Aluminium Alloys for High Pressure Die Casting

Raw material — supply and processing

There are large amounts of aluminium in the earth’s crust, where it is the third most common basic element; only oxygen and silicon are present in greater quantity. Aluminium, which never occurs in a free state in nature, forms compounds primarily with silicon, oxygen, alkali and alkaline earth metals.\(^1\) The concentration of aluminium in the earth's crust is about 8% (iron, ca. 5%).\(^2\)

Primary aluminium is extracted from the mineral, bauxite, which consists mainly of hydrated oxides of aluminium, iron and silicon. The largest known bauxite reserves are located in Australia, Brazil, Jamaica and Suriname. After it is mined, bauxite ore is usually converted to the aluminium oxide, alumina (\(\text{Al}_2\text{O}_3\)), which in turn is converted to primary aluminium with an electrolysis process that includes the use of cryolite. It takes 4-5 tonnes (metric tons) of bauxite to produce two tonnes of aluminium oxide which can then be converted to one tonne of primary aluminium. The second step of the process uses large amounts of electric energy: To produce one tonne of primary aluminium from two tonnes of aluminium oxide requires 15,000 kWh.

Total world production of primary aluminium is about 30 million tonnes per annum. It is estimated that known bauxite reserves are sufficient to last 200-400 years at the current rate of production.

Secondary aluminium is derived from recycled aluminium products. Re-smelting requires only five per cent of the energy used in primary production from bauxite ore. Aluminium can be re-smelted several times without any significant decline in quality.\(^3\) Technically and economically, it is difficult to reduce iron and copper levels to less than 0.2% in alloys refined from aluminium scrap.\(^4\)

Applications

Pure aluminium is soft, has relatively low strength and is difficult to cast. For these reasons, it is not widely used in cast products. But pure aluminium is useful for a special type of application — mass production of small and medium-sized rotors for electric motors. Pure aluminium is used for that purpose because it is a good conductor of electricity and is non-magnetic. It is used both as a structural material and an electrical conductor.\(^5\)

The broadest range of applications for aluminium alloy castings is within the motor vehicle industry. Among the types of components cast in aluminium are engine blocks, cylinder heads, intake manifolds, rear axle mounts and transmission housings.

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\(^1\) Aluminium  
\(^2\) Introduktionskurs i pressgjutning i Jönköping 2006  
\(^3\) Introduktionskurs i pressgjutning i Jönköping 2006  
\(^4\) Metallurgi för aluminiumgjutlegeringar  
\(^5\) Karlebo Gjuteriteknisk handbok
Another major area of applications for aluminium alloy castings is within the electric power and electronics industries. Among the aluminium castings produced for the electric power industry are housings for high-tension circuit breakers. The electronics industry uses aluminium cast products for casings, equipment cabinets and mobile telephones, among other things.

Aluminium castings are also being used to a growing extent in furniture, household appliances and portable equipment.  

**Advantages of aluminium:**
- Lightweight, with density of 2.7 g/cm$^3$
- Strong in alloyed form. Breaking point is ca. 70-700 Mpa in pure form, but ca. 200-450 Mpa in cast alloys.
- Good corrosion-resistance properties
- Good conductor of heat and electricity
- Weldable
- Recyclable
- Workable
- High impact strength, even at low temperatures
- Non-magnetic
- High reflectivity

**Disadvantages of aluminium:**
- Low strength at higher temperatures
- Low fusing point
- Low E-module (70-72 Gpa)
- Low hardness
- Low wear and abrasion resistance
- Low coefficient of thermal expansion
- Low creep strength
- Low fatigue strength

**Material properties**

**Density**
One important reason for the increasing use of aluminium alloys as a structural material is its favourable combination of low weight and relatively high mechanical strength. Its density is ca. 2.7 g/cm$^3$, compared with 7.2 g/cm$^3$ for cast iron.

**Fusion temperature**
Every pure metal solidifies at a specific temperature, the solidifying or fusion point. The fusion point of pure aluminium is 660°C. The inclusion of alloy additives shifts the starting point of the solidification process, usually to a lower temperature in the case of aluminium.

