

CHAPTER 7

Aluminum and Aluminum Alloys

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Introduction

Aluminum castings are used for a wide range of functions, from decorative components, such as lighting fixtures, to highly engineered safety-critical components for automotive and aerospace applications. Following the Hall-Heroult electrolytic process of reduction of aluminum oxide in the nineteenth century, aluminum could be made available at a greatly reduced cost. Since about 1915, a combination of air transportation, development of specific casting alloys, improved properties, impetus provided by two world wars, and demand for lightweight components in automobiles to improve fuel efficiency have resulted in an ever-increasing use of aluminum castings. Alloy development and characterization of physical and mechanical characteristics provided the basis for new product development through the decades that followed. Casting processes were developed to extend the capabilities of foundries in new commercial and technical applications. The technology of molten metal processing, solidification processing, and property development has been advanced to assist the foundryman with the means of economical and reliable production of parts that consistently meet specified requirements. Today, aluminum alloy castings are produced in hundreds of compositions by all commercial casting processes including greensand, dry sand, lost foam, plaster mold, investment casting, permanent mold, counter-gravity low-pressure casting, and pressure die casting [1]. Typical cast components are shown in Fig. 7.1.

The market for aluminum castings for the past 10 years is shown in Table 7.1 [6].

Advantages of Aluminum Alloys

Certain engineering advantages are inherent in the use of aluminum alloys for castings. Light weight (per unit volume) is the one most commonly cited. With

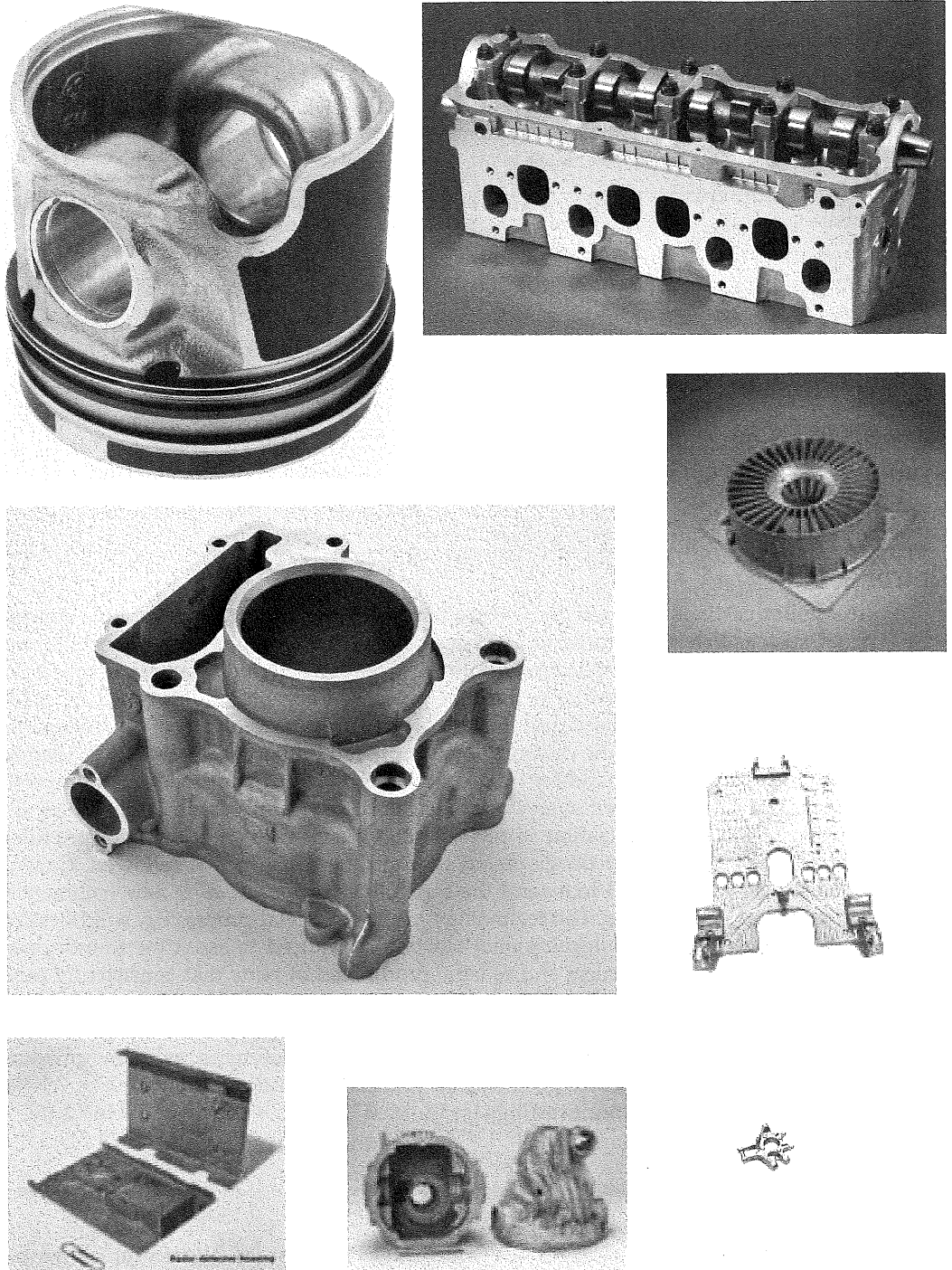


FIGURE 7.1 Typical aluminum alloy castings. (Courtesy of NADCA [2], American Foundry Society [3], Kasprzak [4], and of ECK Industries [5].) (Continued)

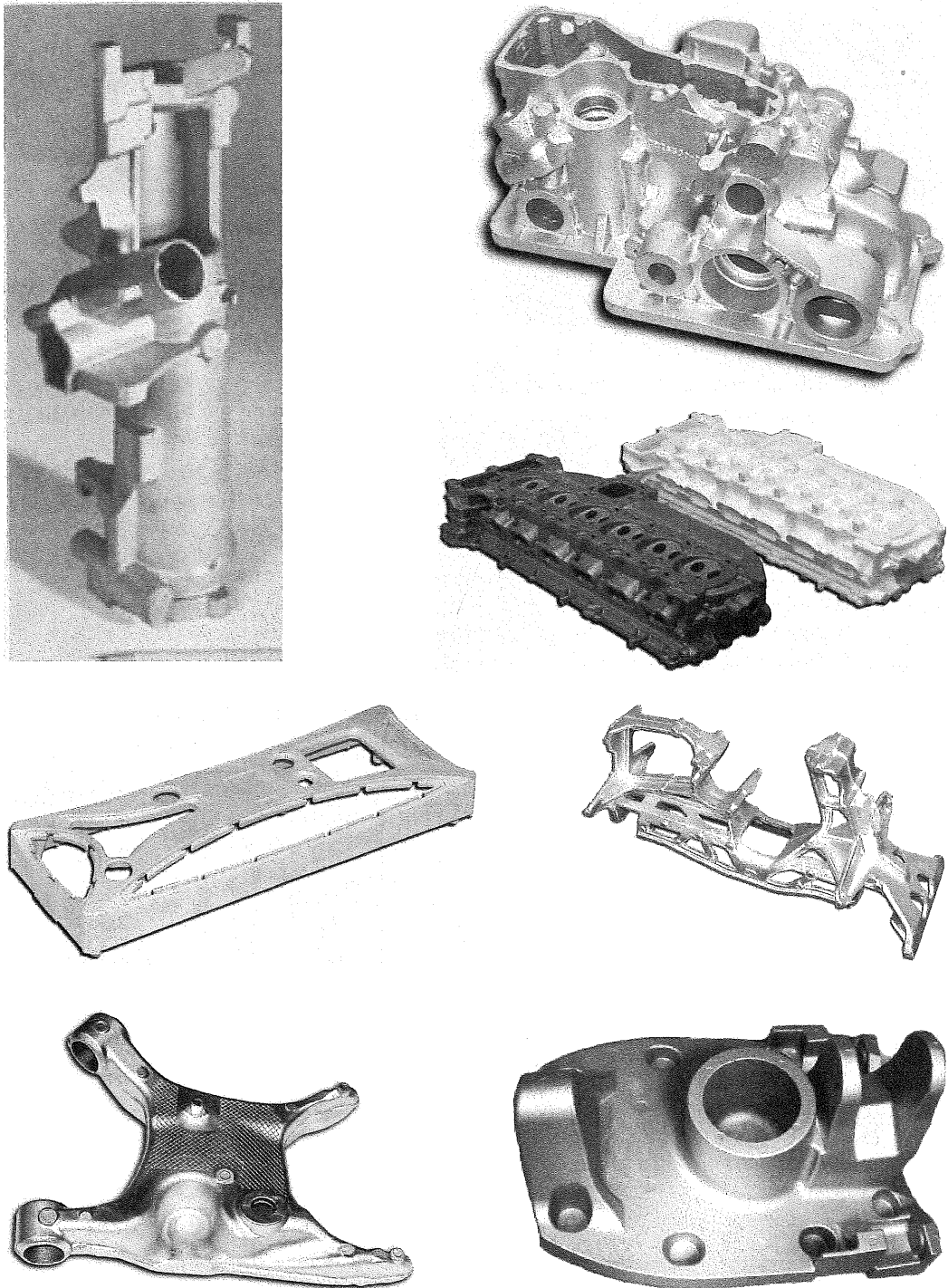


FIGURE 7.1 (Continued)

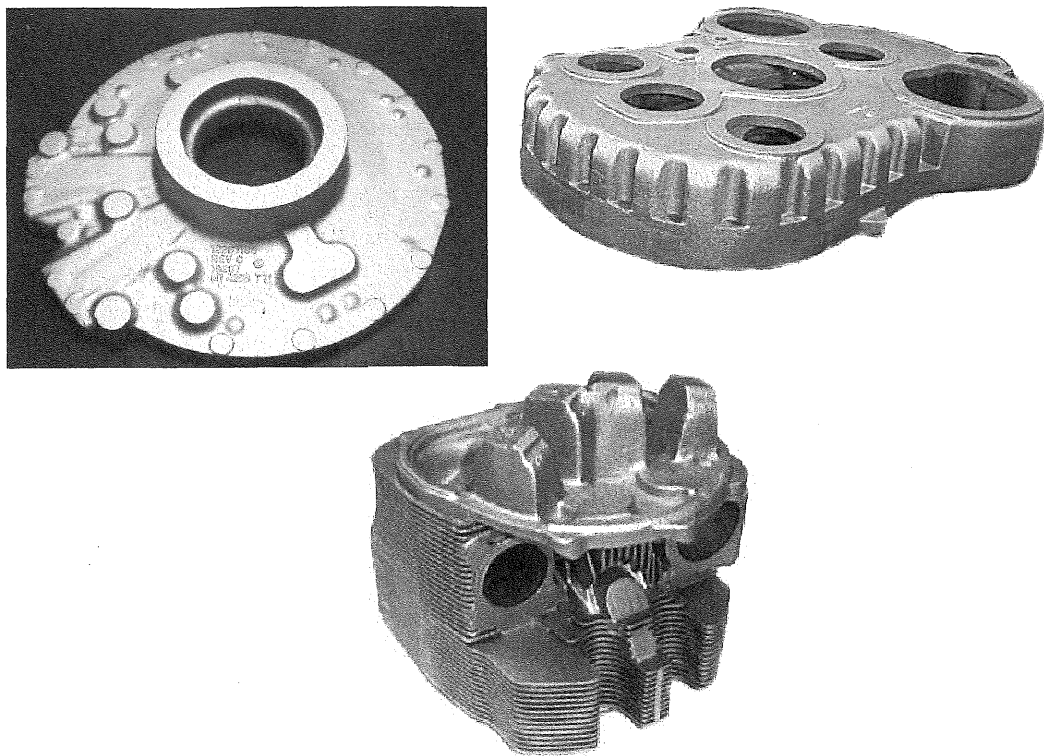


FIGURE 7.1 (Continued)

Year	Aluminum	Copper Base	Magnesium	Zinc	Other	Total Non-Ferrous
1999	2,042	329	68	400	48	2,887
2000	2,052	325	74	420	47	2,918
2001	1,910	300	78	322	45	2,655
2002	2,047	294	66	400	45	2,852
2003	2,152	305	81	380	50	2,968
2004	2,165	315	88	360	52	2,980
2005	2,293	322	111	345	54	3,125
2006	2,115	317	116	334	57	2,939
2007	2,036	312	121	328	59	2,856
2008	1,918	303	121	302	58	2,702
2009	1,191	179	66	166	120	1,722
2010	1,234	265	106	204	60	1,869
2011	1,523	263	99	181	60	2,126
2012	1,591	279	102	200	69	2,241

Source: From Spada [6].

