Elements of Metallurgy and Engineering Alloys
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CHAPTER 26

Aluminum

ALUMINUM has many outstanding attributes that lead to a wide range of applications, including:

- Good corrosion and oxidation resistance
- High electrical and thermal conductivities
- Low density
- High reflectivity
- High ductility and reasonably high strength
- Relatively low cost

Aluminum is a consumer metal of great importance. Aluminum and its alloys are used for foil, beverage cans, cooking and food-processing utensils, architectural and electrical applications, and structures for boats, aircraft, and other transportation vehicles. As a result of a naturally occurring tenacious surface oxide film (Al_2O_3), a great number of aluminum alloys have exceptional corrosion resistance in many atmospheric and chemical environments. Its corrosion and oxidation resistance is especially important in architectural and transportation applications. On an equal weight and cost basis, aluminum is a better electrical conductor than copper. Its high thermal conductivity leads to applications such as radiators and cooking utensils. Its low density is important for hand tools and all forms of transportation, especially aircraft. Wrought aluminum alloys display a good combination of strength and ductility. Aluminum alloys are among the easiest of all metals to form and machine. The precipitation-hardening alloys can be formed in a relatively soft state and then heat treated to much higher strength levels after forming operations are complete. In addition, aluminum and its alloys are not toxic and are among the easiest to recycle of any of the structural materials.

26.1 Aluminum Metallurgy

Aluminum is a lightweight metal with a density of 2.70 g/cm^3 (0.1 lb/in.^{3}) and a moderately low melting point of 655 °C (1215 °F). Since it has a face-centered cubic crystalline structure, the formability of aluminum and aluminum alloys is good. The good formability is further aided by its rather low work-hardening rate. Aluminum alloys are classified as either wrought or cast alloys. Some of the wrought alloys are hardened by work hardening, while others are precipitation hardenable. Likewise, some of the cast alloys can be hardened by precipitation hardening, while others cannot. Some of the important properties of each of the wrought alloy series are given in Table 26.1.

Microstructural control is extremely important in the production and processing of aluminum alloys. Important microstructural features include constituent particles and dispersoids. Constituent particles are coarse intermetallic compounds that form by eutectic decomposition during ingot solidification. Some are soluble, while others are virtually insoluble. The insoluble compounds usually contain the impurity elements iron or silicon and form compounds such as $Al_6(Fe,Mn)$, Al_2Fe, Al_7FeCu_2, and $\alpha Al(Fe,Mn,Si)$. The soluble compounds are equilibrium intermetallic compounds of one of the major alloying elements, such as $CuAl_2$ or $SiMg_2$. One of the major reasons for ingot homogenization before hot working is to dissolve these soluble compounds. During hot working, the large insoluble compounds are broken up and aligned as stringers in the working direction. Dispersoids are smaller submicron particles (typically 0.05 to 0.5 μm) that form during ingot homogenization by solid-state precipitation from elements that have only limited solubility and that diffuse slowly. Once they form, they resist dissolution and/or coarsening. They usually consist of one of the transition elements; examples are $Al_{20}Cu_2Mn_3$, $Al_{12}CrMg_2$, and Al_3Zr. Dispersoids are useful in retarding recrystallization and grain growth. Other microstructural features that can affect properties include oxide inclusions, porosity,

Table 26.1 Major attributes of wrought aluminum alloys

1*xxx*: Pure Al. The major characteristics of the 1*xxx* series are:

- Strain hardenable
- Exceptionally high formability, corrosion resistance, and electrical conductivity
- Typical ultimate tensile strength range: 69–186 MPa (10–27 ksi)
- Readily joined by welding, brazing, soldering

2*xxx*: Al-Cu Alloys. The major characteristics of the 2*xxx* series are:

- Heat treatable
- High strength at room and elevated temperatures
- Typical ultimate tensile strength range: 186–428 MPa (27–62 ksi)
- Usually joined mechanically, but some alloys are weldable
- Not as corrosion resistant as other alloys

3*xxx*: Al-Mn Alloys. The major characteristics of the 3*xxx* series are:

- High formability and corrosion resistance; medium strength
- Typical ultimate tensile strength range: 110–283 MPa (16–41 ksi)
- Readily joined by all commercial procedures
- Hardened by strain hardening

4*xxx*: Al-Si Alloys. The major characteristics of the 4*xxx* series are:

- Some heat treatable
- Good flow characteristics; medium strength
- Typical ultimate tensile strength range: 172–379 MPa (25–55 ksi)
- Easily joined, especially by brazing and soldering

5*xxx*: Al-Mg Alloys. The major characteristics of the 5*xxx* series are:

- Strain hardenable
- Excellent corrosion resistance, toughness, weldability; moderate strength
- Building and construction, automotive, cryogenic, marine applications
- Typical ultimate tensile strength range: 124–352 MPa (18–58 ksi)

6*xxx*: Al-Mg-Si Alloys. The major characteristics of the 6*xxx* series are:

- Heat treatable
- High corrosion resistance, excellent extrudability; moderate strength
- Typical ultimate tensile strength range: 124–400 MPa (18–58 ksi)
- Readily welded by gas metal arc welding and gas tungsten arc welding methods
- Outstanding extrudability

7*xxx*: Al-Zn Alloys. The major characteristics of the 7*xxx* series are:

- Heat treatable
- Very high strength; special high-toughness versions
- Typical ultimate tensile strength range: 221–607 MPa (32–88 ksi)
- Mechanically joined

8*xxx*: Alloys with Al/other elements (not covered by other series). The major characteristics of the 8*xxx* series are:

- Heat treatable
- High conductivity, strength, hardness
- Typical ultimate tensile strength range: 117–414 MPa (17–60 ksi)
- Common alloying elements include Fe, Ni, and Li

Source: Ref 1

grain size and shape, and crystallographic textures that can lead to anistropic properties.

Strengthening of non-heat-treatable alloys is a result of a combination of solid-solution strengthening, second-phase constituents, dispersoid precipitates, and work hardening. The alloys normally hardened by work or strain hardening include the commercially pure aluminums (1*xxx*), the aluminum-manganese alloys (3*xxx*), some of the aluminum-silicon alloys (4*xxx*), and the aluminum-magnesium alloys (5*xxx*). These can be work hardened to various strength levels with a concurrent reduction in ductility. Since these alloys will undergo recovery at moderate temperatures, they are used mainly for lower-temperature applications.

The highest strength levels are attained by the precipitation-hardenable alloys, which include the aluminum-copper alloys (2*xxx*), the aluminum-magnesium + silicon alloys (6*xxx*), the aluminum-zinc alloys (7*xxx*), and the aluminum-lithium alloys of the 8*xxx* series. For the cast alloys, this includes the aluminum-copper alloys (2*xx.x*), some of the aluminum-silicon + copper and/or magnesium alloys (3*xx.x*), and the aluminum-zinc alloys (7*xx.x*). One rather disappointing property of high-strength aluminum alloys is their fatigue performance. Increases in static tensile properties have not been accompanied by proportionate improvements in fatigue properties (Fig. 26.1). The precipitation-hardened alloys exhibit only minimal fatigue improvement because of two factors: (1) cracks initiating at precipitate-free zones adjacent to grain boundaries, and (2) the re-solution of precipitate particles when they are cut by dislocations. The cut precipitate particles become smaller than the critical size for thermodynamic stability and redissolve.

26.2 Aluminum Alloy Designation

A four-digit numerical designation system, developed by the Aluminum Association, is used to designate wrought aluminum and aluminum alloys. As shown in Table 26.2, the first digit defines the major alloying element of the series. The 1*xxx* series is handled a little differently than the 2*xxx* through 8*xxx* series. In the 1*xxx* series of commercially pure aluminums, the last two of the four digits in the designation indicate the minimum aluminum percentage. These digits are the same as the two digits to the right of the decimal point in the minimum aluminum percentage when expressed to the nearest 0.01%. When the second digit is a number other than zero, it indicates that special control has been used to control one or more of the naturally occurring impurities.

In the 2*xxx* through 8*xxx* alloy series, the second digit in the designation indicates the alloy modification. When the second digit is zero, it indicates the original alloy. The numbers 1 through 9, assigned consecutively, indicate modifications of the original alloy. Explicit rules have been established for determining whether a proposed composition is merely a modification of a previously registered alloy or if it is an entirely new alloy. The last two of the four digits in the 2*xxx* through 8*xxx* series have no special significance but serve only to identify the different alloys in the series.

For cast alloys (Table 26.3), a four digit numerical designation incorporating a decimal point is used. The first digit indicates the major alloying element, while the second and third digits identify the specific alloy. For the 1*xx.x* series, the second two digits indicate purity. The last digit, which is separated from the others by a

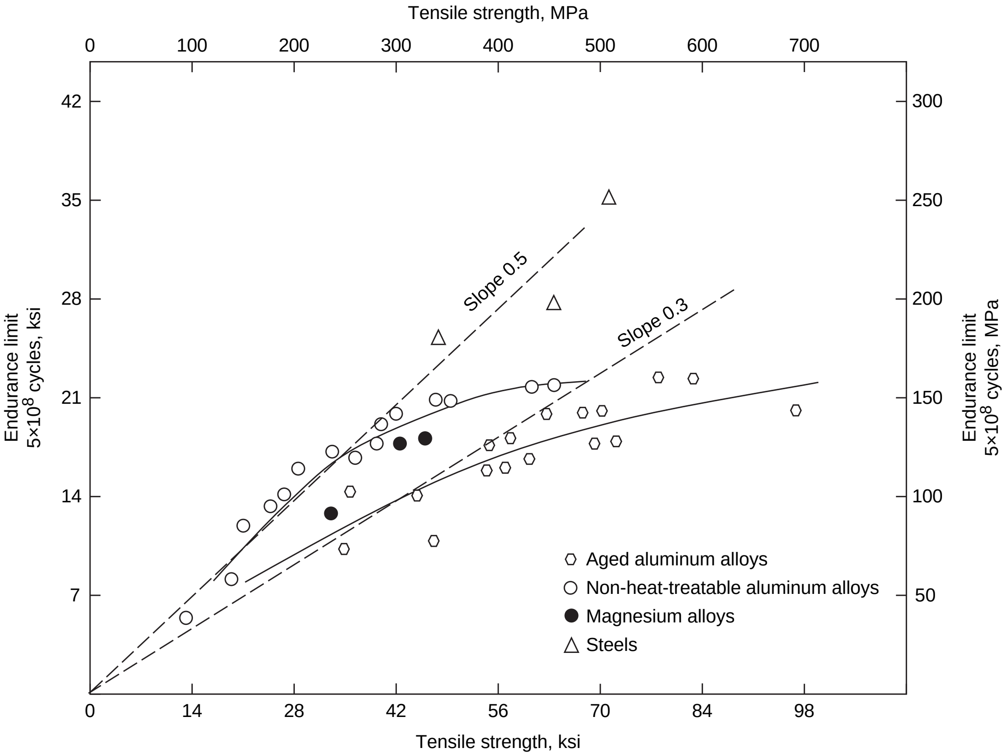


Fig. 26.1 Fatigue strength comparison for aluminum. Source: Ref 2

Table 26.2 Designations for aluminum wrought alloys

Series	Aluminum content or main alloying element
1*xxx*	99.00% minimum
2*xxx*	Copper
3*xxx*	Manganese
4*xxx*	Silicon
5*xxx*	Magnesium
6*xxx*	Magnesium and silicon
7*xxx*	Zinc
8*xxx*	Others
9*xxx*	Unused

Table 26.3 Designations for aluminum casting alloys

Series	Aluminum content or main alloying element
1*xx*.0	99.00% minimum
2*xx*.0	Copper
3*xx*.0	Silicon with copper and/or magnesium
4*xx*.0	Silicon
5*xx*.0	Magnesium
6*xx*.0	Unused
7*xx*.0	Zinc
8*xx*.0	Tin
9*xx*.0	Other

decimal point, indicates the product form, whether casting or ingot; the zero after a period identifies the alloy as a cast product. If the period is followed by the number 1, it indicates an ingot composition that would be supplied to a casting house. A modification of an original alloy, or of the impurity limits for unalloyed aluminum, is indicated by a serial letter preceding the numerical designation. The serial letters are assigned in alphabetical sequence starting with "A" but omitting "I," "O," "Q," and "X," the "X" being reserved for experimental alloys. For example, the designation A357.0 indicates a higher purity level than the original alloy 357.0.

