must be sound, clear, smooth, of uniform thickness, and without defects.

Army-Navy Aeronautical Specification AN-NN-P-511 covers aircraft plywood. This specification provides for the use of the woods listed above and for thickness and plies as tabulated below.

Army-Navy Aeronautical Specification AN-P-69 describes only one type of plywood, namely a waterproof plywood. Earlier specifications also

TABLE 23. Tensile Strength of Aircraft Plywood (Estimated)*

Nominal thickness (in.)	Number of plies	Birch face plies Birch inner plies		Birch face plies Poplar inner plies		Mahogany face plies Poplar inner plies		Poplar face plies Poplar inner plies	
		Long	Tran.	Long.	Tran.	Long.	Tran.	Long.	Tran.
3/64	3	600	440	600	260	300	240	340	250
1/16	3	820	730	810	430	430	390	470	420
3/32	3	1210	880	1200	530	620	470	680	520
1/8	3	1270	1420	1260	820	680	760	740	810
5/32	3	1670	1670	1660	970	880	890	970	970
3/16	3	2000	2000	1990	1170	1050	1075	1160	1160
3/16	5			1660	1170	1085	1100	1140	1160
7/32	5			2740	1060	1800	970	1910	1050
¼	5			2790	1340	1860	1230	1960	1320
5/16	5			3400	1420	2240	1300	2370	1410
3/8	5			3150	2340	2220	2230	2320	2320
7/16	7			3900	2720	2730	2600	2870	2700
½	7			4370	3160	3210	3040	3340	3140
9/16	7			5120	3250	3510	3090	3740	3230
5/8	9			5230	3570	4070	3440	4190	3550
¾	9			6290	4410	4740	4250	4900	4390

*Strength is given in pounds per inch width. Estimated by Haskelite from data given in ANC-5 of tests on 3-ply veneer in which all 3 plies were same thickness and species.

Table 24. Bearing Strength of Aircraft Plywood (Estimated)*

Nominal thickness (in.)	Number of plies	Birch face plies Birch inner plies		Birch face plies Poplar inner plies		Mahogany face plies Poplar inner plies		Poplar face plies Poplar inner plies	
		Long	Tran.	Long.	Tran.	Long.	Tran.	Long.	Tran.
3/64	3	230	154	221	110	202	115	154	106
1/16	3	307	269	298	182	269	192	202	182
3/32	3	451	317	442	221	394	221	307	211
1/8	3	461	528	451	365	403	374	317	355
5/32	3	614	614	595	432	538	432	413	413
3/16	3	739	739	720	518	643	518	499	499
3/16	5	720	739	624	509	576	509	490	499
7/32	5	1306	566	1114	394	1037	403	893	374
¼	5	1325	768	1123	538	1046	538	902	518
5/16	5	1613	787	1373	547	1277	547	1094	518
3/8	5	1478	1478	1219	1018	1142	1018	998	998
7/16	7			1517	1171	1421	1171	1238	1142
½	7			1728	1363	1632	1363	1450	1334
9/16	7			2016	1373	1891	1382	1651	1344
5/8	9			2131	1498	2035	1498	1853	1469
¾	9			2515	1872	2390	1882	2150	1843

*Strength is given in pounds per inch width. Estimated by Haskelite for their product, based on following values in pounds per square inch.

	Birch	*Mahogany*	*Poplar*	*Spruce*
Bearing strength along grain of veneer	7300	6500	5000	5000
Bearing strength across grain of veneer	400	440	220	220

described a so-called standard plywood but this has been completely displaced by waterproof plywood for aircraft use.

Standard plywood is the older type of plywood assembled with blood albumin, soya bean, or starch glue. It is not resistant to boiling water or prolonged soaking in water and is subject to fungus attack. A comparison of the shear strength of standard and waterproof plywood after water soaking and fungus attack is as follows:

Type	Shear strength—minimum (p.s.i.)		
	Dry	Soaked in water 48 hours	After 10-day fungus exposure
Standard	300	160	
Waterproof	300	250	250

Waterproof Plywood. Waterproof plywood is resistant to water and fungus. It can be steamed or soaked in boiling water as an aid in bending without affecting the glue.

Waterproof plywood is a hot-pressed resin plywood assembled with a synthetic resin adhesive. At the present time a thermosetting phenol formaldehyde resin glue is universally used for this purpose. This glue is inserted between the veneer panels as a thin solid film, or as a liquid glue. Heat and pressure are then applied to cure the glue. A temperature of 300°F. is required but the pressure varies depending upon the wood. A 125 p.s.i. pressure is required for spruce, and a 250 p.s.i. pressure for birch. The temperature and pressure must be maintained for about 5 minutes for $^1/_{16}$-inch plywood, and about 12 minutes for $^5/_{16}$-inch plywood. In thick plywoods it is difficult to cure the inner layers of glue without damaging the outer veneer layers with the excessive heat. A high-frequency electric method of curing resins in thick plywoods has been devised to overcome this difficulty. In this method the desired heat is generated in the resin layers and to a lesser extent in the wood veneer. This method of curing is applicable to the shanks of aircraft propeller blades constructed of resin-impregnated wood or plywood.

All plywood, whether standard or waterproof, must be protected by paint to prevent moisture absorption by the wood. The normal moisture content of plywood is 7% to 12% but this will vary with the humidity if the plywood is not properly protected. The edges are particularly important.

Superpressed Resin Plywood. This plywood is the same as the waterproof resin plywood described above but is assembled under pressures from 500 to 1500 p.s.i. Under these pressures the density of the plywood is greatly increased, and plywood manufactured in this manner is sometimes referred to as high-density plywood. This development is only in the experimental stage but tests already conducted indicate that shear strength can be increased about 7 times when the density of the plywood is slightly more than doubled.

Molded Airplane Parts. With proper dies it is a simple matter to cure resin-bounded plywood in the desired shape. Wing leading edges are frequently supplied by the plywood manufacturer with the required curve. This arrangement eliminates the necessity for steaming or soaking in boiling water to permit bending.

This technique of curing to shape has been applied successfully to entire half fuselages. By the use of properly designed jigs it is possible to glue rings, longitudinals, or stiffeners to the plywood fuselage shell in the same operation. One solid form is used and an even pressure is exerted on the opposite side of the plywood by means of air pressure in a restrained rubber bag.

The main limitation on the molding of plywood parts to finished shape is the cost of the jig or dies. If a sufficient number of parts are involved the cost can probably be justified. This technique has definite possibilities for large-scale production.

CHAPTER XVII

FABRICS AND DOPE

Some modern airplanes are of all-metal construction, including the wing and fuselage covering. A good many, however, still use fabric for covering wings, fuselages, and control surfaces. In this country cotton fabric is used exclusively for this purpose; in England, homegrown linen is used for covering in place of the rarer cotton. The strengths of cotton and linen fabric are equivalent, so that the selection of one or the other depends wholly upon the source of supply.

To facilitate the discussion of fabrics and tapes the following definitions are given:

Warp is the direction along the length of the fabric.

Warp ends are the woven threads that run the length of the fabric.

Filling or *weft* is the direction across the width of the fabric.

Filling picks are the woven threads that run across the fabric.

Count is the number of threads per inch in warp or filling.

Ply is the number of yarns making up a thread. Thus a thread designated as 16/4 means four yarns of size 16 twisted together to form one thread.

Twist refers to the direction of twist of the yarn making up a thread. Twist is said to be right-handed when a thread is held vertically and the spirals or twists incline downward in a right-hand direction.

Mercerization is the process of momentarily dipping cotton yarn or fabric, preferably under tension, in a hot solution of dilute caustic soda. The material acquires greater strength and luster due to this treatment. Its stretch is also somewhat reduced.

Sizing is a material, such as starch, which is used to condition the yarns to facilitate the weaving of the cloth.

AIRPLANE FABRIC

A mercerized cotton cloth is universally used in this country for fabric covering of wings, fuselages, and tail surfaces. This cloth can be obtained commercially in the following widths: 36, 42, 60, 69 and 90 inches. The 36-inch width is standard, but the others are used when for some special reason it is desired to have fewer seams in the covering.

Grade A fabric contains from 80 to 84 threads per inch in both warp and filling. A 2-ply yarn is used. A minimum tensile strength of 80 pounds per inch in both warp and filling is required. The normal weight of this fabric is 4 ounces per square yard, and it must be under 4.5 ounces to meet government specifications. This fabric must have a smooth, napless surface to obtain the best results. The cloth is rolled or calendered to obtain this surface. The sizing content is limited to a maximum of 2½%. Another requirement is the mercerization of the yarn prior to weaving while under tension. This method of mercerization is preferable to mercerizing the woven cloth. A 60/2 yarn will give the strength properties required for this grade of fabric.

Light airplane fabric and glider fabric have the following approximate characteristics:

	Light airplane	*Glider*
Weight (oz./sq. yd.)	2.6	2.7
Threads per inch—warp	115	95
Threads per inch—fill	115	100
Strength per inch—warp	50	45
Strength per inch—fill	40	36
Width (standard)	37	38

Linen fabric made from the best grade of Irish flax is used universally in England but not at all in this country. This fabric is practically identical with Grade A cotton fabric insofar as weight, strength, and threads per inch are concerned. While linen fabric will take on acetate dope finish excellently, cotton fabric will not.

Surface Tape. Surface tape is the finishing tape that is doped over each rib or seam to cover the stitching. It provides a neat, smooth, finished appearance. It can be obtained with serrated or pinked edges, or with a straight edge impregnated with a sealing compound. The compound edges or pinked edges provide better adherence to the fabric covering. Surface tape is made from Grade A fabric in various widths from 1¼ to 3¾ inches, from glider fabric in 1½- and 2-inch widths, and from a balloon cloth in 2¼ , 3-, and 4-inch widths. This latter cloth is usually required for military airplanes.

The balloon cloth used for surface tape is a cotton cloth that has been singed, desized, and calendered to give it a smooth finish without fuzz or nap. This cloth weighs 2.0 ounces per square yard and has a tensile strength of 40 pounds per inch in the warp or fill. It is made with a single-ply thread of which there are at least 120 per inch. Tape made from this cloth is pre-doped on both sides with a nitrate dope to obtain best results. Sufficient dope must be used to increase the weight at least ½ ounce per square yard when dry.

Reinforcing Tape. Reinforcing tape is used over fabric and under the rib stitching to prevent the stitching cord from cutting through the fabric. It is also used for cross-bracing ribs and for binding. This tape has an extremely strong warp. The warp ends are made from cotton yarn No. 20/3/4 or its equivalent, and the filling picks are cotton yarn No. 24/2. Tape made from these yarns has the following characteristics:

Width (inch)	*Warp ends, total*	*Filling picks per inch*	*Strength (pounds)*	*Weight per 144 yds. (ounces)*
¼	7	20	80	16
⅜	10	20	120	22
½	14	20	150	31
⅝	18	20	170	40
¾	22	20	200	48
1	30	20	250	67

A herringbone tape largely used for commercial airplanes can be obtained in widths from ¼ inch to 1¼ inches. This tape is less bulky than that described above and is amply strong.

Sewing Thread. To machine-sew a Grade A fabric, an unbleached silk-finish left-twist cotton thread is used. It is a No. 16/4 thread and has a tensile strength of 6.80 pounds minimum. Silk (or glace) finished thread is polished and has a smooth dressed surface.

A No. 24/4 thread is used for machine sewing of light airplane or glider fabric. It is the same as No. 16/4 thread but is lighter and has a tensile strength of 4.70 pounds minimum.

For hand sewing a No. 30 3-cord right-twist linen thread is mostly used. This thread is made from long-line flax fiber and has a tensile strength of 10 pounds minimum. A slightly heavier thread, No. 25/3, with a 12-pound breaking strength is sometimes preferred. A cotton hand-sewing thread is also used. This thread is a No. 10/3 right-twist cotton thread with a 10-pound breaking strength.

Rib Lacing Cord. Rib lacing cord is used to sew the fabric to the ribs. It must be strong to transmit the suction on the upper surface of the wing from the fabric to the ribs which, in turn, carry the load into the main wing structure. The cord must also resist fraying due to the weaving action of the fabric and wing ribs. Both linen and cotton cords are used for rib lacing cord.

A 5-ply silk-finished cotton cord is frequently used on small commercial planes. It makes a tight knot, resists fraying, and is quite durable.

Another cotton cord, No. 20/3/3/3, which is unusually strong and fray resistant, is also used. This type is used on military airplanes.

A third type of cord, No. 8/11, with a soft or natural cotton finish is also used. It has a breaking strength of 42 pounds.

A linen thread is preferred for naval airplanes and for large transport planes. A 9-ply, lock-stitch-twist cord with a breaking strength of 55 pounds is used. This cord is made from the best Irish flax.

APPLICATION OF CLOTH SURFACES

The proper application of cloth on the surfaces is essential if a good appearance, the best results, and strength are to be obtained from the material selected. A good covering job is not only important from a strength and appearance standpoint, but also because it affects the performance of the airplane in no small degree. It is essential that all covering be taut and smooth for best performance. To obtain smoothness, it is common practice to sand the surface after each coat of dope is applied. This sanding can be overdone and cause injury to the fabric and should, therefore, be practiced with caution.

All fabric materials to be used in covering should be stored in a dry place and protected from direct sunlight until needed. The room in which the sewing and application of the covering is done should be clean and well ventilated. Its relative humidity should be slightly lower than the relative humidity of the dope room.

All machine sewing should have two rows of stitches with 8 to 10 stitches per inch. A lock stitch is preferred. All seams should be made with the aim of securing the smoothest job possible combined with adequate strength. Stitches should be approximately 1/16 inch from the edge of the seam, and ¼ to 3/8 inch from the adjacent row of stitches. Longitudinal seams should be as nearly parallel to the line of flight as possible. Seams should never be located over a rib in order to avoid penetrating a seam with the rib lacing cord.

Hand sewing is necessary to close up the final openings in the covering. This closing is sometimes done by tacking on wooden wings, but sewing is preferable. In hand sewing, a baseball stitch of 6 to 8 stitches per inch is used. It is finished with a lock stitch and knot. A ½-inch hem should be turned under on all seams to be hand-sewn. Holding the fabric under tension preparatory to hand sewing can be done by tacks on wooden wings, or by pinning the fabric to a piece of adhesive tape pasted to the trailing edge of metal wings.

Thread for hand sewing and lacing cord should be waxed lightly before using. The wax should not exceed 20% of the weight of the finished cord. A beeswax free from paraffin should be used for waxing.

Reinforcing tape is used under all lacing to protect the fabric from cutting through. This tape should be under a slight tension and secured at both ends. It should be slightly wider than the member it covers. A double width is sometimes necessary for very wide members.

Surface tape or finishing tape should be placed over all lacing, seams (both machine- and hand-sewn), corners, edges, and places where wear is likely to occur. It is placed around the entire leading and trailing edges of wings. Tape is applied after the first coat of dope has dried, and is set on a second wet coat, after which another coat of dope is applied immediately over the tape. By this means both surfaces of the tape are impregnated with dope, and it adheres firmly to the covering.

Reinforcing patches are always placed over holes in fabric-covered surfaces through which wires, controls, or other items project. These patches may be either another layer of fabric doped on, or a leather patch sewed to the fabric covering. Patches should fit the protruding part as closely as possible to prevent the entrance of moisture and dirt.

Celluloid drainage grommets should be doped to the underside of fabric surfaces wherever moisture can be trapped. It is customary to place one of these grommets adjacent to the trailing edge of each wing rib. They also serve to ventilate fabric-covered surfaces. Ventilation is necessary to reduce corrosion and also to relieve the pressure inside the surface when the plane is at altitude.

Inspection doors and access holes are required in all surfaces, whether fabric or metal covered. On fabric-covered surfaces the simplest way to provide these holes is to dope a zipper-equipped patch in the desired place. When the dope dries the fabric is cut along the line of the zipper. Each patch is equipped with two zippers that meet at an angle and thus provide a triangular opening for access or inspection. Another method applicable to cloth or metal surfaces is the provision of a boundary framework inside the wing to which a cover plate can be attached by screws. These frameworks are built into the structure wherever access or inspection holes are necessary—for example, where wing wires are attached.

Wing Covering. Wings may be covered with fabric by the envelope, blanket, or combination method. The envelope method is preferable and should be used whenever possible. In all methods the warp of the cloth should run parallel to the line of flight.

The envelope method of covering wings consists of sewing several widths of fabric of definite dimensions, and then running a transverse seam to make an envelope or sleeve. This sleeve is then pulled over the wing through its one open end. The open end is then hand-sewed or tacked. If the envelope is of the proper dimensions it will fit the wing snugly. When possible the transverse seam should be placed along the trailing edge. The advantage of this method lies in the fact that practically all sewing is by machine, and there is an enormous saving in labor in fitting the covering. It is particularly applicable to production airplanes.

The blanket method consists of machine sewing a number of widths of fabric together, placing it over the wing, and hand sewing the transverse seam along the trailing edge. Care must be taken to apply equal tension over the whole surface. This method of covering wings is almost invariably used on experimental airplanes.

The combination method consists of using the envelope method as much as possible, and the blanket method on the remainder of the covering. This method is applicable to wings with obstructions or recesses that prevent full application of an envelope.

After the cover is sewed in place, reinforcing tape is placed over each rib and the fabric is laced to each rib. Except on very thick wings the rib lacing passes completely around the rib. On thick wings the lacing passes around one chord member only, but both top and bottom surfaces must be laced in this manner. Lacing should be as near as possible to the capstrip. The rib should not have any rough or sharp edges in contact with the lacing or it will fray and break. Each time the lacing cord goes around the rib it is tied over the upper center or edge of the rib, and then the next stitch is made at the specified distance away. The first and last stitches are made with slip knots to provide for tightening these stitches. All other stitches are tied with a nonslip or seine knot. Rib lacing should extend from the leading to the trailing edge, except when the leading edge of the wing is covered with plywood or metal. In these cases the lacing should start immediately after these coverings.

In order not to overstress the lacing, it is necessary to space the stitches a definite distance apart, depending upon the speed of the airplane. Due to the additional buffeting caused by the propeller slipstream, a closer spacing of the stitching must be used on all ribs included within the propeller circle. It is customary to use this closer spacing on the rib just outboard of the propeller diameter as well. A satisfactory spacing for rib lacing is as follows:

Airplane, speed (max.)	*Outside slipstream*	*Inside slipstream*
Up to 175 m.p.h.	4 in.	2 in.
176 to 250 m.p.h.	2 in.	1 in.
Over 250 m.p.h.	1 in.	1 in.

In very high-speed airplanes difficulty is often experienced with rib lacing breaking or with fabric tearing. These troubles are usually experienced in the slipstream. To overcome this trouble a double rib-lacing job is sometimes done in this region, simply by rib lacing the wing twice in the affected region. Each lacing job is wholly independent of the other except that the same holes are picked up in the fabric to avoid making too many holes. A tape of Grade A fabric cut on a bias is often sewed and doped to the fabric covering under the reinforcing tape to strengthen the fabric against tearing at the stitching holes. After the wing surface has been covered, rib laced, and given several coats of dope, a blanket is sometimes doped over entire areas to reinforce the whole assembly. This blanket consists of Grade A fabric extending over the affected area of the wing (the slipstream usually) and runs from the trailing edge up over the leading edge and back on the under surface to the trailing edge again. In placing this blanket the under area is thoroughly soaked with dope, the blanket laid and rubbed smooth to eliminate all trapped air, and then the outer surface of the blanket is doped immediately. Only small areas are doped and laid at any one time. High-speed airplanes with all three reinforcing measures described in this paragraph, including double stitching, bias tape, and blanket, have stood up perfectly in service.

Fuselage Covering. Fuselages are covered by either the sleeve or blanket method, similar to the methods described for covering wings. In the sleeve method several widths of fabric are joined by machine-sewed seams to form a sleeve which when drawn over the end of the fuselage will fit snugly. When the sleeve is in place, all seams should be as nearly parallel as possible to longitudinal members of the fuselage.

In the blanket method all seams are machine-sewed, except one final longitudinal seam along the bottom center of the fuselage. In some cases the blanket is put on in two or three sections and hand-sewed on the fuselage. All seams should run fore and aft.

Fuselage fabric is seldom laced in place. When the fuselage has convex sides, the tension of the fabric holds it taut. The front and rear ends of the cover are tacked or sewed in place. In high-speed planes or flat-sided fuselages the fabric can be laced to a longitudinal fairing strip parallel to the line of flight.

DOPES AND DOPING

In order to tauten fabric covering, and to make it air- and watertight, the cloth is brushed or sprayed with dope. This dope also protects the fabric from deterioration by weather or sunlight, and when polished imparts a smooth surface to the fabric which reduces skin friction. Dopes must be applied under ideal conditions to obtain satisfactory and consistent results. A clean, fresh, dry atmosphere with a temperature above 70°F. and a relative humidity below 60%, combined with good ventilation, are necessary in the dope room. The dope must be of the proper consistency and be applied uniformly over the entire surface.

Dopes will deteriorate seriously if stored in too warm a place for a long period. The temperature should not exceed 60°F. for long-time storage, and must not exceed 80°F. for periods up to four months. Precautions against fire should be taken wherever dope is stored or used because of its inflammable nature. Dope and paint rooms are always isolated from the rest of the factory by metal partitions and fireproof doors when they are not located in a separate building.

As stated above, the most desirable condition in a dope room is a temperature above 70°F. and a relative humidity below 60%. At lower temperatures the dope will not flow freely without the addition of excessive thinners. The relative humidity can be lowered by raising the temperature if the dope shop is not equipped with humidity control. In order to condition fabric surfaces to the desired temperature and moisture conditions they should be allowed to stand about 4 hours in the dope room after covering and prior to doping. By this means an ideal dry condition of the fabric will be obtained.

The number of coats of dope applied to a fabric surface depends upon the finish desired. It is customary to put 2 to 4 coats of clear dope on, followed by two coats of pigmented dope. Sufficient clear dope should be put on to increase the weight of the fabric by 2.25 to 2.50 ounces per square yard. The clear-dope fit should weigh this amount after drying for 72 hours. The pigmented dope film should weigh at least 2.00 ounces per square yard. With fabric weighing 4 ounces the total weight of fabric and dope is approximately 9.5 ounces per square yard.

Panels should be doped in a horizontal position whenever possible, to prevent dope running to the bottom of the panel. The first coat of dope should be brush-applied and worked uniformly into the fabric. A minimum of 30 minutes under good atmospheric conditions should be allowed for drying between coats. Surface tape and patches should be applied just prior to the second coat of dope. This second coat should also be brushed on as smoothly as possible. A third and fourth coat of clear dope can be applied by either brushing or spraying. These coats of clear dope provide a taut and rigid surface to the fabric covering. If desired this surface may be smoothed by lightly rubbing with #0000000 sandpaper or a similar abrasive. When it is being rubbed, all surfaces should be electrically grounded to dissipate static electricity. The doping is completed by spraying the proper colored pigmented dope on the surface in two or more coats.

Under certain unfavorable atmospheric conditions a freshly doped surface will blush. Blushing is caused by the precipitation of cellulose ester which is due largely to a high rate of evaporation and/or high humidity. High temperatures or currents of air blowing over the work increase the evaporation rate and increase blushing tendencies. Blushing seriously reduces the strength of the dope film and should be guarded against. When a doped surface blushes it becomes dull in spots—or white in extreme cases.

