
Aluminum and Aluminum Alloys

Introduction and Overview

General Characteristics. The unique combinations of properties provided by aluminum and its alloys make aluminum one of the most versatile, economical, and attractive metallic materials for a broad range of uses—from soft, highly ductile wrapping foil to the most demanding engineering applications. Aluminum alloys are second only to steels in use as structural metals.

Aluminum has a density of only 2.7 g/cm³, approximately one-third as much as steel (7.83 g/cm³). One cubic foot of steel weighs about 490 lb; a cubic foot of aluminum, only about 170 lb. Such light weight, coupled with the high strength of some aluminum alloys (exceeding that of structural steel), permits design and construction of strong, lightweight structures that are particularly advantageous for anything that moves—space vehicles and aircraft as well as all types of land- and water-borne vehicles.

Aluminum resists the kind of progressive oxidization that causes steel to rust away. The exposed surface of aluminum combines with oxygen to form an inert aluminum oxide film only a few ten-millionths of an inch thick, which blocks further oxidation. And, unlike iron rust, the aluminum oxide film does not flake off to expose a fresh surface to further oxidation. If the protective layer of aluminum is scratched, it will instantly reseal itself.

The thin oxide layer itself clings tightly to the metal and is colorless and transparent—invisible to the naked eye. The discoloration and flaking of iron and steel rust do not occur on aluminum.

Appropriately alloyed and treated, aluminum can resist corrosion by water, salt, and other environmental factors, and by a wide range of other chemical and physical agents. The corrosion characteristics of aluminum alloys are examined in the section “Effects of Alloying on Corrosion Behavior” in this article.

Aluminum surfaces can be highly reflective. Radiant energy, visible light, radiant heat, and electromagnetic waves are efficiently reflected, while anodized and dark anodized surfaces can be reflective or absorbent. The reflectance of polished aluminum, over a broad range of wave lengths, leads to its selection for a variety of decorative and functional uses.

Aluminum typically displays excellent electrical and thermal conductivity, but specific alloys have been developed with high degrees of electrical resistivity. These alloys are useful, for example, in high-torque electric motors. Aluminum is often selected for its electrical conductivity, which is nearly twice that of copper on an equivalent weight basis. The requirements of high conductivity and mechanical strength can be met by use of long-line, high-voltage, aluminum steel-cored reinforced transmission cable. The thermal conductivity of aluminum alloys, about 50 to 60% that of copper, is advantageous in heat exchangers, evaporators, electrically heated appliances and utensils, and automotive cylinder heads and radiators.

Aluminum is nonferromagnetic, a property of importance in the electrical and electronics industries. It is nonpyrophoric, which is important in applications involving inflammable or explosive-materials handling or exposure. Aluminum is also non-toxic and is routinely used in containers for food and beverages. It has an attractive appearance in its natural finish, which can be soft and lustrous or bright and shiny. It can be virtually any color or texture.

The ease with which aluminum may be fabricated into any form is one of its most important assets. Often it can compete successfully with cheaper materials having a lower degree of workability. The metal can be cast by any method known to foundrymen. It can be rolled to any desired thickness down to foil thinner than paper. Aluminum sheet can be stamped, drawn, spun, or roll formed. The metal also may be hammered or forged. Aluminum wire, drawn from rolled rod, may be stranded into cable of any desired size and type. There is almost no limit to the different profiles (shapes) in which the metal can be extruded.

Alloy Categories. It is convenient to divide aluminum alloys into two major categories: wrought compositions and cast compositions. A further differentiation for each category is based on the primary mechanism of property development. Many alloys respond to thermal treatment based on phase solubilities. These treatments include solution heat treatment, quenching, and precipitation, or age, hardening. For either casting or wrought alloys, such alloys are described as heat treatable. A large number of other wrought compositions rely instead on work hardening through mechanical reduction, usually in combination with various annealing procedures for property development. These alloys are referred to as work hardening. Some casting alloys are essentially not heat treatable and are

used only in as-cast or in thermally modified conditions unrelated to solution or precipitation effects.

Cast and wrought alloy nomenclatures have been developed. The Aluminum Association system is most widely recognized in the United States. Their alloy identification system employs different nomenclatures for wrought and cast alloys, but divides alloys into families for simplification. For wrought alloys a four-digit system is used to produce a list of wrought composition families as follows:

- 1xxx: Controlled unalloyed (pure) composition, used primarily in the electrical and chemical industries
- 2xxx: Alloys in which copper is the principal alloying element, although other elements, notably magnesium, may be specified. 2xxx-series alloys are widely used in aircraft where their high strength (yield strengths as high as 455 MPa, or 66 ksi) is valued.
- 3xxx: Alloys in which manganese is the principal alloying element, used as general-purpose alloys for architectural applications and various products
- 4xxx: Alloys in which silicon is the principal alloying element, used in welding rods and brazing sheet
- 5xxx: Alloys in which magnesium is the principal alloying element, used in boat hulls, gangplanks, and other products exposed to marine environments
- 6xxx: Alloys in which magnesium and silicon are the principal alloying elements, commonly used for architectural extrusions and automotive components
- 7xxx: Alloys in which zinc is the principal alloying element (although other elements, such as copper, magnesium, chromium, and zirconium, may be specified), used in aircraft structural components and other high-strength applications. The 7xxx series are the strongest aluminum alloys, with yield strengths ≥ 500 MPa (≥ 73 ksi) possible.
- 8xxx: Alloys characterizing miscellaneous compositions. The 8xxx series alloys may contain appreciable amounts of tin, lithium, and/or iron.
- 9xxx: Reserved for future use

Wrought alloys that constitute heat-treatable (precipitation-hardenable) aluminum alloys include the 2xxx, 6xxx, 7xxx, and some of the 8xxx alloys. The various combinations of alloying additions and strengthening mechanisms used for wrought aluminum alloys are shown in Table 1. The strength ranges achievable with various classes of wrought and cast alloys are given in Tables 2 and 3.

Casting compositions are described by a three-digit system followed by a decimal value. The decimal .0 in all cases pertains to casting alloy limits. Decimals .1, and .2 concern ingot compositions, which after melting and processing should result in chemistries conforming to casting specification requirements. Alloy families for casting compositions include the following:

- 1xx.x: Controlled unalloyed (pure) compositions, especially for rotor manufacture
- 2xx.x: Alloys in which copper is the principal alloying element. Other alloying elements may be specified.
- 3xx.x: Alloys in which silicon is the principal alloying element. The other alloying elements such as copper and magnesium are specified. The 3xx.x series comprises nearly 90% of all shaped castings produced.
- 4xx.x: Alloys in which silicon is the principal alloying element.
- 5xx.x: Alloys in which magnesium is the principal alloying element.
- 6xx.x: Unused
- 7xx.x: Alloys in which zinc is the principal alloying element. Other alloying elements such as copper and magnesium may be specified.
- 8xx.x: Alloys in which tin is the principal alloying element.
- 9xx.x: Unused

Heat-treatable casting alloys include the 2xx, 3xx, and 7xx series.

Tables 4 and 5 list nominal compositions for representative wrought and cast aluminum alloys. It should be noted that the alloy compositions listed in these tables make up a rather small percentage of the total amount of compositions developed. More than 500 alloy designations/compositions have been registered by the Aluminum Association Inc. for aluminum alloys. Composition limits for these alloys can be found in the *Metals Handbook Desk Edition*, 2nd ed., (see the article “Chemical Compositions and International Designations on pages 426–436) and in Registration Records on wrought alloys, castings, and ingots published by the Aluminum Association.

Table 1 Classification of wrought aluminum alloys according to their strengthening mechanism

Alloy system	Aluminum series
Work-hardenable alloys	
Pure Al	1xxx
Al-Mn	3xxx
Al-Si	4xxx
Al-Mg	5xxx
Al-Fe	8xxx
Al-Fe-Ni	8xxx
Precipitation-hardenable alloys	
Al-Cu	2xxx
Al-Cu-Mg	2xxx
Al-Cu-Li	2xxx
Al-Mg-Si	6xxx
Al-Zn	7xxx
Al-Zn-Mg	7xxx
Al-Zn-Mg-Cu	7xxx
Al-Li-Cu-Mg	8xxx

Applications. Aluminum alloys are economical in many applications. They are used in the automotive industry, aerospace industry, in construction of machines, appliances, and structures, as cooking utensils, as covers for housings for electronic equipment, as pressure vessels for cryogenic applications, and in innumerable other areas. Tables 6 and 7 list typical applications for some of the more commonly used wrought and cast alloys, respectively.

Table 2 Strength ranges of various wrought aluminum alloys

Aluminum Association series	Type of alloy composition	Strengthening method	Tensile strength range	
			MPa	ksi
1xxx	Al	Cold work	70–175	10–25
2xxx	Al-Cu-Mg (1–2.5% Cu)	Heat treat	170–310	25–45
2xxx	Al-Cu-Mg-Si (3–6% Cu)	Heat treat	380–520	55–75
3xxx	Al-Mn-Mg	Cold work	140–280	20–40
4xxx	Al-Si	Cold work (some heat treat)	105–350	15–50
5xxx	Al-Mg (1–2.5% Mg)	Cold work	140–280	20–40
5xxx	Al-Mg-Mn (3–6% Mg)	Cold work	280–380	40–55
6xxx	Al-Mg-Si	Heat treat	150–380	22–55
7xxx	Al-Zn-Mg	Heat treat	380–520	55–75
7xxx	Al-Zn-Mg-Cu	Heat treat	520–620	75–90
8xxx	Al-Li-Cu-Mg	Heat treat	280–560	40–80

Table 3 Strength ranges of various cast aluminum alloys

Alloy system (AA designation)	Tensile strength range	
	MPa	ksi
Heat treatable sand cast alloys (various tempers)		
Al-Cu (201–206)	353–467	51–68
Al-Cu-Ni-Mg (242)	186–221	27–32
Al-Cu-Si (295)	110–221	16–32
Al-Si-Cu (319)	186–248	27–36
Al-Si-Cu-Mg (355, 5% Si, 1.25% Cu, 0.5% Mg)	159–269	23–39
Al-Si-Mg (356, 357)	159–345	23–50
Al-Si-Cu-Mg (390, 17% Si, 4.5% Cu, 0.6% Mg)	179–276	26–40
Al-Zn (712, 713)	241	35
Non-heat treatable die cast alloys		
Al-Si (413, 443, F temper)	228–296	33–43
Al-Mg (513, 515, 518, F temper)	276–310	40–45
Non-heat treatable permanent mold cast alloys		
Al-Sn (850, 851, 852, T5 temper)	138–221	20–32

Table 4 Product forms and nominal compositions of common wrought aluminum alloys

AA number	Product(a)	Composition, %							
		Al	Si	Cu	Mn	Mg	Cr	Zn	Others
1050	DT	99.50 min	...	...	...	...	...	...	...
1060	S, P, ET, DT	99.60 min	...	...	...	...	...	...	...
1100	S, P, F, E, ES, ET, C, DT, FG	99.00 min	...	0.12	...	...	...	...	...
1145	S, P, F	99.45 min	...	...	...	...	...	...	...
1199	F	99.99 min	...	...	...	...	...	...	...
1350	S, P, E, ES, ET, C	99.50 min	...	...	...	...	...	...	...
2011	E, ES, ET, C, DT	93.7	...	5.5	...	...	...	...	0.4 Bi; 0.4 Pb
2014	S, P, E, ES, ET, C, DT, FG	93.5	0.8	4.4	0.8	0.5	...	...	...
2024	S, P, E, ES, ET, C, DT	93.5	...	4.4	0.6	1.5	...	...	...
2036	S	96.7	...	2.6	0.25	0.45	...	...	...
2048	S, P	94.8	...	3.3	0.4	1.5	...	...	...
2124	P	93.5	...	4.4	0.6	1.5	...	...	...
2218	FG	92.5	...	4.0	...	1.5	...	...	2.0 Ni
2219	S, P, E, ES, ET, C, FG	93.0	...	6.3	0.3	...	...	...	0.06 Ti; 0.10 V; 0.18 Zr
2319	C	93.0	...	6.3	0.3	...	...	...	0.18 Zn; 0.15 Ti; 0.10 V
2618	FG	93.7	0.18	2.3	...	1.6	...	...	1.1 Fe; 1.0 Ni; 0.07 Ti
3003	S, P, F, E, ES, ET, C, DT, FG	98.6	...	0.12	1.2	...	...	...	...
3004	S, P, ET, DT	97.8	...	...	1.2	1.0	...	...	...
3105	S	99.0	...	...	0.55	0.50	...	...	...
4032	FG	85.0	12.2	0.9	...	1.0	...	...	0.9 Ni
4043	C	94.8	5.2	...	...	...	...	...	...
5005	S, P, C	99.2	...	...	...	0.8	...	...	...
5050	S, P, C, DT	98.6	...	...	...	1.4	...	...	...
5052	S, P, F, C, DT	97.2	...	...	...	2.5	0.25	...	...
5056	F, C	95.0	...	...	0.12	5.0	0.12	...	...
5083	S, P, E, ES, ET, FG	94.7	...	...	0.7	4.4	0.15	...	...
5086	S, P, E, ES, ET, DT	95.4	...	...	0.4	4.0	0.15	...	...
5154	S, P, E, ES, ET, C, DT	96.2	...	...	...	3.5	0.25	...	...
5182	S	95.2	...	...	0.35	4.5	...	...	...
5252	S	97.5	...	...	...	2.5	...	...	...
5254	S, P	96.2	...	...	...	3.5	0.25	...	...
5356	C	94.6	...	...	0.12	5.0	0.12	...	0.13 Ti
5454	S, P, E, ES, ET	96.3	...	...	0.8	2.7	0.12	...	...
5456	S, P, E, ES, ET, DT, FG	93.9	...	...	0.8	5.1	0.12	...	...
5457	S	98.7	...	...	0.3	1.0	...	...	...
5652	S, P	97.2	...	...	...	2.5	0.25	...	...
5657	S	99.2	...	...	...	0.8	...	...	...
6005	E, ES, ET	98.7	0.8	...	...	0.5	...	...	...
6009	S	97.7	0.8	0.35	0.5	0.6	...	...	...
6010	S	97.3	1.0	0.35	0.5	0.8	...	...	...
6061	S, P, E, ES, ET, C, DT, FG	97.9	0.6	0.28	...	1.0	0.2	...	...
6063	E, ES, ET, DT	98.9	0.4	...	...	0.7	...	...	...
6066	E, ES, ET, DT, FG	95.7	1.4	1.0	0.8	1.1	...	...	...
6070	E, ES, ET	96.8	1.4	0.28	0.7	0.8	...	...	...
6101	E, ES, ET	98.9	0.5	...	...	0.6	...	...	...
6151	FG	98.2	0.9	...	...	0.6	0.25	...	...
6201	C	98.5	0.7	...	...	0.8	...	...	...
6205	E, ES, ET	98.4	0.8	...	0.1	0.5	0.1	...	0.1 Zr
6262	E, ES, ET, C, DT	96.8	0.6	0.28	...	1.0	0.09	...	0.6 Bi; 0.6 Pb
6351	E, ES	97.8	1.0	...	0.6	0.6	...	...	...
6463	E, ES	98.9	0.4	...	...	0.7	...	...	...
7005	E, ES	93.3	...	...	0.45	1.4	0.13	4.5	0.04 Ti; 0.14 Zr
7049	P, E, ES, FG	88.2	...	1.5	...	2.5	0.15	7.6	...
7050	P, E, ES, FG	89.0	...	2.3	...	2.3	...	6.2	0.12 Zr
7072	S, F	99.0	...	...	...	...	...	1.0	...
7075	S, P, E, ES, ET, C, DT, FG	90.0	...	1.6	...	2.5	0.23	5.6	...
7175	S, P, FG	90.0	...	1.6	...	2.5	0.23	5.6	...
7178	S, P, E, ES, C	88.1	...	2.0	...	2.7	0.26	6.8	...
7475	S, P, FG	90.3	1.5	...	...	2.3	0.22	5.7	...

(a) S, sheet; P, plate; F, foil; E, extruded rod, bar and wire; ES, extruded shapes; ET, extruded tubes; C, cold finished rod, bar and wire; DT, drawn tube; FG, forgings

Wrought Alloy Classes

As described in the “Introduction and Overview” to this article, aluminum alloys are commonly grouped into an alloy designation series. The general characteristics of the wrought alloy groups are described below. Strength ranges, nominal compositions, and applications for wrought aluminum alloys are listed in Tables 2, 4, and 6, respectively.

