

Aluminum Mill and Engineered Wrought Products

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ALUMINUM mill products are those aluminum products that have been subjected to plastic deformation by hot- and cold-working mill processes (such as rolling, extruding, and drawing, either singly or in combination), so as to transform cast aluminum ingot into the desired product form. The microstructural changes associated with the working and with any accompanying thermal treatments are used to control certain properties and characteristics of the worked, or wrought, product or alloy.

Typical examples of mill products include plate or sheet (which is subsequently formed or machined into products such as aircraft or building components), household foil, and extruded shapes such as storm window frames. A vast difference in the mechanical and physical properties of aluminum mill products can be obtained through the control of the chemistry, processing, and thermal treatment.

Wrought Alloy Series

Aluminum alloys are commonly grouped into an alloy designation series, as described earlier in the article "Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys" in this Volume. The general characteristics of the alloy groups are described below, and the comparative corrosion and fabrication characteristics and some typical applications of the commonly used grades or alloys in each group are presented in Table 1.

1xxx Series. Aluminum of 99.00% or higher purity has many applications, especially in the electrical and chemical fields. These grades of aluminum are characterized by excellent corrosion resistance, high thermal and electrical conductivities, low mechanical properties, and excellent workability. Moderate increases in strength may be obtained by strain hardening. Iron and silicon are the major impurities. Typical uses include chemical equipment, reflectors, heat exchangers, electrical conductors and ca-

pacitors, packaging foil, architectural applications, and decorative trim.

2xxx Series. Copper is the principal alloying element in 2xxx series alloys, often with magnesium as a secondary addition. These alloys require solution heat treatment to obtain optimum properties; in the solution heat-treated condition, mechanical properties are similar to, and sometimes exceed, those of low-carbon steel. In some instances, precipitation heat treatment (aging) is employed to further increase mechanical properties. This treatment increases yield strength, with attendant loss in elongation; its effect on tensile strength is not as great.

The alloys in the 2xxx series do not have as good corrosion resistance as most other aluminum alloys, and under certain conditions they may be subject to intergranular corrosion. Therefore, these alloys in the form of sheet usually are clad with a high-purity aluminum or with a magnesium-silicon alloy of the 6xxx series, which provides galvanic protection of the core material and thus greatly increases resistance to corrosion.

Alloys in the 2xxx series are particularly well suited for parts and structures requiring high strength-to-weight ratios and are commonly used to make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, and structural parts and those parts requiring good strength at temperatures up to 150 °C (300 °F). Except for alloy 2219, these alloys have limited weldability, but some alloys in this series have superior machinability.

3xxx Series. Manganese is the major alloying element of 3xxx series alloys. These alloys generally are non-heat treatable but have about 20% more strength than 1xxx series alloys. Because only a limited percentage of manganese (up to about 1.5%) can be effectively added to aluminum, manganese is used as a major element in only a few alloys. However, three of them—3003, 3X04, and 3105—are widely used as general-purpose alloys for moderate-strength applications requiring good workability.

These applications include beverage cans, cooking utensils, heat exchangers, storage tanks, awnings, furniture, highway signs, roofing, siding, and other architectural applications.

4xxx Series. The major alloying element in 4xxx series alloys is silicon, which can be added in sufficient quantities (up to 12%) to cause substantial lowering of the melting range without producing brittleness. For this reason, aluminum-silicon alloys are used in welding wire and as brazing alloys for joining aluminum, where a lower melting range than that of the base metal is required. Most alloys in this series are non-heat treatable, but when used in welding heat-treatable alloys, they will pick up some of the alloying constituents of the latter and so respond to heat treatment to a limited extent. The alloys containing appreciable amounts of silicon become dark gray to charcoal when anodic oxide finishes are applied and hence are in demand for architectural applications. Alloy 4032 has a low coefficient of thermal expansion and high wear resistance, and thus is well suited to production of forged engine pistons.

5xxx Series. The major alloying element in 5xxx series alloys is magnesium. When it is used as a major alloying element or with manganese, the result is a moderate-to-high-strength work-hardenable alloy. Magnesium is considerably more effective than manganese as a hardener, about 0.8% Mg being equal to 1.25% Mn, and it can be added in considerably higher quantities. Alloys in this series possess good welding characteristics and good resistance to corrosion in marine atmospheres. However, certain limitations should be placed on the amount of cold work and the safe operating temperatures permissible for the higher-magnesium alloys (over about 3.5% for operating temperatures above about 65 °C, or 150 °F) to avoid susceptibility to stress-corrosion cracking.

Uses include architectural, ornamental, and decorative trim; cans and can ends; household appliances; streetlight standards;

Table 1 Comparative corrosion and fabrication characteristics and typical applications of wrought aluminum alloys

Alloy temper	Resistance to corrosion				Weldability(f)			Brazeability(f)	Solderability(g)	Some typical applications of alloys
	General(a)	Stress-corrosion cracking(b)	Workability (cold)(e)	Machinability(e)	Gas	Arc	Resistance spot and seam			
1050 0.....	A	A	A	E	A	A	B	A	A	Chemical equipment, railroad tank cars
H12.....	A	A	A	E	A	A	A	A	A	
H14.....	A	A	A	D	A	A	A	A	A	
H16.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	B	D	A	A	A	A	A	
1060 0.....	A	A	A	E	A	A	B	A	A	Chemical equipment, railroad tank cars
H12.....	A	A	A	E	A	A	A	A	A	
H14.....	A	A	A	D	A	A	A	A	A	
H16.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	B	D	A	A	A	A	A	
1100 0.....	A	A	A	E	A	A	B	A	A	Sheet-metal work, spun hollowware, fin stock
H12.....	A	A	A	E	A	A	A	A	A	
H14.....	A	A	A	D	A	A	A	A	A	
H16.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	C	D	A	A	A	A	A	
1145 0.....	A	A	A	E	A	A	B	A	A	Foil, fin stock
H12.....	A	A	A	E	A	A	A	A	A	
H14.....	A	A	A	D	A	A	A	A	A	
H16.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	B	D	A	A	A	A	A	
1199 0.....	A	A	A	E	A	A	B	A	A	Electrolytic capacitor foil, chemical equipment, railroad tank cars
H12.....	A	A	A	E	A	A	A	A	A	
H14.....	A	A	A	D	A	A	A	A	A	
H16.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	B	D	A	A	A	A	A	
1350 0.....	A	A	A	E	A	A	B	A	A	Electrical conductors
H12, H111.....	A	A	A	E	A	A	A	A	A	
H14, H24.....	A	A	A	D	A	A	A	A	A	
H16, H26.....	A	A	B	D	A	A	A	A	A	
H18.....	A	A	B	D	A	A	A	A	A	
2011 T3.....	D(c)	D	C	A	D	D	D	D	C	Screw-machine products
T4, T451.....	D(c)	D	B	A	D	D	D	D	C	
T8.....	D	B	D	A	D	D	D	D	C	
2014 0.....	D	D	D	B	D	C	Truck frames, aircraft structures
T3, T4, T451.....	D(c)	C	C	B	D	B	B	D	C	
T6, T651, T6510, T6511.....	D	C	D	B	D	B	B	D	C	
2024 0.....	D	D	D	D	D	C	Truck wheels, screw-machine products, aircraft structures
T4, T3, T351, T3510, T3511.....	D(c)	C	C	B	C	B	B	D	C	
T361.....	D(c)	C	D	B	D	C	B	D	C	
T6.....	D	B	C	B	D	C	B	D	C	
T861, T81, T851, T8510, T8511.....	D	B	D	B	D	C	B	D	C	
T72.....	.....	.....	.....	B	.....	.....	.....	.....	.....
2036 T4.....	C	B	C	B	B	D	Auto-body panel sheet
2124 T851.....	D	B	D	B	D	C	B	D	C	
2218 T61.....	D	C	C	C	Jet engine impellers and rings
T72.....	D	C	.....	B	D	C	B	D	C
2219 0.....	D	A	B	D	Structural uses at high temperatures (to 315 °C, or 600 °F) high-strength weldments
T31, T351, T3510, T3511.....	D(c)	C	C	B	A	A	A	D	NA	
T37.....	D(c)	C	D	B	A	A	A	D	.....
T81, T851, T8510, T8511.....	D	B	D	B	A	A	A	D	.....
T87.....	D	B	D	B	A	A	A	D	.....
2618 T61.....	D	C	B	D	C	B	D	NA	Aircraft engines
3003 0.....	A	A	A	E	A	A	B	A	A	
H12.....	A	A	A	E	A	A	A	A	A	Cooking utensils, chemical equipment, pressure vessels, sheet-metal work, builder's hardware, storage tanks
H14.....	A	A	B	D	A	A	A	A	A	
H16.....	A	A	C	D	A	A	A	A	A	
H18.....	A	A	C	D	A	A	A	A	A	
H25.....	A	A	B	D	A	A	A	A	A	
3004 0.....	A	A	A	D	B	A	B	B	B	Sheet-metal work, storage tanks
H32.....	A	A	B	D	B	A	A	B	B	
H34.....	A	A	B	C	B	A	A	B	B	
H36.....	A	A	C	C	B	A	A	B	B	
H38.....	A	A	C	C	B	A	A	B	B	
3105 0.....	A	A	A	E	B	A	B	B	B		Residential siding, mobile homes, rain-carrying goods, sheet-metal work
H12.....	A	A	B	E	B	A	A	B	B	
H14.....	A	A	B	D	B	A	A	B	B	
H16.....	A	A	C	D	B	A	A	B	B	
H18.....	A	A	C	D	B	A	A	B	B	

(continued)

(a) Ratings A through E are relative ratings in decreasing order of merit, based on exposures to sodium chloride solution by intermittent spraying or immersion. Alloys with A and B ratings can be used in industrial and seacoast atmospheres without protection. Alloys with C, D, and E ratings generally should be protected at least on faying surfaces. (b) Stress-corrosion cracking ratings are based on service experience and on laboratory tests of specimens exposed to the 3.5% sodium chloride alternate immersion test. A = No known instance of failure in service or in laboratory tests. B = No known instance of failure in service; limited failures in laboratory tests of short transverse specimens. C = Service failures with sustained tension stress acting in short transverse direction relative to grain structure; limited failures in laboratory tests of long transverse specimens. D = Limited service failures with sustained longitudinal or long transverse stress. (c) In relatively thick sections the rating would be E. (d) This rating may be different for material held at elevated temperature for long periods. (e) Ratings A through D for workability (cold), and A through E for machinability, are relative ratings in decreasing order of merit. (f) Ratings A through D for weldability and brazeability are relative ratings defined as follows: A = Generally weldable by all commercial procedures and methods. B = Weldable with special techniques or for specific applications; requires preliminary trials or testing to develop welding procedure and weld performance. C = Limited weldability because of crack sensitivity or loss in resistance to corrosion and mechanical properties. D = No commonly used welding methods have been developed. (g) Ratings A through D and NA for solderability are relative ratings defined as follows: A = Excellent. B = Good. C = Fair. D = Poor. NA = Not applicable

Table 1 (continued)

Alloy temper	Resistance to corrosion			Machinability(e)	Weldability(f)			Brazeability(f)	Solderability(g)	Some typical applications of alloys
	General(a)	Stress-corrosion cracking(b)	Workability (cold)(c)		Gas	Arc	Resistance spot and seam			
H25.....	A	A	B	D	B	A	A	B	B	Pistons Welding electrode Appliances, utensils, architectural, electrical conductors
4032 T6.....	C	B	B	B	D	B	C	D	NA	
4043.....	B	A	NA	C	NA	NA	NA	NA	NA	
5005 0.....	A	A	A	E	A	A	B	B	B	
H12.....	A	A	A	E	A	A	A	B	B	
H14.....	A	A	B	D	A	A	A	B	B	
H16.....	A	A	C	D	A	A	A	B	B	
H18.....	A	A	C	D	A	A	A	B	B	
H32.....	A	A	B	E	A	A	A	B	B	
H34.....	A	A	C	D	A	A	A	B	B	
H36.....	A	A	C	D	A	A	A	B	B	
H38.....	A	A	D	A	A	A	A	B	B	
5050 0.....	A	A	A	E	A	A	B	B	C	Builders' hardware, refrigerator trim, coiled tubes
H32.....	A	A	A	D	A	A	A	B	C	
H34.....	A	A	B	D	A	A	A	B	C	
H36.....	A	A	C	C	A	A	A	B	C	
H38.....	A	A	C	C	A	A	A	B	C	
5052 0.....	A	A	A	D	A	A	B	C	D	Sheet-metal work, hydraulic tube, appliances
H32.....	A	A	B	D	A	A	A	C	D	
H34.....	A	A	B	C	A	A	A	C	D	
H36.....	A	A	C	C	A	A	A	C	D	
H38.....	A	A	C	C	A	A	A	C	D	
5056 0.....	A(d)	B(d)	A	D	C	A	B	D	D	Cable sheathing, rivets for magnesium, screen wire, zippers
H111.....	A(d)	B(d)	A	D	C	A	A	D	D	
H12, H32.....	A(d)	B(d)	B	D	C	A	A	D	D	
H14, H34.....	A(d)	B(d)	B	C	C	A	A	D	D	
H18, H38.....	A(d)	C(d)	C	C	C	A	A	D	D	
H192.....	B(d)	D(d)	D	B	C	A	A	D	D	
H392.....	B(d)	D(d)	D	B	C	A	A	D	D	
5083 0.....	A(d)	A(d)	B	D	C	A	B	D	D	
H321, H116.....	A(d)	A(d)	C	D	C	A	A	D	D	
H111.....	A(d)	B(d)	C	D	C	A	A	D	D	
5086 0.....	A(d)	A(d)	A	D	C	A	B	D	D	Unfired, welded pressure vessels, marine, auto aircraft cryogenics, TV towers, drilling rigs, transportation equipment, missile components
H32, H116.....	A(d)	A(d)	B	D	C	A	A	D	D	
H34.....	A(d)	B(d)	B	C	C	A	A	D	D	
H36.....	A(d)	B(d)	C	C	C	A	A	D	D	
H38.....	A(d)	B(d)	C	C	C	A	A	D	D	
H111.....	A(d)	A(d)	B	D	C	A	A	D	D	
5154 0.....	A(d)	A(d)	A	D	C	A	B	D	D	
H32.....	A(d)	A(d)	B	D	C	A	A	D	D	
H34.....	A(d)	A(d)	B	C	C	A	A	D	D	
H36.....	A(d)	A(d)	C	C	C	A	A	D	D	
H38.....	A(d)	A(d)	C	C	C	A	A	D	D	
5182 0.....	A	A(d)	A	D	C	A	B	D	D	Automobile body sheet, can ends
H19.....	A	A(d)	D	B	C	A	A	D	D	
5252 H24.....	A	A	B	D	A	A	A	C	D	Automotive and appliance trim
H25.....	A	A	B	C	A	A	A	C	D	
H28.....	A	A	C	C	A	A	A	C	D	
5254 0.....	A(d)	A(d)	A	D	C	A	B	D	D	Hydrogen peroxide and chemical storage vessels
H32.....	A(d)	A(d)	B	D	C	A	A	D	D	
H34.....	A(d)	A(d)	B	C	C	A	A	D	D	
H36.....	A(d)	A(d)	C	C	C	A	A	D	D	
H38.....	A(d)	A(d)	C	C	C	A	A	D	D	
5356.....	A	A	NA	B	NA	NA	NA	NA	NA	Welding electrode
5454 0.....	A	A	A	D	C	A	B	D	D	
H32.....	A	A	B	D	C	A	A	D	D	Welded structures, pressure vessels, marine service
H34.....	A	A	B	C	C	A	A	D	NA	
H111.....	A	A	B	D	C	A	A	D	D	
5456 0.....	A(d)	B(d)	B	D	C	A	B	D	D	High-strength welded structures, storage tanks, pressure vessels, marine applications
H111.....	A(d)	B(d)	C	D	C	A	A	D	D	
H321, H115.....	A(d)	B(d)	C	D	C	A	A	D	NA	
5457 0.....	A	A	A	E	A	A	B	B	B	Hydrogen peroxide and chemical storage vessels
5652 0.....	A	A	A	D	A	A	B	C	D	
H32.....	A	A	B	D	A	A	A	C	D	
H34.....	A	A	B	C	A	A	A	C	D	
H36.....	A	A	C	C	A	A	A	C	D	
H38.....	A	A	C	C	A	A	A	C	D	
5657 H241.....	A	A	A	D	A	A	A	B	B	Anodized auto and appliance trim

(continued)

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Table 1 (continued)

Alloy temper	Resistance to corrosion		Workability (cold)(e)	Machinability(e)	Weldability(f)			Brazeability(f)	Solderability(g)	Some typical applications of alloys
	General(a)	Stress-corrosion cracking(b)			Gas	Arc	Resistance spot and seam			
H25	A	A	B	D	A	A	A	B	NA	
H26	A	A	B	D	A	A	A	B		
H28	A	A	C	D	A	A	A	B		
6005 T5	B	A	C	C	A	A	A	A	NA	Heavy-duty structures requiring good corrosion-resistance applications, truck and marine, railroad cars, furniture, pipelines
6009 T4	A	A	A	C	A	A	A	A	B	Automobile body sheet
6010 T4	A	A	B	C	A	A	A	A	B	Automobile body sheet
6061 0	B	A	A	D	A	A	B	A	B	Heavy-duty structures requiring good corrosion resistance, truck and marine, railroad cars, furniture, pipelines
T4, T451, T4510, T4511	B	B	B	C	A	A	A	A	B	
T6, T651, T652, T6510, T6511	B	A	C	C	A	A	A	A	B	
6063 T1	A	A	B	D	A	A	A	A	B	Pipe railing, furniture, architectural extrusions
T4	A	A	B	D	A	A	A	A	B	
T5, T52	A	A	B	C	A	A	A	A	B	
T6	A	A	C	C	A	A	A	A	B	
T83, T831, T832	A	A	C	C	A	A	A	A	B	
6066 0	C	A	B	D	D	B	B	D	NA	Forgings and extrusions for welded structures
T4, T4510, T4511	C	B	C	C	D	B	B	D	NA	
T6, T6510, T6511	C	B	C	B	D	B	B	D	NA	
6070 T4, T4511	B	B	B	C	A	A	A	B	NA	Heavy-duty welded structures, pipelines
T6	B	B	C	C	A	A	A	B	NA	High-strength bus conductors
6101 T6, T63	A	A	C	C	A	A	A	A	NA	
T61, T64	A	A	B	D	A	A	A	A		
6151 T6, T652									B	Moderate-strength, intricate forgings for machine and auto parts
6201 T81	A	A		C	A	A	A	A	NA	High-strength electric conductor wire
6262 T6, T651, T6510, T6511	B	A	C	B	A	A	A	A	NA	Screw-machine products
T9	B	A	D	B	A	A	A	A		
6351, T5, T6	B	A	C	C	A	A	A	A	B	Heavy-duty structures requiring good corrosion resistance, truck and tractor extrusions
6463 T1	A	A	B	D	A	A	A	A		Extruded architectural and trim sections
T5	A	A	B	C	A	A	A	A	NA	
T6	A	A	C	C	A	A	A	A		
7005 T53	B	B	C	A	B	B	B	B	B	Heavy-duty structures requiring good corrosion resistance, trucks, trailers, dump bodies
7049 T73, T7351, T7352	C	B	D	B	D	C	B	D	D	Aircraft and other structures
T76, T7651	C	B	D	B	D	C	B	D	D	
7050 T74, T7451, T7452	C	B	D	B	D	C	B	D	D	Aircraft and other structures
T76, T761	C	B	D	B	D	C	B	D	D	
7072	A	A	A	D	A	A	A	A	A	Fin stock, cladding alloy
7075 0				D	D	C	B	D	D	Aircraft and other structures
T6, T651, T652, T6510, T6511	C(c)	C	D	B	D	C	B	D	D	
T73, T7351	C	B	D	B	D	C	B	D	D	
7175, T74, T7452	C	B	D	B	D	C	B	D	D	Aircraft and other structures, forgings
7178 0					D	C	B	D	D	Aircraft and other structures
T6, T651, T6510, T6511	C(c)	C	D	B	D	C	B	D	D	
7475 T6, T651	C	C	D	B	D	C	B	D	D	Aircraft and other structures
T73, T7351, T7352	C	B	D	B	D	C	B	D	D	
T76, T7651	C	B	D	B	D	C	B	D	D	

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boats and ships, cryogenic tanks; crane parts; and automotive structures.

6xxx Series. Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicide (Mg₂Si), thus making them heat treatable. Although not as strong as most 2xxx and 7xxx alloys, 6xxx series alloys have good formability, weldability, machinability, and corrosion resistance, with medium strength. Alloys in this

heat-treatable group may be formed in the T4 temper (solution heat treated but not precipitation heat treated) and strengthened after forming to full T6 properties by precipitation heat treatment. Uses include architectural applications, bicycle frames, transportation equipment, bridge railings, and welded structures.

7xxx Series. Zinc, in amounts of 1 to 8%, is the major alloying element in 7xxx series alloys, and when coupled with a smaller

percentage of magnesium results in heat-treatable alloys of moderate to very high strength. Usually other elements, such as copper and chromium, are also added in small quantities. 7xxx series alloys are used in airframe structures, mobile equipment, and other highly stressed parts.

Higher strength 7xxx alloys exhibit reduced resistance to stress corrosion cracking and are often utilized in a slightly overaged temper to provide better combinations

of strength, corrosion resistance, and fracture toughness.

Types of Mill Products

Commercial wrought aluminum products are divided basically into five major categories based on production methods as well as geometric configurations. These are:

- Flat-rolled products (sheet, plate, and foil)
- Rod, bar, and wire
- Tubular products
- Shapes
- Forgings

In the aluminum industry, rod, bar, wire, tubular products, and shapes are termed mill products, as they are in the steel industry, even though they often are produced by extrusion rather than by rolling. Aluminum forgings, although usually not considered mill products, are wrought products and are briefly reviewed in this section.

In addition to production method and product configuration, wrought aluminum products also may be classified into heat-treatable and non-heat-treatable alloys. Initial strength of non-heat-treatable (1xxx, 3xxx, 4xxx, and 5xxx) alloys depends on the hardening effects of elements such as manganese, silicon, iron, and magnesium, singly or in various combinations. Because these alloys are work hardenable, further strengthening is made possible by various degrees of cold working, denoted by the H series of tempers, as discussed earlier in this Volume in the article on temper designations of aluminum and aluminum alloys. Alloys containing appreciable amounts of magnesium when supplied in strain-hardened tempers usually are given a final elevated-temperature treatment, called stabilizing, to ensure stability of properties. Initial strength of heat-treatable (2xxx, 4xxx, 6xxx, 7xxx, and some 8xxx) alloys is enhanced by addition of alloying elements such as copper, magnesium, zinc, lithium, and silicon. Because these elements, singly or in various combinations, show increasing solid solubility in aluminum with increasing temperature, it is possible to subject them to thermal treatments that will impart pronounced strengthening.

Flat-rolled products include sheet, plate, and foil. They are manufactured by either hot or hot-and-cold rolling, are rectangular in cross section and form, and have uniform thickness.

Plate. In the United States, plate refers to a product whose thickness is greater than 0.250 in. (6.3 mm). Plate up to 8 in. (200 mm) thick is available in some alloys. It usually has either sheared or sawed edges. Plate can be cut into circles, rectangles, or odd-shape blanks. Plate of certain alloys—notably the high-strength 2xxx and 7xxx series alloys—also are available in Alclad

form, which comprises an aluminum alloy core having on one or both sides a metallurgically bonded aluminum or aluminum alloy coating that is anodic to the core, thus electrolytically protecting the core against corrosion. Most often, the coating consists of a high-purity aluminum, a low magnesium-silicon alloy, or an alloy containing 1% Zn. Usually, coating thickness (one side) is from 2.5 to 5% of the total thickness. The most commonly used plate alloys are 2024, 2124, 2219, 7050, 7075, 7150, 7475, and 7178 for aircraft structures; 5083, 5086, and 5456 for marine, cryogenics, and pressure vessels; and 1100, 3003, 5052, and 6061 for general applications.

Sheet. In the United States, sheet is classified as a flat-rolled product with a thickness of 0.006 to 0.249 in. (0.15 to 0.63 mm). Sheet edges can be sheared, slit, or sawed. Sheet is supplied in flat form, in coils, or in pieces cut to length from coils. Current facilities permit production of a limited amount of extra-large sheet, for example, up to 200 in. (5 m) wide by 1000 in. (25 m) long. The term strip, as applied to narrow sheet, is not used in the U.S. aluminum industry. Aluminum sheet usually is available in several surface finishes such as mill finish, one-side bright finish, or two-side bright finish. It may also be supplied embossed, perforated, corrugated, painted, or otherwise surface treated; in some instances, it is edge conditioned. As with aluminum plate, sheet made of the heat-treatable alloys in which copper or zinc are the major alloying constituents, notably the high-strength 2xxx and 7xxx series alloys, also is available in Alclad form for increased corrosion resistance. In addition, special composites may be obtained such as Alclad non-heat-treatable alloys for extra corrosion protection, for brazing purposes, or for special surface finishes.

With a few exceptions, most alloys in the 1xxx, 2xxx, 3xxx, 5xxx, and 7xxx series are available in sheet form. Along with alloy 6061, they cover a wide range of applications from builders' hardware to transportation equipment and from appliances to aircraft structures.

Foil is a product with a thickness less than 0.006 in. (0.15 mm). Most foil is supplied in coils, although it is also available in rectangular form (sheets). One of the largest end uses of foil is household wrap. There is a wider variety of surface finishes for foil than for sheet. Foil often is treated chemically or mechanically to meet the needs of specific applications. Common foil alloys are limited to the higher-purity 1xxx series and 3003, 5052, 5056, 8111, and 8079 (Al-1.0Fe-0.15Si).

Bar, rod, and wire are all solid products that are extremely long in relation to their cross section. They differ from each other only in cross-sectional shape and in thickness or diameter. In the United States,

when the cross section is round or nearly round and over $\frac{3}{8}$ in. (10 mm) in diameter, it is called rod. It is called bar when the cross section is square, rectangular, or in the shape of a regular polygon and when at least one perpendicular distance between parallel faces (thickness) is over $\frac{3}{8}$ in. (10 mm). Wire refers to a product, regardless of its cross-sectional shape, whose diameter or greatest perpendicular distance between parallel faces is less than $\frac{3}{8}$ in. (10 mm).

Rod and bar can be produced by either hot rolling or hot extruding and brought to final dimensions with or without additional cold working. Wire usually is produced and sized by drawing through one or more dies, although roll flattening is also used. Alclad rod or wire for additional corrosion resistance is available only in certain alloys. Many aluminum alloys are available in bar, rod, and wire; among these alloys, 2011 and 6262 are specially designed for screw-machine products, 2117 and 6053 for rivets and fittings. Alloy 2024-T4 is a standard material for bolts and screws. Alloys 1350, 6101, and 6201 are extensively used as electrical conductors. Alloy 5056 is used for zippers and alclad 5056 for insect screen wire.

Tubular products include tube and pipe. They are hollow wrought products that are long in relation to their cross section and have uniform wall thickness except as affected by corner radii. Tube is round, elliptical, square, rectangular, or regular polygonal in cross section. When round tubular products are in standardized combinations of outside diameter and wall thickness, commonly designated by "Nominal Pipe Sizes" and "ANSI Schedule Numbers," they are classified as pipe.

Tube and pipe may be produced by using a hollow extrusion ingot, by piercing a solid extrusion ingot, or by extruding through a porthole die or a bridge die. They also may be made by forming and welding sheet. Tube may be brought to final dimensions by drawing through dies. Tube (both extruded and drawn) for general applications is available in such alloys as 1100, 2014, 2024, 3003, 5050, 5086, 6061, 6063, and 7075. For heat-exchanger tube, alloys 1060, 3003, alclad 3003, 5052, 5454, and 6061 are most widely used. Clad tube is available only in certain alloys and is clad only on one side (either inside or outside). Pipe is available only in alloys 3003, 6061, and 6063.

Shapes. A shape is a product that is long in relation to its cross-sectional dimensions and has a cross-sectional shape other than that of sheet, plate, rod, bar, wire, or tube. Most shapes are produced by extruding or by extruding plus cold finishing; shapes are now rarely produced by rolling because of economic disadvantages. Shapes may be solid, hollow (with one or more voids), or semihollow. The 6xxx series (Al-Mg-Si) alloys, because of their easy extrudability, are the most popular alloys for producing

shapes. Some 2xxx and 7xxx series alloys are often used in applications requiring higher strength.