The temper designations for aluminum alloys are shown in Table 26.4. The basic temper designations are as follows.

As-fabricated (F) applies to products in which there is no special control over the thermal conditions or work hardening (if applied), and there are no mechanical property limits.

Annealed (O) applies to wrought and cast products that are annealed to produce the lowest strength condition. Cast products are often annealed to improve ductility and dimensional stability.

Work hardened (H) applies only to wrought products that have been strengthened by work or strain hardening. A subsequent thermal treatment is sometimes used to produce some reduction in strength. The work-hardened condition H is always followed by one digit and sometimes two. The first digit signifies the specific work-hardening process, and the second digit gives the amount of residual hardening.

Solution heat treated (W) applies to products that are solution heat treated. The W condition is unstable since alloys will slowly age at room temperature. Wrought heat treatable alloys are often formed in the W condition since their formability is almost as good as the annealed condition. In this case, they are refrigerated after solution heat treating but before forming to retard natural aging. The refrigeration temperature must be in the range of −45 to −75 °C (−50 to −100 °F).

Solution heated treated and aged (T) applies to products that have been solution heat treated and either aged at room temperature (naturally aged) or aged at elevated temperature (artificially aged). The specific aging treatment is designated with a "T" followed by a number (1 through 10) for the specific aging treatment. Wrought products are also stress relieved after solution treating but before aging, designated as T*x*5*x*. This is conducted by stretching in tension (T*x*51), compression (T*x*52), or a combination of tension and compression (T*x*54). The small amount of stress relief (1 to 5%) reduces warpage during machining and improves the fatigue and stress-corrosion resistance. If the product is an extrusion, a third digit may be used. The number "1" for extruded products indicates the product was straightened by stretching, while

Table 26.4 Temper designations for aluminum alloys

Suffix letter "F," "O," "H," "T," or "W" indicates basic treatment condition	First suffix digit indicates secondary treatment used to influence properties	Second suffix digit for condition H only indicates residual hardening
F—As-fabricated		
O—Annealed-wrought products only		
H—Cold worked, strain hardened		
	1—Cold worked only	2—1/4 hard
	2—Cold worked and partially annealed	4—1/2 hard
	3—Cold worked and stabilized	6—3/4 hard
		8—Hard
		9—Extra hard
W—Solution heat treated		
T—Heat treated, stable		
T1—Cooled from an elevated-temperature shaping operation + natural aged		
T2—Cooled from an elevated-temperature shaping operation + cold worked + natural aged		
T3—Solution treated + cold worked + natural aged		
T4—Solution treated + natural aged		
T5—Cooled from an elevated-temperature shaping operation + artificial aged		
T6—Solution treated + artificial aged		
T7—Solution treated + overaged		
T8—Solution treated + cold worked + artificial aged		
T9—Solution treated + artificial aged + cold worked		
T10—Cooled from an elevated-temperature shaping operation + cold worked + artificial aged		

Source: Ref 3

the number "0" indicates that it was not mechanically straightened.

26.3 Aluminum Alloys

The principal alloying elements in wrought aluminum alloys include copper, manganese, magnesium, silicon, and zinc. Alloys containing copper, magnesium + silicon, and zinc are precipitation hardenable to fairly high strength levels, while those containing manganese or magnesium are hardened primarily by cold working.

26.3.1 Wrought Non-Heat-Treatable Alloys

The wrought non-heat-treatable alloys include the commercially pure aluminum alloys (1*xxx*), the aluminum-manganese alloys (3*xxx*), the aluminum-silicon alloys (4*xxx*), and the aluminum-magnesium alloys (5*xxx*). These alloys cannot be hardened by heat treatment and are therefore hardened by a combination of solid-solution strengthening (Fig. 26.2) and cold working (Fig. 26.3). The chemical compositions of a number of wrought non-heat-treatable alloys are shown in Table 26.5, and representative mechanical properties are given in Table 26.6.

Commercially Pure Aluminum Alloys (1*xxx*). The 1*xxx* alloys normally have tensile strengths in the range of 69 to 186 MPa (10 to 27 ksi). The 1*xxx* series of aluminum alloys include both the superpurity grades (99.99%) and the commercially pure grades containing up to 1 wt% impurities or minor additions. The last two digits of the alloy number denote the two digits to the right of the decimal point of the percentage of the material that is aluminum. For example, 1060 denotes an alloy that is 99.60% Al. The more prevalent commercially pure grades (99.0 wt% minimum aluminum) are available in most product forms and are used for applications such as electrical conductors, chemical processing equipment, aluminum foil, cooking utensils, and architectural products. Since these alloys are essentially free of alloying additions, they exhibit excellent corrosion resistance to atmospheric conditions. The most

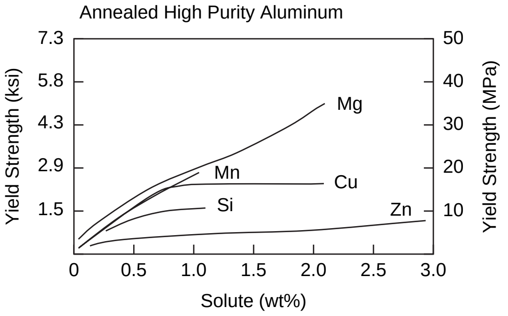


Fig. 26.2 Solid-solution strengthening of aluminum. Source: Ref 4

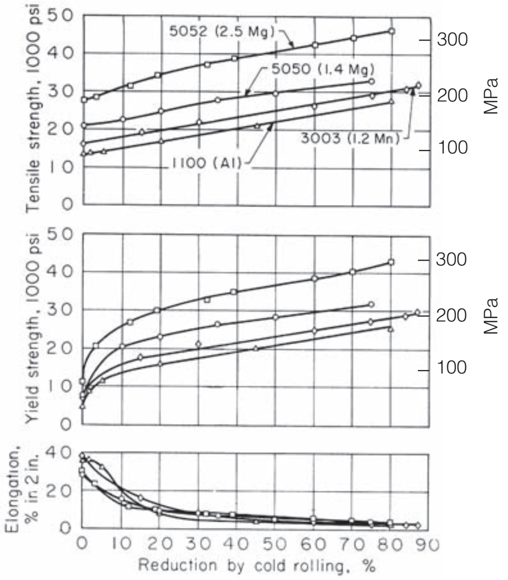


Fig. 26.3 Work-hardening curves for wrought non-heat-treatable aluminum alloys. Source: Ref 5

Table 26.5 Compositions of select wrought non-heat-treatable aluminum alloys

	Alloying element content, wt%			
Alloy	Cu	Mn	Mg	Cr
3003	0.12	1.2	. . .	. . .
3004	. . .	1.2	1.0	. . .
3005	. . .	1.2	0.4	. . .
3105	. . .	0.6	0.5	. . .
5005	. . .	. . .	0.8	. . .
5050	. . .	. . .	1.4	. . .
5052	. . .	. . .	2.5	0.25
5252	. . .	. . .	2.5	. . .
5154	. . .	. . .	3.5	0.25
5454	. . .	0.8	2.7	0.12
5056	. . .	0.12	5.0	0.12
5456	. . .	0.8	5.1	0.12
5182	. . .	0.35	4.5	. . .
5083	. . .	0.7	4.4	0.15
5086	. . .	0.45	4.0	0.15

All contain iron and silicon as impurities. Source: Ref 6 popular 1*xxx* alloy is alloy 1100; it has a tensile strength of 90 MPa (13 ksi), which can be increased to 165 MPa (24 ksi) by work hardening. The 1*xxx* series are also used for electrical applications, primarily alloy 1350, which has relatively tight controls on impurities that would adversely affect electrical conductivity.

Aluminum-Manganese Alloys (3*xxx*). The 3*xxx* alloys are often used where higher strength levels are required along with good ductility and excellent corrosion resistance. The aluminum-manganese alloys contain up to 1.25 wt% Mn; higher amounts are avoided because the presence of iron impurities can result in the formation of large primary particles of Al_6Mn, which causes embrittlement. Additions of magnesium provide improved solid-solution hardening, as in the alloy 3004, which is used for beverage cans, the highest single usage of any aluminum alloys, accounting for approximately 1/4 of the total usage of aluminum. Their moderate strength (ultimate tensile strengths of 110 to 297 MPa, or 16 to 43 ksi) often eliminates their consideration for structural applications. These alloys are welded with 1*xxx*-, 4*xxx*-, and 5*xxx*-series filler alloys, dependening on the specific chemistry, specific application, and service requirements.