In order to prevent the dope from "lifting" the paint on the surface under the fabric, it must be protected by some means. The commonest method is the application of dope-proof paint or zinc chromate primer over all parts of the surface that come in contact with doped fabric. Another excellent method is to cover this surface with aluminum foil 0.0005 inch thick. This foil is glued to the surface and prevents the penetration of dope. It is applied over the regular finish. Other materials, such as a cellophane tape, have also been successfully used in place of aluminum foil.

Cellulose-Nitrate Dope. Nitrocellulose dope is a solution of nitrocellulose and a plasticizer, such as glycol sebacate, ethyl acetate, butyl alcohol, and toluene. The nitrocellulose base is made by treating cotton in nitric acid. The plasticizer aids in producing a flexible film. Both the plasticizer and the solvents are responsible for the tautening action of dope. Thinners such as benzol or ethyl alcohol are sometimes added to the dope to obtain the proper consistency. These thinners evaporate off with the volatile solvents.

Pigmented dopes must be applied over the clear dopes in order to protect the fabric from sunlight. Sufficient pigment must be added to the dope to form an opaque surface. Pigmented dopes consist of the proper colored pigment added to the clear dope. When an aluminum finish is desired, one gallon of the clear nitrocellulose dope is mixed with 12 ounces of aluminum powder and an equal additional amount of glycol sebacate plasticizer. Sufficient thinner is then added, so that two coats of this dope will give a film weight of about 2 ounces per yard.

Nitrocellulose dopes are very generally used in this country. They are cheap, have good tautening qualities, and are not particularly susceptible to changes in the atmosphere.

Cellulose-Acetate-Butyrate Dope. This type of dope is composed of cellulose-acetate-butyrate and a plasticizer triphenyl phosphate, which are nonvolatile, mixed with ethyl acetate, butyl acetate, diacetone alcohol and methyl-ethyl-ketone, all of which are volatile. A pigment is added to obtain a desired color.

Cellulose-acetate-butyrate dopes are also very generally used in this country. This type of dope is more fire resistant than nitrocellulose dope.

CHAPTER XVIII

PLASTICS

Plastics are a large group of synthetic and natural organic materials which can be molded under heat and pressure, cast, extruded, or fabricated into a variety of shapes. There are some eight hundred trade names describing plastic products, many of which are identical materials. Plastics may be classified in a number of ways as described below.

Plastics have been used in many aircraft applications and recent developments indicate a broadening of such applications. As in automotive practice they have been used for knobs, handles, paneling, and similar items. In addition they have been used in the manufacture of ammunition chutes and boxes, fairings, emergency hatch covers, control-surface tabs, wing tips, droppable fuel tanks, wheel fairings, air ducts, and similar parts. Plywood impregnated with plastic resin has frequently been used in the manufacture of entire airplanes. Experimentation is currently underway in the manufacture of fuselages and wings of a glass fiber impregnated with plastic. This material has a tensile and compressive strength of around 50,000 p.s.i.

The first plastic ever developed was made by treating cotton cellulose with nitric acid. The resulting nitrocellulose plastic was named celluloid. Later a second plastic was developed when sour milk was mixed with formaldehyde. The casein plastic that resulted is used commercially in the manufacture of buttons and buckles. The real development of plastics began with the discovery of bakelite, which is obtained by mixing phenol (carbolic acid) and formaldehyde. Micarta and formica are similar materials. Plastics of this type are referred to as phenolics.

Plastics are formed by polymerization, which is a chemical process resulting in the formation of a new compound whose molecular weight is a multiple of the original substance. This new compound has entirely different physical properties. The resins which are components of plastic materials are high polymers, the chemistry of which is not yet fully understood. The chemical composition and the molecular size and structure of these resins, however, are largely responsible for the physical properties of the plastic materials they form.

CLASSIFICATION

An infinite number of plastics can be developed but at the present time only about twenty are in commercial use. These can be classified into four different types, namely, synthetic resin plastics, natural resins, cellulose, and protein. Plastics may also be subdivided into two major classifications which are dependent on their reaction to heat, namely the thermoplastic and the thermosetting types.

Synthetic Resin Plastics. This group of plastics is the largest and is manufactured by the use of raw materials such as phenol, urea, formaldehyde, glycerol, phthalic anhydride, acetylene, and petroleum. Phenol formaldehyde, urea formaldehyde, and melamine formaldehyde are the thermosetting plastics of this group that are most commonly used; the acrylic, vinyl, and styrene plastics are the most commonly used thermoplastics.

Natural Resins. These resins are used in the production of thermoplastic type molding compounds. Hot-molding compositions are prepared by adding suitable fillers to shellac, rosin, or asphalt. Shellac compositions are used for electrical insulators, telephone parts, and phonograph records.

Cellulose. Plastics derived from cellulose are widely used and well known. Cellulose, the basic raw material, is obtainable as ordinary cotton or pulped wood. Cellulose plastics are used in the manufacture of pen and pencil barrels, tool handles, drafting instruments, photographic film, artificial leather, transparent window material, airplane dopes, and lacquers. Cellulose nitrate (celluloid), cellulose acetate, and regenerated cellulose (cellophane) are cellulose plastics.

Protein Plastics. These plastics are manufactured from the casein of skimmed milk and from soybean meal. These proteins are kneaded into a colloidal mass, and then formed into sheets, rods, or tubes by means of suitable presses or extrusion machines. The formed pieces are then hardened by treatment with formaldehyde. Buttons, knobs, etc. can be machined from the hardened raw material, or the colloidal protein mass can be shaped to the desired form and then hardened with formaldehyde. This type of plastic is very hygroscopic and will warp and crack if exposed to varying moisture conditions.

Thermoplastics. Thermoplastic materials will repeatedly soften when heated and harden when cooled. These materials can be heated until soft, molded into the desired shape, and when cooled will retain this shape. The same material can be reheated any number of times and reshaped. Data on thermoplastic materials are given in Table 25. The values listed should be used only comparatively and the manufacturer should be consulted if exact values for design purposes are required.

Thermosetting Plastics. Thermosetting plastics are chemically changed by the first application of heat and are thereafter infusible. They will not soften on further application of heat and cannot be reshaped after once being fully

TABLE 25. Thermoplastic Materials

Type	Composition	Form	Specific gravity	Tensile strength (p.s.i.)	Heat resistance	Trade names	Typical uses
Cellulose	Cellulose nitrate	Sheet, rod, tubing, ribbon, film	1.35	6,000	140°F.	Celluloid, Nitron, Nixonoid, Pyralin, Kodaloid, Herculoid	Spectacle frames, novelties
	Cellulose acetate	Sheet, rod, tubing, foil, film, molding compounds	1.28	5,600	150°F.	Fibestos, Kodapak, Lumarith, Vuepak, Tenite I, Plastecele, Nixonite, Macite, Chemaco, Bakelite C.A. Class I	Hardware, movie film, cabin windows
	Cellulose acetate butyrate	Molding compounds	1.20	4,000	130°F.	Tenite II, Hervose C, Bakelite C.A. Class II	Hardware, flashlight cases, pencils
Vinyl	Vinylidene chloride	Tubing, tubing fittings, molding compounds, extrusions	1.65	6,000	170°F.	Saran, Velon	Tubing for water, chemicals, and airwoven screening, water-resistant fabrics
	Polyvinyl butyral	Sheet, resin, molding compounds	1.07	2,000	160°F.	Vinylite X, Saflex, Butacite, Butvar	Safety-glass interlayer, waterproof coatings
	Polyvinyl alcohol	Sheet, rod, tubing, molding compounds				PVA, Resistoflex	Tank linings, tubing, safety-glass interlayer
	Polyvinyl chloride	Molding compounds	1.30	2,000	175°F.	Geon, Vinylite Q, Chemaco	Electric cable jacketing
	Polyvinyl acetate	Sheet, film, molding compounds	1.35	9,400	130°F.	Vinylite A, Gelva	Plotting and navigating instruments, insulation, raincoats, map and chart protection
Acrylic	Methyl methacrylate	Sheet, rod, tubing, molding powder	1.18	8,100	190°F.	Plexiglas, Lucite	Aircraft enclosures, windows, windshields, lenses
Polyethylene	Polyethylene	Sheet, rod, tubing, molding powder	0.92	1,800	190°F.	Polythene, Polyethylene	Electrical insulation
Polystyrene	Polystyrene	Molding compound, extrusions	1.06	4,700	170°F.	Bakelite Polystyrene, Loalin, Styramic, Styron, Polyflex, Cerex	Insulators, coaxial cable insulation, battery boxes, bottle covers
Polyamide	Polyamide derivative	Molding compounds, filaments	1.15	5,000	165°F.	Nylon, Norelco	Rope, bristles, window screening, electric insulation

cured by the application of heat. Recently, thermosetting-plastic laminates have been made available commercially in a condition not fully cured and these can be given a final heating which softens them momentarily, thus permitting reshaping. This operation is known as post-forming.

Data on thermosetting plastics are given in Table 26. Due to the infinite variety of products obtainable by using different fillers, reinforcements, and processes, only general values are listed. The manufacturer should be consulted for specific design values.

MANUFACTURING PROCESSES

A number of manufacturing processes are employed to create usable forms of plastics for industrial applications. Some of these processes are applicable only to thermosetting materials or thermoplastic materials while others are used for either type of plastic. These processes are described briefly below.

Molding. Both thermoplastic and thermosetting materials can be molded satisfactorily. The molding compound usually consists of the plastic resin and a filler, and sometimes a plasticizer which improves the molding properties. Fillers such as alpha cellulose and wood flour increase the strength somewhat and reduce the cost since they are cheaper than the resin; mica and asbestos are used to obtain good electrical properties and heat resistance; macerated fabric or cotton cord give the best mechanical properties.

Compression Molding. This process is equivalent to the press forging of metals. It consists of placing molding compound in a heated mold cavity, and then applying pressure to the other half of the mold. The molding compound softens, flows throughout the mold cavity, and then sets in final form to a rigid, heat-resisting solid. When this process is used with thermoplastic materials the mold must be aftercooled to harden the plastic part before it is ejected. Molding pressures of from 1000 to 20,000 p.s.i. and temperatures around 300°F. are used in this process.

Compression molding is applicable to relatively simple parts with thick sections and weighing up to 50 pounds. Metal inserts can be molded in place. The removal of the flash or fin is usually the only finishing operation required on compression-molded parts.

Transfer Molding. This process is a modification of compression molding in which just the required amount of material is heated in a container above the mold and is then forced into the mold under high pressure. Pressures as high as 100,000 p.s.i. are used. Complicated parts can be made with this process.

Injection Molding. This process is equivalent to die-casting of metals. It is applicable to thermoplastic parts of relatively simple design not weighing

TABLE 26. Thermosetting Plastics

Type	Composition	Form	Specific gravity	Tensile strength (p.s.i.)	Trade names	Typical uses
Phenolic	Phenol-formaldehyde	Cast	1.25–1.70	2,000–10,500	Bakelite, Cast Resinoid, Catalin, Marblette, Prystal, Durez, Opalon, Textolite	Knobs, buttons, handles, small machined parts
	Phenol-formaldehyde, Furfural-aldehyde-phenol	Molded—wood flour, paper, fabric, asbestos, etc., fillers	1.25–2.00	3,500–9,500	Bakelite, Durez, Durite, Haveg, Indur, Makalot, Michrock, Resinox, Textolite, Corolite, Heresite, Insurok, Neillite	Pulleyes, knobs, handles, instrument cases, terminal blocks, electrical plugs
	Phenol-formaldehyde	Laminated—paper, fabric, asbestos, or glass-cloth base	1.34–1.80	10,000–38,000 (See Table 27)	Aqualite, Catabond, Celeron, Coffite, Dilecto, Duraloy, Formica, Insurok, Lamicoid, Lamitex, Micarta, Ohmoid, Panclyte, Phenolite, Spauldite, Synthane, Taylor, Textolite, Veinite, Vulclid	Gears, electrical applications, paneling, structural parts
Amino	Melamine-formaldehyde	Molded—cellulose, fabric, asbestos fillers	1.40–2.00	5,500–7,000	Melmac, Resimene, Plaskon Melamine, Catalon Melamine	Electrical applications
	Urea-formaldehyde	Molded—cellulose filler	1.45–1.55	6,000–13,000	Bakelite Urea, Beetle, Plaskon, Phonite, Ufromite, Sylplast	Containers, kitchenware, thermos caps
	Urea-formaldehyde	Laminated—cotton base	1.22	5,000–7,000		Molded shapes
Allyl	Allyl	Cast	1.31	5,000–6,000	Allite 39	Aircraft enclosures, lenses
	Allyl	Laminated—glass-fabric base	1.72–1.83	34,200–56,100		Structural applications

over 2 pounds. Metal inserts may be molded in place. Parts manufactured by this process have good dimensional accuracy. In this process the molding compound is heated in a chamber from which it is forced by a ram into a relaively cool mold. The part hardens in a few seconds in the cool mold and is then ejected. High-speed production is obtainable in this process with fully automatic machinery.

Jet Molding. This process is a modification of injection molding which is applicable to thermosetting materials. In jet molding the nozzle leading into the mold is continuously cooled by water except when the same pressure is applied, at which time extreme heat is generated at the nozzle. The material passing through the nozzle is thoroughly heated and plasticized as it enters the mold cavity. After this brief application of heat the nozzle is again cooled with water, thus keeping the material in it uncured and plasticized and ready for the next stroke of the ram. The material in the heated mold cavity sets fairly quickly and is then removed.

Complicated parts weighing up to about 1 pound can be jet-molded. These parts require very little finishing. A high production rate is obtainable with this process.

Casting. This process is usually limited to thermosetting materials which are poured into molds and hardened by slow baking. Since a long time is required for curing, sheet, rod, and tubing are normally cast and the required parts are machined from them.

Extruding. This process is applicable to thermoplastic materials. It is used to produce rods, tubes, strips, and other sections as well as to insulate wire and cable. In this process the molding compound is softened by heating, and is then forced through a die with an aperture of the desired shape. Continuous extruding is obtained by using a self-feeding screw-type ram or stuffer.

Extrusion molding is a variation of injection molding in which the extruder nozzle is used to feed the mold. Pressures are lower than in injection molding but larger parts can be manufactured.

Laminating. This process is applicable to thermosetting plastic materials. It is used in the manufacture of sheet, tubing, rod, and simple shapes. These laminates consist essentially of a reinforcing material such as paper, fabric, or glass fiber, impregnated with a synthetic-resin binder, layers of which are fused together under heat and pressure. The commonly used binding resins are phenol-formaldehyde, melamine-formaldehyde, and urea-formaldehyde.

The reinforcing material is thoroughly impregnated with the resin binder, is dried, and is then cut into sheets of the desired size. To manufacture laminated sheet a number of the impregnated sheets are piled on top of each other and placed in a hydraulic press. They are then subjected to a temperature around 300°F and a pressure of from 1000 to 2500 p.s.i. During this curing operation the resin is transformed into an infusible solid, after which the laminate is removed from the press. Polished plates are used in the press and a polished surface is obtained on the sheet laminate.

Laminated tubing is made either by rolling or molding. Rolled tubing is formed by rolling impregnated reinforcing material on a mandrel under high tension and pressure, after which it is cured by baking without further pressure. Molded tubing is made by rolling the impregnated material on a mandrel and then curing it in a mold under heat and pressure. The mandrel is then removed. Rod is made in the same manner as molded tubing without the use of a mandrel.

The manufacture of the laminates as just described is frequently referred to as high-pressure molding or laminating. A similar process known as low-pressure laminating is often used in the manufacture of curved or odd-shaped parts. In this process layers of wood veneer or other material are coated with a bonding resin and are supported in or over a form of the desired shape. The entire assembly is placed in a rubber bag which is then evacuated, following which the bag and its contents are placed in a closed vessel containing from 75 to 250 pounds per square inch of steam pressure. The bonding time varies from several minutes to 2 hours, after which the work is removed.

A number of low-pressure laminating plastics have recently been developed The use of these new resins in bonding and impregnating permits the fabrication of laminated structures in large and complex shapes at low temperatures and pressures. In some cases only sufficient pressure is required to insure good contact between the laminations. Cotton fabric, glass fabric glass fiber, and paper are used as reinforcements in low-pressure laminates.

PHYSICAL PROPERTIES

The strength of cast and molded plastics is not sufficiently high to justify their use as structural components of aircraft. Some cast phenolic resins do have good compressive properties, however, and are used to make forms and dies. Properties of molded parts vary with the resin, the filler, the method of molding, and the thickness of the sections. Data obtained on test specimens are seldom representative of production parts. It is obvious that this type of material can only be used in secondary parts in aircraft construction.

Laminated plastics show much better promise of being used in aircraft structural applications. The average physical properties of a number of laminates are given in Table 27.

Until recently, laminated plastic materials were developed and used primarily for their electrical properties. The classification of these materials was

TABLE 27. Physical Properties—Laminated Plastics (Average)

Material	Sp. grav.	Grain direction	Tension			Compression		Bending		Shear		Bearing strength	Use
			Ultimate strength (p.s.i.)	Modulus of elasticity (X 10⁻⁶)	% Elong. before fracture	Ultimate strength (p.s.i.)	Modulus of elasticity (X 10⁻⁶)	Modulus of rupture (p.s.i.)	Modulus of elasticity (X 10⁻⁶)	Flat-wise	Edge-wise		
Grade C phenolic	1.34	With	14,700	1.23	2	27,800	1.60	21,400	1.35			16,750	Gears, Good impact strength
		Cross	9,600	1.0	2	27,500	1.20	16,300	1.05			18,350	
Grade XX phenolic	1.34	With	16,700	1.64	2	23,800	2.15	18,400	1.55	12,850	14,080	20,000	Electrical applications; good machinability
		Cross	14,600	1.31	2	23,400	1.62	16,100	1.28	13,950	14,300	19,650	
Grade L phenolic	1.34	With	18,900	1.60	2	25,800	1.72	21,400	1.36	10,250	13,850		Small gears and fine machining applications
		Cross	12,500	1.11	3	24,700	1.32	18,200	1.06	12,650	14,250		
Grade AA phenolic	1.58	With						17,250	1.34	11,900	9,600		Moisture and heat resistant
		Cross						15,400	1.24	14,900	12,210		
High-strength paper base phenolic	1.39	With	24,600	2.20	1½	22,700	2.33	28,400	2.26	13,600	14,500	33,000	Structural material
		Cross	24,200	2.18	1½			29,700	2.15	13,500	15,100	33,000	
		45°	26,100	2.24	2								
Glass-cotton-base phenolic (high-pressure)	1.64	With	38,000	2.16	2	26,800	2.36	34,800	2.15	17,200	13,500	28,500	Structural material
		Cross	37,700	2.13	2	22,900	2.31	33,800	1.81	17,900	15,700	31,600	
		45°				18,200		24,900	1.26				
Glass-fabric base urea-phenolic (low-pressure)	1.74	With	27,400	1.76	3½	6,600		18,400	1.54				Molded shapes, radomes
		Cross	19,700	1.14	2½								
		45°	10,400	.86	4								
Cotton-base urea-phenolic (low-pressure)	1.22	With	5,100	.56	22	7,000		6,400	.43				Molded shapes
		Cross	6,900	.83	8	8,700		9,600	.42				
Fiberglass base CR-149 resin (low-pressure)	1.76	With	54,700	2.49		54,100		84,600	2.98				Primary structure
		Cross	45,700	2.13		56,800		62,600	2.34				
		45°	19,500			27,900		40,900	1.36				

made by the National Electrical Manufacturers Association (NEMA) according to the type of reinforcing material employed. Thus the four grades listed in Table 27 consist of the following:

Grade C	Cotton fabric weighing over 4 ounces per square yard.
Grade XX	Paper base.
Grade L	Fine-weave cotton fabric weighing 4 ounces or less per square yard.
Grade AA	Asbestos fabric base.

Later developments have been for structural or commercial purposes and have not been classified.

A very good example of the growth of a typically good plastic called polyethylene is described in detail in the following paragraph.

> Polyethylene was discovered in England in 1933 when researchers subjected ethylene gas to extremely high pressure and found that it became a white, wax-like solid. Its first major use was as a superior insulating material for aircraft radar cable during the Battle of Britain. In the United States the Bakelite Company and E.I. duPont de Nemours and Company started producing polyethylene for defense purposes in 1943. After the war, polyethylene was tried as a replacement for vinyl, which was in short supply, for such things as plastic cloths, but it really found its use as a film for packaging. Today approximately 35% of the polyethylene produced goes into film, with only cellophane outranking it in this particular field. Other companies were licensed to produce this wonder plastic by the end of 1955 and soon the estimated production will amount to 500,000,000 pounds a year. Polyethylene is used in the manufacturing of squeeze bottles, semi-rigid house-ware (mixing bowls, ice cube trays, etc.) and transparent film bags for wrapping food. To the building trade, polyethylene is known as the material which enables workmen to complete important jobs in any type of weather (for the covering of scaffolds). It is also used by some builders as a film under the concrete slabs of new homes for a moisture barrier.

FIBERGLASS

The need for a plastic material with high strength, electronic transparency (for radomes), and light in weight became evident during the days of World War II. The first announcement of a resin to meet these properties was made in 1944. The resin was actually a salt, the result of a reaction between an alcohol and an acid, defined as a polyester. During this same period, the fibrous glass industry was beginning to expand rapidly and since this new plastic was compatible with fiberglass the two were combined and called low-pressure plastics. Soon after, radomes, wing fairings, antenna masts, and fin caps were made in large quantities. By 1945, 4 million pounds of polyester resins were produced per year. The next refinement of these processes was the introduction of glass mat, which greatly reduced the cost of the build-ups. New resins with better and more controllable viscosities became available and also higher pressures and metal molds were being used. These steps lead us to today's modern reinforced plastics industry.

Glass fibers are available in three basic forms for reinforced plastics use. These are, 1. woven cloth; 2. mat; 3. roving. Roving is usually wound in a standard 35-pound package. It is manufactured from strands which are produced by feeding molten glass into a platinum bushing. The molten glass is then drawn through small orifices and a water spray over a binder applicator, and then wound on a constant speed floor winder. The strand is then wound on a paper tube which is dried to remove excess moisture. After drying, the paper tubes are withdrawn and the inside end located. This end is then drawn through a porcelain die and wound into roving. Roving might be hard or soft, depending upon the end use. Soft roving will wet very easily and is used for such products as fishing rods. Hard roving is usually chopped to a desired length.

Woven cloth may be ordered in a variety of weaves, such as plain or square, where each warp and each fill passes over one yarn and under the next; the crowfoot satin where each yarn goes over one yarn and under three; and eight-shaft satin where each yarn goes over one yarn and under seven. A common type fabric is 143 which is a shaft satin with the filling yarn one-sixth of the weight of the warp yarn, and correspondingly has greater strength in the warp compared with the fill direction. This type of fabric is excellent for applications where load pattern is mostly in one direction. If non-unidirectional properties are desired, cross-laminating is recommended because of higher strength, moduli, and impact resistance.

Mats are random arrangements of fine glass fibers uniformly distributed o form thin, porous, felt-like materials. They are used for the manufacture of nany parts although usually in applications where low-pressure laminating vill suffice. This product does not possess the high strength properties of voven cloths but is lower in cost, has good dimensional stability, low moisture ıbsorption, and equal strengths in all directions.