Standard structural shapes such as I beams, channels, and angles produced in alloy 6061 are made in different and fewer configurations than similar shapes made of steel; the patterns especially designed for aluminum offer better section properties and greater structural stability than the steel design by using the metal more efficiently. The dimensions, weights, and properties of the alloy 6061 standard structural shapes, along with other information needed by structural engineers and designers, are contained in the Aluminum Construction Manual, published by the Aluminum Association, Inc.

Most aluminum alloys can be obtained as precision extrusions with good as-extruded surfaces; major dimensions usually do not need to be machined because tolerances of the as-extruded product often permit manufacturers to complete the part with simple cutoff, drilling, or other minor operations.

In many instances, long aircraft structural elements involve large attachment fittings at one end. Such elements often are more economical to machine from stepped aluminum extrusions, with two or more cross sections in one piece, rather than from an extrusion having a uniform cross section large enough for the attachment fitting.

Aluminum Alloy Forgings. Aluminum alloys can be forged into a variety of shapes and types of forgings with a broad range of final part forging design criteria based on the intended application. As a class of alloys, however, aluminum alloys are generally considered to be more difficult to forge than carbon steels and many alloy steels. Compared to the nickel/cobalt-base alloys and titanium alloys, aluminum alloys are considerably more forgeable, particularly in conventional forging-process technology, in which dies are heated to 540 °C (1000 °F) or less.

Figure 1 illustrates the relative forgeability of ten aluminum alloys that constitute the bulk of aluminum alloy forging production. This arbitrary unit is principally based on the deformation per unit of energy absorbed in the range of forging temperatures typically employed for the alloys in question. Also considered in this index is the difficulty of achieving specific degrees of severity in deformation as well as the cracking tendency of the alloy under forging-process conditions. There are wrought aluminum alloys, such as 1100 and 3003, whose forgeability would be rated significantly above those presented; however, these alloys have limited application in forging because they cannot be strengthened by heat treatment.

The 15 aluminum alloys that are most commonly forged, as well as recommended temperature ranges, are listed in Table 2.

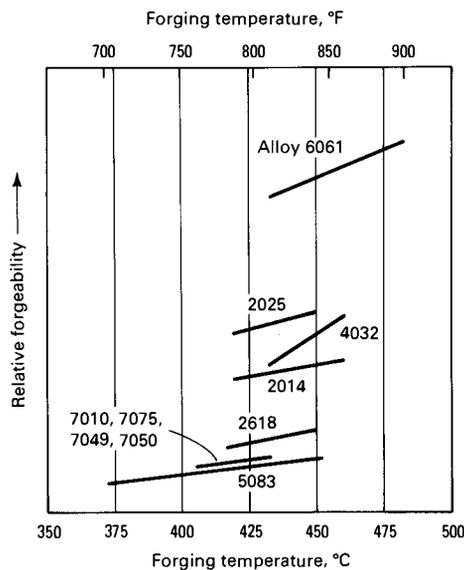


Fig. 1 Forgeability and forging temperatures of various aluminum alloys

All of these alloys are generally forged to the same severity, although some alloys may require more forging power and/or more forging operations than others. The forging temperature range for most alloys is relatively narrow (generally <55 °C, or 100 °F), and for no alloy is the range greater than 85 °C (155 °F). Obtaining and maintaining proper metal temperatures in the forging of aluminum alloys is critical to the success of the forging process. Die temperature and deformation rates play key roles in the actual forging temperature achieved.

Forging Methods. Aluminum alloys are produced by all of the current forging methods available, including open-die (or hand) forging, closed-die forging, upsetting, roll forging, orbital (rotary) forging, spin forging, mandrel forging, ring rolling, and extrusion. Selection of the optimal forging method for a given forging shape is based on the desired forged shape, the sophistication of the forged-shape design, and cost. In many cases, two or more forging methods are combined in order to achieve the desired forging shape and to obtain a thoroughly wrought structure. For example, open-die forging frequently precedes closed-die forging in order to prework the alloy (especially when cast ingot forging stock is being employed) and in order to preshape (or preform) the metal to conform to the subsequent closed dies and to conserve input metal.

Most aluminum alloy forgings are produced in closed dies. However, open-die forging is frequently used to produce small quantities of aluminum alloy forgings when the construction of expensive closed dies is not justified or when such quantities are needed during the prototype fabrication stages of a forging application. The quantity that warrants the use of closed dies varies

Table 2 Recommended forging temperature ranges for aluminum alloys

Aluminum alloy	Forging temperature range	
	°C	°F
1100.....	315-405	600-760
2014.....	420-460	785-860
2025.....	420-450	785-840
2219.....	425-470	800-880
2618.....	410-455	770-850
3003.....	315-405	600-760
4032.....	415-460	780-860
5083.....	405-460	760-860
6061.....	430-480	810-900
7010.....	370-440	700-820
7039.....	380-440	720-820
7049.....	360-440	680-820
7050.....	360-440	680-820
7075.....	380-440	720-820
7079.....	405-455	760-850

considerably, depending on the size and shape of the forging and on the application for the part. However, open-die forging is by no means confined to small or prototype quantities, and in some cases, it may be the most cost-effective method of aluminum forging manufacture. For example, as many as 2000 pieces of biscuit forgings have been produced in open dies when closed dies did not provide sufficient economic benefits. Further information on the forging of aluminum alloys is given in *Forming and Forging*, Volume 14 of the 9th Edition of *Metals Handbook*.

Design of Shapes

Aluminum shapes can be produced in a virtually unlimited variety of cross-sectional designs that place the metal where needed to meet functional and appearance requirements. Full utilization of this capability of the extrusion process depends principally on the ingenuity of designers in creating new and useful configurations. The cross-sectional design of an extruded shape, however, can have an important influence on its producibility, production rate, cost of tooling, surface finish, and ultimate production cost. The optimum design of an extruded shape must take into account alloy thickness or thicknesses involved, and the size, type, and complexity of the shape. Therefore, the extruder should be consulted during design to ensure adequate dimensional control, satisfactory finish, and lowest cost while retaining the desired functional and appearance characteristics.

Classification of Shapes. The complexity of a shape producible as an extrusion is a function of metal-flow characteristics of the process and the means available to control flow. Control of metal flow places a few limitations on the design features of the cross section of an extruded shape that affect production rate, dimensional and surface quality, and costs. Extrusions are classified by shape complexity from an extrusion-production viewpoint into solid,

hollow, and semihollow shapes. Each hollow shape—a shape with any part of its cross section completely enclosing a void—is further classified by increasing complexity as follows:

- Class 1: A hollow shape with a round void 25 mm (1 in.) or more in diameter and with its weight equally distributed on opposite sides of two or more equally spaced axes
- Class 2: Any hollow shape other than Class 1, not exceeding a 125 mm (5 in.) diam circle and having a single void of not less than 9.5 mm (0.375 in.) diam or 70 mm² (0.110 in.²) area
- Class 3: Any hollow shape other than Class 1 or 2

A semihollow shape is a shape with any part of its cross section partly enclosing a void having the following ratios for the area of the void to the square of the width of the gap leading to the void:

Gap width		Ratio
mm	in.	
0.9–1.5	0.035–0.061	Over 2
1.6–3.1	0.062–0.124	Over 3
3.2–6.3	0.125–0.249	Over 4
6.4–12.6	0.250–0.499	Over 5
12.7 and greater	0.500 and greater	Over 6

Alloy Extrudability. Aluminum alloys differ in inherent extrudability. Alloy selection is important because it establishes the minimum thickness for a shape and has a basic effect on extrusion cost. In general, the higher the alloy content and the strength of an alloy, the more difficult it is to extrude and the lower its extrusion rate.

The relative extrudabilities, as measured by extrusion rate, for several of the more important commercial extrusion alloys are given below:

Alloy	Extrudability, % of rate for 6063
1350	160
1060	135
1100	135
3003	120
6063	100
6061	60
2011	35
5086	25
2014	20
5083	20
2024	15
7075	9
7178	8

Actual extrusion rate depends on pressure, temperature, and other requirements for the particular shape, as well as ingot quality.

Shape and Size Factors. The important shape factor of an extrusion is the ratio of its perimeter to its weight per unit length. For a single classification, increasing shape factor is a measure of increasing complexi-

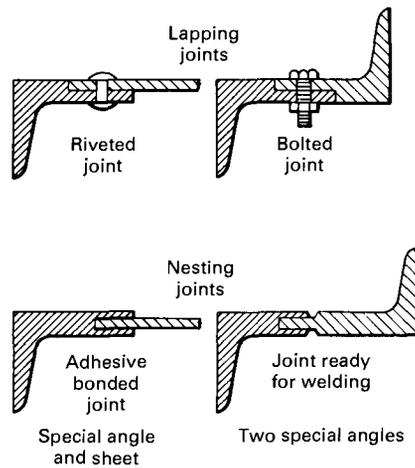


Fig. 2 Four examples of interconnecting extrusions that fit together or fit other products, and four examples of joining methods

ty. Designing for minimum shape factor promotes ease of extrusion.

The size of an extruded shape affects ease of extrusion and dimensional tolerances. As the circumscribing circle size (smallest diameter that completely encloses the shape) increases, extrusion becomes more difficult. In extrusion, the metal flows fastest at the center of the die face. With increasing circle size, the tendency for different metal flow increases, and it is more difficult to design and construct extrusion dies with compensating features that provide uniform metal-flow rates to all parts of the shape.

Ease of extrusion improves with increasing thickness; shapes of uniform thickness are most easily extruded. A shape whose cross section has elements of widely differing thicknesses increases the difficulty of extrusion. The thinner a flange on a shape, the less the length of flange that can be satisfactorily extruded. Thinner elements at the ends of long flanges are difficult to fill properly and make it hard to obtain desired dimensional control and finish. Although it is desirable to produce the thinnest shape feasible for an application, reducing thickness can cause an increase in cost of extrusion that more than offsets the savings in metal cost. Extruded shapes 1 mm (0.040 in.) thick and even less can be produced, depending on alloy, shape, size, and design. Manufacturing limits on minimum practical thickness of extruded shapes are given in Table 3.

Size and thickness relationships among the various elements of a shape can add to its complexity. Rod, bar, and regular shapes of uniform thickness are easily produced. For example, a bar 3.2 mm (0.125 in.) thick, a rod 25 mm (1 in.) in diameter, and an angle 19 by 25 mm (0.75 by 1 in.) in cross section, and 1.6 mm (0.0625 in.) thick are readily extruded, whereas extrusion of a 75 mm (3 in.) bar-type shape with a 3.2 mm (0.125 in.) flange is more difficult.

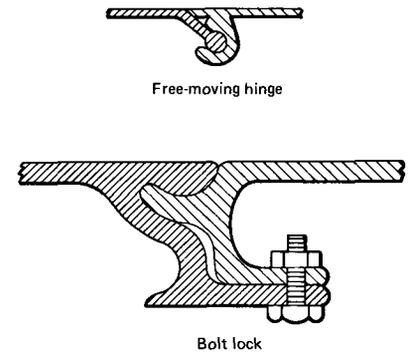


Fig. 3 Two examples of extrusions with nonpermanent interconnections

Semihollow and channel shapes require a tongue in the extrusion die, which must have adequate strength to resist the extrusion force. Channel shapes become increasingly difficult to produce as the depth-to-width ratio increases. Wide, thin shapes are difficult to produce and make it hard to control dimension. Channel-type shapes and wide, thin shapes may be fabricated if they are not excessively thin. Thin flanges or projections from a thicker element of the shape add to the complexity of an extruded design. On thinner elements at the extremities of high flanges, it is difficult to get adequate fill to obtain desired dimensions. The greater the difference in thickness of individual elements comprising a shape, the more difficult the shape is to produce. The effect of such thickness differences can be greatly diminished by blending one thickness into the other by tapered or radiused transitions. Sharp corners should be avoided wherever possible because they reduce maximum extrusion speed and are locations of stress concentrations in the die opening that can cause premature die failure. Fillet radii of at least 0.8 mm (0.031 in.) are desirable, but corners with radii of only 0.4 mm (0.015 in.) are feasible.

In general, the more unbalanced and unsymmetrical an extruded-shape cross section, the more difficult that shape is to produce. Despite this, production of grossly unbalanced and unsymmetrical shapes is the basis of the great growth that has occurred in the use of aluminum extrusions, and such designs account for the bulk of extruded shapes produced today.

Interconnecting Shapes. It is becoming increasingly common to include an interconnecting feature in the design of an extruded shape to facilitate its assembly to a similar shape or to another product. This feature can be a simple step to provide a smooth lapping joint, or a tongue and groove for a nesting joint (see Fig. 2). Such connections can be secured by any of the common joining methods. Of special interest when the joint is to be arc welded is the fact that lapping and nesting types of interconnections can be designed to provide

Table 3 Standard manufacturing limits (in inches) for aluminum extrusions

Diameter of circumscribing circle, in.	Minimum wall thickness, in.				
	1060, 1100, 3003	6063	6061	2014, 5086, 5454	2024, 2219, 5083, 7001, 7075, 7079, 7178
Solid and semihollow shapes, rod, and bar					
0.5-2	0.040	0.040	0.040	0.040	0.040
2-3	0.045	0.045	0.045	0.050	0.050
3-4	0.050	0.050	0.050	0.050	0.062
4-5	0.062	0.062	0.062	0.062	0.078
5-6	0.062	0.062	0.062	0.078	0.094
6-7	0.078	0.078	0.078	0.094	0.109
7-8	0.094	0.094	0.094	0.109	0.125
8-10	0.109	0.109	0.109	0.125	0.156
10-11	0.125	0.125	0.125	0.125	0.156
11-12	0.156	0.156	0.156	0.156	0.156
12-17	0.188	0.188	0.188	0.188	0.188
17-20	0.188	0.188	0.188	0.188	0.250
20-24	0.188	0.188	0.188	0.250	0.500
Class 1 hollow shapes(a)					
1.25-3	0.062	0.050	0.062	...	...
3-4	0.094	0.050	0.062	...	...
4-5	0.109	0.062	0.062	0.156	0.250
5-6	0.125	0.062	0.078	0.188	0.281
6-7	0.156	0.078	0.094	0.219	0.312
7-8	0.188	0.094	0.125	0.250	0.375
8-9	0.219	0.125	0.156	0.281	0.438
9-10	0.250	0.156	0.188	0.312	0.500
10-12.75	0.312	0.188	0.219	0.375	0.500
12.75-14	0.375	0.219	0.250	0.438	0.500
14-16	0.438	0.250	0.375	0.438	0.500
16-20.25	0.500	0.375	0.438	0.500	0.625
Class 2 and 3 hollow shapes(b)					
0.5-1	0.062	0.050	0.062	...	...
1-2	0.062	0.055	0.062	...	...
2-3	0.078	0.062	0.078	...	...
3-4	0.094	0.078	0.094	...	...
4-5	0.109	0.094	0.109	...	...
5-6	0.125	0.109	0.125	...	...
6-7	0.156	0.125	0.156	...	...
7-8	0.188	0.156	0.188	...	...
8-10	0.250	0.188	0.250	...	...

(a) Minimum inside diameter is one-half the circumscribing diameter, but never under 1 in. for alloys in first three columns or under 2 in. for alloys in last two columns. (b) Minimum hole size for all alloys is 0.110 sq. in. in area or 0.375 in. in diam.

edge preparation and/or integral backing for the weld (see the sketch at bottom left in Fig. 2).

Interlocking joints can be designed to incorporate a free-moving hinge (see top sketch in Fig. 3) when one part is slid lengthwise into the mating portion of the next extrusion. Panel-type extrusions with hinge joints have found application in conveyor belts and roll-up doors.

A more common type of interlocking feature used in interconnecting extrusions is the nesting type that requires rotation of one part relative to the mating part for assembly (see bottom sketch in Fig. 3). Such joints can be held together by gravity or by mechanical devices. If a nonpermanent joint is desired, a bolt or other fastener can be used, as illustrated in the bottom sketch in Fig. 3.

When a permanent joint is desired, a snapping or crimping feature can be added to interlocking extrusions (see Fig. 4). Crimping also can be used to make a permanent joint between an interlocking extrusion and sheet (Fig. 4). Extrusions also can be provided with longitudinal teeth or serrations, which will permanently grip smooth surfaces as well as surfaces provided with mating teeth or serrations; this is illustrated in the sketch at the bottom of Fig. 4.

Applications for interconnecting extrusions include doors, wall, ceiling and floor panels, pallets, aircraft landing mats, highway signs, window frames, and large cylinders.

Physical Metallurgy

The principal concerns in the physical metallurgy of aluminum alloys include the effects of composition, mechanical working, and/or heat treatment on mechanical and physical properties. In terms of properties, strength improvement is a major objective in the design of aluminum alloys because the low strength of pure aluminum (about a 10 MPa , or 1.5 ksi, tensile yield strength in the annealed condition) limits its commercial usefulness. The two most common methods for increasing the strength of aluminum alloys are to:

- Disperse second-phase constituents or elements in solid solution and cold work the alloy (non-heat-treatable alloys)

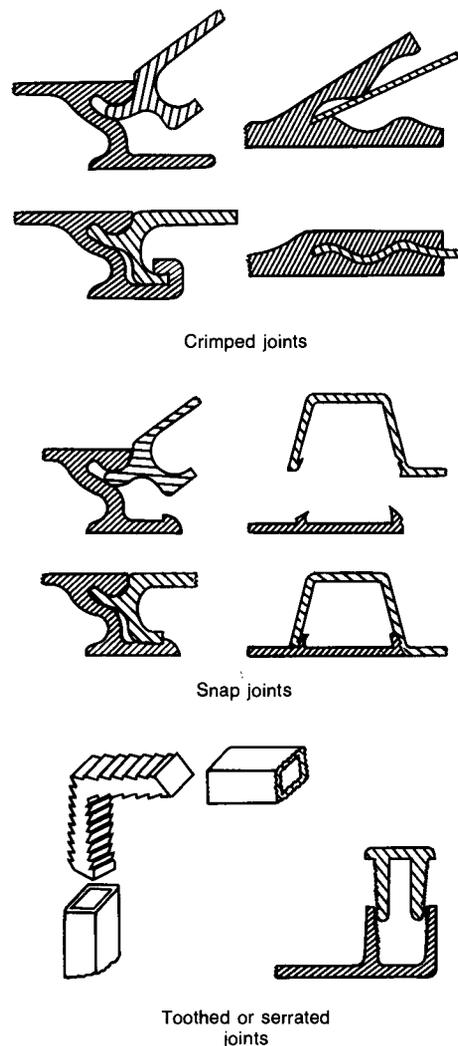


Fig. 4 Six examples of interconnecting extrusions that lock together or lock to other products

- Dissolve the alloying elements into solid solution and precipitate them as coherent submicroscopic particles (heat-treatable or precipitation-hardening alloys)

The factors affecting these strengthening mechanisms and the fracture toughness and physical properties of aluminum alloys are discussed in the following portions of this section.

Phases in Aluminum Alloys

The elements that are most commonly present in commercial aluminum alloys to provide increased strength—particularly when coupled with strain hardening by cold working or with heat treatment, or both—are copper, magnesium, manganese, silicon, and zinc. These elements all have significant solid solubility in aluminum, and in all cases the solubility increases with increasing temperature (see Fig. 5).

Of all the elements, zinc has the greatest solid solubility in aluminum (a maximum of 66.4 at%). In addition to zinc, the solid

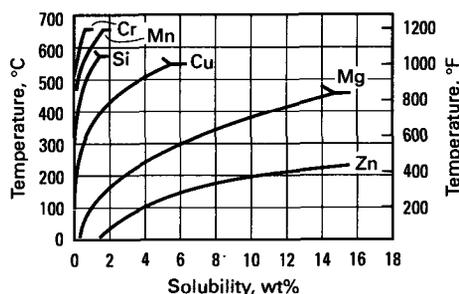


Fig. 5 Equilibrium binary solid solubility as a function of temperature for alloying elements most frequently added to aluminum

solubilities of silver, magnesium, and lithium are greater than 10 at% (in order of decreasing maximum solubility). Gallium, germanium, copper, and silicon (in decreasing order) have maximum solubilities of less than 10 but greater than 1 at%. All other elements are less soluble. With the one known exception of tin (which shows a retrograde solid solubility between the melting point of aluminum and the eutectic temperature, 228.3 °C, with a maximum of 0.10% at approximately 660 °C), the maximum solid solubility in aluminum alloys occurs at the eutectic, peritectic, or monotectic temperature. With decreasing temperature, the solubility limits decrease. This decrease from appreciable concentrations at elevated temperatures to relatively low concentrations at low temperatures is one fundamental characteristic that provides the basis for substantially increasing the hardness and strength of aluminum alloys by solution heat treatment and subsequent precipitation aging operations.

For those elements in concentrations below their solubility limits, the alloying elements are essentially in solid solution and constitute a single phase. However, no element is known to have complete miscibility with aluminum in the solid state. Among the commercial alloys, only the bright-finishing alloys such as 5657 and 5252, which contain 0.8 and 2.5% Mg (nominal), respectively, with very low limits on all impurities, may be regarded as nearly pure solid solutions.

Second-Phase Constituents. When the content of an alloying element exceeds the solid-solubility limit, the alloying element produces "second-phase" microstructural constituents that may consist of either the pure alloying ingredient or an intermetallic-compound phase. In the first group are silicon, tin, and beryllium. If the alloy is a ternary or higher-order alloy, however, silicon or tin may form intermetallic-compound phases. Most of the other alloying elements form such compounds with aluminum in binary alloys and more complex phases in ternary or higher-order alloys.

Manganese and chromium are included in the group of elements that form predominantly second-phase constituents, because

in commercial alloys they have very low equilibrium solid solubilities. In the case of many compositions containing manganese, this is because iron and silicon are also present and form the quaternary-phase $\text{Al}_{12}(\text{Fe},\text{Mn})_3\text{Si}$. In alloys containing copper and manganese, the ternary-phase $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$ is formed. Most of the alloys in which chromium is present also contain magnesium, so that during solid-state heating they form $\text{Al}_{12}\text{Mg}_2\text{Cr}$, which also has very low-equilibrium solid solubility. Smelter-grade primary metal, whether in ingot or wrought-product form, contains a small volume fraction of second-phase particles, chiefly iron-bearing phases—the metastable Al_6Fe , the stable Al_3Fe , which forms from Al_6Fe on solid-state heating, and $\text{Al}_{12}\text{Fe}_3\text{Si}$. Proportions of the binary and ternary phases depend on relative iron and silicon contents.

In quaternary systems, intermetallic phases of the respective binary and ternary systems are occasionally isomorphous, forming continuous series of solid solutions in equilibrium with aluminum solid solution. An important example is in the aluminum-copper-magnesium-zinc quaternary system where there are three such pairs: $\text{CuMg}_4\text{Al}_6 + \text{Mg}_3\text{Zn}_3\text{Al}_2$, $\text{Mg}_2\text{Zn}_{11} + \text{Cu}_6\text{Mg}_2\text{Al}_5$, and $\text{MgZn}_2 + \text{CuMgAl}$. The first pair have similar lattice parameters and form extensive mutual solid solution, the others less so. Neither $\text{Cu}_6\text{Mg}_2\text{Al}_5$ nor CuMgAl are equilibrium phases in aluminum-copper-magnesium, although both $\text{Mg}_2\text{Zn}_{11}$ and MgZn_2 are equilibrium phases in aluminum-magnesium-zinc. Another instance is in the aluminum-iron-manganese-silicon quaternary system; here the stable phase $(\text{FeMn})_3\text{Si}_2\text{Al}_{15}$ (body-centered cubic) can vary from $\text{Mn}_3\text{Si}_2\text{Al}_{15}$, $a = 1.2652 \text{ nm}$ (12.652 Å) to $\sim(\text{Mn}_{0.1}\text{Fe}_{0.9})_3\text{Si}_2\text{Al}_{15}$, $a = 1.2548 \text{ nm}$ (12.548 Å). The stable phase of the closest composition in aluminum-iron-silicon is Fe_2SiAl_8 (hexagonal); the hexagonal-to-cubic transition is also accomplished by small additions of vanadium, chromium, molybdenum, and tungsten, and larger additions of copper (Ref 1). Such chemical stabilization effects, coupled with the metastability introduced by casting, frequently cause complex alloy structure.

Prediction of Intermetallic Phases in Aluminum Alloys. The wide variety of intermetallic phases in aluminum alloys, which occur because aluminum is highly electronegative and trivalent, has been the subject of considerable study (Ref 2-4). Details depend on ratios and total amounts of alloying elements present and require reference to the phase diagrams for prediction. It must be kept in mind, however, that metastable conditions frequently prevail that are characterized by the presence of phases that are not shown on the equilibrium diagrams. Transition metals, for example, exhibit frequent metastability, in which one

phase introduced during fast solidification transforms in the solid state to another, for example, $\text{FeAl}_6 \rightarrow \text{FeAl}_3$, or a metastable variant precipitates from supersaturated solid solution such as MnAl_{12} .

Calculation of Phase Diagrams. Recently, considerable advances have been made in the thermodynamic evaluation of phase diagrams, particularly through the application of computer techniques (Ref 5). The available data and computational procedures have been systemized internationally since 1971 through the CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry) project (Ref 6). Application for multicomponent aluminum alloy phase diagram prediction has some inherent problems, particularly regarding the unexpected occurrence of ternary intermetallic phases, but is rapidly becoming an effective procedure. As of 1980, the following ternary aluminum-containing systems have been examined: Al-Fe-Ti, Al-Ga-Ge, Al-Ga-In, Al-Ge-Sn, Al-Li-Mg, and Al-Ni-Ti. As well as the 15 binaries required for these systems, phase diagrams of the following binary systems have also been examined: Al-Ca, Al-Ce, Al-Co, Al-Cr, Al-Cu, Al-Mn, Al-Mo, Al-Nb, Al-O, Al-P, and Al-Si (Ref 7). In principle, any ternary or quaternary combination of these binary systems can be analyzed.

Strengthening Mechanisms

The predominant objective in the design of aluminum alloys is to increase strength, hardness, and resistance to wear, creep, stress relaxation, or fatigue. Effects on these properties are specific to the different combinations of alloying elements, their alloy phase diagrams, and to the microstructures and substructures they form as a result of solidification, thermomechanical history, heat treatment, and/or cold working. These factors, to a large extent, depend on whether the alloy is a non-heat-treatable alloy or a heat-treatable (precipitation-strengthening) alloy.

Strength at elevated temperatures is improved mainly by solid-solution and second-phase hardening because at least for temperatures exceeding those of the precipitation-hardening range—230 °C (450 °F) and over—the precipitation reactions continue into the softening regime. For supersonic aircraft and space vehicle applications subject to aerodynamic heating, the heat-treatable alloys of the 2xxx group can be used for temperatures up to about 150 °C (300 °F).

Strengthening in non-heat-treatable alloys occurs from solid-solution formation, second-phase microstructural constituents, dispersoid precipitates, and/or strain hardening. Wrought alloys of this type are mainly those of the 3xxx and 5xxx groups containing magnesium, manganese, and/or chromium as well as the 1xxx aluminums

Table 4 Solid-solution effects on strength of principal solute elements in super-purity aluminum

Element	Difference in atomic radii, $r_x - r_{Al}$, % (a)	Strength/addition values(b)							
		Yield strength/% addition(c)				Tensile strength/% addition(d)			
		MPa/at%	ksi/at%	MPa/wt%	ksi/wt%	MPa/at%	ksi/at%	MPa/wt%	ksi/wt%
Si	-3.8	9.3	1.35	9.2	1.33	40.0	5.8	39.6	5.75
Zn	-6.0	6.6	0.95	2.9	0.42	20.7	3.0	15.2	2.2
Cu	-10.7	16.2	2.35	13.8	2.0	88.3	12.8	43.1	6.25
Mn	-11.3	(e)	(e)	30.3	4.4	(e)	(e)	53.8	7.8
Mg	+11.8	17.2	2.5	18.6	2.7	51.0	7.4	50.3	7.3

(a) Listed in order of increasing percent difference in atomic radii. (b) Some property-percent addition relationships are nonlinear. Generally, the unit effects of smaller additions are greater. (c) Increase in yield strength (0.2% offset) for 1% (atomic or weight basis) alloy addition. (d) Increase in ultimate tensile strength for 1% (atomic or weight basis) alloy addition. (e) 1 at% of manganese is not soluble.

and some alloys of the 4xxx group that contain only silicon. Non-heat-treatable casting alloys are of the 4xx.x or 5xx.x groups, containing silicon or magnesium, respectively, and the 1xx.x aluminums.