TABLE 7.1 U.S. Nonferrous Casting Shipments (000 tons)

a density of 2.7 g/cc, aluminum castings can be handled easily in the foundry, compared to ferrous castings. Some of the numerous other desirable properties include:

- *A wide range of mechanical properties.* Strength, hardness, and other properties may be greatly altered by alloying and/or heat treatment. Properties of the strongest alloys can be favorably compared with those of the cast irons and lower-strength steels, especially if the weight factor is considered. Suitable strength for many engineering uses is thus available.
- *Architectural and decorative value.* Cast surfaces have good surface finish, are lustrous, and have no blemishes.
- *Corrosion resistance.* This property is, of course, relative, but resistance to atmospheric and water-corrosion conditions makes possible the use of aluminum for building construction, outboard-motor parts, food-handling equipment, etc.
- *Nontoxicity.* The use of aluminum castings for cooking utensils and other food-handling equipment requires that no chemical-reaction products, toxic to humans, be formed by action of the food on the aluminum alloy.
- *Electrical conductivity.* Rotor bars in induction motors are cast of aluminum because of its desirable electrical conductivity.
- *Ease of machining.* Most aluminum alloys are relatively easy to machine.
- *Casting properties.* Since aluminum has a relatively low melting point, about 660°C or 1220°F, and its alloys have a considerably lower operating temperature range (650 to 760°C or 1200 to 1400°F), the problems of melting and pouring are greatly simplified when compared with steels and cast irons. Both permanent metal molds and die casting are extensively practiced. Problems with furnace refractories and molding sands are reduced because of the lower pouring temperatures.
- *Lower casting shipping cost per piece.* This is due to the relatively lower density.
- *Good fluidity.* Aluminum alloys possess excellent casting fluidity and hence, thin sections can be filled easily.
- *Fast heat exchange.* Heat transfer from the molten aluminum alloy to the mold is relatively fast, providing faster casting cycles in metal molds.
- *Casting versatility.* In many cases, multicomponent welded or joined assemblies can be replaced with a single cast part.

Limitations

Cost is a major disadvantage since the cost of aluminum alloys in dollars per pound is greater than that of cast irons and many steels. However, the cost in dollars per pound is misleading unless it is recognized that the volume per pound of aluminum is about 2.90 times that of a pound of the ferrous alloys.

Engineering limitations include the following:

- Lack of resistance to abrasion and wear.
- Absence of aluminum alloys which can develop the combination of high tensile strength, toughness, and hardness obtainable in ferrous alloys.

- Lack of resistance to severe corrosion to the degree offered by numerous copper and nickel-base alloys and stainless steels. Obviously, in the selection of aluminum as a casting material demands that its advantages outweigh its limitations in any particular application.

Alloy Groups

Systems used to designate casting compositions are not internationally standardized. In the United States, comprehensive listings are maintained by general procurement specifications issued through government agencies (federal and military, for example) and by technical societies such as the American Society for Testing and Materials and the Society of Automotive Engineers. Alloy registrations by The Aluminum Association are in broadest use; its nomenclature is decimalized to define foundry alloy composition variations [1].

Designations in the form $xxx.1$ and $xxx.2$ include the composition of specific alloys in remelt ingot form suitable for foundry use. Designations in the form $xxx.0$ in all cases define composition limits applicable to castings. Prefix letters used primarily to define differences in impurity limits denote further variations in specified compositions. Accordingly, one of the most common gravity cast alloys, 356, is shown in variations A356, B356, and C356; each of these alloys has identical major alloy contents but has decreasing limits applicable to impurities, especially iron content. The Aluminum Association composition limits for registered aluminum foundry alloys used to cast shapes are given in Table 7.2, which does not include wrought alloys that are cast into ingots or billets intended for fabrication by mechanical deformation [1, 7].

Although the nomenclature and designations for various casting alloys are standardized in North America, many important alloys have been developed for engineered casting production worldwide. For the most part, each nation (and in many cases the individual firm) has developed its own alloy nomenclature. Excellent references are available that correlate, cross reference, or otherwise define significant compositions in international use [8–10].

The Aluminum Association designation system attempts alloy family recognition by the following scheme:

- $1xx.x$: Controlled unalloyed compositions
- $2xx.x$: Aluminum alloys containing copper as the major alloying element
- $3xx.x$: Aluminum-silicon alloys also containing magnesium and/or copper
- $4xx.x$: Binary aluminum-silicon alloys
- $5xx.x$: Aluminum alloys containing magnesium as the major alloying element
- $7xx.x$: Aluminum alloys containing zinc as the major alloying element. Also containing additions of either copper, magnesium, chromium, manganese, or combinations of these elements
- $8xx.x$: Aluminum alloys containing tin as the major alloying element

A separate four-digit Aluminum Association designation system exists for wrought Al compositions.

AA No.	Products ^(a)	Composition ^(b) , wt%									
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn
201.0	S	0.10	0.15	4.0–5.2	0.20–0.50	0.15–0.55	–	–	–	0.15–0.35	–
A201.0	S	0.05	0.10	4.0–5.0	0.20–0.50	0.15–0.55	–	–	–	0.15–0.35	–
B201.0	S	0.05	0.05	4.0–5.0	0.20–0.50	0.25–0.35	–	–	–	0.15–0.35	–
204.0	S, P	0.20	0.35	4.2–5.0	0.10	0.15–0.35	–	0.05	0.10	0.15–0.30	0.05
206.0	S, P	0.10	0.15	4.2–5.0	0.20–0.50	0.15–0.35	–	0.05	0.10	0.15–0.30	0.05
A206.0	S, P	0.05	0.10	4.2–5.0	0.20–0.50	0.15–0.35	–	0.05	0.10	0.15–0.30	0.05
B206.0	S, P	0.05	0.10	4.2–5.0	0.20–0.50	0.15–0.35	–	0.05	0.10	0.15–0.30	0.05
319.0	S, P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	–	0.35	1.0	0.25	–
A319.0	S, P	5.5–6.5	1.0	3.0–4.0	0.50	0.10	–	0.35	3.0	0.25	–
B319.0	S, P	5.5–6.5	1.2	3.0–4.0	0.8	0.10–0.50	–	0.50	1.0	0.25	–
354.0	P	8.6–9.4	0.20	1.6–2.0	0.10	0.40–0.6	–	–	0.10	0.20	–
355.0	S, P	4.5–5.5	0.6 ^(c)	1.0–1.5	0.50 ^(c)	0.40–0.6	0.25	–	0.35	0.25	–
A355.0	S, P	4.5–5.5	0.09	1.0–1.5	0.05	0.45–0.6	–	–	0.05	0.04–0.20	–
C355.0	S, P	4.5–5.5	0.20	1.0–1.5	0.10	0.45–0.6	–	–	0.10	0.20	–
356.0	S, P	6.5–7.5	0.6 ^(c)	0.25	0.35 ^(c)	0.20–0.45	–	–	0.35	0.25	–
A356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.25–0.45	–	–	0.10	0.20	–
B356.0	S, P	6.5–7.5	0.09	0.05	0.05	0.25–0.45	–	–	0.05	0.04–0.20	–
C356.0	S, P	6.5–7.5	0.07	0.05	0.05	0.25–0.45	–	–	0.05	0.04–0.20	–
F356.0	S, P	6.5–7.5	0.20	0.20	0.10	0.17–0.25	–	–	0.10	0.04–0.20	–
357.0	S, P	6.5–7.5	0.15	0.05	0.03	0.45–0.6	–	0.05	0.20	0.04–0.20	–
A357.0	S, P	6.5–7.5	0.20	0.20	0.10	0.40–0.7	–	0.05	0.10	0.04–0.20	–
B357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.40–0.6	–	0.05	0.05	0.04–0.20	–

TABLE 7.2 Chemical Composition Limits for Registered Aluminum Alloys in the Form of xxx.0 Casting, xxx.1 Ingot, and xxx.2 Ingot (*Continued*)

AA No.	Products ^(a)	Composition ^(b) , wt%									
		Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Sn
C357.0	S, P	6.5–7.5	0.09	0.05	0.05	0.45–0.7	–	–	0.05	0.04–0.20	–
D357.0	S	6.5–7.5	0.20	–	0.10	0.55–0.6	–	–	–	0.10–0.20	–
E357.0	S, P, I	6.5–7.5	0.10	–	0.10	0.55–0.6	–	–	–	0.10–0.20	–
F357.0	S, P, I	6.5–7.5	0.10	0.20	0.10	0.40–0.7	–	–	0.10	0.04–0.20	–
A380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	–	0.50	3.0	–	0.35
B380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10	–	0.50	1.0	–	0.35
C380.0	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10–0.30	–	0.50	3.0	–	0.35
D380	D	7.5–9.5	1.3	3.0–4.0	0.50	0.10–0.30	–	0.50	3.0	–	0.35
390.0	D	16.0–18.0	1.3	4.0–5.0	0.10	0.45–0.65	–	–	0.10	0.20	–
A390.0	S, P	16.0–18.0	0.50	4.0–5.0	0.10	0.45–0.85	–	–	0.10	0.20	–
B390.0	D	16.0–18.0	1.3	4.0–5.0	0.50	0.45–0.65	–	0.10	1.5	0.20	–
413	D	11.0–13.0	2.0	1.0	0.35	0.10	–	0.60	0.50	–	0.15
A413.0	D	11.0–13.0	1.3	1.0	0.35	0.10	–	0.50	0.50	–	0.15
B413.0	S, P	11.0–13.0	0.50	0.10	0.35	0.05	–	0.05	0.10	0.25	–
443.0	S, P	4.5–6.0	0.8	0.6	0.50	0.05	0.25	–	0.50	0.25	–
A443.0	S	4.5–6.0	0.8	0.30	0.50	0.05	0.25	–	0.50	0.25	–
B443.0	S, P	4.5–6.0	0.8	0.16	0.35	0.05	–	–	0.35	0.25	–
C443.0	D	4.5–6.0	2.0	0.6	0.35	0.10	–	0.50	0.50	–	0.15
444.0	S, P	6.5–7.5	0.6	0.25	0.35	0.10	–	–	0.35	0.25	–
A444.0	P	6.5–7.5	0.6	0.25	0.35	0.10	–	–	0.10	0.20	–
520.0	S	0.25	0.30	0.25	0.15	9.5–10.6	–	–	0.15	0.25	–
535.0	S	0.15	0.15	0.05	0.10–0.25	6.2–7.5	–	–	–	0.10–0.25	–
A535.0	S	0.20	0.20	0.10	0.10–0.25	6.2–7.5	–	–	–	0.25	–
B535.0	S	0.15	0.15	0.10	0.05	6.2–7.5	–	–	–	0.120–0.25	–

710.0	S	0.15	0.50	0.35–0.6	0.05	0.6–0.8	–	–	6.0–7.0	0.25	–
711.0	P	0.30	0.7–1.4	0.35–0.6	0.05	0.25–0.45	–	–	6.0–7.0	0.20	–
712.0	S	0.30	0.50	0.25	0.10	0.50–0.65	0.40–0.6	–	5.0–8.5	0.15–0.25	–
713.0	S, P	0.25	1.1	0.40–0.10	0.6	0.20–0.50	0.35	0.15	7.0–8.0	0.25	–
771.0	S	0.15	0.15	0.10	0.10	0.8–1.0	0.06–0.20	–	6.5–7.5	0.10–0.20	–
772.0	S	0.15	0.15	0.10	0.10	0.6–0.8	0.06–0.20	–	6.0–7.0	0.10–0.20	–
850.0	S, P	0.7	0.7	0.7–1.3	0.10	0.10	–	0.7–1.3	–	0.20	5.5–7.0
853.0	S, P	5.5–6.5	0.7	3.0–4.0	0.60	–	–	–	–	0.20	5.5–7.0

Note: Only composition limits that are identical to those listed herein or are registered with The Aluminum Association should be designated as “AA” alloys.