Table 26.6 Mechanical properties of select wrought non-heat-treatable aluminum alloys

Alloy	Temper	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %
		MPa	ksi	MPa	ksi	
3003	O	100	16	40	6	30
	H14	125	18	115	17	9
	H18	165	24	150	22	5
3004	O	180	26	70	10	20
	H34	240	35	200	29	9
	H38	285	41	250	36	5
	H19	295	43	285	41	2
3005	O	130	19	55	8	25
	H14	180	26	165	24	7
	H18	240	35	225	33	4
3105	O	115	17	55	8	24
	H25	180	26	160	23	8
	H18	215	31	195	28	3
5005	O	125	18	40	6	25
	H34	160	23	140	20	8
	H38	200	29	185	27	5
5050	O	145	21	55	8	24
	H34	190	28	165	24	8
	H38	220	32	200	29	6
5052	O	195	28	90	13	25
	H34	260	38	265	31	10
	H38	290	42	255	37	7
5252	O	180	26	85	12	23
	H25	235	34	170	25	11
	H28	285	41	240	35	5
5154	O	240	35	115	17	27
	H34	290	42	230	33	13
	H38	330	48	270	39	10
	H12	240	35	115	17	25
5454	O	250	36	115	17	22
	H34	305	44	240	35	10
	H111	250	36	125	18	18
	H112	250	36	125	18	18
5056	O	290	42	150	22	35
	H18	435	63	405	59	10
	H38	415	60	345	50	15
5456	O	310	45	160	23	24
	H112	310	45	165	24	22
	H116	350	51	255	37	16
5182	O	275	40	130	19	21

Source: Ref 6

Aluminum-Silicon Alloys (4*xxx*). The 4*xxx* series of alloys is not as widely used as the 3*xxx* and 5*xxx* alloys. Ultimate tensile strengths range from 172 to 379 MPa (25 to 55 ksi). Because of the relatively high silicon content, the 4*xxx* series has excellent flow characteristics, making them the alloys of choice for two major applications. Alloy 4032 is used for forged pistons; the high silicon content contributes to complete filling of complex dies and provides wear resistance in service. The 4*xxx* alloys are also used for weld and braze filler metals, where the silicon content promotes molten metal flow to fill grooves and joints during welding and brazing. Although aluminum-silicon alloys will not respond to heat treatment, some of the 4*xxx* alloys also contain magnesium or copper, which allows them to be hardened by precipitation heat treating.

Aluminum-Magnesium Alloys (5*xxx*). The 5*xxx* alloys have the highest strengths of the non-heat-treatable alloys, with tensile strengths ranging from 124 to 434 MPa (18 to 63 ksi). They develop moderate strengths when work hardened; have excellent corrosion resistance, even in saltwater; and have very high toughness, even at cryogenic temperatures to near absolute zero. They are readily weldable by a variety of techniques, at thicknesses up to 20 cm (8 in.). Since aluminum and magnesium form solid solutions over a wide range of compositions, alloys containing magnesium in amounts from 0.8 to approximately 5 wt% are widely used. The 5*xxx*-series alloys have relatively high ductility, usually in excess of 25%.

The 5*xxx* alloys, although still having very good overall corrosion resistance, can be subject to intergranular and stress-corrosion cracking attack. In alloys with more than 3 to 4 wt% Mg, there is a tendency for the β phase (Mg_5Al_8)

to precipitate at the grain boundaries, making the alloy susceptible to grain-boundary attack. The precipitation of β occurs slowly at room temperature but can accelerate at elevated temperatures or under highly work-hardened conditions. A second problem that can be encountered with the 5*xxx* alloys is one of age softening at room temperature; that is, over a period of time, there is some localized recovery within the work-hardened grains. To avoid this effect, a series of H3 tempers is used in which the alloy is work hardened to a slightly greater level and then subjected to a stabilization aging treatment at 120 to 150° C (250 to 300 °F). This treatment also helps reduce the tendency for β precipitation.

The 5*xxx* alloys are used extensively in the transportation industries for boat and ship hulls; dump truck bodies; large tanks for carrying gasoline, milk, and grain; and pressure vessels, especially where cryogenic storage is required. The weldability of these alloys is excellent, and they have excellent corrosion resistance.

26.3.2 Wrought Heat Treatable Alloys

The wrought heat treatable alloys include the aluminum-copper (2*xxx*) series, the aluminum-magnesium-silicon series (6*xxx*), the aluminum-zinc (7*xxx*) series, and the aluminum-lithium alloys of the 8*xxx* series. These alloys are strengthened by precipitation hardening, which is covered in more detail in Chapter 9, "Precipitation Hardening," in this book. The importance of precipitation hardening of aluminum alloys can be appreciated by examining the data presented in Fig. 26.4 for naturally aged 2024 and artificially aged 7075. Note the dramatic increase in strength of both due to precipitation hardening, with only moderate reductions in elongation. The chemical compositions of a number of the wrought heat treatable aluminum alloys are given in Table 26.7, and the mechanical properties of a number of alloys are shown in Table 26.8.

Aluminum-Copper Alloys (2*xxx*). The high-strength 2*xxx* and 7*xxx* alloys are competitive on a strength-to-weight ratio with the higher-strength but heavier titanium and steel alloys and thus have traditionally been the dominant structural material in both commercial and military aircraft. In addition, aluminum alloys are not embrittled at low temperatures and become even stronger as the temperature is decreased, without significant ductility losses, making them ideal for cryogenic fuel tanks for rockets and launch vehicles.

The wrought heat treatable 2*xxx* alloys generally contain magnesium in addition to copper as an alloying element. Other significant alloying additions include titanium to refine the grain

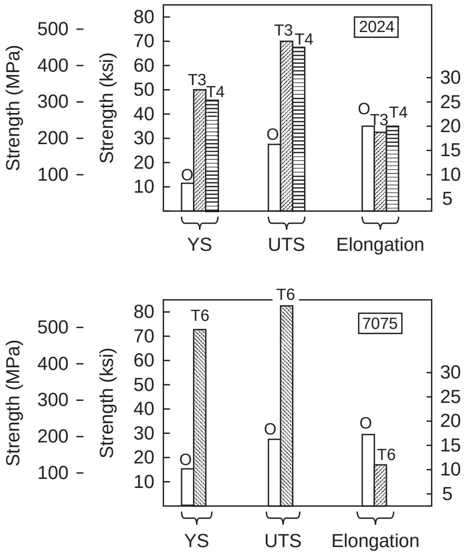


Fig. 26.4 Effect of heat treatment on 2024 and 7075. YS, yield strength; UTS, ultimate tensile strength. Source: Ref 7

Table 26.7 Compositions of select wrought heat treatable aluminum alloys

	Alloying element content, wt%							
Alloy	Fe	Si	Cu	Mn	Mg	Cr	Zn	Zr
2008	0.40(a)	0.65	0.9	0.3(a)	0.4	...	...	...
2219(b)	0.30(a)	0.20(a)	6.3	0.3	...	...	...	0.18
2519(b)	0.39(a)(c)	0.30(a)(c)	5.8	0.3	0.25	...	...	0.18
2014	0.7(a)	0.8	4.4	0.8	0.5	...	...	...
2024	0.50(a)	0.50(a)	4.4	0.6	1.5	...	...	...
2124	0.30(a)	0.20(a)	4.4	0.6	1.5	...	...	...
2224	0.15(a)	0.12(a)	4.4	0.6	1.5	...	...	...
2324	0.12(a)	0.10(a)	4.4	0.6	1.5	...	...	...
2524	0.12(a)	0.06(a)	4.25	0.6	1.4	...	...	...
2036	0.50(a)	0.50(a)	2.6	0.25	0.45	...	...	...
6009	0.50(a)	0.8	0.4	0.5	0.6	...	...	...
6061	0.7(a)	0.6	0.3	...	1.0	0.2	...	...
6063	0.50(a)	0.4	...	...	0.7	...	...	...
6111	0.4(a)	0.9	0.7	0.3	0.8	...	...	...
7005	0.40(a)	0.35(a)	...	0.45	1.4	0.13	4.5	0.14
7049	0.35(a)	0.25(a)	1.6	...	2.4	0.16	7.7	...
7050	0.15(a)	0.12(a)	2.3	...	2.2	...	6.2	0.12
7150	0.15(a)	0.10(a)	2.2	...	2.4	...	5.4	0.12
7055	0.15(a)	0.10(a)	2.3	...	2.1	...	8.0	0.12
7075	0.50(a)	0.40(a)	1.6	...	2.5	0.25	5.6	...
7475	0.12(a)	0.10(a)	1.6	...	2.2	0.20	5.7	...

(a) Maximum allowable amount.

(b) 2219 and 2519 also contain 0.10% V and 0.06% Ti.

(c) 0.40% max Fe plus Si. Source: Ref 6

structure during ingot casting, and transition element additions (manganese, chromium, and/or zirconium) that form dispersoid particles ($Al_{20}Cu_2Mn_3$, $Al_{18}Mg_3Cr_2$, and Al_3Zr), which help control the wrought grain structure. Iron and silicon are considered impurities and are held to an absolute minimum, because they form intermetallic compounds (Al_7Cu_2Fe and Mg_2Si) that are detrimental to both fatigue and fracture toughness.

Due to their superior damage tolerance and good resistance to fatigue crack growth, the 2*xxx* alloys are used for aircraft fuselage skins for lower wing skins on commercial aircraft. The 7*xxx* alloys are used for upper wing skins, where strength is the primary design driver. The alloy 2024-T3 is normally selected for tension-tension applications because it has superior fatigue performance in the 10^5 cycle range as compared to the 7*xxx* alloys.

Alloy 2024 has been the most widely used of the 2*xxx* series, although there are now newer alloys with better performance. Alloy 2024 is normally used in the solution-treated, cold-worked, and then naturally aged condition (T3 temper). Cold working is achieved at the mill by roller or stretcher rolling, which helps to produce flatness along with 1 to 4% strains. It has a moderate yield strength (448 MPa, or 65 ksi) but good resistance to fatigue crack growth and fairly high fracture toughness. Another common heat treatment for 2024 is the T8 temper (solution treated, cold worked, and artificially aged). Like the T3 temper, cold working prior to aging helps in nucleating fine precipitates and reduces the number and size of grain-boundary precipitates. In addition, the T8 temper reduces the susceptibility to stress-corrosion cracking.

One of the developments that led to improved properties in the high-strength 2*xxx* and 7*xxx* aluminum alloys is impurity control, specifically the reduction in the impurities iron and silicon. While 2024 has a combined iron and silicon

Table 26.8 Mechanical properties of select wrought heat treatable aluminum alloys

Alloy	Temper	Product form	Tensile strength		Yield strength		Elongation in 50 mm (2 in.), %
			MPa	ksi	MPa	ksi	
2008	T4	Sheet	250	36	125	18	28
	T6	Sheet	300	44	240	35	13
2014	T6, T651	Plate, forging	485	70	415	60	13
2024	T3, T351	Sheet, plate	450	65	310	45	18
	T361	Sheet, plate	495	72	395	57	13
	T81, T851	Sheet, plate	485	70	450	65	6
	T861	Sheet, plate	515	75	490	71	6
2224	T3511	Extrusion	530	77	400	58	16
2324	T39	Plate	505	73	415	60	12
2524	T3, T351	Sheet, plate	450	65	310	45	21
2036	T4	Sheet	340	49	195	28	24
2219	T81, T851	Sheet, plate	455	66	350	51	10
	T87	Sheet, plate	475	69	395	57	10
2519	T87	Plate	490	71	430	62	10
6009	T4	Sheet	220	32	125	18	25
	T62	Sheet	300	44	260	38	11
6111	T4	Sheet	285	41	165	24	25
	T6	Sheet	350	51	310	45	10
6061	T6, T6511	Sheet, plate, extrusion, forging	310	45	275	40	12
	T9	Extruded rod	405	59	395	57	12
6063	T5	Extrusion	185	27	145	21	12
	T6	Extrusion	240	35	215	31	12
7005	T5	Extrusion	350	51	290	42	13
7049	T73	Forging	540	78	475	69	10
7050	T74, T745X	Plate, forging, extrusion	520	74	450	65	13
7150	T651, T6151	Plate	600	87	560	81	11
	T77511	Extrusion	650	94	615	89	12
7055	T7751	Plate	640	93	615	89	10
	T77511	Extrusion	670	97	655	95	11
7075	T6, T651	Sheet, plate	570	83	505	73	11
	T73, T735X	Plate, forging	505	73	435	63	13
7475	T7351	Plate	505	73	435	63	15
	T7651	Plate	455	66	390	57	15

Source: Ref 6

impurity level of 0.50 wt%, the newer alloy 2224 contains a maximum iron and silicon level of only 0.22 wt%. This lower fraction of impurities produces a better combination of strength and fracture toughness (Fig. 26.5). Other improvements for the plate materials include increasing the amount of cold work by stretching after quenching and the development of improved aging procedures.