When the possibility of using reinforced fiberglass presents itself to the ircraft designer, the following good and bad points should be kept in mind.

1. It has good corrosion resistance.
2. It has good impact strength.
3. It can be formed into finished parts relatively cheaply because of the simple jigging and fixtures required.
4. It will result in a tensile strength in excess of 40,000 p.s.i. if properly fabricated.

5. It can be manufactured from resins that will produce laminates which retain their strength at 500°F. Their strength at this temperature is better than the strength of the common aluminum alloys.
6. It has a low elastic modulus.
7. It has low interlaminar strength and offers little resistance to high-speed rain erosion.
8. It is mandatory that close control be used during the manufacturing of a fiberglass part, because poor quality seriously lowers strength.
9. If the good features of fiberglass are taken advantage of, and the bad points are allowed for in design, efficient, economical, and serviceable fiberglass parts should result.

The fabrication of fiberglass in the shop is usually by hand laminating or press molding. Hand laminating should be avoided if a large number of parts are to be produced, because of the variation in quality which is associated with this method and its high cost. Matched metal molds have been used successfully in the past to produce high-quality, inexpensive laminates. This method of manufacture involves the mounting of matched male and female dies in a press; properly coating the molds with a parting agent; placing the cloth or mat reinforcement in the mold; pouring a measured amount of a catalysed resin in; and closing the molds. Pressure and heat are applied until the resin has properly cured. Parts produced by this method are free of the defects usually associated with hand laminating.

Polyester resins are usually cured in an oven, in heated dies, or by means of infra-red lamps. The curing temperature for polyesters is 250°F. while the epoxy resins require temperatures around 325°F.

WORKING PROPERTIES

Joining. Plastic materials are usually joined by means of rivets, bolts, screws, or inserts. When using rivets or bolts it is advisable to use washers under the heads to distribute the compressive load of the riveting or nut tightening. Washers also resist the tendency to pull the head of the rivet through when a joint is eccentrically loaded. When screws are used, coarse threads should be specified.

Thermosetting materials can also be joined by cementing. Cements of the Cycleweld type will develop shear strengths of 3000 p.s.i. and failure under test will occur in the plastic and not the joint. This type of cement is cured at a temperature around 300°F. in 15 minutes, with sufficient pressure being applied to insure contact between the two surfaces being bonded. A Vinylseal cement is also used for bonding thermosetting plastics but this cement is a thermoplastic and will soften when heated. It is not satisfactory for bonding joints under continued stress.

In joining laminated-plastic materials it is important that the fatsenings apply the loads across the laminations. The interlaminar strength is low (except in compression) and cleavage of the bonding plane will result if loads are in a direction that tend to delaminate the material.

Machining. Plastics can be machined without difficulty but the reinforced thermosetting plastics are very hard on cutting tools, causing them to dull rapidly. In general, tools with cemented tungsten carbide or satellite tips are used. In turning, high speed and light cuts are best. Overheating caused by excessively high speed or a dull tool will result in a poor finish and inaccurate dimensions. In milling, large-diameter cutters with many teeth operating at high speed should be used. Drilling should be done with high-speed steel drills which are kept sharp. Reaming and tapping can be done with the same tools used for metal. Fine threads are best cut on a lathe, but self-opening dies or milling cutters should be used for normal production threading. Band and circular saws can be used for sawing, but should operate at approximately 5,000 and 10,000 feet per minute respectively. In punching, the clearance between die and punch must be much less than used for metal and both punch and die must be sharp.

Forming. Thermosetting plastics have very little ductility at room temperatures and cannot be formed like metals. Single-curvature parts with a large radius can be formed but must be held in this shape by adequate fastening. Reinforced thermosetting plastics such as laminates can be originally cured to a desired shape but the die cost is high and only justifiable when large quantities are involved. It is difficult to mold the high-pressure laminates in any but flat or simple curved shapes; but low pressure laminates can be molded to practically any desired shape.

In the last few years an undercured laminated phenolic sheet has become available commercially that can be formed by the aircraft manufacturer. Grade C material which is reinforced with a coarse-weave fabric appears to be the best for this purpose. The forming of a thermosetting material after it has once been heat-set is referred to as post-forming.

Post-forming is the reshaping of a partially cured laminated sheet which still retains some thermoplastic qualities that permit forming. In this process the work must be brought up to temperature and formed quickly, since final polymerization and setting will occur with heat and time. Heating is usually done in hot-air ovens, in an oil bath, or in contact with hot plates. It takes from 20 to 60 seconds to bring the material up to a temperature just under 350°F. The material begins to soften at 250°F. and blisters at 350°F. When the work is at temperature it must be quickly placed in the dies and pressure applied and held for a short time. The formed part should be allowed to cool before removing it from the form, but this process can be accelerated by air cooling; cooling normally requires one to two minutes.

A 3-inch-diameter cup of 1/16-inch material has been drawn 1½ inches deep by this process. Close dimensions are hard to hold, however, and square outside corners are not obtainable. The thickness of the formed part is fairly constant. Bend radii of 3*t* (where *t* is the thickness of the material) can be obtained on material up to 1/8 inch thick, and 4*t* on material up to 3/16 inch thick.

The formed part has the physical characteristics of the Grade C material from which it was made. It is suitable for applications exposed to temperatures from −70°F. to + 200°F. In general, these parts are used for such nonstructural purposes as fairings, wheel pockets, and similar pressed parts. Material 1/16 inch thick 36 by 96 inches in size is most generally used for aircraft applications.

USES

Throughout this chapter, applications of the various plastic materials have been described. At the present time in aircraft construction plastics have established themselves for many nonstructural applications which are similar to their use in automobiles and home appliances. Their use as fairings, radomes, doors, and ducts is also well established. They have not yet received general acceptance as primary structural material, but current developments with glass-fabric reinforced laminates give promise of meeting aircraft structural requirements.

The use of thermoplastic sheeting materials for cabin enclosures is of course universal. This application is described more fully in Chapter XIX.

CHAPTER XIX

TRANSPARENT MATERIALS

TRANSPARENT materials are used in aircraft for windshields and for general cabin glazing. Two types of material are used: glass and a variety of transparent plastics. A shatterproof glass is used in the interest of safety. A high-grade laminated plate glass is used for windshields and bombers' windows where perfect vision is essential. In military aircraft a laminated bullet-resistant glass is used for the part of the windshield directly in front of the pilot or other crew members. For the relatively unimportant side windows and skylights a cheaper grade of laminated sheet glass or one of the transparent plastics is used. In some planes, where weight and/or expense are important considerations, transparent plastics are used throughout. In general, transparent plastics will scratch, discolor, and distort much more than glass and must be frequently replaced.

Many types of glazing materials are available for the aircraft designer. Here we cover the more generally used ones. The selection of a glazing material depends upon many considerations such as:

Optical Properties. This qualification depends upon many things including the type of aircraft (commercial, military), the specific purpose of the glazing material and the amount of night flying expected, plus many others.

Strength Properties. These specifications are dependent upon the speed of the aircraft, the expected altitude, the size of the window or canopy, the landing conditions, etc.

Weathering Characteristics. These design considerations are predicated upon the length of flights, the general environment in which the plane will operate, and the type of maintenance expected.

Heat Resistance. This qualification is very important and depends upon the airplane's general environment specifications, speed, altitude, and range.

GLASS

Shatterproof or nonscatterable glass consists of two or more pieces of glass held together by a single-ply filler of a transparent plastic. A vinyl plastic is most often used for this purpose. An adhesive is used on both sides of the filler to bind the two pieces of glass together. The filler is cut back a short distance from the edge to allow space for a sealing compound. This sealing compound is waterproof and protects the adhesive. It extends from $^1/_{16}$ to $^5/_{32}$ inch in from the edge of the glass.

There are two types of nonscatterable glass available.

1. *Laminated plate glass.* This glass is made of two pieces of class A polished plate glass. It is obtainable in thickness from 3/16 inch up. Generally 3/16- and ¼-inch glass are used for aircraft windshields. The dimensions of the windshield determine the thickness necessary. It is easier to obtain ¼-inch glass because of the difficulty in procuring clear plate glass thin enough so that two layers will be only 3/16 inch thick.

Laminated plate glass for aircraft windshields is procurable either flat or curved. To relieve mounting strains which will crack the glass and to provide a mechanical mounting means this type of glass is procurable with an extended plastic edge. This plastic edge is a thickened-up extension of the plastic filler between the layers of plate glass. This plastic edge frequently incorporates metal reinforcing strips. The extended edge can be drilled and mounted with screws to the windshield frame. This arrangement provides a positive mounting without inducing strains in the glass. It is particularly desirable when using curved glass since the curve of the glass and windshield frame are seldom exactly alike.

Bullet-resistant laminated plate glass as commonly used for windshields of military aircraft is composed of a number of varying thicknesses of plate glass. The front layer of glass is usually specified to be 1/8 inch thick and the rear layer not greater than 5/32 inch thick. The intermediate layers, of which there must be at least two, may be of any thickness. A ¾-inch-thick glass overall has been generally used for military windshields. Bullet-resistant glass of this thickness will prevent complete penetration of a .30 caliber bullet hitting the glass at an angle 45° and a velocity of 2700 feet per second. Bullet-resistant glass can be procured with either of two degrees of light transmission—the glass having the greatest light transmission being the most expensive but being desirable for night-flying airplanes.

In some military installations the illuminated gunsight reflects directly on the bullet-resistant glass and to avoid a double image it is mandatory that the front and rear faces of the glass in this area be parallel to each other. It is usually necessary to specially grind the glass in this area to obtain parallelism since the number of glass laminations and plastic fillers precludes obtaining the required parallelism by manufacturing controls.

2. *Laminated sheet glass.* This glass is made from class B, clear window glass of the best quality. It is obtainable in thicknesses from 1/8 inch up. For side windows, skylights, and similar secondary applications 1/8 inch glass is generally used. This type glass has considerably more distortion than plate glass and should not be used for windshields.

Modulus of Elasticity	10.5 X 10^4
Tensile Strength (p.s.i.)	6,500
Modulus of Rupture	6,000 p.s.i. annealed 18,000 p.s.i. semi-tempered 30,000 p.s.i. fully-tempered
Compressive Strength	36,000 p.s.i.

The physical properties of glass are as follows:

Specific heat	0.202 BTU/1b./°F. at 32–212°F.
Thermal Conductivity	0.202 BTU/in./sq. ft. per hour per °F.

The plate-glass expansion coefficient (–70°F. to 100°F.) is .00000451 per °F. This expansion is two-thirds that of steel and one-third that of aluminum.

Density	155 lb./cu.ft.
Index of Refraction	1.52

Testing Nonscatterable Glass. An impact test is made on this type of glass to determine its effectiveness in preventing flying of glass in a crash.

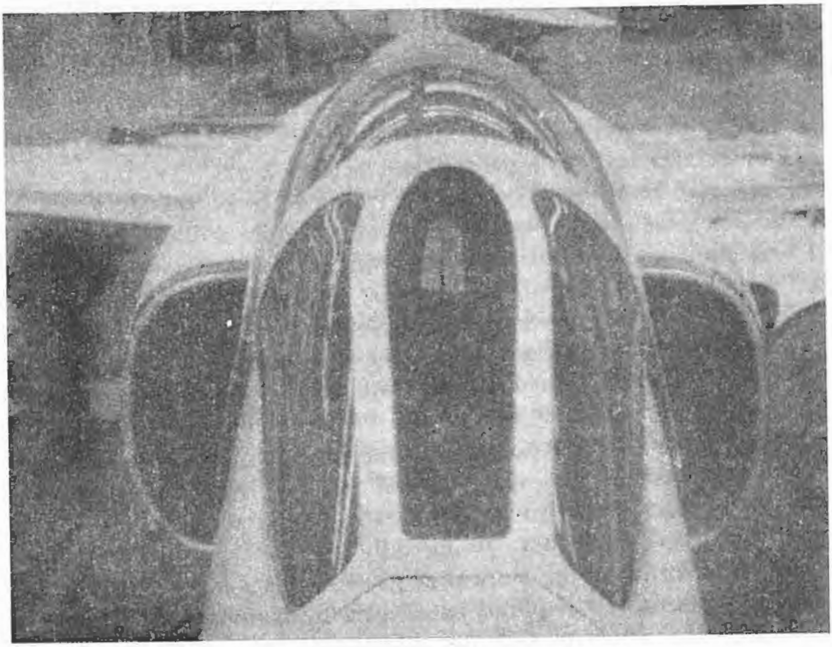


FIGURE 63. Windshield—Bullet-proof Glass Pane

The impact test consists of dropping a ½-pound spherical steel weight from a height of 16 feet on the center of a 1-square-foot surface of the glass. The glass is supported along all edges by a wooden frame extending ³/₈ inch in from each edge. The glass must be at a temperature between 70°F. and 80°F. To pass this test the glass must not separate from the adhesive and there must be no puncture of the filler. Small chips of glass may leave the underside of the sheet due to fracture within the bottom plate.

The glass must also stand a heat-resistance test without signs of cracking. In this test the glass is maintained at 32°F. for 30 minutes and then raised uniformly within 2 minutes to 104°F. It is maintained at this temperature for 40 minutes and then cooled down to 32°F. again within 5 minutes. This test simulates an airplane climbing to altitude, where the temperature is colder, and then descending to a warmer temperature somewhat more quickly.

Bubbles, scratches, and other defects are checked by the unaided eye under good illumination.

A test for definition and distortion is made by means of a 6-power telescope focused on a distant target. When the glass is interposed in the line of vision the target must still appear clearly defined and undistorted. The glass specimen should be shifted in order to check different portions.

TEMPERED GLASS

This is an exceptionally strong glass that is used for large windshields. It is produced by heating glass uniformly over the entire surface to 1250°F. and then suddenly quenching it to room temperature. By this process the outermost surface of the glass is placed under high compression and the inside under tension. The strength of tempered glass is due to the surface compression which must first be overcome before the ordinary strength of the glass comes into play. Tempered glass has a compressive tensile strength of approximately 36,000 p.s.i. Its coefficient of expansion is only .000003 per °F. It can be manufactured only in ¼-inch thickness or greater.

TRANSPARENT PLASTICS

The ideal transparent plastic for aircraft use should be strong, scratch resistant, noninflammable, colorless, transparent, and unaffected by sunlight or by temperature changes. In addition, it should be possible to mold it to the desired shape in the aircraft manufacturer's plant and it should be obtainable in reasonably large sizes. In common with all aircraft materials it should also be homogeneous, light, and readily available at a reasonable price. Unfortunately, no transparent material yet devised can meet all these specifications. At the present time it is customary to replace windshields and cabin enclosures at frequent intervals when the old material becomes distorted, discolored, or excessively scratched.

The chief problem in the use of plastics for windshields and cabin hoods is to allow for the expansion and contraction of these materials with change in temperature. In almost any flight to altitude an airplane goes through a temperature differential of well over 50°F. Military Specification MIL-P-6997 which describes the proper installation of transparent sheet plastic material, requires provision for contraction and expansion from –67°F to +158°F. If 77°F. is the manufacturing temperature, the amount of contraction that will occur in the temperature ranges specified is about twice as much as the amount of expansion. When installing transparent plastics in a framework, it is necessary to allow for a $^1/_8$-inch movement in 12 inches to permit free expansion and contraction of cellulose acetate plastic sheeting; acrylate and allyl-base plastics require only about 0.09-inch movement in 12 inches. This allowance is usually provided by drilling oversize holes in the plastic material and using shoulder rivets or screws inserted through tubular spacers in the frame to avoid clamping down on the plastic material. If tight riveting is employed, the plastic material will contract sufficiently to cause it to crack under the slightest outside pressure. If touched lightly with the finger under these conditions it will shatter. At the temperatures reached around 25,000 feet it will crack of its own accord due to the magnitude of internal contraction strains. Installation in channels is the ideal method for eliminating contraction strains. A $^1/_{16}$-inch-thick packing should be pasted to the plastic sheet before insertion in the channel. A flush channel installation is made by routing the plastic sheet to a depth equal to the thickness of the supporting channel leg plus packing. Since this leaves the plastic a little thin in this region a reinforcing strip of plastic is cemented on the inside. By properly shaping the inside channel leg it can be hooked around the ledge formed by the reinforcing strip, thus obtaining a positive and secure mounting. The expansion that occurs when it is exposed to a hot sun and warm weather will permanently distort the material unless clearances are provided to permit the take-up.

Several transparent plastic materials commonly used for aircraft windshields and cabin enclosures, as well as for inspection hole covers, are described below.

Pyralin. This material is a pyroxylin nitrocellulose plastic. It is a solution of nitrocellulose in camphor. The nitrocellulose used is nonexplosive and less inflammable than guncotton nitrocellulose. The nitrocellulose used is known as pyroxylin. The pyroxylin is mixed with camphor and alcohol, heated, and pressed into solid blocks. The desired thickness of sheet is sliced from these blocks.

Sheets of this material may be purchased for aircraft work from 0.030 to

0.150 inch thick. A full sheet is usually limited in size to 21 by 50 inches. The weight of a sheet of this size in the thicknesses available are listed below:

Thickness (in.)	*Weight (pounds)*
.030	1⅔
.040	2¼
.050	2⅔
.060	3⅓
.070	3¾
.080	4¼
.090	4¾
.100	5¼
.125	6½
.150	8–0

Pyralin is a thermoplastic material that can be softened by heating and molded under pressure into forms with double curvature such as are used on the tops of sliding cabin hoods. It can be readily sawed and drilled. Pyralin is inflammable. In the past it has been very commonly used on commercial airplanes.

Plastecele. This material is a cellulose acetate plastic. It is manufactured in the same manner as nitrocellulose plastics. The sizes obtainable and their weights are the same as listed above for pyralin.

This material is flame-resisting and is frequently used on military airplanes. It will burn only slowly when a lighted match is held to it. The test for transparency requires that standard typewritten copy on blueprint paper, which is white on a blue background, shall be wholly legible to the normal eye when held 6 inches behind the material and viewed through it in daylight.

This material is thermoplastic and can be readily shaped by means of heat and pressure. Hot water at 150°F can be used to soften the material, and air applied at 50 p.s.i. pressure will press the softened material into the mold. This air also cools and sets the material.

Like other transparent plastics this material suffers from too great contraction and expansion. It is fairly satisfactory in other respects. Proper mounting to permit give-and-take with temperature changes will greatly increase its service life.

Vinylite. This material is a copolymer resin of vinyl chloride and vinyl acetate. It is noninflammable and has the general properties required for aircraft cabin enclosures. It is available in the usual range of commercial sizes.

Plexiglas and Lucite. These are acrylic thermoplastics. They are colorless and transparent and do not discolor with age. They are inflammable only to the extent that they will burn slowly when warmed and ignited by a flame. Acrylic plastics will not scratch quite as easily as cellulose plastics. They

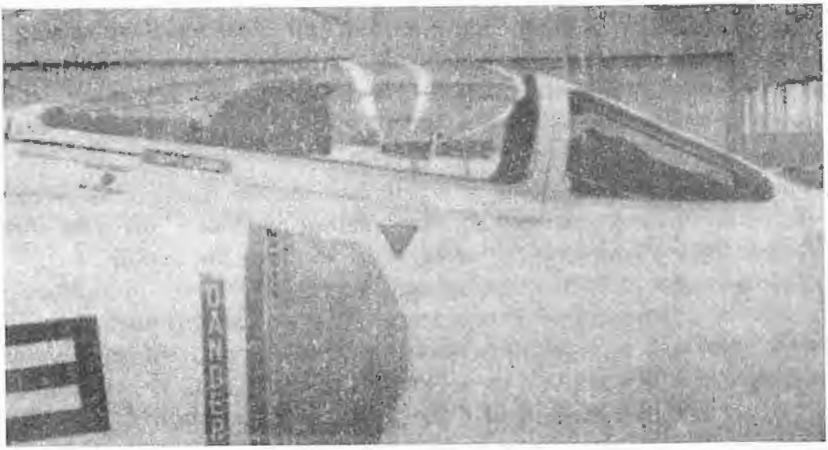


FIGURE 64. Cabin Enclosure—Plexiglas

have a coefficient of expansion about two-thirds that of the cellulose plastics but also require installation in channels or other methods permitting free movement.

The acrylic plastics are formed at temperatures between 200° and 250°F. There are two basic types of acrylic plastics available commercially—standard and heat resistant. The maximum recommended continuous service temperature is 140°F. for the standard type and 176°F. for the heat-resistant type.

Acrylic plastics are obtainable in sizes up to 53 inches by 80 inches, and in thicknesses from 0.060 to 0.500 inches.

Detailed information on plexiglas 1, 2, and 55 is given below.

Plexiglas I & II. Plexiglas I-A is an acrylic sheet supplied in accordance with the requirements of Military Specification MIL-P-6886. This material was used extensively for aircraft glazing during World War II and has generally been used for making laminated acrylic sheet.

Plexiglas II-UVA is a heat-resistant plastic manufactured under Military Specification MIL-P-5425 and is finding wide use because of its good heat-resistant properties. The manufacturer of Plexiglas I-A and Plexiglas II UVA is the Rohm & Hass Co. of Philadelphia, Pa. The properties of these materials are listed below. Caution should be exercised in the use of mechanical properties listed for plastics. Plastic materials exhibit elastic and plastic deformation and are subject to creep under constant load. It is a good rule, when designing parts from plexiglas materials, not to use more than 1,000 p.s.i. outer fiber stress for Plexiglas I, and 1500 p.s.i. for Plexiglas II UVA if these materials are to be subjected to continual loads at 77°F. or lower. If higher temperatures are to be encountered, exacting laboratory tests should be performed on the finished parts in order to check the design.

Values listed below are average value:

	Plexiglas I-A	*Plexiglas II UVA*
Heat Distortion Temperature	154°F.	199°.F.
Coefficient of Thermal Expansion (in./in./°C)	9×10^{-5}	7.5×10^{-5}
Tensile Strength		
77°F.	8,000 p.s.i.	9,500 p.s.i.
140°F.	4,000 p.s.i.	5,700 p.s.i.
160°F.	2,400 p.s.i.	4,400 p.s.i.
Flexural Strength (77°F.)	13,000 p.s.i.	16,000 p.s.i.
Shear Strength (77°F.)	8,000 p.s.i.	9,000 p.s.i.
Coefficient of Thermal Conductivity (B.T.U./hr/sq.ft/°F./in.)	1.31–1.44	1.27–1.36

When forming Plexiglas II UVA, it should be heated for approximately 30 minutes ($^5/_{16}$ in. material) in a forced air oven, then immediately placed on the forming jig and formed to contour. After forming it is mandatory to anneal the parts at a temperature of 170–180°F. for 12 hours. (Other heating-time cycles are also possible.)

An optical acceptance standard involves the placing of a ruled grid 25 feet from the pilot's normal eye position and approximately 90° to the line of vision through the area being checked. One axis of the grid is kept longitudinal. Excessive bending or blurring of the grid lines when viewed from the pilot's normal eye position is not acceptable.

Stretching of the acrylic plastic materials has helped to improve several properties but, since many methods of stretching are possible, general statements can be made as follows:

Stretched acrylic plastic materials are considerably better than unstretched materials in resistance to crazing, impact strength, and notch sensitivity properties. They are equivalent to unstretched materials in optical properties and dimensional stability. Stretched material is inferior to unstretched materials in abrasion resistance.