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

Table 5 Designations and nominal compositions of common aluminum alloys used for casting

AA number	Product(a)	Composition, %				
		Cu	Mg	Mn	Si	Others
201.0	S	4.6	0.35	0.35	...	0.7 Ag, 0.25 Ti
206.0	S or P	4.6	0.25	0.35	0.10(b)	0.22 Ti, 0.15 Fe(b)
A206.0	S or P	4.6	0.25	0.35	0.05(b)	0.22 Ti, 0.10 Fe(b)
208.0	S	4.0	...	...	3.0	...
242.0	S or P	4.0	1.5	...	...	2.0 Ni
295.0	S	4.5	...	...	0.8	...
96.0	P	4.5	...	...	2.5	...
308.0	S or P	4.5	...	...	5.5	...
319.0	S or P	3.5	...	...	6.0	...
336.0	P	1.0	1.0	...	12.0	2.5 Ni
354.0	P	1.8	0.50	...	9.0	...
355.0	S or P	1.2	0.50	0.50(b)	5.0	0.6 Fe(b), 0.35Zn(b)
C355.0	S or P	1.2	0.50	0.10(b)	5.0	0.20 Fe(b), 0.10Zn(b)
356.0	S or P	0.25(b)	0.32	0.35(b)	7.0	0.6 Fe(b), 0.35 Zn(b)
A356.0	S or P	0.20(b)	0.35	0.10(b)	7.0	0.20 Fe(b), 0.10 Zn(b)
357.0	S or P	...	0.50	...	7.0	...
A357.0	S or P	...	0.6	...	7.0	0.15 Ti, 0.005 Be
359.0	S or P	...	0.6	...	9.0	...
360.0	D	...	0.50	...	9.5	2.0 Fe(b)
A360.0	D	...	0.50	...	9.5	1.3 Fe(b)
\380.0	D	3.5	...	...	8.5	2.0 Fe(b)
A380.0	D	3.5	...	...	8.5	1.3 Fe(b)
383.0	D	2.5	...	...	10.5	...
384.0	D	3.8	...	...	11.2	3.0 Zn(b)
A384.0	D	3.8	...	...	11.2	1.0 Zn(b)
390.0	D	4.5	0.6	...	17.0	1.3 Zn(b)
A390.0	S or P	4.5	0.6	...	17.0	0.5 Zn(b)
413.0	D	...	...	...	12.0	2.0 Fe(b)
A413.0	D	...	...	...	12.0	1.3 Fe(b)
4430	S	0.6(b)	...	...	5.2	...
A443.0	S	0.30(b)	...	...	5.2	...
B443.0	S or P	0.15(b)	...	...	5.2	...
C443.0	D	0.6(b)	...	...	5.2	2.0 Fe(b)
514.0	S	...	4.0	...	...	...
518.0	D	...	8.0	...	...	...
520.0	S	...	10.0	...	...	...
535.0	S	...	6.8	0.18	...	0.18 Ti
A535.0	S	...	7.0	0.18	...	...
B535.0	S	...	7.0	...	...	0.18 Ti
712.0	S or P	...	0.6	...	...	5.8 Zn, 0.5 Cr, 0.20 Ti
713.0	S or P	0.7	0.35	...	...	7.5 Zn, 0.7 Cu
771.0	S	...	0.9	...	...	7.0 Zn, 0.13 Cr, 0.15 Ti
850.0	S or P	1.0	...	...	...	6.2 Sn, 1.0 Ni

(a) S, sand casting; P, permanent mold casting; D, die casting. (b) Maximum

Table 6 Selected applications for wrought aluminum alloys

Alloy	Description and selected applications	Alloy	Description and selected applications	Alloy	Description and selected applications
1100	Commercially pure aluminum highly resistant to chemical attack and weathering. Low cost, ductile for deep drawing, and easy to weld. Used for high-purity applications such as chemical processing equipment. Also for nameplates, fan blades, flue lining, sheet metal work, spun holloware, and fin stock	3105	Residential siding, mobile homes, rain-carrying goods, sheet metal work, appliance parts and trim, automotive parts, building products, electronics, fin stock, furniture, hospital and medical equipment, kitchen equipment, recreation vehicles, trucks and trailers	5454	For all types of welded assemblies, tanks, pressure vessels. ASME code approved to 205 °C (400 °F). Also used in trucking for hot asphalt road tankers and dump bodies; also, for hydrogen peroxide and chemical storage vessels
1350	Electrical conductors	5005	Specified for applications requiring anodizing; anodized coating is cleaner and lighter in color than 3003. Uses include appliances, utensils, architectural, applications requiring good electrical conductivity, automotive parts, containers, general sheet metal, hardware, hospital and medical equipment, kitchen equipment, name plates, and marine applications	5456	For all types of welded assemblies, storage tanks, pressure vessels, and marine components. Used where best weld efficiency and joint strength are required. Restricted to temperatures below 65 °C (150 °F)
2011	Screw machine products. Appliance parts and trim, ordnance, automotive, electronic, fasteners, hardware, machine parts			5657	For anodized auto and appliance trim and name plates
2014	Truck frames, aircraft structures, automotive, cylinders and pistons, machine parts, structurals			6061	Good formability, weldability, corrosion resistance, and strength in the T-temper. Good general-purpose alloy used for a broad range of structural applications and welded assemblies including truck components, railroad cars, pipelines, marine applications, furniture, agricultural applications, aircrafts, architectural applications, automotive parts, building products, chemical equipment, dump bodies, electrical and electronic applications, fasteners, fence wire, fan blades, general sheet metal, highway signs, hospital and medical equipment, kitchen equipment, machine parts, ordnance, recreation equipment, recreation vehicles, and storage tanks
2017	Screw machine products, fittings, fasteners, machine parts			6063	Used in pipe railing, furniture, architectural extrusions, appliance parts and trim, automotive parts, building products, electrical and electronic parts, highway signs, hospital and medical equipment, kitchen equipment, marine applications, machine parts, pipe, railroad cars, recreation equipment, recreation vehicles, trucks and trailers
2024	For high-strength structural applications. Excellent machinability in the T-temper. Fair workability and fair corrosion resistance. Alclad 2024 combines the high strength of 2024 with the corrosion resistance of the commercially pure cladding. Used for truck wheels, many structural aircraft applications, gears for machinery, screw machine products, automotive parts, cylinders and pistons, fasteners, machine parts, ordnance, recreation equipment, screws and rivets	5052	Stronger than 3003 yet readily formable in the intermediate tempers. Good weldability and resistance to corrosion. Uses include pressure vessels, fan blades, tanks, electronic panels, electronic chassis, medium-strength sheet metal parts, hydraulic tube, appliances, agricultural applications, architectural uses, automotive parts, building products, chemical equipment, containers, cooking utensils, fasteners, hardware, highway signs, hospital and medical equipment, kitchen equipment, marine applications, railroad cars, recreation vehicles, trucks and trailers	7050	High-strength alloy in aircraft and other structures. Also used in ordnance and recreation equipment
2219	Structural uses at high temperature (to 315 °C, or 600 °F). High-strength weldments			7075	For aircraft and other applications requiring highest strengths. Alclad 7075 combines the strength advantages of 7075 with the corrosion-resisting properties of commercially pure aluminum-clad surface. Also used in machine parts and ordnance
3003	Most popular general-purpose alloy. Stronger than 1100 with same good formability and weldability. For general use including sheet metal work, stampings, fuel tanks, chemical equipment, containers, cabinets, freezer liners, cooking utensils, pressure vessels, builder's hardware, storage tanks, agricultural applications, appliance parts and trim, architectural applications, electronics, fin stock, fan equipment, name plates, recreation vehicles, trucks and trailers. Used in drawing and spinning.	5056	Cable sheathing, rivets for magnesium, screen wire, zippers, automotive applications, fence wire, fasteners		
		5083	For all types of welded assemblies, marine components, and tanks requiring high weld efficiency and maximum joint strength. Used in pressure vessels up to 65 °C (150 °F) and in many cryogenic applications, bridges, freight cars, marine components, TV towers, drilling rigs, transportation equipment, missile components, and dump truck bodies. Good corrosion resistance		
3004	Sheet metal work, storage tanks, agricultural applications, building products, containers, electronics, furniture, kitchen equipment, recreation vehicles, trucks and trailers	5086	Used in generally the same types of applications as 5083, particularly where resistance to either stress corrosion or atmospheric corrosion is important		

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.

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, a magnesium-silicon alloy of the 6xxx series, or an alloy containing 1% Zn. The coating, usually from $2\frac{1}{2}$ to 5% of the total thickness on each side, 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

Table 7 Selected applications for aluminum casting alloys

Alloy	Representative applications	Alloy	Representative applications
100.0	Electrical rotors larger than 152 mm (6 in.) in diameter	360.0	Outboard motor parts; instrument cases; cover plates; marine and aircraft castings
201.0	Structural members; cylinder heads and pistons; gear, pump, and aerospace housings	A360.0	Cover plates; instrument cases; irrigation system parts; outboard motor parts; hinges
208.0	General-purpose castings; valve bodies, manifolds, and other pressure-tight parts	380.0	Housings for lawn mowers and radio transmitters; air brake castings; gear cases
222.0	Bushings; meter parts; bearings; bearing caps; automotive pistons; cylinder heads	A380.0	Applications requiring strength at elevated temperature
238.0	Sole plates for electric hand irons	384.0	Pistons and other severe service applications; automatic transmissions
242.0	Heavy-duty pistons; air-cooled cylinder heads; aircraft generator housings	390.0	Internal combustion engine pistons, blocks, manifolds, and cylinder heads
A242.0	Diesel and aircraft pistons; air-cooled cylinder heads; aircraft generator housings	413.0	Architectural, ornamental, marine, and food and dairy equipment applications
B295.0	Gear housings; aircraft fittings; compressor connecting rods; railway car seat frames	A413.0	Outboard motor pistons; dental equipment; typewriter frames; street lamp housings
308.0	General-purpose permanent mold castings; ornamental grilles and reflectors	443.0	Cookware; pipe fittings; marine fittings; tire molds; carburetor bodies
319.0	Engine crankcases; gasoline and oil tanks; oil pans; typewriter frames; engine parts	514.0	Fittings for chemical and sewage use; dairy and food handling equipment; tire molds
332.0	Automotive and heavy-duty pistons; pulleys, sheaves	A514.0	Permanent mold casting of architectural fittings and ornamental hardware
333.0	Gas meter and regulator parts; gear blocks; pistons; general automotive castings	518.0	Architectural and ornamental castings; conveyor parts; aircraft and marine castings
354.0	Premium-strength castings for the aerospace industry	520.0	Aircraft fittings; railway passenger car frames; truck and bus frame sections
355.0	Sand: air compressor pistons; printing press bedplates; water jackets; crankcases. Permanent: impellers; aircraft fittings; timing gears; jet engine compressor cases	535.0	Instrument parts and other applications where dimensional stability is important
356.0	Sand: flywheel castings; automotive transmission cases; oil pans; pump bodies. Permanent: machine tool parts; aircraft wheels; airframe castings; bridge railings	A712.0	General-purpose castings that require subsequent brazing
A356.0	Structural parts requiring high strength; machine parts; truck chassis parts	713.0	Automotive parts; pumps; trailer parts; mining equipment
357.0	Corrosion-resistant and pressure-tight applications	850.0	Bushings and journal bearings for railroads
359.0	High-strength castings for the aerospace industry	A850.0	Rolling mill bearings and similar applications

make truck and aircraft wheels, truck suspension parts, aircraft fuselage and wing skins, structural parts, and those parts requiring good strength at temperatures up to 150 °C (300 °F). Figure 1 shows the relationships between some of the more commonly used alloys in the 2xxx series.

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, one of these, the popular 3003 alloy, is widely used as a general-purpose alloy for moderate-strength applications requiring good workability.

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

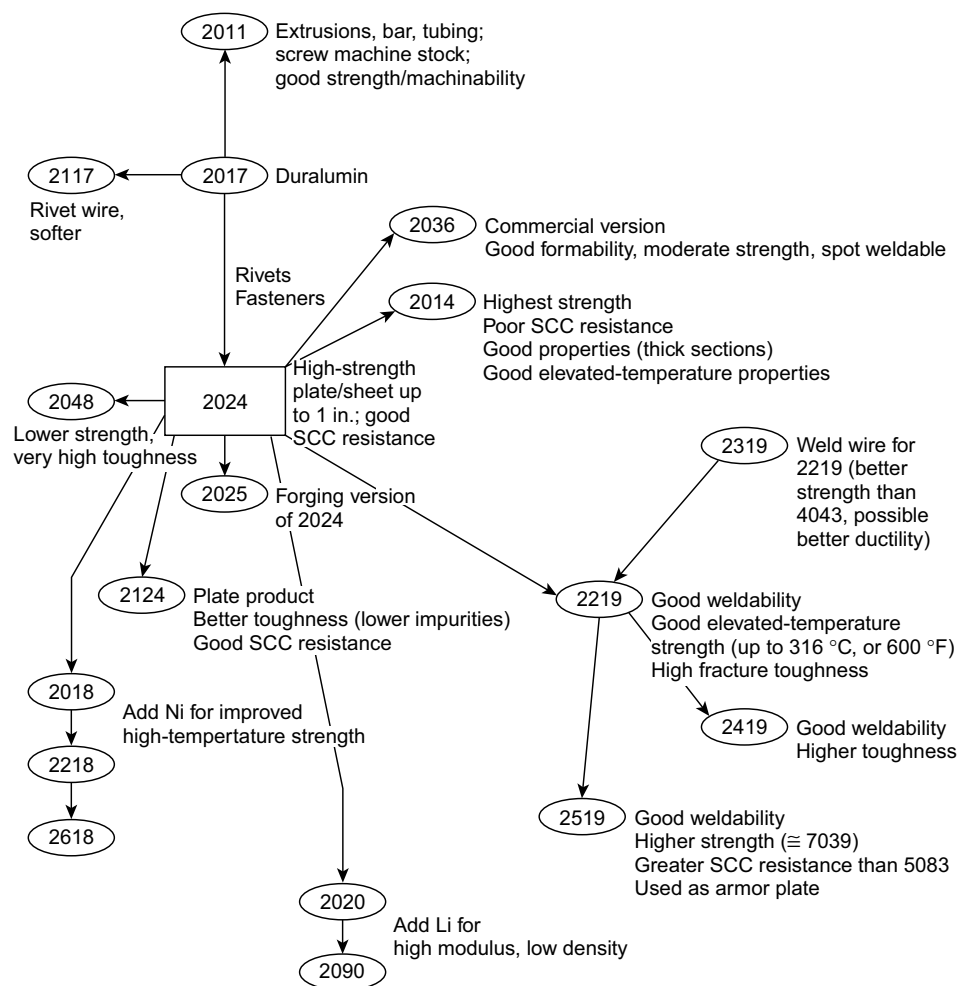


Fig. 1 Relationships among commonly used alloys in the 2xxx series (Al-Cu)

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 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; thus it 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 workhardenable 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 ~3.5% for operating temperatures above ~65 °C, or 150 °F) to avoid susceptibility to stress-corrosion cracking. Figure 2 shows the relationships between some of the more commonly used alloys in the 5xxx series.

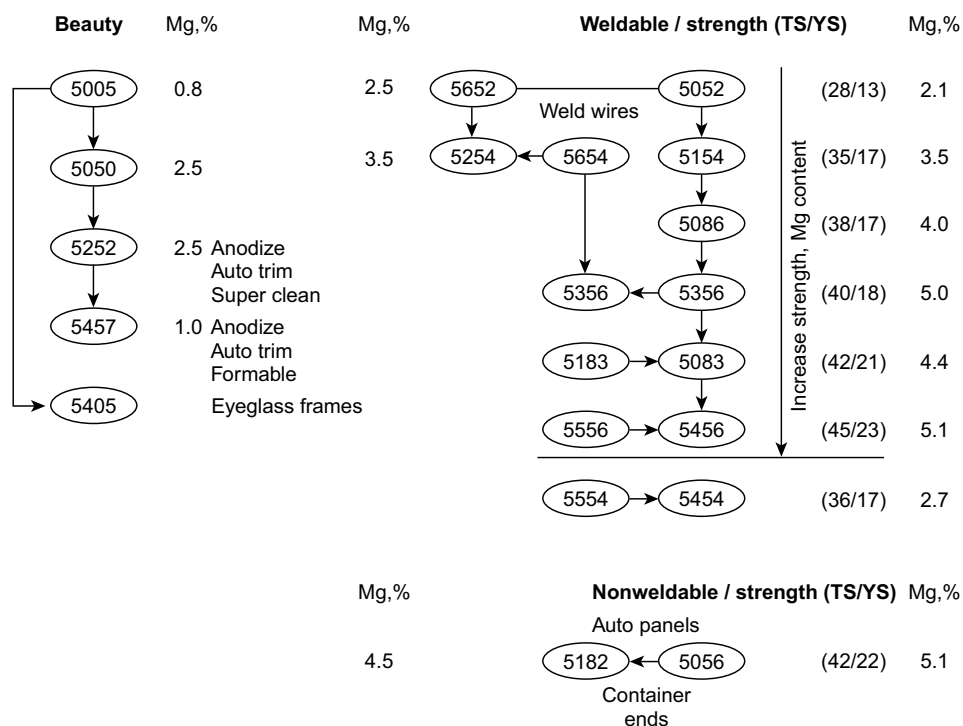


Fig. 2 Relationships among commonly used alloys in the 5xxx series (Al-Mg). Tensile strength (TS) and yield strength (YS) are in ksi units.

6xxx Series. Alloys in the 6xxx series contain silicon and magnesium approximately in the proportions required for formation of magnesium silicide (Mg_2Si), 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. Figure 3 shows the relationships between some of the more commonly used alloys in the 6xxx series.

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 added in small quantities. Dilute additions of scandium also improve properties. 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

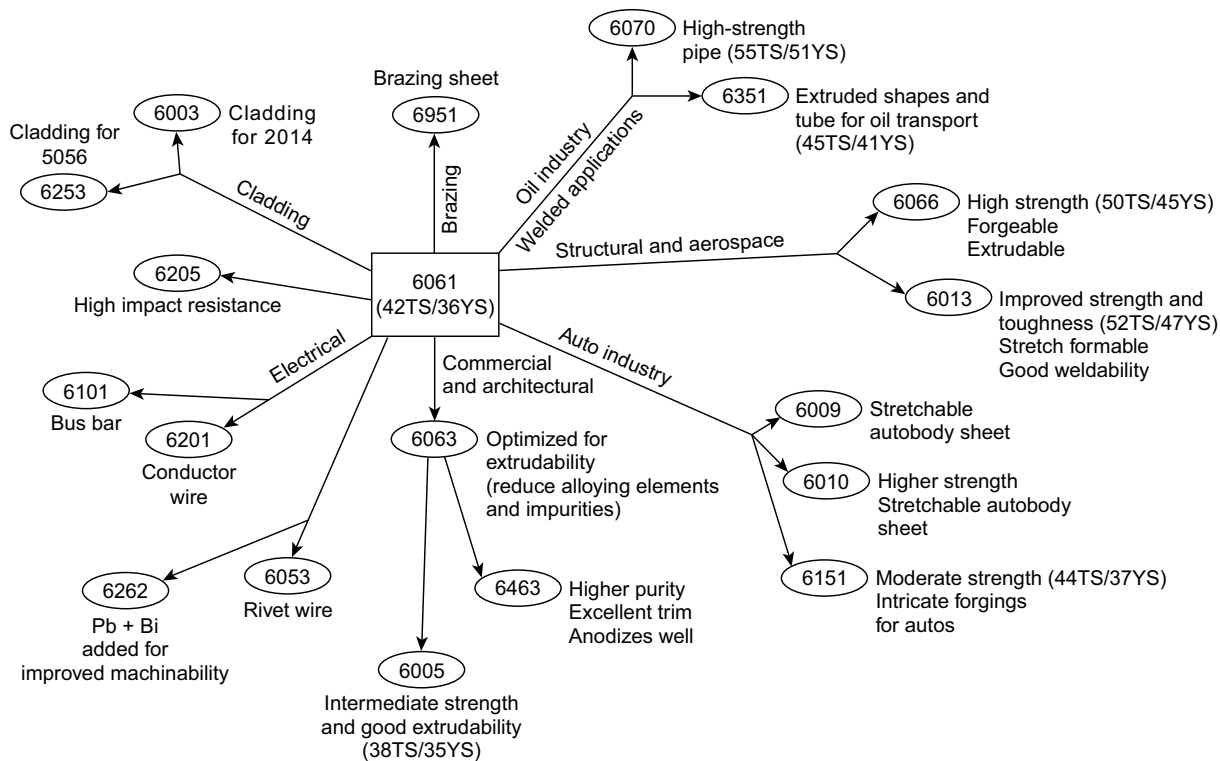


Fig. 3 Relationships among commonly used alloys in the 6xxx series (Al-Mg-Si). Tensile strength (TS) and yield strength (YS) are in ksi units

toughness. Figure 4 shows the relationships between some of the more commonly used alloys in the 7xxx series.

8xxx series alloys constitute a wide range of chemical compositions. For example, improved elevated-temperature performance is achieved through the use of dispersion-strengthened Al-Fe-Ce alloys (e.g., 8019) or Al-Fe-V-Si alloys (e.g., 8009) made by powder metallurgy processing. Lower density and higher stiffness can be achieved in lithium-containing alloys (e.g., 8090). The latter alloy, which is precipitation hardenable, has replaced medium-to-high strength 2xxx and 7xxx alloys in some aircraft/aerospace applications (e.g., helicopter components).