The high-strength 2*xxx* alloys, which usually contain approximately 4 wt% Cu, are the least corrosion resistant of the aluminum alloys. Therefore, sheet products are usually clad on both surfaces with a thin layer of an aluminum alloy containing 1 wt% Zn. Since the clad is anodic to the underlying core alloy, it preferentially corrodes, leaving the core protected. The clad, which amounts to 1.5 to 10% of the thickness, is applied during hot rolling. Since the clad is weaker than the core alloy, there is a slight sacrifice in mechanical properties, especially fatigue cracking resistance.

Aluminum-Magnesium-Silicon Alloys (6*xxx*). The combination of magnesium (0.6 to 1.2 wt%) and silicon (0.4 to 1.3 wt%) in aluminum forms the basis of the 6*xxx* precipitation-hardenable alloys. During precipitation hardening, the intermetallic compound Mg_2Si provides the strengthening. Manganese or chromium is added to most 6*xxx* alloys for increased strength and grain size control. Copper also increases the strength of these alloys, but if present in amounts over 0.5 wt%, it reduces the corrosion resistance. These alloys are widely used throughout the welding fabrication industry, are used predominantly in the form of extrusions, and are incorporated in many structural components.

The 6*xxx* alloys are heat treatable to moderately high strength levels, have better corrosion resistance than the 2*xxx* and 7*xxx* alloys, are weldable, and offer superior extrudability. With a yield strength comparable to that of mild steel, 6061 is one of the most widely used of all aluminum alloys. The highest strengths are obtained when artificial aging is started immediately after quenching. Losses of 21 to 28 MPa (3 to 4 ksi) in strength occur if these alloys are room-temperature aged for 1 to 7 days. Alloy 6063 is widely used for general-purpose structural extrusions because its chemistry allows it to be quenched directly from the extrusion press. Alloy 6061 is used where higher strength is required, and 6071 where the highest strength is required.

The 6*xxx* alloys can be welded, while most of the 2*xxx* and 7*xxx* alloys have very limited weldability. However, these alloys are solidification crack sensitive and should not be arc welded without filler material. The addition of adequate amounts of filler material during arc welding processes is essential to prevent base metal dilution, thereby preventing the hot cracking problem. They are welded with both

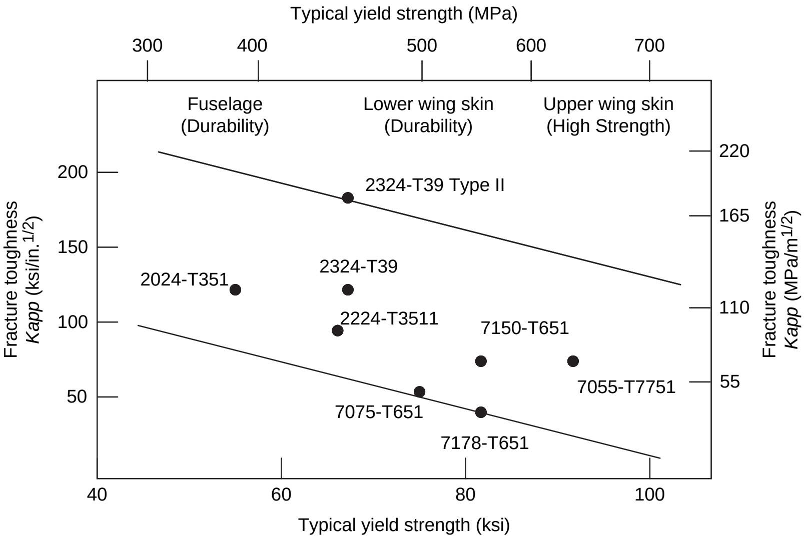


Fig. 26.5 Fracture toughness versus yield strength for high-strength aluminum alloys. Source: Ref 8

4*xxx* and 5*xxx* filler materials, depending on the application and service requirements.

Although the 6*xxx* alloys have not traditionally been able to compete with the 2*xxx* and 7*xxx* alloys in applications requiring high strength, a relatively new alloy (6013-T6) has 12% higher strength than clad 2024-T3, with comparable fracture toughness and resistance to fatigue crack growth rate, and it does not have to be clad for corrosion protection.

Aluminum-Zinc Alloys (7*xxx*). The wrought heat treatable 7*xxx* alloys are even more responsive to precipitation hardening than the 2*xxx* alloys and can obtain higher strength levels, approaching tensile strengths of 690 MPa (100 ksi). These alloys are based on the Al-Zn-Mg(-Cu) system. The 7*xxx* alloys can be naturally aged but are not because they are not stable if aged at room temperature; that is, their strength will gradually increase with increasing time and can continue to do so for years. Therefore, all 7*xxx* alloys are artificially aged to produce a stable alloy.

Although the Al-Zn-Mg alloys cannot attain as high a strength level as those containing copper, they have the advantage of being weldable. In addition, the heat provided by the welding process can serve as the solution heat treatment, and they will age at room temperature to tensile strengths of approximately 310 MPa (45 ksi). The yield strengths may be as much as twice that of the commonly welded alloys of the 5*xxx* and 6*xxx* alloys. To reduce the chance of stress-corrosion cracking, these alloys are air quenched from the solution heat treating temperature and then overaged. Air quenching reduces residual stresses and reduces the electrode potential in the microstructure. The aging treatment is often a duplex aging treatment of the T73 type. The commonly welded alloys in this series, such as 7005, are predominantly welded with the 5*xxx*-series filler alloys.

The Al-Zn-Mg-Cu alloys attain the highest strength levels when precipitation hardened. Since these alloys contain up to 2 wt% Cu, they are the least corrosion resistant of the series. However, copper additions reduce the tendency for stress-corrosion cracking because they allow precipitation hardening at higher temperatures. As a class, these alloys are not weldable and are therefore joined with mechanical fasteners. The best known of these alloys is alloy 7075.

Some of the newer alloys have been produced to optimize their fracture toughness and resistance to corrosion, primarily stress-corrosion cracking and exfoliation corrosion. This has been accomplished through a combination of compositional control and processing, primarily through the development of new overaging heat treatments. As for some of the newer 2*xxx* alloys, reduced iron and silicon impurity levels are used to maximize fracture toughness. As an example, the older 7075 alloy contains a total iron and silicon content of 0.90 wt%, while it has been reduced to a maximum of only 0.22 wt% in 7475. The improvement in fracture toughness with reduced impurity levels is shown in Table 26.9, where the newer alloys 7149 and 7249 have higher fracture toughness values that the original 7049 composition.

One of the problems with 7075 and similar alloys when they are heat treated to the peak-aged T6 temper has been stress-corrosion cracking (SCC). Thick plate, forging, and extrusions of these alloys are particularly vulnerable when stressed in the through-the-thickness (short-transverse) direction. In response to these in-service failures, a number of overaged T7 tempers have been developed. Although there is some sacrifice in strength properties, they have dramatically reduced the occurrence of SCC failures. The T73 temper reduces the yield strength of 7075 by 15% but increases the SCC threshold stress by a factor of 6. Additional overaged tempers (T74, T75, and T77) have been developed that provide trade-offs in strength and SCC and exfoliation corrosion resistance. The T77 temper, developed by Alcoa, is of particular interest because

Table 26.9 Effect of impurity content on high-strength aluminum extrusions

	Composition, wt %			Fracture toughness yield strength		Fracture toughness ultimate tensile strength		Elongation, %	K_{Ic}	
Alloy and temper	Si max	Fe max	Mn max	MPa	ksi	MPa	ksi		$MPa \cdot m^{1/2}$	$ksi \cdot in.^{1/2}$
7049-T73511	0.25	0.35	0.35	503	73	552	80	11.6	26	24
7149-T73511	0.15	0.20	0.20	517	75	565	82	13.3	33	30
7249-T73511	0.20	0.12	0.12	531	77	579	84	13.3	37	34

Source: Ref 9

it maintains strength levels close to the T6 temper. This temper is a variation of a treatment called retrogression and reaging and produces the best combination of mechanical properties and corrosion resistance. Although the specific heat treatment parameters depend on the alloy composition, the part is first heat treated to the T6 temper. It is then reheated to approximately 205 °C (400 °F) for 1 h, water quenched, and reaged again for 24 h at 120 °C (250 °F).

Other Aluminum Alloys (8*xxx*). The 8*xxx* series is reserved for those alloys with less commonly used alloying elements, such as iron, nickel, and lithium. A series of electrical conductor alloys contains iron and nickel for strength, with only a minimal loss in conductivity. A number of aluminum-iron alloys have been studied for high-temperature applications. In addition, the 8*xxx* series, along with the 2*xxx* series, contains some of the high-strength aluminum-lithium alloys that have been evaluated for aerospace applications.

Aluminum-lithium alloys, part of both the 2*xxx* and 8*xxx* alloy series, are attractive for aerospace applications, owing to their reduced densities and higher elastic moduli. Lithium is an even lighter element than aluminum, and each 1 wt% of lithium alloyed with aluminum reduces the density by 3%. In addition, lithium additions increase the elastic modulus of aluminum alloys, with each 1 wt% Li producing an increase in the modulus by approximately 6%. However, lithium is a very active metal, making melting and casting difficult and expensive. Aluminum-lithium alloys cost approximately three times as much as conventional competitive high-strength aluminum alloys.