Plexiglas 55.-This is a cast acrylic sheet with good resistance to stress-solvent crazing and to stress crazing. The elevated temperature properties are slightly higher than Plexiglas II. General rules for the handling, design and manufacturing procedures follow those for Plexiglas II, but different cements and cementing techniques must be used. The annealing temperature of Plexiglas 55 is a minimum of 176°F. for 24 hours although higher temperatures are used in production, thus cutting the time. Specification MIL-P-8184 covers this material.

Average physical and mechanical properties are as follows:

Specific Gravity	1.19
Tensile Strength	11,000 p.s.i.
Flexural Strength	16,000 p.s.i.
Shear Strength	9,000 p.s.i.
Refractive Index	1.50
Heat Distribution Temperature	212°F.
Coefficient of Thermal Expansion (in./in./°C. at 50°C.)	10

Gafite. Gafite is the trade name for General Aniline & Film corporation's polymethyl alpha-chloroacrylate polymer glazing material. This material is relatively new and has excellent resistance to heat, crazing, abrasion and scratching. It has a heat distortion temperature of 276–288°F. and a slightly higher specific gravity than Plexiglas II UVA, the value being 1.47. Gafite can be readily formed at 320°F. and due to this high softening point, this material can be drilled or turned on a lathe without the gumming encountered with many other types of plastics. Properties of this material are as follows:

	Tensile Strength (p.s.i.)	
60°F.	15,500	
100°F.	14,200	
140°F.	12,000	
200°F.	8,500	
Flexural Strength at 75°F		22,000–24,500 p.s.i.
Linear Coefficient of Thermal Expansion in./in./°C		6.2 X 10^{-5}

Sierracin 611. This material is manufactured by the Sierracin Corporation under Military Specification MIL-P-8257. It is a highly cross-linked thermosetting material produced by balancing the physical properties of various polyester resins against each other. The non-crazing characteristic of Sierracin 611 is one of its most important properties. Sierracin 611 has been in use for some time, but owing to recent interest in high-temperature glazing materials, it is being re-evaluated by several airframe producers.

Properties of Sierracin 611 are as follows:

CONTROLLED PROPERTIES

	Tensile Strength (p.s.i.)	
60°F.	12,000	
77°F.	10,000–12000	
100°F.	8,500	
150°F.	5,500	
Flexural Strength, p.s.i. (plain specimen)		18,000–22,000
Heat Distortion Point		190–205°F.

It should be mentioned here that, owing to aerodynamic heating alone, some of the metallic materials are approaching limits which permit satisfactory use at elevated temperatures. The temperatures which are expected on windshields and canopies will make all of the currently available glazing materials unusable. It is predicted that future canopies will be constructed of glass and plastics with a dead air-space between them. Annealed glass possesses good optical properties but very poor thermal shock properties. Tempered glass might be of some help since its thermal shock properties are superior to annealed glass but the optical properties are not as good.

As previously stated, it would be next to impossible to obtain a glazing material which would be best in all of the above designs. A well-calculated comprise is often necessary.

In order to properly design a windshield and canopy for an aircraft, it is essential that consideration be given to many factors. The environmental testing specification, MIL-E-5272A dated 16 September 1952, should be consulted for various specified conditions.

Cabin pressurization can cause a pressure differential of approximately 10 to 12 p.s.i. This load is many times coupled with aerodynamic loading, vibration loads, impact loads and loads created by temperature differences.

When an airplane suddenly flies through a cloud, large thermal gradients can exist owing to water droplets impinging on the windshield.

Crazing is a very undesirable type of defect which can be avoided in most cases if good design and maintenance is practiced. Good practices, in order to minimize crazing, are as follows:

1. Proper forming temperatures should be used.
2. Proper annealing time allowed and correct temperatures should be used.
3. Proper quality control over the various fabricating methods such as drilling, sawing, routing, sanding, polishing, and handling should be observed.
4. Proper use of cleaners must be followed making sure that only approved cleaners are used.
5. Proper design and proper installation techniques should be practiced. Care should be taken to prevent any bending, rubbing, or over-stretching.

CHAPTER XX

RUBBER AND SYNTHETIC RUBBER

THE shortage of natural rubber during the war years resulted in large-scale developments for the manufacture of synthetic rubber. Five basic types of synthetic rubber have been developed commercially and are currently in general use in industry. These basic types are commonly known as buna S, buna N, neoprene, butyl, and thiokol. These materials have been used in many aircraft applications during the war and will continue to be used in the future.

Hundreds of different compounds of each of the five basic types are obtainable by variations in compounding and processing. Emphasis on any desired characteristic is possible but usually is accompanied by a loss in other desirable properties. Each compound must be developed to meet specific engineering requirements. Unless the designer has had experience with a specific compound in a similar application it is best to consult with technicians of the rubber-products manufacturer. The manufacturer should be informed fully and accurately of the service conditions under which the part will be used. For example: in the case of a bellows-type seal to be used on the firewall of an airplane around a throttle rod, it should be explained that the seal will be subjected to hot, oily conditions, and will be flexed repeatedly. With this type of information the best compound for this application can be prescribed.

Table 28 has been prepared to give a general idea of the properties of the five common types of synthetic rubber as compared to natural rubber. In general, natural rubber has better physical properties but the synthetic rubbers have greater resistance to deterioration, heat, and abrasion. It should be noted that the synthetic rubbers that have the greatest resistance to deterioration are least like rubber in processing and application.

Both the natural and synthetic rubbers are polymers or copolymers and are chemically similar to the plastics. A polymer is a complex material formed by a polymerization reaction. In this reaction a relatively simple chemical is converted to an extremely complex material with entirely different properties due to reaction with itself. Catalysts are usually required to aid this chemical reaction. In copolymerization two simple chemicals react to form a single complex product with new properties.

Synthetic rubbers are commercially available as latex, sheet, tubes, extrusions, moldings, rubberized fabrics, sponge materials, cements, and adhesives.

TABLE 28. Comparative Properties of Natural and Synthetic Rubber

Properties	Natural rubber	Buna S	Buna N	Neoprene	Butyl	Thiokol
Available forms	Latex, solid	Latex, solid	Latex, solid	Latex, solid	Solid	Dispersion, powder, solid
Adhesion and cohesion	Excellent	Fair	Fair	Good	Good	Good
Vulcanizability	Excellent	Good	Good	Good	Fair	Fair
Extensibility	Excellent	Good	Good	Excellent	Excellent	Good
Resilience	Excellent	Good	Fair	Very good	Low	Good
Tensile strength	Excellent	Fair	Good	Very good	Good	Fair
Impermeability to gases	Good	Good	Good	Very good	Excellent	Excellent
Resistance to cold flow	Very good	Good	Good	Good	Fair	Low
Resistance to abrasion	Very good	Very good	Very good	Very good	Fair	Low
Resistance to tear	Very good	Fair	Fair	Good	Good	Fair
Resistance to heat	Good	Very Good	Very good	Very good	Fair	Low
Resistance to cold	Very good	Very good	Good	Very good	Good	Good
Resistance to air	Fair	Good	Good	Excellent	Excellent	Excellent
Resistance to light	Fair	Fair	Low	Excellent	Excellent	Excellent
Resistance to petroleum	Low	Low	Excellent	Good	Low	Excellent
Resistance to aromatic oils	Inadequate	Inadequate	Fair	Low	Inadequate	Excellent

*This table should be used to obtain a general idea of the inherent properties of the synthetic rubber types listed.

In the following pages the various types of rubber are described in more detail, together with the applications they have found in industry.

NATURAL RUBBER

Natural rubber is a polymer of isoprene. It is prepared from the sap of a number of plants and is easier to process than the synthetic rubbers. Natural rubber can be readily vulcanized, or cured, to almost any desired degree of hardness. It has better tensile strength and resilience than the synthetic rubbers but deteriorates much more rapidly when subjected to air, ozone, light, heat, petroleum products, or aromatic oils.

Natural rubber has been used for tires and tubes, electrical insulation, and numerous other everyday products.

SYNTHETIC RUBBER

Buna S. Buna S is a copolymer of butadiene and styrene. The name buna S is derived as follows: Bu is the first syllable of butadiene. Na (for natrium) is the chemical symbol for sodium, which in the early days was used as a catalyst in the polymerization of butadiene. S stands for styrene. This material is also referred to as GR-S which is the abbreviation of Government Rubber—Styrene. This name is a result of the large United States government developments of synthetic-rubber plants during the war.

Buna S synthetic rubber is the most nearly like natural rubber. It can be vulcanized with sulfur and cured to a hardness equal to hard rubber. Buna S must be compounded with a black pigment such as carbon black to bring out its best physical properties. As a consequence commercial buna S is usually black. Buna S is the synthetic rubber normally used for tires and tubes as a substitute for natural rubber. It can be used to replace rubber in most applications.

Buna N. Buna N is a copolymer of butadiene and acrylonitrile. The N is the first letter of nitrile. These compounds are sometimes referred to as nitrile rubbers. This material is also known as GR-A, which is the abbreviation of Government Rubber—Acrylonitrile. Some commercial names of buna N are Perbunan, Hycar, Chemigum, Thiokol RD, and Butaprene. None of these compounds are identical but merely belong to the same family.

Buna N is similar to rubber in that it can be vulcanized with sulfur and can be cured to hard rubber. It has excellent resistance to oil and will resist heat up to 250°F. in normal applications. It stiffens at –45°F. It has good abrasion resistance and has good "breakaway" properties when used in contact with metal. For example, when it is used as a seal on a hydraulic piston it will not stick to the cylinder wall. This material is adversely affected by ozone and sunlight. Its properties are improved by the addition of carbon black.

Buna N can be bonded by vulcanization or cement to metal surfaces. It is not necessary to brass-plate the metal as is done to obtain good adherence with natural rubber. A sandblasted surface is desirable. Uncured stock can be made to adhere to the metal by applying heat and pressure, thus curing the stock at the same time. Cured stock can be made to adhere by using the proper cement and applying heat only. Phenol-formaldehyde resin cements are satisfactory for this purpose. Cold-setting cements have also been used but not very satisfactorily.

Buna N is used for oil and gasoline hose, tank linings, hydraulic accumulator bags, gaskets, and seals.

Neoprene. Neoprene is a polymer of chloroprene. Neoprene is available in many different types, some of which are copolymers. Its designation GR-M refers to Government Rubber—Monovinyl Acetylene type. Neoprene was the first commercially successful synthetic rubber.

Neoprene is a good general-purpose rubber that has good resistance to oil and excellent resistance to heat, air, light, and flame. It has better light resistance than any other rubber. It can be vulcanized without sulfur but cannot be cured to as hard a condition as hard rubber.

Neoprene is used for oil-resistant hose, carburetor diaphragms, gaskets, shoe soles, barrage balloons, truck tires, cements, tape, and caulking.

Butyl. Butyl is a copolymer of isobutylene and small amounts of unsaturated hydrocarbons such as butadiene or isoprene. It is produced cheaply from petroleum by-products, one of which is isobutylene. It is also referred to as GR-I, which is the abbreviation of Government Rubber—Isobutylene. It is also known as Flexon.

Butyl can be vulcanized with sulfur but cannot be hardened to the condition of hard rubber. Butyl has excellent gas impermeability and for this reason may become the first-choice material for tire tubes. It is also used for gas masks, plywood molding bags, life jackets, and chemical storage.

Thiokol. Thiokol is a polysulfide polymer. It is sometimes referred to as polysulfide synthetic rubber. Its designation GR-P is the abbreviation for Government Rubber—Polysulfide.

Thiokol has the highest resistance to deterioration but the lowest physical properties. It is particularly noted for its resistance to aromatic hydrocarbons and aromatic blended gasolines. Thiokol can be vulcanized with zinc oxide but not to a hardness comparable with hard rubber.

Thiokol is used for oil hose, tank linings for aromatic aviation gasolines, paint spray hose, gaskets, and seals.

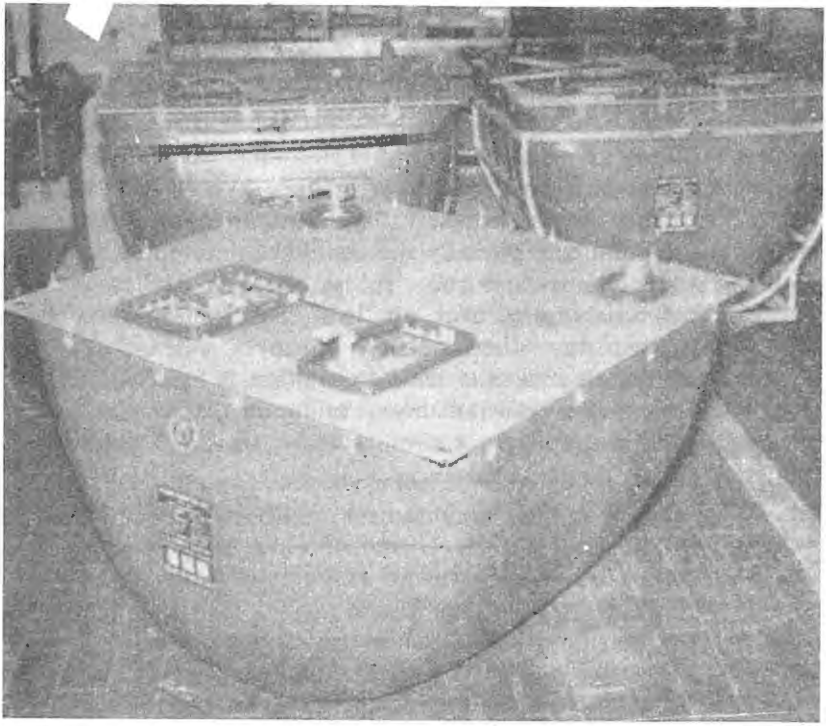


FIGURE 65. Bullet-proof Fuel Tank—Synthetic Rubber

MANUFACTURING PROCESSES

Synthetic-rubber materials are available in fabricated solid forms. Tubes, window strips, and miscellaneous shapes are extruded in the same manner as plastics or metal. After extrusion the finished shape is vulcanized or cured to the desired hardness by placing the material in an open steam trough.

Molded rubber parts are superior to extrusions. They are denser, have better physical properties, and can be held to closer tolerances. In compression molding the raw stock is prepared by extruding to the approximate shape, or by die punching pieces to shape. This prepared raw stock is similar to the finished article in density and has the consistency of a semihard tough puttylike substance. This material is worked into a shape closely approximating the finished article and is placed into a mold cavity. A temperature of 250–350°F. and a pressure of 1000–4000 p.s.i. are applied to cure the part in the mold. The excess stock escapes into an overflow cavity, leaving a thin flash on the finished part which must be trimmed off. A cooling-shrinkage allowance of about $^{3}/_{16}$ inch per foot must be allowed in the manufacture of the mold.

Injection molding of synthetic-rubber parts is now under development. In this process the raw stock is forced into the mold under high pressure and both the mold and the stock are pre-heated. Very close tolerances are obtainable in this type of molding.

CALENDERING

Calendering is a process in which raw rubber stocks are fed through a series of steel cylinders and parallel mounted. The space between the rolls can be adjusted by the operator. The finished product is sheet stock of various thicknesses. After calendering, the sheet stock is vulcanized. Many punched rubber products are produced from the material.

Injection molding of synthetic-rubber parts is now under development. In this process the raw stock is forced into the mold under high pressure and both the mold and the stock are preheated. Very close tolerances are obtainable in this type of molding.

VULCANIZING

Vulcanizing is the name applied to a number of processes which increase the elasticity and strength and reduce the tackiness of rubberlike materials. Curing has the same meaning as vulcanizing when used in connection with rubber processing.

The process of vulcanizing was first introduced by Charles Goodyear in 1839. In this process, sulfur was intimately mixed with rubber and heated. A certain amount of the sulfur disappears, apparently dissolving in the rubber and giving the material new properties. In later years other agents, such as peroxides and polynitro compounds, were found to produce the same results as the original sulfur.

Unvulcanized or uncured rubber is thermoplastic and softens when heated. The plasticity of uncured rubber is greatly reduced after vulcanization. Vulcanized rubber will not soften when heated but will burn if the temperature is high enough. It is customary to form or mold uncured rubber materials to the desired shape and then to vulcanize them to the required degree of stiffness and mechanical stability.

CHAPTER XXI

TITANIUM AND ITS ALLOYS

TITANIUM the so-called wonder metal, was first discovered in 1789 by an English clergyman named Gregor but it was five years later that the German chemist Klaprath called the new element Titan because of the strong chemical bond it had with other elements. Owing to titanium's very intense chemical reactivity at moderately elevated temperatures, it has never been found in the uncombined state. Titanium ores are widely distributed over the earth's crust and the ore discoveries to date in North America indicate that there is sufficient ore for many years to come. Only six metallic elements and two nonmetallic elements are more abundant. Most of the ores of titanium contain its dioxide. The most important titanium ores are Rutile (TiO_2) and ilmenite ($FeO\text{-}TiO_2$). Prior to 1942 these ores were mined for the purpose of producing titanium compounds for use in smoke bombs, paint pigments, heat-resistant glass, porcelain glaze, and small quantities of pure titanium. Ilmenite, the principal ore, is an iron ilmenite (approximately 52% TiO_2) and can be concentrated by magnetic and gravity methods. The concentrate of TiO_2 is further treated by being dissolved in sulfuric acid and precipitated by hydrolysis. The actual chemical equations which represent the final refining process look very simple to the novice chemist. These equations are:

$$TiO_2 + 2C + 2Cl_2\ Cl_2 \rightarrow TiCl_4 + 2CO$$
$$TiCl_4 + 2Mg \rightarrow Ti + 2\ MgCl_2$$

Although the equations might look simple, it should be remembered that titanium is extremely active at elevated temperatures and will combine with practically anything it comes into contact with. Molten magnesium is also a very active element and can cause violent fires and explosions if air is allowed to contact it. These are just a few of the precautions which must be coped with in the refining of titanium. (See flow chart on p. 344.)

The ingots thus produced, if clean and free of any scale, are a silvery-gray color. The physical characteristics of the commercially pure metal as compared with 18-8 stainless steel and 7075 aluminum are shown in Table 29.

Titanium, like some other elements, can exist in two crystal forms. Pure titanium at room temperature and up to 1625°F. exists in the hexagonal close-packed crystal form; above 1625°F. titanium immediately transforms into a body-centered cubic structure. When the temperature goes below 1625°F. the reverse takes place. It is this transformation which will enable the metallurgist

TABLE 29. Comparative Representative Properties of Titanium, 7075 Aluminum and Austenitic Stainless Steel

Physical Properties	*Titanium*	*7075 Aluminum*	18-8 *Austenitic stainless steel*
Atomic Number	22	(13)	(26)
Atomic Weight	47.9	(26.97)	(55.84)
Crystal Structure	Alpha—H.C.P. (below 1625°F.) Beta–B.C.C. (above 1625°F.)	F.C.C.	F.C.C.
Transformation	1625°F.	None	None
Density	4.5 gm. per c.c.	2.80 gm. per c.c.	7.92 gm. per c.c.
Melting Point	3272°F.	1220°F.	2795°F.
Linear Coefficient of Thermal Expansion	4.3 X 10^{-6}/°F.	12.7 X 10^{-6}/°F.	9.5 X 10^{-6}°F.
Specific Heat	0.129 Cal./gm./°C.	0.23 Cal./gm./°C	0.12 Cal./gm./°C
Electrical Conductivity	3.5% I.A.C.S.*	35% I.A.C.S.	2.5% I.A.C.S.
Magnetic	Para	Para	Para (annealed)
Electrode Potential	1.75	(1.67)	(0.44)

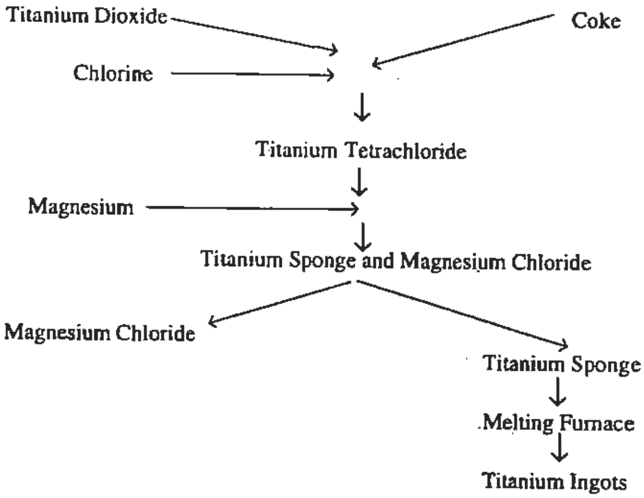
( ) indicated pure metal.

Although the winning of titanium is very difficult, rapid strides are being made daily in overcoming manufacturing difficulties.

* I.A.C.S.—International Annealed Copper Standard.

to devise various titanium alloy systems and be able to control ductility and strength by the proper heat treatments. By the addition of the proper alloying elements, it is possible to raise or lower the transformation point in the titanium alloy system. Such elements as columbium, vanadium, molybdenum, and tantalum can lower the transformation point to below room temperature. In certain percentage ranges, these four alloys can cause a transformation range in which both the hexagonal close-packed and body-centered cubic-crystal systems occur together. Elements such as aluminum, carbon, oxygen, and nitrogen have the ability to raise the transformation temperature above 1625°F. These additives show future promise for excellent high-temperature titanium alloys.

In the following discussion the name Alpha titanium will be used when the crystal structure is hexagonal close-packed, and Beta titanium will be used when the crystal structure is body-centered cubic. It is possible to have all Alpha or all Beta or a combination of the two depending upon the alloying elements.



Flow Chart for the Manufacture of Titanium

A simplified phase diagram might better help the reader understand the constitutional diagram of titanium alloys (see Figure 66).

The advantages and disadvantages of the different titanium alloys are shown by the table on the next page.