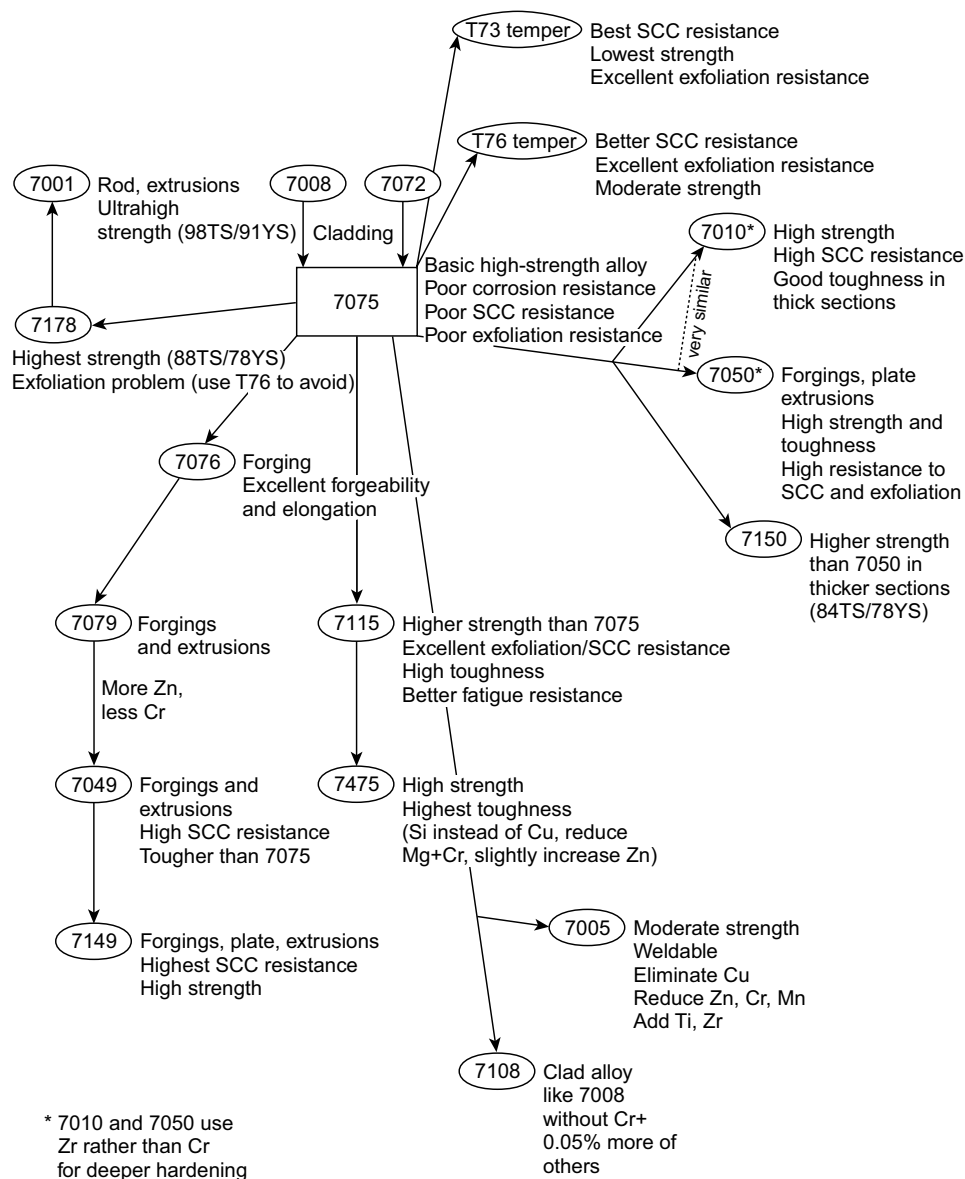


Fig. 4 Relationships among commonly used alloys in the 7xxx series (Al-Zn-Cu-Mg-Cr). Tensile strength (TS) and yield strength (YS) are in ksi units

Cast Alloy Classes

Aluminum casting alloys are based on the same alloy systems as those of wrought aluminum alloys, are strengthened by the same mechanisms (with the general exception of strain hardening), and are similarly classified into non-heat-treatable and heat treatable types. The major difference is that the casting alloys used in the greatest volumes contain alloying additions of silicon far in excess of the amounts in most wrought alloys. Silicon is the alloying element that literally makes the commercial viability of the high-volume aluminum casting industry possible. Silicon contents from ~4% to the eutectic level of ~12% reduce scrap losses, permit production of much more intricate designs with greater variations in section thickness, and yield castings with higher surface and internal quality. These benefits derive from the effects of silicon in increasing fluidity, reducing cracking, and improving feeding to minimize shrinkage porosity.

Figure 5 shows the complete phase diagram of the binary aluminum-silicon system. This is a simple eutectic system with limited terminal solubility and is the basis for the 4xx.x alloys. Metallographic structures of the pure components and of several intermediate compositions show typical morphologies. The intermediate compositions are mixtures of aluminum

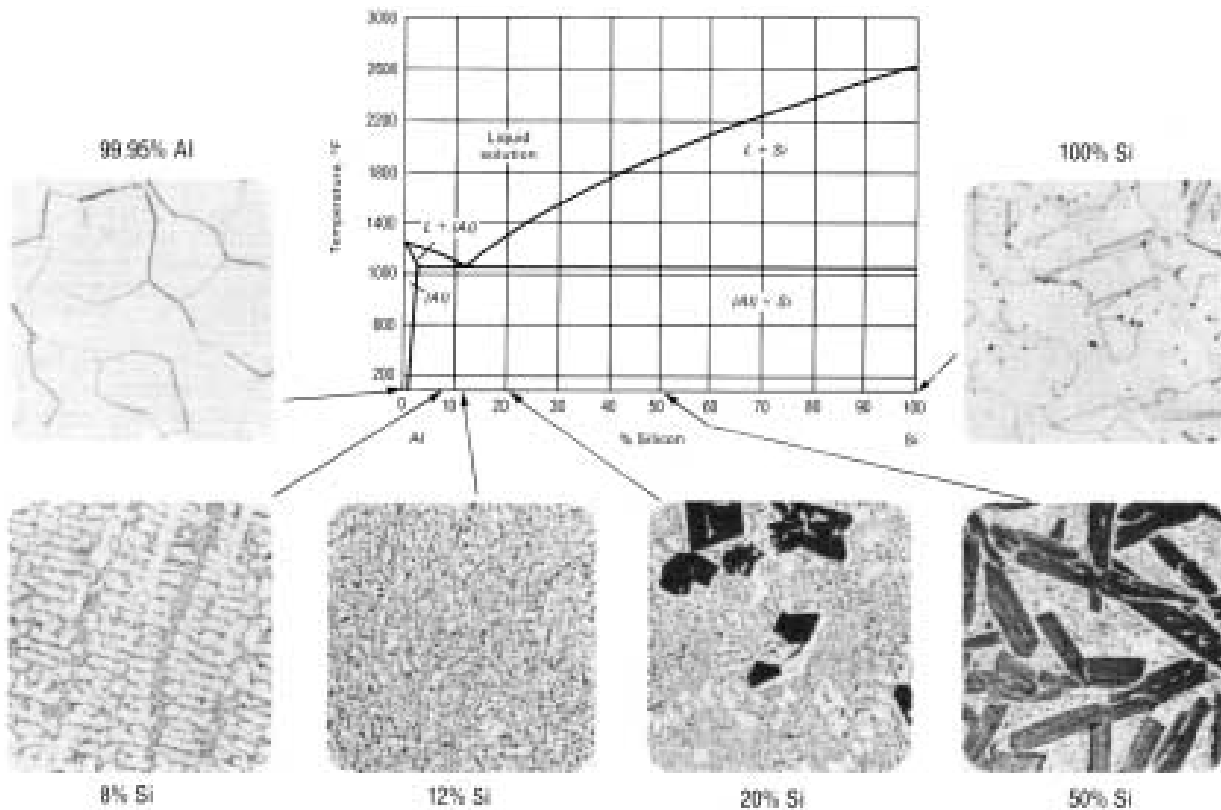


Fig. 5 Aluminum-silicon phase diagram and cast microstructures of pure components and of alloys of various compositions. Alloys with less than 12% Si are referred to as hypoeutectic, those with close to 12% Si as eutectic, and those with over 12% Si as hypereutectic

containing ~1% Si in solid solution as the continuous phase, with particles of essentially pure silicon. Alloys with <12% Si are referred to as “hypo-eutectic,” those with close to 12% Si as “eutectic,” and those with >12% Si as “hyper-eutectic.”

The general characteristics of the cast alloy series are described below. Strength ranges, nominal compositions, and applications for cast aluminum alloys are listed in Tables 3, 5, and 7, respectively.

2xx.x Series. The 2xx.x aluminum-copper group includes compositions capable of developing the highest strengths among all casting alloys, and these alloys are used where this is a predominant requirement. These alloys (A201.0, 202.0, 204.0, and A206.0) contain 4 to 6% Cu and 0.25 to 0.35% Mg, with highly restrictive impurity (iron and silicon) limits, and in some cases also contain 0.25 to 0.35% Mn or Cr and (in alloys 201.0, A201.0, and 202.0) 0.7% Ag. Good casting design and foundry techniques must be employed to realize full mechanical-property capabilities and consistently high quality for these alloys.

The 2xx.x alloys also have the highest strengths and hardnesses of all casting alloys at elevated temperatures (to 300 °C, or 600 °F), and this factor accounts for their use in some applications. Alloys 222.0, 224.0, 238.0, 240.0, 242.0, and 243.0, some with higher copper contents up to 2% Mg (6% in alloy 240.0) and additions of manganese, nickel, vanadium, and/or zirconium, are used primarily at elevated temperatures.

Heat treatment is required with the 2xx.x alloys for development of highest strength and ductility and must be properly applied to ensure high resistance to stress-corrosion cracking. General corrosion resistance of these alloys is lower than those of other types of casting alloys, and protection by surface coatings is required in critical applications.

3xx.x Series. The highest-volume-usage alloys are those in the 3xx.x group, which, in addition to silicon, contain magnesium, copper, or both, and in specific cases, supplementary additions of nickel or beryllium. In general, they fall into one of three types: Al-Si-Mg, Al-Si-Cu, or Al-Si-Cu-Mg. Silicon contents range from 5 to 22%. Copper contents range from 0% (alloys 356.0 through 361.0) to a maximum of 4.5%. Most of these alloys have nominal magnesium contents ranging from as low as 0.3% to ~0.6% for the high-strength compositions and 1.0% for the piston alloys 332.0 and 336.0. The principal alloys of this group requiring low magnesium contents (0.10% maximum) are the die casting compositions 380.0 through 384.0.

Both copper and magnesium increase strength and hardness in the as-cast (F) temper through increased solid-solution hardening. Much greater increases are afforded by artificial aging only (T5-type tempers) or by complete solution plus artificial aging treatments (T6- or T7-type tempers). Depending on composition, the precipitation hardening is the result of precipitate structures based on Mg_2Si , Al_2Cu , Al_2CuMg , or combinations of

these phases. The alloys containing both copper and magnesium have higher strengths at elevated temperatures.

Higher-silicon-content alloys are preferred for casting by the permanent mold and die casting processes. The thermal expansion coefficient decreases with increasing silicon and nickel contents. A low expansion coefficient is beneficial for engine applications such as pistons and cylinder blocks. When the silicon content exceeds 12%, as in alloys 390.0 through 393.0, primary silicon crystals are present and, if fine and well distributed, enhance wear resistance.

4xx.x Series. Alloys of the 4xx.x group, based on the binary aluminum-silicon system and containing from 5 to 12% Si, find many applications where combinations of moderate strength and high ductility and impact resistance are required. Bridge railing support castings are a representative example.

5xx.x Series. The aluminum-magnesium alloys in the 5xx.x group are essentially single phase binary alloys with moderate-to-high strength and toughness properties. High corrosion resistance, especially to seawater and marine atmospheres, is the primary advantage of castings made of Al-Mg alloys. Best corrosion resistance requires low impurity content (both solid and gaseous), and thus alloys must be prepared from high-quality metals and handled with great care in the foundry. These alloys are suitable for welded assemblies and are often used in architectural and other decorative or building needs. Aluminum-magnesium alloys also have good machinability and an attractive appearance when anodized.

7xx.x Series. The 7xx.x aluminum-zinc-magnesium alloys are notable for their combinations of good finishing characteristics, good general corrosion resistance, and the capability of developing high strength through natural aging without heat treatment.

8xx.x Series. Alloys of the 8xx.x group contain ~6% Sn and small amounts of copper and nickel for strengthening. These alloys were developed for bearing applications (tin imparts lubricity), for example, connecting rods and crankcase bearings for diesel engines.

Alloying and Second-Phase Constituents

The predominant reason for alloying is to increase strength, hardness, and resistance to wear, creep, stress relaxation or fatigue. Effects on these properties are specific to the different alloying elements and combinations of them, and are related to their alloy phase diagrams and to the

microstructures and substructures that they form as a result of solidification, thermomechanical history, heat treatment and/or cold working.

The tensile yield strength of super-purity aluminum in its annealed (softest) state is approximately 10 MPa (1.5 ksi), whereas those of some heat treated commercial high-strength alloys exceed 550 MPa (80 ksi). When the magnitude of this difference (an increase of over 5000%) is considered, this practical, everyday accomplishment, which is just one aspect of the physical metallurgy of aluminum, is truly remarkable. Higher strengths, up to a yield strength of 690 MPa (100 ksi) and over, may be readily produced, but the fracture toughness of such alloys does not meet levels considered essential for aircraft or other critical-structure applications.

The elements that are most commonly present in commercial 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 (Fig. 6). These elements all have significant solid solubility in aluminum, and in all cases the solubility increases with increasing temperature (see Fig. 7).

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 8, 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

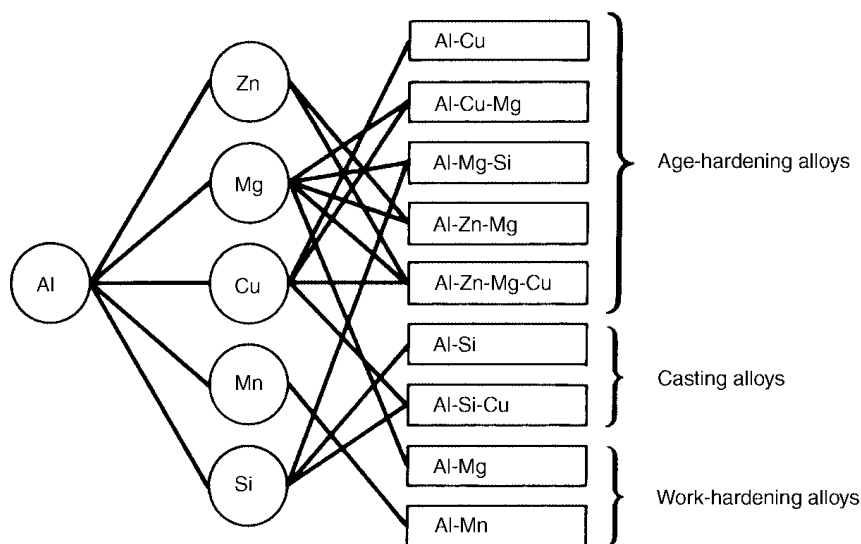


Fig. 6 The principal aluminum alloys

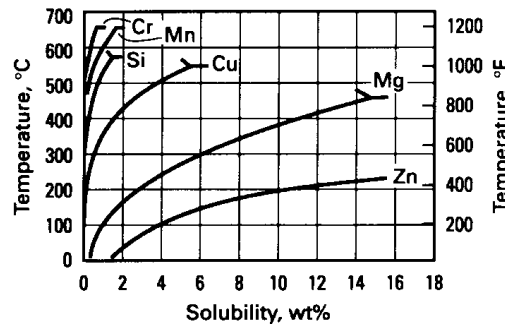


Fig. 7 Equilibrium binary solid solubility as a function of temperature for alloying elements most frequently added to aluminum

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 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 8 illustrates the effect of magnesium in solid solution on the yield strength and tensile elongation for most of the common aluminum-magnesium commercial alloys.

Second-Phase Constituents. Elements and combinations that form predominantly second-phase constituents with relatively low solid solubility include iron, silicon, magnesium, copper, manganese and chromium, and combinations thereof (see also the section “Alloying Effects on Phase Formation”). 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

Table 8 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 to 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.

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.

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. The concentrations of manganese and/or chromium held in solid solution in as-cast ingot that has been rapidly solidified and cooled from the molten state greatly exceed the equilibrium solubility. The solid solution is thus supersaturated and metastable. Ingot preheating for wrought commercial alloys containing these elements is designed to cause solid-state precipitation of the complex phase containing one or the other of these elements that is appropriate to the alloy composition. 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

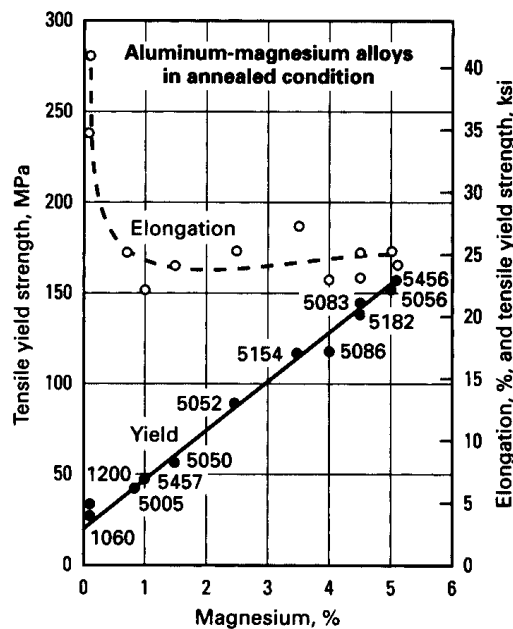


Fig. 8 Correlation between tensile yield, strength elongation, and magnesium content for some commercial aluminum alloys

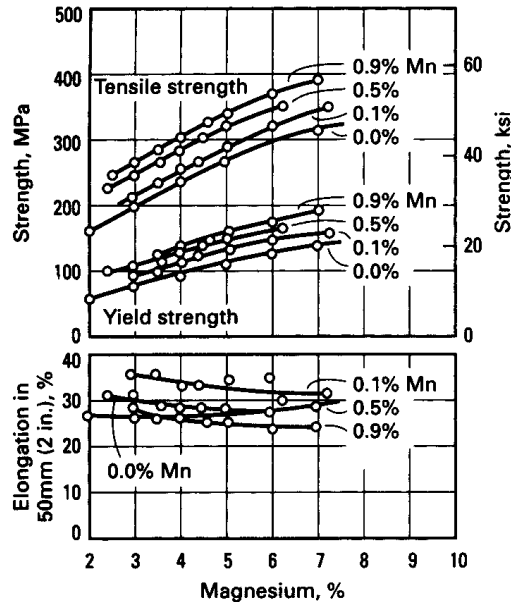


Fig. 9 Tensile properties in Al-Mg-Mn alloys in the form of annealed (O temper) plate 13 mm (0.5 in.) thick

and grain growth in the alloy during subsequent heatings. The precipitate particles of $\text{Al}_{12}(\text{Fe},\text{Mn})_3\text{Si}$, $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$, or $\text{Al}_{12}\text{Mg}_2\text{Cr}$ 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.