Solid-Solution Strengthening. For those elements that form solid solutions, the strengthening effect when the element is in solution tends to increase with increasing difference in the atomic radii of the solvent (Al) and solute (alloying element) atoms. This factor is evident in data obtained from super-purity binary solid-solution alloys in the annealed state, presented in Table 4, but it is evident that other effects are involved, chief among which is an electronic bonding factor. The effects of multiple solutes in solid solution are somewhat less than additive and are nearly the same when one solute has a larger and the other a smaller atomic radius than that of aluminum as when both are either smaller or larger. Manganese in solid solution is highly effective in strengthening binary alloys. Its contribution to the strength of commercial alloys is less, because in these compositions, as a result of commercial mill fabricating operations, the manganese is largely precipitated.

The principal alloys that are strengthened by alloying elements in solid solution (often coupled with cold work) are those in the aluminum-magnesium (5xxx) series, ranging from 0.5 to 6 wt% Mg. These alloys often contain small additions of transition elements such as chromium or manganese, and less frequently zirconium to control the grain or subgrain structure and iron and silicon impurities that usually are present in the form of intermetallic particles. Figure 6 illustrates the effect of magnesium in solid solution on the yield strength and tensile elongation for most of the common aluminum-magnesium commercial alloys.

Strengthening From Second-Phase Constituents. Elements and combinations that form predominantly second-phase constituents with relatively low solid solubility include iron, nickel, titanium, manganese, and chromium, and combinations thereof. The presence of increasing volume fractions of the intermetallic-compound phases formed by these elements and the elemental

silicon constituent formed by silicon during solidification or by precipitation in the solid state during postsolidification heating also increases strength and hardness. The rates of increase per unit weight of alloying element added are frequently similar to but usually lower than those resulting from solid solution. This "second-phase" hardening occurs even though the constituent particles are of sizes readily resolved by optical microscopy. These irregularly shaped particles form during solidification and occur mostly along grain boundaries and between dendrite arms.

Grain Refinement With Dispersed Precipitates. Manganese and/or chromium additions in wrought aluminum alloys allow the formation of complex precipitates that not only retard grain growth during ingot reheating but also assist in grain refinement during rolling. This method involves rapid solidification and cooling during the casting of ingots, so that a solid-solution state is formed with concentrations of manganese and/or chromium that greatly exceed their equilibrium solubility. During reheating of the as-cast ingot for wrought processing, this supersaturated metastable solid solution is designed to cause solid-state precipitation of complex phases. This precipitation does not cause appreciable hardening, nor is it intended that it should. Its purpose is to produce finely divided and dispersed particles that retard or inhibit recrystallization and grain growth in the alloy during subsequent heatings. The precipitate particles of $Al_{12}(Fe,Mn)_3Si$, $Al_{20}Cu_2Mn_3$, or $Al_{12}Mg_2Cr$ are incoherent with the matrix, and concurrent with their precipitation the original solid solution becomes less concentrated. These conditions do not provide appreciable precipitation hardening. Changes in electrical conductivity constitute an effective measure of the completeness of these precipitation reactions that occur in preheating.

The newer "in-line" or integrated processes that shorten the path from molten metal to wrought product, avoiding ingot preheating and reducing the overall time-temperature history, are changing this conventional or traditional picture. It seems very probable that in order to obtain the

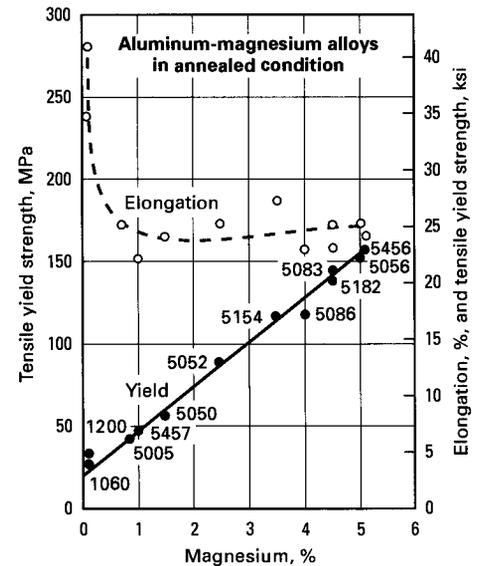


Fig. 6 Correlation between tensile yield, elongation, and magnesium content for some commercial aluminum alloys

best results from such processes, traditional alloy compositions should be adjusted taking into account the fact that larger proportions of these elements would be expected to remain in solid solution through such abbreviated and truncated thermomechanical operations. New capabilities may be obtained with currently standard alloys in some instances, but it would not be expected that a particular alloy would exhibit the same properties when produced by the two types of processes.

For alloys that are composed of both solid-solution and second-phase constituents and/or dispersoid precipitates, all of these components of microstructure contribute to strength, in a roughly additive manner. This is shown in Fig. 7 for Al-Mg-Mn alloys in the annealed condition.

Strain hardening by cold rolling, drawing, or stretching is a highly effective means of increasing the strength of non-heat-treatable alloys. Work- or strain-hardening curves for several typical non-heat-treatable commercial alloys (Fig. 8) illustrate the increases in strength that accompany increasing reduction by cold rolling of initially annealed temper sheet. This increase is obtained at the expense of ductility as measured by percent elongation in a tensile test and by reducing formability in operations such as bending and drawing. It is often advantageous to use material in a partially annealed (H2x) or stabilized (H3x) temper when bending, forming, or drawing is required, since material in these tempers has greater forming capability for the same strength levels than does strain-hardened only (H1x) material (see Table 5, for example).

All mill products can be supplied in the strain-hardened condition, although there are limitations on the amounts of strain that

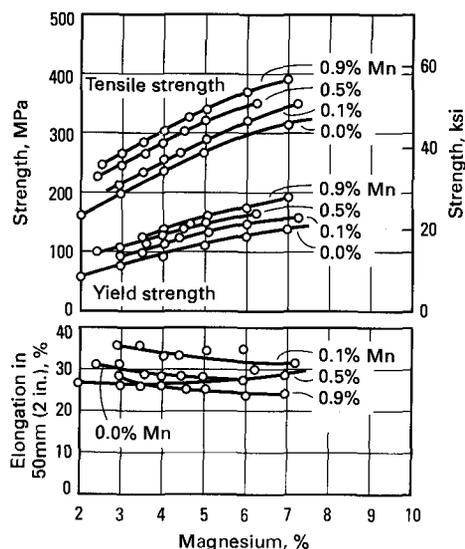


Fig. 7 Tensile properties in Al-Mg-Mn alloys in the form of annealed (O temper) plate 13 mm (0.5 in.) thick

can be applied to products such as die forgings and impacts. Even aluminum castings have been strengthened by cold pressing for certain applications. The heat-treatable alloys described below can also be subjected to strain hardening.

Heat-treatable (precipitation-hardening) aluminum alloys for wrought and cast products contain elements that decrease in solubility with decreasing temperature, and in concentrations that exceed their equilibrium solid solubility at room- and moderately higher temperatures. However, these features alone do not make an alloy capable of (precipitation hardening) during heat treatment. The strengths of most binary alloys containing magnesium, silicon, zinc, chromium, or manganese alone exhibit little change from thermal treatments regardless of whether the solute is completely in solid solution, partially precipitated, or substantially precipitated.

The mechanism of strengthening by age hardening involves the formation of coherent clusters of solute atoms (that is, the solute atoms have collected into a cluster but still have the same crystal structure as the solvent phase). This causes a great deal of strain because of mismatch in size between the solvent and solute atoms. The cluster stabilizes dislocations, because dislocations tend to reduce the strain, similar to the reduction in strain energy of a single solute atom by a dislocation. When dislocations are anchored or trapped by coherent solute clusters, the alloy is considerably strengthened and hardened.

However, if the precipitates are semicoherent (sharing a dislocation-containing interface with the matrix), incoherent (sharing a disordered interface, akin to a large-angle grain boundary, with the matrix), or are incapable of reducing strain behavior be-

Table 5 Tensile-property data illustrating typical relationships between strength and elongation for non-heat-treatable alloys in H1x versus H2x or H3x tempers

Alloy and temper	Tensile strength		Yield strength		Elongation, %
	MPa	ksi	MPa	ksi	
3105-H14	172	25	152	22	5
3105-H25	179	26	159	23	8
3105-H16	193	28	172	25	4

cause they are too strong, a dislocation can circumvent the particles only by bowing into a roughly semicircular shape between them under the action of an applied shear stress. Consequently, the presence of the precipitate particles, and even more importantly the strain fields in the matrix surrounding the coherent particles, provide higher strength by obstructing and retarding the movement of dislocations. The characteristic that determines whether a precipitate phase is coherent or noncoherent is the closeness of match or degree of disregistry between the atomic spacings on the lattice of the matrix and on that of the precipitate.

Heat treatment for precipitation strengthening includes a solution heat treatment at a high temperature to maximize solubility, followed by rapid cooling or quenching to a low temperature to obtain a solid solution supersaturated with both solute elements and vacancies. Solution heat treatments are designed to maximize the solubility of elements that participate in subsequent aging treatments. They are most effective near the solidus or eutectic temperature, where maximum solubility exists and diffusion rates are rapid. However, care must be taken to avoid incipient melting of low-temperature eutectics and grain-boundary phases. Such melting results in quench cracks and loss in ductility. The maximum temperature may also be set with regard to grain growth, surface effects, and economy of operation. The minimum temperature should be above the solvus, or the desired properties derived from aging will not be realized. The optimum heat-treatment range may be quite small, with a margin of safety sometimes only ± 5 K.

The high strength is produced by the finely dispersed precipitates that form during aging heat treatments (which may include either natural aging or artificial aging as described below). This final step must be accomplished not only below the equilibrium solvus temperature, but below a metastable miscibility gap called the Guinier-Preston (GP) zone solvus line. The supersaturation of vacancies allows diffusion, and thus zone formation, to occur much faster than expected from equilibrium diffusion coefficients. In the precipitation process, the saturated solid solution first develops solute clusters, which then become involved in the formation of transi-

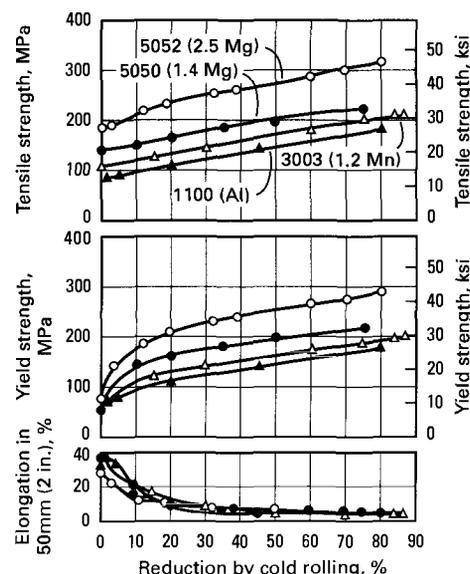


Fig. 8 Strain-hardening curves for aluminum (1100), and for Al-Mn (3003) and Al-Mg (5050 and 5052) alloys

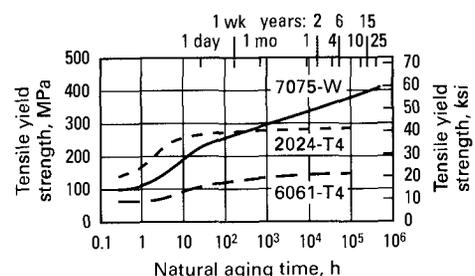


Fig. 9 Natural aging curves for three solution heat-treated wrought aluminum alloys

tional (nonequilibrium) precipitates. The final structure consists of equilibrium precipitates, which do not contribute to age hardening (precipitation strengthening).

Natural aging refers to the spontaneous formation of a G-P zone structure during exposure at room temperature. Solute atoms either cluster or segregate to selected atomic lattice planes, depending on the alloy system, to form the G-P zones, which are more resistant to movement of dislocations through the lattice, and hence are stronger. Curves showing the changes in tensile yield strength with time at room temperature (natural aging curves) for three wrought commercial heat-treatable alloys of different alloy systems are shown in Fig. 9. The magnitudes of increase in this property are considerably different for the three alloys, and the differences in rate of change with time are of practical importance. Because 7075 and similar alloys never become completely stable under these conditions, they are rarely used in the naturally aged temper. On the other hand, 2024 is widely used in this condition.

Of the binary alloys, aluminum-copper alloys exhibit natural aging after being solu-

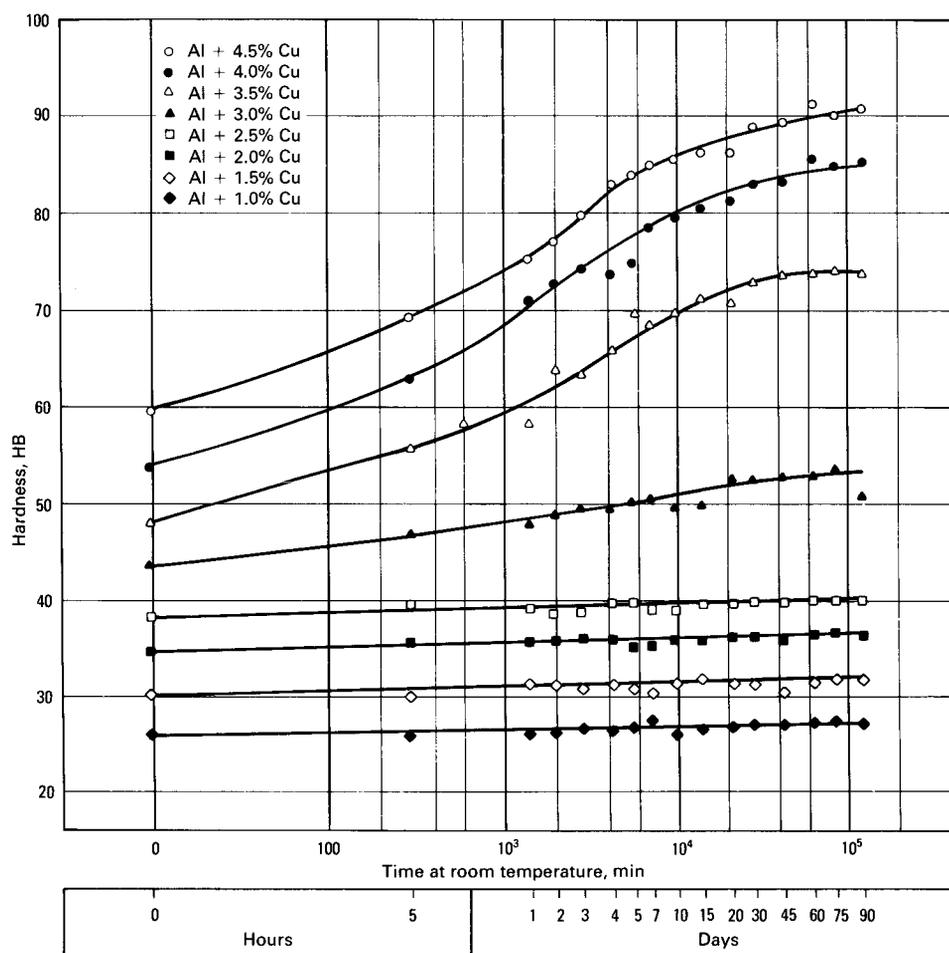


Fig. 10 Natural aging curves for binary Al-Cu alloys quenched in water at 100 °C (212 °F)

tion heat treated and quenched. The amounts by which strength and hardness increase become larger with time of natural aging and with the copper content of the alloy from about 3% to the limit of solid solubility (5.65%). Natural aging curves for slowly quenched, high-purity Al-Cu alloys with 1 to 4.5% Cu are shown in Fig. 10. The rates and amounts of the changes in strength and hardness can be increased by holding the alloys at moderately elevated temperatures (for alloys of all types, the useful range is about 120 to 230 °C, or 250 to 450 °F). This treatment is called precipitation heat treating or artificial aging. In the Al-Cu system, alloys with as little as 1% Cu, again slowly quenched, start to harden after about 20 days at a temperature of 150 °C, or 300 °F (see Fig. 11). The alloys of this system, having less than about 3% Cu, show little or no natural aging after low-cooling-rate quenching, which introduces little stress.

Artificial aging includes exposure at temperatures above room temperature so as to produce the transitional (metastable) forms of the equilibrium precipitate of a particular alloy system. These transitional precipitates remain coherent with the solid-solution ma-

trix and thus contribute to precipitation strengthening. With further heating at temperatures that cause strengthening or at higher temperatures, the precipitate particles grow, but even more importantly convert to the equilibrium phases, which generally are not coherent. These changes soften the material, and carried further, produce the softest or annealed condition. Even at this stage, the precipitate particles are still too small to be clearly resolved by optical microscopy, although etching effects are readily observed—particularly in alloys containing copper.

Precipitation heat treatment or artificial aging curves for the Al-Mg-Si wrought alloy 6061 (which is widely used for structural shapes) are shown in Fig. 12. This is a typical family of curves showing the changes in tensile yield strength that accrue with increasing time at each of a series of temperatures. In all cases, the material had been given a solution heat treatment followed by a quench just prior to the start of the precipitation heat treatment. For detailed presentation of heat-treating operations, parameters, and practices, see *Heat Treating*, Volume 4 of the 9th Edition of *Metals Handbook*.

The commercial heat-treatable aluminum alloys are, with few exceptions, based on ternary or quaternary systems with respect to the solutes involved in developing strength by precipitation. The most prominent systems are: Al-Cu-Mg, Al-Cu-Si, and Al-Cu-Mg-Si, alloys of which are in the 2xxx and 2xx.x groups (wrought and casting alloys, respectively); Al-Mg-Si (6xxx wrought alloys); Al-Si-Mg, Al-Si-Cu, and Al-Si-Mg-Cu (3xx.x casting alloys); and Al-Zn-Mg and Al-Zn-Mg-Cu (7xxx wrought and 7xx.x casting alloys). In each case the solubility of the multiple-solute elements decreases with decreasing temperature.

These multiple alloying additions of both major solute elements and supplementary elements employed in commercial alloys are strictly functional and serve with different heat treatments to provide the many different combinations of properties—physical, mechanical, and electrochemical—that are required for different applications. Some alloys, particularly those for foundry production of castings, contain amounts of silicon far in excess of the amount that is soluble or needed for strengthening alone. The function here is chiefly to improve casting soundness and freedom from cracking, but the excess silicon also serves to increase wear resistance, as do other microstructural constituents formed by manganese, nickel, and iron. Parts made of such alloys are commonly used in gasoline and diesel engines (pistons, cylinder blocks, and so forth). The system of numerical nomenclature used to designate the alloys, and that for the strain-hardened and heat-treated tempers, is described in the article “Alloy and Temper Designation Systems for Aluminum and Aluminum Alloys” in this Volume.

Alloys containing the elements silver, lithium, and germanium are also capable of providing high strength with heat treatment, and in the case of lithium, both increased elastic modulus and lower density, which are highly advantageous—particularly for aerospace applications (see the article “Aluminum-Lithium Alloys” in this Volume). Commercial use of alloys containing these elements has been restricted either by cost or by difficulties encountered in producing them. Such alloys are used to some extent, however, and research is being directed toward overcoming their disadvantages.

In the case of alloys having copper as the principal alloying ingredient and no magnesium, strengthening by precipitation can be greatly increased by adding small fractional percentages of tin, cadmium, or indium, or combinations of these elements. Alloys based on these effects have been produced commercially but not in large volumes because of costly special practices and limitations required in processing, and in the case of cadmium, the need for special facilities to avoid health hazards from formation and release of cadmium vapor during alloying. Such alloys,

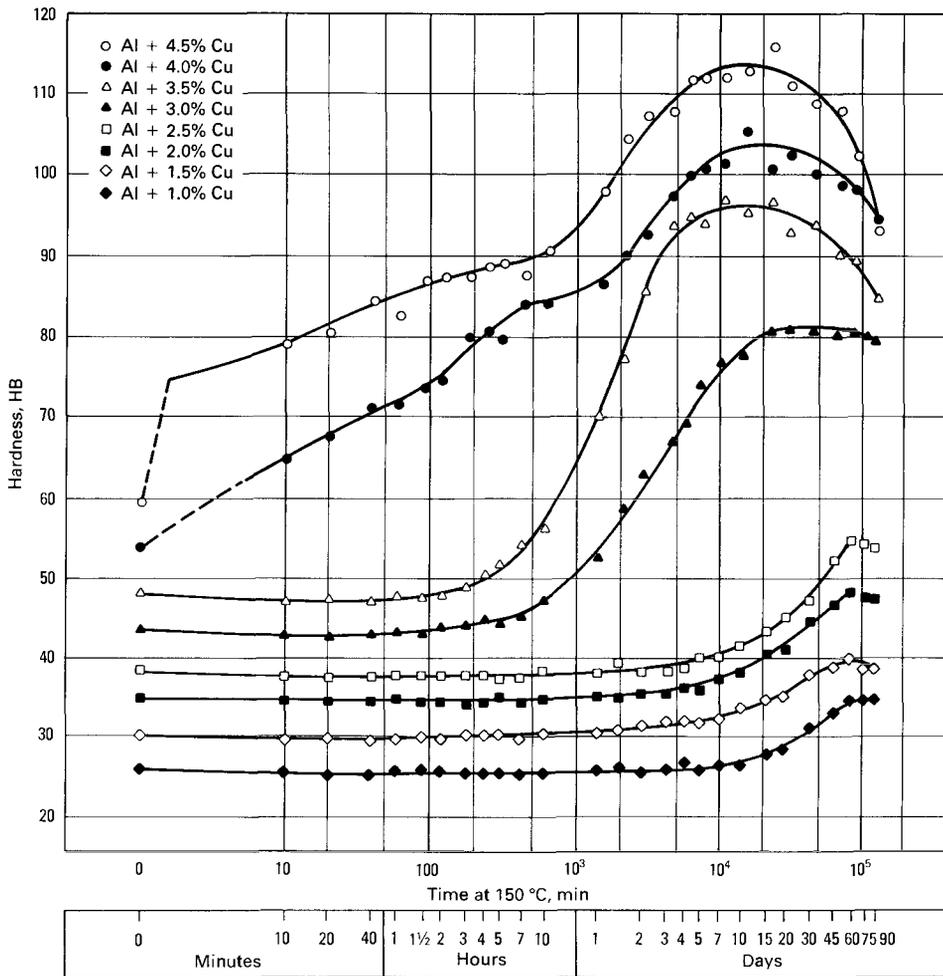


Fig. 11 Precipitation hardening curves for binary Al-Cu alloys quenched in water at 100 °C (212 °F) and aged at 150 °C (300 °F)

as well as those containing silver, lithium, or other particle-forming elements, may be used on a selective basis in the future.

Effects on Physical and Electrochemical Properties. The above description of the precipitation processes in commercial heat-treatable aluminum alloys (as well as the heat-treatable binary alloys, none of which is used commercially) affect not only mechanical properties but also physical properties (density and electrical and thermal conductivities) and electrochemical properties (solution potential). On the microstructural and submicroscopic scales, the electrochemical properties develop point-to-point nonuniformities that account for changes in corrosion resistance.

Measurements of changes in physical and electrochemical properties have played an important role in completely describing precipitation reactions and are very useful in analyzing or diagnosing whether heat-treatable products have been properly or improperly heat treated. Although they may be indicative of the strength levels of products, they cannot be relied upon to determine whether or not the product meets specified

mechanical-property limits. Since elements in solid solution are always more harmful to electrical conductivity than the same elements combined with others as intermetallic compounds, thermal treatments are applied to ingots used for fabrication of electrical conductor parts. These thermal treatments are intended to precipitate as much as possible of the dissolved impurities. Iron is the principal element involved, and although the amount precipitated is only a few hundredths of a percent, the effect on electrical conductivity of the wire, cable, or other product made from the ingot is of considerable practical importance. These alloys may or may not be heat treatable with respect to mechanical properties. Electrical conductor alloys 6101 and 6201 are heat treatable. These alloys are used in tempers in which their strengthening precipitate, the transition form of Mg_2Si , is largely out of solid solution to optimize both strength and conductivity.

Metallurgical Factors of Other Mechanical Properties

Forming. The formability of a material is the extent to which it can be deformed in a

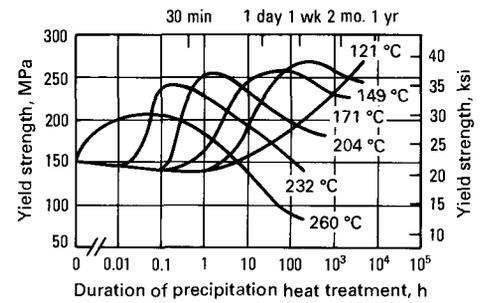


Fig. 12 Precipitation heat treatment or artificial aging curves for solution heat-treated aluminum alloy 6061

particular process before the onset of failure. Aluminum sheet or aluminum shapes usually fail by localized necking or by ductile fracture. Necking is governed largely by bulk material properties such as work hardening and strain-rate hardening and depends critically on the strain path followed by the forming process. In dilute alloys, the extent of necking or limit strain is reduced by cold work, age hardening, gross defects, a large grain size, and the presence of alloying elements in solid solution. Ductile fracture occurs as a result of the nucleation and linking of microscopic voids at particles and the concentration of strain in narrow shear bands. Fracture usually occurs at larger strains than does localized necking and therefore is usually important only when necking is suppressed. Common examples where fracture is encountered are at small radius bends and at severe drawing, ironing, and stretching near notches or sheared edges.

Considerable advances have been made in developing alloys with good formability, but in general, an alloy cannot be optimized on this basis alone. The function of the formed part must also be considered and improvements in functional characteristics, such as strength and ease of machining, often tend to reduce the formability of the alloy.

The principal alloys that are strengthened by alloying elements in solid solution (often coupled with cold work) are those in the aluminum-magnesium (5xxx) series, ranging from 0.5 to 6 wt% Mg. Figure 6 illustrates the effect of magnesium in solid solution on the yield strength and tensile elongation for most of the common aluminum-magnesium commercial alloys. Note the large initial reduction in the tensile elongation with the addition of small amounts of magnesium.

The reductions in the forming limit produced by additions of magnesium and copper appear to be related to the tendency of the solute atoms to migrate to dislocations (strain age). This tends to increase work hardening at low strains, where dislocations are pinned by solute atoms, but produces a decrease in work hardening at large strains. Small amounts of magnesium or copper also

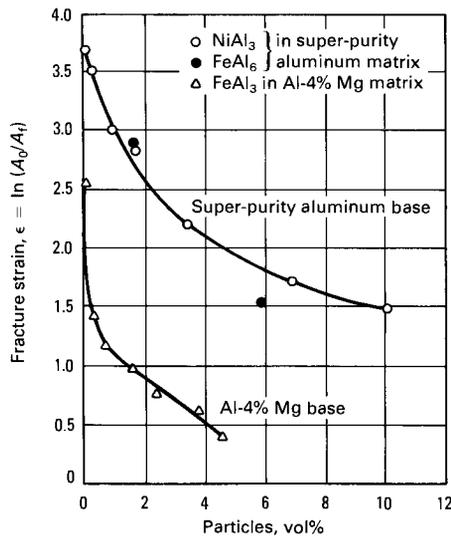


Fig. 13 Effect of volume percent fraction of micron-size intermetallic particles and composition of the matrix on the fracture strain of 5 mm (0.2 in.) diam tensile specimens. A_0 is initial cross-sectional area. A_f is area of fracture.

reduce the strain-rate hardening, which will reduce the amount of useful diffuse necking that occurs after the uniform elongation. Zinc in dilute alloys has little effect on work hardening or necking, and it does not cause strain aging.

Elements that have low solid solubilities at typical processing temperatures, such as iron, silicon, and manganese, are present in the form of second-phase particles and have little influence on either strain hardening or strain-rate hardening and thus a relatively minor influence on necking behavior. Second-phase particles do, however, have a large influence on fracture, as is shown in Fig. 13 and 14. In these examples an increase in the iron, nickel, or manganese content produces an increase in the number of microscopic particles that promote fracture. The addition of magnesium promotes an additional reduction in fracture strain because the higher flow stresses aid in the formation and growth of voids at the intermetallic particles. Magnesium in solid solution also promotes the localization of strain into shear bands, which concentrates the voids in a thin plane of highly localized strain.