Titanium alloy substitution for aluminum alloy or steel fittings indicates that weight savings of up to 20% can result. The same situation exists for bolts since tests have indicated that titanium alloy bolts having a tensile strength of approximately 150,000 p.s.i. can be directly substituted for NAS (high heat-treat) bolts for shear applications and these same bolts may be substituted for AN bolts if tension is a factor. Titanium alloy sheet is not as efficiently substituted

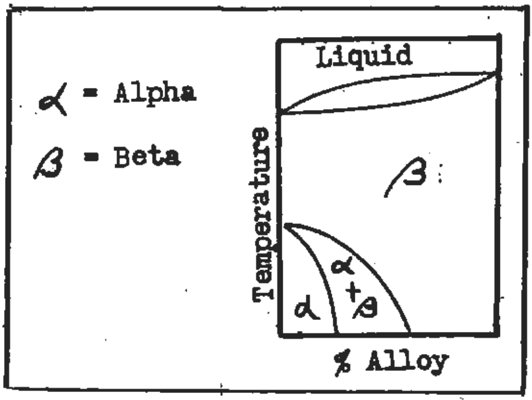


FIGURE 66. Simplified Phase Diagram for Titanium

Advantages and Disadvantages of Different Titanium Alloys

Advantages	Disadvantages
All-Alpha	
Useful strength to almost 1200°F. Resistant to air contamination to 2000°F., permitting higher forging temperature. No embrittling heat treatment response. Weld ductility and strength comparable to that of base metal. Tough at low temperatures.	Sheet bend ductility not as good as alpha-beta alloys, considerably poorer than beta alloys. Requires more power than alpha-beta alloys for hot working.
Combined Alpha-Beta	
Double the strength of unalloyed titanium and about as strong below 600°F. as all-alpha and all-beta. Good ductility, including bend. Forging, rolling and forming easier than alpha and beta alloys (beta has better bend ductility). Relatively simple to produce in quality. Heat-treatable to high strengths.	Has heat treatment response that results in loss of ductility, if not controlled. Poorer weld ductility than alpha. Temperature ceiling for useful strength about 800°F.
Heat Treatable Beta	
Quenchable to give medium strength with high ductility. Can be heat-treated to higher strength (with some loss in ductility) after little fabrication. Elevated-temperature properties similar to alpha-beta alloys.	Embrittled by 24 to 96 hr. at 350 to 800°F. Control of composition critical. Restricted to parts that can be heat-treated after fabrication or require little forming after heat-treating. Requires relatively high content of strategic alloying materials.
Non-Heat Treatable Beta	
Excellent ductility, particularly bend. High strength useful to approx. 1000°F. Does not require heat treatment for high strength. No heat-treatment response. Good weldability with some compositions.	Greater springback in forming. Uses higher content of strategic alloying materials than unstable beta. Relatively high density.

for aluminum alloy because of compressive buckling considerations. As soon as any part of the airplane structure becomes heated, either aerodynamically or by engine radiation, titanium sheet shows excellent potentialities especially if the temperature exceeds 300°F. for this temperature starts to seriously impair the properties of the high-strength aluminum alloys. An excellent example of how weight can be saved at moderately elevated temperatures is the use of commercially pure titanium sheet on a large commercial transport. The use of titanium on the engine nacelles of this airplane saved over 250 pounds. The titanium was substituted (gage for gage) for 18-8 type stainless steel. The nacelles were manufactured from sheet material ranging in thicknesses from .016" to .050" and lengths up to 120".

The nacelle skin is stretch-formed at room temperature. The ribs and stringers are shaped to cross-section by brake or roll forming, then stretch-formed to longitudinal curvature. Both spot welding and riveting are employed in assembly. Dimpling operations required to accommodate flush fitting flat-headed rivets are performed hot (approximately 575°F.).

It should be mentioned here that the hexagonal close-packed structure of Alpha titanium may be cold-worked better and more uniformly by very slow, rather than by rapid, deformation. Ductility as measured by the conventional methods is sometimes misleading when applied to stretch forming. This is due to the necking down during a tensile test. About half of the elongation as determined by a standard tensile test is uniform elongation. In room-temperature forming the narrow spread between yield strength and ultimate strength requires that close control be exercised over cold forming operations.

Many of the sheet alloys available today have to be hot-formed. This characteristic is a definite disadvantage, since forming procedure is complicated when heated dies and heated material are necessary.

Titanium alloys can be readily forged, providing a few simple rules are used in the design of the part. The designer should allow larger radii than steel parts and a larger draft angle. These precautions are necessary because titanium alloys are much more resistant to deformation than steel. Use of existing steel dies might be possible if the design is simple and sufficiently overstrength. Shrinkage allowances for titanium are also different from other metals.

Currently, there is a large number of titanium alloys under development, but only a few have been developed sufficiently for use in airframe parts. Of these, the alloys now available are shown in Table 30.

The raw forging stock for a titanium forging must be very clean and free from scale. Titanium will pick up any die imperfections and scale can easily be driven into the finished part. The forge shop has several basic rules to follow when working with titanium alloys. Forging temperatures are such

TABLE 30. The Chemistry of Titanium Alloys

Designation	Producer	Ti	Al	Cr	Fe	Mn	V	Mo	W
Ti-55A	Titanium Metals	Bal.	—	—	.10	—	—	—	.02 max.
Ti-75A	Titanium Metals	"	—	—	.10	—	—	—	.02 max.
A55	Rem-Cru	"	—	—	—	—			
MST-Grade III (L2851)	Mallory-Sharon	"	—	—	—				
A 70	Rem-Cru								
MST-Grade IV (L2749)	Mallory-Sharon								
Ti-100A	Titanium Metals	"	—	—	0.1	—	—	—	.02 max.
MST-2Al-2Fe (L2852)	Mallory-Sharon	"	2.0	—	2.0	—	—	—	—
C-130 AM	Rem-Cru	"	4.0	—	—	4.0	—	—	—
MST-3Al-5Cr (L2748)	Mallory-Sharon	"	3.0	5	—	—	—	—	—
Ti-140A	Titanium Metals	"	—	2	2	—	—	2.0	2.0
Ti-150A	Titanium Metals	"	—	2.4-3.1	1.2–1.8	—	—	—	.02 max.
Ti-155 AX	Titanium Metals	"	4.75/ 6.00	.8/2.0	.90-1.70	—	—	.8/2.0	—
Ti-175A	Titanium Metals	"	—	3.0	1.5	—	—	—	.02 max.
Ti-150B	Titanium Metals	"	—	5.0	5.0	—	—	5.0	.02 max.
MST-2.5Fe-2.5V (L2841)	Mallory-Sharon	"	—	—	2.5	—	2.5	—	
C-110M	Rem-Cru	"	—	—	—	8.0	—	—	—
A-110 AT	Rem-Cru	92.5	5	—	—	—	—	—	(2.5 S.)
RS 40	Republic	99.5	—	—	—	—	—	—	—
RS 55	"	99.5	—	—	—	—	—	—	—
RS 70	"	99.5	—	—	—	—	—	—	—
RS 110	"	Bal.	—	3.5	2.0	—	—	—	—
RS 120	"	Bal.	—	—	—	7.0	—	—	—

These are nominal analyses.

that grain growth is encountered and thus the forger must perform his task as rapidly as possible and also the forger should continue to work the metal down to relatively cool temperatures in order to prevent any re-heating treatment. The correct reductions are necessary in order to break up any large grains which come about owing to the elevated forging temperature. This phase of forging is very important, since titanium alloys do not experience any grain refinement upon subsequent heat treatment. When pre-heating a forging billet it is necessary to heat slowly, up to 1300°F., then heat rapidly to the forging temperature (ranging from 1300–1800°F.). If these recommendations are followed, a minimum of scale results.

Specifications are currently being written for several titanium alloys. Specifications released to date are shown below:

MIL-T-9047B. This specification covers:
1. Unalloyed titanium bars and forgings:
2. 3 aluminum, 5 chromium alloy bars and forgings.
3. 2 iron, 2 chromium, 2 molybdenum bars and forgings.
4. 6 aluminum, 4 vanadium bars and forgings.
5. 4 aluminum, 4 manganese bars and forgings.
MIL-T-9046A. This specification covers titanium alloy sheet material.
MIL-T-7993 covers unalloyed titanium sheet material.

Table 31 lists the average properties obtainable from the various grades.

Typical elevated temperature properties of several presently produced high-strength titanium alloys are given in Table 32.

Much progress has been made during the past few years in the forging of titanium and titanium alloys. The improvements came about by the controlling of several variables in forging stock quality and forging technique. The scatter has been greatly reduced and the service problems have been reduced in a marked degree.

TABLE 31. Mechanical Properties of Titanium Alloys

Alloy	Condition	Ultimate	2% Offset	Elong	R. A.	Hardness
Ti-55A	annealed	65,000	48,000	26.5	—	80 Rb
Ti-75A	annealed	80,000	60,000	25.0	—	190 BHN
A-55	annealed	75,000	65,000	15.0	20.0	50-54 RA
A-70	as forged	90,000	80,000	20.0	50.0	54-58 RA
MST-III	as forged	80,000	72,000	25.0	55.0	62 Ra
MST-IV	as forged	80,000	75,000	18.0	50.0	61 Ra
Ti-100 A	annealed	102,000	88,000	20.0	—	252 BHN
MST-2Al-2Fe	as forged	145,000	135,000	12.0	35.0	68 Ra
C-130-AM	as forged	150,000	130,000	15.0	30.0	33.36 Rc
MST-3Al-5Cr	as forged	165,000	153,000	8.0	25.0	71 Ra
Ti-150 A	annealed	150,000	120,000	15.0	—	341 BHN
Ti-150 B	annealed	160,000	135,000	10.0	—	322 BHN
Ti-175 A	annealed	170,000	140,000	10.0	—	379 BHN
MST-2.5Fe-2.5V	as forged	130,000	105,000	12.0	35.0	65Ra

TABLE 32. Elevated Temperature Properties of Titanium Alloys

Alloy	Temperature	Ultimate	.2% Yield	Elong.	R.A.
Ti-150 A	200°F.	135,000	108,000	28.0	—
C-130 AM	"	134,000	124,000	15.0	—
MST-3Al-5Cr	"	163,000	147,000	12.0	30.0
Ti-150 A	400°F.	108,000	76,000	36.0	—
C-130 AM	"	121,000	108,000	12.0	—
MST-3Al-5Cr	"	144,000	120,000	12.0	38.0
Ti-150 A	600°F.	90,000	64,000	28.0	—
C-130 AM	"	110,000	94,000	13.0	—
MST-3Al-5Cr	"	136,000	108,000	12.0	40.0
Ti-150 A	800°F.	76,000	55,000	23.0	—
C-130 AM	"	94,000	76,000	18.0	—
MST-3Al-5Cr	"	124,000	92,000	16.0	44.0
Ti-150 A	1000°F.	43,000	36,000	58.0	—
C 130 AM	"	65,000	40,000	33.0	—
MST-3Al-5Cr	"	84,000	60,000	24.0	68.0

Titanium scale is a troublesome item since the scale is very difficult to remove owing to its hardness. If chemical removal is attempted, careful control of the pickling bath is absolutely necessary.

The heating equipment used when treating the titanium for hot forming should be very clean and so constructed that no flame plays directly on the work. In order to minimize the possibility of hydrogen pick-up, a slightly oxidizing atmosphere is recommended.

After a part has been successfully forged, it should be stress-relieved or annealed. The commercially pure grades of titanium should be annealed at a temperature of approximately 1300°F. for a time, depending upon the thickness. This treatment will result in a forging possessing good ductility.

The alloy grades can be given several types of thermal treatment depending on the strength and ductility required in the end product.

Many surface treatments have been given to titanium and titanium alloys in an attempt to overcome the characteristics of the metal to gall and seize when subjected to pressure contact with itself and other metals. Successful treatments indicate that nitriding, carburizing, and carbo-nitriding, are feasible. These treatments are undergoing exhaustive tests to determine which process is superior.

All of the conventional welding methods have been attempted on titanium and its alloys. In any case, it is necessary to have a clean surface and if any prolonged melting occurs, the presence of oxygen, nitrogen, or water vapor will cause brittle and unsatisfactory welds.

FIGURE 67. Titanium Alloy Forging—Arresting Hook Shank

Spot welding is used extensively on commercially pure titanium and several of the commercially available sheet alloys. Since the welding characteristics of titanium and its alloys are different from steel and aluminum alloys, test samples of the same thickness, as the parts being spot-welded, should be welded in order to set up welding cycles. Welding current is approximately 50% greater than that used for steel. When welding titanium, the pressure on the electrodes is from 20–50% higher. The tension-shear ratio of titanium spot welds is approximately 0.32.

Successful flash welds have been made on several titanium alloys, but in order to assure fair ductility, inert atmosphere should be used. The burn-off length should be held to a minimum because of the possibility of the heat-affected zone becoming too large. If the heat-affected zone becomes too large, the possibility of contamination is greatly increased. Pressure welding is used successfully by several companies but when specifying this type of welding the design of the part must be such that removal of both the internal and external flash is possible.

Strengths of pressure welds are approximately equal to the strength of the parent metal.

Several years ago, many unexplained cracks occurred in formed titanium sheet parts many months after the parts were in use. Subsequent investigation indicated that embrittlement was one of the causes for this phenomenon. Hydrogen can contaminate titanium in several ways such as:

1. Introduction during sponge production.
2. During hot working of the ingot.
3. During heating.
4. During descaling.
5. During pickling.

The effects of hydrogen are most prevalent when very slow strain rates are applied (0.02 inch per inch per minute). The reduction in area and elongation are seriously impaired if appreciable hydrogen is present in the metal. Alpha type titanium alloys are not as hydrogen-sensitive as other types but it is advisable to specify a maximum allowable hydrogen content when purchasing the raw material. The hydrogen content is specified in parts per million. The tolerable amount might range from 125 parts per million down to 15 parts per million, depending upon the application and use. Hydrogen embrittlement has little effect at elevated temperature. It is most severe around room temperature. There are many factors which affect the tolerable level of hydrogen in titanium alloys such as variances in chemistry and poor structure. Aluminum tends to raise the hydrogen tolerance and the effects of oxygen and nitrogen tend to be additive with hydrogen.

It is believed that some type of hydrogen embrittlement comes about due to microsegregation of titanium hydride in the metal and these hydrides propagate and initiate cracks. This process requires time to take place and therefore is not as prevalent when fast strain rates prevail.

At high temperatures, different types of embrittlement seem to occur. One is the type of embrittlement caused by the retention of meta-stable beta phase. Another type occurs when beta phase transforms to alpha.

Various methods to determine hydrogen in titanium alloy are as follows:

1. *Vacuum fusion*. The combining of all gases in a molten metal with oxygen and the ensuing analysis of the quantity of all the gases.
2. *Vacuum fusion*. Done at a lower temperature than in #1 and all the gases that are removed are assumed to be hydrogen.
3. *Vacuum extraction*. Gases extracted at a lower temperature (1050°C.) in a vacuum. The gases are measured and assumed to be hydrogen.
4. *Equilibrium pressure*. Hydrogen is assumed to be an ideal gas. The specimen is raised to temperature and the gaseous pressure is linear to the logarithm of hydrogen pressure in the titanium.
5. *Macro-combustion*. Small chips are used and ignited. The amount of water collected is proportional to hydrogen in the titanium. Generally, analysis reads low, possibly due to the loss of hydrogen during machining.
6. *Micro-combustion*. Standard organic chemical equipment is used.

Most titanium producing companies have made great strides in the reduction of hydrogen in their products. Steps for better products include:

1. Use of low-hydrogen sponge.
2. Vacuum melting.
3. Close control of any heating operations.
4. Use of oxidizing atmospheres.

Descaling and Pickling. As previously described in this chapter, the scaling of titanium is a serious problem. Removal of the scale by machining is very difficult and expensive. Scale removal by chemical methods is practical but must be closely controlled or serious embrittlement of the titanium alloy parts can result. Scale is formed on titanium alloys as soon as the temperature of approximately 600°F. is reached and if temperatures of 1700°F. are used for fabrication, scale can be formed having thicknesses in excess of 0.003 in. depending, of course, on the atmosphere, time at a particular temperature, and other factors.

Table 33 attempts to describe scale thickness and appearance.

The pickling procedure used on light scale is not a complicated one if the acid concentrations are closely controlled. If acid concentrations are loosely controlled, hydrogen embrittlement problems will show up and excessive metal etching will result. A widely used pickling solution is 20% HNO_3 plus 2% hydrofluoric by weight. The bath is heated to 150°F. and immersion time will vary depending upon scale thickness (1–3 minutes is average). Heavy scale can be removed by a molten, sodium-hydride salt bath with subsequent acid pickling but, here again, the temperatures and bath control must be closely controlled. The use of abrasive cleaning is finding wide use; liquid honing gives an excellent finish on descaled titanium forgings.

Violent unexplained reactions have been recorded when alloy titanium has been immersed in fuming nitric acid.

Casting. Titanium and its alloys have been successfully cast using modifications of standard techniques. The use of split molds has produced castings of excellent surface finish, a high degree of soundness, and good mechanical properties. Owing to titanium's affinity for oxygen, nitrogen, and carbon, it is necessary to melt under a vacuum or in the presence of an inert gas. Since molten titanium attacks any crucible which has been tried to date, melting is carried out in a shell of solid titanium which in turn is inside of a graphite crucible. Power for melting is supplied by a D.C. welding generator. Molds are given a special refractory slurry to prevent carbon pick-up. Patterns for split mold castings are made by conventional methods using a shrinkage

TABLE 33. Titanium Scale Characteristics

Temp. °F	Appearance of Scale	Thickness
650	Straw color	Superficial
800	Purple color	"
1050	Dark purple	"
1200	Dull dark purple	0.00015
1300	Light greenish-gray deposit	0.00025
1400	Heavy yellow surface with reddish brown spots	0.0003
1500	Heavy yellow with more reddish brown spots	0.001
1600	Solid heavy gray deposit	0.001
1700	Very heavy gray deposit	0.0016–0.003

factor of about 1/8 inch per foot. The method of casting described is covered in a patent application by the National Research Corporation.

Machining. The machining of titanium and its alloys at first makes the machine shop very cautious but as experience is gained using different rake angles, cutting speeds, setups and lubricants, the problem is not so difficult. Turning operations compare favorably with 18-8 stainless providing carbide cutters are used and skin contamination is not excessive. Milling presents some problems due to the welding of the titanium chip to the cutter. A climb cut is recommended for slab milling. The work should be positioned so that the start of the cut has the largest bite and as the cut progresses the bite becomes smaller; in this setup the welded chip is at a minimum. Drilling operations are made easier by

1. Using as short a drill as possible.
2. Using a coolant.
3. Keeping feed approximately 0.005 in. per revolution and RPM approximately 500.
4. Keeping a point of approximately 90° on large drill sizes.

Tapping is difficult but if the following recommendations are followed, successfully tapped holes should result with a minimum of trouble.

1. Use slow tapping speed.
2. Use the largest possible tap drill.
3. Use active cutting fluids.
4. Relieve all taps.

Saw cutting is very difficult on titanium since blade life is very short but if slow speeds are used and a positive feed with a light friction feed, results are satisfactory.

In conclusion it can be stated that the future of titanium and its alloys is unlimited. Airframe manufacturers are gaining experience daily, the producers are working very hard on uniformity, reliability, cost reduction and better elevated temperature properties. A major problem of very low scrap value (only approximately 1/50th of sheet price) is on its way to being solved and it will not be long before large portions of airframes are made almost entirely of titanium alloys.

CHAPTER XXII

HIGH TEMPERATURE PROBLEMS

BEFORE the problems associated with high temperatures are mentioned in detail, it might be well to list several of the terms used by designers of high temperature equipment:

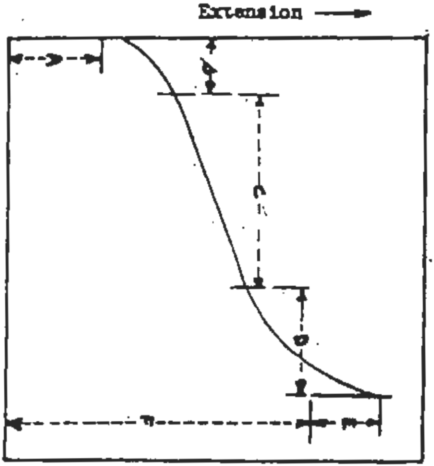
Creep. The continuous deformation of a metal under stress. A continuing change at constant stress in the deformation or deflection of a stressed member. It is generally associated with a time rate of deformation continuing under stress intensities well within the yield point, the proportional limit, or the apparent elastic limit, for a given temperature.

Creep Limit. The maximum stress that will cause creep to occur at less than a predetermined maximum rate.

Creep Strength. The unit stress that causes a specified amount of plastic deformation in a given time at a stated temperature. It is usually expressed as the stress that will produce 0.10% elongation in 10,000 hours at a given temperature.

A typical curve is shown in Figure 68. When a load is applied, an immediate elastic extension (*A*) occurs. Then the specimen gradually stretches at a decreasing rate. This is called first stage creep (*B*). The rate then becomes constant for a certain period of time. This is called second stage creep (*C*). The rate of creep increases in the third stage (*D*) until the specimen fails.

The standard creep strengths in common use are, 1. the stress producing a creep rate of 0.0001% per hour expressed as 1% in 10,000 hours or, 2. the stress for a creep rate of 0.00001% per hour or 1% in 100,000 hours.



A Elastic extension;
B creep at decreasing rate;
C creep at approximately constant rate;
D creep at increasing rate;
E elastic contractions;
F permanent change of shape

FIGURE 68. Schematic Creep Curve—Extension Plotted Against Elapsed Time

Stress Rupture. This expression usually is associated with the last stages of the creep test. In reporting stress rupture data, the applied stress is usually plotted against the time for failure. Stress rupture values are generally reported as the stress for fracture in 10, 100, 1,000, 10,000, or 100,000 hours.

Short Time Tensile Values. These values are obtained by applying heat to the specimen during standard type tensile tests. As a general rule, the strength of metal decreases with increasing temperature, so short-time tensile values are usually lower than standard room temperature tensile test values.

With each new design of a fighter type aircraft and transport type aircraft, more emphasis is put on high temperature problems. Most structural adhesives lose much of their strength at temperatures over 200°F. Structural plastic laminates of the phenolic type do not lose their strength as rapidly as other similar materials but the aluminum alloys 7075 and 2024, which are the most widely used, decrease in strength very quickly above 300°F. (See Figure 69.)

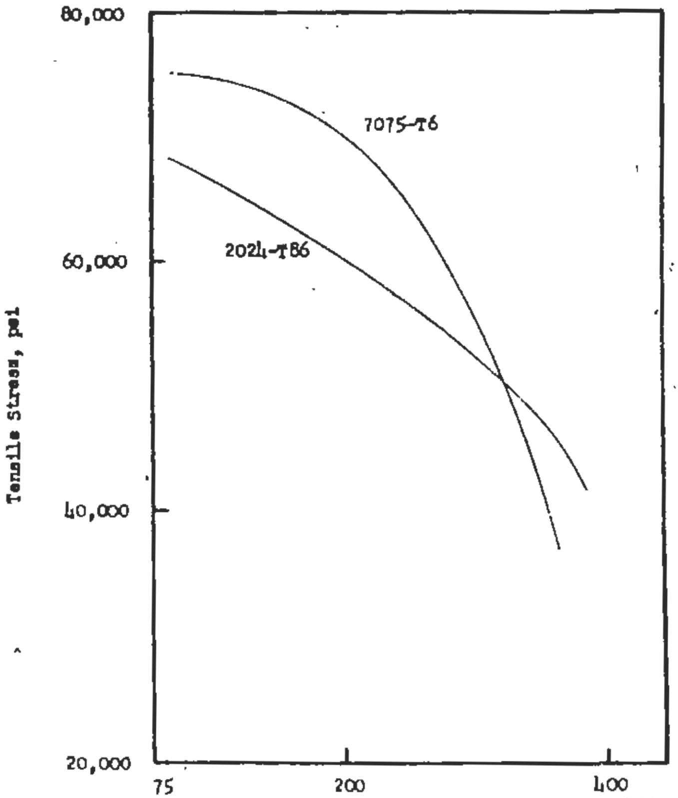


FIGURE 69. Tensile Strength vs. Temperature for 7075-T6 and 2024-T86 Aluminum Alloys

Heat in a supersonic airframe comes from several sources. Engine heating is one source which is handled by shrouds and insulating blankets. In jet aircraft, using cooling air between the tail pipe and the aluminum alloy structure, the airplane usually suffers operational losses which can he equivalent to a 5% power loss. This loss is due to added drag. Engine exhaust heating is another source of heat which causes trouble, usually in the aft section. This type of heating requires heat resisting materials to be in the tail structure.

