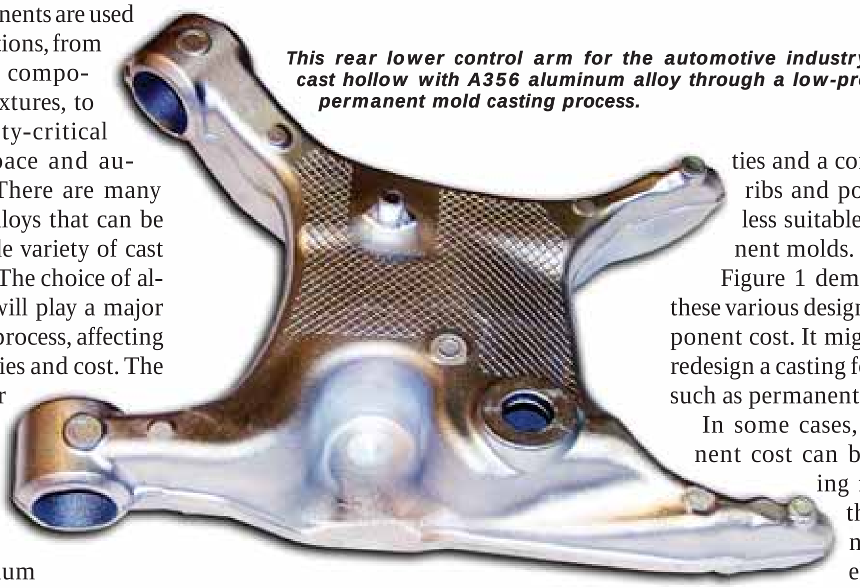
Aluminum Alloys

The American Foundry Society Technical Dept., _Schaumburg, Illinois_

Cast aluminum components are used for many varied functions, from decorative home-owner components, such as lighting fixtures, to highly engineered, safety-critical components for aerospace and automotive applications. There are many different methods and alloys that can be used to produce this wide variety of cast aluminum components. The choice of alloy and casting process will play a major role in the procurement process, affecting both component properties and cost. The procurement process for cast aluminum parts always should begin by the design engineers defining the three major factors that drive the quality and cost on a cast aluminum component—functionality (service requirements), design (shape and size) and production quantity. Each of these factors will have a large bearing on the choice of casting method, alloy selection and cost as well as final component quality.



This rear lower control arm for the automotive industry was cast hollow with A356 aluminum alloy through a low-pressure permanent mold casting process.

Functionality & Service Requirements

When determining how a component will function, the first question to ask is: what purpose will the component serve? Choosing the alloy, casting process and thermal treatment requires knowledge of the service conditions of the proposed part, so defining the end-use functions and requirements is always the starting place in the procurement of an aluminum casting. If high-strength, safety-critical components are required, the number of potential casting processes is narrowed, and a high-integrity casting process, such as permanent molding, premium sand casting or a semisolid casting process, will be chosen. The alloy selection also cannot be determined until the component's application and end-use requirements are defined. The range of possible mechanical properties varies widely because there are many alloy and thermal treatment combinations. For example, many commercial castings often do not have critical service requirements, therefore a more economical alloy and production method can be utilized.

Design

Once the function of the desired component is determined, engineers and purchasers must ask questions relating to design issues, such as size, weight and the complexity of the part. The size and design features of the casting and available alloys can drive the choice of casting process and cost of the component. Sand casting often is used to produce parts with hollow cavities and a complex arrangement of ribs and pockets that make them less suitable for casting in permanent molds.

Figure 1 demonstrates the effect of these various design complexities on component cost. It might be advantageous to redesign a casting for a lower cost process, such as permanent mold or diecasting.

In some cases, the finished component cost can be reduced by including features in the design that will produce a near net-shape cast part and eliminate or minimize additional costs found with post-casting processes, such as machining. However, features like complexity and surface finish or special properties can increase the cost of the casting.

Regardless of cost, the process choice might be limited because of the component's size. For example, sand casting may be the only process option for large or heavy castings. Although this process typically requires lower tooling cost, the unit price of the castings and the finished part can be high (Fig 2). Permanent mold casting has higher tooling cost, but the unit price is lower, particularly for higher quantities.