Precipitation-strengthened alloys are usually formed in the naturally aged (T4) condition, or in the annealed (O) condition, but only very rarely in the peak strength (T6) condition where both the necking and fracture limits are low. In Fig. 15 the effect of a wide range of precipitate structures on some of the forming properties is illustrated for alloy 2036 (2.5% Cu-0.5% Mg). Curves similar in shape can be drawn for most of the precipitation-strengthened alloys in the 2xxx and 6xxx series. The properties in Fig. 15 were obtained from sheet tensile specimens first solution heat treated, then aged

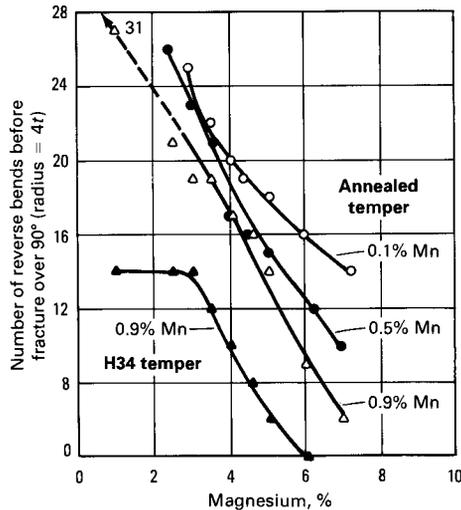


Fig. 14 Effect of magnesium and manganese on the formability of aluminum alloys in the annealed and H34 tempers; 1.6 mm (0.064 in.) thick sheet

at temperatures ranging from room temperature to 350 °C (660 °F). This produced a full range of structures from solid solution (as-quenched) through T4 and T6 tempers to various degrees of overaging and precipitate agglomeration.

Fracture toughness and fatigue behavior, which are important characteristics of the high-strength aluminum alloys used in aerospace applications, are known to be influenced by the following three types of constituent particles:

Type	Size		Typical examples
	μm	mil	
Constituent particles.....	2-50	0.08-2	Cu_2FeAl_7 , CuAl_2 , FeAl_6
Dispersoid particles.....	0.01-0.5	0.0004-0.02	ZrAl_3 , $\text{CrMg}_2\text{Al}_{12}$
Strengthening precipitates...	0.001-0.5	0.00004-0.02	Guinier-Preston zones

Consequently, the design of damage-tolerant aluminum alloys such as 7475, 7050, or 2124 has been primarily based upon the control of microstructure through composition and fabrication practice.

Effect of Second-Phase Constituents on Fracture Toughness. It is generally accepted that the fracture of brittle constituent particles leads to preferential paths for crack advance and reduced fracture toughness. Consequently, an often-used approach to improve the toughness of high-strength aluminum alloys has been the reduction of iron and silicon levels. The recent development of improved alloys such as 7475, 7050, and 2124 has hinged, in large part, upon the use of higher-purity base metal than 7075 or 2024. Figure 16 illustrates the influence of base metal purity on the fracture resistance of alloy 7475

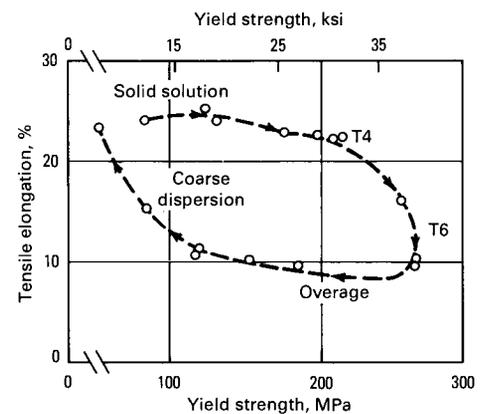


Fig. 15 Effect of precipitation on yield strength and elongation in alloy 2036

sheet. The partially soluble constituents exert a similar effect on the fracture behavior of other high-strength alloys. Figure 17 shows the reduction in toughness experienced as the volume fraction of Al_2CuMg is increased in alloy 7050 plate.

For superior toughness, the amount of dispersoid-forming element should be held to the minimum required for control of grain structure, mechanical properties, or resistance to stress-corrosion cracking. Results for 7xxx alloy sheet (Fig. 18) show the marked decrease in unit propagation energy as chromium is increased. Substitution of other elements, such as zirconium or manganese, for chromium can also influence fracture toughness. However, the observed effects of the different dispersoids on fracture toughness can quite possibly be related to the particular toughness parameter chosen and the influence of the dispersoid on the grain structure of the wrought product.

The primary effect of hardening precipitates on fracture toughness of high-strength aluminum alloys is through the increase in yield strength and depends upon the particular working and heat-treatment practices

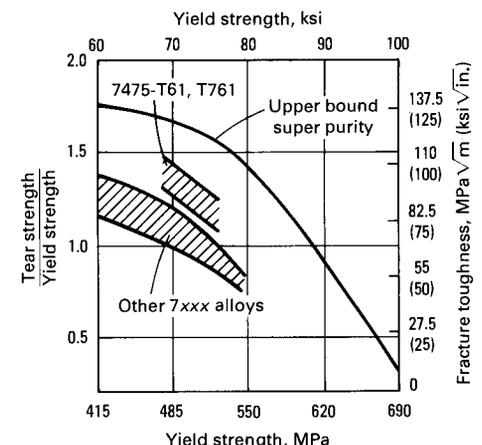


Fig. 16 Tear strength and yield strength ratio of alloy 7475 sheet

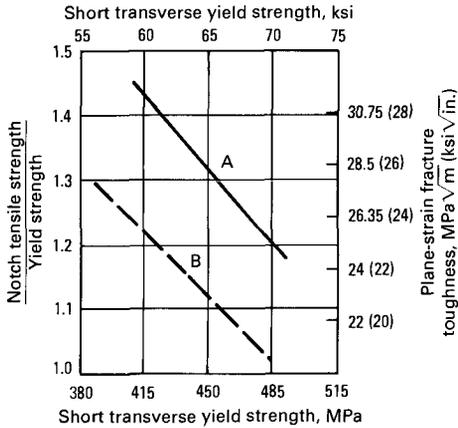


Fig. 17 Effects of amount of Al_2CuMg constituent on the toughness of 7050 plate

applied to the wrought products. However, composition changes, particularly magnesium level, can produce significant effects on toughness of 7xxx alloys. These variations in composition do not alter the basic character of the hardening precipitates, but exert a subtle influence on the overall precipitate structure.

Effect of Second-Phase Constituents on Fatigue Behavior. Although the three types of constituent particles may influence fatigue behavior, the effect of constituent particles on fatigue behavior is highly dependent upon the type of fatigue test or the stress regime chosen for evaluation. Consequently, the design of aluminum alloys to resist failure by fatigue mechanisms has not proceeded to the same extent as for fracture toughness. In the case of large constituent particles, for example, reduced iron and silicon contents do not always result in improved fatigue resistance commensurate with the previously described improvements in fracture toughness. Increased purity level does not, for instance, produce any appreciable improvement in notched or smooth $S-N$ fatigue strength.

In terms of fatigue crack growth (FCG) rates, no consistent differences have been observed for low- and high-purity 7xxx alloy variants at low to intermediate ΔK levels. However, at high stress-intensity ranges, FCG rates are notably reduced for low iron and silicon alloys. The reason for the observed improvement is undoubtedly related to the higher fracture toughness of high-purity metals. At high stress-intensity ranges, where crack growth per cycle (da/dN) values are large, localized fracture and void nucleation at constituent particles become the dominant FCG mechanism. For samples subjected to periodic spike overloads, low-purity alloys were shown to exhibit slower overall FCG rates than higher-purity materials. This effect was attributed to localized crack deviation induced by the insoluble constituents. Secondary cracks at these

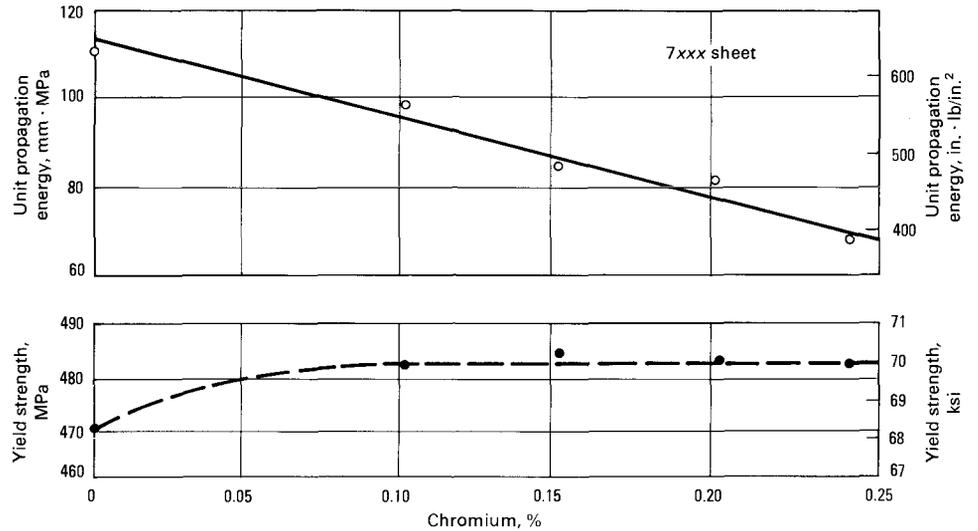


Fig. 18 Effect of chromium content on unit crack propagation energy and yield strength on a Zn-Mg-Cu aluminum alloy (5.5 Zn, 2.4 Mg, 1.4 Cu, 0.30 Fe, 0.08 Si, 0.03 Ti, 0.01 Mn)

particles acted to lower crack tip stress-intensity values and to reduce measured FCG rates.

No clear-cut influence of dispersoid particles on the fatigue behavior of aluminum alloys has emerged. Two separate studies have concluded that dispersoid type has little effect on either FCG resistance or notched fatigue resistance of 7xxx alloys. The only expected effect of dispersoid type

on fatigue performance should occur for high ΔK fatigue crack growth, where mechanisms similar to those for fracture toughness predominate.

Within a given alloy system, slight changes in composition that influence hardening precipitates have not been shown to influence the $S-N$ fatigue resistance of aluminum alloys. However, significant differences have been observed in comparison of

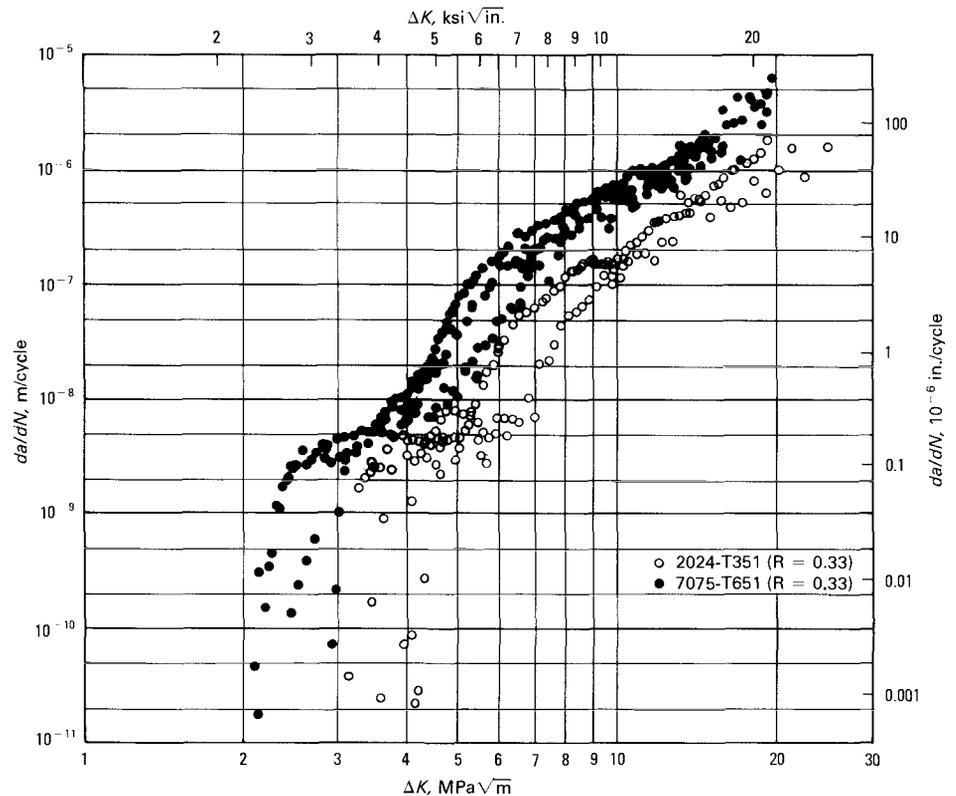


Fig. 19 Fatigue crack growth of 2024-T3 versus 7075-T6 plate over entire $da/dN-\Delta K$ range

alloys of different systems. For instance, 2024-T3 is known to outperform 7075-T6 at stresses where fatigue lives are short ($\sim 10^5$ cycles). The superior fatigue performance of alloy 2024-T3 in the 10^5 cycle range has led most aircraft designers to specify it in preference to 7075-T6 in applications where tension-tension loads are predominant.

Alloy 2024-T3 shows a similar advantage over 7075-T6 and other 7xxx alloys in fatigue crack growth. The superior performance for 2024-T3 plate versus 7075-T6 extends over the entire $d/dN-\Delta K$ range, as shown in Fig. 19. Within the 7xxx alloy system, increasing copper content improves FCG performance in high humidity. This result was attributed to an increased resistance of the high-copper alloy to corrosion in the moist environment.

Fatigue designers are currently beginning to use increasingly complex “spectrum” FCG tests to predict the performance of materials in service. Early work in the area of spectrum fatigue showed that high-toughness alloy 7475-T76 performed better than either 2024-T3 or 7075-T6.

General Effects of Alloying

Although the predominant reason for alloying is to increase strength, alloying also has important effects on other characteristics of aluminum alloys. Some of these effects are discussed below. Effects of specific elements are discussed in the section “Specific Alloying Elements and Impurities” in this article.

Alloy Effects on Physical Properties. Most of the physical properties—density, melting-temperature range, heat content, coefficient of thermal expansion, and electrical and thermal conductivities—are changed by addition of one or more alloying elements. The rates of change in these properties with each incremental addition are specific for each element and depend, in many cases drastically, on whether a solid solution or a second phase is formed. In those cases in which the element or elements may be either dissolved or precipitated by heat treatment, certain of these properties, particularly density and conductivity, can be altered substantially by heat treatment. Density and conductivity of such alloys show relatively large differences from one temper to another.

Electrochemical properties and corrosion resistance are strongly affected by alloying elements that form either solid solutions, or additional phases, or both. For those systems exhibiting substantial changes in solid solubility with temperature, these properties may change markedly with heat-treated tempers, and although infrequently, even with room-temperature aging (for example, the stress-corrosion resistance of high-Mg 5xxx alloys in strain-hardened tempers). The strongest electrochemical effects are from copper or zinc in solid solution. Addi-

tions of copper in solid solution change the electrochemical solution potential in the cathodic direction at the rate of 0.047 V/wt% (0.112 V/at%), and additions of zinc change it in the anodic direction at the rate of 0.063 V/wt% (0.155 V/at%). These potentials are those measured in aqueous solution of 53 g NaCl + 3 g H₂O₂ per liter. Magnesium and silicon, which are the basis for the 4xxx, 5xxx, and 6xxx series wrought alloys and the 3xx.x, 4xx.x, and 5xx.x series casting alloys, and which are prominent in the compositions of many other alloys, have relatively mild effects on solution potential and are not detrimental to corrosion resistance.

Although aluminum is a thermodynamically reactive metal, it has excellent resistance to corrosion in most environments, which may be attributed to the passivity afforded by a protective film of aluminum oxide. This film is strongly bonded to the surface of the metal, and if damaged re-forms almost immediately. The continuity of the film is affected by the microstructure of the metal—in particular, by the presence and volume fraction of second-phase particles. Corrosion resistance is affected by this factor and by the solution-potential relationships between the second-phase particles or constituents and the solid-solution matrix in which they occur. In most environments, resistance to corrosion of unalloyed aluminum increases with increasing purity. The resistance of an alloy depends not only on the microstructural relationships involving the specific types, amounts, and distributions of the second-phase constituents but even more strongly on the nature of the solid solutions in which they are present. Copper reduces corrosion resistance despite the fact that when in solid solution it makes the alloy more cathodic (less active thermodynamically). This is explained by the fact that copper ions taken into solution in aqueous, corroding media replate on the aluminum alloy surface as minute particles of metallic copper, forming even more active corrosion couples because metallic copper is highly cathodic to the alloy. Manganese, which in solid solution changes solution potential in the cathodic direction as strongly as does copper, does not impair corrosion resistance of commercial alloys that contain it, because the amounts left in solid solution in commercial products, which undergo extensive solid-state heating in process, are very small, and the manganese does not replate from solution as does copper.

The differences in solution potential among alloys of different compositions are used to great advantage in the composite Alclad products. In these products, the structural component of the composite, usually a strong or heat-treatable alloy, is made the core of the product and is covered by a cladding alloy of a composition that not only is highly corrosion resistant but also has a solution potential that is anodic to that

of the core. Analogous to the protection of the underlying steel afforded by zinc on the surfaces of galvanized steel products, the aluminum alloy core is protected electrolytically by the more-anodic cladding. The composition of the cladding material is designed specifically to protect the core alloy, so that, for those containing copper as the principal alloying ingredient (2xxx type), the more-anodic unalloyed aluminum (1xxx type) serves to protect the core electrolytically. In the case of the strong alloys containing zinc along with magnesium and copper (such as 7049, 7050, 7075, and 7178), an aluminum-zinc alloy (7072) or an aluminum-zinc-magnesium alloy (7008 or 7011) provides protection. The latter provides higher strength.

Impurity Effects. Although major differences in properties and characteristics are usually associated with alloying additions of one to several percent, many alloying elements produce highly significant effects when added in small fractions of 1% or when increased by such small amounts. With respect to mechanical properties, this is particularly true for combinations of certain elements. The interactions are quite complex, and a given element may be either highly beneficial or highly detrimental depending on the other elements involved and on the property or combination of properties needed.

The presence or absence of amounts on the order of one thousandth of one percent of certain impurities—sodium and calcium, for example—may make the difference between success or complete failure in fabricating high-magnesium 5xxx alloy ingots into useful wrought products. There are many other examples of equal practical importance. Impurity limits specified for commercial alloys reflect some of these effects, but producers of mill products must adhere to even more-restrictive limits in many cases to ensure good product recovery.

Silicon-Modifying Additions. Additions of similarly small percentages of both metallic and nonmetallic substances—sodium and phosphorus, for example—are used to enhance the mechanical and machining properties of silicon-containing casting alloys.

Grain-Refining Additions. Most alloys produced as “fabricating ingots” for fabricating wrought products, as well as those in the form of foundry ingot, have small additions of titanium or boron, or combinations of these two elements, in controlled proportions. The purpose of these additions is to control grain size and shape in the as-cast fabricating ingot or in castings produced from the foundry ingot. These grain-refining additions have little effect on changes in grain size that occur during or as a result of working or recrystallization. Welding filler alloys and casting alloys generally have higher contents of the grain-refining elements to ensure highest resistance to crack-

Table 6 Typical physical properties of aluminum alloys

Alloy	Average coefficient of thermal expansion(a)		Approximate melting range(b)(c)		Temper	Thermal conductivity at 25 °C (77 °F)		Electrical conductivity at 20 °C (68 °F), %IACS		Electrical resistivity at 20 °C (68 °F)	
	µm/m · °C	µin./in. · °F	°C	°F		W/m · °C	Btu · in./ft ² · h · °F	Equal volume	Equal weight	Ω · mm ² /m	Ω · circ mil/ft
1060	23.6	13.1	645-655	1195-1215	0	234	1625	62	204	0.028	17
1100	23.6	13.1	643-655	1190-1215	H18	230	1600	61	201	0.028	17
					0	222	1540	59	194	0.030	18
1350	23.75	13.2	645-655	1195-1215	All	218	1510	57	187	0.030	18
2011	22.9	12.7	540-643(d)	1005-1190(d)	T3	234	1625	62	204	0.028	17
2014	23.0	12.8	507-638(e)	945-1180(e)	T8	151	1050	39	123	0.045	27
					0	172	1190	45	142	0.038	23
					T4	193	1340	50	159	0.035	21
					T6	134	930	34	108	0.0515	31
2017	23.6	13.1	513-640(e)	955-1185(e)	T6	154	1070	40	127	0.043	26
					0	193	1340	50	159	0.035	21
					T4	134	930	34	108	0.0515	31
2018	22.3	12.4	507-638(d)	945-1180(d)	T61	154	1070	40	127	0.043	26
2024	23.2	12.9	500-638(e)	935-1180(e)	0	193	1340	50	160	0.035	21
2025	22.7	12.6	520-640(e)	970-1185(e)	T3, T4, T361	121	840	30	96	0.058	35
					T6, T81, T861	151	1050	38	122	0.045	27
					T6	154	1070	40	128	0.043	26
					T4	159	1100	41	135	0.0415	25
2036	23.4	13.0	555-650(d)	1030-1200(d)	T4	154	1070	40	130	0.043	26
2117	23.75	13.2	555-650(d)	1030-1200(d)	T4	154	1070	40	130	0.043	26
2124	22.9	12.7	500-638(e)	935-1180(e)	T851	152	1055	38	122	0.045	27
2218	22.3	12.4	505-635(e)	940-1175(e)	T72	154	1070	40	126	0.043	26
2219	22.3	12.4	543-643(e)	1010-1190(e)	0	172	1190	44	138	0.040	24
2618	22.3	12.4	550-638	1020-1180	T31, T37	112	780	28	88	0.0615	37
					T6, T81, T87	121	840	30	94	0.058	35
					T6	147	1020	37	120	0.0465	28
3003	23.2	12.9	643-655	1190-1210	0	193	1340	50	163	0.035	21
3004	23.9	13.3	630-655	1165-1210	H12	163	1130	42	137	0.0415	25
					H14	159	1100	41	134	0.0415	25
					H18	154	1070	40	130	0.043	26
					All	163	1130	42	137	0.0415	25
3105	23.6	13.1	635-655	1175-1210	All	172	1190	45	148	0.038	23
4032	19.4	10.8	532-570(e)	990-1060(e)	0	154	1070	40	132	0.043	26
4043	22.1	12.3	575-632	1065-1170	T6	138	960	35	116	0.050	30
					0	163	1130	42	140	0.0415	25
4045	21.05	11.7	575-600	1065-1110	All	172	1190	45	151	0.038	23
4343	21.6	12.0	577-613	1070-1135	All	180	1250	42	158	0.0415	25
5005	23.75	13.2	632-655	1170-1210	All	200	1390	52	172	0.033	20
5050	23.75	13.2	625-650	1155-1205	All	193	1340	50	165	0.035	21
5052	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5056	24.1	13.4	568-638	1055-1180	0	117	810	29	98	0.060	36
5083	23.75	13.2	590-638	1095-1180	H38	108	750	27	91	0.063	38
					0	117	810	29	98	0.060	36
5086	23.75	13.2	585-640	1085-1185	All	125	870	31	104	0.055	33
5154	23.9	13.3	593-643	1100-1190	All	125	870	32	107	0.053	32
5252	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5254	23.9	13.3	593-643	1100-1190	All	125	870	32	107	0.053	32
5356	24.1	13.4	570-635	1060-1175	0	117	810	29	98	0.060	36
5454	23.6	13.1	600-645	1115-1195	0	134	930	34	113	0.0515	31
5456	23.9	13.3	568-638	1055-1180	H38	134	930	34	113	0.0515	31
					0	117	810	29	98	0.060	36
5457	23.75	13.2	630-655	1165-1210	All	176	1220	46	153	0.038	23
5652	23.75	13.2	607-650	1125-1200	All	138	960	35	116	0.050	30
5657	23.75	13.2	638-657	1180-1215	All	205	1420	54	180	0.0315	19
6005	23.4	13.0	610-655(d)	1125-1210(d)	T1	180	1250	47	155	0.0365	22
6053	23	12.8	575-650(d)	1070-1205(d)	T5	190	1310	49	161	0.035	21
					0	172	1190	45	148	0.038	23
					T4	154	1070	40	132	0.043	26
					T6	163	1130	42	139	0.0415	25
6061	23.6	13.1	580-650(d)	1080-1205(d)	0	180	1250	47	155	0.0365	22
					T4	154	1070	40	132	0.043	26
					T6	167	1160	43	142	0.040	24
					0	218	1510	58	191	0.030	18
6063	23.4	13.0	615-655	1140-1210	T1	193	1340	50	165	0.035	21
					T5	209	1450	55	181	0.032	19
					T6, T83	200	1390	53	175	0.033	20
					0	154	1070	40	132	0.043	26
6066	23.2	12.9	565-645(e)	1045-1195(e)	T6	147	1020	37	122	0.0465	28
					0	172	1190	44	145	0.040	24
6070	...	...	565-650(e)	1050-1200(e)	T6	172	1190	44	145	0.040	24
6101	23.4	13.0	620-655	1150-1210	T6	218	1510	57	188	0.030	18
					T61	222	1540	59	194	0.030	18
					T63	218	1510	58	191	0.030	18
					T64	226	1570	60	198	0.028	17
					T65	218	1510	58	191	0.030	18

(continued)

(a) Coefficient from 20 to 100 °C (68 to 212 °F). (b) Melting ranges shown apply to wrought products of 6.35 mm (1/4 in.) thickness or greater. (c) Based on typical composition of the indicated alloys. (d) Eutectic melting can be completely eliminated by homogenization. (e) Eutectic melting is not eliminated by homogenization. (f) Although not formerly registered, the literature and some specifications have used T736 as the designation for this temper. (g) Homogenization may raise eutectic melting temperature 10 to 20 °C (20 to 40 °F) but usually does not eliminate eutectic melting.

Table 6 (continued)

Alloy	Average coefficient of thermal expansion(a)		Approximate melting range(b)(c)		Temper	Thermal conductivity at 25 °C (77 °F)		Electrical conductivity at 20 °C (68 °F), % IACS		Electrical resistivity at 20 °C (68 °F)		
	μm/m · °C	μin./in. · °F	°F	°F		W/m · °C	Btu · in./ft ² · h · °F	Equal volume	Equal weight	Ω · mm ² /m	Ω · circ mil/ft	
6105	23.4	13.0	600–650(d)	1110–1200(d)	T1	176	1220	46	151	0.038	23	
					T5	193	1340	50	165	0.035	21	
6151	23.2	12.9	590–650(d)	1090–1200(d)	0	205	1420	54	178	0.0315	19	
					T4	163	1130	42	138	0.0415	25	
					T6	172	1190	45	148	0.038	23	
6201	23.4	13.0	607–655(d)	1125–1210(d)	T81	205	1420	54	180	0.0315	19	
6253	...	...	600–650	1100–1205	...	...	...	...	...	...	...
6262	23.4	13.0	580–650(d)	1080–1205(d)	T9	172	1190	44	T9	145	0.040	24
6351	23.4	13.0	555–650	1030–1200	T6	176	1220	46	151	0.038	23	
6463	23.4	13.0	615–655	1140–1210	T1	193	1340	50	165	0.035	21	
					T5	209	1450	55	181	0.0315	19	
					T6	200	1390	53	175	0.033	20	
6951	23.4	13.0	615–655	1140–1210	0	213	1480	56	186	0.0315	19	
					T6	198	1370	52	172	0.033	20	
7049	23.4	13.0	475–635	890–1175	T73	154	1070	40	132	0.043	26	
7050	24.1	13.4	490–630	910–1165	T74(f)	157	1090	41	135	0.0415	25	
7072	23.6	13.1	640–655	1185–1215	0	222	1540	59	193	0.030	18	
7075	23.6	13.1	475–635(g)	890–1175(g)	T6	130	900	33	105	0.0515	31	
7178	23.4	13.0	475–630(g)	890–1165(g)	T6	125	870	31	98	0.055	33	
8017	23.6	13.1	645–655	1190–1215	H12, H22	...	...	59	193	0.030	18
					H212	...	...	61	200	0.028	17
8030	23.6	13.1	645–655	1190–1215	H221	230	1600	61	201	0.028	17	
8176	23.6	13.1	645–655	1190–1215	H24	230	1600	61	201	0.028	17	

(a) Coefficient from 20 to 100 °C (68 to 212 °F). (b) Melting ranges shown apply to wrought products of 6.35 mm (¼ in.) thickness or greater. (c) Based on typical composition of the indicated alloys. (d) Eutectic melting can be completely eliminated by homogenization. (e) Eutectic melting is not eliminated by homogenization. (f) Although not formerly registered, the literature and some specifications have used T736 as the designation for this temper. (g) Homogenization may raise eutectic melting temperature 10 to 20 °C (20 to 40 °F) but usually does not eliminate eutectic melting.

ing during solidification of welds and castings.