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6 Karlebo Gjuteriteknisk handbok
7 Introduktionskurs i Pressgjutning
8 Karlebo Gjuteriteknisk handbok
Normally, the temperature decreases further during solidification so that, instead of a solidifying point, a solidification interval is formed. But in an aluminium alloy with 12.5% Si the interval is reduced to a single point. Such an alloy is called eutectic; like a pure metal, it has a fusion point. Technical alloys usually have concentrations of alloy additives that are lower than the level corresponding to the eutectic. The most common types of die-cast alloys contain 7-12% Si and have a fusion point of 490-570°, depending on the types and amounts of alloy additives.

**Elasticity module**
The elasticity module (E-module) is a measure of the slope of the tensile test curve in the elastic portion of the strength curve (tensile strength increase per length unit). and is noted in Pa. In other words, it is a measure of a metal’s springiness.

The E-module for aluminium alloys is between 70 and 75 GPa, which is about one third of the E-module for steel. This means that the elastic change of form in response to a given stress is three times greater than that of steel, and two thirds that of cast iron.

The elasticity module of aluminium decreases with increasing temperature, and reverts upon cooling. The E-module is somewhat higher at low temperatures than at room temperature. It varies little with type of alloy.

**Mechanical properties**
The values for breaking point, yield strength and ductility are used in the calculation of overall strength. The values are derived by drawing special test bars with a specific tension at a constant elongation rate until they break.

**Breaking point**
The breaking point, Rm, is the highest tension to which a test bar is subjected until it breaks. Compared with copper, iron and steel, lightweight metals such as aluminium have low breaking points.

The breaking point of unalloyed aluminium is 60-80 MPa, depending on degree of purity. The breaking points of common, standardized die-cast aluminium alloys are around 240 MPa. The values for special alloys can be even higher. The strength of aluminium increases as its temperature decreases.

The rate of solidification is another factor that affects the strength of aluminium. Higher rates result in lower DAS values (secondary dendrite arm length), which in turn result in greater strength.

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9 Aluminium
10 Metallurgi för aluminiumgjutlegeringar
11 Metallurgi för aluminiumgjutlegeringar
12 Aluminium
13 Aluminium
14 Metallurgi för aluminiumgjutlegeringar
15 Gjutlegeringar
16 Metallurgi för aluminiumgjutlegeringar
17 Karlebo Gjuteriteknisk handbok
Yield strength & residual elongation limit
Aluminium does not have any definite yield strength. Instead, the parameters that apply are residual elongation limit Rp0.2, which is the tension at a remaining ductile elongation of 0.2%. For the most common die-cast alloys, an elongation limit of 140 MPa is normally attained.

Ductility
Ductility is a measure of a material’s ability to change form. Ductility is stated as a percentage and indicates the extent to which a test bar can be deformed before breaking. A low value indicates that the material will not break as a result of temporary overloading.\(^{18}\) The normal standard for die-cast aluminium alloys is around one per cent. Significantly higher values can be attained if the alloy is refined or is heat treated.

Hardness
Testing the hardness of metals is based on the principle that the harder the material, the better it is able to resist ductile deformation when subjected to pressure from an external object in other words, the more difficult it is to make a permanent impression in the material.\(^ {19}\) There are three different methods for measuring hardness:

- the Brinell method which uses a ball of hard metal
- Rockwell C which uses a diamond cone, and Rockwell B a ball of tempered steel
- Vickers which uses a pyramidal diamond tip with a quadratic surface.

Hardness measurements can be used to calculate the breaking point.\(^ {20}\) The hardness of die-cast aluminium alloys usually ranges from 50 to 90 HBW.

Fatigue characteristics
Aluminium has good dynamic strength, which makes it suitable for components that are subjected to tension loads and fatigue stresses.\(^ {21}\)

Fatigue failure is normally the result of either tensile stress or the combined effect of alternating pressure and tensile stress. Failure may occur even if loads remain below the material’s yield point.