Diecasting has the highest tooling cost but also the lowest piece price on large quantities.

Changes from the initial design can improve design efficiency and/or decrease production costs. Still, even if a casting has a sound design for a specific process, it may have a shape that is conducive to distortion during heat treating. Such errors can be minimized through design changes.

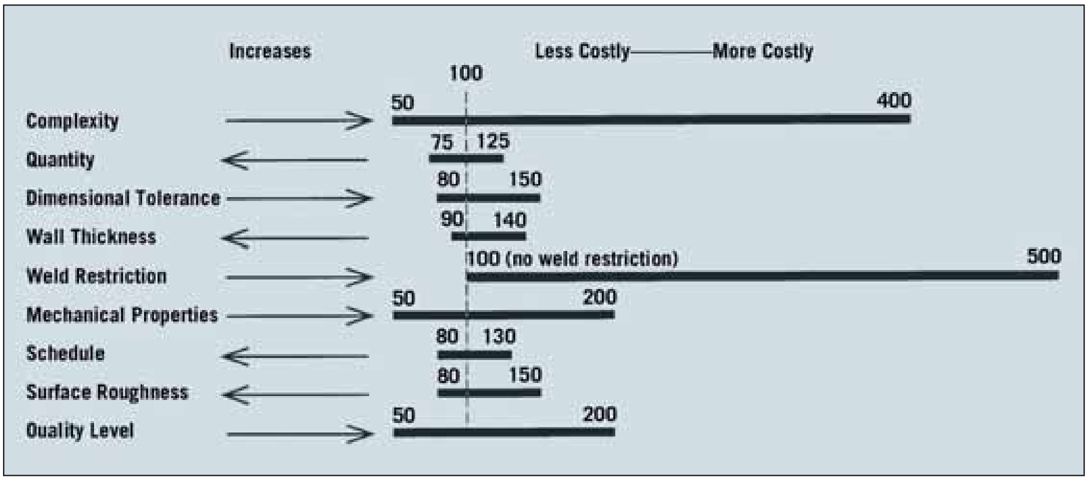
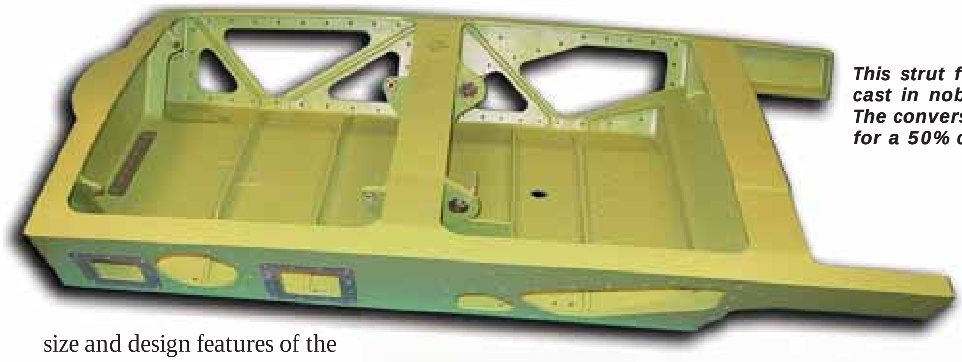


Fig. 1. This chart displays the effects certain design features and service requirements have on casting cost.

Production Quantity

Another critical factor in determining casting process selection and cost is how many parts will be purchased. Permanent mold, diecasting or automated sand casting processes can be used to produce high quantities if the



This strut fan cowl support beam for Boeing was cast in nobake molds with D357 aluminum alloy. The conversion from an 11-piece assembly allowed for a 50% cost savings.

size and design features of the casting and available alloys are suitable. However, the tooling for permanent mold and diecasting can be costly, so a large quantity would be required to justify the tooling costs. If low-quantity parts and ultra-large castings are required, the best option is sand casting, which offers the lowest tooling cost with the capabilities to cast large components multiple times.

Aluminum Casting Metallurgy

The specification of an aluminum alloy for a cast component is based upon the mechanical properties it can achieve. Aluminum casting properties result from three primary factors: casting alloy, melting and casting operations, and thermal treatment.

The properties obtained from one particular combination of these factors may not be identical to those achieved with the same alloy in a different metalcasting facility or with a different thermal treating source.