The elements that have relatively great and controlling effects on grain sizes and shapes produced by the mechanical working required to produce wrought products (their thermomechanical history) are manganese, chromium, and zirconium. Small amounts (fractional percentages) of these elements, singly or in combination, are included in the compositions of many alloys to control grain size and recrystallization behavior through fabrication and heat treatment. Such grain control has many purposes, which include ensuring good resistance to stress-corrosion cracking (SCC), high fracture toughness, and good forming characteristics. In specific alloys, these elements have highly significant supplementary beneficial effects on strength, resistance to fatigue, or strength at elevated temperatures. In order to fulfill their grain-control functions, these elements must be precipitated as finely distributed particles termed dispersoids. Their precipitation is accomplished primarily by the high-temperature, solid-state heating involved in ingot preheating.

Secondary Aluminum. Aluminum recovered from scrap (secondary aluminum) has been an important contributor to the total metal supply for many years. For some uses, secondary aluminum alloys may be treated to remove certain impurities or alloying elements. Chief among the alloying elements removed is magnesium, which is frequently present in greater amounts in secondary metal than in the alloys to be produced from it. Magnesium is usually

removed by fluxing with chlorine gas or halide salts.

Specific Alloying Elements and Impurities

The important alloying elements and impurities are listed here alphabetically as a concise review of major effects. Some of the effects, particularly with respect to impurities, are not well documented and are specific to particular alloys or conditions.

Antimony is present in trace amounts (0.01 to 0.1 ppm) in primary commercial-grade aluminum. Antimony has a very small solid solubility in aluminum (<0.01%). It has been added to aluminum-magnesium alloys because it was claimed that by forming a protective film of antimony oxychloride, it enhances corrosion resistance in salt water. Some bearing alloys contain up to 4 to 6% Sb. Antimony can be used instead of bismuth to counteract hot cracking in aluminum-magnesium alloys.

Arsenic. The compound AsAl is a semiconductor. Arsenic is very toxic (as AsO₃) and must be controlled to very low limits where aluminum is used as foil for food packaging.

Beryllium is used in aluminum alloys containing magnesium to reduce oxidation at elevated temperatures. Up to 0.1% Be is used in aluminizing baths for steel to improve adhesion of the aluminum film and restrict the formation of the deleterious iron-aluminum complex. The mechanism of protection is attributed to beryllium diffusion to the surface and the formation of a protective layer.

Oxidation and discoloration of wrought aluminum-magnesium products are greatly reduced by small amounts of beryllium because of the diffusion of beryllium to the surface and the formation of an oxide of high-volume ratio. Beryllium does not affect the corrosion resistance of aluminum. Beryllium is generally held to <8 ppm in welding filler metal, and its content should be limited in wrought alloys that may be welded.

Beryllium poisoning is an allergic disease, a problem of individual hypersensitivity that is related to intensity and duration of exposure. Inhalation of dust containing beryllium compounds may lead to acute poisoning. Beryllium is not used in aluminum alloys that may contact food or beverages.

Bismuth. The low-melting-point metals such as bismuth, lead, tin, and cadmium are added to aluminum to make free-machining alloys. These elements have a restricted solubility in solid aluminum and form a soft, low-melting phase that promotes chip breaking and helps to lubricate the cutting tool. An advantage of bismuth is that its expansion on solidification compensates for the shrinkage of lead. A 1-to-1 lead-bismuth ratio is used in the aluminum-copper alloy, 2011, and in the aluminum-Mg₂Si alloy, 6262. Small additions of bismuth (20 to 200 ppm) can be added to aluminum-magnesium alloys to counteract the detrimental effect of sodium on hot cracking.

Boron is used in aluminum and its alloys as a grain refiner and to improve conductivity by precipitating vanadium, titanium, chromium, and molybdenum (all of which are harmful to electrical conductivity at

Table 7 Nominal densities of aluminum and aluminum alloys

Alloy	Density	
	g/cm ³	lb/in. ³
1050	2.705	0.0975
1060	2.705	0.0975
1100	2.71	0.098
1145	2.700	0.0975
1175	2.700	0.0975
1200	2.70	0.098
1230	2.70	0.098
1235	2.705	0.0975
1345	2.705	0.0975
1350	2.705	0.0975
2011	2.83	0.102
2014	2.80	0.101
2017	2.79	0.101
2018	2.82	0.102
2024	2.78	0.101
2025	2.81	0.101
2036	2.75	0.100
2117	2.75	0.099
2124	2.78	0.100
2218	2.81	0.101
2219	2.84	0.103
2618	2.76	0.100
3003	2.73	0.099
3004	2.72	0.098
3005	2.73	0.098
3105	2.72	0.098
4032	2.68	0.097
4043	2.69	0.097
4045	2.67	0.096
4047	2.66	0.096
4145	2.74	0.099
4343	2.68	0.097
4643	2.69	0.097
5005	2.70	0.098
5050	2.69	0.097
5052	2.68	0.097
5056	2.64	0.095
5083	2.66	0.096
5086	2.66	0.096
5154	2.66	0.096
5183	2.66	0.096
5252	2.67	0.096
5254	2.66	0.096
5356	2.64	0.096
5454	2.69	0.097
5456	2.66	0.096
5457	2.69	0.097
5554	2.69	0.097
5556	2.66	0.096
5652	2.67	0.097
5654	2.66	0.096
5657	2.69	0.097
6003	2.70	0.097
6005	2.70	0.097
6053	2.69	0.097
6061	2.70	0.098
6063	2.70	0.097
6066	2.72	0.098
6070	2.71	0.098
6101	2.70	0.097
6105	2.69	0.097
6151	2.71	0.098
6162	2.70	0.097
6201	2.69	0.097
6262	2.72	0.098
6351	2.71	0.098
6463	2.69	0.097
6951	2.70	0.098
7005	2.78	0.100
7008	2.78	0.100
7049	2.84	0.103
7050	2.83	0.102
7072	2.72	0.098
7075	2.81	0.101
7178	2.83	0.102
8017	2.71	0.098
8030	2.71	0.098
8176	2.71	0.098
8177	2.70	0.098

their usual impurity level in commercial-grade aluminum). Boron can be used alone (at levels of 0.005 to 0.1%) as a grain refiner during solidification, but becomes more effective when used with an excess of titanium. Commercial grain refiners commonly contain titanium and boron in a 5-to-1 ratio. Boron has a high neutron capture cross section and is used in aluminum alloys for certain atomic energy applications, but its content has to be limited to very low levels in alloys used in reactor areas where this property is undesirable.

Cadmium is a relatively low-melting element that finds limited use in aluminum. Up to 0.3% Cd may be added to aluminum-copper alloys to accelerate the rate of age hardening, increase strength, and increase corrosion resistance. At levels of 0.005 to 0.5%, it has been used to reduce the time of aging of aluminum-zinc-magnesium alloys. It has been reported that traces of Cd lower the corrosion resistance of unalloyed aluminum. In excess of 0.1%, cadmium causes hot shortness in some alloys. Because of its high neutron absorption, cadmium has to be kept very low for atomic energy use. It has been used to confer free-cutting characteristics, particularly to aluminum-zinc-magnesium alloys; it was preferred to bismuth and lead because of its higher melting point. As little as 0.1% provides an improvement in machinability. Cadmium is used in bearing alloys along with silicon. The oral toxicity of cadmium compounds is high. In melting, casting, and fluxing operations cadmium oxide fume can present hazards.

Calcium has very low solubility in aluminum and forms the intermetallic CaAl_4 . An interesting group of alloys containing about 5% Ca and 5% Zn have superplastic properties. Calcium combines with silicon to form CaSi_2 , which is almost insoluble in aluminum and therefore will increase the conductivity of commercial-grade metal slightly. In aluminum-magnesium-silicon alloys, calcium will decrease age hardening. Its effect on aluminum-silicon alloys is to increase strength and decrease elongation, but it does not make these alloys heat treatable. At the 0.2% level, calcium alters the recrystallization characteristics of 3003. Very small amounts of calcium (10 ppm) increase the tendency of molten aluminum alloys to pick up hydrogen.

Carbon may occur infrequently as an impurity in aluminum in the form of oxycarbides and carbides, of which the most common is Al_4C_3 , but carbide formation with other impurities such as titanium is possible. Al_4C_3 decomposes in the presence of water and water vapor, and this may lead to surface pitting. Normal metal transfer and fluxing operations usually reduce carbon to the ppm level.

Cerium, mostly in the form of mischmetal (rare earths with 50 to 60% Ce), has been added experimentally to casting alloys to

increase fluidity and reduce die sticking. In alloys containing high iron (>0.7%), it is reported to transform acicular FeAl_3 into a nonacicular compound.

Chromium occurs as a minor impurity in commercial-purity aluminum (5 to 50 ppm). It has a large effect on electrical resistivity. Chromium is a common addition to many alloys of the aluminum-magnesium, aluminum-magnesium-silicon, and aluminum-magnesium-zinc groups, in which it is added in amounts generally not exceeding 0.35%. In excess of these limits, it tends to form very coarse constituents with other impurities or additions such as manganese, iron, and titanium. This limit is decreased as the content of transition metals increases. In casting alloys, excess chromium will produce a sludge by peritectic precipitation on holding.

Chromium has a slow diffusion rate and forms fine dispersed phases in wrought products. These dispersed phases inhibit nucleation and grain growth. Chromium is used to control grain structure, to prevent grain growth in aluminum-magnesium alloys, and to prevent recrystallization in aluminum-magnesium-silicon or aluminum-magnesium-zinc alloys during hot working or heat treatment. The fibrous structures that develop reduce stress corrosion susceptibility and/or improve toughness. Chromium in solid solution and as a finely dispersed phase increases the strength of alloys slightly. The main drawback of chromium in heat-treatable alloys is the increase in quench sensitivity when the hardening phase tends to precipitate on the preexisting chromium-phase particles. Chromium imparts a yellow color to the anodic film.

Cobalt is not a common addition to aluminum alloys. It has been added to some aluminum-silicon alloys containing iron, where it transforms the acicular β (aluminum-iron-silicon) into a more rounded aluminum-cobalt-iron phase, thus improving strength and elongation. Aluminum-zinc-magnesium-copper alloys containing 0.2 to 1.9% Co are produced by powder metallurgy.

Copper. Aluminum-copper alloys containing 2 to 10% Cu, generally with other additions, form important families of alloys. Both cast and wrought aluminum-copper alloys respond to solution heat treatment and subsequent aging with an increase in strength and hardness and a decrease in elongation. The strengthening is maximum between 4 and 6% Cu, depending upon the influence of other constituents present. The properties of aluminum-copper alloy sheet in a number of thermal conditions are assembled in Fig. 20. The aging characteristics of binary aluminum-copper alloys have been studied in greater detail than any other system, but there are actually very few commercial binary aluminum-copper alloys. Most commercial alloys contain other alloying elements.

Copper-Magnesium. The main benefit of adding magnesium to aluminum-copper alloys is the increased strength possible following solution heat treatment and quenching. In wrought material of certain alloys of this type, an increase in strength accompanied by high ductility occurs on aging at room temperature. On artificial aging, a further increase in strength, especially in yield strength, can be obtained, but at a substantial sacrifice in tensile elongation.

On both cast and wrought aluminum-copper alloys, as little as about 0.5% Mg is effective in changing aging characteristics. In wrought products, the effect of magnesium additions on strength can be maximized in artificially aged materials by cold working prior to aging (Fig. 21). In naturally aged materials, however, the benefit to strength from magnesium additions can decrease with cold working (Fig. 22). The effect of magnesium on the corrosion resistance of aluminum-copper alloys depends on the type of product and the thermal treatment.

Copper-Magnesium Plus Other Elements. The cast aluminum-copper-magnesium alloys containing iron are characterized by dimensional stability and improved bearing characteristics, as well as by high strength and hardness at elevated temperatures. However, in a wrought Al-4%Cu-0.5%Mg alloy, iron in concentrations as low as 0.5% lowers the tensile properties in the heat-treated condition, if the silicon content is less than that required to tie up the iron as the αFeSi constituent. In this event, the excess iron unites with copper to form the Cu_2FeAl_7 constituent, thereby reducing the amount of copper available for heat-treating effects. When sufficient silicon is present to combine with the iron, the properties are unaffected. Silicon also combines with magnesium to form Mg_2Si precipitate and contributes in the age-hardening process.

Silver substantially increases the strength of heat-treated and aged aluminum-copper-magnesium alloys. Nickel improves the strength and hardness of cast and wrought aluminum-copper-magnesium alloys at elevated temperatures. Addition of about 0.5% Ni lowers the tensile properties of the heat-treated, wrought Al-4%Cu-0.5%Mg alloy at room temperature.

The alloys containing manganese form the most important and versatile system of commercial high-strength wrought aluminum-copper-magnesium alloys. The substantial effect exerted by manganese on the tensile properties of aluminum-copper alloys containing 0.5% Mg is shown in Fig. 23. It is apparent that no one composition offers both maximum strength and ductility. In general, tensile strength increases with separate or simultaneous increases in magnesium and manganese, and the yield strength also increases, but to a lesser extent. Further increases in tensile and partic-

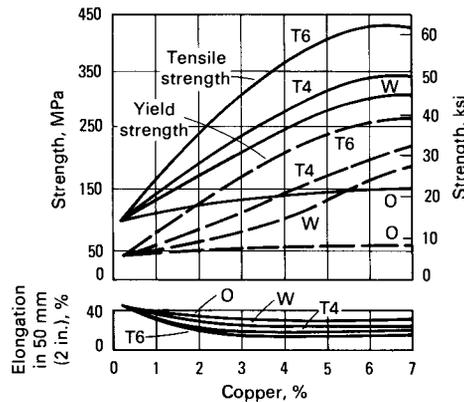


Fig. 20 Tensile properties of high-purity, wrought aluminum-copper alloys. Sheet specimen was 13 mm (0.5 in.) wide and 1.59 mm (0.0625 in.) thick. O, annealed; W, tested immediately after water quenching from a solution heat treatment; T4, as in W, but aged at room temperature; T6, as in T4, followed by precipitation treatment at elevated temperature

ularly yield strength occur on cold working after heat treatment. Additions of manganese and magnesium decrease the fabricating characteristics of the aluminum-copper alloys, and manganese also causes a loss in ductility; hence, the concentration of this element does not exceed about 1% in commercial alloys. Additions of cobalt, chromium, or molybdenum to the wrought Al-4%Cu-0.5%Mg type of alloy increase the tensile properties on heat treatment, but none offers a distinct advantage over manganese.

Alloys with lower copper content than the conventional 2024 and 2014 type alloys were necessary to provide the formability required by the automobile industry. Copper-magnesium alloys developed for this purpose are 2002, AU2G, and 2036 variations. These have acceptable formability, good spot weldability, reasonable fusion weldability, good corrosion resistance, and freedom from Lüder lines. The paint-baking

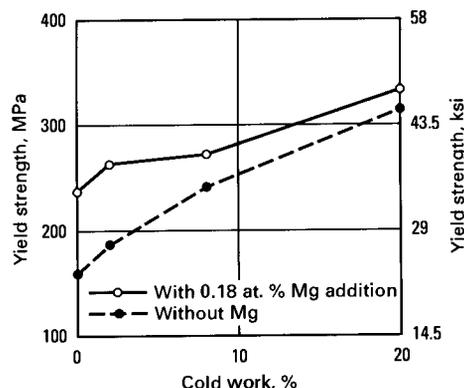
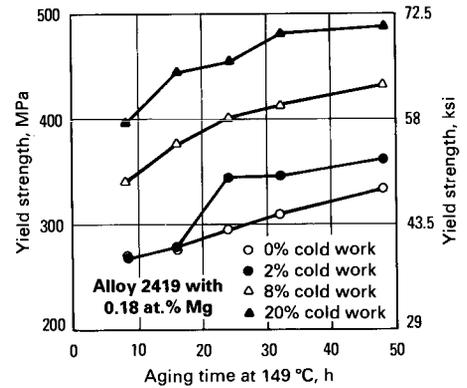
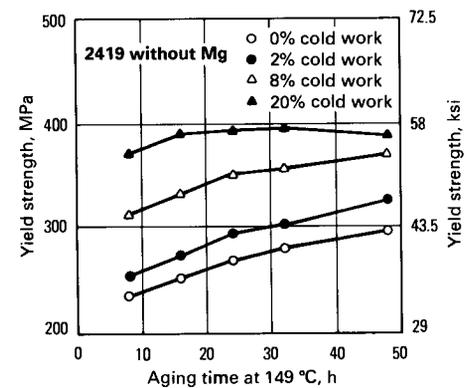


Fig. 22 The effect of cold work on yield strength of aluminum-copper alloy 2419 in naturally aged materials. Source: Ref 8



(a)



(b)

Fig. 21 Effect of cold work and Mg addition on alloy 2419. (a) The effect of cold work on the yield strength response to aging at 149 °C (300 °F) for the alloy with 0.18 at. % Mg. (b) The effect of cold work on the yield strength response to aging at 149 °C (300 °F) for the alloy without Mg. Source: Ref 8

cycle serves as a precipitation treatment to give final mechanical properties.

Copper and Minor Additions. In the wrought form, an alloy family of interest is the one containing small amounts of several metals known to raise the recrystallization temperature of aluminum and its alloys, specifically manganese, titanium, vanadium, or zirconium. An alloy of this nature retains its properties well at elevated temperatures, fabricates readily, and has good casting and welding characteristics. Figure

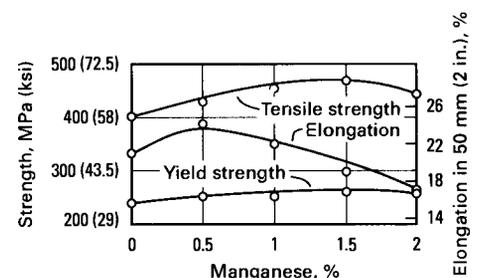


Fig. 23 Relationship between tensile properties and manganese content of Al-4%Cu-0.5%Mg alloy, heat treated at 525 °C (980 °F)

Table 8 Typical mechanical properties of various aluminum alloys

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %		Hardness, HB(a)	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	MPa	ksi	MPa	ksi	1.6 mm (1/16 in.) thick specimen	1.3 mm (1/2 in.) diam specimen		MPa	ksi	MPa	ksi	GPa	10 ⁶ psi
1060-0	70	10	30	4	43	...	19	50	7	20	3	69	10.0
1060-H12	85	12	75	11	16	...	23	55	8	30	4	69	10.0
1060-H14	95	14	90	13	12	...	26	60	9	35	5	69	10.0
1060-H16	110	16	105	15	8	...	30	70	10	45	6.5	69	10.0
1060-H18	130	19	125	18	6	...	35	75	11	45	6.5	69	10.0
1100-0	90	13	35	5	35	45	23	60	9	35	5	69	10.0
1100-H12	110	16	105	15	12	25	28	70	10	40	6	69	10.0
1100-H14	125	18	115	17	9	20	32	75	11	50	7	69	10.0
1100-H16	145	21	140	20	6	17	38	85	12	60	9	69	10.0
1100-H18	165	24	150	22	5	15	44	90	13	60	9	69	10.0
1350-0	85	12	30	4	...	(d)	...	55	8	...	...	69	10.0
1350-H12	95	14	85	12	...	...	...	60	9	...	...	69	10.0
1350-H14	110	16	95	14	...	...	...	70	10	...	...	69	10.0
1350-H16	125	18	110	16	...	...	...	75	11	...	...	69	10.0
1350-H19	185	27	165	24	...	(e)	...	105	15	50	7	69	10.0
2011-T3	380	55	295	43	...	15	95	220	32	125	18	70	10.2
2011-T8	405	59	310	45	...	12	100	240	35	125	18	70	10.2
2014-0	185	27	95	14	...	18	45	125	18	90	13	73	10.6
2014-T4, T451	425	62	290	42	...	20	105	260	38	140	20	73	10.6
2014-T6, T651	485	70	415	60	...	13	135	290	42	125	18	73	10.6
Alclad 2014-0	175	25	70	10	21	...	...	125	18	...	...	72	10.5
Alclad 2014-T3	435	63	275	40	20	...	...	255	37	...	...	72	10.5
Alclad 2014-T4, T451	420	61	255	37	22	...	...	255	37	...	...	72	10.5
Alclad 2014-T6, T651	470	68	415	60	10	...	...	285	41	...	...	72	10.5
2017-0	180	26	70	10	...	22	45	125	18	90	13	72	10.5
2017-T4, T451	425	62	275	40	...	22	105	260	38	125	18	72	10.5
2018-T61	420	61	315	46	...	12	120	270	39	115	17	74	10.8
2024-0	185	27	75	11	20	22	47	125	18	90	13	73	10.6
2024-T3	485	70	345	50	18	...	120	285	41	140	20	73	10.6
2024-T4, T351	470	68	325	47	20	19	120	285	41	140	20	73	10.6
2024-T361(f)	495	72	395	57	13	...	130	290	42	125	18	73	10.6
Alclad 2024-0	180	26	75	11	20	...	...	125	18	...	...	73	10.6
Alclad 2024-T3	450	65	310	45	18	...	...	275	40	...	...	73	10.6
Alclad 2024-T4, T351	440	64	290	42	19	...	...	275	40	...	...	73	10.6
Alclad 2024-T361(f)	460	67	365	53	11	...	...	285	41	...	...	73	10.6
Alclad-2024-T81, T851	450	65	415	60	6	...	...	275	40	...	...	73	10.6
Alclad 2024-T861(f)	485	70	455	66	6	...	...	290	42	...	...	73	10.6
2025-T6	400	58	255	37	...	19	110	240	35	125	18	71	10.4
2036-T4	340	49	195	28	24	...	...	...	...	125(g)	18 (g)	71	10.3
2117-T4	295	43	165	24	...	43	70	195	28	95	14	71	10.3
2124-T851	485	70	440	64	...	8	...	...	...	...	...	73	10.6
2218-T72	330	48	255	37	...	11	95	205	30	...	...	74	10.8
2219-0	175	25	75	11	18	...	...	...	...	...	...	73	10.6
2219-T42	360	52	185	27	20	...	...	...	...	...	...	73	10.6
2219-T31, T351	360	52	250	36	17	...	...	...	...	...	...	73	10.6
2219-T37	395	57	315	46	11	...	...	...	...	...	...	73	10.6
2219-T62	415	60	290	42	10	...	...	...	...	105	15	73	10.6
2219-T81, T851	455	66	350	51	10	...	...	...	...	105	15	73	10.6
2219-T87	475	69	395	57	10	...	...	...	...	105	15	73	10.6
2618-T61	440	64	370	54	...	10	115	260	38	125	18	74	10.8
3003-0	110	16	40	6	30	40	28	75	11	50	7	69	10.0
3003-H12	130	19	125	18	10	20	35	85	12	55	8	69	10.0
3003-H14	150	22	145	21	8	16	40	95	14	60	9	69	10.0
3003-H16	180	26	170	25	5	14	47	105	15	70	10	69	10.0
3003-H18	200	29	185	27	4	10	55	110	16	70	10	69	10.0
Alclad 3003-0	110	16	40	6	30	40	...	75	11	...	...	69	10.0
Alclad 3003-H12	130	19	125	18	10	20	...	85	12	...	...	69	10.0
Alclad 3003-H14	150	22	145	21	8	16	...	95	14	...	...	69	10.0
Alclad 3003-H16	180	26	170	25	5	14	...	105	15	...	...	69	10.0
Alclad 3003-H18	200	29	185	27	4	10	...	110	16	...	...	69	10.0
3004-0	180	26	70	10	20	25	45	110	16	95	14	69	10.0
3004-H32	215	31	170	25	10	17	52	115	17	105	15	69	10.0
3004-H34	240	35	200	29	9	12	63	125	18	105	15	69	10.0
3004-H36	260	38	230	33	5	9	70	140	20	110	16	69	10.0
3004-H38	285	41	250	36	5	6	77	145	21	110	16	69	10.0
Alclad 3004-0	180	26	70	10	20	25	...	110	16	...	...	69	10.0
Alclad 3004-H32	215	31	170	25	10	17	...	115	17	...	...	69	10.0
Alclad 3004-H34	240	35	200	29	9	12	...	125	18	...	...	69	10.0
Alclad 3004-H36	260	38	230	33	5	9	...	140	20	...	...	69	10.0
Alclad 3004-H38	285	41	250	36	5	6	...	145	21	...	...	69	10.0
3105-0	115	17	55	8	24	...	...	85	12	...	...	69	10.0

(continued)

(a) 500 kg load and 10 mm ball. (b) Based on 500 000 000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-0 wire will have an elongation of approximately 23% in 250 mm (10 in.). (e) 1350-H19 wire will have an elongation of approximately 1 1/2% in 250 mm (10 in.). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural type testing of sheet specimens. (h) T7451, although not previously registered, has appeared in literature and in some specifications as T73651.