Aluminum-lithium alloys were initially produced as early as the 1950s and have progressed through several generations of improvements. The so-called second-generation alloys that were produced in the 1980s were designed as drop-in replacements for existing high-strength alloys. These alloys were classified as high strength (2090, 8091), medium strength (8090), and damage tolerant (2091, 8090). These alloys contain 1.9 to 2.7 wt% Li, which results in approximately a 10% lower density and 25% higher specific stiffness than equivalent 2*xxx* and 7*xxx* alloys. One of the major initial applications was for structural members on the C-17 transport aircraft. However, due to property and manufacturing problems, they were removed and replaced with conventional high-strength aluminum alloys. Technical problems included excessive anisotropy in the mechanical properties, lower-than-desired fracture toughness and ductility, hole cracking and delamination during drilling, and low SCC thresholds. The anisotropy experienced by these alloys is a result of the strong crystallographic textures that develop during processing, with the fracture toughness problem being one of primarily low strength in the short-transverse direction.

A third generation of alloys has been developed with lower lithium contents. One success story is alloy 2195, which has a lower copper content and has replaced 2219 for the cryogenic fuel tank on the space shuttle, where it provides a higher strength, higher modulus, and lower density than 2219.

26.4 Melting and Primary Fabrication

To produce pure aluminum, alumina (Al_2O_3) is first extracted from the mineral bauxite, which contains approximately 50% Al_2O_3. In the Bayer process, a sodium hydroxide solution is used to precipitate aluminum hydroxide, which is then calcined to form alumina. Alumina is then converted to pure aluminum by electrolysis, using the Hall-Héroult process illustrated in Fig. 26.6. The cell is lined with carbon cathodes, and consumable electrodes are gradually fed into the top of the cell. The electrolyte is cryolite (Na_3AlF_6) with 8 to 10 wt% Al_2O_3 dissolved in it. The cell operates at temperatures in the range of 955 to 1010 °C (1750 to 1850 °F), with a power rating of 10 to 12 kW·h/kg aluminum. Pure aluminum (99 wt%) is reduced at the cathode and forms a molten pool in the bottom of the cell, which is drained from the bottom and cast into aluminum ingots. Since impurities such as iron and silicon are reduced along with the aluminum, the raw materials used in the Bayer process are carefully controlled to minimize these metal oxides. Since the production of aluminum takes a lot of electrical energy, and recycling aluminum takes much less energy, a large portion of general-purpose aluminum currently is made from recycled material.

During casting of aluminum alloy ingots, oxides and gases must be controlled. Aluminum oxidizes rapidly in the liquid state and reverts back to alumina. Once the oxide becomes entrapped in the liquid metal, it is difficult to remove and remains dispersed in the liquid metal. The main source of oxygen is moisture from the furnace charge. Oxides are removed by fluxing with gases, solids, or molten salts. Various filtration methods are also used to remove oxides during pouring. Hydrogen is the only gas with appreciable solubility in molten aluminum and can cause blisters in heat treated parts and porosity in aluminum castings. Again, moisture from the furnace charge is the main source of hydrogen. Hydrogen can also be introduced from moisture in the air and products of combustion. Hydrogen is removed by bubbling chlorine, nitrogen, or argon gas through the melt.

The semicontinuous direct-chill process is the mostly widely used process for casting commercial ingots that will receive further processing, such as rolling, extrusion, or forging. It produces fine-grained ingots at high production rates. As shown in Fig. 26.7, the molten aluminum is poured into a shallow, water-cooled mold of the required shape. When the metal begins to freeze, the false bottom in the mold is lowered at a controlled rate, and water is sprayed on the freshly solidified metal as it exits the mold. A water box or spray rings are placed around the ingot to rapidly cool the ingot. Metals with low melting points, such as magnesium, copper, and zinc, are added directly to the molten charge, while high-melting-point elements (e.g., titanium, chromium, zirconium, and manganese) are added as master alloys. Inoculants, such as titanium and titanium-boron, are added to reduce hot cracking and refine grain size.

One of the main advantages of direct-chill continuous casting is that it helps to eliminate the segregation that occurs in high-strength alloys produced by the older tilt-casting procedures. These alloys, when produced by tilt casting, are highly segregated because of the broad solidification temperature ranges and the shape of the freezing front. Direct-chill casting eliminates most of this type of segregation because the liquid metal freezing front is almost horizontal, and the liquid metal freezes from the bottom to the top of the ingot. During direct-chill casting, the pouring temperature is maintained at only approximately 28 °C (50 °F) above the liquidus temperature; this helps reduce oxide formation and hydrogen pickup and produces a fine-grained structure. It can also produce fairly large ingots at slow speeds, a necessary requirement for the high-strength alloys to prevent cracking. Typical casting speeds are in the range of 2.5 to 13 cm/min (1 to 5 in./min).

26.4.1 Rolling Plate and Sheet

Rolled aluminum is the most common of the wrought aluminum product forms. Sheet is defined as rolled aluminum in the range of 0.15 to 6.3 mm (0.006 to 0.250 in.) thick. If the thickness is greater than 6.3 mm (0.250 in.), then it is called plate. Foil refers to aluminum product that is less than 0.15 mm (0.006 in.) thick. Aluminum foil, sheet, and plate are

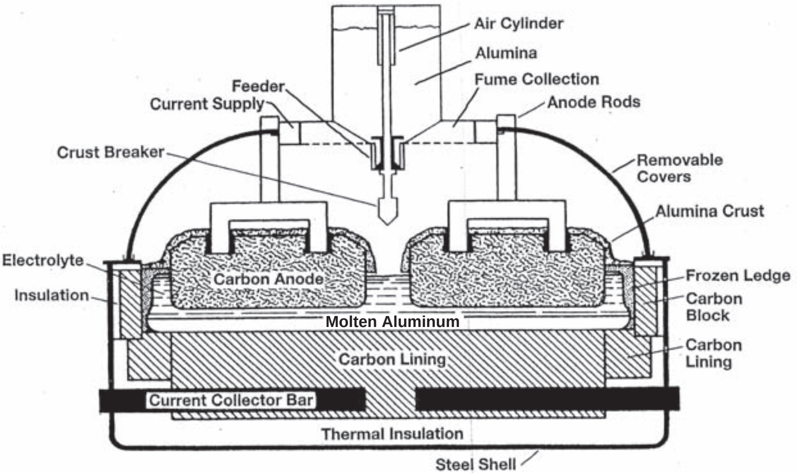


Fig. 26.6 Electrolytic cell used to produce aluminum. Courtesy of Alcoa, Inc.

produced from aluminum ingots using the following steps:

1. Scalping of the ingot
2. Preheating and homogenizing the ingot
3. Reheating the ingot, if required, to the hot rolling temperature
4. Hot rolling to form a slab
5. Intermediate annealing
6. Cold rolling along with intermediate anneals to form foil and sheet product forms

Scalping of Ingots. To prevent surface defects on the cast ingot from being rolled into the surface, approximately 6.3 to 9.5 mm (0.250 to 0.375 in.) are removed from the surfaces to be rolled. Some alloys, such as 1100, 3003, and 3015, have fairly smooth as-cast surfaces and do not require scalping. Other, more highly alloyed ingots, such as magnesium-containing alloys and high-strength aircraft alloys, are always scalped.

Preheating or homogenizing puts into solid solution all the constituents that are soluble and reduces the coring that occurs during the casting process. It relieves stresses in the ingot and makes the cast structure more uniform and more readily hot worked. Soaking temperatures and times depend on the specific alloy. For example, 1100 aluminum is soaked for approximately 1 h at 455 to 510 °C (850 to 950 °F), while 7075 requires up to 24 h at 455 to 470 °C (850 to 875 °F). Ingots that are going to be clad during hot rolling are scalped after preheating to avoid the heavy oxidation that occurs during the long preheating cycle. This allows the cladding to form a better bond during hot rolling.

Hot rolling conducted above the recrystallization temperature produces a fine grain structure

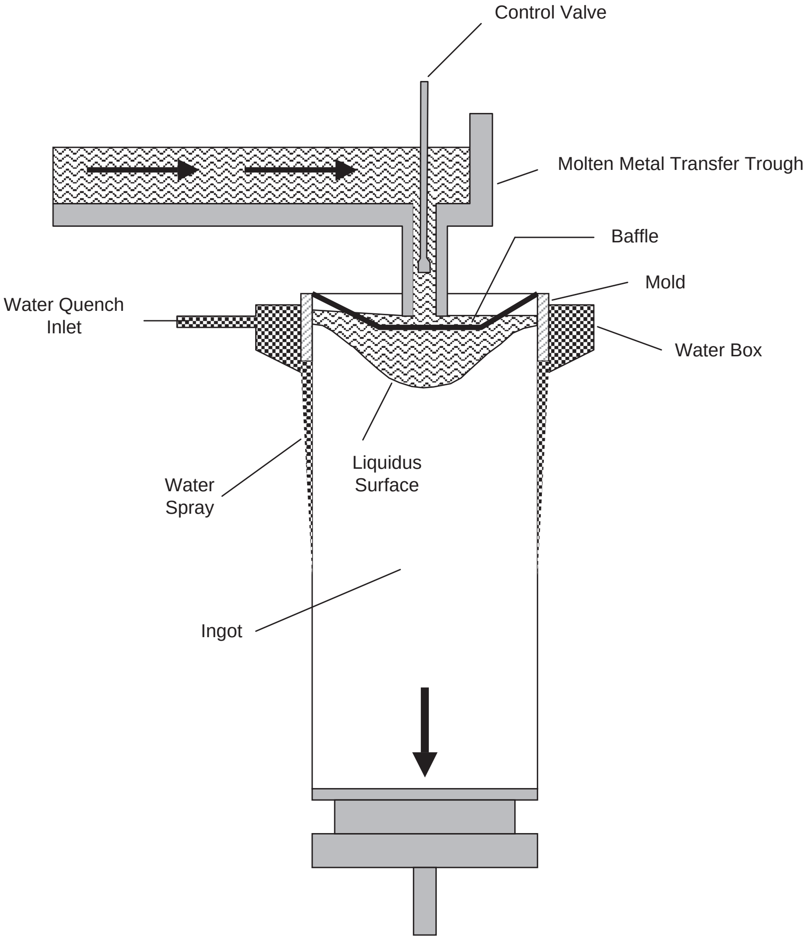


Fig. 26.7 Semi-continuous direct-chill casting. Source: Ref 10

and a minimum of grain directionality. The upper limit is set by the lowest-melting-point eutectic present in the alloy, while the lower temperature is the temperature at which the metal is hot enough to be sufficiently reduced with each pass through the mill without cracking. The ingot is removed from the soaking pit and initially put through a series of four-high rolling mills to break down the ingot structure. Breakdown temperatures are in the range of 400 to 540 °C (750 to 1000 °F), with continuous rolling temperatures of approximately 290 to 455 °C (550 to 850 °F). Since the work rapidly lengthens in the direction of rolling, it is necessary to remove the slab from the mill, turn it around, and then cross roll it to produce wide sheet or plate. The grain structure becomes elongated in the rolling direction, as shown in Fig. 26.8. This results in anistropic mechanical properties in which the properties are lowest in the through-the-thickness (short-transverse) direction. Rolling into thinner plate and sheet is then conducted on five-stand four-high mills, with successive reductions at each mill. Aluminum sheet stock, which can exit the last mill at speeds approaching 485 km/h (300 mph), is coiled into large coils prior to cold rolling.