Aluminum Processing

Molten aluminum has several characteristics that can be controlled to maximize casting properties. It is prone to picking up hydrogen gas and oxides in the molten state as well as being sensitive to minor trace elements. Although some decorative or commercial castings may have quality requirements that can be met without additional processing, tight melt control and specialized molten metal processing techniques can help provide enhanced mechanical properties when needed.

Alloy Chemistry—During molten aluminum processing, the percentages of alloying elements and impurities must be controlled carefully. If they are not, characteristics, such as soundness, machinability, corrosion resistance, mechanical properties and conductivity, are affected adversely.

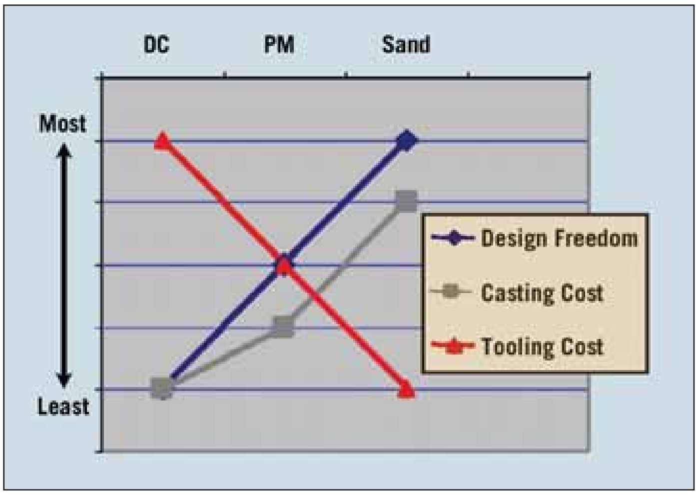


Fig. 2. The cost of aluminum casting varies with the casting process, as can be seen in the chart above.

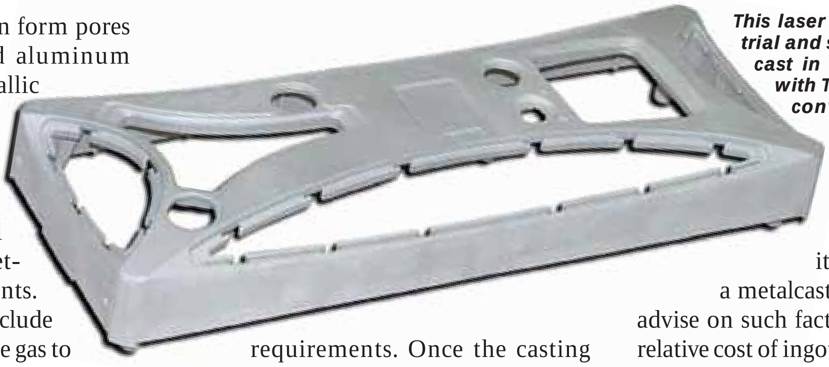
Molten aluminum alloys are prone to chemistry changes that can be controlled during melting and holding. The most significant of these changes is the potential to lose magnesium and pick up iron, which can alter the mechanical properties significantly. If the service requirements of the cast component demand high material properties, these reactions must be controlled through facility melting and holding practices.

Grain Refining & Modification—Molten aluminum is sensitive to trace elements, but this sensitivity can be used as an advantage by adding trace amounts of materials to create beneficial changes in the casting microstructure. Both grain refining and silicon modification can improve mechanical properties in the final component. They also can act as useful tools to optimize properties and heat treatment response to meet specific component service requirements and aid the development of certain casting properties.

During solidification, aluminum freezes in long columnar grain structures. These grains will grow until they impinge on another grain or the mold wall. Grain refining is a treatment process in which nucleating sites (in the form of titanium and boron master alloys) are added to the molten metal to aid the growth of additional grains. This leads to the creation of more grains, which causes the grains to remain smaller.

With modification, a sodium or strontium addition is made to the molten aluminum to change the morphology (shape) of the silicon crystal.