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. 9 for Al-Mg-Mn alloys in the annealed condition.

Effects of Specific Alloying Elements and Impurities

The mechanical, physical, and chemical properties of aluminum alloys depend upon composition and microstructure. The addition of selected elements to pure aluminum greatly enhances its properties and usefulness. Because of this, most applications for aluminum utilize alloys having one or more elemental additions. The major alloying additions used with aluminum are copper, manganese, silicon, magnesium, and zinc. The total amount of these elements can constitute up to 10% of the alloy composition (all percentages given in weight percent unless otherwise noted). Impurity elements are also present, but their total percentage is usually less than 0.15% in aluminum alloys.

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 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 it 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 cadmium 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 operation, 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 misch metal (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. Cerium has also been added to rapidly solidified powder metallurgy (RS-P/M) alloys (e.g., 8019, an Al-9Fe-4Ce alloy). Cerium forms thermally stable dispersoid particles in these alloys.

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 finely 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-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 pre-existing 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 0.4 to 1.5% Co are produced by RS-P/M (e.g., alloys 7090 and 7091). Cobalt forms Co_2Al_9 or $(\text{Co,Fe})_2\text{Al}_9$ particles, which are homogeneously dispersed. These dispersoids refine the grain size for improved high strength and ductility and enhance resistance to stress-corrosion cracking.

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. 10. 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. 11). As shown in Fig. 12, cold working also influences the strength of naturally aged aluminum-copper alloys, with or without magnesium additions. 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

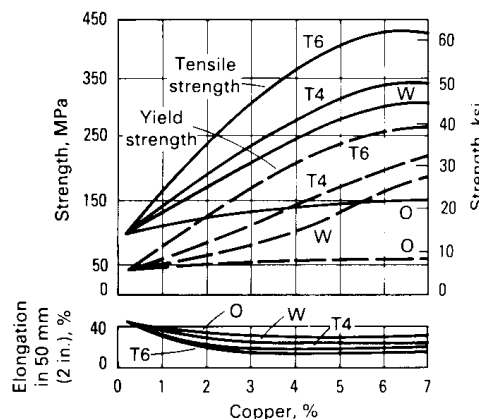
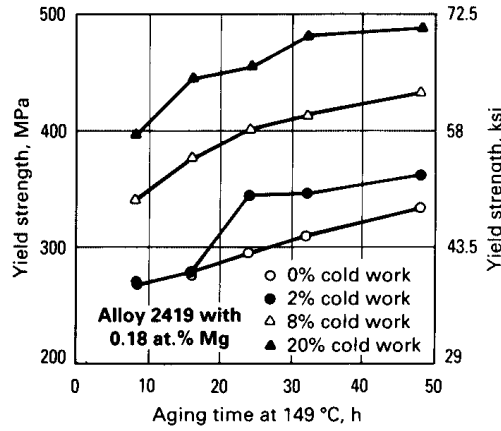
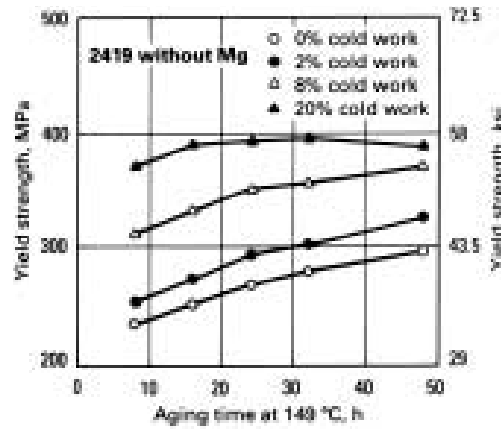


Fig. 10 Tensile properties of high-purity, wrought aluminum-copper alloys. Sheet specimen was 13 mm (0.5 in.) wide and 1.59 mm (0.0625 in.) thick. O, annealed; W, tested immediately after water quenching from a solution heat treatment; T4, as in W, but aged at room temperature; T6, as in T4, followed by precipitation treatment at elevated temperature



(a)



(b)

Fig. 11 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.

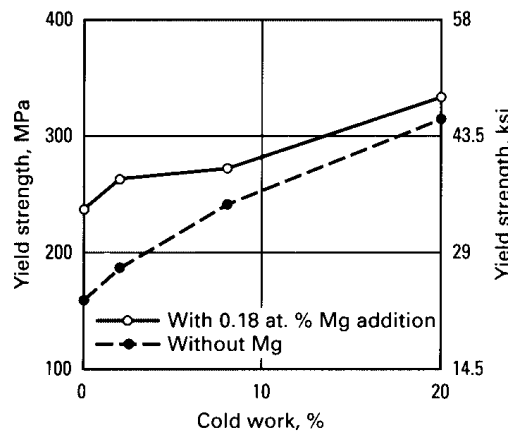


Fig. 12 The effect of cold work on yield strength of aluminum-copper alloy 2419 in naturally aged materials

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. 13. 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 particularly 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 of 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 and 2036 variations. These have acceptable formability, good spot weldability, reasonable fusion weldability, good corrosion resistance, and freedom from Lüders lines. The paint-baking cycle serves as a precipitation treatment to give final mechanical properties.

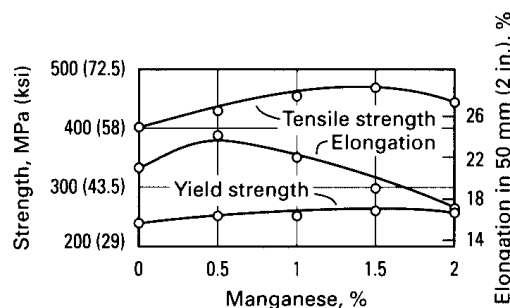


Fig. 13 Relationship between tensile properties and manganese content of Al-4%Cu-0.5%Mg alloy, heat treated at 525 °C (980 °F)

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 14 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

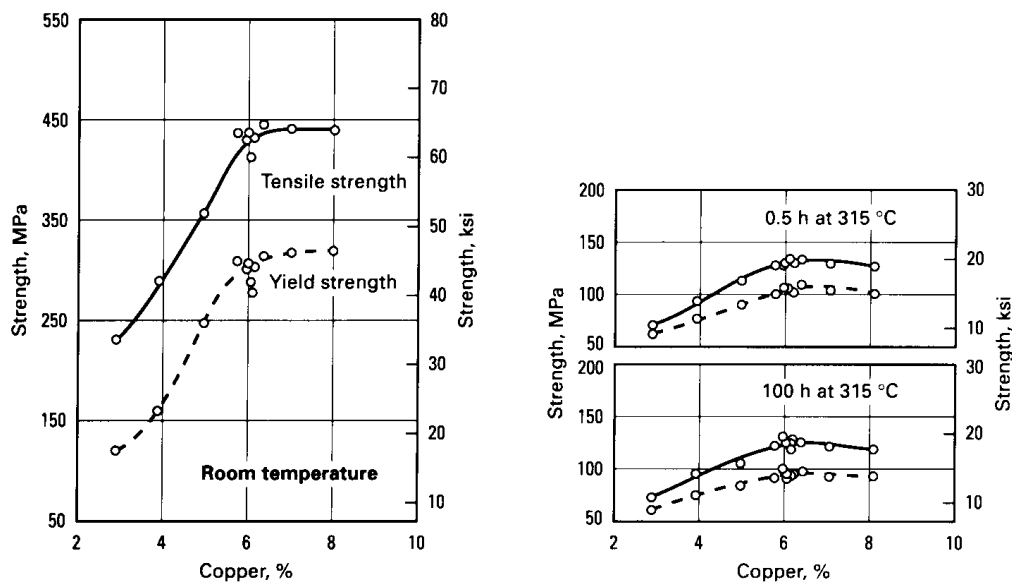


Fig. 14 Variation of tensile properties with copper content in Al-0.3%Mn-0.2%Zr-0.1%V alloy in the T6 temper

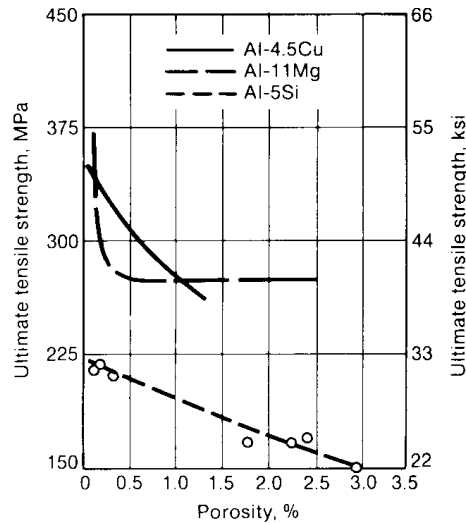


Fig. 15 Ultimate tensile strength versus hydrogen porosity for sand-cast bars of three aluminum alloys

metal increase the pickup of hydrogen in the liquid. Other elements, such as beryllium, copper, tin, and silicon, decrease hydrogen pickup.

Hydrogen porosity adversely affects mechanical properties in a manner that varies with the alloy. Figures 15 and 16 show the effect of porosity on the ultimate tensile strength of selected compositions.

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

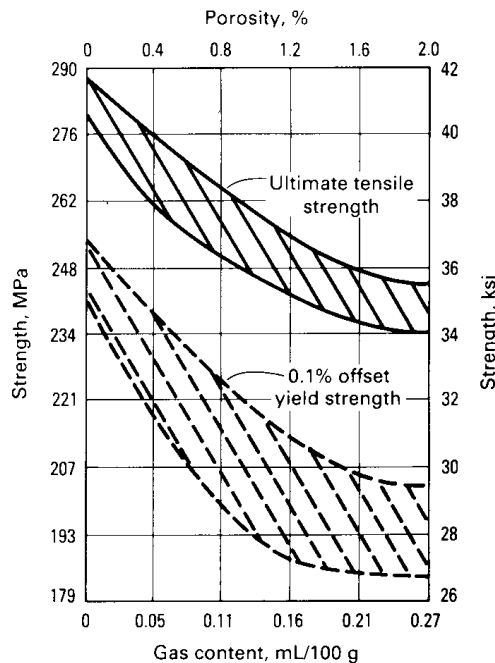


Fig. 16 Influence of gas content on the tensile and yield strengths of aluminum alloy 356

grain-boundary decohesion during stress-corrosion cracking. 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-temperature 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 (~0.05%); 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. 17) 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 lead will tend to segregate during casting and cause hot shortness in aluminum-copper-magnesium alloys. Lead compounds are toxic.

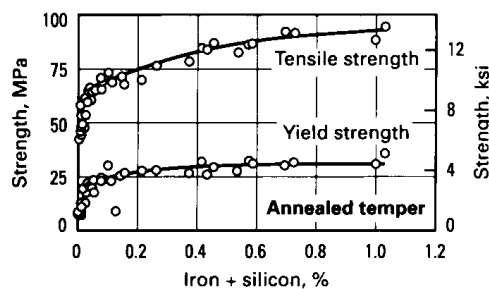


Fig. 17 Effect of iron plus silicon impurities on tensile strength and yield strength of aluminum

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 comparable to those of 7xxx alloys. 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_5Al_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 Lüders 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 magnesium 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. 9 for the O temper and in Fig. 18 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 (G-P) 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-Mg₂Si 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% Mg₂Si. 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 plus silicon and other additions such as 0.3% Cu, which increases strength in the T6 temper. Elements 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 of 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

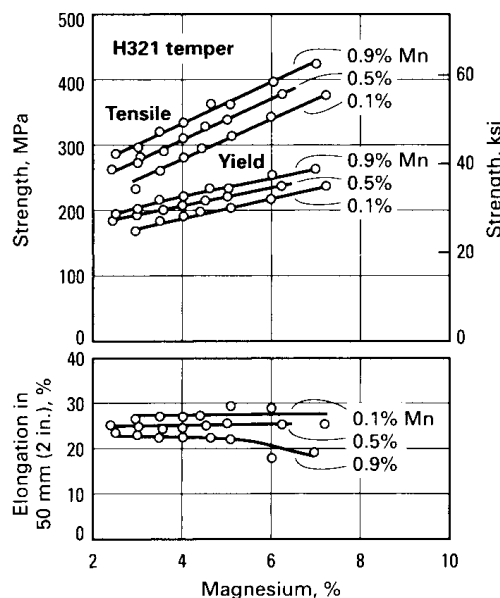


Fig. 18 Tensile properties of 13 mm (0.5 in.) aluminum-magnesium-manganese plate in H321 temper

structures. Additions of manganese, chromium, or zirconium counteract the effect of silicon by preventing recrystallization during heat treatment. Common alloys of this group are 6009, 6010, and 6351. 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. 19). 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

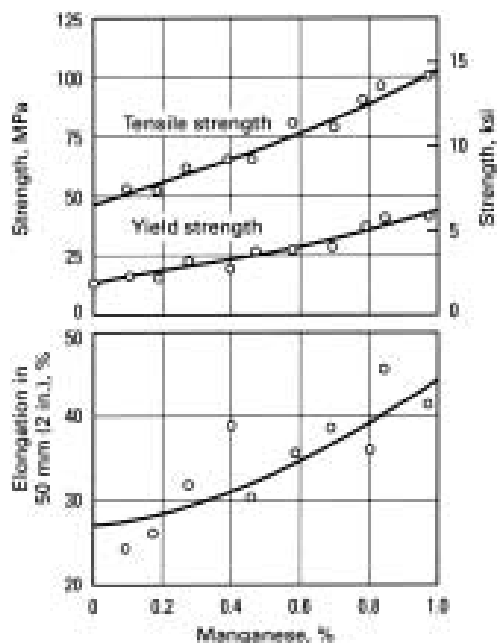


Fig. 19 Effect of manganese on tensile properties of wrought 99.95% Al, 1.6 mm (0.064 in.) thick specimens, quenched in cold water from 565 °C (1050 °F)

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 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%, respectively, to prevent the formation of primary $(\text{Fe,Mn})\text{Al}_6$ 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 ($\sim 0.01\%$ 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 compounds reacts with water vapor to give phosphine (PH_3), 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 Mg_2Si 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 alloys. Small amounts of magnesium added to any silicon-containing alloy will render it heat-treatable, but the converse is not true because 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. Hypereutectic casting alloys used for wear applications contain up to 23% Si. 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.

Sodium is a chemical modifier in hypoeutectic aluminum-silicon alloys (see the section “Alloying Elements that Modify and Refine Hypoeutectic Al-Si Alloys”).

Strontium. Traces of strontium (0.01 to 0.1 ppm) are found in commercial-grade aluminum. Strontium is also a chemical modifier in hypoeutectic aluminum-silicon alloys (see the section “Alloying Elements that Modify and Refine Hypoeutectic Al-Si Alloys”).

Sulfur. As much as 0.2 to 20 ppm sulfur is 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 antiscoring 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 conductivity 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 on 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 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. 20.

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 resistance to stress corrosion and to exfoliation attack. For example, depending on 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 below)
- 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. 21.

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

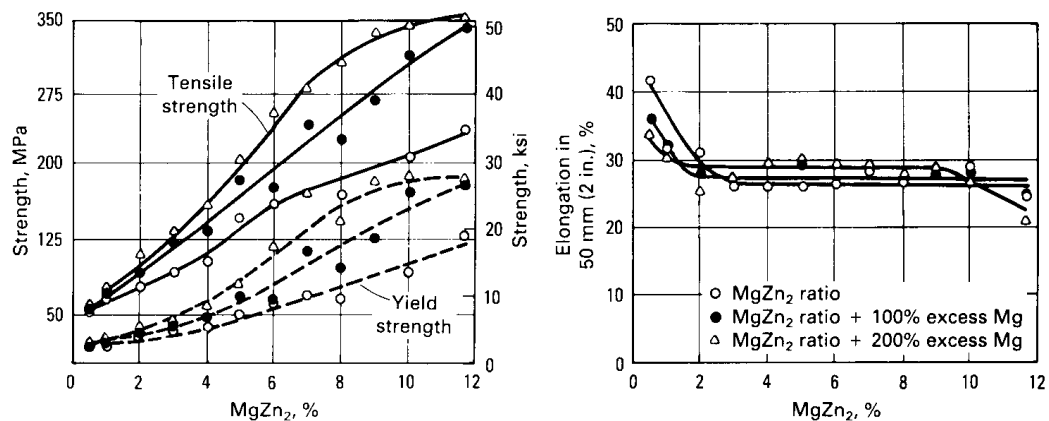


Fig. 20 Effect of $MgZn_2$ and $MgZn_2$ with excess magnesium on tensile properties of wrought 95% Al; 1.59 mm (0.0625 in.) specimens, quenched in cold water from 470 °C (875 °F)

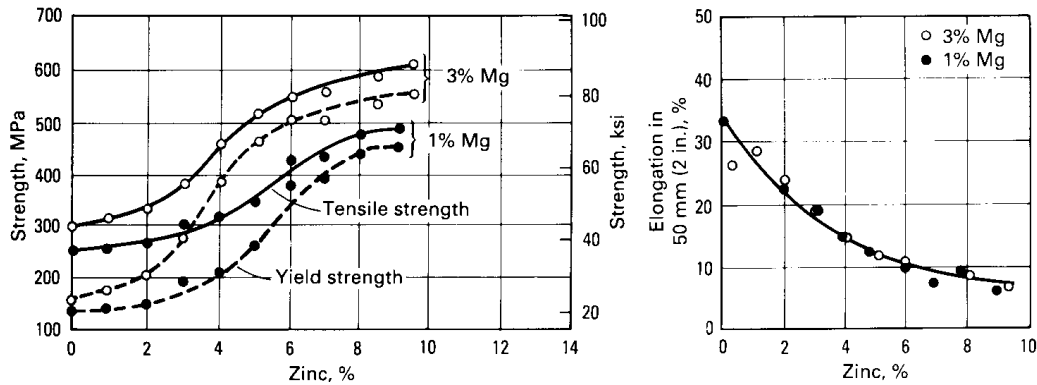


Fig. 21 Effect of zinc on aluminum alloy containing 1.5% Cu and 1 and 3% Mg; 1.6 mm (0.064 in.) thick sheet. Alloy with 1% Mg heat treated at 495°C (920 °F); that with 3% Mg heat treated at 460 °C (860 °F). All specimens quenched in cold water, aged 12 h at 135 °C (275 °F)

supersaturation and perhaps through nucleation of the CuMgAl_2 phase. Copper also increases quench sensitivity upon heat treatment. In general, copper reduces the resistance to general corrosion 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 of 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-sensitive than similar chromium additions. Higher levels of zirconium (0.3 and 0.4%) 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.