Intermediate Annealing. Since hot rolling produces some cold work, coiled aluminum sheet stock is given an intermediate anneal prior

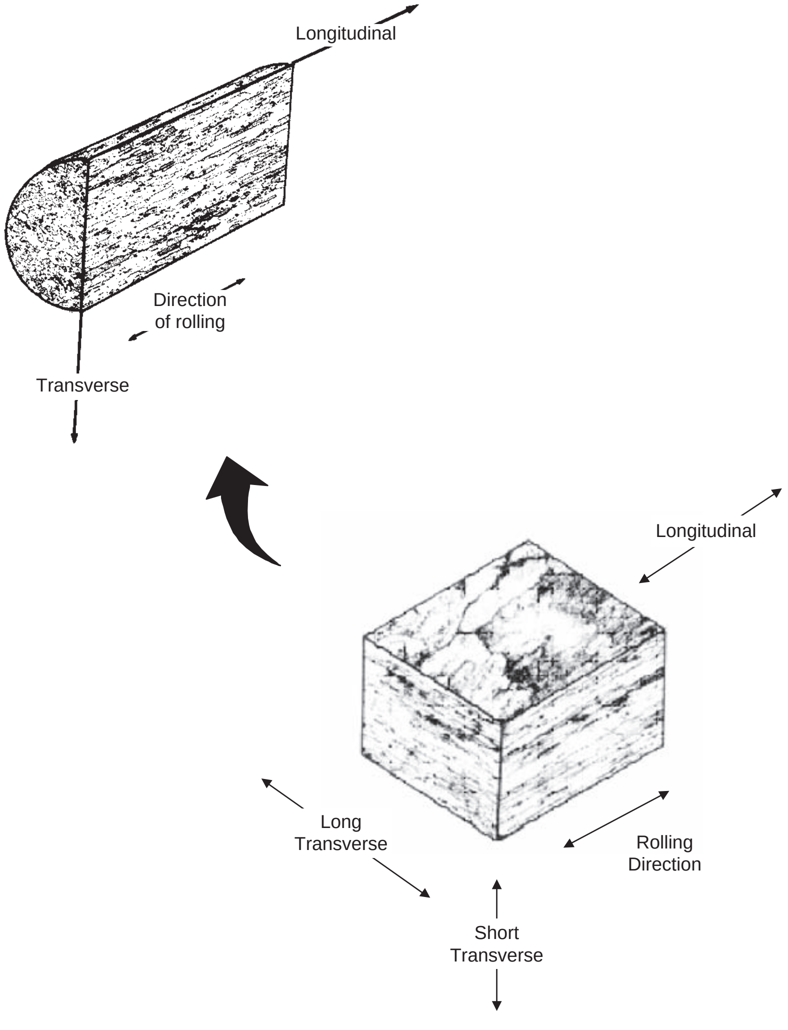


Fig. 26.8 Grain directionality due to rolling. Original magnification at 40×. Source: Ref 11

to cold rolling. Since the amount of cold work introduced during hot rolling is sufficient to cause recrystallization, annealing not only lowers the strength and increases ductility, it also imparts a fine grain structure.

Cold Rolling. Sheet and foil are cold rolled after hot rolling to produce a much better surface finish and control the strength and ductility through work hardening. Again, four-high mills are used along with lubricants and, if a bright surface finish is required, polished rolls. Depending on the amount of reduction and the final strength required, intermediate anneals are conducted during the cold rolling process. Normally, reductions in the range of 45 to 85% are taken between anneals.

26.4.2 Extrusion

Both cold and hot extrusion methods are used to produce extruded aluminum shapes. Cold or impact extrusions are made by a single sharp blow of a punch into a die cavity that contains a blank or slug of the correct size and shape. Almost all aluminum alloys can be formed by impact extrusion. The slugs are annealed and then generally impact extruded at room temperature, although the temperature may rise to as much as 230 °C (450 °F) due to the extensive plastic deformation. The slugs are also lubricated prior to extrusion to prevent excessive galling and die wear.

Direct hot extrusion is used to make structural shapes. In the direct extrusion process, the cylindrical ingot is preheated and then extruded in the temperature range of 340 to 510 °C (650 to 950 °F), depending on the specific alloy. The preheated ingot is placed in a hydraulic press and squeezed at high pressure through a steel die to produce the desired shape. During extrusion, the metal flows most rapidly at the center of the ingot. Since oxide and surface defects are left in the last 10 to 15% of the ingot, this part of the ingot (called the butt) is discarded. The 6*xxx*-series alloys, because of their easy extrudability, are the most popular alloys for producing shapes. The 2*xxx*- and 7*xxx*-series alloys are used in applications requiring higher strength; however, these alloys are more difficult to extrude.

26.5 Casting

Aluminum castings can offer significant cost savings by reducing the number of components and the associated assembly cost. Three types of casting processes are used extensively for aluminum alloys: sand casting for small numbers of large pieces, permanent mold casting for small and medium part sizes, and die castings for small parts where a large quantity can justify the cost of the die-casting tooling.

26.5.1 Aluminum Casting Alloys

The major attributes of the aluminum casting series are shown in Table 26.10. Although all of the aluminum casting alloys are covered in this section, it should be emphasized that the

Table 26.10 Major attributes of cast aluminum alloys

2*xx.x*: Al-Cu Alloys. The major characteristics of the 2*xx.x* series are:

- Heat treatable; sand and permanent mold castings
- High strength at room and elevated temperatures; some high-toughness alloys
- Approximate ultimate tensile strength range: 131–448 MPa (19–65 ksi)

3*xx.x*: Al-Si + Cu or Mg Alloys. The major characteristics of the 3*xx.x* series are:

- Heat treatable; sand, permanent mold, and die castings
- Excellent fluidity; high-strength/some high-toughness alloys
- Approximate ultimate tensile strength range: 131–276 MPa (19–40 ksi)
- Readily welded

4*xx.x*: Al-Si Alloys. The major characteristics of the 4*xx.x* series are:

- Non-heat-treatable; sand, permanent mold, and die castings
- Excellent fluidity; good for intricate castings
- Approximate ultimate tensile strength range: 117–172 MPa (17–25 ksi)

5*xx.x*: Al-Mg Alloys. The major characteristics of the 5*xx.x* series are:

- Non-heat-treatable; sand, permanent mold, and die
- Tougher to cast; provides good finishing characteristics
- Excellent corrosion resistance, machinability, surface appearance
- Approximate ultimate tensile strength range: 117–172 MPa (17–25 ksi)

7*xx.x*: Al-Zn Alloys. The major characteristics of the 7*xx.x* series are:

- Heat treatable; sand and permanent mold cast (harder to cast)
- Excellent machinability and appearance
- Approximate ultimate tensile strength range: 207–379 MPa (30–55 ksi)

8*xx.x*: Al-Sn Alloys. The major characteristics of the 8*xx.x* series are:

- Heat treatable; sand and permanent mold castings (harder to cast)
- Excellent machinability
- Bearings and bushings of all types
- Approximate ultimate tensile strength range: 103–207 MPa (15–30 ksi)

Source: Ref 1

aluminum-silicon alloys with magnesium and/or copper, the 3*xx.x* alloys, are by far the most widely used of the aluminum casting alloys. The silicon addition greatly increases liquid metal fluidity and produces superior castings. The order of the alloy series in order of decreasing castability is 3*xx.x*, 4*xx.x*, 5*xx.x*, 2*xx.x*, and 7*xx.x*.

Commercially pure aluminum alloys (1*xx.x*) are used only for applications where high electrical conductivity is needed and strength is not very important.

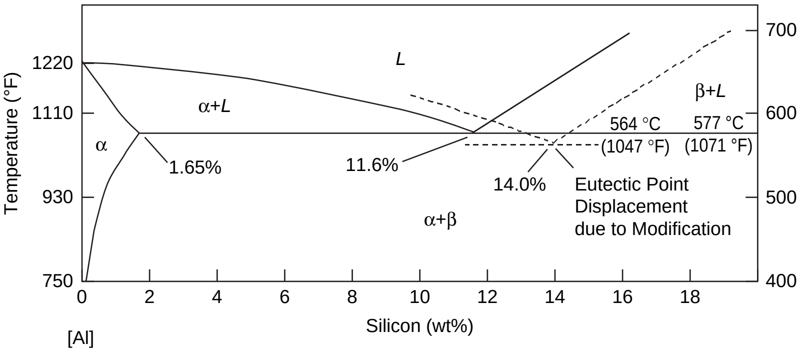
Aluminum-Copper Alloys (2*xx.x*). The heat treatable aluminum-copper alloys that contain 4 to 5 wt% Cu include the highest-strength aluminum castings available and are often used for premium-quality aerospace products. The ductility can also be quite good, if prepared from ingot containing less than 0.15 wt% Fe. When these alloys are cast in permanent molds, special gating and risering techniques are required to relieve shrinkage stresses. However, when done correctly, the aluminum-copper alloys are capable of producing high-strength and ductile castings. Aluminum-copper alloys have somewhat marginal castability and are susceptible to SCC when heat treated to high strength levels. Manganese can be added to combine with iron and silicon and reduce the embrittling effect of insoluble phases. However, this reduces the castability. Manganese-containing alloys are mainly sand cast; when they are cast in permanent molds, silicon must be added to increase fluidity and reduce hot shortness, but silicon additions reduce ductility. Aluminum-copper alloys retain reasonable strength at elevated temperatures (up to 315 °C, or 600 °F). The high-temperature strength is a result of copper, nickel, and magnesium additions.

Aluminum-Silicon+Copper and/or Magnesium Alloys (3*xx.x*). The 3*xx.x* alloys are the workhorses of the aluminum casting industry, accounting for more than 95% of all die castings and 80% of all sand and permanent mold castings produced. Silicon is by far the most important alloying element in aluminum casting alloys. Silicon greatly improves the fluidity of molten aluminum, especially when the amount approaches the eutectic composition. Silicon increases fluidity, reduces cracking, and improves feeding to minimize shrinkage porosity.