Source: From *ASM Handbook* [1, 7].

TABLE 7.2 Chemical Composition Limits for Registered Aluminum Alloys in the Form of xxx.0 Casting, xxx.1 Ingot, and xxx.2 Ingot (*Continued*)

Alloying Principles

The aluminum-base alloys may in general be characterized as eutectic systems, containing intermetallic compounds or elements as the excess phases [11]. Because of the relatively low solubilities of most of the alloying elements in aluminum and the complexity of the alloys that are produced, any one aluminum-base alloy may contain several metallic phases, which sometimes are quite complex in composition. These phases usually are appreciably more soluble near the eutectic temperatures than at room temperature, making it possible to heat-treat some of the alloys by solution and aging heat treatments.

All the properties of interest are, of course, influenced by the effects of the various elements with which aluminum is alloyed. The principal alloying elements in aluminum-base casting alloys are copper, silicon, magnesium, zinc, chromium, manganese, tin, and titanium. Iron is an element normally present and usually considered as an impurity. Some of the simpler effects of alloying can be considered as described below. The details can be found in Ref. 1.

Major Alloying Elements

Copper

The first and most widely used aluminum alloys were those containing 4 to 10% Cu. Copper substantially improves strength and hardness in the as-cast and heat-treated conditions. Alloys containing 4 to 6% Cu respond most strongly to thermal treatment. Copper generally reduces resistance to general corrosion and, in specific compositions and material conditions, stress corrosion susceptibility. Addition of copper also reduces hot tear resistance and decreases castability.

Silicon

The outstanding effect of silicon in aluminum alloys is the improvement of casting characteristics. Additions of silicon to pure aluminum dramatically improve fluidity, hot tear resistance, and feeding characteristics. The most prominently used compositions in all casting processes are those of the aluminum-silicon family. Commercial alloys span the hypoeutectic and hypereutectic ranges up to about 25% Si.

In general, an optimum range of silicon content can be assigned to casting processes. For slow cooling rate processes (such as plaster, investment, and sand), the range is 5 to 7%, for permanent mold 7 to 9%, and for die casting 8 to 20%. The bases for these recommendations are the relationship between cooling rate and fluidity and the effect of percentage of eutectic on feeding. Silicon additions are also accompanied by a reduction in specific gravity and coefficient of thermal expansion.

Magnesium

Mg is the basis for strength and hardness development in heat-treated Al-Si alloys and is commonly used in more complex Al-Si alloys containing copper, nickel, and other elements for the same purpose. The Mg₂Si-based precipitation hardening system displays a useful solubility limit corresponding to approximately 0.70% Mg, beyond which either no further strengthening occurs or matrix softening takes place. Common premium-strength compositions in the Al-Si family employ magnesium in the range of 0.40 to 0.70%.

Binary Al-Mg alloys are widely used in applications requiring a bright surface finish and corrosion resistance, as well as attractive combinations of strength and ductility.

Common compositions range from 4 to 10% Mg, and compositions containing more than 7% Mg are heat treatable.

Zinc

No significant benefits are obtained by the addition of zinc alone to aluminum. However, zinc is used as a principal alloying element in some alloys. Its chief beneficial effect seems to be that of making it possible to obtain a maximum of mechanical properties in the as-cast condition. Accompanied by the addition of copper and/or magnesium, zinc results in attractive heat treatable or naturally aging compositions. A number of such compositions are in common use. Zinc is also commonly found in secondary gravity and die-casting compositions.

Chromium

Chromium additions are commonly made in low concentrations to room temperature aging and thermally unstable compositions in which germination and grain growth are known to occur. Chromium typically forms the compound CrAl_7 , which displays extremely limited solid-state solubility and is therefore useful in suppressing grain growth. Sludge that contains iron, manganese, and chromium is sometimes encountered in die-casting compositions, but it is rarely encountered in gravity casting alloys. Cr improves corrosion resistance in certain alloys and increases quench sensitivity at higher concentrations.

Manganese

Manganese is used for two main purposes in shape casting. The first is to correct the Fe phases, which form in secondary foundry alloy compositions, from β needles to α script thereby improving ductility. The second use is in advanced die-casting processes, where Mn can be substituted for Fe to reduce die soldering. Manganese's higher solubility in Al combined with its lower tendency to form brittle phases gives an alloy with better properties than those in which Fe is used as the exclusive remedy for die soldering. Some evidence also exists that a high volume fraction of MnAl_6 in alloys containing more than 0.5% Mn may beneficially influence internal casting soundness.

Tin

Tin is effective in improving antifriction characteristics, and is therefore useful in bearing applications. Casting alloys may contain up to 25% Sn. Additions can also be made to improve machinability. Sn may influence precipitation-hardening response in some alloy systems at levels in the hundreds of ppm.

Titanium

Titanium is extensively used to refine the grain structure of aluminum casting alloys, often in combination with smaller amounts of boron. Titanium in excess of the stoichiometry of TiB_2 is necessary for effective grain refinement of wrought alloys. Foundry alloys are effectively grain refined with ratios of Ti to B of 5:1. Titanium is often employed at concentrations greater than those required for grain refinement to reduce cracking tendencies in hot short compositions.

Iron

Iron improves hot tear resistance and decreases the tendency for die sticking or soldering in die casting. Increases in iron content are, however, accompanied by substantially

decreased ductility. Iron reacts to form a myriad of insoluble phases in aluminum alloy melts, the most common of which are FeAl_3 , FeMnAl_6 , and αAlFeSi . In Al-Si alloys the two most common are β -needles (FeSiAl_5) and the Mn corrected α -script [$(\text{Fe,Mn})_3\text{Si}_2\text{Al}_{15}$]. These essentially insoluble phases are responsible for improvements in strength, especially at elevated temperature. They do, however, reduce the ductility. As the fraction of insoluble phase increases with increased iron content, casting considerations such as flowability and feeding characteristics are adversely affected. Iron participates in the formation of sludging phases with manganese, chromium, and other elements; particularly at the concentrations and low holding temperatures normally associated with high-pressure die casting. In fact, the sludging factor (SF), a simple expression combining the concentrations of Fe, Mn, and Cr, is given as

$$\text{SF} = \% \text{Fe} + 2 \times \% \text{Mn} + 3 \times \% \text{Cr} \quad (7.1)$$

Plots of this factor versus temperature delineate the minimum temperature below which sludging can commonly be expected in high-pressure die casting.

Minor Alloying Elements and Impurities

The minor alloying elements or impurities present in the aluminum alloys greatly influence their properties. Two alloy characteristics which may be seriously impaired are ductility (and toughness) and corrosion resistance.

Antimony

At concentration levels equal to or greater than 0.05%, antimony refines eutectic aluminum-silicon phase to lamellar form in hypoeutectic compositions. The effectiveness of antimony in altering the eutectic structure depends on an absence of phosphorus and on an adequately rapid rate of solidification. Antimony also reacts with either sodium or strontium to form coarse intermetallics with adverse effects on castability and eutectic structure. Antimony will chemically combine with and precipitate common modifiers Na and Sr, and hence Sb has the potential to act as a modification poisoner if it enters the scrap recycling stream. This is compounded by the fact that Sb is very difficult to analyze for using even modern optical emission spectrometers due to the overlap which exists between its spectrum and that of Fe.

Antimony is classified as a heavy metal with potential toxicity and hygiene implications, especially as associated with the possibility of stibine gas formation and the effects of human exposure to other antimony compounds.

Beryllium

Beryllium additions of as low as a few parts per million may be effective in reducing oxidation losses and associated inclusions in magnesium-containing compositions. Studies have shown that proportionally increased beryllium concentrations are required for oxidation suppression as magnesium content increases.

At higher concentrations ($>0.04\%$), beryllium affects the form and composition of iron-containing intermetallics, markedly improving strength and ductility. In addition to beneficially changing the morphology of the insoluble phase, beryllium changes its composition, rejecting magnesium from the Al-Fe-Si complex and thus permitting its full use for hardening purposes.

Beryllium-containing compounds are, however, numbered among the known carcinogens that require specific precautions in melting, molten metal handling, dross handling and disposition, and blasting, grinding, and welding. Standards define the maximum beryllium in welding rod and weld base metal as 0.008 and 0.010%, respectively. Both acute and chronic beryllioses are possible upon exposure to Be fumes. The chronic form can appear years after the exposure has ended. For these reasons there has been a movement to eliminate this element from aluminum alloys in general.

Bismuth

Bismuth improves the machinability of cast aluminum alloys at concentrations greater than 0.1%. It is also known to increase shrinkage tendencies in Al-Si alloys at concentrations greater than 30 ppm.

Boron

Boron combines with other metals to form borides present as solid particles in liquid Al, such as AlB_2 and TiB_2 . The titanium boride particles then act as nucleation sites for the active grain-refining phase $TiAl_3$. Once nucleated from the molten aluminum this last phase serves as the nucleating point for new grains.

Intermetallic borides reduce tool life in machining operations, and as coarse particles, form objectionable inclusions with detrimental effects on mechanical properties and ductility. At high boron concentrations, borides contribute to furnace sludging, particle agglomeration, and increased risk of casting inclusions. However, boron treatment of aluminum-containing peritectic elements is practiced to improve purity and electrical conductivity in rotor casting. Higher rotor alloy grades may specify boron to exceed titanium and vanadium contents to ensure either the complexing or precipitation of these elements for improved electrical performance.

Cadmium

In concentrations exceeding 0.1%, Cd improves machinability. Precautions that acknowledge volatilization at 767°C (1413°F) are essential for toxicity reasons.

Calcium

Calcium is a weak aluminum-silicon eutectic modifier. It increases hydrogen solubility and is often responsible for casting porosity at trace concentration levels. Ca concentrations greater than approximately 0.005% also adversely affect ductility in aluminum-magnesium alloys.

Hydrogen

Hydrogen is the only gaseous species appreciably soluble in liquid aluminum. The fact that the solubility of hydrogen is considerably lower in solid aluminum means that there is the propensity for hydrogen to cause porosity through precipitation from the liquid in the form of bubbles as the metal solidifies. Commonly called *gas porosity*, this is avoided by degassing the metal with low hydrogen inert or active gasses using either a lance, porous media, or rotary impeller degasser in increasing order of cost and effectiveness.

The most common source of hydrogen is moisture from the atmosphere over the metal as aluminum will reduce water vapor to form alumina and dissolved hydrogen in the melt. For this reason air used to pump low-pressure furnaces is normally dried to a low dew point. Inert gas covers may be used over the metal in critical applications.

Indium

Indium is added, together with Zn, in the casting of sacrificial anodes. Indium helps to disrupt the normally tough coherent alumina surface coating typical of aluminum alloys and hence enhances its ability to sacrificially corrode.

Lead

Lead is commonly used in aluminum casting alloys at greater than 0.1% for improved machinability.

Mercury

Compositions containing mercury were developed as sacrificial anode materials for cathodic protection systems, especially in marine environments. The use of these optimally electronegative alloys, which did not passivate in seawater, was severely restricted for environmental reasons.

Nickel

Nickel is usually employed with copper to enhance elevated-temperature properties. It also reduces the coefficient of thermal expansion. Ni will accelerate filiform corrosion in applications such as coated automotive wheels if present in high enough trace quantities. Values up to roughly 100 ppm seem to be acceptable, however.