Table 8 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %		Hardness, HB(a)	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	MPa	ksi	MPa	ksi	1.6 mm (1/16 in.) thick specimen	1.3 mm (1/2 in.) diam specimen		MPa	ksi	MPa	ksi	GPa	10 ⁶ psi
	3105-H12.....	150	22	130	19	7		95	14	...	...	69	10.0
3105-H14.....	170	25	150	22	5	...	...	105	15	...	...	69	10.0
3105-H16.....	195	28	170	25	4	...	...	110	16	...	...	69	10.0
3105-H18.....	215	31	195	28	3	...	...	115	17	...	...	69	10.0
3105-H25.....	180	26	160	23	8	...	...	105	15	...	...	69	10.0
4032-T6.....	380	55	315	46	...	9	120	260	38	110	16	79	11.4
5005-0.....	125	18	40	6	25	...	28	75	11	...	...	69	10.0
5005-H12.....	140	20	130	19	10	...	...	95	14	...	...	69	10.0
5005-H14.....	160	23	150	22	6	...	...	95	14	...	...	69	10.0
5005-H16.....	180	26	170	25	5	...	...	105	15	...	...	69	10.0
5005-H18.....	200	29	195	28	4	...	...	110	16	...	...	69	10.0
5005-H32.....	140	20	115	17	11	...	36	95	14	...	...	69	10.0
5005-H34.....	160	23	140	20	8	...	41	95	14	...	...	69	10.0
5005-H36.....	180	26	165	24	6	...	46	105	15	...	...	69	10.0
5005-H38.....	200	29	185	27	5	...	51	110	16	...	...	69	10.0
5050-0.....	145	21	55	8	24	...	36	105	15	85	12	69	10.0
5050-H32.....	170	25	145	21	9	...	46	115	17	90	13	69	10.0
5050-H34.....	195	28	165	24	8	...	53	125	18	90	13	69	10.0
5050-H36.....	205	30	180	26	7	...	58	130	19	95	14	69	10.0
5050-H38.....	220	32	200	29	6	...	63	140	20	95	14	69	10.0
5052-0.....	195	28	90	13	25	30	47	125	18	110	16	70	10.2
5052-H32.....	230	33	195	28	12	18	60	140	20	115	17	70	10.2
5052-H34.....	260	38	215	31	10	14	68	145	21	125	18	70	10.2
5052-H36.....	275	40	240	35	8	10	73	160	23	130	19	70	10.2
5052-H38.....	290	42	255	37	7	8	77	165	24	140	20	70	10.2
5056-0.....	290	42	150	22	...	35	65	180	26	140	20	71	10.3
5056-H18.....	435	63	405	59	...	10	105	235	34	150	22	71	10.3
5056-H38.....	415	60	345	50	...	15	100	220	32	150	22	71	10.3
5083-0.....	290	42	145	21	...	22	...	170	25	...	...	71	10.3
5083-H321, H116.....	315	46	230	33	...	16	...	...	...	160	23	71	10.3
5086-0.....	260	38	115	17	22	...	...	160	23	...	...	71	10.3
5086-H32, H116.....	290	42	205	30	12	...	...	...	...	...	...	71	10.3
5086-H34.....	325	47	255	37	10	...	...	185	27	...	...	71	10.3
5086-H112.....	270	39	130	19	14	...	...	...	...	...	...	71	10.3
5154-0.....	240	35	115	17	27	...	58	150	22	115	17	70	10.2
5154-H32.....	270	39	205	30	15	...	67	150	22	125	18	70	10.2
5154-H34.....	290	42	230	33	13	...	73	165	24	130	19	70	10.2
5154-H36.....	310	45	250	36	12	...	78	180	26	140	20	70	10.2
5154-H38.....	330	48	270	39	10	...	80	195	28	145	21	70	10.2
5154-H112.....	240	35	115	17	25	...	63	...	...	115	17	70	10.2
5252-H25.....	235	34	170	25	11	...	68	145	21	...	...	69	10.0
5252-H38, H28.....	285	41	240	35	5	...	75	160	23	...	...	69	10.0
5254-0.....	240	35	115	17	27	...	58	150	22	115	17	70	10.2
5254-H32.....	270	39	205	30	15	...	67	150	22	125	18	70	10.2
5254-H34.....	290	42	230	33	13	...	73	165	24	130	19	70	10.2
5254-H36.....	310	45	250	36	12	...	78	180	26	140	20	70	10.2
5254-H38.....	330	48	270	39	10	...	80	195	28	145	21	70	10.2
5254-H112.....	240	35	115	17	25	...	63	...	...	115	17	70	10.2
5454-0.....	250	36	115	17	22	...	62	160	23	...	...	70	10.2
5454-H32.....	275	40	205	30	10	...	73	165	24	...	...	70	10.2
5454-H34.....	305	44	240	35	10	...	81	180	26	...	...	70	10.2
5454-H111.....	260	38	180	26	14	...	70	160	23	...	...	70	10.2
5454-H112.....	250	36	125	18	18	...	62	160	23	...	...	70	10.2
5456-0.....	310	45	160	23	...	24	...	...	...	...	...	71	10.3
5456-H112.....	310	45	165	24	...	22	...	...	...	...	...	71	10.3
5456-H321, H116.....	350	51	255	37	...	16	90	205	30	...	...	71	10.3
5457-0.....	130	19	50	7	22	...	32	85	12	...	...	69	10.0
5457-H25.....	180	26	160	23	12	...	48	110	16	...	...	69	10.0
5457-H38, H28.....	205	30	185	27	6	...	55	125	18	...	...	69	10.0
5652-0.....	195	28	90	13	25	30	47	125	18	110	16	70	10.2
5652-H32.....	230	33	195	28	12	18	60	140	20	115	17	70	10.2
5652-H34.....	260	38	215	31	10	14	68	145	21	125	18	70	10.2
5652-H36.....	275	40	240	35	8	10	73	160	23	130	19	70	10.2
5652-H38.....	290	42	255	37	7	8	77	165	24	140	20	70	10.2
5657-H25.....	160	23	140	20	12	...	40	95	14	...	...	69	10.0
5657-H38, H28.....	195	28	165	24	7	...	50	105	15	...	...	69	10.0
6061-0.....	125	18	55	8	25	30	30	85	12	60	9	69	10.0
6061-T4, T451.....	240	35	145	21	22	25	65	165	24	95	14	69	10.0
6061-T6, T651.....	310	45	275	40	12	17	95	205	30	95	14	69	10.0
Alclad 6061-0.....	115	17	50	7	25	...	...	75	11	...	...	69	10.0
Alclad 6061-T4, T451.....	230	33	130	19	22	...	...	150	22	...	...	69	10.0

(continued)

(a) 500 kg load and 10 mm ball. (b) Based on 500 000 000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-0 wire will have an elongation of approximately 23% in 250 mm (10 in.). (e) 1350-H19 wire will have an elongation of approximately 1½% in 250 mm (10 in.). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural type testing of sheet specimens. (h) T7451, although not previously registered, has appeared in literature and in some specifications as T73651.

Table 8 (continued)

Alloy and temper	Ultimate tensile strength		Tensile yield strength		Elongation in 50 mm (2 in.), %		Hardness, HB(a)	Ultimate shearing strength		Fatigue endurance limit(b)		Modulus of elasticity(c)	
	MPa	ksi	MPa	ksi	1.6 mm (1/16 in.) thick specimen	1.3 mm (1/2 in.) diam specimen		MPa	ksi	MPa	ksi	GPa	10 ⁶ psi
Alclad 6061-T6, T651	290	42	255	37	12	...	...	185	27	...	...	69	10.0
6063-0	90	13	50	7	...	...	25	70	10	55	8	69	10.0
6063-T1	150	22	90	13	20	...	42	95	14	60	9	69	10.0
6063-T4	170	25	90	13	22	...	...	...	...	...	...	69	10.0
6063-T5	185	27	145	21	12	...	60	115	17	70	10	69	10.0
6063-T6	240	35	215	31	12	...	73	150	22	70	10	69	10.0
6063-T83	255	37	240	35	9	...	82	150	22	...	...	69	10.0
6063-T831	205	30	185	27	10	...	70	125	18	...	...	69	10.0
6063-T832	290	42	270	39	12	...	95	185	27	...	...	69	10.0
6066-0	150	22	85	12	...	18	43	95	14	...	...	69	10.0
6066-T4, T451	360	52	205	30	...	18	90	200	29	...	...	69	10.0
6066-T6, T651	395	57	360	52	...	12	120	235	34	110	16	69	10.0
6070-T6	380	55	350	51	10	...	...	235	34	95	14	69	10.0
6101-H111	95	14	75	11	...	...	...	...	...	...	...	69	10.0
6101-T6	220	32	195	28	15	...	71	140	20	...	...	69	10.0
6351-T4	250	36	150	22	20	...	...	...	...	...	...	69	10.0
6351-T6	310	45	285	41	14	...	95	200	29	90	13	69	10.0
6463-T1	150	22	90	13	20	...	42	95	14	70	10	69	10.0
6463-T5	185	27	145	21	12	...	60	115	17	70	10	69	10.0
6463-T6	240	35	215	31	12	...	74	150	22	70	10	69	10.0
7049-T73	515	75	450	65	...	12	135	305	44	...	...	72	10.4
7049-T7352	515	75	435	63	...	11	135	295	43	...	...	72	10.4
7050-T73510, T73511	495	72	435	63	...	12	...	...	...	...	...	72	10.4
7050-T7451(h)	525	76	470	68	...	11	...	305	44	...	...	72	10.4
7050-T7651	550	80	490	71	...	11	...	325	47	...	...	72	10.4
7075-0	230	33	105	15	17	16	60	150	22	...	...	72	10.4
7075-T6, T651	570	83	505	73	11	11	150	330	48	160	23	72	10.4
Alclad 7075-0	220	32	95	14	17	...	...	150	22	...	...	72	10.4
Alclad 7075-T6, T651	525	76	460	67	11	...	...	315	46	...	...	72	10.4

(a) 500 kg load and 10 mm ball. (b) Based on 500 000 000 cycles of completely reversed stress using the R.R. Moore type of machine and specimen. (c) Average of tension and compression moduli. Compression modulus is about 2% greater than tension modulus. (d) 1350-0 wire will have an elongation of approximately 23% in 250 mm (10 in.). (e) 1350-H19 wire will have an elongation of approximately 1 1/2% in 250 mm (10 in.). (f) Tempers T361 and T861 were formerly designated T36 and T86, respectively. (g) Based on 10⁷ cycles using flexural type testing of sheet specimens. (h) T7451, although not previously registered, has appeared in literature and in some specifications as T73651.

24 illustrates the effect of 3 to 8% Cu on an alloy of Al-0.3%Mn-0.2%Zr-0.1%V at room temperature and after exposure at 315 °C (600 °F) for two different periods of time. The stability of the properties should be noted, as reflected in the small reduction in strength with time at this temperature.

Gallium is an impurity in aluminum and is usually present at levels of 0.001 to

0.02%. At these levels its effect on mechanical properties is quite small. At the 0.2% level, gallium has been found to affect the corrosion characteristics and the response to etching and brightening of some alloys. Liquid gallium metal penetrates very rapidly at aluminum grain boundaries and can produce complete grain separation. In sacrificial anodes, an

addition of gallium (0.01 to 0.1%) keeps the anode from passivating.

Hydrogen has a higher solubility in the liquid state at the melting point than in the solid at the same temperature. Because of this, gas porosity can form during solidification. Hydrogen is produced by the reduction of water vapor in the atmosphere by aluminum and by the decomposition of hydrocarbons. Hydrogen pickup in both solid and liquid aluminum is enhanced by the presence of certain impurities, such as sulfur compounds, on the surface and in the atmosphere. Hydride-forming elements in the metal increase the pickup of hydrogen in the liquid. Other elements such as beryllium, copper, tin, and silicon decrease hydrogen pickup.

In addition to causing primary porosity in casting, hydrogen causes secondary porosity, blistering, and high-temperature deterioration (advanced internal gas precipitation) during heat treating. It probably plays a role in grain-boundary decohesion during SCC. Its level in melts is controlled by fluxing with hydrogen-free gases or by vacuum degassing.

Indium. Small amounts (0.05 to 0.2%) of indium have a marked influence on the age hardening of aluminum-copper alloys, particularly at low copper contents (2 to 3% Cu). In this respect, indium acts very much like cadmium in that it reduces room-tem-

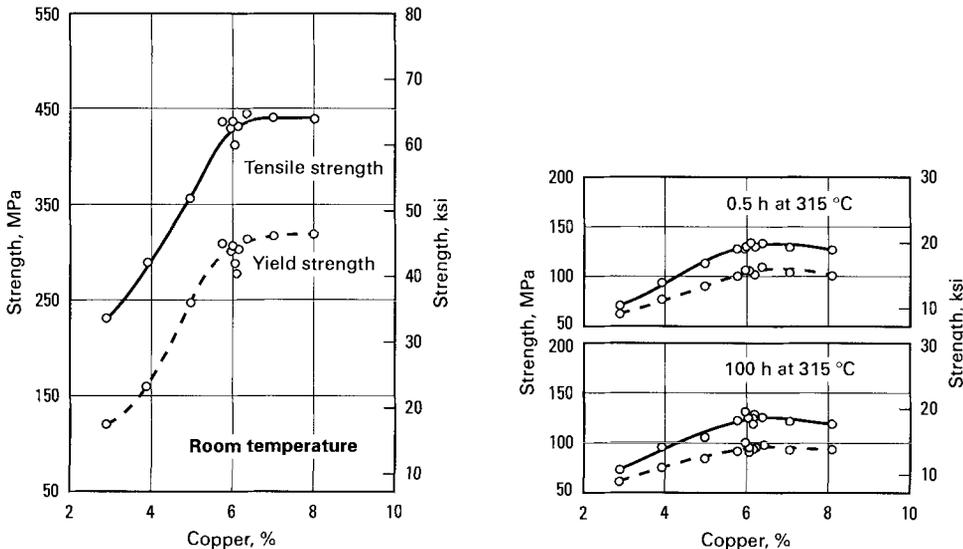


Fig. 24 Variation of tensile properties with copper content in Al-0.3%Mn-0.2%Zr-0.1%V alloy in the T6 temper

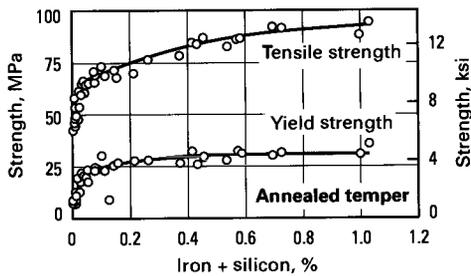


Fig. 25 Effect of iron plus silicon impurities on tensile strength and yield strength of aluminum

perature aging but increases artificial aging. The addition of magnesium decreases the effect of indium. Small amounts of indium (0.03 to 0.5%) are claimed to be beneficial in aluminum-cadmium-bearing alloys.

Iron is the most common impurity found in aluminum. It has a high solubility in molten aluminum and is therefore easily dissolved at all molten stages of production. The solubility of iron in the solid state is very low ($\sim 0.04\%$) and therefore, most of the iron present in aluminum over this amount appears as an intermetallic second phase in combination with aluminum and often other elements. Because of its limited solubility, it is used in electrical conductors in which it provides a slight increase in strength (Fig. 25) and better creep characteristics at moderately elevated temperatures.

Iron reduces the grain size in wrought products. Alloys of iron and manganese near the ternary eutectic content, such as 8006, can have useful combinations of strength and ductility at room temperature and retain strength at elevated temperatures. The properties are due to the fine grain size that is stabilized by the finely dispersed iron-rich second phase. Iron is added to the aluminum-copper-nickel group of alloys to increase strength at elevated temperatures.

Lead. Normally present only as a trace element in commercial-purity aluminum, lead is added at about the 0.5% level with the same amount as bismuth in some alloys (2011 and 6262) to improve machinability. Additions of lead may be troublesome to the fabricator as it will tend to segregate during casting and cause hot shortness in aluminum-copper-magnesium alloys. Lead compounds are toxic.

Lithium. The impurity level of lithium is of the order of a few ppm, but at a level of less than 5 ppm it can promote the discoloration (blue corrosion) of aluminum foil under humid conditions. Traces of lithium greatly increase the oxidation rate of molten aluminum and alter the surface characteristics of wrought products. Binary aluminum-lithium alloys age harden but are not used commercially. Present interest is on the aluminum-copper-magnesium-lithium alloys, which can be heat treated to strengths

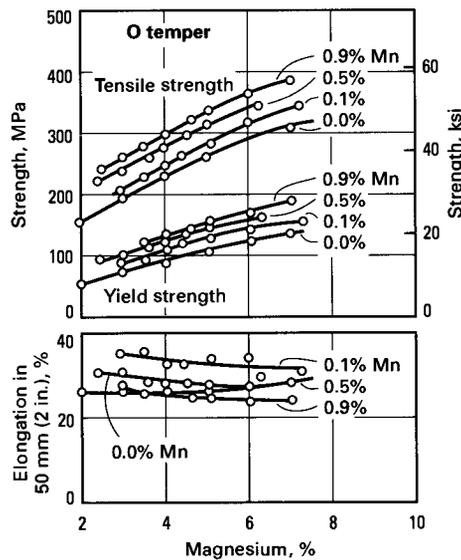


Fig. 26 Tensile properties of 13 mm (0.5 in.) aluminum-magnesium-manganese plate in O temper

comparable to present aircraft alloys (see the article "Aluminum-Lithium Alloys" in this Volume). In addition, the density is decreased and the modulus is increased. This type of alloy has a high volume fraction of coherent, ordered LiAl_3 precipitate. In addition to increasing the elastic modulus, the fatigue crack growth resistance is increased at intermediate levels of stress intensity.

Magnesium is the major alloying element in the 5xxx series of alloys. Its maximum solid solubility in aluminum is 17.4%, but the magnesium content in current wrought alloys does not exceed 5.5%. Magnesium precipitates preferentially at grain boundaries as a highly anodic phase (Mg_2Al_3 or Mg_5Al_8), which produces susceptibility to intergranular cracking and to stress corrosion. Wrought alloys containing up to 5% Mg properly fabricated are stable under normal usage. The addition of magnesium markedly increases the strength of aluminum without unduly decreasing the ductility. Corrosion resistance and weldability are good. In the annealed condition, magnesium alloys form Lüder lines during deformation.

Magnesium-Manganese. In wrought alloys, this system has high strength in the work-hardened condition, high resistance to corrosion, and good welding characteristics. Increasing amounts of either magnesium or manganese intensify the difficulty of fabrication and increase the tendency toward cracking during hot rolling, particularly if traces of sodium are present. The two main advantages of manganese additions are that the precipitation of the magnesium phase is more general throughout the structure, and that for a given increase in strength, manganese allows a lower mag-

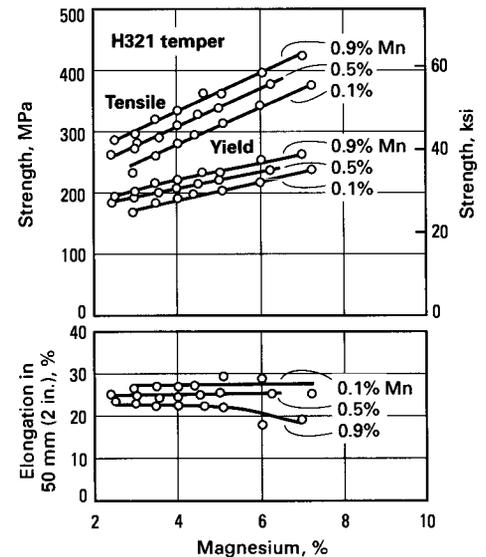


Fig. 27 Tensile properties of 13 mm (0.5 in.) aluminum-magnesium-manganese plate in H321 temper

nesium content and ensures a greater degree of stability to the alloy.

The tensile properties of 13 mm (0.5 in.) plate at various magnesium and manganese concentrations are shown in Fig. 26 for the O temper and in Fig. 27 for a work-hardened temper. Increasing magnesium raises the tensile strength by about 35 MPa (5 ksi) for each 1% increment; manganese is about twice as effective as magnesium.

Magnesium-Silicide. Wrought alloys of the 6xxx group contain up to 1.5% each of magnesium and silicon in the approximate ratio to form Mg_2Si , that is, 1.73:1. The maximum solubility of Mg_2Si is 1.85%, and this decreases with temperature. Precipitation upon age hardening occurs by formation of Guinier-Preston zones and a very fine precipitate. Both confer an increase in strength to these alloys, though not as great as in the case of the 2xxx or the 7xxx alloys.

Al- Mg_2Si alloys can be divided into three groups. In the first group, the total amount of magnesium and silicon does not exceed 1.5%. These elements are in a nearly balanced ratio or with a slight excess of silicon. Typical of this group is 6063, widely used for extruded architectural sections. This easily extrudable alloy nominally contains 1.1% Mg_2Si . Its solution heat-treating temperature of just over 500 °C (930 °F) and its low quench sensitivity are such that this alloy does not need a separate solution treatment after extrusion but may be air quenched at the press and artificially aged to achieve moderate strength, good ductility, and excellent corrosion resistance.

The second group nominally contains 1.5% or more of magnesium + silicon and other additions such as 0.3% Cu, which increases strength in the T6 temper. Ele-

Table 9 Recommended minimum bend radii for 90° cold forming of sheet and plate

		Radii(a)(b)(c)(d) for various thicknesses expressed in terms of thickness, <i>t</i>										Radii(a)(b)(c)(d) for various thicknesses expressed in terms of thickness, <i>t</i>							
Alloy	Temper	0.4 mm (1/64 in.)	0.8 mm (1/32 in.)	1.6 mm (1/16 in.)	3.2 mm (1/8 in.)	4.8 mm (3/16 in.)	6.35 mm (1/4 in.)	9.5 mm (3/8 in.)	13 mm (1/2 in.)	Alloy	Temper	0.4 mm (1/64 in.)	0.8 mm (1/32 in.)	1.6 mm (1/16 in.)	3.2 mm (1/8 in.)	4.8 mm (3/16 in.)	6.35 mm (1/4 in.)	9.5 mm (3/8 in.)	13 mm (1/2 in.)
1100	0	0	0	0	0	1/2t	1t	1t	1 1/2t	5052	H34	0	1t	1 1/2t	2t	2t	2 1/2t	2 1/2t	3t
	H12	0	0	0	1/2t	1t	1t	1 1/2t	2t		H36	1t	1t	1 1/2t	2 1/2t	...	...	...	...
	H14	0	0	0	1t	1t	1 1/2t	2t	2 1/2t		H38	1t	1 1/2t	2 1/2t	3t	...	...	...	...
	H16	0	1/2t	1t	1 1/2t	...	...	...	...	5083	0	...	...	1/2t	1t	1t	1 1/2t	1 1/2t	2t
	H18	1t	1t	1 1/2t	2 1/2t	...	...	...	...		H321	...	...	...	...	1 1/2t	1 1/2t	2t	2 1/2t
2014	0	...	0	0	1/2t	1t	1t	2 1/2t	4t	5086	0	...	0	1/2t	1t	1t	1t	1 1/2t	1 1/2t
	T3	...	2 1/2t	3t	4t	5t	5t	...	...		H32	...	1/2t	1t	1 1/2t	1 1/2t	2t	2 1/2t	3t
	T4	...	2 1/2t	3t	4t	5t	5t	...	...		H34	1/2t	1t	1 1/2t	2t	2 1/2t	3t	3 1/2t	4t
	T6	...	4t	4t	5t	6t	8t	...	...		H36	1 1/2t	2t	2 1/2t	...	...	...	...	...
2024	0	0	0	0	1/2t	1t	1t	2 1/2t	4t	5154	...	...	0	1/2t	1t	1t	1t	1 1/2t	1 1/2t
	T3	2 1/2t	3t	4t	5t	5t	6t	...	...		H32	...	1/2t	1t	1 1/2t	1 1/2t	2t	2 1/2t	3 1/2t
	T361(d)	...	4t	5t	6t	6t	8t	8 1/2t	9 1/2t		H34	1/2t	1t	1 1/2t	2t	2 1/2t	3t	3 1/2t	4t
	T4	2 1/2t	3t	4t	5t	5t	6t	...	...		H36	1t	1 1/2t	2t	3t	...	...	...	...
	T81	4 1/2t	5 1/2t	6t	7 1/2t	8t	9t	...	...		H38	1 1/2t	2 1/2t	3t	4t	...	...	...	...
	T861(d)	...	6t	7t	8 1/2t	9 1/2t	10t	11 1/2t	11 1/2t	5252	H25	...	0	1t	...	...	...	...	...
2036	T4	...	1t	1t	...	...	...	...	...		H28	...	1 1/2t	2 1/2t	...	...	...	...	...
3003	0	0	0	0	1/2t	1t	1t	1 1/2t	2t	5254	0	...	0	1/2t	1t	1t	1t	1 1/2t	1 1/2t
	H12	0	0	0	1/2t	1t	1t	1 1/2t	2t		H32	...	1/2t	1t	1 1/2t	1 1/2t	2t	2 1/2t	3 1/2t
	H14	0	0	0	1t	1t	1 1/2t	2t	2 1/2t		H34	1/2t	1t	1 1/2t	2t	2 1/2t	3t	3 1/2t	4t
	H16	1/2t	1t	1t	1 1/2t	...	...	...	...		H36	1t	1 1/2t	2t	3t	...	...	...	...
	H18	1t	1 1/2t	2t	2 1/2t	...	...	...	...		H38	1 1/2t	2 1/2t	3t	4t	...	...	...	...
3004	0	0	0	0	1/2t	1t	1t	1 1/2t	2t	5454	0	...	1/2t	1t	1t	1t	1 1/2t	1 1/2t	2t
	H32	0	0	1/2t	1t	1t	1 1/2t	1 1/2t	2t		H32	...	1/2t	1t	2t	2t	2 1/2t	3t	4t
	H34	0	1t	1t	1 1/2t	1 1/2t	2 1/2t	2 1/2t	3t		H34	...	1t	1 1/2t	2t	2 1/2t	3t	3 1/2t	4t
	H36	1t	1t	1 1/2t	2 1/2t	...	...	...	...	5456	0	...	...	1t	1t	1 1/2t	1 1/2t	2t	2t
	H38	1t	1 1/2t	2 1/2t	3t	...	...	...	...		H321	...	...	...	...	2t	2 1/2t	3t	3 1/2t
3105	H25	1/2t	1/2t	1/2t	...	...	...	...	...	5457	0	...	0	0	...	...	...	...	...
5005	0	0	0	0	1/2t	1t	1t	1 1/2t	2t	5652	0	0	0	0	1/2t	1t	1t	1 1/2t	1 1/2t
	H12	0	0	0	1/2t	1t	1t	1 1/2t	2t		H32	0	0	1t	1 1/2t	1 1/2t	1 1/2t	1 1/2t	2t
	H14	0	0	0	1t	1 1/2t	1 1/2t	2t	2 1/2t		H34	0	1t	1 1/2t	2t	2t	2 1/2t	2 1/2t	3t
	H16	1/2t	1t	1t	1 1/2t	...	...	...	...		H36	1t	1t	1 1/2t	2 1/2t	...	...	...	...
	H18	1t	1 1/2t	2t	2 1/2t	...	...	...	...		H38	1t	1 1/2t	2 1/2t	3t	...	...	...	...
	H32	0	0	0	1/2t	1t	1t	1 1/2t	2t	5657	H25	...	0	0	...	...	...	...	...
	H34	0	0	0	1t	1 1/2t	1 1/2t	2t	2 1/2t		H28	...	1 1/2t	2 1/2t	...	...	...	...	...
	H36	1/2t	1t	1t	1 1/2t	...	...	...	...	6061	0	0	0	0	1t	1t	1t	1 1/2t	2t
	H38	1t	1 1/2t	2t	2 1/2t	...	...	...	...		T4	0	0	1t	1 1/2t	2 1/2t	3t	...	...
5050	0	0	0	0	1/2t	1t	1t	1 1/2t	1 1/2t		T6	1t	1t	1 1/2t	2 1/2t	3t	3 1/2t	...	...
	H32	0	0	0	1t	1t	1 1/2t	...	...	7050	T7	...	...	...	...	...	8t	9t	9 1/2t
	H34	0	0	1t	1 1/2t	1 1/2t	2t	...	...	7072	0	0	0	...	...	...	...	...	...
	H36	1t	1t	1 1/2t	2t	...	...	...	...		H14	0	0	...	...	...	...	...	...
	H38	1t	1 1/2t	2 1/2t	3t	...	...	...	...		H18	1t	1t	...	...	...	...	...	...
5052	0	0	0	0	1/2t	1t	1t	1 1/2t	1 1/2t	7075	0	0	0	1t	1t	1 1/2t	2 1/2t	3 1/2t	4t
	H32	0	0	1t	1 1/2t	1 1/2t	1 1/2t	2t	2t		T6	3t	4t	5t	6t	6t	8t	9t	9 1/2t

(a) The radii listed are the minimum recommended for bending sheets and plates without fracturing in a standard press brake with air bend dies. Other types of bending operations may require larger radii or permit smaller radii. The minimum permissible radii will also vary with the design and condition of the tooling. (b) Alclad sheet in the heat-treatable alloys can be bent over slightly smaller radii than the corresponding tempers of the bare alloy. (c) Heat-treatable alloys can be formed over appreciably smaller radii immediately after solution heat treatment. (d) The H112 temper (applicable to non-heat-treatable alloys) is supplied in the as-fabricated condition without special property control but usually can be formed over radii applicable to the H14 (or H34) temper or smaller. (e) Tempers T361 and T861 formerly designated T36 and T86, respectively

ments such as manganese, chromium, and zirconium are used for controlling grain structure. Alloys of this group, such as the structural alloy 6061, achieve strengths about 70 MPa (10 ksi) higher than in the first group in the T6 temper. Alloys of the second group require a higher solution-treating temperature than the first and are quench sensitive. Therefore, they generally require a separate solution treatment followed by rapid quenching and artificial aging.

The third group contains an amount of Mg₂Si overlapping the first two but with a substantial excess silicon. An excess of 0.2% Si increases the strength of an alloy containing 0.8% Mg₂Si by about 70 MPa (10 ksi). Larger amounts of excess silicon are less beneficial. Excess magnesium, however, is of benefit only at low Mg₂Si contents because magnesium lowers the solubility of Mg₂Si. In excess silicon alloys, segregation of silicon to the boundary causes grain-boundary fracture in recrystallized struc-

tures. Additions of manganese, chromium, or zirconium counteract the effect of silicon by preventing recrystallization during heat treatment. Common alloys of this group are 6351 and the more recently introduced alloys 6009 and 6010. Additions of lead and bismuth to an alloy of this series (6262) improves machinability. This alloy has a better corrosion resistance than 2011, which also is used as a free-machining alloy.

Manganese is a common impurity in primary aluminum, in which its concentration normally ranges from 5 to 50 ppm. It decreases resistivity. Manganese increases strength either in solid solution or as a finely precipitated intermetallic phase. It has no adverse effect on corrosion resistance. Manganese has a very limited solid solubility in aluminum in the presence of normal impurities but remains in solution when chill cast so that most of the manganese added is substantially retained in solution, even in large ingots. As an addition, it is

used to increase strength and to control the grain structure (Fig. 28). The effect of manganese is to increase the recrystallization temperature and to promote the formation of fibrous structure upon hot working. As a dispersed precipitate it is effective in slowing recovery and in preventing grain growth. The manganese precipitate increases the quench sensitivity of heat-treatable alloys.

Manganese is also used to correct the shape of acicular or of platelike iron constituents and to decrease their embrittling effect. Up to the 1.25% level, manganese is the main alloying addition of the 3xxx series of alloys, in which it is added alone or with magnesium. This series of alloys is used in large tonnages for beverage containers and general utility sheet. Even after high degrees of work hardening, these alloys are used to produce severely formed can bodies.

