



Article

Aluminum and Aluminum Alloys Casting Problems

Abstract:

Aluminum castings have played an integral role in the growth of the aluminum industry since its inception in the late 19th century. The first commercial aluminum products were castings, such as cooking utensils and decorative parts, which exploited the novelty and utility of the new metal. Those early applications rapidly expanded to address the requirements of a wide range of engineering specifications.

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, and property development has been advanced to assist the foundry man with the means of economical and reliable production of parts that consistently meet specified requirements.

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Today, aluminum alloy castings are produced in hundreds of compositions by all commercial casting processes, including green sand, dry sand, composite mold, plaster mold, investment casting, permanent mold, counter-gravity low-pressure casting, and pressure die casting.

Alloys can also be divided into two groups: those most suitable for gravity casting by any process and those used in pressure die casting. A finer distinction is made between alloys suitable for permanent mold application and those for other gravity processes.

Material constraints that formerly limited the design engineer's alloy choice once a casting process had been selected are increasingly being blurred by advances in foundry technique. In the same way, process selection is also less restricted today. For example, many alloys thought to be unusable in permanent molds because of casting characteristics are in production by that process.

Melting and Metal Treatment

Aluminum and aluminum alloys can be melted in a variety of ways. Coreless and channel induction furnaces, crucible and open-hearth reverberatory furnaces fired by natural gas or fuel oil, and electric resistance and electric radiation furnaces are all in routine use. The nature of the furnace charge is as varied and important as the choice of furnace type for metal casting operations. The furnace charge may range from prealloyed ingot of high quality to charges made up exclusively from low-grade scrap.

Even under optimum melting and melt-holding conditions, molten aluminum is susceptible to three types of degradation:

- With time at temperature, adsorption of hydrogen results in increased dissolved hydrogen content up to an equilibrium value for the specific composition and temperature
- With time at temperature, oxidation of the melt occurs; in alloys containing magnesium, oxidation losses and the formation of complex oxides may not be self-limiting
- Transient elements characterized by low vapor pressure and high reactivity are reduced as a function of time at temperature; magnesium, sodium, calcium, and strontium, upon which mechanical properties directly or indirectly rely, are examples of elements that display transient characteristics.

Turbulence or agitation of the melt and increased holding temperature significantly increase the rate of hydrogen solution, oxidation, and transient element loss. The mechanical properties of aluminum alloys depend on casting soundness, which is strongly influenced by hydrogen porosity and entrained nonmetallic inclusions.

Hydrogen influence on aluminum

Hydrogen is the only gas that is appreciably soluble in aluminum and its alloys. Its solubility varies directly with temperature and the square root of pressure. During the cooling and solidification of molten aluminum, dissolved hydrogen in excess of the extremely low solid solubility may precipitate in molecular form, resulting in the formation of primary and/or secondary voids.

Drossing fluxes are designed to promote separation of the aluminum oxide (Al_2O_3) dross layer that forms on the surface of the melt from the molten metal. Drosses and liquid or solid metal are usually intermingled in the dross layer. The drossing fluxes are designed to react with Al_2O_3 in the slag or dross layer and to recover metal. The fluorides wet and dissolve thin oxide films according to the general reaction.

Hydrogen Sources. There are numerous sources of hydrogen in aluminum. Moisture in the atmosphere dissociates at the molten metal surface, offering a concentration of atomic hydrogen capable of diffusing into the melt. The barrier oxide of aluminum resists hydrogen solution by this mechanism, but

disturbances of the melt surface that break the oxide barrier result in rapid hydrogen dissolution. Alloying elements, especially magnesium, may also affect hydrogen absorption by forming oxidation reaction products that offer reduced resistance to the diffusion of hydrogen into the melt and by altering liquid solubility.

Hydrogen Porosity. Two types or forms of hydrogen porosity may occur in cast aluminum. Of greater importance is inter-dendritic porosity, which is encountered when hydrogen contents are sufficiently high that hydrogen rejected at the solidification front results in solution pressures above atmospheric. Secondary (micron-size) porosity occurs when dissolved hydrogen contents are low, and void formation is characteristically subcritical.

Finely distributed hydrogen porosity may not always be undesirable. Hydrogen precipitation may alter the form and distribution of shrinkage porosity in poorly fed parts or part sections. Shrinkage is generally more harmful to casting properties. In isolated cases, hydrogen may actually be intentionally introduced and controlled in specific concentrations compatible with the application requirements of the casting in order to promote superficial soundness.

Hydrogen in Solid Solution. The disposition of hydrogen in a solidified structure depends on the dissolved hydrogen level and the conditions under which solidification occurs. Because the presence of hydrogen porosity is a result of diffusion-controlled nucleation and growth, decreasing the hydrogen concentration and increasing the rate of solidification act to suppress void formation and growth. For this reason, castings made in expendable mold processes are more susceptible to hydrogen-related defects than parts produced by permanent mold or pressure die casting.

Hydrogen Removal. Dissolved hydrogen levels can be reduced by a number of methods, the most important of which is fluxing with dry, chemically pure nitrogen, argon, chlorine, and freon. Compounds such as hexachloroethane are in common use; these compounds dissociate at molten metal temperatures to provide the generation of fluxing gas.