Alloying Effects on Phase Formation

All commercial aluminum alloys contain iron and silicon as well as two or more elements intentionally added to enhance properties. The phases formed and the function of the alloying elements are described below. Figure 6 summarizes the most common alloying additions in aluminum alloys.

Iron. Virtually all aluminum alloys contain some iron that is an impurity remaining after refining bauxite and smelting. The phase diagram predicts

that during solidification of an aluminum-iron alloy containing a few tenths of a percent of iron, most of the iron remains in the liquid phase until a eutectic of solid solution plus Al_3Fe intermetallic constituent particles having a monoclinic crystal structure freezes. Depending on solidification rate and on the presence of other elements such as manganese, constituent particles of the metastable orthorhombic Al_6Fe phase can form instead of the equilibrium Al_3Fe . The maximum solid solubility of iron in aluminum is 0.05%, but the solubility is much lower in most structural alloys.

Silicon. This element is also a ubiquitous impurity in commercial aluminum alloys. Two ternary phases, cubic $\alpha\text{-Al}_{12}\text{Fe}_3\text{Si}$ and monoclinic $\beta\text{-Al}_9\text{Fe}_2\text{Si}_2$, form by a eutectic reaction. At low silicon contents, almost all of the iron is present as Al_3Fe . With increasing silicon contents, first the α - then the β -Al-Fe-Si phases appear. Phases in commercial products may not be those predicted by the equilibrium phase diagrams because of the long times at high temperatures required to approach equilibrium. In large amounts, silicon improves castability and fluidity. Consequently, it is used in 4xxx brazing sheet and in 3xx.x and 4xx.x casting alloys. Silicon ranges from about 5 to 20% in casting alloys. Hypereutectic alloys (those containing >12.6% Si, the eutectic composition) are used for engine blocks because the primary silicon particles are wear resistant. Some 3xx.x casting alloys contain small additions of magnesium to render them capable of being age hardened.

Silicon is deliberately added to some alloys containing magnesium to provide precipitation hardening. The Al-Mg-Si system is the basis for the 6xxx alloys. At low magnesium contents, elemental silicon may be present as second-phase particles. As magnesium increases, both silicon particles and equilibrium hexagonal Mg_2Si constituents may be present. At higher magnesium contents, only Mg_2Si is present. Ternary alloys are strengthened by precipitation of metastable precursors to Mg_2Si . With the addition of copper, a complex quaternary $\text{Al}_4\text{CuMg}_5\text{Si}_4$ phase can form. A precursor to this quaternary phase strengthens Al-Cu-Mg-Si alloys.

Manganese. The aluminum-manganese system is the basis for the oldest aluminum alloys. Such alloys, known as 3xxx, are the most widely used wrought alloys because of their excellent formability and resistance to corrosion. Commercial aluminum-manganese alloys contain both iron and silicon. During solidification of commercial size ingots, some of the manganese forms $\text{Al}_6(\text{Mn,Fe})$ and cubic $\text{Al}_{12}(\text{Fe,Mn})\text{Si}$ by eutectic reactions. The remaining manganese remains in solution and is precipitated during the ingot preheat as $\text{Al}_{12}(\text{Mn,Fe})\text{Si}$ and $\text{Al}_6(\text{Mn,Fe})$ dispersoids. These dispersoids strengthen the material and control recrystallized grain size. In alloys containing copper, manganese precipitates as $\text{Al}_{20}\text{Cu}_2\text{Mn}_3$

dispersoid particles. Effects on strength are minor, but the dispersoids aid in grain size control after solution heat treatment.

Magnesium. The aluminum-magnesium system is the basis for the wrought 5xxx and cast 5xx.x non-heat-treatable aluminum alloys, which provide excellent combinations of strength and corrosion resistance by solid-solution strengthening and work hardening. Although in principle this phase diagram exhibits a positively sloping solvus, a necessary condition for a precipitation-hardening system, difficulty in nucleating the face-centered cubic (fcc) Al_3Mg_2 precipitates has precluded commercialization of heat-treatable aluminum-magnesium alloys, unless they contain enough silicon, copper, or zinc to form Mg_2Si , Al-Cu-Mg, or Al-Zn-Mg precipitates.

Copper. The aluminum-copper system is the basis for the wrought 2xxx and cast 2xx.x alloys, and many other heat-treatable alloys contain copper. In commercial aluminum-copper alloys, some of the copper chemically combines with aluminum and iron to form either tetragonal $\text{Al}_7\text{Cu}_2\text{Fe}$ or orthorhombic $\alpha(\text{Al,Cu,Fe})$ constituent particles during solidification. These constituents cannot be dissolved during subsequent thermal treatments, but one can transform to the other during thermal treatments of ingots or castings. During heat treatment of aluminum-copper alloys containing little magnesium, Al_2Cu precipitates as the strengthening phase.

Adding magnesium to aluminum-rich aluminum-copper alloys results in the formation of the Al_2CuMg phase by eutectic decomposition. Metastable precursors to face-centered orthorhombic Al_2CuMg precipitates are used to strengthen several structural alloys used in the aerospace industry because they confer a desirable combination of strength, fracture toughness, and resistance to the growth of fatigue cracks.

Zinc. This element confers little solid-solution strengthening or work hardening to aluminum, but Al-Zn-Mg precipitates provide the basis for the 7xxx wrought alloys and the 7xx.x cast alloys. Two phases can form by eutectic decomposition in commercial Al-Zn-Mg alloys: hexagonal MgZn_2 and body-centered cubic (bcc) $\text{Al}_2\text{Mg}_3\text{Zn}_3$. Depending on the zinc/magnesium ratio, copper-free alloys are strengthened by metastable precursors to either MgZn_2 or $\text{Al}_2\text{Mg}_3\text{Zn}_3$. In Al-Zn-Mg-Cu alloys, copper and aluminum substitute for zinc in MgZn_2 to form $\text{Mg}(\text{Zn,Cu,Al})_2$. Al_2CuMg particles can also form in these alloys by eutectic decomposition and solid-state precipitation.

Chromium. In commercial alloys, the solubility can be reduced to such an extent that Al_7Cr primary particles can form by a peritectic reaction at chromium contents lower than that indicated by the binary aluminum-chromium phase diagram. Because coarse primary particles are harmful to

ductility, fatigue, and fracture toughness, the upper limits of chromium depend on the amount and nature of the other alloying and impurity elements. In 5xxx alloys, fcc cubic $\text{Al}_{18}\text{Mg}_3\text{Cr}_2$ dispersoids precipitate during ingot preheating. In 7xxx alloys, the composition of the dispersoids is closer to $\text{Al}_{12}\text{Mg}_2\text{Cr}$. Chromium dispersoids contribute to strength in non-heat-treatable alloys and control grain size and degree of recrystallization in heat-treatable alloy products.

Zirconium. This element also forms a peritectic with aluminum. The phase diagram predicts that the equilibrium Al_3Zr phase is tetragonal, but fine dispersoids of metastable cubic Al_3Zr form during ingot preheating treatments. Most 7xxx and some 6xxx and 5xxx alloys developed since the 1960s contain small amounts of zirconium, usually less than 0.15%, to form Al_3Zr dispersoids for recrystallization control.

Lithium. This element reduces the density and increases the modulus of aluminum alloys. In binary alloys it forms metastable Al_3Li precipitates and combines with aluminum and copper in Al-Cu-Li alloys to form a large number of Al-Cu-Li phases. Because of its high cost relative to other alloying elements, lithium alloys have been found to be cost effective thus far only in space and military applications.

Grain Refiners

All aluminum alloys can be made to solidify with a fully equiaxed, fine-grain structure through the use of suitable grain-refining additions. The most widely used grain refiners are master alloys of titanium, boron, or titanium and boron, in aluminum. Aluminum-titanium refiners generally contain from 3 to 10% Ti. The same range of titanium concentrations is used in Al-Ti-B refiners, with boron contents from 0.2 to 2.5% and titanium-to-boron ratios ranging from about 5:1 to 50:1. Although grain refiners of these types can be considered conventional hardeners or master alloys, they differ from master alloys added to the melt for alloying purposes alone. To be effective, grain refiners must introduce controlled, predictable, and operative quantities of aluminides (and borides) in the correct form, size, and distribution for grain nucleation. Wrought refiner in rod form, developed for the continuous treatment of aluminum in primary operations, is available in sheared lengths for foundry use. The same grain-refining compositions are furnished in waffle form. In addition to grain-refining master alloys, salts (usually in compacted form) that react with molten aluminum to form combinations of TiAl_3 and TiB_2 are also available.

Despite the successful use of titanium as a grain refiner for foundry alloys, it has recently been found that boron alone may be a more effec-

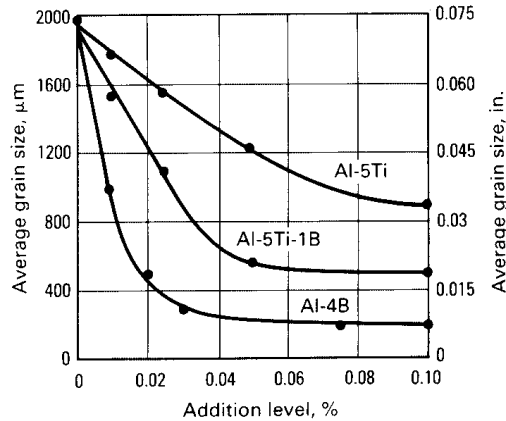


Fig. 22 Comparison of the effectiveness of various master alloy grain refiners in aluminum alloy 356

tive refiner than titanium in aluminum-silicon alloys. Figure 22 compares the grain sizes achieved with additions of boron, titanium, and a titanium-boron mixture on alloy 356.

Figure 23 demonstrates the effectiveness of Al-2.5Ti-2.5B master alloys to 356 and 319 foundry alloys compared to the Al-5Ti-1B alloys previously used. Clearly, the use of higher levels of boron and lower levels of titanium than those previously used can have substantial

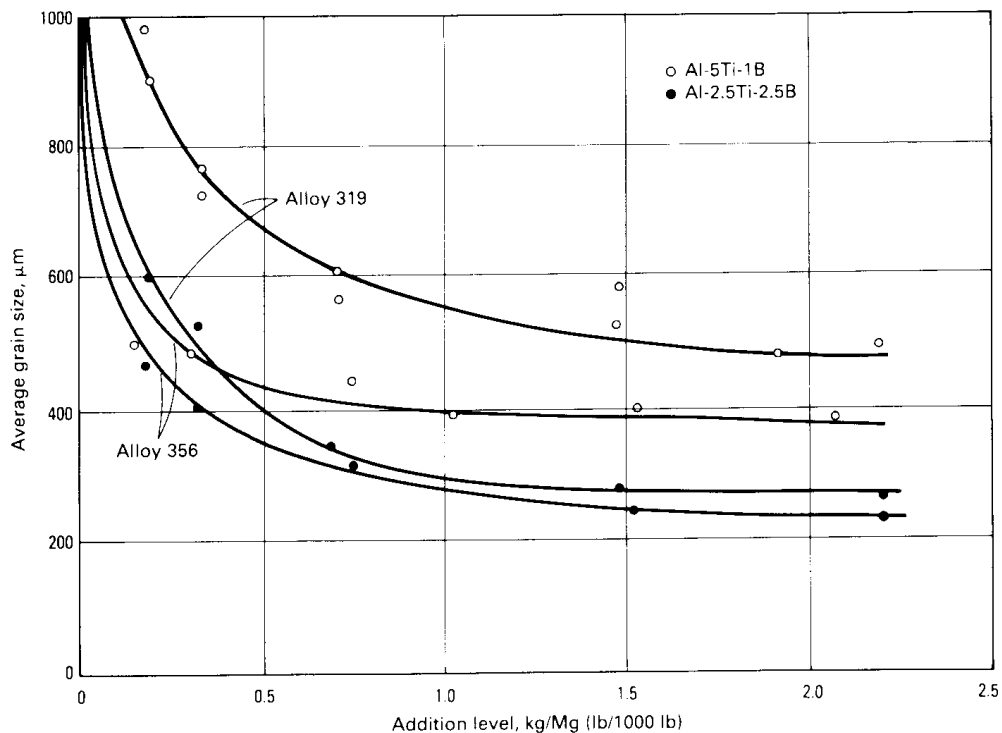


Fig. 23 Effectiveness of titanium-boron grain refiners in aluminum alloys 356 and 319

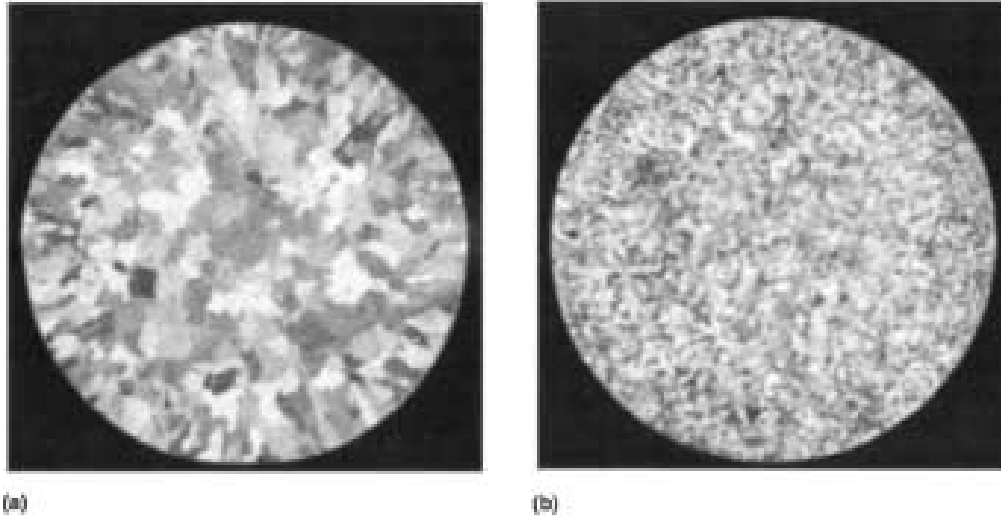


Fig. 24 As-cast Al-7Si ingots showing the effects of grain refinement. (a) No grain refiner. (b) Grain-refined. Both etched using Poulton's etch; both 2x

benefits for foundry alloys. Figure 24 illustrates the comparison of an adequately grain-refined Al-7Si alloy before and after grain-refining addition.

Alloying Elements that Modify and Refine Hypoeutectic Al-Si Alloys

Hypoeutectic aluminum-silicon alloys can be improved by inducing structural modification of the normally occurring eutectic. In general, the greatest benefits are achieved in alloys containing from 5% Si to the eutectic concentration; this range includes most common gravity cast compositions.

Chemical Modifiers. The addition of certain elements, such as calcium, sodium, strontium, and antimony, to hypoeutectic aluminum-silicon alloys results in a finer lamellar or fibrous eutectic network. It is also understood that increased solidification rates are useful in providing similar structures. There is, however, no agreement on the mechanisms involved. The most popular explanations suggest that modifying additions suppress the growth of silicon crystals within the eutectic, providing a finer distribution of lamellae relative to the growth of the eutectic. Various degrees of eutectic modification are shown in Fig. 25.

The results of modification by strontium, sodium, and calcium are similar. Sodium has been shown to be the superior modifier, followed by strontium and calcium, respectively. Each of these elements is mutually compatible so that combinations of modification additions can be made without adverse effects. Eutectic modification is, however, transient when artificially promot-

ed by additions of these elements. Figure 26 illustrates the relative effectiveness of various modifiers as a function of time at temperature.

Antimony has been advocated as a permanent means of achieving structural modification. In this case, the modified structure differs; a more acicular refined eutectic is obtained compared to the uniform lace-like dispersed structures of sodium-, calcium-, or strontium-modified metal. As a result, the improvements in castability and mechanical properties offered by this group of elements are not completely achieved. Structural

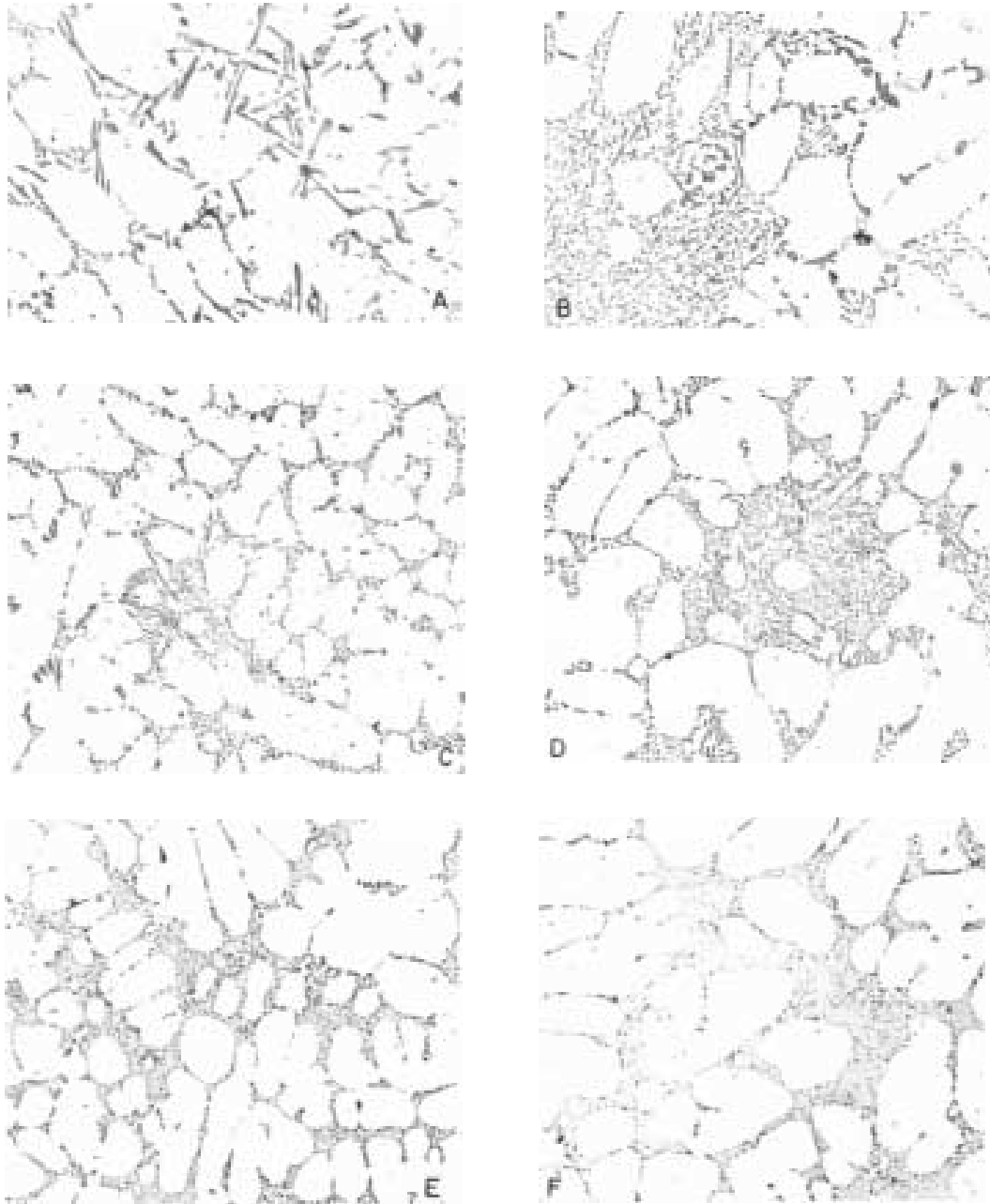


Fig. 25 Varying degrees of aluminum-silicon eutectic modification ranging from unmodified (A) to well modified (F). See Fig. 26 for the effectiveness of various modifiers

refinement is obtained that is time-independent when two conditions are satisfied. First, the metal to be treated must be essentially phosphorus-free, and second, the velocity of the solidification front must exceed a minimum value approximately equal to that obtained in conventional permanent mold casting.