Aerodynamic heating causes trouble over the entire airframe, although the problem is aggravated at areas where direct air impingement is most concentrated (leading edges, nose, canopy, etc.). The aerodynamic heat problem is being combated by the use of high-temperature materials. Figure 70 shows a curve of "Mach Number vs. Temperatures."

The term thermal barrier is appearing in many printed articles. This term is usually applied to the high temperatures met by aircraft above Mach 2, twice the velocity of sound. Serious problems are showing up in discussions concerned with aerodynamic heating. At Mach 5, aluminum melts; at Mach 6, steel melts. When Douglas designed the X-3, it was necessary to use 2024

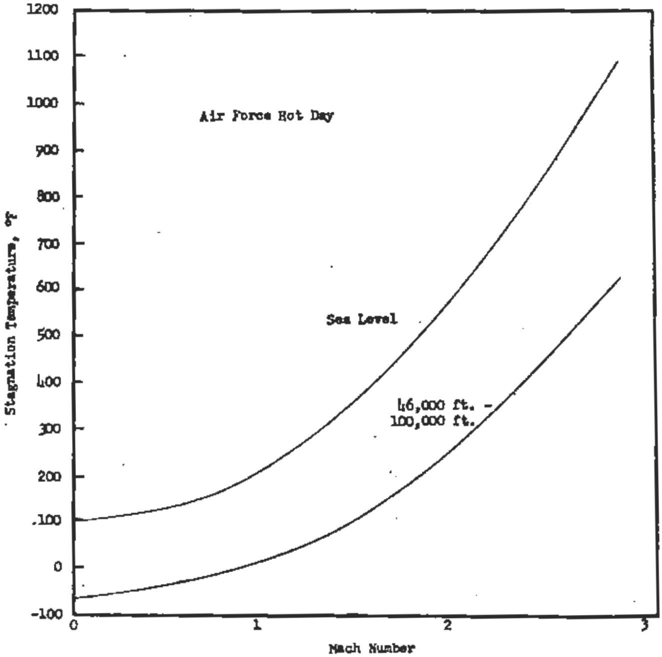


FIGURE 70. Aerodynamic Heating

aluminum alloy rather than the higher-strength 7075, since 7075 loses strength very rapidly over 300°F. (See Figure 69.)

An optimistic point about aerodynamic heating is the fact that skins are fairly thick, so that the temperature gradients are appreciable; therefore, the substructure may not be as critical as the surface of the airplane. Since the airplane will be at its maximum speed for only short times (because of fuel consumption), problems associated with the substructure are not so serious; with long-range bombers, this might not be the case.

Heat generated by the several sources mentioned previously must be dissipated or accounted for in design. The cooling system is the mechanism by which the heat, generated by several factors, is carried to the sink. The sink is the final receiver of the heat and might be: 1. ram air, 2. the fuel of the airplane, since fuel has an excellent thermal capacity to absorb large quantities of heat, or 3. some type of material which can be carried in the airplane specifically for the purpose of absorbing heat. A list of storage sinks and several properties are listed in Table 34.

It is evident that water is an excellent heat sink but if the fuel can be used effectively, the weight penalty can be greatly reduced.

Recent work by the Socony Mobil Oil Company has developed a hydrocracking process which produces a jet fuel, with improved characteristics over present fuels. This new fuel, which is similar to JP-5, has excellent high-temperature stability characteristics and should be suitable for carrying off heat from engine lubricating oil and other sources. Up to the present time the effective use of conventional jet fuels for this purpose has been limited by the instability of the fuel at high temperatures. Gum and sediments formed in

TABLE 34. Heat Storage Sinks

Material	Specific Heat BTU/lb./°F.	Heat of Vaporization, SL BTU/lb.	Boiling Sea Level	Point °F. 60,000 ft.	Freezing Point °F.	Density lb./cu. ft.
Water	1.0	970	212	103	32	62
AN-F-28 Fuel	0.5	120*	100*	0*	***	45
		160	375	275		
Jp-4 Fuel	0.5	95*	225*	50*	***	49
		140	525	350		
Methyl Alcohol	0.6	480	150	50	***	50
Dry Ice (solid)		248**	−110	−150	***	98
Oxygen (liquid)	0.4	92	−298	−340	***	71
Ammonia (liquid)	1.1	590	−28	−140	***	43
Freon 12	0.2	70	−22	−112	***	84

* Fractional distillation range ** Sublimitation *** Less than −65

unstable fuels can plug engine filters and nozzles, causing engine operating difficulties.

When there is the possibility that high temperature problems will exist in a new design, the selection of material should be considered by using or investigating the following points:

1. *Temperature and Stress.* These values are determined by several factors including weight limitations, strength requirements, proximity to a heat source, etc.

2. *Expected Service Life.* This length of time is usually predicated on such considerations as type of airplane, type of missions, range, fatigue considerations, etc.

3. *Permissible Deformation.* This factor depends on clearances, aerodynamics, etc.

4. *Corrosion and Oxidation.* Corrosion has always been an important consideration for airframe producers, especially if aircraft carrier operations are considered. Corrosion rates and oxidation rates increase with increasing temperatures.

5. *Uniformity of Temperature.* This consideration is very important since it might be very easy to over-design a part or structure if the peak-short time temperatures are used for design values. Some temperature surges occur for very short periods of time and if these high points are thoroughly investigated, a much higher design stress might be used.

6. *Frequency of Inspection and Overhaul.* This consideration is very important since more spread is permissible if questionable areas can be inspected frequently. Such service problems as corrosion, deformation, and material defects can thus be easily detected.

7. *Cost.* This consideration is of prime importance. High cost of raw material, in itself, usually implies that either a material is scarce, hard to refine, or must come from outside the continental United States. Cost of processing is also very important since this factor implies that difficulty is encountered when machining, plating, forming, or installing the material.

8. *Availability.* This factor can cause serious difficulty if the alloys selected to do a certain job are not available in the event of war. Materials containing high percentages of nickel, chromium, cobalt, and molybdenum should be avoided wherever possible since these elements are needed in large quantities for such applications as jet engine parts and specialized manufacturing processes.

If conditions exist where direct flame impingement occurs on a metal structure, the possibility of using ceramic coating should be considered.

Ceramic coatings have refined designs in the past by:

1. Allowing thinner gage material to be used.
2. Reducing warpage, cracking, and buckling by decreasing hot spots.
3. Increasing strength and stiffness by lowering effective operating temperature.
4. Protecting the base metal from erosion by high-velocity gases.
5. Protecting the base metal from corrosion.
6. Eliminating surface stress raisers, thus increasing fatigue life.

The selection of a ceramic coating should be made considering the following points:

1. It must adhere well to the base metal.
2. It must have good thermal shock resistance.
3. It must be chemically stable and have coefficient of thermal expansion close to that of the base metal.
4. It must have resistance to vibration, abrasion, impact, and must be easily applied.

Strength will not be the only criterion of material acceptance for elevated temperature application in supersonic aircraft. Emissivity will be one important consideration. *Emissivity* is the expression used to define the ability of a surface to emit radiant heat. The emissivity of a surface is the ratio of radiation from a certain surface compared with the radiation from a black body under the same conditions of wavelength and temperature. A good heat-absorbing surface is at the same time a good emitter of heat energy.

Thermal conductivity will be very important in future designs. *Thermal Conductivity* is the heat conducting power of a uniform or homogeneous material per unit of cross-sectional area, usually measured in BTU per hour per square foot per degree F. for 1 inch of thickness. This characteristic of a material, along with its thermal coefficient of expansion, is a very important design consideration. It is feasible that if the known properties of materials are not intelligently applied, to a design which will be subjected to a high temperature, the airframe could fail from buckling and distortion from heat alone. Several factors are present which can slow up the deleterious effects of high temperatures. It is possible to obtain benefits of creep recovery while a portion of the airframe is resting between applications of high "G" loading and some materials increase in ductility with increasing time at temperature.

Facilities are being designed to allow the elevated temperature testing of complete airframes. Tremendous quantities of electrical power will be necessary for tests of this type in order to duplicate the thermal shock to which an airframe will be subjected. The use of a large sun furnace might help this particular problem since temperatures from sun furnaces exceed 5,000°F. Heat from sun furnaces can heat large masses very rapidly.

The structure of the airplane is not the only portion which is affected by heating. Pumps, lines, fittings, actuators, electrical equipment, canopy material, guns, ammunition and special weapons are also affected and must be properly designed to prevent failure by overheating.

Many individual high temperature tests have been performed on a material which can be used effectively at elevated temperatures. The many alloys available for use at high temperatures can generally be classified into three categories:

1. Wrought alloys possessing good high temperature properties, which are obtained by strain hardening. These alloys usually have an austenitic type structure.
2. Heat-treatable wrought alloys, which obtain good high temperature strength by alloy content and heat treatment.
3. Cast alloys—many alloys which have excellent high-temperature properties are difficult to forge, etc. These cast alloys might be of the austenitic type or might also be heat-treatable.

For reasons of clarity, general alloys which can be used for elevated temperature service are listed below:

A-286. This was developed in order to supply an alloy which has good notch rupture strength, as well as having good properties, up to approximately 1300°F. A-286 is used for jet engine parts, supercharger parts, afterburner attachment fittings and high temperature bolting. This particular alloy can be strengthened by heat treatment.

This alloy is easily handled in the shop, using speeds and general rules as for stainless steel. It is recommended that, if excessive machining is necessary on a part, the full heat treatment (consisting of a solution heat treatment at 1800°F. for one hour, oil quenching, and aging at 1325°F. for 16 hours) should be used. A-286 poses no welding problems if the shielded-arc or inert gas-arc methods are used. For best results, the material should be in the solution heat-treated condition during welding operations.

A-286 is covered by specification AMS-5735—Bars and Forgings.

Physical constants are as follows:

Specific gravity—7.94 gm./c.c.
Density—.286 lb./cu.in.

Coefficient of Thermal Expansion (in./in./°F./10^{-6})

Temp. from 70° to	Coefficient X 10^{-6}
600°F.	9.47
800°F.	9.64
1000°F.	9.78
1200°F.	9.88
1400°F.	10.32

Chemical Composition

	Specification Range	*Typical*
Carbon	0.08 max.	0.045
Manganese	1.00–2.00	1.35
Silicon	0.40–1.00	0.95
Chromium	13.50-16.00	15.52

Nickel	24.00–28.00	26.06
Molybdenum	1.00–1.50	1.25
Titanium	1.75–2.25	1.95
Vanadium	0.10–0.50	0.32
Aluminum	0.35 max	0.20
Iron	balance	balance
Sulfur	0.04 max	0.018
Phosphorus	0.04	0.021

Elevated temperature properties for A-286 are shown below:

ALLOY A-286

Test Temp.	Yield Strength 0.2% Offset p.s.i. Short Time Tests	Tensile Strength p.s.i. Short Time Tests	% Elongation in 2" Short Time Tests	Stress for Minimum Creep Rate of 1% in 10,000 hrs.	Stress for Rupture in 1,000 hrs.
Room	104,500	144,500	23		
600	94,000	138,000	21		
700	93,500	137,500	21		
800	93,000	138,000	18.5		
900	91,000	135,500	18.5		
1000	87,500	131,000	18.5	85,000	88,000
1100	90,000	122,000	15	74,000	71,000
1200	88,000	103,500	13	25,000	45,000
1300		86,500	11		29,000
1400		64,000	18.5		16,000
1500		36,500	68.5		7,500

Special Heat Treatment—Solution treated 1800°F. 1 hour, oil quenched. Aged 1325°F., 16 hours; air cooled.

4340. The aircraft industry uses large quantities of 4340 for structural parts. Recent tests have indicated that this steel should be good for elevated temperature applications up to approximately 700°F. The properties and heat treatment of 4340 are well covered in other chapters of this book so no details will be given here. 4340 is available in bars, forgings, extrusions, plate, and special mill forms. Sheet 4340 is not available. The elevated temperature strengths of 4340 are given in the table below.

Haynes Alloy No. 25. This elevated temperature material was originally designated as L-605, for development purposes. This material has good elevated temperature properties and has found wide use in missile airframe

ALLOY S.A.E. 4340

Heat-treated to 220,000 p.s.i.

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for Minimum Creep Rate of 1% in 1,000 hrs.	Stress for Rupture in 1,000 hrs.
70	196,000	214,000	10	—	—
200	187,000	214,000	11	—	—
300	180,000	210,000	11	—	—
400	173,000	205,000	12	—	—
500	166,000	200,000	15	—	—
600	156,000	186,000	16	—	—
700	145,500	166,000	16	121,000	127,000
820	130,000	142,000	16	—	—

HAYNES ALLOY NO. 25

Temperature °F.	Yield Strength p.s.i.	Ultimate Strength p.s.i.	% Elongation in 2 in.
Room	70,000	155,000	55
600		118,000	77
800		112,000	72
1000		100,000	68
1100		97,000	53
1200	39,400	74,000	25
1350		54,000	13
1500	35,000	50,000	15
1650		33,000	16
1800	21,000	22,700	16
2000		13,950	23
2100		9,000	24
2200		7,200	22
2300		5,100	18

Data from Haynes Laboratories

structure. Haynes 25 can be readily welded and is easily handled in the shop. The chemistry of this alloy is:

Carbon	0.15 max.	Silicon	1.0 max.
Chromium	19.0–21.0	Manganese	1.0–2.0
Nickel	9.0–11.0	Iron	2.0 max.
Tungsten	14.0–16.0	Cobalt	Balance

Physical properties of Haynes 25 are:

Density 9.15 grams per c.c.
Coefficient of Thermal Expansion 7.61 X 10^{-6} in./in./ °F.
(This is an average coefficient between 70°F. and 600°F.)

AM 350. This is the designation of a new stainless steel which was developed to bridge the gap between the 300 series of austenitic stainless steels and the 400 series of stainless steels. By the proper control of the alloying elements, AM 350 is able to be hardened by heat treatment. In shop fabrication, the general procedures used for annealed type 300 stainless steels should be specified. This steel work-hardens at a similar rate as the 300 series stainless steels.

AM 350 has the following nominal composition:

Carbon	0.08	Chromium	17.00
Manganese	0.60	Nickel	4.20
Silicon	0.40	Molybdenum	2.75

Physical properties of AM 350 are as follows:

Density	0.286 lb./cu./in.
Coefficient of Thermal Expansion (annealed)	9.01 in./in./°F. X 10^{-6}
Magnetic Permeability (hardened)	115

AM 350 should be considered for fabricated parts which require forming, corrosion resistance, high strength, and high temperature strength. AM 350 is available in sheet bars and forgings.

The room and elevated temperature properties are listed in the table below.

17–7 PH. This is a very useful alloy which can be used for moderately elevated temperature service. This material is a precipitation-hardening alloy. It can be easily formed in the annealed state and hardened when the part is finished. The corrosion resistance is comparable to other stainless steel. The weldability and heat distortion qualities are excellent.

17-7 PH is available in all of the standard forms, but when specifying the heat condition it should be remembered that many conditions are available. These conditions are:

Alloy AM 350

Test Temp.	Yield Strength 0.2% Offset p.s.i.		Tensile Strength p.s.i.		% Elongation in 2 in.		Stress for Rupture in 1,000 hrs.	
	SCT	DA	SCT	DA	SCT	DA	SCT	DA
Room	152,000	144,000	198,000	174,000	13.0	14.0		
400	130,970	122,675	179,300	163,350	7.5	8.5		
500	123,510	121,920	180,075	164,350	8.0	9.5		
600	129,990	125,500	181,525	165,690	8.5	11.5		
700	113,040	118,000	181,050	171,740	10.0	10.0		
800	105,085	112,400	172,830	165,600	8.5	10.5	161,000	158,000
900	99,060	97,560	149,375	143,900	6.0	12.0	99,000	92,000
1000	79,510	81,560	101,025	109,000	11.5	8.0	53,000	50,000
1200	29,230	25,670	45,240	40,350	42.0	66.0		

Special Heat Treatment

1. SCT—Sub-zero cooling and tempering. Cool to −100°F. for 2 hours, temper 750 to 900°F. for 1–2 hours.
2. DA—Double aged. Heat to 1300–1400°F. for 1–2 hours, followed by temper at 800–900°F. for 1–2 hours.

Condition A—Annealed 1950°F. ±25°F.—air cooled.

Condition C—Cold rolled.

Condition T—This condition is obtained by heating condition A material for 1½ hours at 1400°F. ±25°F. and cooling to 60°F. or lower within one hour after removal from the furnace.

Condition TH 950—Condition T material is heated 30 minutes at 950°F. ±10°F. then air cooled.

Condition TH1050—Condition T material is heated at 1050°F. ±10°F. for 1½ hours and air cooled.

Condition CH—Condition C material is heated at 900°F. ±10°F. for 1 hour and air cooled.

Conditioning C and H—These conditions exhibit high ultimate strengths but the ductilities are very low.

17-7 PH retains a good portion of its room temperature strength up to approximately 700°F. and when used up to 600°F. it is possible to use design values predicated on short-time elevated tensile values.

Chemistry of 17-7 PH

Carbon	0.09 max.	Chromium	16–18
Manganese	1.00 max.	Nickel	6.5–7.75
Phosphorus	0.04 max.	Aluminum	0.75–1.50
Sulfur	0.03 max.		

Physical Constants (Condition TH 1050)

Density	.276 lb./cu. in.
Mean Coefficient of Thermal Expansion 70–600°F.	5.9 in./in./°F. X 10^{-6}
Thermal Conductivity—at 550°F.	approximately 128 BTU/hr./sq. ft./in./°F.

Elevated temperature properties of 17-7 PH are given in the table below.

19–9 DL. This has been designed for applications requiring high strength and resistance to corrosion and oxidation at temperatures up to approximately 1300°F. This alloy is finding wide use in turbine wheels, supercharger wheels, buckets, jet frames, casings, and afterburner parts.

In most applications, 19–9 DL is given a stress relief at 1200°F. but if the alloy is to be used in an application where severe corrosive atmospheres will be encountered, the material should be annealed at 1800°F, then rapidly cooled. This treatment makes the material much less sensitive to intergranular attack. 19-9 DL can be easily fabricated in shops where stainless steel has been worked but if any severe forming is necessary on 19-9 DL sheet, the material should be annealed using the 1800°F. treatment described hereto.

Although 19-9 DL cannot be strengthened by heat treatment, certain thermal treatments are used to:

(a) make the alloy more workable (2100°F. followed by rapid cooling).
(b) stress-relieve cold-worked parts to reduce cracking (1200°F. for 1 hour, then air-cool).

ALLOY 17-7 PH SHEET
(Condition TH1050)

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for Minimum Creep Rate of 1% in 10,000 hrs.	Stress for Rupture in 1,000 hrs.
Room	151,000	180,000	11		
100	149,000	179,000	11		
200	147,000	175,000	9		
300	145,000	171,000	8		
400	142,000	167,000	7		
500	137,000	162,000	6		
600	132,000	157,000	6	145,000	158,000
700	125,000	149,000	6	135,000	122,000
800	115,000	137,000	6	50,000	90,000

Special Heat Treatment—1400°F.—90 minutes, air cooled below 60°F.
1050°F. for 90 minutes.

(c) obtain excellent creep and rupture characteristics (solution heat-treat at 2100°F., cool rapidly, then age at 1300°F. for approximately 6 hours).

19-9 DL is covered by the following specifications:

AMS	5526B	Strip
AMS	5528	Strip
AMS	5720A	Bars (up to 1.5 in. inc.)
AMS	5721	Bars (up to 1 in. inc.)
AMS	5721	Bars and forgings

Physical constants for 19-9 DL are as follows:

Specific gravity	7.93 gm./cc.
Density	0.286 lb./cu. in.
Thermal Coefficient of Expansion	(in./in./ °F. X 10^{-6})
Temp. from 70°F. to	*Coefficient X 10^{-6}*
600	9.31
800	9.59
1000	9.78
1200	9.97
1500	10.01
Modulus of Elasticity	29,000,000 p.s.i.

Elevated temperature properties of 19-9 DL sheet are shown in the chart given below.

Inconel X. This was developed in order to supply an alloy to fabricators of high temperature equipment which would retain a very high percentage of its room temperature properties at elevated temperatures. Properties in Inconel X are attained by heat treatment and, since heat treatment can be called out in several ways, care should be taken to specify the treatment which best meets

Alloy 19-9 DL
(Annealed Sheet)

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for Minimum Creep Rate of 1% in 10,000 hrs.	Stress for Rupture in 1,000 hrs.
Room	40,000	100,000	41		
200	40,000	98,000	39		
400	40,000	96,000	37		
600	39,000	90,000	29		
800	37,000	80,000	22		
1000	31,000	69,000	20		54,000
1200	22,000	50,000	20	23,000	33,000
1400	16,000	32,000	30	8,000	10,000
1600	7,000	16,000	36		

Special Heat Treatment—Annealed 1800°F., oil quenched.

the end requirements. For use above 1100°F., and when constant loading is expected, the following heat treatment should be called out:

1. 2100°F. for 2–4 hours, air cool
2. 1550°F. for 24 hours, air cool
3. 1300°F. for 20 hours, air cool

For parts subjected to temperatures below 1100°F. the following treatment should be called out:

1. Hot worked (forged, etc.)
2. 1625°F. for 24 hours, air cool
3. 1300°F. for 20 hours, air cool

This material can be annealed as follows:

1. 900–200°F. for 15–30 minutes
2. Quench in oil

Machining operations on this alloy are more difficult than most softer alloys but, as experience is gained, no major troubles exist. Welding, by most of the conventional welding procedures, produces good ductile welds. The forging temperature for this alloy is approximately 2200°F. down to 1990°F. and this range should be adhered to since forging below 1800°F. can cause forging defects and mechanical properties will suffer if below 1600°F.

Chemistry

Carbon	0.08 max.	Columbium and Tantalum	0.7–1.2
Manganese	0.3 to 1.0	Titanium	2.25–2.75
Silicon	0.5 max.	Aluminum	0.4–1.0
Sulfur	0.01 max.	Iron	5–9
Chromium	14.0–16.0	Copper	0.2 max
Nickel	70.0 min.		

Specifications

AMS 5542	Sheet
AMS 5667	Bars and forgings
AMS 5668	Bars and forgings solution and precipitation heat-treated
JAN 562	Wire

Physical Properties

Coefficient of Thermal Expansion, 100–1000°F.	8.2 in./in./°F. X 10^{-6}
Specific Heat, room to 1650°F.	0.13 BTU/lb/°F.
Density	.3 lb./cu.in.
Thermal Conductivity at 212°F.	110 BTU/sq.ft./in./hr./°F.
Modulus of Elasticity at room temperature	31,000,000

Elevated temperature properties of Inconel X are given in the table below.

Values for cold-worked stainless steels are given below but it should be noted that cold-worked stainless steels are not selected for extensive use at temperatures above 800°F. Stainless steels work-hardened to the half-hard or full-hard tempers are very difficult for the shop to handle.

ALLOY INCONEL X
(Fully heat-treated)

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for Minimum Creep Rate of 1% in 10,000 hrs.	Stress for Rupture in 1,000 hrs.
Room	92,000	162,000	24		
600	88,000	154,000	28		
800	86,000	148,000	28		
1000	84,000	140,000	22		110,000
1200	82,000	120,000	9	63,000	68,000
1500	44,000	52,000	22	18,000	18,000
1600	24,000	34,000	47		7,000
1700	9,500	15,000	106		
1800	5,500	9,000	89		

304 Stainless Steel. The basic chemistry of stainless steels is well covered earlier but will be repeated here for easy reference.