In a given cross-section of material that is subjected only to varying pressure, fissures do not lead to complete fractures. Fatigue fissures nearly always start at the surface of a material. The fracture sequence can be divided into three stages: initiation, fissure growth, brittle fracture.\(^ {22}\)

Between the fatigue limit and the breaking point, hardenable alloys usually have more favourable characteristics than non-hardenable alloys. Heavy inclusions of oxides, pores and large precipitates reduce fatigue strength.

\(^ {18}\) Aluminium
\(^ {19}\) Metallurgi för aluminiumgjutlegeringar
\(^ {20}\) Karlebo Gjuteriteknisk handbok
\(^ {21}\) Aluminium
\(^ {22}\) Aluminium
The notching effect of a heavily machined surface results in lower fatigue strength than a finely polished surface. The surface of a die casting is very dense and strong, and should therefore be kept as intact as possible.

If a material is exposed to a corrosive environment before or during subjection to stress, its fatigue strength is significantly reduced.23

**Corrosion**

In general, aluminium alloys have good corrosion resistance as long as the neutralizing oxide layer on the surface of the casting remains intact. If it is damaged, the oxide layer re-forms. At pH levels of 4 - 8.5, the oxide layer is thermodynamically passive and corrosion occurs at a slow rate. In addition to environment and temperature, the alloy composition also affects corrosion resistance.24 For aluminium, the general rule is that the purer it is, the greater its corrosion resistance.25 Copper and iron in aluminium alloys reduce corrosion resistance, and such alloys may require surface treatment. Magnesium and silicon in aluminium alloys have positive effects on corrosion resistance.

Galvanic corrosion may occur when aluminium is combined with a more noble metal. In such cases, the presence of copper and carbon steel can result in extensive corrosion, whereas stainless steel reduces the risk. Zinc provides aluminium with cathodic protection.26

In cases of very strict requirements for corrosion proofing, or when the material is to be anodized with an aesthetically attractive coating, an Al-Mg alloy can be used. Such alloys acquire a silvery colour when polished. Anodizing provides good corrosion protection even against salt water and weak alkaline solutions. Alloys of this type are difficult to cast and are prone to developing heat-related fissures.27

**Metallography**

A melt of metal is characterized by great disorder, with the metal atoms moving about randomly. When the melt solidifies, the atoms become fixed within a grid structure. Also, density increases and volume decreases as the metal changes from molten to solid form.

Aluminium crystallizes to a surface-centred cubic structure, fcc, with a grid constant of 0.4049 nm at 20°C.28

Pure aluminium has low strength, which can be increased by various hardening processes, including:

- grain boundary hardening
- solid-solution hardening
- particle hardening
- deformation hardening.

23 Aluminimum
24 Gjutlegeringar
25 Aluminium
26 Gjutlegeringar
27 Karlebo Gjuteriteknisk handbok
28 Thundal, Aluminium, 1991
The first three processes are the most commonly used for cast aluminium. The hardening effect is achieved with various alloy additives.

Essentially all metals are soluble in molten aluminium. However, solubility is limited in the solid state. Therefore, alloy additives are present in two forms after the melt has solidified: partly in solid solution, and partly as separate crystals on grain boundaries.

Solid solutions have the same crystal structure as the pure original metal, with one exception: In solid solutions, some of the grid sections are replaced / exchanged with atoms of the alloy additives. The distribution of alloy additive atoms is random. In aluminium, such an exchange of atoms can only occur to a limited extent.

As a rule, the solubility of alloy additives increases with temperature. Mg, Zn and Cu are highly soluble in aluminium; but the solubility of Mn and Si is moderate, and that of Fe, Ti *et al.* is slight.

An alloy can be supersaturated by warming it. For example, the solubility of magnesium at 20°C is only 1.6%, but increases to 3% at 180°C. If the melt is quenched to room temperature, magnesium remains in solid solution because its diffusion rate is slow. Alloys that consist solely of solid solutions are called homogeneous. Supersaturation is not a stable condition. If it is followed by slight warming, surplus dissolved alloy additives can be separated out. This is an important step in the hardening process.