Antimony is not compatible with other modifying elements. In cases in which antimony and other modifiers are present, coarse antimony-containing intermetallics are formed that preclude the attainment of an effectively modified structure and adversely affect casting results.

Modifier additions are usually accompanied by an increase in hydrogen content (Fig. 27). In the case of sodium and calcium, the reactions involved in element solution are invariably turbulent or are accompanied by compound reactions that increase dissolved hydrogen levels. In the case of strontium, master alloys may be highly contaminated with hydrogen, and there are numerous indications that hydrogen solubility is increased after alloying.

For sodium, calcium, and strontium modifiers, the removal of hydrogen by reactive gases also results in the removal of the modifying element. Recommended practices are to obtain modification through additions of modifying elements added to well-processed melts, followed by inert gas

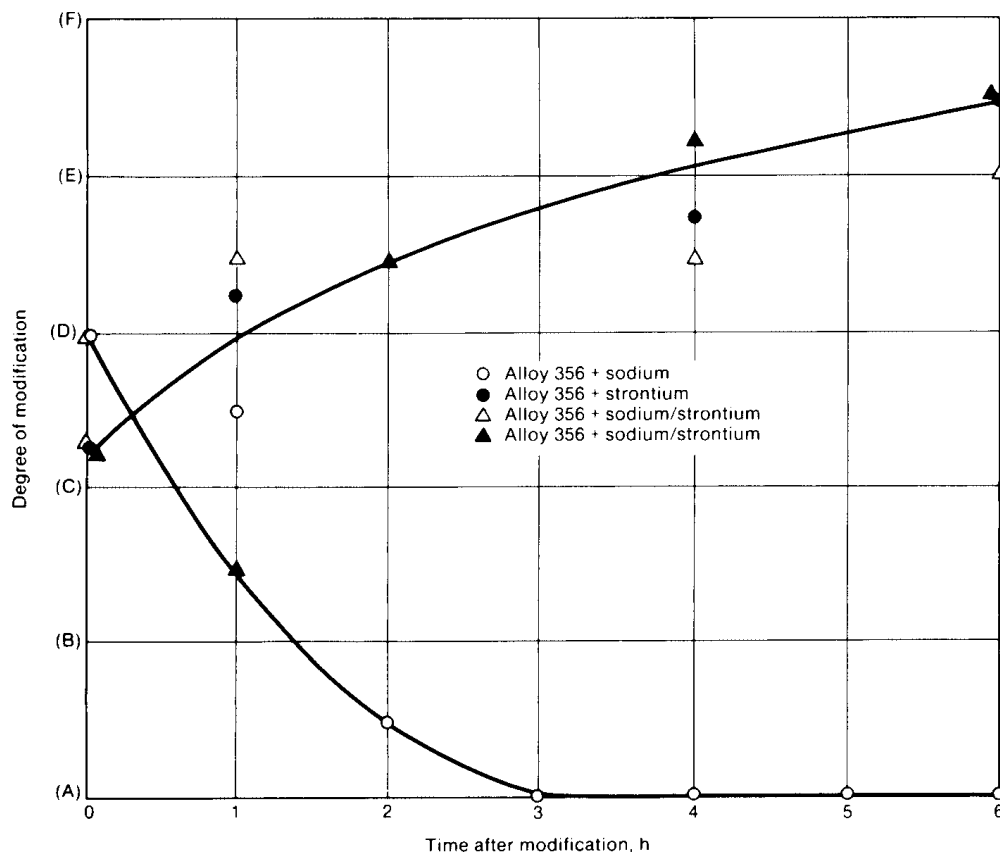


Fig. 26 Effectiveness of sodium and strontium modifiers as a function of time. See Fig. 25 for degrees of modification

fluxing to acceptable hydrogen levels. No such disadvantages accompany antimony use.

Calcium and sodium can be added to molten aluminum in metallic or salt form. Vacuum-prepackaged sodium metal is commonly used. Strontium is currently available in many forms, including aluminum-strontium master alloys ranging from approximately 10 to 90% Sr and Al-Si-Sr master alloys of varying strontium contents.

Very low sodium concentrations ($\sim 0.001\%$) are required for effective modification. More typically, additions are made to obtain a sodium content in the melt of 0.005 to 0.015%. Remodification is performed as required to maintain the desired modification level.

A much wider range of strontium concentrations is in use. In general, addition rates far exceed those required for effective sodium modification. A range of 0.015 to 0.050% Sr is standard industry practice. Normally, good modification is achievable in the range of 0.008 to 0.015% Sr. Remodification through strontium additions may be required, although retreatment is less frequent than for sodium.

To be effective in modification, antimony must be alloyed to approximately 0.06%. In practice, antimony is employed in the much higher range of 0.10 to 0.50%.

It is possible to achieve a state of overmodification, in which eutectic coarsening occurs, when sodium and/or strontium are used in excessive amounts. The corollary effects of reduced fluidity and susceptibility to hydrogen-related problems are usually encountered well before overmodification may be experienced.

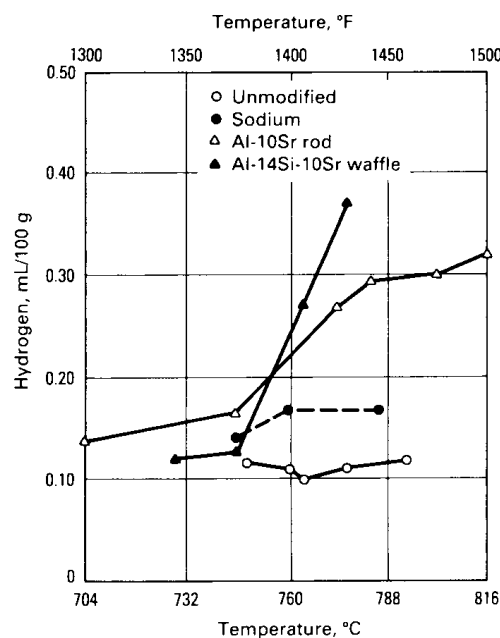


Fig. 27 Hydrogen content as a function of holding temperature for aluminum alloy 356 melts with various modifiers.

The Importance of Phosphorus. It has been well established that phosphorus interferes with the modification mechanism. Phosphorus reacts with sodium and probably with strontium and calcium to form phosphides that nullify the intended modification additions. It is therefore desirable to use low-phosphorus metal when modification is a process objective and to make larger modifier additions to compensate for phosphorus-related losses.

Primary producers may control phosphorus contents in smelting and processing to provide less than 5 ppm of phosphorus in alloyed ingot. At these levels, normal additions of modification agents are effective in achieving modified structures. However, phosphorus contamination may occur in the foundry through contamination by phosphate-bonded refractories and mortars and by phosphorus contained in other melt additions, such as master alloys and alloying elements including silicon.

Effects of Modification. Typically, modified structures display somewhat higher tensile properties and appreciably improved ductility when compared to similar but unmodified structures. Figure 28 illustrates the

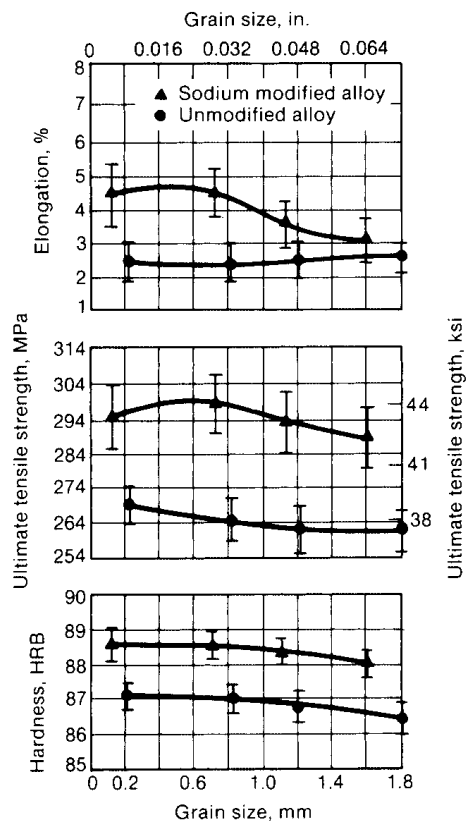


Fig. 28 Mechanical properties of as-cast A356 alloy tensile specimens as a function of modification and grain size

desirable effects on mechanical properties that can be achieved by modification. Improved performance in casting is characterized by improved flow and feeding as well as by superior resistance to elevated-temperature cracking.

Use of Phosphorus to Refine Hypereutectic Al-Si Alloys

The elimination of large, coarse primary silicon crystals that are harmful in the casting and machining of hypereutectic silicon alloy compositions is a function of primary silicon refinement. Phosphorus added to molten alloys containing more than the eutectic concentration of silicon, made in the form of metallic phosphorus or phosphorus-containing compounds such as phosphor-copper and phosphorus pentachloride, has a marked effect on the distribution and form of the primary silicon phase. Investigations have shown that retained trace concentrations as low as 0.0015 through 0.03% P are effective in achieving the refined structure. Disagreements on recommended phosphorus ranges and addition rates have been caused by the extreme difficulty of accurately sampling and analyzing for phosphorus. More recent developments employing vacuum stage spectrographic or quantometric analysis now provide rapid and accurate phosphorus measurements.

Following melt treatment by phosphorus-containing compounds, refinement can be expected to be less transient than the effects of conventional modifiers on hypoeutectic modification. Furthermore, the solidification of phosphorus-treated melts, cooling to room temperature, reheating, remelting, and resampling in repetitive tests have shown that refinement is not lost; however, primary silicon particle size increases gradually, responding to a loss in phosphorus concentration. Common degassing methods accelerate phosphorus loss, especially when chlorine or Freon is used. In fact, brief inert gas fluxing is frequently employed to reactivate aluminum phosphide nuclei, presumably by resuspension.

Practices that are recommended for melt refinement are:

- Melting and holding temperatures should be held to a minimum.
- The alloy should be thoroughly chlorine- or Freon-fluxed before refining to remove phosphorus-scavenging impurities such as calcium and sodium.
- Brief fluxing after the addition of phosphorus is recommended to remove the hydrogen introduced during the addition and to distribute the aluminum phosphide nuclei uniformly in the melt.

Figure 29 illustrates the microstructural differences between refined and unrefined structures.

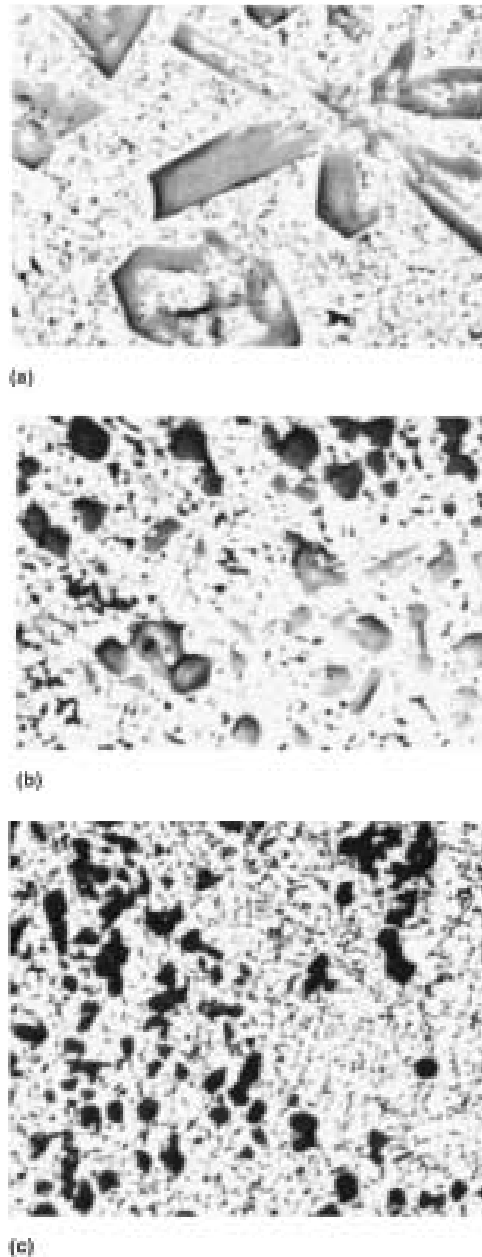


Fig. 29 Effect of phosphorus refinement on the microstructure of Al-22Si-1Ni-1Cu alloy. (a) Unrefined. (b) Phosphorus-refined. (c) Refined and fluxed. All 100x

Effects of Alloying on Corrosion Behavior

Aluminum, as indicated by its position in the electromotive force series, is a thermodynamically reactive metal; among structural metals, only beryllium and magnesium are more reactive. Aluminum owes its excellent corrosion resistance and its usage as one of the primary metals of commerce to the barrier oxide film that is bonded strongly to its surface. The

normal surface film formed in air at ambient temperature is only about 5 nm (50 Å) thick. If damaged, this thin film re-forms immediately in most environments and continues to protect the aluminum from corrosion. When the film is removed or damaged under conditions such that self repair cannot occur, corrosion takes place.

The corrosion resistance of an aluminum alloy depends on both metallurgical and environmental variables. Metallurgical variables that affect corrosion are composition (as described below), heat treatment (proper temper selection), and mechanical working. These determine the microstructure, which decides whether localized corrosion occurs and the method of attack.

Both chemical and physical environmental variables affect corrosion. The chemical influence of the environment depends on its composition and the presence of impurities such as heavy metal ions. Physical variables are temperature, degree of movement and agitation, and pressure. Another physical variable that can cause corrosion of aluminum is the presence of stray electrical currents (alternating or direct).

Because many variables influence corrosion, the suitability of aluminum cannot be considered solely on the basis of a specific product or environment. A detailed knowledge of traces of impurities, conditions of operation, design of a piece of equipment, and alloy microstructure is essential. Experience gained from previously successful service applications is most valuable.

1xxx Wrought Alloys. Pure aluminum (99.00% or purer) is more corrosion resistant than any of the aluminum alloys. Rapid dissolution will occur in highly acidic or alkaline solutions, but in the oxide stable range of pH 4 to 9, aluminum is subject only to water staining of the surface and to localized pitting corrosion. Pure aluminum does not incur any of the more drastic forms of localized corrosion such as intergranular corrosion, exfoliation, or SCC.

Wrought aluminums of the 1xxx series conform to composition specifications that set maximum individual, combined, and total contents for several elements present as natural impurities in the smelter-grade or refined aluminum used to produce these products. Aluminums 1100 and 1135 differ somewhat from the others in this series in having minimum and maximum specified copper contents. Corrosion resistance of all 1xxx compositions is very high, but under many conditions, it decreases slightly with increasing alloy content. Iron, silicon, and copper are the elements present in the largest percentages. The copper and part of the silicon are in solid solution. The second-phase particles present contain either iron or iron and silicon— Al_6Fe , Al_3Fe , and $\text{Al}_{12}\text{Fe}_3\text{Si}_2$ —all of which are cathodic to the aluminum matrix. When these particles are present at the surface, the oxide film over them is thin or nonexistent. The local cells produced by these impurities promote pitting attack of the surface in a conductive

liquid. The number and/or size of such corrosion sites is proportional to the area fraction of the second-phase particles.

Not all impurity elements are detrimental to corrosion resistance of 1xxx series aluminum alloys, and detrimental elements can reduce the resistance of some types of alloys but have no ill effects in others. Therefore, specification limitations established for impurity elements are often based on maintaining consistent and predictable levels of corrosion resistance in various applications rather than on their effects in any specific application.

2xxx wrought alloys and 2xx.x casting alloys, in which copper is the major alloying element, are less resistant to corrosion than alloys of other series, which contain much lower amounts of copper. Alloys of this type were the first heat treatable high-strength aluminum-base materials, dating back to Duralumin developed in Germany in 1919 and subsequently produced in the United States as alloy 2017 (see Fig. 1). Much of the thin sheet made of these alloys is produced as an alclad composite, but thicker sheet and other products in many applications require no protective cladding.

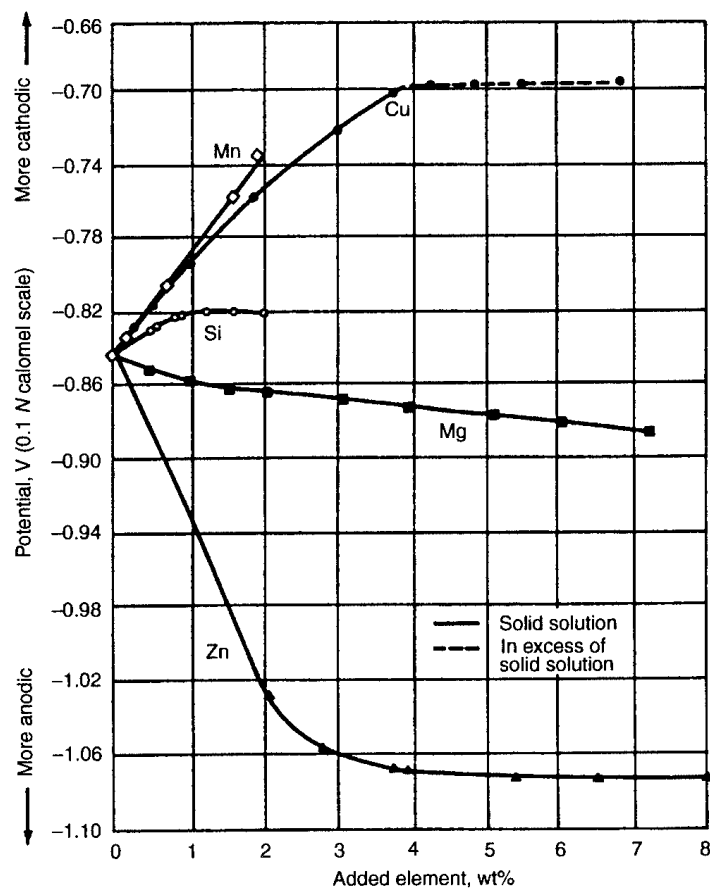


Fig. 30 Effects of principal alloying elements on electrolytic solution potential of aluminum. Potentials are for high-purity binary alloys solution heat treated and quenched. Measured in a solution of 53 g/L NaCl plus 3 g/L H_2O_2 maintained at 25 °C (77 °F)

Electrochemical effects on corrosion can be stronger in these alloys than in alloys of many other types because of two factors: greater change in electrode potential with variations in amount of copper in solid solution (Fig. 30) and, under some conditions, the presence of nonuniformities in solid-solution concentration. However, general resistance to corrosion decreasing with increasing copper content is not primarily attributable to these solid-solution or second-phase solution-potential relationships. The decrease in general corrosion resistance is attributable to galvanic cells created by formation of minute copper particles or films deposited on the alloy surface as a result of corrosion. As corrosion progresses, copper ions, which initially go into solution, replate onto the alloy to form metallic copper cathodes. Reduction of copper ions and increased efficiency of O_2 and H^+ reduction reactions in the presence of copper increase the corrosion rate.