Molten Metal Handling—Molten aluminum is prone to absorb hydrogen from moisture in the atmosphere and other sources, which can lead to defects. Hydrogen gas can form pores in the solid castings, and aluminum oxide and other intermetallic impurities can solidify in the castings as inclusions. Both gas porosity and inclusions have a negative impact on casting quality and will prevent castings from meeting high service requirements. Melting practices typically include degassing with an inert purge gas to remove hydrogen and fluxing to clean the molten aluminum of oxides and other inclusions prior to pouring.



This laser housing for the industrial and scientific industries was cast in A356 aluminum alloy with T51 heat treatment. The conversion from a sheet metal fabrication allowed the customer to augment the appearance of its product.

Alloy Selection

There are a number of available alloys to choose from to satisfy individual requirements. Once the casting method is determined, the alloy choice is limited because not all alloys can be used with all casting methods. Sometimes, the alloy that shows the best properties on paper may have production characteristics that make it less desirable on an overall basis than other eligible alloys. Therefore, it is best to consult with a metalcasting facility, which can advise on such factors as availability and relative cost of ingot, production costs and reproducibility of results.

Service requirements also are a key consideration in alloy selection. If high strength is required, heat-treatable alloys must be used. The alloy options can be narrowed further when considering the remaining requirements, such as pres-

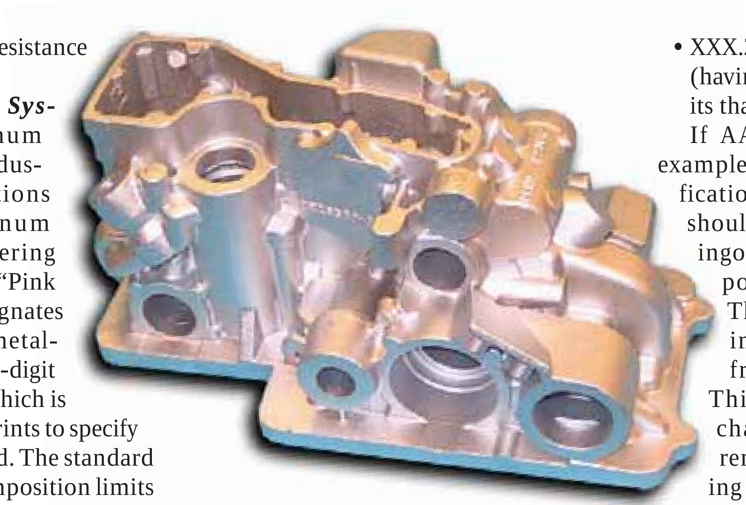
Alloy	Casting Process & Temper	Ultimate Strength (ksi)	Yield Strength (set .02%-ksi)	Elongation (% in 2in.)	Shear Strength (ksi)	Brinell Hardness (500 kg load on 10 mm ball)
201.0 / A201.0	Sand & PM—T42	60	37	17.0	—	—
	Sand & PM—T6	65	55	8.0	42	130
	Sand & PM—T7	68	60	5.5	40	146
A206.0	Sand—T4	51	36	7.0	40	—
	PM—T4	62	38	17.0	42	—
	PM—T7	63	50	12.0	37	—
319.0 / A319.0	Sand—F	27	18	2.0	22	70
	Sand—T5	30	26	1.5	24	80
	Sand—T6	36	24	2.0	29	80
	PM—F	34	19	2.5	24	85
	PM—T6	40	27	3.0	27	95
355.0	Sand—F	23	12	3.0	—	—
	Sand—T51	28	23	1.5	22	65
	Sand—T6	35	25	3.0	28	80
	Sand—T7	38	36	0.5	28	85
	PM—F	27	15	4.0	—	—
	PM—T51	30	24	2.0	24	75
	PM—T6	42	27	4.0	34	90
	PM—T62	45	40	1.5	36	105
	PM—T7	40	30	2.0	30	85
	PM—T7	36	31	3.0	27	85
356.0	Sand—F	24	18	6.0	—	—
	Sand—T51	25	20	2.0	20	60
	Sand—T6	33	24	3.5	26	70
	Sand—T71	28	21	3.5	20	60
	PM—F	26	18	5.0	—	—
	PM—T51	27	20	2.0	—	—
	PM—T6	38	27	5.0	30	80
	PM—T7	32	24	6.0	25	70
A356.0	Sand—F	23	12	6.0	—	—
	Sand—T51	26	18	3.0	—	—
	Sand—T-6	40	30	6.0	—	75
	Sand—T71	30	20	3.0	—	—
	PM—F	27	13	8.0	—	—
	PM—T51	29	20	5.0	—	—
	PM—T6	41	30	12.0	—	80
	PM—T61	41	30	10.0	—	90
535.0	Sand—F	40	20	13.0	27	70

The table above portrays the typical mechanical properties of common cast aluminum alloys and tempers based on heat treatment cycles and casting processes.

sure tightness, corrosion resistance and machinability.