Chemical Composition	Carbon	0.08 max.	Silicon	0.75 max.
	Manganese	2.00 max.	Chromium	18.0–20.0
	Phosphorus	0.03 max.	Nickel	8.0–11.0
	Sulfur	0.03 max.		

Density	0.29 lb./cu.in.
Specific heat (32 to 212°F.)	0.12 BTU/lb./°F.
Mean coefficient of thermal expansion—(32 to 660°F.)	9.9 X 10^{-6}/F.
Thermal conductivity (at 212°F.)	112.8 BTU/hr./sq.ft./in./°F.

304 stainless steel is widely used for parts requiring good oxidation and corrosion resistance. Extended use of 304 stainless steel, in the 800–1500°F. range, causes the precipitation of intergranular carbides and makes the material susceptible to intergranular attack. When forming and handling this material in the shop, care should be taken to avoid the use of high sulfur fuels and strongly reducing atmospheres of this material. This material is annealed by heating to 1900–2000°F. and then rapidly cooled.

Elevated temperature properties are given in the table below.

Type 347 Stainless Steel. Type 347 stainless steel was developed to enable industry to have a good stainless steel for use at elevated temperatures; a stainless which would not require annealing after welding, and a stainless which can be used as a filler rod for welding other stainless steels. Columbium was added to a basic type 304 chemistry to impart freedom from intergranular corrosion. Columbium is added in quantities of 10 times the carbon content. Columbium transfers across a welding arc much better than titanium, which is another stabilizer added to prevent carbide formations (type 321). Type

304 Stainless Steel
(Annealed)

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.
Room	34,000	85,000	63
200	25,000	77,000	
300	23,000	73,000	60
400	20,000	70,000	
500	19,000	69,000	49
600	17,000	67,000	
700	16,500	66,000	46.5
800	15,000	63,000	
Half Hard			
Room	138,000	142,000	14
200	130,000	136,000	11
300	125,000	126,000	9
400	115,000	125,000	3.5
500	113,000	122,000	3.3
600	111,000	120,000	3.0
700	109,000	118,000	3.0
800	101,000	110,000	3.5
Full Hard			
Room	172,600	177,000	8
200	161,000	170,000	6.5
300	155,000	167,000	5
400	144,000	160,000	3
500	142,000	158,500	3.0
600	140,000	156,000	3.0
700	137,000	154,000	3.5
800	120,000	136,000	3.5

347 stainless steel is used for exhaust stacks, collector rings, jet engine shrouds, baffles, jet engine parts, etc.

Chemical Composition	Carbon	0.10 max.	Silicon	0.75 max.
	Manganese	2.00 max.	Chromium	17–20
	Phosphorus	0.03 max.	Nickel	9–13
	Sulfur	0.03 max.		
	Columbium 10 X carbon min., 1.00 max.			

Density	0.29 pounds per cubic inch
Specific heat (32–212°F.)	0.12 BTU/lb./°F.
Mean coefficient of thermal expansion (32–600°F.)	9.5 X 10^{-6}
Thermal conductivity (at 212°F.)	113.6 BTU/hr./sq.ft./in./°F.

Elevated temperature properties are given in the table below.

Type 347 Stainless Steel
(Annealed)

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for 1% Creep 10,000 hrs.	Stress for Rupture 1,000 hrs
Room	39,500	91,000	50		
300	34,000	74,500	47		
400	33,000	70,000			
500	32,000	69,000	41		
600	32,000	67,500			
700	32,000	67,000	35		
800	32,000	66,000			
900	31,500	64,000	35		
1000	30,000	61,000		19,600	
1300	24,000	40,000	51	8200	11,000
1500	19,500	23,000	76	2,500	4500

310 Stainless Steel. This stainless steel is a higher alloy type austenitic stainless used for extreme conditions of corrosion and oxidation.

Elevated temperature properties are given in the table below.

Relaxation stress is a term associated with high temperature bolting problems. It is customary to "torque-up" bolts sufficiently to produce a tensile stress of approximately 50,000 p.s.i. If elevated temperatures are

310 Stainless Steel

Test Temp.	Yield Strength 0.2% Offset p.s.i.	Tensile Strength p.s.i.	% Elongation in 2 in.	Stress for 1% creep 10,000 hrs.	Stress for Rupture 1,000 hrs
Room	40,000	92,000	47		
200	36,000	89,000			
300	35,000	87,500	39		
400	32,000	85,000			
500	32,000	83,500	37		
600	30,000	82,000			
700	29,000	81,000	37		
800	27,000	80,000			
900	26,500	79,500	34		
1000	23,000	76,000		18,000	32,000
1300	22,000	50,000	36	5,000	8,400
1500	19,000	32,500	42	1,000	3,500

expected in service, the bolts should be made of a material which can withstand a relatively high stress without relaxing or extending in length until the strength level is considerably lower. It is difficult to specify a bolting material which will not relax after a sufficiently long time. Special precautions should be taken in order that the bolts be re-tightened periodically to prevent "slop" in the joint.

When selecting bolting materials for elevated temperature use, thought must be given to the coefficients of expansion of the bolting material and the material making up the joint. It is usually advisable to make the bolts from material with a coefficient of thermal expansion close to the coefficient of expansion of the parts being bolted.

If the bolts are to be removed periodically, for servicing parts of the aircraft, care should be taken to coat the threads of the nuts and bolts with a high temperature anti-galling compound. The use of bolts and nuts of different materials has been successful in the past. The grinding or lapping of threads has caused seizing and galling; rough finishes have proved superior.

CHAPTER XXIII

SELECTION OF MATERIALS

The weight, strength, and reliability of materials used in aircraft construction are extremely important. All materials used must have a good strength/weight ratio in the form used, and must be thoroughly reliable to eliminate any possibility of dangerous, unexpected failures. In addition to these general properties the material selected for a definite application must have specific properties that make it suitable for the purpose. No one material is adaptable for all purposes. A particular part, member, or assembly must be studied from many viewpoints before the best material that can be used in its construction is determinable. In order to make the best choice the designer must have a thorough knowledge of the materials available. In the foregoing pages the author has attempted to describe all the materials and processes used in aircraft work in sufficient detail to enable the reader to choose the proper material for any application. In this chapter the author will enumerate the points to be considered in selecting a material. The materials used in the construction of each part of an airplane at the present time will also be given.

CONSIDERATIONS

The author has arbitrarily divided the points to be considered in selecting a material into *economic* considerations and *engineering* considerations. The engineer is apt to neglect the economic considerations, with the result that construction will be very costly because of the cost of the material itself and perhaps also because of delays incident to obtaining the required material and the reworking of jigs and tools.

Economic. The economic points that should be considered before selecting a material may be itemized as follows:

1. *Availability.* It is extremely important that any material selected for use in the construction of aircraft should be available in sufficient quantities to satisfy normal and emergency requirements. The material should also be purchasable from a reputable manufacturer who can guarantee a reasonable delivery date. This latter point is particularly important in the construction of an experimental plane when material requirements cannot be anticipated.

2. *Cost.* The cost per pound should be compared with the cost of other available materials. In making this comparison the savings resulting from a higher strength/weight ratio or better working properties must be considered.

3. *Shop Equipment Required.* The initial and maintenance cost of shop equipment required for the working of the material selected must be considered. In an established factory the possibility of using jigs and dies on hand is a factor in the choice of a material.

4. *Standardization of Materials.* It is advantageous to stock as few materials as possible. In selecting a material for a particular application the possibility of using one already on hand for other purposes should be considered.

5. *Reliability.* It is essential that the material selected be of consistent high quality. The author has known many instances where a batch of material was received that cracked when bent, or would not take the required heat treatment. The selection of a standard material manufactured by a reputable manufacturer will minimize the likelihood of obtaining a sour lot of material.

6. *Supplementary Operations Required.* In selecting a material the cost and time necessary for such operations as heat treatment, cleaning, plating, and so on, should be considered. A material that can be used in its natural state has a great advantage from a manufacturing standpoint over one that requires one or more supplementary operations.

Engineering. The engineering considerations that determine the choice of a particular material may be itemized as follows:

1. *Strength.* The material must be capable of developing the required strength within the limitations imposed by dimensions and weight. Dimensional limitations are particularly important for external members and for wing beams in shallow wings.

2. *Weight.* Weight is usually considered in conjunction with strength. The strength/weight ratio of a material is a fairly reliable indication of its adaptability for structural purposes. In some applications, such as the skin of monocoque structures, bulk is more important than strength. In this instance the material with the lightest weight for a given thickness of sheet is best. Thickness or bulk is necessary to prevent local buckling or damage because of careless handling.

3. *Corrosion.* Due to the thin sections and small safety factors used in the design of aircraft, it would be dangerous to select a material that is subject to severe corrosion under the conditions in which it is to be used. For specialized applications, such as seaplane hull construction, the most corrosion-resistant material available should be used. For other general uses an efficient protective coating should be specified if materials subject to corrosion are used.

4. *Working Properties.* The ability to form, bend, or machine the material selected to the required shape is important. After the type of material is determined, the proper temper must be chosen to facilitate the mechanical operations that are necessary for the fabrication of the fitting or part.

5. *Joining Properties.* The ability to make a structural joint by means of welding or soldering, as well as by mechanical means such as riveting or bolting, is a big help in design and fabrication. When other properties are equal, the material that can be welded has a definite advantage.

6. *Shock and Fatigue Strength.* Aircraft are subject to both shock loads and vibrational stresses. It is essential that materials used for critical parts should be resistant to these loads.

SPECIFIC MATERIAL APPLICATIONS

In the following pages the author will enumerate the various parts of an airplane and list the materials that are used at the present time in their construction. Insofar as possible, the major reasons for the choice of a particular material will also be presented. In many instances two or more materials are used for identical parts. This difference of opinion between designers may be due to local operating conditions, the price range of the airplane, or the previous experience of the designer. Many designers are progressive and adopt new materials rapidly, while others are content to lag behind and let the first type break new ground for them. It must be remembered that new developments in the near future may result in many changes in the present type of construction.

In the listing of aircraft parts, the author has taken a standard, single-engine tractor airplane and named the parts beginning with the propeller and working aft to the tail. It is hoped by this means to make the reader's task easier in spotting a particular part despite any differences in terminology between him and the author. General parts such as bolts, bushings, and so forth, are enumerated at the end.

Propeller Blades. Propeller blades are made from aluminum alloy, wood, steel, magnesium, and pressed wood.

The 2025-T6 aluminum-alloy forgings are most commonly used in this country for propeller blades of high quality. This material is light, strong, uniform, and unaffected by variations in weather. This type of blade is adaptable to adjustable, controllable, and constant-speed propellers.

In this country wooden propellers are used mostly on small commercial planes. They are lighter than metal propellers but must be made thicker for strength, and they do not have as high an efficiency.

Hollow chrome-vanadium steel propeller blades welded along the trailing edge have been successfully used in one type of controllable propeller. They have about the same advantages as aluminum-alloy propeller blades.

Magnesium-alloy propeller blades are still in an experimental stage but because of their light weight may some day supersede aluminum and steel for this purpose. The corrosion of this type blade is somewhat of a problem, particularly when used on seaplanes.

Pressed wood impregnated with resins is being used in the manufacture of large propellers. This type of propeller is relatively light in weight.

Propeller Hubs. Propeller hubs are usually manufactured from forgings of chrome-vanadium steel or chrome-nickel-molybdenum steel. Both these steels machine readily and can be heat-treated to 150,000 p.s.i. which is the usual strength required for a hub. In addition, they both have excellent fatigue strength so essential in a part subjected to vibrational stresses.

Cowl Ring. The engine cowl ring is made from aluminum alloy. It has been customary to use 3003-H14 or 5052-O aluminum alloy. 5052-O is better because of its greater tensile and fatigue strength. A sheet thickness of 0.040 to 0.050 inch is normally used for ring cowls. 2024-O aluminum alloy has been satisfactorily used for spinnings but must be heat-treated before installation. 2024-T4 and Alclad 2024-T4 are used frequently for side panels. 6061-T4 is an excellent material for cowling. Material 3003-H14 has been used as a compromise material with good forming and welding characteristics and moderate strength.

Material 5052 is difficult to form in the harder tempers but can be welded satisfactorily. Its high fatigue strength is ideal for cowling to resist cracking induced by the vibrational stresses imposed by the engine and propeller.

Alloy 2024-T4 has good fatigue and tensile strength.

Exhaust Collector. Exhaust stacks, manifolds, or collectors are made from 18-8 corrosion-resisting steel, Inconel, and carbon steel. The thickness of the material used for exhaust collectors varies from 0.035 to 0.049 inch. The latter thickness is preferable for high-powered engines using high-octane fuel.

An 18-8 corrosion-resisting steel containing a small amount of columbium or titanium is used. The columbium or titanium reduces the corrosion embrittlement at operating temperatures. This material is available in sheet form and as welded or seamless tubing. After fabrication and welding the finished stacks should be heat-treated, or stabilized, to reduce carbide precipitation and corrosion embrittlement.

Inconel is obtainable in sheet form and as welded or seamless tubing. It can be readily fabricated and welded the same as 18-8 steel. Both materials are generally used in the sheet or welded-tubing form for the fabrication of exhaust collectors. Inconel does not require heat treatment after fabrication. It can be heat-treated to eliminate internal stresses due to fabrication or welding if desired.

Mild-carbon or chrome-molybdenum steel stacks are sometimes used in small commercial airplanes that do not use high-octane gasoline. This type stack is likely to scale internally and rust externally due to the temperature variations to which it is subjected.

Other types of material have been tried for exhaust stacks but none have served the purpose so well as 18–8 corrosion-resistant steel or Inconel.

Cowling. In general, the material used for engine cowling is the same as that previously described for the ring cowl. The thickness of sheet is somewhat lighter, however, varying from 0.032 to 0.040 inch. In some airplanes 2024-T4 or Alclad 2024-T4 aluminum alloy is used for engine cowling when excessive forming is not necessary. In many cases this material is used for the cowling support in which strength and rigidity are necessary. Alclad 2014-T6 aluminum alloys are also used for cowling supports.

Engine Mount. Chrome-molybdenum and mild-carbon steel tubing are used for engine mounts. It is customary to weld the entire assembly together, but some mounts are assembled by bolting or riveting.

Firewall. The firewall is usually constructed of a sheet of aluminum alloy either 0.032 or 0.040 inch thick. Some firewalls consist of two sheets of aluminum alloy 0.020 inch thick, with $^1/_8$ inch of asbestos sandwiched between them. Corrosion-resisting steel, Inconel, and terneplate are also used for firewalls.

Firewalls of commercially pure titanium are being specified on many military airplanes.

Oil Tank. Oil tanks are constructed of aluminum or aluminum alloy sheet, although there are also magnesium-alloy tanks. If the tank is welded, either 1100, 3003, 5052 or 6061 aluminum alloy is used. Riveted tanks are made from these materials, 2024-T4, or Alclad aluminum alloy.

In the construction of oil tanks the thickness of the sheet used varies from 0.040 to 0.065 inch, according to the size of the tank, its shape and the size of the unsupported areas.

Oil Lines. Oil lines are made from any of the following materials: 52S-O aluminum alloy, copper, copper-silicon, various types of flexible tubing. A wall thickness of 0.035 to 0.049 inch is used with the solid tubing. This type of tubing requires a flexible connection, which is made by means of a rubber-hose nipple held with hose clamps. Neoprene hose, a synthetic rubber compound, is commonly used because it is not affected by the hot oil.

Engine Controls. Engine controls, such as push-pull rods, jack-shafts, and bell-cranks, are fabricated from chrome-molybdenum or mild-carbon steel. Push-pull rods that pass close to compasses are made from 24ST aluminum-alloy tubing. Push-pull rods are usually $^3/_8$ inch in diameter and have a wall thickness 0.035 for steel and 0.058 for aluminum alloy. These sizes may vary somewhat, depending upon the length of the rod and the force transmitted.

Fuel Tanks. The same materials described above for oil tanks are used for fuel tanks, but the thickness of sheet is somewhat greater because of their larger size.

Fuel Lines. The same materials described above for oil lines are used for fuel lines. The sizes of solid lines vary from ½-inch diameter with an 0.035-inch wall for engines under 600 horsepower to 1¼-inch diameter with an 0.049-inch wall for larger engines.

Landing Gear. Many landing gears have been made of welded chrome-molybdenum tubing. Chrome-molybdenum steel forgings are frequently used for fittings on this type of gear. Sub-assemblies of welded steel landing gears are usually heat-treated to 150,000 to 180,000 p.s.i. On many fighter planes, bombers, and commercial airplanes the landing gears are made from 2014 or 7075 die forgings for the outer cylinders, and some type of chrome-nickel-molybdenum steel is used for the moveable strut. The heat treatment for these moveable struts ranges from 180,000 to 265,000 p.s.i. One experimental airplane has a 7075-T6 axle assembly.

Hydraulic Systems. The hydraulic system on a modern airplane is a complicated maze of tubing, check valves, control valves, filters, gages, relief valves, restrictors, and cylinders. These various items use practically every type of process and material. A brief description of several components of the hydraulic system follows:

1. *Accumulator*. The accumulator is a fluid pressure storage chamber in which pressure energy may be accumulated and from which it may be withdrawn.
2. *Cylinder*. A linear motion device for converting fluid energy into mechanical energy, in which the thrust or force is proportional to the cross-sectional area. Cylinders may be single- or double-acting.
3. *Filter*. A device for the removal of solids from a fluid wherein the resistance to motion of such solids is in a difficult path.
4. *Fluid*. A substance which yields to any pressure tending to alter its shape; fluids include both liquids and gases.
5. *Gage*. An instrument which indicates the pressure in a system.
6. *Pump*. A device which converts mechanical energy into fluid energy.
7. *Reservoir*. A chamber used to store hydraulic fluid.
8. *Valve (Check)*. A valve which permits flow of fluid in one direction only, and self-closes to prevent any flow in the opposite direction.
9. *Valve (Relief)*. A valve which limits the maximum pressure which can be applied to the portion of the circuit to which it is connected.

Due to high speeds, space limitations, high pressures, and other factors, most military airplanes now in use, run fluid temperatures of approximately 150°F., with hot spots up to 225°F. The oil used for these systems is usually MIL-O-5606. If MIL-O-5606 fluid is heated over 200°F., care must be taken to prevent the fluid from coming into contact with air since the oxidation rate increases rapidly over 200°F. Stainless-steel tubing is finding increased use owing to elevated temperatures encountered in hydraulic systems. 18-8 Types 301; and 304 stainless steels in the ⅛ hard and ¼ hard condition are finding wide use. The ductility of ¼ hard stainless is sufficiently good for flaring, providing good quality control is exercised on the end product. Flaring is much easier on ⅛ hard but, of course, there is a loss in the strength of the tubing (¼ hard 18-8 has 125,000 p.s.i. ultimate strength, ⅛ hard has 107,000 p.s.i. ultimate strength). Aluminum alloys 5052 and 6061 have been used in the past for both pressure and return lines but the 6061-T6 aluminum alloy tubing is being replaced by stainless steel for the pressure lines while 5052-O still is being used for return lines.

Tubing properties are:

Material	Ultimate Strength p.s.i.	Yield Strength p.s.i.	Endurance Limit	Elongation in 2 in., %
Annealed 18-8	75,000	30,000	35,000	50
⅛ hard 18-8	107,000	76,000	50,000	30
¼ hard 18-8	125,000	80,000	57,000	22
6061-T6	42,000	35,000	13,500	15
5052-O	27,000	12,000	17,000	25

Tubing sizes are:

¼" OD X 0.028 in. wall
⅜" OD X 0.035 in. wall
½" OD X 0.049 in. wall
¾" OD X 0.083 in. wall

18-8 hydraulic tubing is covered by specification MIL-T-6845.

Vendors producing hydraulic units have agreed to standardize on many items in order to make the logistics problem less severe. Many parts of a hydraulic system are joined to each other by screw threads usually in accordance with Military Specification MIL-S-7742. Class 3 fit, on threaded parts, should be called out on hydraulic parts, since this is the highest grade of interchangeable screw thread work. Usually a fine thread system is used.

In order to prevent leakage and malfunction on sliding parts, such as pistons, etc. where O rings are necessary, great care should be taken to be sure the "O" ring grooves are machined exactly as specified. "O" ring groove dimensions are critical in regard to tolerance and surface finish. Polishing, honing, and lapping are often required for final finishing. Micro-inch finishes are specified between 4 rms. to 16 rms.

Lubrication of many hydraulic parts is mandatory, usually every 25–30 hours, with a general-purpose grease (MIL-L-7711 is specified for external pneumatic devices). For internal pneumatic devices such as internal locks, locks, devices, etc., where the lubricant comes into contact with compressed air, MIL-L-4343 grease is usually specified.

Many aluminum alloys such as 2014, 2024, and 7075 are used as outer bodies. These alloys are usually anodized in certain areas for corrosion protection. The aluminum alloys used for these purposes are usually rolled or forged. Extruded hydraulic parts have also been used but precautions are taken to prevent any high short-transverse stresses.

Sintered tungsten carbide is used where high wear resistance is required.

Where a high hardness is required, AISI 9310, AISI 3312, Carpenter 158, and other carburizing grades of steel are used in hydraulic components. AISI 52100 steel is also used for these applications.

Brass and bronze are used in limited applications, usually for "O" ring back-up rings and some types of bushings. Sintered bronze filters are also used.

The 400 series stainless steels are finding wide use on pistons, slide valves, and other parts where high hardness is required to prevent wear. The 400 series stainless steels most widely used for these applications are as follows:

Type 410. This is a martensitic stainless steel which obtains its excellent properties from heat treatment. The chemistry of this steel is follows:

Carbon	0.15 max.	Silicon	1.0 max.
Chromium	11.5–13.5	Phosphorus	0.04 max.
Manganese	1.0 max.	Sulfur	0.03 max.

The specifications which cover 410 are QQ-S-766, MIL-S-853, MIL-S-854, AMS 5613 and others.

410 STAINLESS STEEL
(The mechanical properties after heat treatment (1800°F., oil quenched, tempered at temperature indicated)

Draw Temperature	Yield Strength p.s.i.	Tensile Strength p.s.i.	% Elongation	Reduction in Area, %
300°F.	150,000	195,000	15	55
500°F.	142,000	185,000	15	55
700°F.	146,000	190,000	16	55

This steel should not be tempered between 750°F. and 1050°F. because of resultant brittleness.

440 A, and C. These higher carbon and chromium versions of the 400 series stainless steels are used for many valve pistons and slide valves. They should be used only in the hardened condition.

The chemistry of these steels is as follows:

	440A	*440C*
Carbon	0.6–0.75	0.95–1.2
Chromium	16.0–18.0	16–18
Molybdenum	0.75 max.	0.75 max.
Manganese	1.0 max.	1.0 max.
Silicon	1.0 max.	1.0 max.

These steels are covered by the following specifications:

440A—AMS-5631
44OC—AMS-5630B QQ-S763

The mechanical properties of the 440 grades are as follows:

	Tensile Strength p.s.i.	Yield Strength p.s.i.	Elongation in 2 in., %	Reduction of Area %
440A	260,000	240,000	5	20
440C	285,000	275,000	2	10

These steels are heat-treated by oil quenching from 1900°F. and drawn at 600°F.