These alloys are invariably solution heat treated and are used in either the naturally aged or the precipitation heat treated temper. Development of these tempers using good heat treating practice can minimize electrochemical effects on corrosion resistance. The rate of quenching and the temperature and time of artificial aging both can affect the corrosion resistance of the final product. Principal strengthening phases of artificially aged 2xxx alloys are $CuAl_2$ for alloys with <1% Mg (e.g., 2014 and 2219), $CuMgAl_2$ for a magnesium content above 1% (e.g., 2024 and 2034), $CuLiAl_2$ when lithium is present (e.g., 2090 as described below), and Mg_2Si for low-copper-content alloys (e.g., 2008 and 2117).

Wrought Aluminum-Lithium Alloys. Lithium additions decrease the density and increase the elastic modulus of aluminum alloys, making aluminum-lithium alloys good candidates for replacing the existing high-strength alloys, primarily in aerospace applications. Both 2xxx and 8xxx series alloys based on the Al-Cu-Mg-Li system have been developed.

One of the earliest aluminum alloys containing lithium was 2020. This alloy in the T6 temper was commercially introduced in 1957 as a structural alloy with good strength properties up to 175 °C (350 °F). It has a modulus 8% higher and a density 3% lower than alloy 7075-T6. Alloy 2020 was rarely used in aircraft because of its relatively low fracture toughness. It was used in the thrust structure of the Saturn S-II, the second stage of the Saturn V launch vehicle.

Two more recently registered lithium-bearing alloys are 2090 and 8090. Alloy 2090, in T8-type tempers, has a higher resistance to exfoliation than 7075-T6 has, and the resistance to SCC is comparable (Ref 23). The corrosion resistance of alloy 8090, which was developed to meet a combination of mechanical property goals, is a strong function of the degree of artificial aging and the microstructure. Alloy 8090 generally displays good exfoliation resistance in atmospheric exposure.

Although lithium is highly reactive, addition of up to 3% Li to aluminum shifts the pitting potential of the solid solution only slightly in the anodic direction in 3.5% NaCl solution. In an extensive corrosion investigation of several binary and ternary aluminum-lithium alloys, modifications to the microstructure that promote formation of the δ phase (AlLi) were found to reduce the corrosion resistance of the alloy in 3.5% NaCl solution. It was concluded that an understanding of the nucleation and growth of the δ phase is central to an understanding of the corrosion behavior of these alloys.

3xxx Wrought Alloys. Wrought alloys of the 3xxx series (aluminum-manganese and aluminum-manganese-magnesium) have very high resistance to corrosion. The manganese is present in the aluminum solid solution, in submicroscopic particles of precipitate, and in larger particles of $\text{Al}_6(\text{Mn,Fe})$ or $\text{Al}_{12}(\text{Mn,Fe})_3\text{Si}$ phases, both of which have solution potentials almost the same as that of the solid-solution matrix. Hence, these constituents are not significant sites for corrosion initiation. Like pure aluminum, 3xxx alloys do not incur any of the more drastic forms of localized corrosion, and pitting corrosion is the principal type of corrosion encountered. Such alloys are widely used for cooking and food-processing equipment, chemical equipment, and various architectural products requiring high resistance to corrosion.

4xxx Wrought Alloys and 3xx.x and 4xx.x Casting Alloys. Elemental silicon is present as second-phase constituent particles in wrought alloys of the 4xxx series, in brazing and welding alloys, and in casting alloys of the 3xx.x and 4xx.x series. Silicon is cathodic to the aluminum solid-solution matrix by several hundred millivolts and accounts for a considerable volume fraction of most of the silicon-containing alloys. However, the effects of silicon on the corrosion resistance of these alloys are minimal because of low corrosion current density resulting from the fact that the silicon particles are highly polarized.

Corrosion resistance of 3xx.x casting alloys is strongly affected by copper content, which can be as high as 5% in some compositions, and by impurity levels. Modifications of certain basic alloys have more restrictive limits on impurities, which benefit corrosion resistance and mechanical properties.

5xxx Wrought Alloys and 5xx.x Casting Alloys. Wrought alloys of the 5xxx series (Al-Mg-Mn, Al-Mg-Cr, and Al-Mg-Mn-Cr) and casting alloys of the 5xx.x series have high resistance to corrosion. This accounts in part for their use in a wide variety of building products and chemical-processing and food-handling equipment, as well as applications involving exposure to seawater.

Alloys in which the magnesium is present in amounts that remain in solid solution or is partially precipitated as Al_8Mg_5 particles dispersed uniformly throughout the matrix are generally as resistant to corrosion as

commercially pure aluminum. These alloys also are more resistant to salt water and some alkaline solutions, such as those of sodium carbonate and amines. The wrought alloys containing about 3% or more magnesium under conditions that lead to an almost continuous intergranular Al_8Mg_5 precipitate, with very little precipitate within grains, can be susceptible to exfoliation or SCC. Tempers have been developed for these higher-magnesium wrought alloys to produce microstructures having extensive Al_8Mg_5 precipitate within the grains, thus eliminating such susceptibility.

In the 5xxx alloys that contain chromium, this element is present as a submicroscopic precipitate, $\text{Al}_{12}\text{Mg}_2\text{Cr}$. Manganese in these alloys is in the form of $\text{Al}_6(\text{Mn},\text{Fe})$ as both submicroscopic and larger particles. Such precipitates and particles do not adversely affect corrosion resistance of these alloys.

6xxx Wrought Alloys. Moderately high strength and very good resistance to corrosion make the heat-treatable wrought alloys of the 6xxx series (Al-Mg-Si) highly suitable in various structural, building, marine, machinery, and process-equipment applications. The Mg_2Si phase, which is the basis for precipitation hardening, is unique in that it is an ionic compound and is not only anodic to aluminum but also reactive in acidic solutions. However, either in solid solution or as submicroscopic precipitate, Mg_2Si has a negligible effect on electrode potential. Because these alloys are normally used in the heat treated condition, no detrimental effects result from the major alloying elements or from the supplementary chromium, manganese, or zirconium, which are added to control grain structure. Copper additions, which augment strength in many of these alloys, are limited to small amounts to minimize effects on corrosion resistance. At copper levels higher than 0.5% some intergranular corrosion can occur in some tempers (e.g., T4 and T6). However, this intergranular corrosion does not result in susceptibility to exfoliation or SCC.

When the magnesium and silicon contents in a 6xxx alloy are balanced (in proportion to form only Mg_2Si), corrosion by intergranular penetration is slight in most commercial environments. If the alloy contains silicon beyond that needed to form Mg_2Si or contains a high level of cathodic impurities, susceptibility to intergranular corrosion increases.

7xxx wrought alloys and 7xx.x casting alloys contain major additions of zinc, along with magnesium or magnesium plus copper in combinations that develop various levels of strength. Those containing copper have the highest strengths and have been used as construction materials, primarily in aircraft applications, for more than 50 years. The copper-free alloys of the series have many desirable characteristics: moderate-to-high strength; excellent toughness; and good workability, formability, and weldability. Use of these copper-free alloys has increased in recent years and now includes automotive applications (such as bumpers), structural

members and armor plate for military vehicles, and components of other transportation equipment.

The 7xxx wrought and 7xx.x casting alloys, because of their zinc contents, are anodic to 1xxx wrought aluminums and to other aluminum alloys. They are among the aluminum alloys most susceptible to SCC. However, SCC can be avoided by proper alloy and temper selection and by observing appropriate design, assembly, and application precautions.

Resistance to general corrosion of the copper-free wrought 7xxx alloys is good, approaching that of the wrought 3xxx, 5xxx, and 6xxx alloys. The copper-containing alloys of the 7xx.x series, such as 7049, 7050, 7075, and 7178, have lower resistance to general corrosion than those of the same series that do not contain copper. All 7xxx alloys are more resistant to general corrosion than 2xxx alloys but less resistant than wrought alloys of other groups.

Although the copper in both wrought and cast alloys of the Al-Zn-Mg-Cu type reduces resistance to general corrosion, it is beneficial from the standpoint of resistance to SCC. Copper allows these alloys to be precipitated at higher temperatures without excessive loss in strength and thus makes possible the development of T73 tempers, which couple high strength with excellent resistance to SCC.

Effects of Additional Alloying Elements. In addition to the major elements that define the alloy systems discussed, commercial aluminum alloys can contain other elements that provide special characteristics. Lead and bismuth are added to alloys 2011 and 6262 to improve chip breakage and other machining characteristics. Nickel is added to wrought alloys 2018, 2218, and 2618, which were developed for elevated-temperature service, and to certain 3xx.x cast alloys used for pistons, cylinder blocks, and other engine parts subjected to high temperatures. Cast aluminum bearing alloys of the 850.0 group contain tin. In all cases, these alloying additions introduce constituent phases that are cathodic to the matrix and decrease resistance to corrosion in aqueous saline media. However, these alloys are often used in environments in which they are not subject to corrosion.

Effects of Alloying on Wear Behavior

Aluminum alloys for wear resistance applications are based on the aluminum-silicon alloy system. This binary system is a simple eutectic alloy system with the eutectic composition at 12.5% Si (Fig. 5). Standard alloys, of course, contain a number of alloying ingredients. Selected commercial alloy compositions are shown in Table 9.

At room temperature, the hypoeutectic alloys consist of the soft, ductile primary aluminum phase and the very hard, brittle silicon phase associated

Table 9 Nominal compositions of selected commercial aluminum-silicon alloys recommended for wear applications

Alloy	Composition, wt%					
	Si	Fe	Cu	Mg	Mn	Other
Hypereutectic alloys						
390.0	16–18	1.3	4–5	0.45–0.65	0.1	...
A390.0	16–18	0.5	4–5	0.45–0.65	0.1	...
B390.0	16–18	1.3	4–5	0.45–0.65	0.5	1.5 Zn
392.0	18–20	1.5	0.4–0.8	0.8–1.2	0.2–0.6	0.5 Ni, 0.5 Zn, 0.3 Sn
393.0	21–23	1.3	0.7–1.1	0.7–1.3	0.1	2–2.5 Ni
Eutectic alloys						
384.0	10.5–12	1.3	3–4.5	0.1	0.5	0.5 Ni, 3 Zn, 0.35 Sn
336.0	11–13	1.2	0.5–1.5	0.7–1.3	0.35	2–3 Ni, 0.35 Zn
339.0	11–13	1.2	1.5–3	0.5–1.5	0.5	0.5–1.5 Ni, 1 Zn
413.0	11–13	2	1	0.1	0.35	0.5 Ni, 0.5 Zn
4032	11–13.5	1	0.5–1.3	0.8–1.3	...	0.5–1.3 Ni
Hypoeutectic alloys						
319.0	5.5–6.5	1	3–4	0.1	0.5	0.35 Ni, 1 Zn
356.0	6.5–7.5	0.6	0.25	0.2–0.45	0.35	0.35 Zn
364.0	7.5–9.5	1.5	0.2	0.2–0.4	0.1	0.25–0.5 Cr, 0.15 Ni, 0.15 Sn
380.0	7.5–9.5	2	3–4	0.1	0.5	0.5 Ni, 3 Zn, 0.35 Sn
333.0	8–10	1	3–4	0.05–0.5	0.5	0.5 Ni, 1 Zn
332.0	8.5–10.5	1.2	2–4	0.5–1.5	0.5	0.5 Ni, 1 Zn
360.0	9–10	2	0.6	0.4–0.6	0.35	0.5 Ni, 0.5 Zn
383.0	9.5–11.5	1.3	2–3	0.1	0.5	0.3 Ni, 3 Zn, 0.15 Sn

Source: Ref 8, 9

with eutectic reaction. It is this silicon phase that contributes to the very good wear resistance of these alloys. The silicon phase is diamond cubic with a density of $\sim 2.6 \text{ g/cm}^3$ (0.094 lb/in.^3) and a Vickers hardness of approximately 10 GPa ($1.5 \times 10^6 \text{ psi}$). Silicon is essentially insoluble in aluminum. Figure 31 illustrates the typical microstructure of a common hypoeutectic alloy, A357.0 (Al-7Si-0.5Mg). Hypereutectic alloys, the most commonly used wear-resistant alloys, contain coarse, angular, primary silicon particles as well as eutectic silicon. These primary silicon particles impart excellent wear resistance to the alloys. A typical microstructure of hypereutectic alloy A390 (Al-17Si-4.5Cu-0.6Mg) is shown in Fig. 32.

Commercial aluminum-silicon alloys generally contain other alloying elements to further enhance or modify the wear resistance or impart additional properties to these alloys.

Iron. The most common alloying element is iron, which can be tolerated up to levels of 1.5 to 2.0% Fe. The presence of iron modifies the silicon phase by introducing several Al-Fe-Si phases. The most common of these are the α and β phases. The α phase has a cubic crystal structure and appears in the microstructure as a “Chinese script” eutectic. The less common β phases generally appear as needles and/or platelets in the structure. Other iron-bearing phases such as Al_6Fe and FeAl_3 can also be found in these alloys. Aluminum-silicon alloys intended for die castings typically

have higher minimum iron levels to reduce sticking between the mold and the casting.

Magnesium is added to provide strengthening through precipitation of Mg_2Si in the matrix. In an Al-Fe-Si-Mg alloy, the Al-Fe-Si phases will not be affected by the addition of magnesium. However, magnesium can combine with insoluble aluminum-iron phases, resulting in a loss of strengthening potential.

Copper. The most common aluminum wear-resistant alloys also contain copper. Copper additions impart additional strengthening of the matrix through the aging or precipitation-hardening process ($AlCu_2$ phase) or through modification of the hard, brittle Al-Fe-Si phases by substitution in these intermetallic phases. As the strength of these alloys increases through magnesium and copper additions, some sacrifice in ductility and corrosion resistance occurs.

Manganese. Many of the important aluminum-silicon alloys also contain low (<1 wt%), but significant, amounts of manganese. The presence of manganese can reduce the solubility of iron and silicon in aluminum and alter the composition and morphology of the Al-Fe-Si primary constituent phases. For example, manganese additions can favor the formation of constituents such as $Al_{12}(Fe,Mn)_3Si$ rather than the $Al_9Fe_2Si_2$ -type constituents. The manganese-bearing constituents are typically less needle-

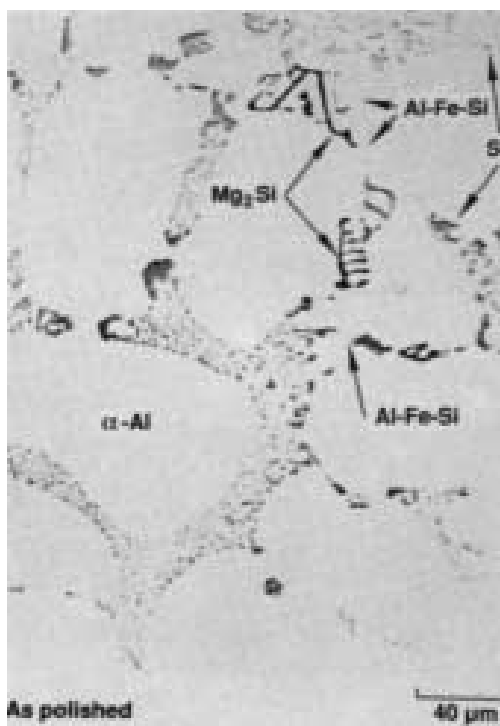


Fig. 31 Typical microstructure of type A357.0 hypoeutectic alloy

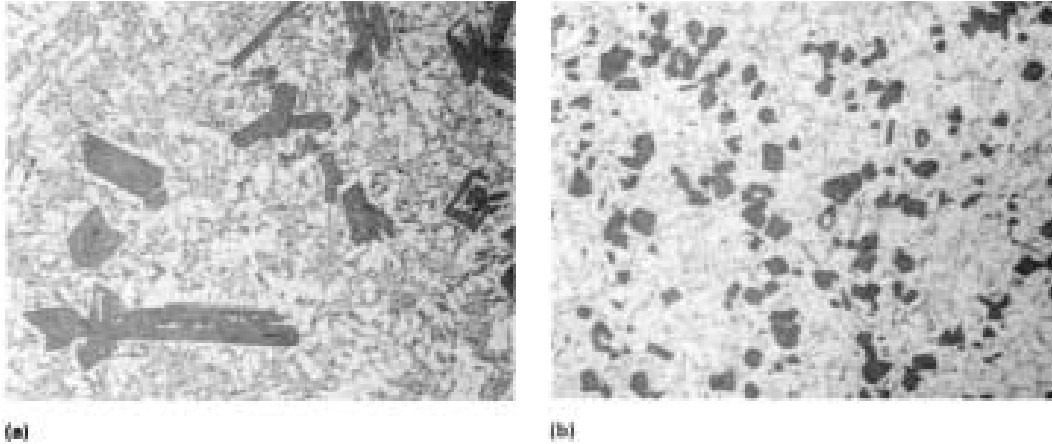


Fig. 32 Microstructure of type A390.0 hypereutectic alloy. (a) Unrefined (Graff-Sargent etch). Dark regions contain coarse primary silicon particles in addition to eutectic silica. (b) Refined (as polished). 120x

like or platelike than the manganese-free iron- or iron/silicon-bearing primary constituents. Manganese additions also improve elevated-temperature properties of the aluminum-silicon alloys.

Cumulative Effect of Alloying Elements. In summary, aluminum wear-resistant alloys are based on alloys containing the hard, brittle silicon phase. Alloying elements such as iron, manganese, and copper increase the volume fraction of the intermetallic silicon-bearing phases, contributing to increased wear resistance compared to binary aluminum-silicon alloys. In addition, magnesium and copper also provide additional strengthening by producing submicroscopic precipitates within the matrix through an age-hardening process.