The combined content of manganese, iron, chromium, and other transition metals

Table 10 Minimum and typical room-temperature plane-strain fracture-toughness values for several high-strength aluminum alloys

Product form	Alloy and temper	Thickness		Plane-strain fracture toughness (K_{Ic})											
				L-T direction(a)				T-L direction(b)				S-L direction(c)			
				Minimum		Typical		Minimum		Typical		Minimum		Typical	
mm	in.	MPa√m	ksi√in.	MPa√m	ksi√in.	MPa√m	ksi√in.	MPa√m	ksi√in.	MPa√m	ksi√in.				
Plate	7050-T7451	25.40-50.80	1.000-2.000	31.9	29.0	37	34	27.5	25.0	33	30	...	...	...	...
		50.83-76.20	2.001-3.000	29.7	27.0	36	33	26.4	24.0	32	29	23.1	21.0	28	25
		76.23-101.60	3.001-4.000	28.6	26.0	35	32	25.3	23.0	31	28	23.1	21.0	28	25
		101.63-127.00	4.001-5.000	27.5	25.0	32	29	24.2	22.0	29	26	23.1	21.0	28	25
		127.03-152.40	5.001-6.000	26.4	24.0	31	28	24.2	22.0	28	25	23.1	21.0	28	25
	7050-T7651	25.40-50.80	1.000-2.000	28.6	26.0	34	31	26.4	24.0	31	28	...	...	...	...
		50.83-76.20	2.001-3.000	26.4	24.0	...	...	25.3	23.0	...	...	22.0	20.0	26	24
		7475-T651	...	33.0	30.0	46	42	30.8	28.0	41	37	...	...	...	...
	7475-T7651	...	36.3	33.0	47	43	33.0	30.0	41	37	...	...	...	...
	7475-T7351	...	41.8	38.0	55	50	35.2	32.0	45	41	27.5	25.0	36	33	
	7075-T651	...	...	...	29	26	...	...	25	23	...	...	20	18	
	7075-T7651	...	...	...	30	27	...	...	24	22	...	...	20	18	
	7075-T7351	...	...	...	32	30	...	...	29	26	...	...	20	18	
	7079-T651	...	...	...	30	27	...	...	25	23	...	...	18	16	
	2124-T851	...	26.4	24.0	32	29	22.0	20.0	26	24	19.8	18.0	26	24	
2024-T351	...	...	...	37	34	...	...	32	29	...	...	26	24		
Die forgings	7050-T74, -T7452	...	...	27.5	25.0	38	35	20.9	19.0	32	29	20.9	19.0	29	26
	7175-T736, -T73652	...	...	29.7	27.0	38	35	23.1	21.0	34	31	23.1	21.0	31	28
	7075-T7352	...	...	...	...	32	29	...	...	30	27	...	...	29	26
Hand forgings	7050-T7452	...	...	29.7	27.0	36	33	18.7	17.0	28	25	17.6	16.0	29	26
	7075-T73, -T7352	...	...	...	...	42	38	...	...	28	25	...	...	28	25
	7175-T73652	...	...	33.0	30.0	40	36	27.5	25.0	30	27	23.1	21.0	28	25
	2024-T852	...	...	...	...	26	24	...	...	22	20	...	...	20	18
Extrusions	7050-T7651x	...	...	...	...	44	40	...	...	31	28	...	...	28	25
	7050-T7351x	...	...	...	...	...	...	...	...	...	...	...	...	...	...
	7075-T651x	...	...	...	...	34	31	...	...	22	20	...	...	20	18
	7075-T7351x	...	...	...	...	33	30	...	...	26	24	...	...	22	20
	7150-T7351x	...	...	24.2	22.0	31	28	...	...	...	...	...	...	...	...
	7175-T7351x	...	...	33.0	30.0	40	36	30.8	28.0	34	31	...	...	...	...

(a) L-T, crack plane and growth direction perpendicular to the rolling direction. (b) T-L, crack plane and growth direction parallel to the rolling direction. (c) S-L, short transverse fracture toughness

must be limited, otherwise large primary intermetallic crystals precipitate from the melt in the transfer system or in the ingot sump during casting. In alloys 3003 and 3004 the iron plus manganese content should be kept below about 2.0 and 1.7%,

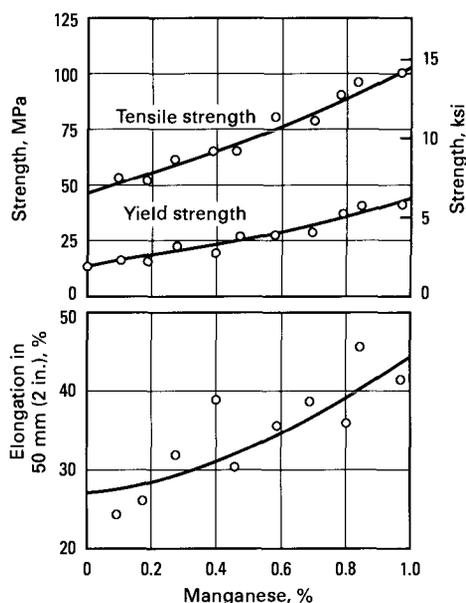


Fig. 28 Effect of manganese on tensile properties of wrought 99.95% Al, 1.6 mm (0.064 in.) thick specimens, quenched in cold water from 565 °C (1050 °F)

respectively, to prevent the formation of primary (Fe,Mn)Al₆ during casting.

Mercury has been used at the level of 0.05% in sacrificial anodes used to protect steel structures. Other than for this use, mercury in aluminum or in contact with it as a metal or a salt will cause rapid corrosion of most aluminum alloys. The toxic properties of mercury must be kept in mind when adding it to aluminum alloys.

Molybdenum is a very low level (0.1 to 1.0 ppm) impurity in aluminum. It has been used at a concentration of 0.3% as a grain refiner, because the aluminum end of the equilibrium diagram is peritectic, and also as a modifier for the iron constituents, but it is not in current use for these purposes.

Nickel. The solid solubility of nickel in aluminum does not exceed 0.04%. Over this amount, it is present as an insoluble intermetallic, usually in combination with iron. Nickel (up to 2%) increases the strength of high-purity aluminum but reduces ductility. Binary aluminum-nickel alloys are no longer in use, but nickel is added to aluminum-copper and to aluminum-silicon alloys to improve hardness and strength at elevated temperatures and to reduce the coefficient of expansion. Nickel promotes pitting corrosion in dilute alloys such as 1100. It is limited in alloys for atomic reactor use, due to its high neutron absorption, but in other areas it is a desirable addition along with iron to improve corrosion resistance to high-pressure steam.

Niobium. As with other elements forming a peritectic reaction, niobium would be expected to have a grain refining effect on casting. It has been used for this purpose, but the effect is not marked.

Phosphorus is a minor impurity (1 to 10 ppm) in commercial-grade aluminum. Its solubility in molten aluminum is very low (~0.01% at 660 °C, or 1220 °F) and considerably smaller in the solid. Phosphorus is used as a modifier for hypereutectic aluminum-silicon alloys where aluminum-phosphide acts as nucleus for primary silicon, thus refining silicon and improving machinability. The aluminum-phosphorus compound reacts with water vapor to give phosphine (PH₃), but the level of phosphorus in aluminum is sufficiently low that this does not constitute a health hazard if adequate ventilation is used when machining phosphorus-nucleated castings. Phosphine can be a problem in furnace teardowns where phosphate-bonded refractories are used.

Silicon, after iron, is the highest impurity level in electrolytic commercial aluminum (0.01 to 0.15%). In wrought alloys, silicon is used with magnesium at levels up to 1.5% to produce Mg₂Si in the 6xxx series of heat-treatable alloys.

High-purity aluminum-silicon alloys are hot short up to 3% Si, the most critical range being 0.17 to 0.8% Si, but additions of silicon (0.5 to 4.0%) reduce the cracking tendency of aluminum-copper-magnesium

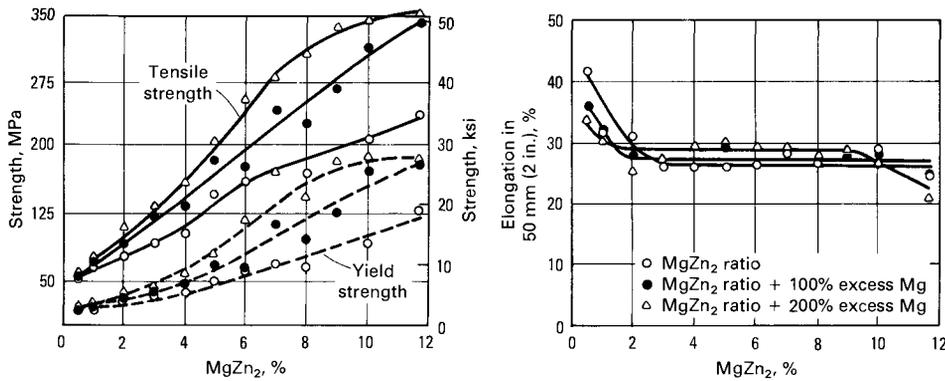


Fig. 29 Effect of $MgZn_2$ and $MgZn_2$ with excess magnesium on tensile properties of wrought 95 Al; 1.59 mm (0.0625 in.) specimens, quenched in cold water from 470 °C (875 °F)

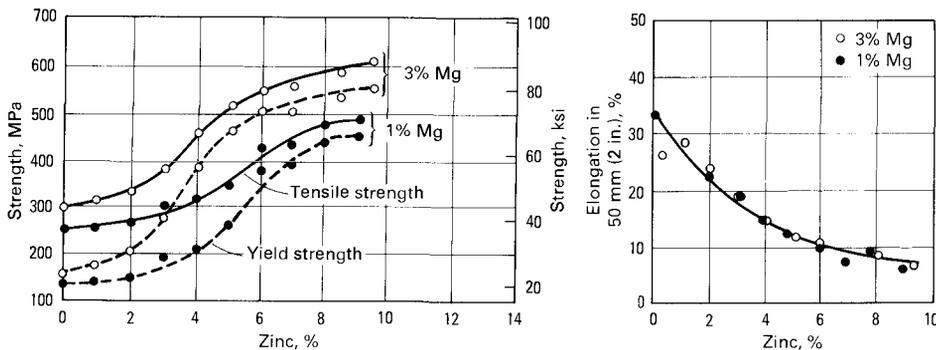


Fig. 30 Effect of zinc on aluminum alloy containing 1.5% Cu and 1 and 3% Mg; 1.6 mm (0.064 in.) thick sheet. Alloy with 1% Mg heat treated at 495 °C (920 °F); that with 3% Mg heat treated at 460 °C (860 °F). All specimens quenched in cold water, aged 12 h at 135 °C (275 °F)

alloys. Small amounts of magnesium added to any silicon-containing alloy will render it heat treatable, but the converse is not true as excess magnesium over that required to form Mg_2Si sharply reduces the solid solubility of this compound. Modification of the silicon can be achieved through the addition of sodium in eutectic and hypoeutectic alloys and by phosphorus in hypereutectic alloys. Up to 12% Si is added in wrought alloys used as cladding for brazing sheet. Alloys containing about 5% Si acquire a black color when anodized and are used for ornamental purposes.

Silver has an extremely high solid solubility in aluminum (up to 55%). Because of cost, no binary aluminum-silver alloys are in use, but small additions (0.1 to 0.6% Ag) are effective in improving the strength and stress-corrosion resistance of aluminum-zinc-magnesium alloys.

Strontium. Traces of strontium (0.01 to 0.1 ppm) are found in commercial-grade aluminum.

Sulfur. As much as 0.2 to 20 ppm sulfur are present in commercial-grade aluminum. It has been reported that sulfur can be used to modify both hypo- and hypereutectic aluminum-silicon alloys.

Tin is used as an alloying addition to aluminum—from concentrations of 0.03 to several percent in wrought alloys, to concentrations of about 25% in casting alloys.

Small amounts of tin (0.05%) greatly increase the response of aluminum-copper alloys to artificial aging following a solution heat treatment. The result is an increase in strength and an improvement in corrosion resistance. Higher concentrations of tin cause hot cracking in aluminum-copper alloys. If small amounts of magnesium are present, the artificial aging characteristics are markedly reduced, probably because magnesium and tin form a noncoherent second phase.

The aluminum-tin bearing alloys, with additions of other metals such as copper, nickel, and silicon are used where bearings are required to withstand high speeds, loads, and temperatures. The copper, nickel, and silicon additions improve load-carrying capacity and wear resistance, and the soft tin phase provides anticorrosion properties.

As little as 0.01% Sn in commercial-grade aluminum will cause surface darkening on annealing and increase the susceptibility to corrosion, which appears to be due to migration of tin to the surface. This effect may be reduced by small additions (0.2%) of copper. Aluminum-zinc alloys with small additions of tin are used as sacrificial anodes in salt water.

Titanium. Amounts of 10 to 100 ppm Ti are found in commercial-purity aluminum. Titanium depresses the electrical conduc-

tivity of aluminum, but its level can be reduced by the addition of boron to the melt to form insoluble TiB_2 . Titanium is used primarily as a grain refiner of aluminum alloy castings and ingots. When used alone, the effect of titanium decreases with time of holding in the molten state and with repeated remelting. The grain-refining effect is enhanced if boron is present in the melt or if it is added as a master alloy containing boron largely combined as TiB_2 . Titanium is a common addition to weld filler wire; it refines the weld structure and prevents weld cracking. It is usually added alone or with TiB_2 during the casting of sheet or extrusion ingots to refine the as-cast grain structure and to prevent cracking.

Vanadium. There is usually 10 to 200 ppm V in commercial-grade aluminum, and because it lowers conductivity, it generally is precipitated from electrical conductor alloys with boron. The aluminum end of the equilibrium diagram is peritectic, and therefore the intermetallic VA_{11} would be expected to have a grain-refining effect upon solidification, but it is less efficient than titanium and zirconium. The recrystallization temperature is raised by vanadium.

Zinc. The aluminum-zinc alloys have been known for many years, but hot cracking of the casting alloys and the susceptibility to stress-corrosion cracking of the wrought alloys curtailed their use. Aluminum-zinc alloys containing other elements offer the highest combination of tensile properties in wrought aluminum alloys. Efforts to overcome the aforementioned limitations have been successful, and these aluminum-zinc base alloys are being used commercially to an increasing extent. The presence of zinc in aluminum increases its solution potential, hence its use in protective cladding (7072) and in sacrificial anodes.

Zinc-Magnesium. The addition of magnesium to the aluminum-zinc alloys develops the strength potential of this alloy system, especially in the range of 3 to 7.5% Zn. Magnesium and zinc form $MgZn_2$, which produces a far greater response to heat treatment than occurs in the binary aluminum-zinc system.

The strength of the wrought aluminum-zinc alloys also is substantially improved by the addition of magnesium. Increasing the $MgZn_2$ concentration from 0.5 to 12% in cold-water quenched 1.6 mm (0.062 in.) sheet continuously increases the tensile and yield strengths. The addition of magnesium in excess (100 and 200%) of that required to form $MgZn_2$ further increases tensile strength, as shown in Fig. 29.

On the negative side, increasing additions of both zinc and magnesium decrease the overall corrosion resistance of aluminum to the extent that close control over the microstructure, heat treatment, and composition are often necessary to maintain adequate

Table 11(a) Ultimate tensile strengths of various aluminum alloys at cryogenic and elevated temperatures

Alloy and temper	Ultimate tensile strength(a), MPa (ksi), at:									
	-195 °C (-320 °F)	-80 °C (-112 °F)	0 °C (-18 °F)	24 °C (75 °F)	100 °C (212 °F)	150 °C (300 °F)	205 °C (400 °F)	260 °C (500 °F)	315 °C (600 °F)	370 °C (700 °F)
1100-0	172 (25)	103 (15)	97 (14)	90 (13)	70 (10)	55 (8)	40 (6)	28 (4)	20 (2.9)	14 (2.1)
1100-H14	207 (30)	138 (20)	130 (19)	125 (18)	110 (16)	97 (14)	70 (10)	28 (4)	20 (2.9)	14 (2.1)
1100-H18	235 (34)	180 (26)	172 (25)	165 (24)	145 (21)	125 (18)	40 (6)	28 (4)	20 (2.9)	14 (2.1)
2011-T3				380 (55)	325 (47)	193 (28)	110 (16)	45 (6.5)	21 (3.1)	16 (2.3)
2014-T6, T651	580 (84)	510 (74)	495 (72)	483 (70)	435 (63)	275 (40)	110 (16)	66 (9.5)	45 (6.5)	30 (4.3)
2017-T4, T451	550 (80)	448 (65)	440 (64)	427 (62)	393 (57)	275 (40)	110 (16)	62 (9)	40 (6)	30 (4.3)
2024-T3 (sheet)	585 (85)	503 (73)	495 (72)	483 (70)	455 (66)	380 (55)	185 (27)	75 (11)	52 (7.5)	35 (5)
2024-T4, T351 (plate)	580 (84)	490 (71)	475 (69)	470 (68)	435 (63)	310 (45)	180 (26)	75 (11)	52 (7.5)	35 (5)
2024-T6, T651	580 (84)	495 (72)	483 (70)	475 (69)	448 (65)	310 (45)	180 (26)	75 (11)	52 (7.5)	35 (5)
2024-T81, T851	585 (85)	510 (74)	503 (73)	483 (70)	455 (66)	380 (55)	185 (27)	75 (11)	52 (7.5)	35 (5)
2024-T861	635 (92)	558 (81)	538 (78)	517 (75)	483 (70)	372 (54)	145 (21)	75 (11)	52 (7.5)	35 (5)
2117-T4	385 (56)	310 (45)	303 (44)	295 (43)	248 (36)	207 (30)	110 (16)	52 (7.5)	32 (4.7)	20 (2.9)
2124-T851	593 (86)	525 (76)	503 (73)	483 (70)	455 (66)	372 (54)	185 (27)	75 (11)	52 (7.5)	38 (5.5)
2218-T61	495 (72)	420 (61)	407 (59)	407 (59)	385 (56)	283 (41)	152 (22)	70 (10)	38 (5.5)	28 (4)
2219-T62	503 (73)	435 (63)	415 (60)	400 (58)	372 (54)	310 (45)	235 (34)	185 (27)	70 (10)	30 (4.4)
2219-T81, T851	572 (83)	490 (71)	475 (69)	455 (66)	415 (60)	338 (49)	248 (36)	200 (29)	48 (7)	30 (4.4)
2618-T61	538 (78)	462 (67)	440 (64)	440 (64)	427 (62)	345 (50)	220 (32)	90 (13)	52 (7.5)	35 (5)
3003-0	228 (33)	138 (20)	117 (17)	110 (16)	90 (13)	75 (11)	59 (8.5)	40 (6)	28 (4)	19 (2.8)
3003-H14	240 (35)	165 (24)	152 (22)	152 (22)	145 (21)	125 (18)	97 (14)	52 (7.5)	28 (4)	19 (2.8)
3003-H18	283 (41)	220 (32)	207 (30)	200 (29)	180 (26)	160 (23)	97 (14)	52 (7.5)	28 (4)	19 (2.8)
3004-0	290 (42)	193 (28)	180 (26)	180 (26)	180 (26)	152 (22)	97 (14)	70 (10)	52 (7.5)	35 (5)
3004-H34	360 (52)	262 (38)	248 (36)	240 (35)	235 (34)	193 (28)	145 (21)	97 (14)	52 (7.5)	35 (5)
3004-H38	400 (58)	303 (44)	290 (42)	283 (41)	275 (40)	215 (31)	152 (22)	83 (12)	52 (7.5)	35 (5)
4032-T6	455 (66)	400 (58)	385 (56)	380 (55)	345 (50)	255 (37)	90 (13)	55 (8)	35 (5)	23 (3.4)
5050-0	255 (37)	152 (22)	145 (21)	145 (21)	145 (21)	130 (19)	97 (14)	62 (9)	40 (6)	27 (3.9)
5050-H34	303 (44)	207 (30)	193 (28)	193 (28)	193 (28)	172 (25)	97 (14)	62 (9)	40 (6)	27 (3.9)
5050-H38	317 (46)	235 (34)	220 (32)	220 (32)	215 (31)	185 (27)	97 (14)	62 (9)	40 (6)	27 (3.9)
5052-0	303 (44)	200 (29)	193 (28)	193 (28)	193 (28)	160 (23)	117 (17)	83 (12)	52 (7.5)	35 (5)
5052-H34	380 (55)	275 (40)	262 (38)	262 (38)	262 (38)	207 (30)	165 (24)	83 (12)	52 (7.5)	35 (5)
5052-H38	415 (60)	303 (44)	290 (42)	290 (42)	275 (40)	235 (34)	172 (25)	83 (12)	52 (7.5)	35 (5)
5083-0	407 (59)	295 (43)	290 (42)	290 (42)	275 (40)	215 (31)	152 (22)	117 (17)	75 (11)	40 (6)
5086-0	380 (55)	270 (39)	262 (38)	262 (38)	262 (38)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5154-0	360 (52)	248 (36)	240 (35)	240 (35)	240 (35)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5254-0	360 (52)	248 (36)	240 (35)	240 (35)	240 (35)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5454-0	372 (54)	255 (37)	248 (36)	248 (36)	248 (36)	200 (29)	152 (22)	117 (17)	75 (11)	40 (6)
5454-H32	407 (59)	290 (42)	283 (41)	275 (40)	270 (39)	220 (32)	172 (25)	117 (17)	75 (11)	40 (6)
5454-H34	435 (63)	317 (46)	303 (44)	303 (44)	295 (43)	235 (34)	180 (26)	117 (17)	75 (11)	40 (6)
5456-0	427 (62)	317 (46)	310 (45)	310 (45)	290 (42)	215 (31)	152 (22)	117 (17)	75 (11)	40 (6)
5652-0	303 (44)	200 (29)	193 (28)	193 (28)	193 (28)	160 (23)	117 (17)	83 (12)	52 (7.5)	35 (5)
5652-H34	380 (55)	275 (40)	262 (38)	262 (38)	262 (38)	207 (30)	165 (24)	83 (12)	52 (7.5)	35 (5)
5652-H38	415 (60)	303 (44)	290 (42)	290 (42)	275 (40)	235 (34)	172 (25)	83 (12)	52 (7.5)	35 (5)
6053-T6, T651				255 (37)	220 (32)	172 (25)	90 (13)	38 (5.5)	28 (4)	20 (2.9)
6061-T6, T651	415 (60)	338 (49)	325 (47)	310 (45)	290 (42)	235 (34)	130 (19)	52 (7.5)	32 (4.6)	21 (3)
6063-T1	235 (34)	180 (26)	165 (24)	152 (22)	152 (22)	145 (21)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6063-T5	255 (37)	200 (29)	193 (28)	185 (27)	165 (24)	138 (20)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6063-T6	325 (47)	262 (38)	248 (36)	240 (35)	215 (31)	145 (21)	62 (9)	31 (4.5)	22 (3.2)	16 (2.3)
6101-T6	295 (43)	248 (36)	235 (34)	220 (32)	193 (28)	145 (21)	70 (10)	33 (4.8)	21 (3)	17 (2.5)
6151-T6	393 (57)	345 (50)	338 (49)	330 (48)	295 (43)	193 (28)	97 (14)	45 (6.5)	35 (5)	28 (4)
6262-T651	415 (60)	338 (49)	325 (47)	310 (45)	290 (42)	235 (34)				
6262-T9	510 (74)	427 (62)	415 (60)	400 (58)	365 (53)	262 (38)	103 (15)	59 (8.5)	32 (4.6)	21 (3)
7075-T6, T651	703 (102)	620 (90)	593 (86)	572 (83)	483 (70)	215 (31)	110 (16)	75 (11)	55 (8)	40 (6)
7075-T73, T7351	635 (92)	545 (79)	525 (76)	503 (73)	435 (63)	215 (31)	110 (16)	75 (11)	55 (8)	40 (6)
7178-T6, T651	730 (106)	648 (94)	627 (91)	607 (88)	503 (73)	215 (31)	103 (15)	75 (11)	59 (8.5)	45 (6.5)
7178-T76, T7651	730 (106)	627 (91)	607 (88)	572 (83)	475 (69)	215 (31)	103 (15)	75 (11)	59 (8.5)	45 (6.5)

(a) These data are based on a limited amount of testing and represent the lowest strength during 10 000 h of exposure at testing temperature under no load; stress applied at 34 MPa/min (5000 psi/min) to yield strength and then at strain rate of 0.05 mm/mm/min (0.05 in./in./min) to failure. Under some conditions of temperature and time, the application of heat will adversely affect certain other properties of some alloys.

resistance to stress corrosion and to exfoliation attack. For example, depending upon the alloy, stress corrosion is controlled by some or all of the following:

- Overaging
- Cooling rate after solution treatment
- Maintaining a nonrecrystallized structure through the use of additions such as zirconium
- Copper or chromium additions (see zinc-magnesium-copper alloys)
- Adjusting the zinc-magnesium ratio closer to 3:1

Zinc-Magnesium-Copper. The addition of copper to the aluminum-zinc-magnesium

system, together with small but important amounts of chromium and manganese, results in the highest-strength aluminum-base alloys commercially available. The properties of a representative group of these compositions, after one of several solution and aging treatments to which they respond, are shown in Fig. 30.

In this alloy system, zinc and magnesium control the aging process. The effect of copper is to increase the aging rate by increasing the degree of supersaturation and perhaps through nucleation of the CuMgAl₂ phase. Copper also increases quench sensitivity upon heat treatment. In general, copper reduces the resistance to general corro-

sion of aluminum-zinc-magnesium alloys, but increases the resistance to stress corrosion. The minor alloy additions, such as chromium and zirconium, have a marked effect on mechanical properties and corrosion resistance.