Alloy Designation System—The U.S. Aluminum Assn. (AA) monitors industry standard specifications for designating aluminum alloys through a numbering system known as the AA "Pink Sheets." The system designates individual aluminum metal-casting alloys using a three-digit number plus a decimal, which is included on casting blueprints to specify the casting alloy to be used. The standard specifies the chemical composition limits of aluminum alloys and the percentage of each alloying element or an allowable chemistry range. The first digit of the three-digit number system categorizes the casting alloys by groups (or series) according to their major alloying elements as seen in Table 1.

The balance of the three-digit number identifies the various individual alloys within each alloy series. For example, the 300 series of alloys includes more than 50 individual alloys (319, 356, 357, 380, etc). Some of these individual alloys have multiple variations, all using the same three-digit number. These alloy designations include a letter before the three-digit alloy designation. For instance, variations of 356 are A356, B356, C356 and F356. This letter distinguishes between alloys that fall within the alloy chemistry ranges, but differ slightly in percentages of alloying elements or impurities—such as F357.0, which has a lower minimum level and tighter range for magnesium than 356.0 (Table 2). These variations can determine special casting properties.



This electric valve housing for Hamilton Sundstrand is cast in C355 aluminum via semi-permanent mold casting.

The Pink Sheet standard designations apply to aluminum alloys in the form of both castings and ingot, and the single digit following the decimal indicates how the alloy will be used. These designations include:

- XXX.0 = casting;
- XXX.1 = ingot used to make the casting;
- XXX.2 = ingot used to make the casting (having typically tighter chemical limits than the XXX.1 ingot designation).

If AA alloys 356.1 or 356.2, for example, are listed as the alloy specification on casting blueprints, they should define the chemistry of the ingot used to make the cast components, not the final castings. The number XXX.0 for castings includes a chemistry different from the ingot specifications. This leaves room for chemistry changes that can occur during remelting. The addition of casting returns, such as scrap castings, to the charge material also can alter the casting chemistry. The primary difference is that the XXX.0 specifications allow for some magnesium loss (due to burn out) and iron or zinc pickup that may be experienced during processing. The alloy chemistry of the final 356 cast component should fall within the limits of the 356.0 specifications but may not meet the chemical specification for the 356.1 ingot.

Final cast components also should be properly designated. If a blueprint designates 356.1 as the casting alloy, it would be improper to designate the final castings as 356.1. Components should be shipped designated as 356.0 castings.

Metal Matrix Composites – Aluminum metal matrix composites (Al-MMCs) consist of nonmetallic reinforcements incorporated into an aluminum matrix. Reinforcements can be continuous or discontinuous, the most common being silicon carbide. Other reinforcements include boron, alumina and graphite fibers as well as various particles, short fibers and whiskers. Al-MMCs have better stiffness, wear resistance and thermal conductivity than base aluminum alloys. The American National Standards Institute specifies that Al-MMCs be identified as follows:

Matrix/reinforcement/volume%/form.