Phosphorus

Phosphorus reacts with Al to form AlP which nucleates and refines primary silicon phase in hypereutectic Al-Si alloys. At parts per million concentrations, phosphorus coarsens the eutectic structure in hypoeutectic Al-Si alloys. Phosphorus diminishes the effectiveness of the common eutectic modifiers sodium and strontium as well as the eutectic refiner antimony.

Silver

Silver is used in only a limited range of aluminum-copper premium-strength alloys at concentrations of 0.5 to 1.0%. Ag contributes to precipitation hardening and stress corrosion resistance.

Sodium

Sodium modifies the aluminum-silicon eutectic. Its presence is embrittling in aluminum-magnesium alloys. Sodium reacts with phosphorus, which reduces its own effectiveness in modifying the eutectic in hypoeutectic alloys as well as reducing the refining effect of phosphorus in hypereutectic alloys. The effects of sodium and phosphorus are mutually antagonistic.

Strontium

Strontium is used to modify the aluminum-silicon eutectic. Effective modification can be achieved at very low addition levels, but a range of recovered strontium of 0.004 to 0.02% is commonly used. Higher addition levels are frequently associated with casting porosity, especially in processes or in thick-section parts in which solidification occurs more slowly. This increase in porosity can be used to compensate for shrinkage in castings where increased distributed porosity is tolerable. Degassing efficiency as determined by vacuum solidification tests may also be adversely affected at higher strontium levels. The effects of strontium and phosphorus are mutually antagonistic in the same manner as discussed for sodium.

Structure Control

Microstructural characteristics that strongly affect the mechanical properties of aluminum castings are

- Dendrite arm spacing
- Grain size and shape
- Eutectic modification and primary phase refinement
- Intermetallic phases (size, form, and distribution)

Dendrite Arm Spacing

In all commercial processes, with the exception of semisolid forming, solidification takes place through the formation of dendrites from liquid solution. The cells obtained

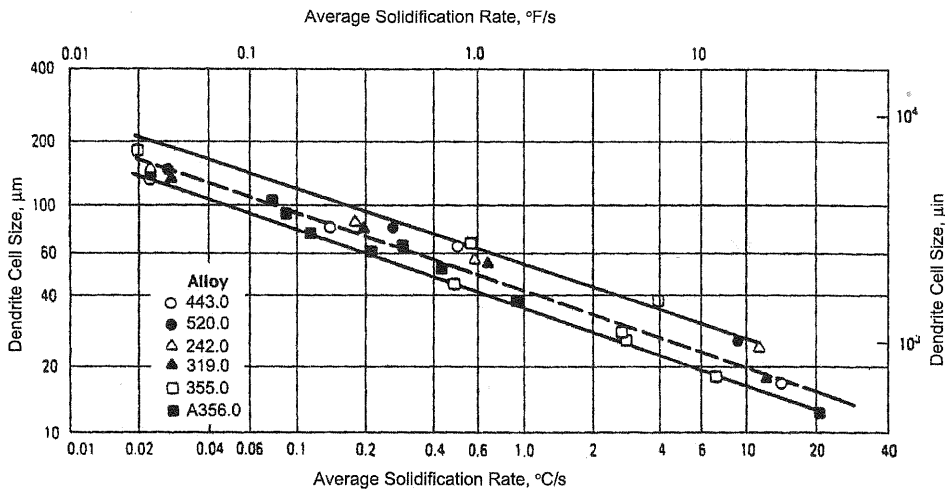


FIGURE 7.8 Dendrite arm spacing and dendrite cell size as a function of local solidification rate. (From Kaufman and Rooy [13].)

within the dendrite structure correspond to the dimensions separating the arms of primary and secondary dendrites and are exclusively controlled for a given composition by solidification rate (Fig. 7.8).

There are at least three measurements used to describe dendrite refinement:

- *Dendrite arm spacing.* The distance between developed secondary arms.
- *Dendrite cell interval.* The distance between centerlines of adjacent dendrite cells.
- *Dendrite cell size.* The width of individual dendrite cells.

The secondary dendrite arm spacing (SDAS) is a simple inverse cube root of the solidification time. The effect of the various conventional casting processes (and hence the cooling rate) on the dendrite cell size is shown in Table 7.5.

Figure 7.9 illustrates the improvement in mechanical properties due to change in dendrite cell size by solidification rate [1]. It is important to note that solidification rate

Casting Processes	Cooling Rate		Dendrite Arm Spacing	
	°C/s	°F/s	μm	Mils
Plaster, investment	1	1.80	100–1000	3.94–39.4
Greensand, shell	10	18.0	50–500	1.97–19.7
Permanent mold	100	180.0	30–70	1.18–2.76
Die	1000	1800	5–15	0.20–0.59

Source: From Kaufman and Rooy [13], p. 40.

TABLE 7.5 DAS for Various Conventional Casting Processes

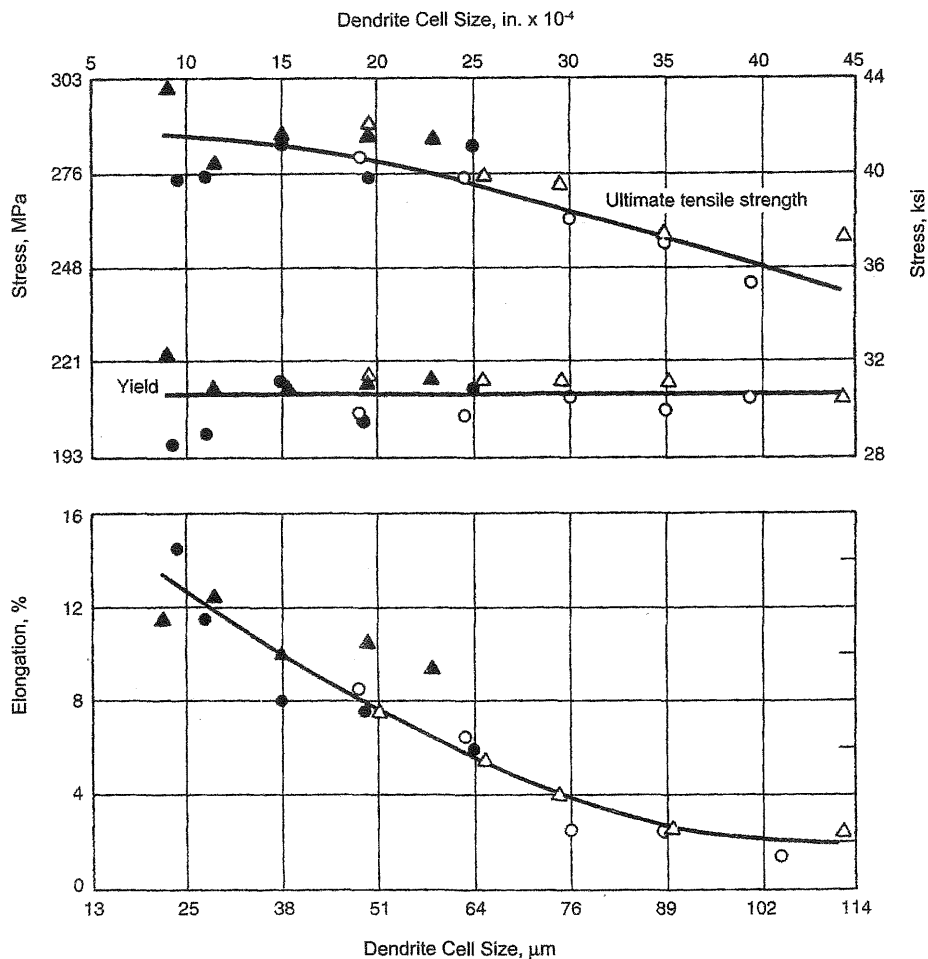


FIGURE 7.9 Tensile properties versus dendrite cell size for four heats of aluminum alloy A356-T62 plaster cast plates. (From *ASM Handbook* [1].)

also affects the morphology of the Al-Si eutectic including size and also the size and distribution of intermetallic phases. However, the DAS is taken as a measurable indication of the solidification rate.

Grain Structure and Grain Refinement

Under normal solidification conditions spanning the full range of commercial casting processes, aluminum alloys without grain refiners exhibit coarse columnar and/or coarse equiaxed structures. However, fine, equiaxed grains are desired for the best combination of strength and ductility by maximizing grain-boundary surface area and more finely distributing grain-boundary constituents [1]. Figure 7.10 illustrates the coarse and fine grain structures in an Al-Cu alloy [18]. A fine grain structure promotes the formation of

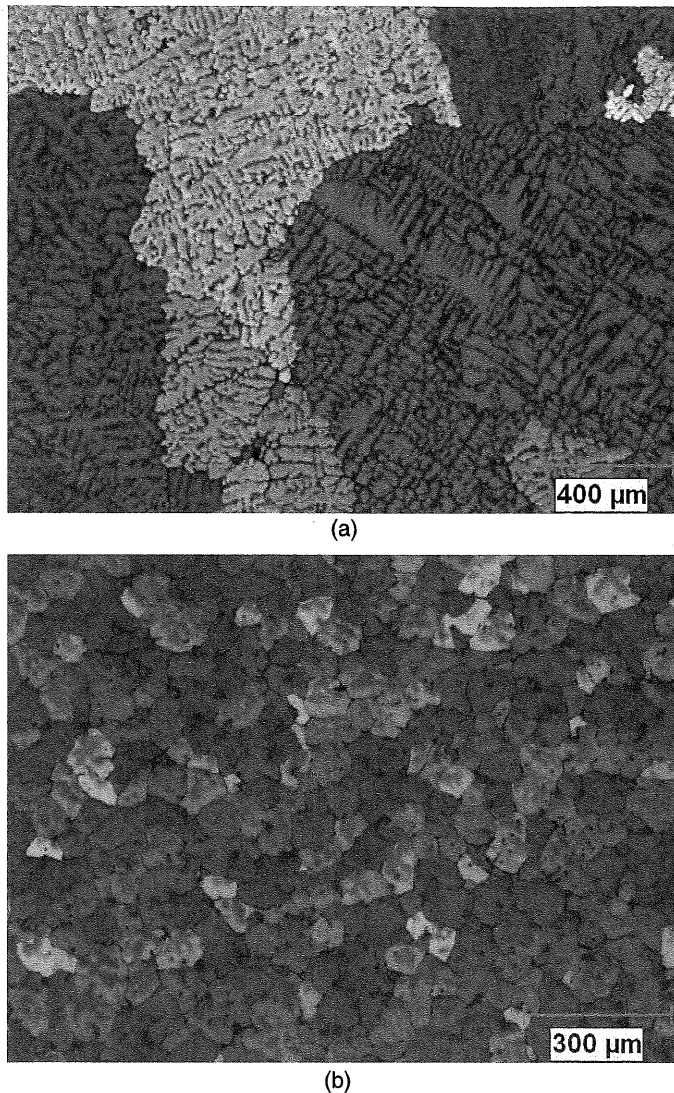


FIGURE 7.10 Anodized microstructures of 206.0 (a) before, and (b) after grain refinement. (From Fasoyinu et al. [18].)

finer, more evenly distributed intermetallic phases with corresponding improvement in feeding characteristics. Porosity, if present, is of smaller discrete void size in fine-grain parts. Other advantages of grain refinement are

- Improved feeding characteristics
- Increased hot tear resistance
- Improved mechanical properties
- Increased pressure tightness

- Improved response to thermal treatment
- Improved appearance following chemical, electrochemical, and mechanical finishing

The type and size of grains formed are functions of alloy composition, solidification rate, and the concentration of effective grain nucleation sites provided by the use of grain refiners. Grain refinement can be achieved by employing faster solidification rates as in permanent mold casting or high-pressure die casting and through the use of suitable grain refiners. The most widely used grain refiners are master alloys of titanium, or of 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 1% and titanium-to-boron ratios ranging from about 1 to 50 [13]. It should be noted that 1:1 ratio Ti:B master alloys, and even pure B, have been shown to be effective grain refiners of Al-Si alloys. They are less effective on non-Si-containing foundry or wrought compositions. Recent developments also include master alloys which include both grain refinement elements and compounds as well as Sr for modification. Titanium and aluminum carbides are also considered effective in the nucleation of grains. Ti-carbide-based grain refiners are used in operations such as direct chill casting in which there is a short residence time between addition in a trough and solidification as a billet as they will eventually convert to Al carbides if left in holding furnaces for long periods [1].