Gas fluxing reduces the dissolved hydrogen content of molten aluminum by partial pressure diffusion. The use of reactive gases such as chlorine improves the rate of degassing by altering the gas/metal interface to improve diffusion kinetics. Holding the melt undisturbed for long periods of time at or near the liquidus also reduces hydrogen content to a level no greater than that defined for the alloy as the temperature-dependent liquid solubility.

Oxidation

Oxide Formation. Aluminum and its alloys oxidize readily in both the solid and molten states to provide a continuous self-limiting film. The rate of oxidation increases with temperature and is substantially greater in molten than in solid aluminum. The reactive elements contained in alloys such as magnesium, strontium, sodium, calcium, beryllium, and titanium are also factors in oxide formation. In both the molten and solid states, oxide formed at the surface offers benefits in self-limitation and as a barrier to hydrogen diffusion and solution. Induced turbulence, however, results in the entrainment of oxide particles, which resist gravity separation because their density is similar to that of molten aluminum.

Oxides are formed by direct oxidation in air, by reaction with water vapor, or by aluminothermic reaction with oxides of other metals, such as iron or silicon, contained in tools and refractories. Aluminum oxide is polymorphic, but at molten metal temperature the common forms of oxide encountered are crystalline and of a variety of types depending on exposure, temperature, and time. Some crystallographic oxide forms affect the appearance and coloration of castings, without other significant effects.

Oxide Separation and Removal. It is usually necessary to treat melts of aluminum and its alloys to remove suspended nonmetallics. This is normally accomplished by using either solid or chemically active gaseous fluxes containing chlorine, fluorine, chlorides, and/or fluorides. In each case, the objective is the dewetting of the oxide/melt interface to provide effective separation of oxides and other included matter and the flotation of these nonmetallics by attachment to either solid or gaseous elements or compounds introduced or formed during flux treatment.

Fluxes can also be used to minimize oxide formation. For this reason, melts containing magnesium are often protected by the use of salts that form liquid layers, most often of magnesium chloride, on the melt surface. These fluxes, termed covering fluxes, must be periodically removed and replaced. Carbon, graphite, and boron powder also effectively retard oxidation when applied to the melt surface.

Effects of Inclusions. In addition to oxides, a number of additional compounds can be considered inclusions in cast structures. All aluminum contains aluminum carbide (Al_4C_3) formed during reduction. Borides may also be present. By agglomeration, borides can assume sufficient size to represent a significant factor in the metal structure, with especially adverse effects in machining.

Under all conditions, inclusions whether in film or particle form are damaging to mechanical properties. The gross effect of inclusions is to reduce the effective cross section of metal under load. The more devastating effect on properties is that of stress concentration when inclusions appear at or near the surface of parts or specimens. Fatigue performance is reduced under the latter condition by the notch effect. Ultimate and yield strengths are typically lower, and ductility may be substantially reduced when inclusions are present.

Hard particle inclusions are frequently found in association with film-type oxides. Borides, carbides, oxides, and nonmetallic particles in the melt are scavenged and then concentrated in localized regions within the cast structure.

Structure Control

A number of factors define the metallurgical structure in aluminum castings. Of primary importance are dendrite cell size or dendrite arm spacing, the form and distribution of microstructural phases, and grain size. The foundryman can control the fineness of dendrite structure by controlling the rate of solidification.

Microstructural features such as the size and distribution of primary and intermetallic phases are considerably more complex dendrite cell size measurements are becoming increasingly important.

Grain Structure

A fine, equiaxed grain structure is normally desired in aluminum castings. The type and size of grains formed are determined by alloy composition, solidification rate, and the addition of master alloys (grain refiners) containing intermetallic phase particles, which provide sites for heterogeneous grain nucleation.

Grain Refinement Effects. A finer grain size promotes improved casting soundness by minimizing shrinkage, hot cracking, and hydrogen porosity. The advantages of effective grain refinement are:

- . Improved feeding characteristics
- . Increased tear resistance
- . Improved mechanical properties
- . Increased pressure tightness
- . Improved response to thermal treatment
- . Improved appearance following chemical, electrochemical, and mechanical finishing

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.

A fine grain structure also minimizes the effects on castability and properties associated with the size and distribution of normally occurring intermetallics. Large, insoluble intermetallic particles that are present or form in the temperature range between liquidus and solidus reduce feeding. A fine grain size promotes the formation of finer, more evenly distributed intermetallic particles with corresponding improvements in feeding characteristics. Because most of these more brittle phases precipitate late in the solidification process, their preferential formation at grain boundaries also profoundly affects tear resistance and mechanical properties in coarse-grain structures.

Porosity, if present, is of smaller discrete void size in fine-grain parts. The size of interdendritic shrinkage voids is directly influenced by grain size.

The finer distribution of soluble intermetallics throughout grain-refined castings results in faster and more complete response to thermal treatment. More consistent mechanical properties can be expected following thermal treatment.

Grain Refinement. 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, 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 5 to 50. 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.

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