Effects of Alloying on Processing

Forming

The formability of a material is the extent to which it can be deformed in a 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 8 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 it decreases work hardening at large strains. Small amounts of magnesium or copper also reduce the strain-hardening rate, 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. 33 and 34. 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. 35 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. 35 were obtained from sheet tensile specimens, first solution heat-

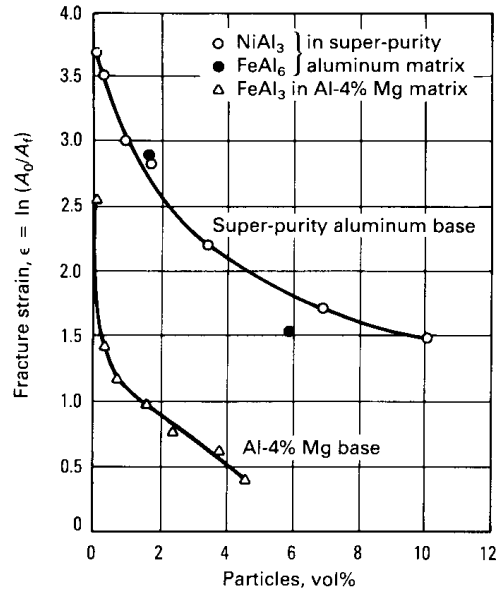


Fig. 33 Effect of volume percent fraction of micronsize intermetallic particles and composition of the matrix on the fracture strain of 5 mm (0.2 in.) diam tensile specimens. A_0 is initial cross-sectional area. A_f is area of fracture

treated, then aged 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.

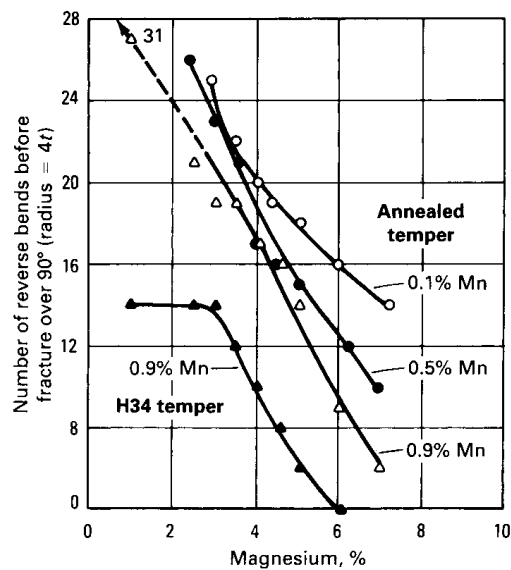


Fig. 34 Effect of magnesium and manganese on the formability of aluminum alloys in the annealed and H34 tempers; 1.6 mm (0.064 in.) thick sheet

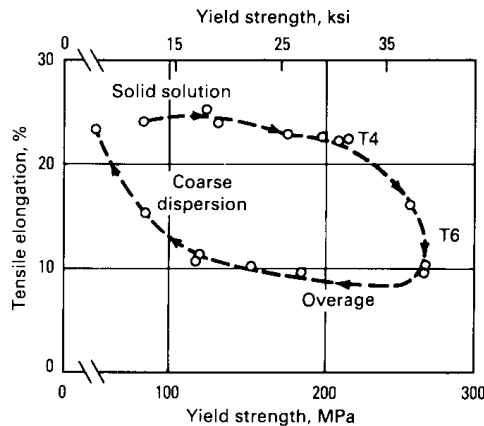


Fig. 35 Effect of precipitation on yield strength and elongation in alloy 2036

Forging

Commercial purity (or higher purity) aluminum is readily forgeable into intricate shapes over a wide range of temperatures. While many aluminum alloys are also readily forgeable, difficulty tends to increase because the addition of alloying elements increases flow strength. The formation of discrete phases that interrupt continuity of the structure also adversely affects forgeability. The higher deformation strength increases pressure requirements, while the discrete phases make flow less uniform and increase the likelihood of cracking. Alloying additions that significantly increase solid solution strength are copper, magnesium, and silicon. Chromium, manganese, titanium, vanadium, and zirconium form insoluble phases. The presence of these elements strengthens the aluminum at elevated temperature, but they have less effect than the higher solid solubility elements. If the low-solubility elements are present in sufficient quantity, massive primary particles may form. These particles can promote local cracking during forging or other hot working operations. Figure 36 shows the effect of several common additions on forgeability in the range of 370 to 455 °C (700 to 850 °F). This figure indicates that forgeability, as measured by deformation resistance, is nearly linear for the temperature and alloy range shown. Forgeability as measured by freedom from cracking falls off abruptly near or at temperature where initial melting occurs in an alloy.

Sound aluminum direct-chilled ingot with a low alloy content can be forged as-cast. Where the alloying content is higher, it is usually advantageous to homogenize the ingots before forging and, in the case of some high-content alloys, heavy sections and intricate finished shapes, it may be desirable to hot roll, extrude, or preforge the stock to obtain a uniform structure more suitable for forging. Thermal treatments should be used to maximize solid solution and to spheroidize the remaining constituents.

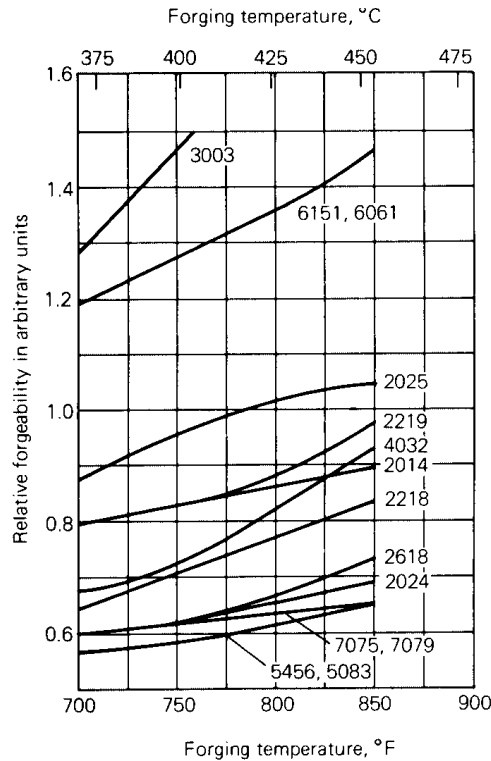


Fig. 36 Effect of temperature on relative forgeability of various aluminum alloys. Vertical scale is based on deformation per unit of energy absorbed estimated from production experience.

Machining

Pure, unalloyed aluminum is relatively soft and ductile and tends to adhere to a cutting tool, forming a builtup edge and long chips. It requires special machining techniques to avoid producing rough surfaces and heavy burrs. Alloying aluminum improves its machinability. Elements in solid solution that make an alloy heat-treatable or work-hardenable increase the hardness of the aluminum matrix and thereby reduce the builtup edge on the cutting tool; formation of burrs, roughness and tearing on the machined surface; and the length of chips.

Elements out of solution can act as chip breakers, thereby reducing the length of chips. Elements such as lead or bismuth form small insoluble globules and are effective chip breakers. If present in sufficient quantity (generally about 0.5% each), lead and bismuth permit increased machining speeds and reduce the need for cutting fluids. Intermetallic constituents such as CuAl_2 or FeAl_3 similarly act as chip breakers without significantly reducing the life of cutting tools. However, the very hard constituents, such as silicon or the complex intermetallics that contain chromium or manganese, while effectively acting as chip breakers, noticeably decrease tool life. The presence of primary silicon in hypereutectic aluminum-silicon cast alloys is

especially harmful in terms of tool life, but at the same time, it produces very short chips, minimum tool edge buildup, and excellent machined surface finish. The elements sodium, strontium, antimony, and phosphorus also effect machinability because they affect the cast microstructure. Sodium, strontium, or antimony modify the eutectic silicon morphology, changing it from acicular or needlelike to a very fine, lacy, or spheroidized structure. Phosphorus refines primary silicon in hypereutectic alloys, reducing its size by a factor of approximately 10 to 1. Modification and refinement both tend to increase tool life significantly.

In summary, the alloys having the poorest machining characteristics are of low alloy content and are in the softest condition. Cold working, increasing alloy concentration, and/or heat treatment all harden an alloy and tend to reduce the built-up edge on the tool. Elements and constituents out of solution promote chip breaking. Hard constituents, especially if large and unrefined, can significantly reduce tool life.

Welding

Aluminum has several chemical and physical properties that need to be understood when using the various joining processes. The specific properties that affect welding are its oxide characteristics; the solubility of hydrogen in molten aluminum; its thermal, electrical, and nonmagnetic characteristics; its lack of color change when heated; and its wide range of mechanical properties and melting temperatures that result from alloying with other metals.

Non-Heat-Treatable Alloys. The absence of precipitate-forming elements in these low- to moderate-strength non-heat-treatable alloys becomes a positive attribute when considering weldability, because many of the alloy additions needed for precipitation hardening (for example, copper plus magnesium, or magnesium plus silicon) can lead to hot cracking, which results from heat-affected zone (HAZ) liquidation during the welding operation. In addition, joint efficiencies are higher in non-heat-treatable alloys because the HAZ is not compromised by the coarsening or dissolution of precipitates. This obviates the need for thick joint lands or postweld heat treatment and favors the use of welded structures in the as-welded condition.

The 2xxx series alloys, having copper as the primary alloying addition, possess high strength but somewhat lower corrosion resistance than most other aluminum alloys. Many of these alloys also possess relatively good elevated-temperature strength. Magnesium is also added to the 2xxx series alloys for increased strength but results in greater weld crack sensitivity. Alloy 2024 is one of the highest-strength 2xxx alloys and is used exten-

sively in the aircraft industry; however, the 1.5% nominal Cu content of 2024 hinders its weldability due to increased weld crack sensitivity. Alloys having controlled levels of magnesium, such as 2014, 2219, and 2519, are used for applications requiring good weldability. Generally, these alloys provide good machinability but less formability than other heat-treatable aluminum alloys.

The 6xxx series alloys containing magnesium and silicon provide moderate strengths and good corrosion resistance in relation to other heat-treatable aluminum alloys. Because they are easily extruded, they are available in a wide range of structural shapes, as well as sheet and plate products. The versatility of these alloys is represented in 6061, which is one of the most commonly used aluminum alloys. Typically, the 6xxx alloys have good formability and good weldability.

The 7xxx series provides the highest strength of all aluminum alloys, although this claim is being challenged by aluminum-lithium alloys. High strength in the 7xxx alloys is achieved by alloying additions of zinc, magnesium, and often copper, combined with controlled thermal and mechanical processing. Copper, in combination with zinc and magnesium in the 7xxx series alloys, increases strength but hampers weldability due to increased susceptibility to weld cracking. Alloy 7075, containing nominally 5.6% Zn, 2.5% Mg, and 1.6% Cu, is a commonly used alloy of this system, but it has a propensity for weld cracking. Alloys 7004, 7005, and 7039 were designed for applications requiring high strength and good weldability. These alloys have limited amounts of copper that reduce the sensitivity to weld cracking. One important characteristic of the 7xxx series is the ability of the HAZ in these alloys to naturally age, or become precipitation-strengthened at room temperature, after welding. Because of this, weld properties continue to improve for up to 30 days after welding.

Brazing

Base Metals. The non-heat-treatable wrought alloys typically used as base metals are listed in Table 10. Those that are most successfully brazed are the 1xxx and 3xxx series and the low-magnesium members of the 5xxx series. The alloys containing a higher magnesium content, such as 5083, 5086, 5154, and 5456, are more difficult to braze by the usual flux methods because of poor wetting and excessive penetration by the filler metal. Filler metals are available that melt below the solidus temperatures of most commercial, non-heat-treatable wrought alloys.

The commonly brazed heat-treatable wrought alloys are the 6xxx series. Because the 2xxx and 7xxx series of aluminum alloys have melting points that are too low, they are not normally brazeable. Exceptions are the 7072

Table 10 Melting ranges and brazeability of some common aluminum alloys

Alloy	Melting range		Brazeability(a)
	°C	°F	
Non-heat-treatable wrought alloys			
1350	646–657	1195–1215	A
1100	643–657	1190–1215	A
3003(b)	643–654	1190–1210	A
3004	629–652	1165–1205	B
5005	632–652	1170–1205	B
5050	627–652	1160–1205	B
5052	593–649	1100–1200	C
Heat-treatable wrought alloys			
6053	593–652	1100–1205	A
6061	593–649	1100–1200	A
6063	616–654	1140–1210	A
6951(c)	616–654	1140–1210	A
7005	607–649	1125–1200	B
Casting alloys(d)			
443.0	574–632	1065–1170	B
356.0	557–613	1035–1135	B
710.0	596–646	1105–1195	B
711.0	604–643	1120–1190	A

(a) A, generally brazeable by all commercial procedures; B brazeable with special techniques or in specific applications that justify preliminary trials or testing to develop the procedure and to check the performance of brazed joints; C, limited brazeability. (b) Used both plain and as the core of brazing sheet. (c) Used only as the core of brazing sheet. (d) Sand and permanent mold castings only

alloy, which is used for cladding material only, and 7005 alloy. Alloys with a solidus temperature above 595 °C (1100 °F) are readily brazed using the aluminum-silicon filler metals.

There are several brazeable cast aluminum alloys, which are listed in Table 10 along with their melting range and degree of brazeability. The most readily brazeable are those with the higher solidus temperatures, such as the 710 and 711 alloys.

Filler Metals. Commercial filler metals for brazing aluminum are aluminum-silicon alloys containing 7 to 12% Si. Lower melting points are attained, with some sacrifice in resistance to corrosion, by adding copper and zinc. Filler metals for vacuum (fluxless) brazing of aluminum usually contain magnesium to enhance oxide film modification, to promote wetting, and to reduce the partial pressures of oxygen-bearing gases in the chamber. The compositions and the solidus, liquidus, and brazing temperatures of the most frequently used brazing filler metals for aluminum are given in Table 11.

Soldering

Wrought Alloys. Although all aluminum alloys can be soldered, alloy composition greatly affects ease of soldering, type of solder, method employed, and ultimate service acceptability of the assembly. The relative solderability of the principal wrought aluminum alloys is listed below:

- *Excellent solderability:* 1100, 1200, 1235, 1350, and 3003
- *Good solderability:* 3004, 5357, 6003, 6061, 6063, 6101, 6151, 6253, 6951, 7072, and 8112
- *Fair solderability:* 2011, 2014, 2017, 2018, 2024, 2025, 2117, 2214, 2218, 2225, 5050, and 7005
- *Poor solderability:* 5052, 5056, 5083, 5086, 5154, 5254, 5356, 5652, 7075, 7178, and 7277

Alloys containing more than 1% Mg cannot be soldered satisfactorily with an organic flux, and alloys containing more than 2.5% Mg are difficult to solder with reaction fluxes. Alloys containing more than 5% Si are difficult to solder by any flux method.

Aluminum alloys containing more than 0.5% Mg are subject to intergranular penetration by molten tin solders. Zinc also penetrates the aluminum-magnesium alloys intergranularly, but the extent of penetration usually is not significant until the magnesium content exceeds 0.7%. Intergranular penetration by molten solder is aggravated if magnesium-containing alloys are prestressed. This can be reduced if the assembly is stress-relieved before soldering. However, when using high-temperature zinc or zinc-aluminum solders that have a solidus temperature of 370 °C (700 °F) or greater, complete stress relief occurs in non-heat-treatable alloys before molten solder contacts the surface of the aluminum. Partial stress relief occurs in the heat-treatable alloys, thus reducing solder penetration.

Aluminum-magnesium-silicon alloys are less susceptible to intergranular penetration than binary aluminum-magnesium alloys and are more solderable than binary aluminum-silicon alloys.

Aluminum alloys containing copper or zinc as a major alloying element generally contain appreciable quantities of other elements. Most such alloys are subject to intergranular penetration by solder and generally are not soldered. Solderability of the highly alloyed materials can be improved, however, by employing an aluminum alloy cladding or by plating the surface.

Table 11 Compositions and solidus, liquidus, and brazing temperature ranges of brazing filler metals for use on aluminum alloys

AWS classification	Composition(a), %						Temperature					
							Solidus		Liquidus		Brazing	
	Si	Cu	Mg	Zn	Mn	Fe	°C	°F	°C	°F	°C	°F
BAISi-2	6.8–8.2	0.25	...	0.20	0.10	0.8	577	1070	613	1135	599–621	1110–1150
BAISi-3(b)	9.3–10.7	3.3–4.7	0.15	0.20	0.15	0.8	521	970	585	1085	571–604	1060–1120
BAISi-4	11.0–13.0	0.30	0.10	0.20	0.15	0.8	577	1070	582	1080	582–604	1080–1120
BAISi-5(c)	9.0–11.0	0.30	0.05	0.10	0.05	0.8	577	1070	591	1095	588–604	1090–1120
BAISi-6(d)	6.8–8.2	0.25	2.0–3.0	0.20	0.10	0.8	559	1038	607	1125	599–621	1110–1150
BAISi-7(d)	9.0–11.0	0.25	1.0–2.0	0.20	0.10	0.8	559	1038	596	1105	588–604	1090–1120
BAISi-8(d)	11.0–13.0	0.25	1.0–2.0	0.20	0.10	0.8	559	1038	579	1075	582–604	1080–1120
BAISi-9(d)	11.0–13.0	0.25	0.10–0.5	0.20	0.10	0.8	562	1044	582	1080	582–604	1080–1120
BAISi-10(d)	10.0–12.0	0.25	2.0–3.0	0.20	0.10	0.8	559	1038	582	1080	582–604	1080–1200
BAISi-11(d)(e)	9.0–11.0	0.25	1.0–2.0	0.20	0.10	0.8	559	1038	596	1105	582–604	1080–1120

(a) Principal alloying elements. (b) Contains 0.15% Cr. (c) Contains 0.20% Ti. (d) Solidus and liquidus temperature ranges vary when used in vacuum. (e) Contains 0.02–0.20% Bi

Thermally treated alloys develop a heavier oxide film than forms naturally; this can hinder soldering. With the heat-treated alloys, it usually is necessary to pretreat the surface chemically before soldering.

Cast Alloys. The substantial amounts of alloying elements present in most casting alloys increase the probability that these elements will be dissolved in the solder, which will reduce its wetting capacity and capillary action. The casting alloys, as a group, thus have poor solderability. The time at soldering temperature must be held to a minimum to reduce penetration of molten solder. Electroplating the cast surface facilitates soldering by controlling solder penetration and improving solder wetting capacity and capillary action.

Any roughness, minute cavity, or porosity in a cast surface can entrap flux and make flux removal difficult. Permanent-mold, plaster mold, and die castings generally present a good surface condition for soldering. However, because die castings are subject to surface blistering when exposed to temperatures over 315 °C (600 °F), they generally cannot be high-temperature soldered. Because most die casting alloys contain a high percentage of silicon and a tenacious oxide film, they are difficult to wet and normally are soldered by fluxless methods.

The three aluminum casting alloys that are relatively easily wetted by solder are 443.0, 443.2, and 356. Casting alloys that are less responsive but still solderable are 213.0, 710.0, and 711.0.

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