To be effective, grain refiners must introduce controlled, predictable, and operative quantities of aluminides and borides or carbides in the correct form, size, and distribution for grain nucleation. Refiners in rod form, developed for the continuous treatment of aluminum in primary operations and displaying clean, fine, unagglomerated microstructures are available in sheared lengths for foundry use. In addition to grain-refining master alloys in waffle or rolled rod form, salts, usually in compacted form that react with molten aluminum to form combinations of TiAl_3 and TiB_2 , are also available.

Transduced ultrasonic energy has been shown to provide degrees of grain refinement under laboratory conditions [19, 20]. No commercial use of this technology has been demonstrated. The application of this method to engineered castings can be a problem.

Despite much progress in understanding the fundamentals of grain refinement, no universally accepted theory or mechanism exists to satisfy laboratory and industrial experience [1]. It is known that TiAl_3 is an active phase in the nucleation of aluminum crystals, ostensibly because of similarities in crystallographic lattice spacing. Nucleation may occur on TiAl_3 substrates that are undissolved or precipitate at sufficiently high titanium concentrations by peritectic reaction. Grain refinement can be achieved at much lower titanium concentrations than those predicted by the binary Al-Ti peritectic point of 0.15%. For this reason, other theories, such as conucleation of the aluminide by TiB_2 or carbides and constitutional effects on the peritectic reaction, are presumed to be influential. Other findings also suggest the active role of more complex borides of the Ti-Al-B type in grain nucleation [21, 22].

Dissolved Ti and other elements, can influence the grain size via the growth restriction factor (GRF). Essentially, each dissolved element is treated as a constitutional undercooling agent and the effects are summed according to

$$\text{GRF} = \sum (k_i - 1)m_i C_0 \quad (7.2)$$

where k_i and m_i are the distribution coefficient between liquid and solid and the slope of the liquidus line for the i th element, respectively, and C_0 is the solute concentration [1].

Modification of Aluminum—Silicon Alloys

Cast components are produced from both hypo- and hypereutectic Al-Si alloys. The silicon morphology in these two groups of alloys should be modified to improve the mechanical properties. In case of hypoeutectic and eutectic alloys, the acicular and flaky form of silicon can be modified to a more fibrous eutectic structure by increasing solidification rate and by the addition of chemical modifiers (Figs. 7.4 and 7.14). Calcium, sodium, strontium, and antimony are known to influence the degree of eutectic modification that can be achieved during solidification. Figures 7.15 and 7.16 illustrate modification achieved by growth conditions and P-modifier additions for hypo- and hypereutectic Al-Si alloys [26].

Sodium is arguably the most potent modifier followed by strontium and calcium, but its effects are transient because of oxidation and vapor pressure losses. Strontium is less transient but may be less effective for modification under slow solidification rates (Fig. 7.17). Very low sodium concentrations ($\sim 0.001\%$) are required for effective

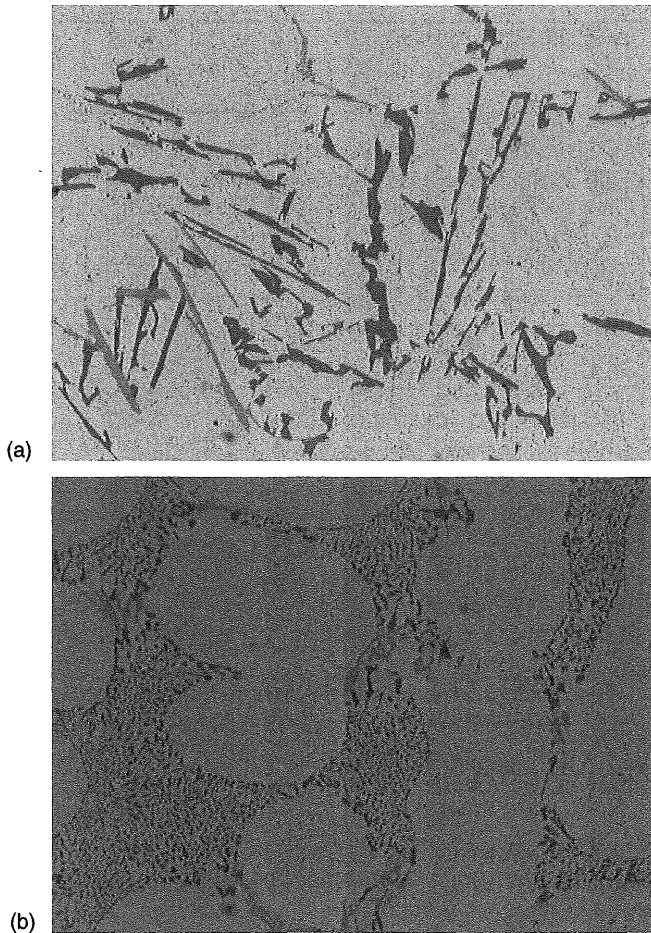


FIGURE 7.14 Optical micrographs of 356 alloy showing unmodified and Sr-modified conditions, $\times 500$. (From Shankar [25].) (a) Unmodified, (b) 0.009% Sr and (Continued)

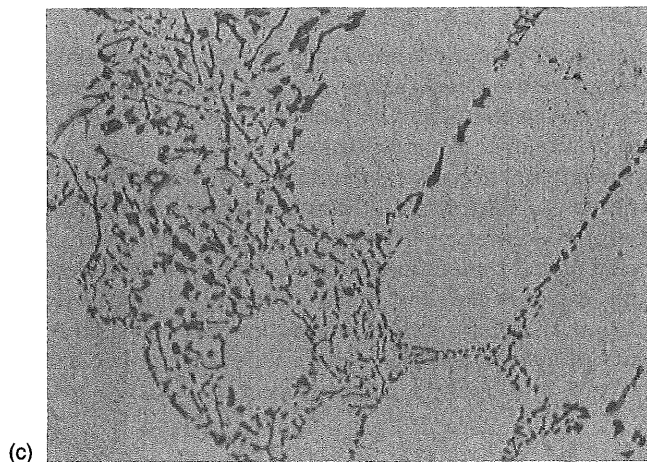


FIGURE 7.14 (c) 0.19% Sr. (Continued)

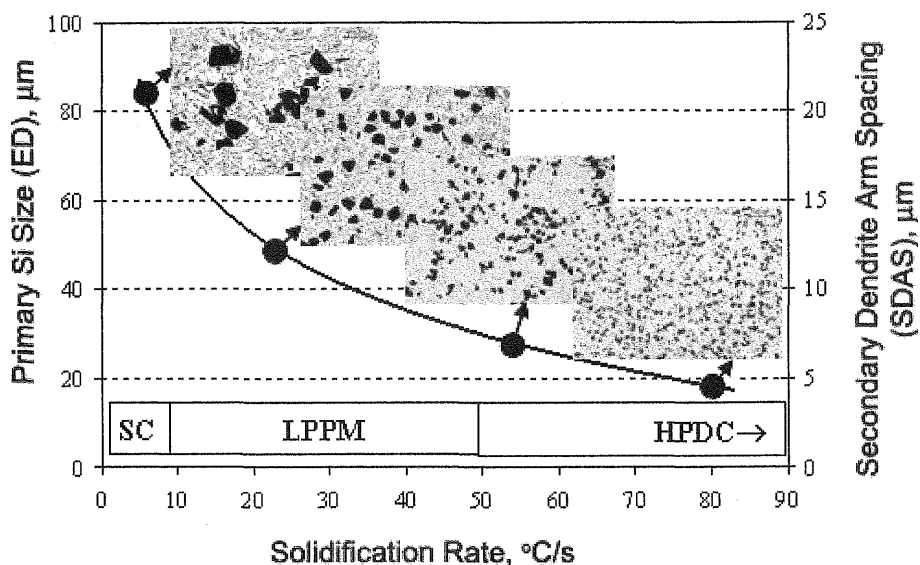


FIGURE 7.15 Microstructure refinement as a function of the cylinder block solidification rate established based on advanced laboratory solidification experiments. Note that the typical solidification rate for sand casting (SC), low-pressure permanent mold (LPPM), and high-pressure die casting (HPDC) are noted. (From Kasprzak et al. [26].)

modification. More typically, additions are made to obtain a sodium content in the melt of 0.005 to 0.015% in order to obtain practical casting times between remodification additions.

The combination of sodium and strontium offers advantages in initial effectiveness. Calcium is a weak modifier with little commercial value. Antimony provides a sustained effect, although the result is a finer lamellar rather than fibrous

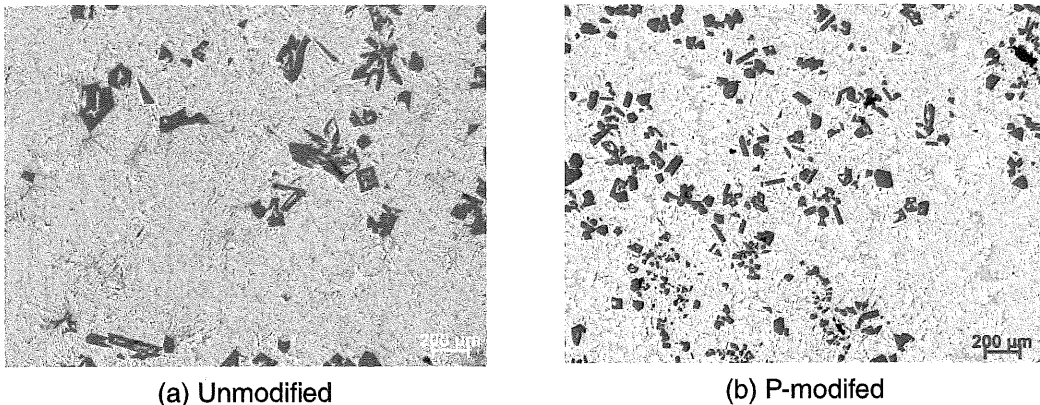


FIGURE 7.16 Optical micrographs of Al-20% Si alloy HPDC cylinder block showing microstructures for unmodified and P-modified conditions. (a) Unmodified and (b) P-modified (From Kasprzak et al. [4].)

eutectic. As a result, although permanent, the end, result obtained via antimony is not as good. In fact, particularly at low freezing rates, very large lamellar structures can arise. Antimony may give worse results than even unmodified alloys. Antimony is not compatible with other modifying elements.

A much wider range of strontium concentrations is in use. In general, addition rates far exceed those required for effective sodium modification. An operating range of 50 ppm wide between 0.004 and 0.020% (40 and 200 ppm) is the modern standard industry practice. Normally, good modification is achievable in the range of 0.004 to 0.015% Sr. Remodification through strontium additions may be required, although retreatment is less frequent than for sodium particularly at the lower Sr levels where fade rates can be quite low. Strontium additions are usually made through master alloys containing either 10 or 90% Sr in aluminum.

Modifier additions are usually accompanied by an increase in porosity. In the case of sodium and calcium, the reactions involved in element solution are invariably turbulent or are accompanied by compound reactions that by their nature increase dissolved hydrogen levels and entrained oxide levels. The use of hygroscopic salts including NaCl and NaF for modification also risks oxide formation and increased dissolved hydrogen content.

Typically, modified structures display higher tensile properties and appreciably improved ductility when compared to unmodified structures (Table 7.6). Property improvement is dependent on the degree to which porosity associated with the addition of modifiers is suppressed. Improved casting results include improved feeding and superior resistance to elevated-temperature cracking.

It is possible to achieve a state of overmodification, in which eutectic coarsening occurs, when sodium and/or strontium are used in excessive amounts (Fig. 7.14c). Reduced fluidity and susceptibility to porosity-related problems are usually encountered well before overmodification may be experienced.