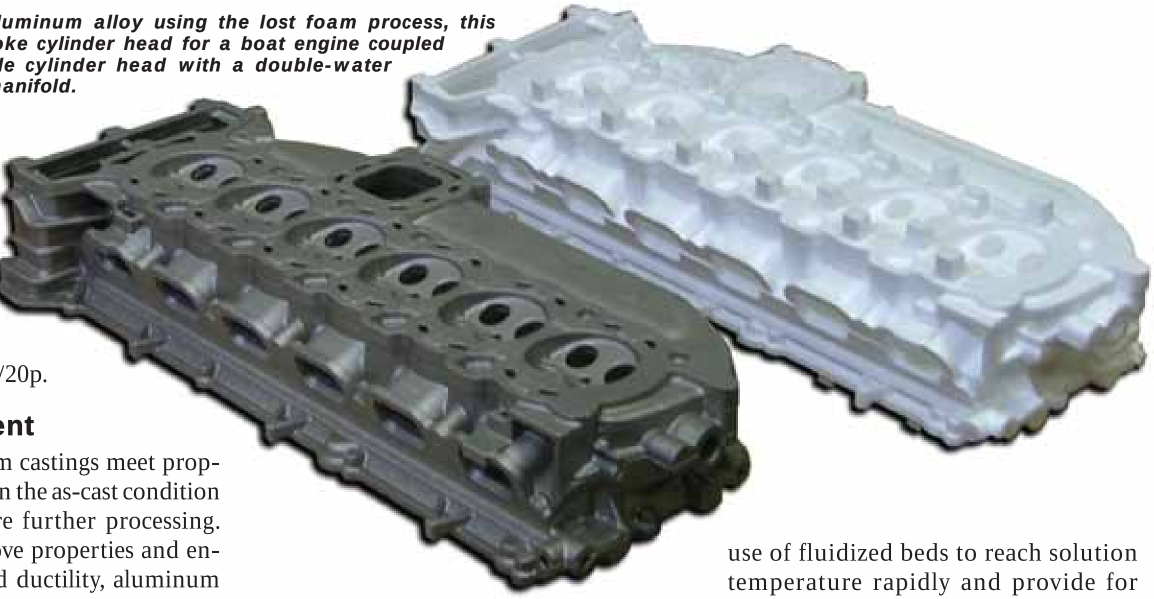
Table 1. Aluminum Alloy "Pink Sheet" Classification System

Alloy Series	Principal Alloy Element
100 series alloys	99% minimum aluminum
200 series alloys	Copper
300 series alloys	Silicon + Magnesium, Silicon + Copper, or Silicon + Magnesium + Copper
400 series alloys	Silicon
500 series alloys	Magnesium
700 series alloys	Zinc
800 series alloys	Tin

(600 series and 900 series are not currently in use.)

Table 2. Aluminum Assn. Standard Chemical Composition Limits for 356 Aluminum Alloy

AA #	Product	Si	Fe	Cu	Mn	Mg	Zn	Ti	Others		Aluminum
									Each	Total	
356.0	S&P	6.5-7.5	0.6	0.25	0.35	0.20-0.45	0.35	0.25	0.05	0.15	remainder
356.1	Ingot	6.5-7.5	0.50	0.25	0.35	0.25-0.45	0.35	0.25	0.05	0.15	remainder
356.2	Ingot	6.5-7.5	0.13-0.25	0.10	0.05	0.30-0.45	0.05	0.20	0.05	0.15	remainder
A356.0	S&P	6.5-7.5	0.20	0.20	0.10	0.25-0.45	0.10	0.20	0.05	0.15	remainder
A356.1	Ingot	6.5-7.5	0.15	0.20	0.10	0.30-0.45	0.10	0.20	0.05	0.15	remainder
A356.2	Ingot	6.5-7.5	0.12	0.10	0.05	0.30-0.45	0.05	0.20	0.05	0.15	remainder
B356.0	S&P	6.5-7.5	0.09	0.05	0.05	0.25-0.45	0.05	0.04-0.20	0.05	0.15	remainder
B356.2	Ingot	6.5-7.5	0.06	0.03	0.03	0.30-0.45	0.03	0.04-0.20	0.03	0.10	remainder
C356.0	S&P	6.5-7.5	0.07	0.05	0.05	0.25-0.45	0.05	0.04-0.20	0.05	0.15	remainder
C356.2	Ingot	6.5-7.5	0.04	0.03	0.03	0.30-0.45	0.03	0.04-0.20	0.03	0.10	remainder
F356.0	S&P	6.5-7.5	0.20	0.20	0.10	0.17-0.25	0.10	0.04-0.20	0.05	0.15	remainder
F356.2	Ingot	6.5-7.5	0.12	0.10	0.05	0.17-0.25	0.05	0.04-0.20	0.05	0.15	remainder



Cast with A356 aluminum alloy using the lost foam process, this verado L6 four-stroke cylinder head for a boat engine coupled an automotive-style cylinder head with a double-water jacketed exhaust manifold.