When any of the 400 series stainless steels are used in a hydraulic system they should be passivated for corrosion reasons. Passivation is well covered in a previous chapter. A very common passivating procedure for the treatment of 400 series stainless steels consists of placing parts in a 20% solution of nitric acid at 150°F. for 10 minutes and then properly rinsing. For the heat treatment of these steels, best results can be obtained from a hydrogen atmosphere or cracked ammonia atmosphere. These steels are susceptible to very fine cracking if carbon is present in the atmosphere.

When very close fits are required in hydraulic components, stabilization should be specified. Cold stabilization is often used where high production rates are required. Stabilization is called out in order to prevent any dimensional change after the part is put into use. Stabilization is necessary because of the sluggish characteristics of such steels as 52100, 440, 410, and others in order to make a 100% change from austenite to martensite upon quenching. The reasons for the possibility of growth in unstabilized steels is explained as follows:

When steel is heated above a certain temperature, the atoms rearrange themselves into a different crystal structure. Above 1670°F. and up to approximately 2800°F. pure iron changes into a F.C.C. crystal structure which is unstable below 1670°F. The F.C.C. is composed of four atoms per cell.

⅛ for the 8 corner atoms = 1
½ for the 6 face atoms = 3
Total = 4

As the 1670°F. temperature is lowered, there is an immediate change in crystal structure to the body centered cubic system which has two atoms per cell as indicated:

⅛ for each corner atom = 1
Center atom = 1
Total = 2

Therefore, when steel or iron cools, there is an expansion (not considering thermal contraction). This is known as an *allotropic* expansion. If it is possible to attain 100% transformation from F.C.C. to B.C.C., the part will remain dimensionally stable. If, however, any Austenite (F.C.C.) is retained in the steel at room temperature, there is a very good possibility that the part will grow in size because the Austenite (F.C.C.) is unstable at room temperature and, as the part is used, or as time passes, it will change into the stable structure (B.C.C.). In order to assure 100% transformation of Austenite (F.C.C.), into the stable B.C.C., all parts which have close tolerances are cold-stabilized. This process involves the placing of partially finished parts in a cold chamber for a period of 20 minutes at –100°F.; then, when the parts come up to room temperature, they are stress-relieved at 300°F. for one hour. The cycle is again repeated resulting in a dimensionally stable product.

Many nonmetallic materials are specified for hydraulic parts. Nylon, teflon, felt, and various types of rubber are specified for such things as back-up (teflon), and "O" rings (rubber), and lubricating wipers (felt).

Processing of hydraulic parts involves the use of many metal-treating specifications. Any treatment which will "build up" should be avoided on finished parts because of close dimensional control. Cadmium plating (QQ-P-416) is used for many steel parts and springs. Anodizing is specified on many aluminum parts (AN-QQ-A-696). Chromium plating (MIL-P-6871) is specified on such components as piston rods and sliding parts. Tin plating is sometimes called out on springs. Electroless nickel is specified for many parts which must have a corrosion resisting coating applied in small openings. The corrosion resistance of electroless nickel coatings is almost as good as pure nickel since (if properly applied) this even coating is practically porosity free.

Fuselage. Fuselages are of either welded steel tubing or aluminum-alloy monocoque construction. In rare instances, monocoque fuselages using corrosion-resisting steel or plywood have been manufactured in this country.

Welded steel fuselages are made from either chrome-molybdenum or steel tubing. The diameter of the tubing used varies from ½ inch up to 1½ inches depending upon the loads carried.

Monocoque fuselages differ in detail construction but usually consist of extruded or rolled sections for frames and bulkheads, covered by sheet between 0.025 and 0.065 inch thick. 2024-T4 aluminum alloy, Alclad 2024-T4 or Alclad 7075-T6 are used for this purpose.

Hulls and Floats. Hulls and floats are very similar to monocoque fuselages in construction and are made with the same materials. Alclad material is preferable because of the severe corrosion conditions that are met.

Several spot-welded corrosion-resisting steel hulls have been manufactured in this country. Their corrosion resistance is excellent, but it is necessary to use much thinner material than is used in aluminum-alloy construction to obtain a comparable weight.

Wings. There are any number of different materials used in the construction of wings. The most common types of wing construction are as follows:

1. Wood with plywood wing covering
2. Wood with fabric covering
3. Wooden beams with metal ribs, covered with fabric
4. Metal, including the covering
5. Metal with fabric covering

The choice of a particular type of wing construction depends upon the type of airplane, the manufacturing skill available, and the preference of the designer.

The specific materials used in wing construction are described below under the title of the subassembly.

Wing Leading Edge. The leading edge of a wing forward of the front beam is usually covered with plywood or sheet metal to maintain a perfect contour in this important region. $^1/_{16}$-inch plywood is normally used for this purpose on wooden wings. In metal wing construction the leading-edge covering is usually 2024-T4, Alclad 2024-T4, Alclad 2014-T6 or Alclad 7075-T6 aluminum-alloy sheet from 0.014 to 0.081 inch thick.

Wing Ribs. Wing ribs are made from wood, aluminum alloys, carbon steel, and corrosion-resisting steel.

Wooden ribs are usually made from spruce. The capstrips and diagonals are ¼ or $^5/_{16}$ inch square in the smaller commercial planes. Plywood gussets glued and tacked in place are used at the joints. The webs of some ribs are made entirely of plywood.

Aluminum-alloy ribs are made from 2024-T4 or Alclad 2014-T6 material. They are either stamped in one piece from sheet stock, or built up from drawn or rolled sections and riveted at the joints. Material from 0.014 to 0.032 inch thick is commonly used in the manufacture of this type of rib.

Steel and corrosion-resisting steel ribs are made from very light-gage material in a U or tubular section. Joints are made by spot welding.

Wing Covering. Wings are covered with fabric, plywood, or aluminum alloy. This latter covering is either 2024-T4, Alclad 2014-T6 or 7075-T6 aluminum alloy. When clad material is used for this purpose there is no need to paint the surface for protection against corrosion. During the past few years many military and a few commercial airplanes have been manufactured using milled 7075-T6 aluminum alloy plate as wing covers. This type of construction eliminates many fasteners; makes possible a leak-resisting structure for extra fuel capacity; and allows higher design allowables to be used because of the fewer rivet holes.

Wing-tip Bow. The wing-tip bow is made from ash bent to shape, from a chrome-molybdenum or mild-steel tube, or from an aluminum-alloy tube or formed section. Aluminum-alloy sections formed to the desired shape are commonly used on metal wings.

Wing Beams. Wing beams are made from spruce, poplar, Douglas fir, steel, corrosion-resisting steel, and aluminum alloys.

Wooden beams are generally made of spruce (although in regions where spruce is scarce or expensive, substitute woods such as fir, poplar, and even white pine have been successfully used). At the present time it is difficult to obtain spruce of aircraft grade in sufficiently long lengths or required cross-sectional dimensions for any but the smaller commercial airplanes.

Aluminum-alloy wing beams are very generally used in this country at the present time. They are made of any one or combination of the following alloys: 2024-T4, Alclad 2024-T4, 2014-T6, Alclad 2014-T6, 7075-T6 or Alclad 7075-T6.

Steel spars have been constructed of chrome-molybdenum steel tubing either round or oval in cross-section, welded at the joints. These spars are usually heat-treated to develop greater strength. They are difficult to manufacture due to the likelihood of welding cracks and of distortion during the heat-treatment operation.

Corrosion-resisting steel beams are fabricated from high-tensile strip or sheet, rolled or drawn to shape and spot-welded together. This type of spar is fairly easy to manufacture if spot-welding equipment is available, and it has good strength properties. It works out well for a heavily loaded wing, which permits the use of moderately heavy sheet without penalizing the strength/weight ratio.

Wing Fittings. Wing fittings are made from the high-strength aluminum alloys such as 2024-T4, 2014-T6 and 7075-T6 and from various types of steel. Chrome-molybdenum steel (4130 or 4140) heat-treated to 15,000 p.s.i. is very commonly used. Chrome-nickel-molybdenum steel (4340) is used in heat treatments up to 200,000 pounds per square inch.

Wing Supporting Struts. Wing struts are streamline tubing made of 24S-T4, 24ST or 61S-T6 aluminum alloy, or chrome-molybdenum steel. Corrosion-resisting steel streamline struts have recently been developed and may find some applications, particularly for bracing seaplane floats.

Wing Wires. Wing wires or tie-rods are made from 1050 carbon steel, and from corrosion-resisting steel. Tie-rods made from corrosion-resisting steel are rapidly displacing carbon steel tie-rods both for external and internal bracing. Their strengths are the same.

Ailerons. Ailerons are usually made from the same materials used in the construction of the wings. Due to the fact that it is necessary to design for static balance of the ailerons, they are usually covered with fabric in order to reduce the weight behind the hinge line. Plywood and metal-covered ailerons have been used to get away from fabric bulging at high speeds.

Wing Flaps. Wing flaps, especially the split type, are constructed with aluminum-alloy sheet backed by stiffeners. The shallow depth of split flaps makes metal construction almost mandatory.

Windshield. Windshields and cabin enclosures are frequently constructed of one of the transparent plastics such as pyralin, plexiglas, lucite, plastecele, Lumarith or Vinylite. A thickness of 3/16 to 5/16 inch of this material is used.

Nonscatterable glass is used for windshield on most airplanes. A minimum thickness of 3/16 inch, preferably ¼ inch, is used in the interest of clear vision.

Windshield frames are made from light steel or aluminum sheet. Inconel strip has also been used successfully.

Instrument Board. Instrument boards are made from magnesium alloy or 2024-T4 aluminum-alloy sheet from 1/16 to 1/8 inch thick. In some planes the instrument board is made from molded or laminated plastic. These materials are from 1/8 to ¼ inch thick when used for this purpose.

Instrument Tubing. Small-diameter tubing with a light wall is used in conjunction with airspeed meters, oil and fuel pressure gages, primers, and other instruments. This tubing is made from one of the following materials. 5052-O aluminum alloy, 1100 aluminum or copper.

Seats. Seats are made from aluminum-alloy or magnesium-alloy sheet and tubing or from light steel tubing. They are usually purchased complete, particularly for commercial planes where padding and tilting devices are desired.

Flooring. Flooring is fabricated from plywood or aluminum-alloy sheet. A composite material made up from plywood and aluminum alloy glued together is also used. Formica or bakelite might work out satisfactorily for flooring in some instances.

Aluminum honeycomb construction has been used for flooring in some aircraft. The honeycomb consists of 7075-T6 face sheets glued to a honeycomb manufactured from 1100 aluminum foil.

Controls. Control parts, such as control sticks, rubber pedals, torsion tubes, push-pull tubes, bell-cranks, and horns are manufactured from aluminum alloys or steel. 2014-T4 aluminum-alloy tubing is frequently used for control parts. Because of their nonmagnetic qualities they are particularly good for control sticks and other parts that operate near a compass. When control parts must be wear-resistant and strong as well as nonmagnetic, the use of K Monel will solve the problem.

Chrome-molybdenum steel sheet and tubing are frequently used in the fabrication of control parts. When parts are welded, it is advisable to normalize them or to give them a moderate heat treatment as a precaution against cracks due to vibration.

Aluminum-alloy casting material No. 195-T4 is frequently used for rudder pedals, sockets, horns and other parts. It is advisable to design these parts 100% overstrength in order to allow for any irregularities in the castings.

Flexible and extra-flexible control cable are both used for the operation of control surfaces. Extra-flexible cable should be used if a marked change in direction is necessary in running the cable.

Tail Surfaces. Tail-surface construction is very similar to wing construction. Fixed surfaces constructed of aluminum alloys are often covered with sheet of the same material from 0.014 to 0.032 inch thick. Movable surfaces such as the elevators and rudder are usually fabric covered to help obtain static balance, although modern high-speed airplanes use metal-covered movable surfaces. Tail surfaces are also built with steel tubing welded at the joints and covered with fabric. In this type of construction about ¼-inch-diameter tubing is used for the rib members and large-diameter tubing for the spar members.

Tail Wheel Structure. Tail-wheel structures are built chiefly from steel tubing and sheet, the same as are used for the main landing gear. In some cases aluminum-alloy forgings are used.

Bushings. Bushings are used in all fittings subjected to reversals of stress. They are held in place by a drive fit and can be replaced when worn. They are made from chrome-molybdenum steel tubing or bar stock heat-treated to 125,000 or 150,000 p.s.i.

Bearings. Bearings are used in joints that rotate. Ball or roller bearings packed with grease are generally the most satisfactory. Controls and control-surface hinges are ideal places to use ball bearings. In some places where loads are heavy and rotation is slight, such as the joints of a retractable landing gear, bronze bushings are used. These bronze bushings are grooved and the surrounding fitting tapped for a grease fitting to permit thorough lubrication. Chrome-plated hardened-steel bushings are used in landing-gear joints and similar applications.

Bolts. AN standard bolts made from nickel steel (2330) are used for all structural connections. Occasionally it is necessary to position a bolt in place by tack-welding the head. For this purpose the bolt is manufactured from chrome-molybdenum steel, since nickel steel cannot be welded satisfactorily. Unless the entire assembly to which the head of the bolt is tack-welded is subsequently heat-treated, the chrome-molybdenum bolt will not have quite as high strength as the standard nickel-steel bolt. AN standard bolts are all heat-treated to 125,000 p.s.i. Special high-strength bolts heat-treated to 200,000 p.s.i. are made of chrome-nickel-molybdenum steel (4340).

Rivets. 2017-T4 and 2024-T4 aluminum-alloy rivets are used for joining structural assemblies. The 2024-T4 rivets are seldom used because of their tendency to crack if not used almost immediately after treatment. 2117 rivets which do not require heat treatment just before driving are being used very generally in all but heavily loaded structural assemblies.

Steel rivets are available but are used only in highly loaded joints. High-shear steel rivets are made from 8630 steel rod or equivalent, heat-treated to 125,000 p.s.i.

Springs. Flat springs are made from high-carbon steel (1090) sheet stock. Small unimportant coil springs are also made from this material in wire form. Larger coil springs, like those used for engine valve springs and landing-gear oleos, are made from chrome-vanadium steel (6140).

APPENDICES

Appendix 1. Weights of Common Aircraft Materials

Material	Specific gravity	Weight (p.s.i.)
Aluminum alloys		
2S	2.71	.098
3S	2.73	.099
4S	2.72	.098
14S	2.80	.101
17S	2.79	.101
24S	2.77	.100
25S	2.79	.101
43	2.67	.096
A51S	2.69	.097
52S	2.67	.096
53S	2.69	.097
61S	2.72	.098
75S	2.80	.101
195	2.77	.100
R30	2.80	.101
Asbestos	2.46	.089
Bakelite	1.35	.049
Brass	8.45	.305
Bronze, aluminum	7.70	.278
Bronze, phosphor	8.88	.322
Copper	8.90	.323
Cork, compressed	.23	.008
Felt	.08	.003
Formica	1.35	.049
Glass, nonscatterable	2.53	.091
Inconel	8.55	.309
K Monel	8.58	.310
Lead	11.40	.411
Magnesium alloys	1.80	.065
Micarta	1.35	.049
Monel	8.90	.323
Plastecele	1.35	.04
Plexiglas	1.18	.04
Pyralin	1.35	.049
Steel	7.84	.283
Steel, corrosion-resisting	7.86	.284
Titanium	4.43	.160
Wood	(See Table 21)	

APPENDIX 2. Standard Gage Thickness in Decimal Fractions of an Inch

Gage number	Gage names		
	Birmingham (B.W.G.) or Stubs	American or Browne & Sharpe	American Steel or Washburn & Moen
0	.340	.325	.306
1	.300	.289	.283
2	.284	.258	.262
3	.259	.229	.244
4	.238	.204	.225
5	.220	.182	.207
6	.203	.162	.192
7	.180	.144	.177
8	.165	.128	.162
9	.148	.114	.148
10	.134	.102	.135
11	.120	.091	.120
12	.109	.081	.105
13	.095	.072	.091
14	.083	.064	.080
15	.072	.057	.072
16	.065	.051	.062
17	.058	.045	.054
18	.049	.040	.047
19	.042	.036	.041
20	.035	.032	.035
21	.032	.028	.032
22	.028	.025	.027
23	.025	.023	.026
24	.022	.020	.023
25	.020	.018	.020
26	.018	.016	.018
27	.016	.014	.017
28	.014	.0126	.016
29	.013	.011	.015
30	.012	.010	.014

Birmingham Wire Gage (B.W.G.) is used to specify thicknesses of steel sheet, and all tubing including steel and aluminum alloy.

Browne & Sharpe Gage (B. & S.) is used for nonferrous sheet, particularly aluminum alloy and magnesium alloy sheet. Also wire.

American Steel and Wire Gage (formerly Washburri & Moen) is used for steel and iron wire.

Appendix 3. Standard Sizes, Weights, and Tolerances of Round Steel Tubing

Outside Diameter (in)	Weight (lb./ft.) of tubing of standard wall thickness (in)									Tolerance	
	.022	.028	.035	.049	.058	.065	.083	.095	.120	Outside diameter	Wall thickness
3/16	.039	.048	.057							+0.005 in. –0.000 in.	±15% of wall thickness
¼	.054	.066	.081	.105							
5/16	.068	.085	.104	.138	.158						
⅜	.083	.104	.127	.171	.197						
½			.174		.274						
⅝			.221	.302	.352						
¾			.27	.37	.43						
⅞			.31	.43	.51						
1			.36	.50	.58						
1⅛			.41	.56	.66						
1¼			.45	.63	.74	.82					
1⅜			.50	.69	.82	.91					
1½			.55	.76	.89	1.00	1.25	1.42	1.77	+0.010 in. –0.000 in.	±10% of wall thickness
1⅝				.82	.97	1.08					
1¾				.89	1.05	1.17	1.48	1.68	2.09		
1⅞					1.13	1.26					
2					1.20	1.34	1.70	1.93	2.41		
2¼						1.52	1.92	2.19	2.73		
2½						1.69	2.14	2.44	3.05		
2¾							2.36	2.69	3.37		

Appendix 4. Standard Sizes, Weights, and Tolerances of Round Aluminum-alloy Tubing

Outside diameter (in.)	Weight (lb./ft.) of tubing of standard wall thickness (in.)											Tolerance, outside diameter (in.)
	.022	.028	.032	.035	.042	.049	.058	.065	.072	.083	.095	
¼	.018	.023				.036		.044				±0.003
5/16	.023	.029		.035		.047		.059				
⅜	.028	.036		.043		.058		.074				
7/16	.0.33	.042		.051			.080					
½	.038	.049		.059		.080	.094	.104				
⅝		.061		.075		.103	.120	.133				±0.004
¾		.074		.091		.125	.147	.163				
⅞				.107		.147	.173	.193				
1				.123		.170	.200	.222				
1⅛				.139		.193	.23					±0.005
1¼				.155		.21	.26	.27				
1⅜				.17		.24						
1½				.18		.26	.31	.33				
1⅝				.19								
1¾				.21			.36	.39				
1⅞				.23								
2				.25			.35	.45				

APPENDIX 4

	.022	.028	.032	.035	.042	.049	.058	.065	.072	.083	.095	
2 3/8						.37						±0.006
2¼						.39	.47	.51				
2 3/8						.42						
2½						.44	.52	.57				
2 5/8							.545					
2¾							.57	.63				
2 7/8								.66				
3								.69	.77			
3¼									.83			
3½									.90	1.04		
3¾										1.11		
4										1.19	1.34	
4¼											1.43	±0.008
Tolerance, wall thickness		±0.002 in.			±0.003 in.				±0.004 in.			

APPENDIX 5. Streamline Tubing: Aluminum Alloy, Corrosion-resisting Steel, Chrome-molybdenum Steel-Standard Sizes and Dimensions

Basic round tube diameter (in.)	Wall thickness (in.)	Major axis = length (in.)	Minor axis = width (in.)
1	.035	1.349	0.571
1 1/8	.035	1.517	0.643
1¼	.035	1.685	0.714
	.049		
1 3/8	.035	1.855	0.786
1½	.049	2.023	0.857
1 5/8	.049	2.192	0.929
	.058		
1¾	.049	2.360	1.000
	.058		
	.065		
1 7/8	.049	2.528	1.071
	.058		
	.065		
2	.058	2.697	1.143
2½	.065	3.372	1.429
2¾	.065	3.708	1.571
	.083		
3	.065	4.045	1.714
3¼	.083	2.383	1.857
3½	.095	4.720	2.000
3¾	.095	5.057	2.143
4	.120	5.394	2.285
4¼	.134	5.732	2.428
4½	.156	6.069	2.571
4¾	.188	6.406	2.714

APPENDIX 6. Strength of Steel Cable

Construction	Diameter (in.)	Tinned carbon steel Spec. MIL-C-1511		Corrosion-resisting Steel Spec.-MIL-C-5424	
		Breaking strength (lb.)	Weight (lb./100ft.)	Breaking strength (lb.)	Weight (lb./100ft.)
7 X 7	1/16	480	0.75	480	0.75
	3/32	920	1.53	920	1.53
7 X 19	1/8	2,000	2.90	1,900	2.90
	5/32	2,800	4.44	2,600	4.44
	3/16	4,200	6.47	3,900	6.7
	7/32	5,600	9.50	5,200	9.50
	¼	7,000	12.00	6,600	12.00
	9/32	8,000	14.56	8,000	14.56
	5/16	9,800	17.71	9,600	17.71
6 X 19 (IWRC)	3/8	14,400	26.45	13,000	26.45
	7/16	17,600	35.60	16,000	35.60
	½	22,800	45.80	22,800	45.80
	9/16	28,500	59.00	28,500	59.00
	5/8	35,000	71.50	35,000	71.50
	¾	49,600	105.20	49,600	105.20
	7/8	66,500	143.00	66,500	143.00
	1	85,400	187.00	85,400	187.00
	1 1/8	106,400	240.00	106,400	2400.00
	1¼	129,400	290.00	129,400	290.00
	1 3/8	153,600	330.00	153,600	330.00
	1½	180,500	420.00	180,500	420.00

APPENDIX 7. Streamline, Round, and Square Tie-rods

Material	Size	Strength (lb.)		Bend-test requirements (see note)	
		Round, square	Streamline	Round, square	Streamline
Carbon steel—S.A.E. 1050	6–40	1,000	1,200	11	12
	10–32	2,100	2,400	11	12
	¼–28	3,400	4,200	9	10
	5/16–24	6,100	6,900	7	8
	3/8–24	8,000	10,000	7	8
	7/16–20	11,500	13,700	7	8
	½–20	15,500	18,500	7	8
	9/16–18	20,200	24,00		6
Corrosion-resisting steel	6–40	1,000	1,200	14	12
	10–32	2,100	2,400	12	12
	¼–28	3,400	4,200	10	10
	5/16–24	6,100	6,900	10	8
	3/8–24	8,000	10,000	9	8
	7/16–20	11,500	13,700	8	8
	½–20	15,500	18,500	7	8
	9/16–18	20,200	24,000		6
	5/8–18	24,700	29,500		6

The number listed under "Bend-test requirements" refers to the number of 90° bends the tie-rod must withstand when bent over a radius equal to three times its minor axis.

INDEX