It has been well established that phosphorus interferes with the modification mechanism. Phosphorus reacts with sodium and probably with strontium and calcium to

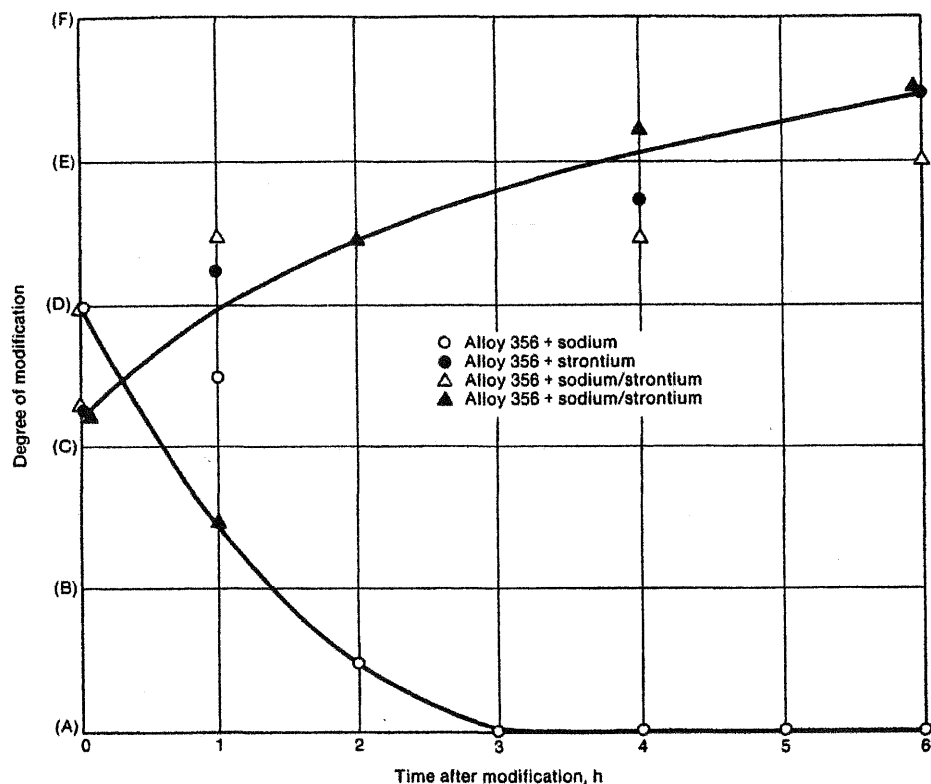


FIGURE 7.17 Effectiveness of sodium and strontium modifiers as a function of time. (From Kaufman and Rooy [13].)

form phosphides that nullify the modification additions. It is, therefore, desirable to use low-phosphorus metal when modification is a process objective and/or to make larger modifier additions to compensate for phosphorus-related losses. Primary producers control phosphorus contents in smelting and processing through the judicious choice of feed materials to provide less than 0.001% of phosphorus in alloyed ingot.

Thermal analysis is useful in assessing the degree of modification that can be displayed by the melt. This is shown schematically in Fig. 7.18 [23]. The effectiveness of modification treatment is defined by the degree and duration of undercooling at the solidus. With modification, the eutectic temperature is depressed, the undercooling for nucleation of the eutectic is increased, and the period of this undercooling is lengthened. Test results must be correlated with the degree of modification established metallographically for the castings since cooling rates for the sample will differ.

The feature most used in thermal analysis control of modification is the depression of the eutectic temperature by 6 to 8°C from the unmodified state (Fig. 7.19). Since the eutectic temperature is easy to measure, it is most often employed by foundries to assess whether a melt is properly modified or not.

Alloy and Temper	Product	Modification Treatment	Tensile Yield Strength		Ultimate Tensile Strength		Elongation %
			Ksi	MPa	Ksi	MPa	
13% Si	Sand cast test bars	None	—	—	18.0	124	2.0
		Na-modified	—	—	28.0	193	13.0
	Permanent mold test bars	None	—	—	28.0	193	3.6
		Na-modified	—	—	32.0	221	8.0
359.0	Permanent mold test bars	None	—	—	26.1	180	5.5
		0.07% Sr	—	—	30.5	210	12.0
356.0-T6	Sand cast test bars	None	30.1	208	41.9	289	2.0
		0.07% Sr	31.6	218	42.2	291	7.2
	Bars cut from chilled sand casting	None	30.9	213	41.2	293	3.0
		0.07% Sr	31.6	218	32.2	291	7.2
A356.0-T6	Sand cast test bars	None	26.0	179	40.0	226	4.8
		0.01% Sr	30.0	207	43.0	297	8.0
A444.0-T4	Permanent mold test bars	None	—	—	21.9	151	24.0
		0.07% Sr	—	—	21.6	149	30.0
A413.2	Sand cast test bars	None	16.3	112	19.8	137	1.8
		0.005-0.05% Sr	15.6	108	23.0	159	8.4
	Permanent mold test bars	None	18.1	125	24.4	168	6.0
		0.005–0.08% Sr	18.1	125	27.7	191	12.0
	Test bar cut from auto wheel	0.05% Sr	17.5	121	28.0	193	10.6
		0.06% SR	18.2	126	28.0	193	12.8

Source: From Kaufman and Rooy [13].

TABLE 7.6 Typical Mechanical Properties of Modified and Unmodified Cast Aluminum Alloys

Refinement of Hypereutectic Aluminum-Silicon Alloys

Hypereutectic Al-Si alloys commonly used in the foundry industry contain 14 to 20% Si. Microstructure of such alloys is characterized by coarse primary silicon crystals that are harmful in the casting and machining of components [13, 26–28]. Normal practice is to add phosphorus 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 which lead to a marked effect on the distribution and form of the primary silicon phase (Fig. 7.16). Retained concentrations

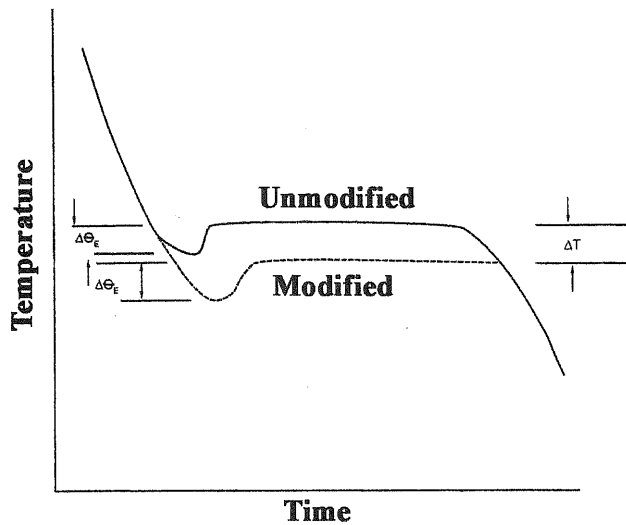


FIGURE 7.18 A comparison of the cooling curves of the eutectic regions of modified and unmodified alloys. (From Gruzleski and Closset [23].)

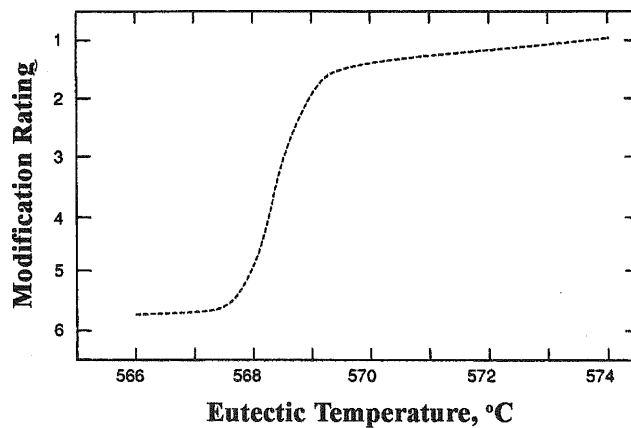


FIGURE 7.19 Relation between modification rating and the eutectic temperature for A356 alloy. (From Gruzleski and Closset [23].)

of phosphorus as low as 0.0015% are effective in achieving refinement of the primary phase. Primary silicon crystals can also be modified by increasing the cooling rate as shown in Fig. 7.15 and comparing Figs. 7.16*a* and *b* [28].

Phosphorus content can vary between 0.0015 and 0.03%. 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 used to reactivate aluminum phosphide nuclei, (which is responsible for silicon refinement) presumably by resuspension.

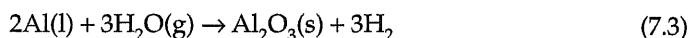
Practices recommended for melt refinement are as follows:

- Melting and holding temperature should be minimum.
- Calcium and sodium contents should be controlled to low concentration levels.
- Brief nitrogen or argon 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.

Porosity

Internal porosity in complex aluminum castings has detrimental effects on the mechanical properties and pressure tightness. Porosity in aluminum is caused by the precipitation of hydrogen from liquid solution or by shrinkage during solidification, and more usually by a combination of these effects.

Hydrogen is the only gas that is appreciably soluble in aluminum and its alloys. The main source of hydrogen is the water vapor in the atmosphere, which reacts with aluminum by the reaction [23, 29]:



Other sources of hydrogen include

- Fluxes, which are often hygroscopic and contain chemically attached water
- Solid additives, such as scrap, grain refiners, or even virgin ingots. All of these may contain adsorbed moisture or entrapped gases originating in a prior processing operation
- Tools, crucibles, furnace linings, and mold materials, which, if not preheated, may contain moisture
- Scraps, castings, machine turnings and borings, die-cast trim press scrap, gates and risers, and sand and other nonmetallic molding material debris.
- Fuel-fired furnaces (natural gas, oil) which have hydrogen available from fossil fuels
- Mold materials

Hydrogen solubility in both liquid and solid pure aluminum follows Sievert's law, which states that

$$\text{Solubility} = K_s \sqrt{P_{\text{GAS}}} \quad (7.4)$$

where K_s is Sievert's constant and P_{GAS} is the partial pressure of the gas in the atmosphere above the melt.

Since solubility of hydrogen is directly proportional to the square root of the hydrogen partial pressure, a lowering of the partial pressure by 25 times results in only a fivefold solubility decrease [29].

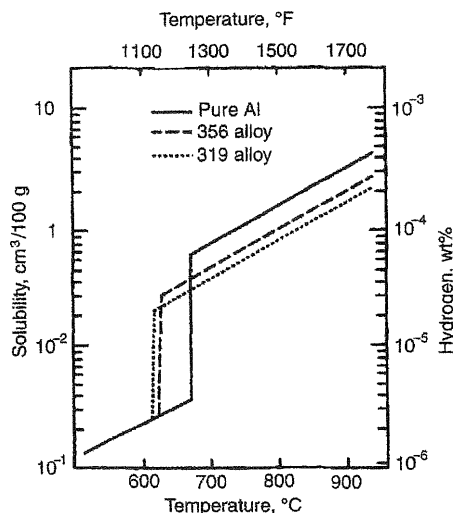


FIGURE 7.20 Hydrogen solubility in aluminum casting alloys. (From *ASM Handbook* [1, p. 185].)

Temperature is the most important factor affecting hydrogen solubility. As shown in Fig. 7.20 [1], hydrogen solubility is considerably greater in the liquid than in the solid state. Actual liquid and solid solubilities in pure aluminum just above and below the solidus are 0.69 and 0.04 ppm ($\text{cm}^3/100 \text{ g}$) at the melting point (660°C or 1220°F) [29].

This confirms the facts that the solubility of hydrogen in liquid pure aluminum is more than 16 times the solubility of hydrogen in solid aluminum, and the equilibrium partition coefficient of hydrogen in aluminum is significantly less than 1.

Alloying elements have a strong and varying influence on the solubility of hydrogen in aluminum. For example, in liquid aluminum, silicon, copper, zinc, and iron decrease hydrogen solubility, whereas lithium, magnesium, and titanium increase it as shown in Fig. 7.21 [1].