Using this formula, a 356 aluminum alloy reinforced with 20% SiC particulate would be designated as 356/SiC/20p.

Heat Treatment

Many aluminum castings meet property requirements in the as-cast condition and do not require further processing. However, to improve properties and enhance strength and ductility, aluminum castings often are thermally processed by a series of heating and cooling cycles called heat treatment. This thermal processing involves three basic operations: solution, quench and age. Solution treatment involves heating the casting to near the eutectic temperature to dissolve the eutectic constituent and form a solid homogeneous solution.

Following this solution treatment, castings can be quenched or rapidly cooled, often in boiling water, which helps retain the homogeneous solution at room temperature. A third step used in heat treatment of aluminum castings is natural or artificial aging, which increases strength and hardness. Age hardening principles also can be used to tailor heat treatments to each application. Combinations of these three heat treatments are called tempers (Table 3). The principal purpose for heat treating aluminum castings is to develop the best combination of mechanical properties that will meet the critical needs of the component application.

The three basic thermal operations often are combined into heat treatment cycles that provide various properties. Although aluminum casting-related books offer "typical" or "recommended" solutions, quench and age times and temperatures for each alloy and temper, these heat treatment cycles often are varied and manipulated to change the mechanical properties of the casting to meet specific component requirements for strength and ductility. Recent research includes the use of fluidized beds to reach solution temperature rapidly and provide for quicker heat treatment cycles.

The benefits of heat treatment include:

- ***homogenization of alloying elements***—this is desirable to distribute elements evenly throughout the matrix, so properties in the casting will be uniform;
- ***stress relief***—residual stresses are created during cooling from elevated casting and solution temperatures. Heating the casting to an intermediate temperature can relieve these residual stresses;
- ***improved dimensional stability and machinability***—changes in the microstructure can cause castings to grow over time. To maintain tight dimensional tolerances during and after machining, castings should be heat treated to form stable precipitate phases;
- ***mechanical property improvement***—the greatest use of heat treatment is to enhance mechanical and corrosion properties through spheroidizing constituent phase particles and by precipitation hardening.

Rarely are all of the desired properties optimized in a single casting. More often, heat treatment is a compromise, maximizing some properties at the expense of others. For example, tensile and yield strengths can be increased, but this results in lower elongation. Contrarily, higher elongations result in lower tensile and yield strengths ECS

Table 3. Common Aluminum Heat Treatment Tempers

Temper	Thermal Processing
T4	Solution treat and age naturally to a substantially stable condition. Natural aging may continue slowly, particularly at elevated service temperatures, so structural stability may not be satisfactory.
T6	Solution treat and age artificially. In castings, T6 commonly describes optimum strength and ductility.
T61	Solution treat, quench and age artificially for maximum hardness and strength. This variant of T6 yields additional strength and stability but at reduced ductility.
T7	Solution treat, quench and artificially overage or stabilize. This temper improves ductility, thermal stability and resistance to stress corrosion cracking.
T71	Solution treat, quench and artificially overage to a substantially stable condition. This temper further increases thermal stability and resistance to stress corrosion cracking and reduces strength.
T5	Age only. Stress relief or stabilization treatment. Cool from casting temperature and artificially age or stabilize (without prior solution treatment). Frequently, the as-cast condition provides acceptable mechanical properties but is accompanied by microstructural instability or undesirable residual stresses. Perhaps the possibility of in-service growth is the only constraint against using a casting in the as-cast state. In each case, the T5 temper is appropriate.
Annealing	Castings that have low strength requirements but require high dimensional stability are annealed. Annealing also substantially reduces residual stress, a need in die castings. Annealing is a severe stabilization treatment and an elevated temperature variant of the T5 temper. Softening occurs because annealing depletes the matrix of solutes, and the precipitates formed are too large to provide hardening.

For more information, consult: "Designations and Chemical Composition Limits for Aluminum Alloys in the Form of Castings and Ingot," (Pink Sheets), Aluminum Assn., Washington, D.C., www.aluminum.org; "Aluminum Casting Technology," American Foundry Society, Schaumburg, Ill.; and "Design and Procurement of High-Strength Structural Aluminum Castings," American Foundry Society, Schaumburg, Ill.