The most widely used aluminum casting alloys are those containing between 9.0 and 13.0 wt% Si. These alloys are of approximately eutectic composition (Fig. 26.9), which makes them suitable as die-casting alloys, since their freezing range is small. However, they form a rather coarse eutectic structure (Fig. 26.9a) that is refined by a process known as modification, where small amounts of sodium (~0.01% by weight) are added to the melt just before casting. The sodium delays the precipitation of silicon when the normal eutectic temperature is reached and also causes a shift of the eutectic composition toward the right in the phase diagram. Therefore, as much as 14 wt% Si may be present in a modified alloy without any primary silicon crystals forming in the structure (Fig. 26.9b). It is thought that sodium collects in the liquid at its interface with the newly formed silicon crystals, inhibiting and delaying their growth. Thus, undercooling occurs and new silicon nuclei are formed in large numbers, resulting in a relatively fine-grained eutectic structure. Modification raises the tensile strength and the elongation in the manner shown in Fig. 26.10. The relatively high ductility of this cast eutectic alloy is due to the solid-solution phase in the eutectic constituting nearly 90% of the total structure. Therefore, the solid-solution phase is continuous in the microstructure and acts as a cushion against much of the brittleness arising from the hard silicon phase. More recently, modifying with strontium is replacing sodium, because there is less loss during melting due to oxidation or evaporation; overmodification (too much addition) is not a problem because it forms the innocuous compound $SrAl_3Si_3$, and strontium suppresses the formation of large primary silicon particles in hypereutectic alloys.

Aluminum-Silicon alloys (4*xx.x*) are used when good castability and good corrosion resistance are requirements. Alloys of the 4*xx.x* group, based on the binary aluminum-silicon system and containing from 5 to 12 wt% Si, are used in applications where combinations of moderate strength and high ductility and impact resistance are required.

Aluminum-Magnesium Alloys (5*xx.x*). The aluminum-magnesium casting alloys are single-phase binary alloys with moderate-to-high strength and toughness. The aluminum-magnesium alloys have excellent corrosion resistance. High corrosion resistance, especially to seawater and marine atmospheres, is the primary advantage of castings made of these alloys. The best corrosion resistance requires low impurity content (both solid and gases), and



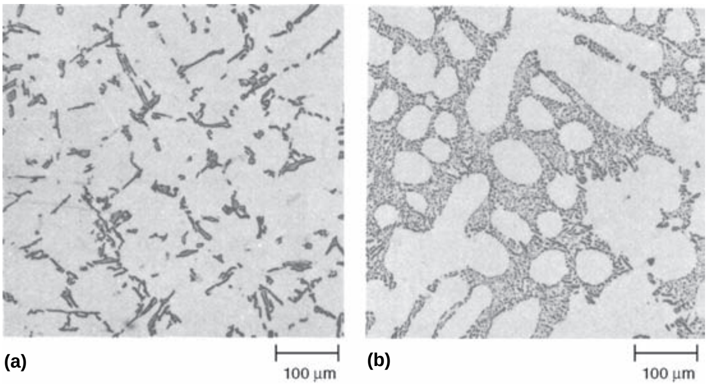


Fig. 26.9 Modification of aluminum-silicon casting alloys. (a) Unmodified. (b) Modified. Original magnification: 100×. Source: Ref 12

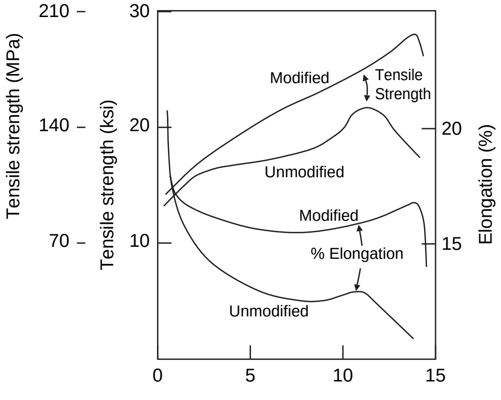


Fig. 26.10 Effects of silicon content and modification on aluminum casting alloy

thus, alloys must be prepared from high-quality metals and handled with great care at the foundry. The aluminum-magnesium alloys lack fluidity, are prone to hot tearing, and have a greater tendency to oxidize when molten. The 5*xx.x* alloys are weldable, have good machinability, and have an attractive appearance when anodized.

Aluminum-Zinc Alloys (7*xx.x*). The aluminum-zinc casting alloys do not have the good fluidity or shrinkage-feeding characteristics of the silicon-containing alloys, and hot cracking can be a problem in large, complex shapes. However, the aluminum-zinc alloys are used where the castings are going to be brazed, because they have the highest melting points of all of the aluminum casting alloys. The 7*xx.x* alloys have moderate-to-good tensile properties in the as-cast condition. Annealing can be used to increase dimensional stability. They are also capable of self-aging at room temperature after casting, reaching quite high strengths after 20 to 30 days. Therefore, they are used in applications requiring moderate-to-high strength levels, where a full solution heating and quenching operation could cause severe warpage or cracking. They have good machinability and resistance to general corrosion but can be somewhat susceptible to SCC. They should not be used at elevated temperatures due to rapid overaging.

Aluminum-Tin alloys (8*xx.x*) are used for cast bearings and bushings where good compression strength is required. Heat treatment to the T5 condition improves their compression strength. Aluminum-tin alloys with approximately 6 wt% Sn, along with copper and nickel additions for strengthening, have excellent lubricity due to the tin content. These alloys can be cast by sand or permanent mold casting, but they are susceptible to hot cracking and therefore have rather poor castability. The best bearing properties are obtained when the casting has a small interdendritic spacing, produced by rapid cooling rates.

26.5.2 Aluminum Casting Control

Molten aluminum alloys are extremely reactive and readily combine with other metals, gas, and sometimes with refractories. Molten aluminum dissolves iron from crucibles; therefore, aluminum is usually melted and handled in refractory-lined containers. For convenience in making up the charge, and to minimize the chance of error, most foundries use standard prealloyed ingot for melting rather than doing their own alloying. Most alloying elements used in aluminum castings, such as copper, silicon, manganese, zinc, nickel, chromium, and titanium, are not readily lost by oxidation, evaporation, or precipitation. Alloying elements that melt at temperatures higher than the melting temperature of aluminum, such as chromium, silicon, manganese, and nickel, are added to the molten metal as alloy-rich ingots or master alloys. Some elements, such as magnesium, sodium, and calcium, which are removed from the molten bath by oxidation and evaporation, are added in elemental form to the molten bath, as required, to compensate for loss.

Because of its reactivity, molten aluminum is easily contaminated. The principal contaminants are iron, oxides, and inclusions. When the iron content exceeds 0.9 wt%, an undesirable acicular grain structure develops in the thicker sections of the casting. When the iron content exceeds 1.2 wt% in the higher-silicon alloys, sludging is likely to occur, particularly if the temperature drops below 650 °C (1200 °F). To prevent sludging, the quantity $\text{wt\%Fe} + 2(\text{wt\%Mn}) + 3(\text{wt\%Cr})$ should not exceed 1.9 wt%. When this quantity exceeds 1.9 wt%, the castings are likely to contain hard spots that impair machining and may initiate stress cracks in service. Iron also causes excessive shrinkage in aluminum castings and becomes more severe as the iron content increases beyond 1 wt%.

Oxides must be removed from the melt; if they remain in the molten metal, the castings will contain harmful inclusions. Magnesium is a strong oxide former, making magnesium-containing alloys difficult to control when melting and casting. Oxides of aluminum and magnesium form quickly on the surface of the molten bath, developing a thin, tenacious skin that prevents further oxidation as long as the surface is not disturbed. Molten aluminum also reacts with moisture to form aluminum oxide, releasing hydrogen. Oxidation is also caused by excessive stirring, overheating of the molten metal, pouring from too great a height, splashing of the metal, or disturbing the metal surface with the ladle before dipping. Oxides that form on the surface of the molten bath can be removed by surface-cleaning fluxes. These fluxes usually contain low-melting-point ingredients that react exothermically on the surface of the bath. The oxides separate from the metal to form a dry, powdery, floating dross that can be skimmed. Some denser oxides sink to the bottom and are removed by gaseous fluxing or through a drain hole located in the bottom of the furnace.

Hydrogen is the only gas that dissolves to any extent in molten aluminum alloys and, if not removed, will result in porosity in the castings. As shown in Fig. 26.11, the solubility of hydrogen is significantly higher in the liquid than in the solid state. During cooling and solidification, the solubility decreases, and hydrogen is precipitated as porosity. Hydrogen is introduced in the molten aluminum by moisture and dirt in the charge and by the products of combustion. Degassing fluxes to remove hydrogen are used after the surface of the bath has been fluxed to remove oxides. The degassing fluxes also help to lift fine oxides and particles to the top of the bath. Removal of hydrogen by degassing is a mechanical action; hydrogen gas does not combine with the fluxing gases. Degassing fluxes include chlorine gas, nitrogen-chlorine mixtures, and hexachloroethane.

The grain size of aluminum alloy castings can be as small as 0.13 mm (0.005 in.) in diameter to as large as 13 mm (0.5 in.) in diameter. Fine-grained castings are desired for several reasons. First, while any porosity is undesirable, coarse porosity is the most undesirable. Since the coarseness of porosity is proportional to grain size, porosity in fine-grained castings is finer and less harmful in fine-grained castings. Second, shrinkage and hot cracking are usually associated with coarse-grained structures. A finer grain size minimizes shrinkage, resulting in sounder castings. Third, the mechanical properties, such as tensile strength and ductility, are better for fine-grained castings than those of coarse-grained castings.

The grain size of aluminum alloy castings is influenced by pouring temperature, solidification rate, and the presence or absence of grain refiners. For all aluminum alloys, the grain size increases as the pouring temperature is increased. This is the main reason that aluminum alloy castings should be poured at the lowest temperature that will produce a sound casting. Rapid solidification rates produce finer grain sizes; therefore, castings done in steel dies will have finer grain sizes due to the faster solidification rates than those produced by sand casting. Grain-refining elements, such as titanium, boron, and zirconium, are helpful in producing finer-grained castings.

26.6 Heat Treating

The most common heat treatments of aluminum alloys are precipitation hardening and annealing. The details of the precipitation-hardening process have previously been covered in Chapter 9, "Precipitation Hardening," in this book. Annealing can be used for both the non-heat-treatable and the precipitation-hardenable grades of wrought and cast alloys. In this chapter, only the specifics of annealing of aluminum alloys are covered.

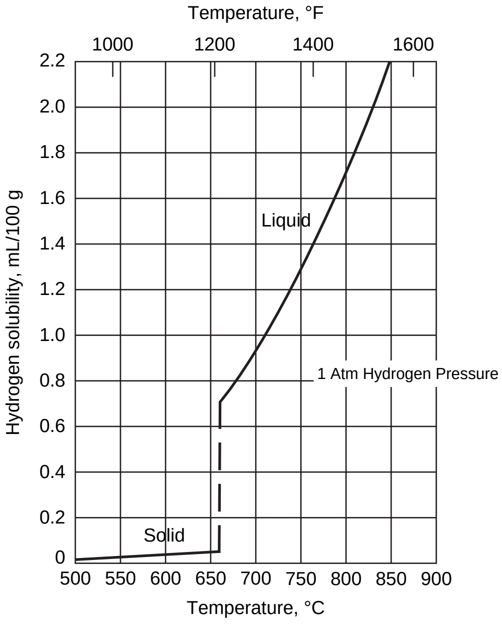


Fig. 26.11 Solubility of hydrogen in aluminum. Source: Ref 13

26.6.1 Annealing

Full annealing (O temper) produces the lowest strength and highest ductility. Cold-worked products will normally undergo recrystallization, while hot-worked products may remain unrecrystallized, depending on the amount of cold work introduced during hot deformation. The recrystallization temperature is not a fixed value; it depends on alloy composition, amount of cold work, rate of heating, and time at temperature.