Shrinkage Porosity

Shrinkage porosity is caused by volumetric contraction during solidification, especially from the liquid to the solid state which ranges from 3 to 8.5% for aluminum alloys. It is also affected by the solidification range of the alloy.

Shrinkage can appear as distributed voids or microshrinkage because of failure during the last stages of interdendritic feeding. The other form of shrinkage is centerline or piping voids resulting from gross directional effects. Short freezing range alloys such as 356.0 and 413.0 exhibit extensive piping as opposed to distributed shrinkage porosity due to directional solidification. By contrast, long freezing range alloys are prone to extensive microporosity resulting from interdendritic feeding. Effective gating and

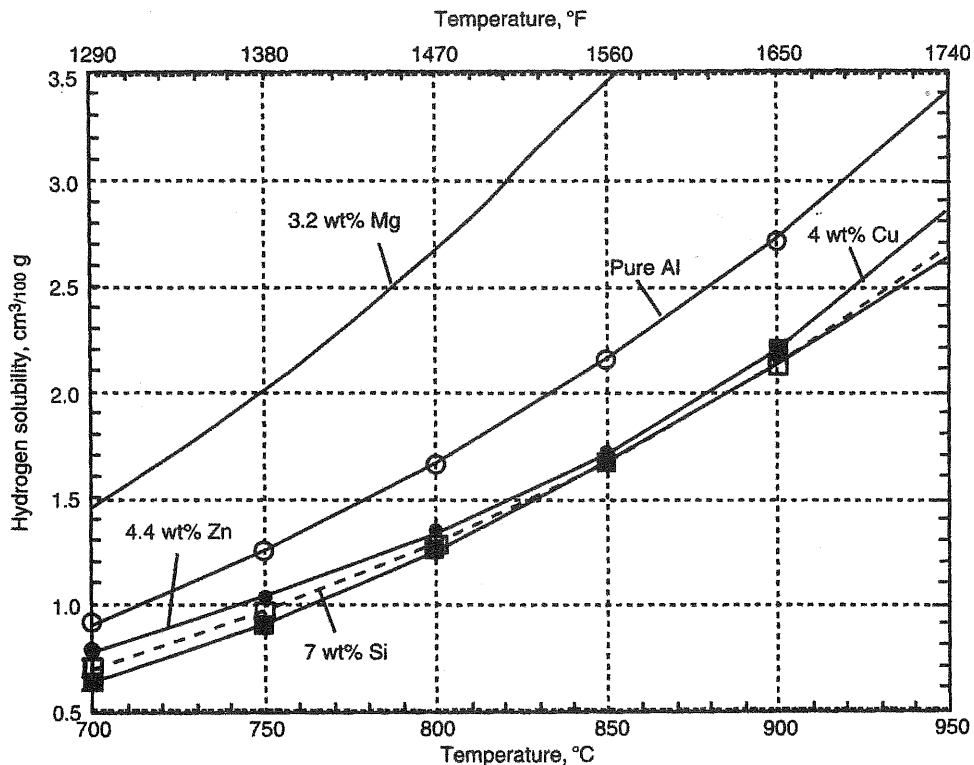


FIGURE 7.21 Hydrogen solubility in liquid pure aluminum and binary aluminum alloys at 1 atm hydrogen partial pressure. (From *ASM Handbook* [1, p. 68].)

rising design together with use of chills to promote directional solidification is likely to minimize the formation of microporosity.

Improved modification and refinement of aluminum-silicon alloys, improved grain refinement, and reduced oxide contents all improve feedability and therefore reduce shrinkage severity.

Typical porosity in cast aluminum alloys is shown in Fig. 7.22 [23].

Inclusions

Two types of inclusions are found in castings. These are exogenous and indigenous. The former originates from outside the bulk melt and consists of refractory bits broken off from furnace linings or crucible, flux particles or pieces of slags or dross, broken ceramic filters or loose sand left in the gating system. Indigenous inclusions are a result of the chemical reaction between the melt and some other chemical species.

Alumina (Al_2O_3) is the most common inclusion in aluminum alloy castings since aluminum oxidizes readily in liquid and solid states. Oxidation rate is greater at molten metal temperatures and increases with temperature and time of exposure. Magnesium

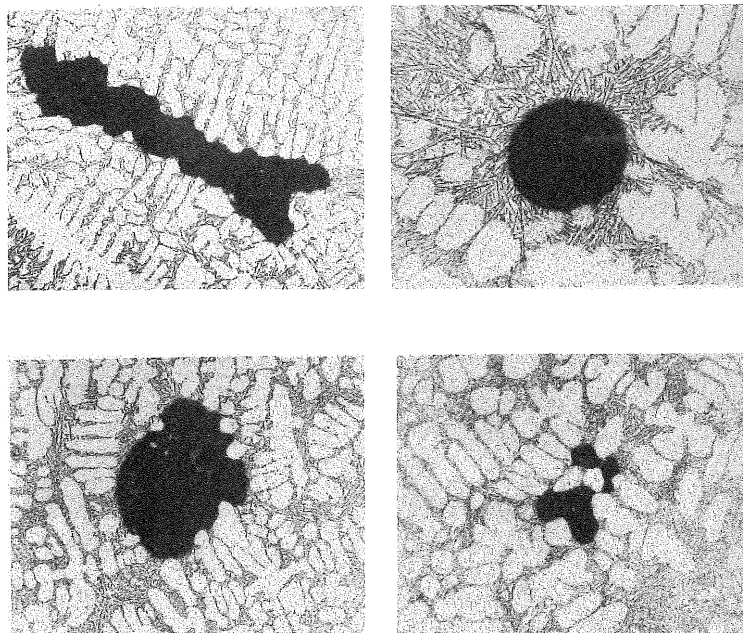
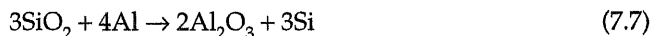


FIGURE 7.22 Typical porosity in cast aluminum alloys. (From Gruzleski and Closset [23].)

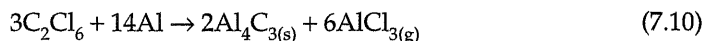
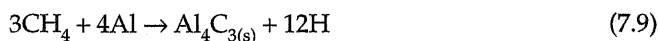
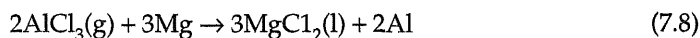
in aluminum alloys oxidizes and with time and temperature reacts with oxygen and aluminum oxide to form spinel as shown below [29]:



Liquid aluminum being a powerful oxidant can react with various refractory materials such as silica to form small alumina inclusions as shown below:



Other sources of inclusion due to chemical reaction are those between magnesium and aluminum chloride gas (due to halide flux treatment), aluminum—methane reaction due to combustion of natural gas and decomposition of hexachloroethane tablets [29].



These inclusions are categorized in Table 7.7 [13].

While the oxide that initially forms on the surface of molten aluminum is highly protective and self-limiting, any agitation or turbulence in the treatment and handling of molten aluminum increases the risk of oxide entrainment and the immediate reformation of additional oxides. Oxide concentration can increase when alloying additions

Classification	Types Observed	Potential Source(s)
Nonmetallic exogenous	Various refractory particles, Al_4C_3 , etc.	Refractory degradation, remelt ingot, refractory/metal reactions
Nonmetallic in situ	MgO , Al_2O_3 films, clusters, and dispersoids; MgAl_2O_4 films and clusters	Melting, alloying metal transfer turbulence
Homogenous halide salts	MgCl_2 - NaCl - CaCl_2 , etc.	Poor separation of fluxing reaction products
Particle/salt	MgCl_2 - NaCl - CaCl_2 / MgO , etc.	Salt generated during chlorine fluxing of magnesium-containing alloys, filter and metal-handling system releases

Source: From Kaufman and Rooy [13], p. 51.

TABLE 7.7 Inclusion Sources and Types in Aluminum Alloy Castings

are stirred into the melt, when reactive elements and compounds are immersed, when metal is drawn for pouring, and when metal is poured and conducted by the gating system into the mold cavity. Induction melting is highly energy efficient and effective for melting fines and poor-quality scrap, but electromagnetically induced eddy currents result in a high level of entrained oxides.

Care should be taken in pouring, gating, and minimizing the reoxidation of the metal to control inclusions in castings. Molten metal filtrations can be effective in minimizing the inclusion level. This is needed to produce high-integrity, high-strength castings where fracture toughness characteristics are important.

Hydrogen pore formation can be suppressed by removing oxides from the melt.

Degassing

Gas purging is the most common method of degassing a melt. The principle is illustrated in Fig. 7.23. A bubble of some gas is introduced into the bottom of a melt. The gas may be inert or reactive with the metal concerned, but initially it must contain no atoms of the gas species to be removed from solution. Since partial pressure of the gas to be removed is initially zero in the bubble, there exists a driving force for diffusion of gas atoms from the liquid into the introduced bubble. As this bubble rises through the bath, it will pick up progressively more and more of the undesirable dissolved gas until it finally escapes from the free surface of the melt [29].

The first application of this principle was through decomposition of hexachloroethane (C_2Cl_6) tablet where the tablet is plunged into the aluminum melt using a perforated bell-shaped steel plunger. When submerged and plunged into the melt, the hexachloroethane decomposes into its respective components. The chlorine component immediately forms a metastable aluminum chloride gaseous compound, which is insoluble in the melt and serves as the purge gas. With any purge gas, the monatomic hydrogen diffuses into the purge gas bubble, combines with another hydrogen atom to form molecular hydrogen, and the bubble rises to the surface, where both gaseous species are released. Despite the environmental concerns because of the chlorine gas, this method of degassing is still used in some foundries.

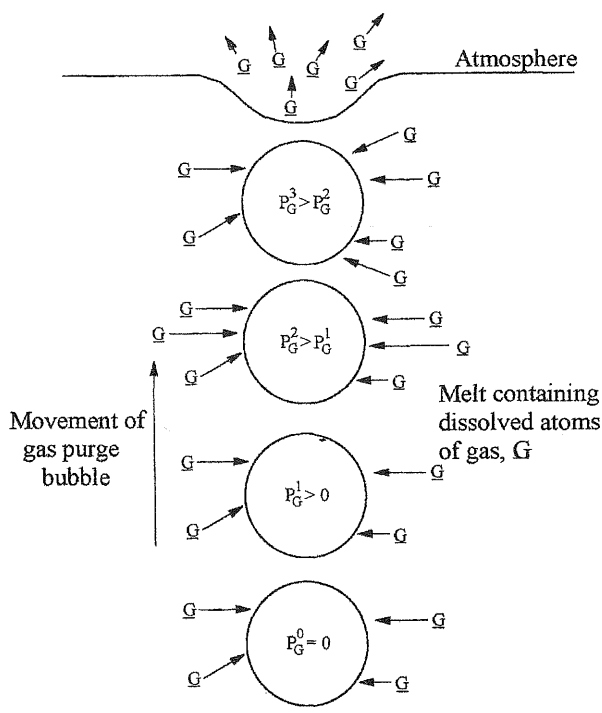


FIGURE 7.23 The principle of gas purging to remove dissolved gas. (From Gruzleski [29].)

The second method is purging an inert gas such as argon and nitrogen through a steel or graphite lance under low pressure (less than 207 kPa or 30 Psi) into the melt. The insoluble nitrogen or argon gas bubble then rises within the melt, and the hydrogen atoms diffuse to this process gas bubble and form a hydrogen molecule. When the bubble reaches the surface of the melt, the hydrogen is released. If the relative humidity in the atmosphere is particularly high, this will be a dynamic process because new hydrogen may become absorbed into the melt.

The lance degassing technology is relatively inefficient because of the large bubble size that emanates from the bottom of the lance, especially in the case of large vessels. It is important to produce a very fine dispersion of bubbles to be effective in a minimum of time. To this end, gas purging through a rotary impeller degasser consisting of a series of vanes which chops a gas stream into a mass of fine gas bubbles and then disperses them throughout the melt (Fig. 7.24). The effect of bubble size in degassing efficiency is shown in Fig. 7.25.