Zirconium additions in the range 0.1 to 0.3% are used to form a fine precipitate of intermetallic particles that inhibit recovery and recrystallization. An increasing number of alloys, particularly in the aluminum-zinc-magnesium family, use zirconium additions to increase the recrystallization temperature and to control the grain structure in wrought products. Zirconium additions leave this family of alloys less quench sen-

Table 11(b) Tensile yield strengths of various aluminum alloys at cryogenic and elevated temperatures

Alloy and temper	0.2% offset yield strength(a), MPa (ksi), at:-									
	-195 °C (-320 °F)	-80 °C (-112 °F)	0 °C (-18 °F)	24 °C (75 °F)	100 °C (212 °F)	150 °C (300 °F)	205 °C (400 °F)	260 °C (500 °F)	315 °C (600 °F)	370 °C (700 °F)
1100-0	40 (6)	38 (5.5)	35 (5)	35 (5)	32 (4.6)	29 (4.2)	24 (3.5)	18 (2.6)	14 (2)	11 (1.6)
1100-H14	138 (20)	125 (18)	117 (17)	117 (17)	103 (15)	83 (12)	52 (7.5)	18 (2.6)	14 (2)	11 (1.6)
1100-H18	180 (26)	160 (23)	160 (23)	152 (22)	130 (19)	97 (14)	24 (3.5)	18 (2.6)	14 (2)	11 (1.6)
2011-T3				295 (43)	235 (34)	130 (19)	75 (11)	26 (3.8)	12 (1.8)	10 (1.4)
2014-T6, T651	495 (72)	448 (65)	427 (62)	415 (60)	393 (57)	240 (35)	90 (13)	52 (7.5)	35 (5)	24 (3.5)
2017-T4, T451	365 (53)	290 (42)	283 (41)	275 (40)	270 (39)	207 (30)	90 (13)	52 (7.5)	35 (5)	24 (3.5)
2024-T3 (sheet)	427 (62)	360 (52)	352 (51)	345 (50)	330 (48)	310 (45)	138 (20)	62 (9)	40 (6)	28 (4)
2024-T4, T351 (plate)	420 (61)	338 (49)	325 (47)	325 (47)	310 (45)	248 (36)	130 (19)	62 (9)	40 (6)	28 (4)
2024-T6, T651	470 (68)	407 (59)	400 (58)	393 (57)	372 (54)	248 (36)	130 (19)	62 (9)	40 (6)	28 (4)
2024-T81, T851	538 (78)	475 (69)	470 (68)	448 (65)	427 (62)	338 (49)	138 (20)	62 (9)	40 (6)	28 (4)
2024-T861	585 (85)	530 (77)	510 (74)	490 (71)	462 (67)	330 (48)	117 (17)	62 (9)	40 (6)	28 (4)
2117-T4	228 (33)	172 (25)	165 (24)	165 (24)	145 (21)	117 (17)	83 (12)	38 (5.5)	23 (3.3)	14 (2)
2124-T851	545 (79)	490 (71)	470 (68)	440 (64)	420 (61)	338 (49)	138 (20)	55 (8)	40 (6)	28 (4.1)
2218-T61	360 (52)	310 (45)	303 (44)	303 (44)	290 (42)	240 (35)	110 (16)	40 (6)	20 (3)	17 (2.5)
2219-T62	338 (49)	303 (44)	290 (42)	275 (40)	255 (37)	228 (33)	172 (25)	138 (20)	55 (8)	26 (3.7)
2219-T81, T851	420 (61)	372 (54)	360 (52)	345 (50)	325 (47)	275 (40)	200 (29)	160 (23)	40 (6)	26 (3.7)
2618-T61	420 (61)	380 (55)	372 (54)	372 (54)	372 (54)	303 (44)	180 (26)	62 (9)	31 (4.5)	24 (3.5)
3003-0	59 (8.5)	48 (7)	45 (6.5)	40 (6)	38 (5.5)	35 (5)	30 (4.3)	23 (3.4)	17 (2.4)	12 (1.8)
3003-H14	172 (25)	152 (22)	145 (21)	145 (21)	130 (19)	110 (16)	62 (9)	28 (4)	17 (2.4)	12 (1.8)
3003-H18	228 (33)	200 (29)	193 (28)	185 (27)	145 (21)	110 (16)	62 (9)	28 (4)	17 (2.4)	12 (1.8)
3004-0	90 (13)	75 (11)	70 (10)	70 (10)	70 (10)	70 (10)	66 (9.5)	52 (7.5)	35 (5)	20 (3)
3004-H34	235 (34)	207 (30)	200 (29)	200 (29)	200 (29)	172 (25)	103 (15)	52 (7.5)	35 (5)	20 (3)
3004-H38	295 (43)	262 (38)	248 (36)	248 (36)	248 (36)	185 (27)	103 (15)	52 (7.5)	35 (5)	20 (3)
4032-T6	330 (48)	317 (46)	317 (46)	317 (46)	303 (44)	228 (33)	62 (9)	38 (5.5)	22 (3.2)	14 (2)
5050-0	70 (10)	59 (8.5)	55 (8)	55 (8)	55 (8)	55 (8)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)
5050-H34	207 (30)	172 (25)	165 (24)	165 (24)	165 (24)	152 (22)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)
5050-H38	248 (36)	207 (30)	200 (29)	200 (29)	200 (29)	172 (25)	52 (7.5)	40 (6)	29 (4.2)	18 (2.6)
5052-0	110 (16)	90 (13)	90 (13)	90 (13)	90 (13)	90 (13)	75 (11)	52 (7.5)	38 (5.5)	21 (3.1)
5052-H34	248 (36)	220 (32)	215 (31)	215 (31)	215 (31)	185 (27)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5052-H38	303 (44)	262 (38)	255 (37)	255 (37)	248 (36)	193 (28)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5083-0	165 (24)	145 (21)	145 (21)	145 (21)	145 (21)	130 (19)	117 (17)	75 (11)	52 (7.5)	29 (4.2)
5086-0	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5154-0	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5254-0	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5454-0	130 (19)	117 (17)	117 (17)	117 (17)	117 (17)	110 (16)	103 (15)	75 (11)	52 (7.5)	29 (4.2)
5454-H32	248 (36)	215 (31)	207 (30)	207 (30)	200 (29)	180 (26)	130 (19)	75 (11)	52 (7.5)	29 (4.2)
5454-H34	283 (41)	248 (36)	240 (35)	240 (35)	235 (34)	193 (28)	130 (19)	75 (11)	52 (7.5)	29 (4.2)
5456-0	180 (26)	160 (23)	160 (23)	160 (23)	152 (22)	138 (20)	117 (17)	75 (11)	52 (7.5)	29 (4.2)
5652-0	110 (16)	90 (13)	90 (13)	90 (13)	90 (13)	90 (13)	75 (11)	52 (7.5)	38 (5.5)	21 (3.1)
5652-H34	248 (36)	220 (32)	215 (31)	215 (31)	215 (31)	185 (27)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
5652-H38	303 (44)	262 (38)	255 (37)	255 (37)	248 (36)	193 (28)	103 (15)	52 (7.5)	38 (5.5)	21 (3.1)
6053-T6, T651				220 (32)	193 (28)	165 (24)	83 (12)	28 (4)	19 (2.7)	14 (2)
6061-T6, T651	325 (47)	290 (42)	283 (41)	275 (40)	262 (38)	215 (31)	103 (15)	35 (5)	19 (2.7)	12 (1.8)
6063-T1	110 (16)	103 (15)	97 (14)	90 (13)	97 (14)	103 (15)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6063-T5	165 (24)	152 (22)	152 (22)	145 (21)	138 (20)	125 (18)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6063-T6	248 (36)	228 (33)	220 (32)	215 (31)	193 (28)	138 (20)	45 (6.5)	24 (3.5)	17 (2.5)	14 (2)
6101-T6	228 (33)	207 (30)	200 (29)	193 (28)	172 (25)	130 (19)	48 (7)	23 (3.3)	16 (2.3)	12 (1.8)
6151-T6	345 (50)	317 (46)	310 (45)	295 (43)	275 (40)	185 (27)	83 (12)	35 (5)	27 (3.9)	22 (3.2)
6262-T651	325 (47)	290 (42)	283 (41)	275 (40)	262 (38)	215 (31)				
6262-T9	462 (67)	400 (58)	385 (56)	380 (55)	360 (52)	255 (37)	90 (13)	40 (6)	19 (2.7)	12 (1.8)
7075-T6, T651	635 (92)	545 (79)	517 (75)	503 (73)	448 (65)	185 (27)	90 (13)	62 (9)	45 (6.5)	32 (4.6)
7075-T73, T7351	495 (72)	462 (67)	448 (65)	435 (63)	400 (58)	185 (27)	90 (13)	62 (9)	45 (6.5)	32 (4.6)
7178-T6, T651	648 (94)	580 (84)	558 (81)	538 (78)	470 (68)	185 (27)	83 (12)	62 (9)	48 (7)	38 (5.5)
7178-T76, T7651	615 (89)	538 (78)	525 (76)	503 (73)	440 (64)	185 (27)	83 (12)	62 (9)	48 (7)	38 (5.5)

sitive than similar chromium additions. Higher levels of zirconium are employed in some superplastic alloys to retain the required fine substructure during elevated-temperature forming. Zirconium additions have been used to reduce the as-cast grain size, but its effect is less than that of titanium. In addition, zirconium tends to reduce the grain-refining effect of titanium plus boron additions so that it is necessary to use more titanium and boron to grain refine zirconium-containing alloys.

Properties of Wrought Aluminum Alloys

Property data on aluminum alloys are of two basic types:

- Typical property values

- Property limits

The data on wrought aluminum alloys presented in this section are primarily typical property values, although sources and tabular data for some mechanical property limits are also mentioned.

Typical values are considered nominal or representative values. Physical properties (Tables 6 and 7), for example, are median values determined in laboratory tests of representative commercial products. Typical mechanical properties (Table 8) are average or median values, near the peaks of distribution curves derived from routine quality-control tests of commercial products processed by standard mill procedures. The values listed are representative of products of moderate cross section or thickness,

and are most useful for demonstrating relationships between alloys and tempers. These data are not intended to be used for critical design purposes. Static-strength values from tensile tests listed as typical do not represent the somewhat higher values (5 to 10% higher) obtained in tests (longitudinal direction) of extruded products of moderate section thickness nor do they represent the lower values expected in tests of very thick, heat-treated products.

Mechanical property limits are established on a statistical "A"-value basis, whereby 99% of the material is expected to conform at a confidence of 0.95. In most instances limits are based on a normally distributed database of a minimum of 100 tests from at least 10 different lots of material. Mechanical property limits are typically used for design or lot

Table 11(c) Elongation of various aluminum alloys at cryogenic and elevated temperatures

Alloy and temper	Elongation in 50 mm (2 in.), %, at:									
	-195 °C (-320 °F)	-80 °C (-112 °F)	0 °C (-18 °F)	24 °C (75 °F)	100 °C (212 °F)	150 °C (300 °F)	205 °C (400 °F)	260 °C (500 °F)	315 °C (600 °F)	370 °C (700 °F)
1100-0	50	43	40	40	45	55	65	75	80	85
1100-H14	45	24	20	20	20	23	26	75	80	85
1100-H18	30	16	15	15	15	20	65	75	80	85
2011-T3				15	16	25	35	45	90	125
2014-T6, T651	14	13	13	13	15	20	38	52	65	72
2017-T4, T451	28	24	23	22	18	15	35	45	65	70
2024-T3 (sheet)	18	17	17	17	16	11	23	55	75	100
2024-T4, T351 (plate)	19	19	19	19	19	17	27	55	75	100
2024-T6, T651	11	10	10	10	10	17	27	55	75	100
2024-T81, T851	8	7	7	7	8	11	23	55	75	100
2024-T861	5	5	5	5	6	11	28	55	75	100
2117-T4	30	29	28	27	16	20	35	55	80	110
2124-T851	9	8	8	9	9	13	28	60	75	100
2218-T61	15	14	13	13	15	17	30	70	85	100
2219-T62	16	13	12	12	14	17	20	21	40	75
2219-T81, T851	15	13	12	12	15	17	20	21	55	75
2618-T61	12	11	10	10	10	14	24	50	80	120
3003-0	46	42	41	40	43	47	60	65	70	70
3003-H14	30	18	16	16	16	16	20	60	70	70
3003-H18	23	11	10	10	10	11	18	60	70	70
3004-0	38	30	26	25	25	35	55	70	80	90
3004-H34	26	16	13	12	13	22	35	55	80	90
3004-H38	20	10	7	6	7	15	30	50	80	90
4032-T6	11	10	9	9	9	9	30	50	70	90
5050-0										
5050-H34										
5050-H38										
5052-0	46	35	32	30	36	50	60	80	110	130
5052-H34	28	21	18	16	18	27	45	80	110	130
5052-H38	25	18	15	14	16	24	45	80	110	130
5083-0	36	30	27	25	36	50	60	80	110	130
5086-0	46	35	32	30	36	50	60	80	110	130
5154-0	46	35	32	30	36	50	60	80	110	130
5254-0	46	35	32	30	36	50	60	80	110	130
5454-0	39	30	27	25	31	50	60	80	110	130
5454-H32	32	23	20	18	20	37	45	80	110	130
5454-H34	30	21	18	16	18	32	45	80	110	130
5456-0	32	25	22	20	31	50	60	80	110	130
5652-0	46	35	32	30	30	50	60	80	110	130
5652-H34	28	21	18	16	18	27	45	80	110	130
5652-H38	25	18	15	14	16	24	45	80	110	130
6053-T6, T651				13	13	13	25	70	80	90
6061-T6, T651	22	18	17	17	18	20	28	60	85	95
6063-T1	44	36	34	33	18	20	40	75	80	105
6063-T5	28	24	23	22	18	20	40	75	80	105
6063-T6	24	20	19	18	15	20	40	75	80	105
6101-T6	24	20	19	19	20	20	40	80	100	105
6151-T6	20	17	17	17	17	20	30	50	43	35
6262-T651	22	18	17	17	18	20				
6262-T9	14	10	10	10	10	14	34	48	85	95
7075-T6, T651	9	11	11	11	14	30	55	65	70	70
7075-T73, T7351	14	14	13	13	15	30	55	65	70	70
7178-T6, T651	5	8	9	11	14	40	70	76	80	80
7178-T76, T7651	10	10	10	11	17	40	70	76	80	80

Note: Same test conditions as those specified in the footnote of Table 11(a)

acceptance. The distinction between metric and English unit property limits can be important because of rounding from metric to English or vice versa.

Typical physical-property values (Table 6) are given only as a basis for comparing alloys and tempers and should not be specified as engineering requirements or used for design purposes. They are not guaranteed values, since in most cases they are averages for various sizes, product forms, and methods of manufacture and may not be exactly representative of any particular size or product. Density values for the annealed (O) temper are listed in Table 7.

Typical Mechanical Properties. Typical tensile strengths (ultimate and yield), tensile elongations, ultimate shear strengths, fa-

tigue strengths (endurance limits), hardnesses, and elastic moduli are given in Table 8. As typical properties they are for comparative purposes and not design, as discussed previously. The table lists both heat-treatable and non-heat-treatable alloys, and in most cases the properties are averages for various sizes, product forms, and methods of manufacture.

Tensile property limits for various wrought aluminum alloys are given in the article "Properties of Wrought Aluminum and Aluminum Alloys" in this Volume. In addition, the current edition of *Aluminum Standards and Data*, published biennially by The Aluminum Association, provides tensile property limits for most alloy tempers and product forms.

Bend Properties. Recommended minimum 90° cold bend radii for sheet and plate are given in Table 9. Additional forming characteristics (Olsen ball, n , r , minimum bend radii painted sheet, bend radii bus bar) may be found in *Aluminum Standards and Data*, published by The Aluminum Association.

Classification of Alloys for Fracture Toughness. Fracture toughness is rarely, if ever, a design consideration in the 1000, 3000, 4000, 5000, and 6000 series alloys. The fracture toughness of these alloys is sufficiently high that thicknesses beyond those commonly produced would be required to obtain a valid test. Therefore, these alloys are excluded from further consideration in this article. Among the alloys

for which fracture toughness is a meaningful design-related parameter, controlled-toughness high-strength alloys and conventional high-strength alloys merit discussion.

Controlled-toughness high-strength alloys were developed for their high fracture toughness and range in measured K_{Ic} values from about 20 MPa√m (18 ksi√in.) upward. The alloys and tempers currently identified as controlled-toughness high-strength products include:

Alloy	Condition	Product form
2048	.....T8	Sheet and plate
2124	.....T3, T8	Sheet and plate
2419	.....T8	Sheet, plate, extrusions, and forgings
7049	.....T7	Plate, forgings, and extrusions
7050	.....T7	Sheet, plate, forgings, and extrusions
7150	.....T6	Sheet and plate
7175	.....T6, T7	Sheet, plate, forgings, and extrusions
7475	.....T6, T7	Sheet and plate

Typical applications include 2419-T851 used in the lower wing skins of the B-1 bomber and 7475-T7351 and 2124-T851 in the F-16 aircraft.

Conventional High-Strength Alloys. Although these alloys, tempers, and products are not used for fracture-critical components, fracture toughness can be a meaningful design parameter. Conventional aerospace alloys for which fracture toughness minimums may be useful in design include 2014, 2024, 2219, 7075, and 7079. These alloys have toughness levels that are inferior to those of their controlled-toughness counterparts. Consequently, toughness is not guaranteed.

Controlled-toughness alloys are often derivatives of conventional alloys. For example, 7475 alloy is a derivative of 7075 with maximum compositional limits on some elements that were found to decrease toughness.

Fracture toughness quality control and material procurement minimums are appropriate for controlled-toughness, high-strength alloys, tempers, and products, because checks on composition and tensile properties are inadequate assurances that the proper levels of toughness have been achieved. If the minimum specified fracture toughness value is not attained, the material is not acceptable.

Minimum and typical room-temperature plane-strain fracture toughness is listed for selected high-strength aluminum alloys in Table 10. The effect of alloying elements and microstructural constituents on fracture toughness is discussed in the section "Fracture Toughness and Fatigue Behavior" in this article.

Fatigue and Fatigue Crack Growth. Aluminum does not generally exhibit the sharply defined fatigue limit typically shown by low-carbon steel in *S-N* tests. For smooth

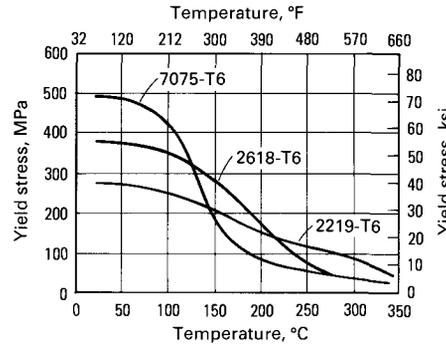


Fig. 31 Values of 0.2% yield stress of aluminum alloys after exposure for 1000 h at temperatures between 0 and 350 °C

or notched coupon tests, where lifetime is governed primarily by crack initiation, the fatigue resistance is expressed as a fatigue strength (stress) for a given number of cycles. Table 8 gives typical data on the fatigue strength of various aluminum alloys.

In tests where fatigue crack growth is of interest, the performance of aluminum is measured by recording the crack growth rate (*da/dN*) as a function of stress intensity range (ΔK). This type of FCG test is currently of prime importance for alloys used in aerospace applications. Fatigue crack growth can be influenced by alloy composition and microstructure, the presence of oxygen, temperature, load ratio (*R*), material thickness (or thickness in relation to plastic zone size), stress intensity range, and the processes used in preparing the alloys. It is recognized that the interactions among these variables complicate the proper interpretation and extrapolation of experimental data and introduce additional uncertainties with respect to damage-tolerant design and failure analysis.

Elevated-Temperature Properties. Tables 11(a), 11(b), and 11(c) list typical tensile properties of various aluminum alloys at elevated temperatures. The 7xxx series of age-hardenable alloys that are based on the Al-Zn-Mg-Cu system develop the highest room-temperature tensile properties of any aluminum alloys produced from conventionally cast ingots. However, the strength of these alloys declines rapidly if they are exposed to elevated temperatures (Fig. 31), due mainly to coarsening of the fine precipitates on which the alloys depend for their strength. Alloys of the 2xxx series such as 2014 and 2024 perform better above these temperatures but are not normally used for elevated-temperature applications.

Strength at temperatures above about 100 to 200 °C (200 to 400 °F) is improved mainly by solid-solution strengthening or second-phase hardening. Another approach to improve the elevated-temperature performance of aluminum alloys has been the use of rapid solidification technology to produce powders or foils containing high super-

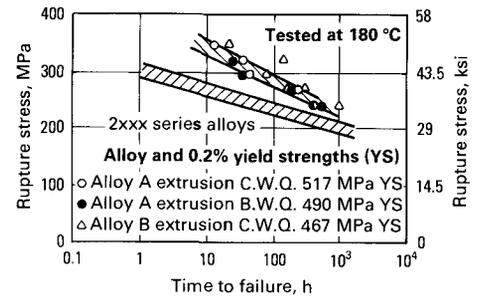


Fig. 32 Stress-rupture results for creep tests at 180 °C (355 °F) on aluminum alloys with silver additions compared with those for 2xxx series alloys. Alloy A: 6.3% Cu, 0.5% Mg, 0.5% Ag, 0.5% Mn, and 0.2% Zr. Alloy B: 6.0% Cu, 0.45% Mg, 0.5% Ag, 0.5% Mn, and 0.14% Zr. CWQ, cold-water quenched before aging; BWQ, boiling-water quenched before aging. Source: Ref 9

saturation of elements such as iron or chromium that diffuse slowly in solid aluminum. In this regard, several experimental materials are now available that have promising creep properties up to 350 °C (650 °F). An experimental Al-Cu-Mg alloy with silver additions has also resulted in improved creep properties (Fig. 32). Iron is also used to improve creep properties (see the heading "Iron" in this article).

Low-Temperature Properties. Aluminum alloys represent a very important class of structural metals for subzero-temperature applications and are used for structural parts for operation at temperatures as low as -270 °C (-450 °F). Below zero, most aluminum alloys show little change in properties; yield and tensile strengths may increase; elongation may decrease slightly; impact strength remains approximately constant. Consequently, aluminum is a useful material for many low-temperature applications; the chief deterrent is its relatively low elongation compared with certain austenitic ferrous alloys. This inhibiting factor affects principally industries that must work with public safety codes. A notable exception to this has been the approval, in the ASME unfired pressure vessel code, to use alloys 5083 and 5456 for pressure vessels within the range from -195 to 65 °C (-320 to 150 °F). With these alloys, tensile strength increases 30 to 40%, yield strength 5 to 10%, and elongation 60 to 100% between room temperature and -195 °C (-320 °F).

The wrought alloys most often considered for low-temperature service are alloys 1100, 2014, 2024, 2219, 3003, 5083, 5456, 6061, 7005, 7039, and 7075. Alloy 5083-O, which is the most widely used aluminum alloy for cryogenic applications, exhibits the following increases in tensile properties when cooled from room temperature to the boiling point of nitrogen (-195.8 °C, or -320.4 °F):

- About 40% in ultimate tensile strength
- About 10% in yield strength

Table 12 Fracture toughness of aluminum alloy plate

Alloy and condition	Room temperature yield strength		Specimen design	Orientation	Fracture toughness, K_{Ic} or $K_{Ic}(J)$ at:							
	MPa	ksi			24 °C (75 °F)		-196 °C (-320 °F)		-253 °C (-423 °F)		-269 °C (-452 °F)	
					MPa√m	ksi√in.	MPa√m	ksi√in.	MPa√m	ksi√in.	MPa√m	ksi√in.
2014-T651	432	62.7	Bend	T-L	23.2	21.2	28.5	26.1	...	...	...	...
2024-T851	444	64.4	Bend	T-L	22.3	20.3	24.4	22.2	...	...	...	...
2124-T851(a)	455	66.0	CT	T-L	26.9	24.5	32.0	29.1	...	...	...	...
	435	63.1	CT	L-T	29.2	26.6	35.0	31.9	...	...	...	...
	420	60.9	CT	S-L	22.7	20.7	24.3	22.1	...	...	...	...
2219-T87	382	55.4	Bend	T-S	39.9	36.3	46.5	42.4	52.5	48.0	...	...
			CT	T-S	28.8	26.2	34.5	31.4	37.2	34.0	...	...
	412	59.6	CT	T-L	30.8	28.1	38.9	32.7	...	...	...	...
5083-O	142	20.6	CT	T-L	27.0(b)	24.6(b)	43.4(b)	39.5(b)	...	...	48.0(b)	43.7(b)
6061-T651	289	41.9	Bend	T-L	29.1	26.5	41.6	37.9	...	...	...	...
7039-T6	381	55.3	Bend	T-L	32.3	29.4	33.5	30.5	...	...	...	...
7075-T651	536	77.7	Bend	T-L	22.5	20.5	27.6	25.1	...	...	...	...
7075-T7351	403	58.5	Bend	T-L	35.9	32.7	32.1	29.2	...	...	...	...
7075-T7351	392	56.8	Bend	T-L	31.0	28.2	30.9	28.1	...	...	...	...

(a) 2124 is similar to 2024 but with higher-purity base and special processing to improve fracture toughness. (b) $K_{Ic}(J)$. Source: Volume 3 of 9th Edition *Metals Handbook*

Table 13 Results of fatigue-life tests on aluminum alloys

Alloy and condition	Stressing mode	Stress ratio, R	K_f	Fatigue strength at 10^6 cycles, at:					
				24 °C (75 °F)		-196 °C (-320 °F)		-253 °C (-423 °F)	
				MPa	ksi	MPa	ksi	MPa	ksi
2014-T6 sheet	Axial	-1.0	1.....	115	17	170	25	315	46
		+0.01	1.....	215	31	325	47	435	63
2014-T6 sheet, GTA welded, 2319 filler	Axial	-1.0	1.....	83	12	105	150	125	18
2219-T62 sheet	Axial	-1.0	1.....	130	19	15	22	255	37
			3.5.....	52	7.5	45	6.5	62	9
2219-T87 sheet	Axial	-1.0	1.....	150	22	115-170	17-25	275	40
			3.5.....	52	7.5	48	7	55	8
2219-T87 sheet, GTA welded, 2319 filler	Axial	-1.0	1.....	69	10	83	12	150	22
5083-H113 plate	Flex	-1.0	1.....	140	20.5	190	27.5	...	...
5083-H113 plate, GMA welded, 5183 filler	Flex	-1.0	1.....	90	13	130	18.8	...	...
6061-T6 sheet(a)	Flex	-1.0	1.....	160	23	220	32	235	34
6061-T6 sheet(b)	Flex	-1.0	1.....	165	24	230	33	230	33
7039-T6 sheet	Axial	-1.0	1.....	140	20	215	31	275	40
		+0.01	1.....	230	33	330	48	440	64
		-1.0	3.5.....	48	7	48	7	62	9
7075-T6 sheet	Axial	-1.0	1.....	96	14	145	21	250	36

(a) Surface finish, 150 μ m. rms. (b) Surface finish, 20 μ m. rms. Source: Volume 3 of 9th Edition *Metals Handbook*

● Sixty percent in elongation

Typical tensile properties of various aluminum alloys at cryogenic temperatures are given in Tables 11(a), 11(b), and 11(c).

Retention of toughness also is of major importance for equipment operating at low temperature. Aluminum alloys have no ductile-to-brittle transition; consequently, neither ASTM nor ASME specifications require low-temperature Charpy or Izod tests of aluminum alloys. Other tests, including notch-tensile and tear tests, assess the notch-tensile and tear toughness of aluminum alloys at low temperatures. The low-temperature characteristics of welds in the weldable aluminum alloys parallel those described above for unwelded material.

Fracture Toughness. Data on fracture toughness of several aluminum alloys at room and subzero temperatures are summarized in Table 12. Of the alloys listed in Table 12, 5083-O has substantially greater toughness than the others. Because this alloy is too tough for obtaining valid K_{Ic} data, the values shown for 5083-O were converted from J_{Ic} data. The fracture toughness of this alloy increases as expo-

sure temperature decreases. Of the other alloys, which were all evaluated in various heat-treated conditions, 2219-T87 has the best combination of strength and fracture toughness, both at room temperature and at -196 °C (-320 °F), of all the alloys that can be readily welded.

Alloy 6061-T651 has good fracture toughness at room temperature and at -196 °C (-320 °F), but its yield strength is lower than that of alloy 2219-T87. Alloy 7039 also is weldable and has a good combination of strength and fracture toughness at room temperature and at -196 °C (-320 °F). Alloy 2124 is similar to 2024 but with a higher-purity base and special processing for improved fracture toughness. Tensile properties of 2124-T851 at subzero temperatures can be expected to be similar to those for 2024-T851.

Several other aluminum alloys, including 2214, 2419, 7050, and 7475, have been developed in order to obtain room-temperature fracture toughness superior to that of other 2000 and 7000 series alloys. Information on subzero properties of these alloys is limited, but it is expected that these alloys also would have improved fracture tough-

ness at subzero temperatures as well as at room temperature.

Fatigue Strength. Results of axial and flexural fatigue tests at 10^6 cycles on aluminum alloy specimens at room temperature and at subzero temperatures are presented in Table 13. These data indicate that, for a fatigue life of 10^6 cycles, fatigue strength is higher at subzero temperatures than at room temperature for each alloy. This trend is not necessarily valid for tests at higher stress levels and shorter fatigue lives, but at 10^6 cycles results are consistent with the effect of subzero temperatures on tensile strength.

ACKNOWLEDGMENT

The information in this article is largely taken from four sources:

- Volume 2 of the 9th Edition of *Metals Handbook*
- "Introduction to Aluminum and Aluminum Alloys" in the *Metals Handbook Desk Edition* (1985)
- "Effects of Alloying Elements and Impurities on Properties" in *Aluminum: Proper-*

- ties and Physical Metallurgy* (ASM, 1984)
 ● *Aluminum Standards and Data 1988*, 9th Edition, Aluminum Association

REFERENCES

1. D. Munson, *J. Inst. Met.*, Vol 95, 1967, p 217-219
2. W. Hume-Rothery and G.V. Raynor, *The Structure of Metals and Alloys*, The Institute of Metals, 1962
3. W.B. Pearson, *Handbook of Lattice Spacings and Structures of Metals and Alloys*, Vol 2, Pergamon Press, 1967
4. L.F. Mondolfo, *Aluminum Alloys: Structure and Properties*, Butterworths, 1976
5. F.L. Kaufman and H. Bernstein, *Computer Calculation of Phase Diagrams*, Academic Press, 1970
6. CALPHAD (Computer Coupling of Phase Diagrams and Thermochemistry), L. Kaufman, Ed., Manlabs Inc.
7. CALPHAD, Pergamon Press, 1976-1980
8. R.K. Wyss and R.E. Sanders, Jr., "Microstructure-Property Relationship in a 2xxx Aluminum Alloy With Mg Addition," *Metall. Trans. A*, Vol 19A, 1988, p 2523-2530
9. I.J. Polmear and M.J. Couper, "Design and Development of an Experimental Wrought Aluminum Alloy for Use at Elevated Temperatures," *Metall. Trans. A*, Vol 19A, p 1027-1035