For both the non-heat-treatable and heat treatable alloys, reduction or elimination of the strengthening effects of cold working is accomplished by heating at temperatures in the range of 260 to 440 °C (500 to 825 °F), depending on the specific alloy. A 1 h soak at a temperature of 345 ± 8 °C (650 ± 15 °F) is a satisfactory annealing treatment for the 1*xxx*- and 5*xxx*-series alloys. Longer times and higher temperatures are necessary for the 3*xxx* alloys. High heating rates to the annealing temperature are desirable to give finer grain structure. The time at temperature depends on the type of anneal, the thickness of the material, the method of furnace loading, and the temperature. The time at temperature for a full anneal is usually 1 h. For heat treatable alloys, the cooling rate should be slow enough so that precipitation reactions do not occur. A cooling rate not exceeding 25 °C/h (50 °F/h) is usually sufficient.

Annealing to remove the effects of cold work is conducted at approximately 345 °C (650 °F). If it is necessary to remove the hardening effects of heat treatment or of cooling from hot working temperatures, a treatment designed to produce a coarse, widely spaced precipitate is used, consisting of soaking at 415 to 440 °C (775 to 825 °F), followed by slow cooling (25 °C/h, or 50 °F/h max) to approximately 260 °C (500 °F). The high diffusion rates during soaking and slow cooling permit maximum coalescence of precipitate particles that result in minimum hardness. In the 7*xxx* alloys, partial precipitation occurs, and a second treatment of soaking at 230 ± 5 °C (450 ± 10 °F) for 2 h is required.

In annealing, it is important to ensure that the proper temperature is reached in all portions of the load; therefore, it is common to specify a soaking period of at least 1 h. The maximum annealing temperature is only moderately critical; however, temperatures exceeding 415 °C (775 °F) can result in oxidation and grain growth. Relatively slow cooling, in still air or in the furnace, is recommended for all alloys to minimize distortion.

Stress-relief anneals are used to reduce stresses without causing recrystallization. Temperatures in the range of 220 °C (425 °F) will produce a reasonable degree of stress relief. The 5*xxx* series of alloys tend to soften at room temperature after cold working. They are normally given stabilization anneals at the mill by heating to 120 to 150 °C (250 to 300 °F) to ensure the stability of mechanical properties after shipment.

26.7 Fabrication

Aluminum alloys are forged using hammers, mechanical presses, and hydraulic presses. Forging is conducted in the range of 360 to 470 °C (680 to 880 °F), depending on the specific alloy. Somewhat surprisingly, aluminum alloys generally require greater working forces for an equal amount of deformation than low-carbon steels, due to the difference in flow stress levels at their optimal hot working temperatures. Therefore, equipment used for forging aluminum must supply higher forces than that used for the low-carbon steels. For larger and more complex parts, hydraulic presses are preferred.

As a result of their face-centered cubic crystalline structure and their relatively low rates of work hardening, aluminum alloys are readily formable at room temperature. The choice of temper for forming depends on the severity of the forming operation and the alloy being formed. Aluminum alloys can be readily formed at room temperature in either the O or W temper. For alloys formed in the W (solution heat treated) temper, it is normal practice to refrigerate the solution heat treated material to prevent natural aging before forming.

Aluminum alloys are extremely easy to machine. Cutting speeds as high as 5 surface m/s (1000 surface ft/min) are common. The implementation of high-speed machining during the 1990s allowed even higher metal removal rates; three times greater metal removal rates are typical. In addition, since the cuts are light, most of the heat is removed with the chips. This allows extremely thin walls and webs to be machined without distortion. The significance is that parts that once had to be assembled from many formed pieces can now be machined from a single block of aluminum, resulting in a weight-competitive assembly at a large cost savings. A comparison of a sheet metal built-up assembly and a high speed machine integral assembly is shown in Fig. 26.12.

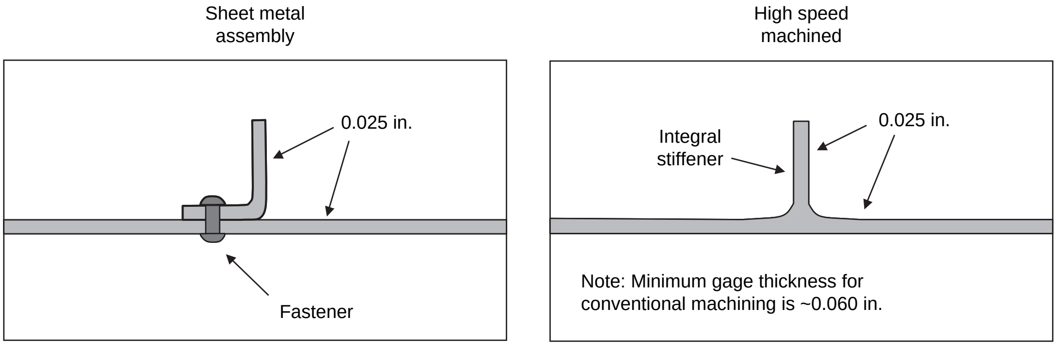
As a metal class, aluminum alloys are rather difficult to weld but can be welded by gas metal arc welding, gas tungsten arc welding, and resistance welding. The 2*xxx* and copper-containing 7*xxx* are either very difficult to weld or unweldable by conventional arc welding methods. However, a relatively new process, called friction stir welding, illustrated in Fig. 26.13, is capable of welding even the most difficult of the aluminum alloys. In this process, the weld joint never becomes a true liquid; it is a solid-state process.

26.8 Corrosion

The corrosion and oxidation resistance of aluminum is due to a very adherent oxide film (Al_2O_3) that immediately forms on exposure to air. Aluminum is corrosion resistant in neutral solutions but is attacked by both basic and acidic solutions. Most, but not all, aluminum alloys are less corrosion resistant than pure aluminum. General corrosion resistance of aluminum alloys is usually an inverse function of the amount of copper used in the alloy. Thus, the 2*xxx*-series alloys are the least corrosion-resistant alloys, since copper is their primary alloying element and all have appreciable (approximately 4 wt%) levels of copper.

Some 7*xxx* series alloys contain approximately 2 wt% Cu in combination with magnesium and zinc to develop strength. Such alloys are the strongest but least corrosion resistant of their series. Low-copper aluminum-zinc alloys, such as 7005, are also available and have become more popular recently. However, copper does have a beneficial effect on the SCC resistance of the 7*xxx* alloys by allowing them to be precipitated at higher temperatures without loss of strength in the T73 temper.

Among the 6*xxx*-series alloys, higher copper content (1 wt% in 6066) generally decreases



Sheet metal assembly

High speed machined

Note: Minimum gage thickness for conventional machining is ~0.060 in.

Was	
Number of Pieces	44
Number of Tools	53
Design and Fabrication hr (Tools)	965
Fabrication hr	13.0
Assembly Manhours	50
Weight (lb)	9.58

Now	
Number of Pieces	6
Number of Tools	5
Design and Fabrication hr (Tools)	30
Fabrication hr	8.6
Assembly Manhours	5.3
Weight (lb)	8.56

Fig. 26.12 Comparison between assembled and high-speed machined assembly

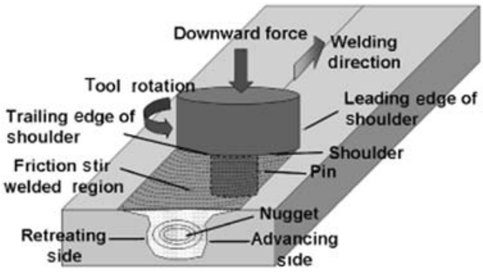


Fig. 26.13 Friction stir welding process. Source: Ref 14

corrosion resistance, but most 6*xxx*-series alloys contain little copper. Some other alloying elements also decrease corrosion resistance. Lead (added to 2011 and 6262 for machinability), nickel (added to 2018, 2218, and 2618 for elevated-temperature service), and tin (used in 8*xx.x* castings) tend to decrease the corrosion resistance but not enough to matter in most applications. Many of the 5*xxx*-series alloys have corrosion resistance as good as commercially pure aluminum, are more resistant to saltwater, and thus are useful in marine applications.

Single-phase alloys tend to be more corrosion resistant than the two-phase precipitation-hardened alloys. With multiple phases, galvanic cells can arise between the phases. Therefore, the 3*xxx* and 5*xxx* alloys are more corrosion resistant than the 2*xxx* and 7*xxx* alloys. In the 2*xxx* alloys, precipitation of $CuAl_2$ at the grain boundaries can cause a depletion of copper adjacent to the boundaries, making these regions anodic relative to the centers of the grains, resulting in rapid intergranular corrosion. Of the precipitation-hardenable alloys, the 6*xxx* alloys have the best corrosion resistance but are not as strong as the heat treated 2*xxx* and 7*xxx* alloys.

The naturally forming alumina (Al_2O_3) coating is thin (0.005 to 0.015 mm, or 0.0002 to 0.0006 in. thick) and a poor base for paint. Two types of coatings, chemical conversion coatings and anodizing, are used to form a more uniform and thicker oxide for enhanced corrosion protection. Chemical conversion coatings produce a porous and absorptive oxide (0.05 to 0.076 mm, or 0.002 to 0.003 in. thick) that is very uniform and morphologically tailored to bond well with paint primers. The oxides are chromate- or phosphate-based, which further aids in corrosion protection.

To further enhance corrosion resistance, finished parts are frequently anodized before being placed in service to increase the thickness of the Al_2O_3 layer on the surface. Anodizing is an electrolytic process that produces thicker (0.05 to 0.13 mm, or 0.002 to 0.005 in.) and more durable oxides than those produced by conversion coatings; therefore, it provides better corrosion resistance. Both sulfuric and chromic acid baths are used along with an electrical current to deposit a porous oxide layer on the surfaces. The component is the anode in an electrolytic cell, while the acid bath serves as the cathode. Anodizing consists of degreasing, chemical cleaning, anodizing, and then sealing the anodized coating in a slightly acidified hot water bath. Depending on the temperature and time of the anodizing operation, the oxide layer can range from 5 to 13 μm (0.2 to 0.5 mil) to provide enhanced corrosion protection to the underlying metal. After anodizing, the pores in the oxide film are sealed by placing the part in slightly acidified 80 to 90 °C (180 to 200 °F) water. This sealing treatment converts the aluminum oxide to aluminum monohydrate, which expands to fill the pores.

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