The rotary impeller degassing technique was introduced into the aluminum foundry industry in the mid-1980s and is used extensively in melting furnaces, transfer ladles, and in continuous-flow launder systems.

The basic components of a rotor degassing system include a mechanical drive unit to rotate the shaft/rotor assembly, a gas source, and controls to manipulate the gas injection into the system, and the shaft/rotor assembly itself. Equipment can be as simple as well-mounted drive unit or more complex, with a fixed-mast drive-up ladle treatment station or a mobile unit that can be moved from furnace to furnace.

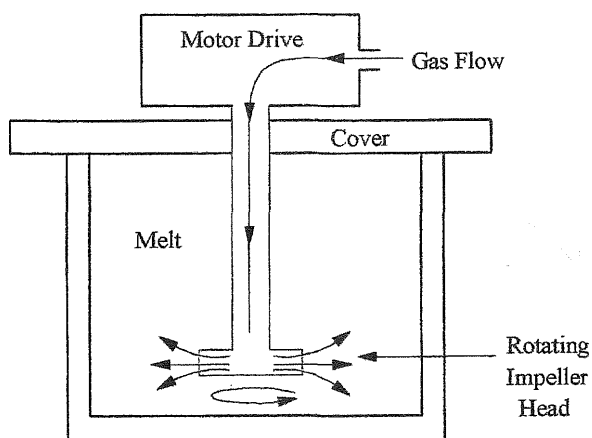


FIGURE 7.24 A schematic of a rotary impeller degassing unit is shown. The rotating impeller chops the gas stream into a mass of fine bubbles that provide very efficient degassing of the melt. (From Gruzleski [29].)

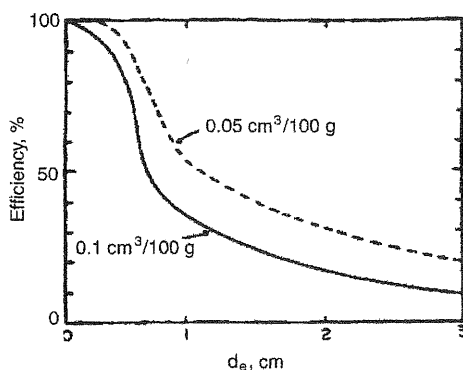


FIGURE 7.25 Degassing efficiency as a function of purge gas bubble size. (From ASM Handbook [1, p. 187].)

Drossing

Melting occurs most rapidly if a heel of molten aluminum is present when the charge is added. Melting down with minimum dross formation occurs when the charge is protected from combustion products and melting is rapid. Drossing is the formation of aluminum oxide and other oxides which accumulate on the melt surface. Complete separation of dross and metal would be favored by large differences in their specific gravities. Unfortunately, the specific gravities of the oxides and the molten metal are of similar magnitude, as revealed in Table 7.8. Some oxides float on the melt surface (i.e., dross) whereas others sink and form a sludge.

Compound	Specific Gravity (20°C)
Al_2O_3	3.99
$\text{Al}_2\text{O}_3 \cdot 3\text{H}_2\text{O}$	2.42
Al	2.70
MgO	3.65
Mg	1.74
Si	2.40
SiO_2	2.20–2.60
CuO	6.40
Cu_2O	6.0

Source: From Heine et al. [11].

TABLE 7.8 Specific Gravity of Some Materials in Drosses

Mechanical and Physical Properties

Typical mechanical and physical properties of some common aluminum casting alloys are summarized in Tables 7.14 and 7.15, respectively. The mechanical properties for sand and permanent mold casting conditions are for both cast and heat treated conditions and are aimed at comparing with other alloys. In the case of die-casting alloys, as-cast mechanical properties are included except alloy 390, where T5 condition mechanical properties have been added. In general, the mechanical properties of casting alloys are dependent on alloying, heat treatment, and casting conditions.

Other mechanical properties such as fatigue strength, creep, endurance limit, compressive strength, and shear strength are also important from a design point of view. These data can be obtained from pertinent specifications, design standards, and producers.

The physical properties include solidification range, electrical conductivity, thermal conductivity, and coefficient of thermal expansion.

		Ultimate Tensile Strength		0.2% Offset Yield Strength		Elongation In	
Alloy	Temper	MPa	Ksi	MPa	Ksi	50 mm (2 In)	HB*
Sand Casting Alloys							
201.0	T43	414	60	255	37	17.0	–
	T6	448	65	379	55	8.0	130
	T7	467	68	414	60	5.5	–
A206.0	T4	354	51	250	36	7.0	–
319.0	F	186	27	124	18	2.0	70
	T5	207	30	179	26	1.5	80
	T6	250	36	164	24	2.0	80
355.0	F	159	23	83	12	3.0	–
	T51	193	28	159	23	1.5	65
	T6	241	35	172	25	3.0	80
	T61	269	39	241	35	1.0	90
	T7	264	38	250	26	0.5	85
	T71	241	35	200	29	1.5	75
C355.0	T6	269	39	200	29	5.0	85
356.0	F	164	24	124	18	6.0	–
	T51	172	25	138	20	2.0	60
	T6	228	33	164	24	3.5	70
	T7	234	34	207	30	2.0	75
	T71	193	28	145	21	3.5	60
A356.0	F	159	23	83	12	6.0	–
	T51	179	26	124	18	3.0	–
	T6	278	40	207	30	6.0	75
	T71	207	30	138	20	3.0	–
357.0	F	172	25	90	13	5.0	–
	T51	179	26	117	17	3.0	–
	T6	345	50	296	43	2.0	90
	T7	278	40	234	34	3.0	60
A357.0	T6	317	46	248	36	3.0	85
A390.0	F	179	26	179	26	<1.0	100
	T5	179	26	179	26	<1.0	100
	T6	278	40	278	40	<1.0	140
	T7	250	36	250	36	<1.0	115
443.0	F	131	19	55	8	8.0	40
A444.0	F	145	21	62	9	9.0	–
	T4	159	23	62	9	12.0	–
520.0	T4	331	48	179	26	16.0	75
A535.0	F	250	36	124	18	9.0	65

TABLE 7.14 Typical Mechanical Properties of Aluminum Casting Alloys (Continued)

Alloy	Temper	Ultimate Tensile Strength		0.2% Offset Yield Strength		Elongation in 50 mm (2 in)	HB*
		MPa	Ksi	MPa	Ksi		
712.0 (h)	F	241	35	172	25	5.0	75
850.0	T5	138	20	76	11	8.0	45
Permanent Mold Casting Alloys							
A206.0	T4	431	62	264	38	17.0	–
	T7	436	63	347	50	11.7	–
319.0	F	185	27	125	18	2.0	85
	T6	248	36	165	24	2.0	95
A356.0	T61	283	41	207	30	10.0	90
357.0	F	193	28	103	15	6.0	–
	T51	200	29	145	21	4.0	–
	T6	359	52	296	43	5.0	100
A357.0	T6	359	52	290	42	5.0	100
A390.0	F	200	29	200	29	<1.0	110
	T5	200	29	200	29	<1.0	110
	T6	310	45	310	45	<1.0	145
	T7	262	38	262	38	<1.0	120
A444.0	F	165	24	76	11	13.0	44
	T4	159	23	69	10	21.0	45
513.0	F	186	27	110	16	7.0	60
711.0	F	248	36	130	36	8.0	70
850.0	T5	159	23	76	11	12.0	45
Die-Casting Alloys							
360.0	F	324	47	172	25	3.0	75
A360.0	F	317	46	165	24	5.0	75
364.0	F	296	43	159	23	7.5	–
380.0	F	331	48	165	24	3.0	80
A380.0	F	324	47	159	23	4.0	75
384.0	F	324	47	172	25	1.0	–
390.0	F	279	40.5	241	35	1.0	120
	T5	296	43	265	38.5	1.0	–
392.0	F	290	42	262	38	<0.5	–
413.0	F	296	43	145	21	2.5	80
A413.0	F	241	35	110	16	3.5	80
513.0	F	276	40	152	22	10.0	–
515.0	F	283	41	–	–	10.0	–
518.0	F	310	45	186	27	8.0	80

*500 kg (1100 lb) load on 10 mm (0.4 in) ball.

Source: From *ASM Handbook* [1, p. 1080] (sand casting), Davis [12, p. 113] (permanent mold and die casting).

TABLE 7.14 Typical Mechanical Properties of Aluminum Casting Alloys (*Continued*)

Alloy	Temper and Product Form	Approximate Melting Range		Electrical Conductivity, % IACS	Thermal Conductivity at 25°C (77°F), W/m·K	Coefficient of Thermal Expansion per °C × 10 ⁻⁶ (per °F × 10 ⁻⁶)	
		°C	°F			20–100°C (68–212°F)	20–300°C (68–570°F)
201.0	T6 (S)	570–650	1060–1200	27–32	0.29	34.7 (19.3)	44.5 (24.7)
206.0		570–650	1060–1200	–	0.29	–	–
A206.0		570–650	1060–1200	–	0.29	–	–
319.0	F (S)	520–605	970–1120	27	0.27	21.6 (12.0)	24.1 (13.4)
	F (P)	520–605	970–1120	28	0.28	21.6 (12.0)	24.1 (13.4)
354.0	F (P)	540–600	1020–1150	32	0.30	20.9 (11.6)	22.9 (12.7)
355.0	T51 (S)	550–620	1020–1150	43	0.40	22.3 (12.4)	24.7 (13.7)
	T6 (S)	550–620	1020–1150	36	0.34	22.3 (12.4)	24.7 (13.7)
356.0	T6 (S)	560–615	1040–1140	39	0.36	21.4 (11.9)	23.4 (13.0)
A356.0	T6 (S)	560–610	1040–1130	40	0.36	21.4 (11.9)	23.4 (13.0)
357.0	T6 (S)	560–615	1040–1140	39	0.36	21.4 (11.9)	23.4 (13.0)
A357.0	T6 (S)	555–610	1030–1130	40	0.38	21.4 (11.9)	23.6 (13.1)
A380.0	F (D)	520–590	970–1090	27	0.26	21.1 (11.7)	22.7 (12.6)
390.0	F (D)	510–650	950–1200	25	0.32	18.5 (10.3)	–
413.0	F (D)	575–585	1070–1090	39	0.37	20.5 (11.4)	22.5 (12.5)
A413.0	F (D)	575–585	1070–1090	39	0.37	–	–
443.0	F (D)	575–630	1070–1170	37	0.35	22.1 (12.3)	24.1 (13.4)
A444.0	F (P)	575–630	1070–1170	41	0.38	21.8 (12.1)	23.8 (13.2)
520	T4 (S)	450–600	840–1110	21	0.21	25.2 (14.0)	27.0 (15.0)
535.0	F (S)	550–630	1020–1170	23	0.24	23.6 (13.1)	26.5 (14.7)
A535.0	F (D)	550–620	1020–1150	23	0.24	24.1 (13.4)	26.1 (14.5)
B535.0	F (S)	550–630	1020–1170	24	0.23	24.5 (13.6)	26.5 (14.7)
710.0	F (S)	600–650	1110–1200	35	0.33	24.1 (13.4)	26.3 (14.6)
711.0	F (P)	600–645	1110–1190	40	0.38	23.6 (13.1)	25.6 (14.2)
712.0	F (S)	600–640	1110–1180	40	0.38	23.6 (13.1)	25.6 (14.2)
713.0	F (S)	595–630	1110–1170	37	0.37	23.9 (13.3)	25.9 (14.4)
850.0	T5 (S)	225–650	440–1200	47	0.44	–	–
851.0	T5 (S)	230–630	450–1170	43	0.40	22.7 (12.6)	–
852.0	T5 (S)	210–635	410–1180	45	0.42	23.2 (12.9)	–

Note: S = sand cast, P = permanent mold, D = die cast. The specific gravity and weight data in this table assume solid (void-free) metal because some porosity cannot be avoided in commercial castings; their specific gravity or weight is slightly less than theoretical value.

Source: From *ASM Handbook*, [1, p. 1078].

TABLE 7.15 Typical Physical Properties of Aluminum Casting Alloys