If an alloy contains larger quantities of an additive than can be included in solid solution, the surplus forms separate crystals. Such an alloy is called heterogeneous. ²⁹

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### Alloys

**Standards**

Aluminium alloys are subject to two European standards. At present, 37 cast alloys conform to both EN 1706 Aluminium and aluminium alloys. Castings. Chemical composition and mechanical properties, and EN 1676 Aluminium and aluminium alloys. Alloied ingots for remelting. Specifications.

Cast alloys are produced in both hardenable and non-hardenable forms. They can be sorted into seven categories, based on alloy composition. What generally distinguishes die-casting alloys from those for sand casting and chill casting is that die casting alloys can contain up to 1.2% iron. This is believed to reduce the risk of soldering and flushing in the mould tool. ³⁰

The alloy categories that are most commonly used for die casting are:

**Aluminium-silicon**

This category includes EN AC-44 000 and EN AC-47 000 alloys. They have good casting properties, including flow and fluidity. They also have medium-level strength, good corrosion resistance and are weldable. They are suitable for complex thin-walled and pressure tight components. They have very good mechanical properties. The most important alloy in this category is AlSi12. Alloys with lower silicon levels result in denser castings.

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²⁹ Aluminium

³⁰ Aluminium
Aluminium-silicon-copper
This category includes EN AC-46 000 alloys. The copper additive increases strength, hardness, and cutability. Alloys in this category have good casting properties. Normally, they are not heat treated, but can be under optimal casting conditions. Among other things, alloys in this category are used for large-scale production of castings that are to be finished by cutting. This is the lowest-price category of aluminium alloys.

Aluminium-magnesium
This category includes EN AC-42 000 and EN AC-43 000 alloys. They are distinguished by good corrosion resistance, especially against salt water, and have good polishing and anodizing properties. They are used for armatures in the shipyard branch, piping components in the chemical industry, and decorative anodized fittings for buildings. Strength increases in proportion to magnesium content.

Special alloys
Although they have good properties, these alloys are used less widely because they are difficult to cast and are prone to developing heat fissures. They include Al-Mg alloys which are suitable for anodizing and have good corrosive resistance. The Al-Zn-Mg alloy which is self-ageing and develops optimal strength after some four weeks at room temperature. Al-Cu-Ti-(Mg) alloys have exceptionally high strength. Al-Si-Cu-Ni-Mg is an alloy with improved heat retention and abrasion resistance.

Table 1. Properties of common standardized die-casting alloys.31, 32

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<th>Alloy category</th>
<th>Code number</th>
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<th>Breaking point Rm (MPa)</th>
<th>Elongation limit, Rp0,2, (MPa)</th>
<th>Elongation A50mm (%)</th>
<th>Brinell hardness HBS</th>
<th>Solidification interval °C, c:a</th>
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</table>

31 EN 1706-Aluminium och aluminiumlegeringar- gjutgods- kemisk sammansättning och mekaniska egenskaper
32 Stena Aluminium, Gjutlegeringar av aluminium
International standards notation
In addition to the notations used with the European standards, national notation systems are sometimes used by individual European countries, and by other countries such as the United States and Japan (see Table 2). Alloys are seldom fully comparable, as there are frequent variations in notation.

Alloy additives
Since pure aluminium has low strength and is difficult to cast, it is used only for special applications such as electric motor components for which high electric and thermal conductivity is required.33 In order to ensure the desired properties in die-cast products, aluminium must be alloyed in the proper manner. Commonly used alloy additives include the following:

- **Silicon (Si)** is the most important additive in aluminium alloys. Most such alloys have a Si content of 7-12%. Silicon lowers the melting point and increases the melt's flow, fluidity, hardness and strength.
- **Copper (Cu)** may be unintentionally included as a contaminant in some alloys made with scrap metal. There are also alloys in which copper is intentionally added for the purpose of increasing hardness and machinability.34 Die casting aluminium alloys can contain up to 3-4% copper. It reduces corrosion resistance, but increases hardness and strength, enables some types of heat treatment, and increases cutability.
- **Magnesium (Mg)** is usually added to Al-Si alloys in concentrations of ca. 0.65%, and up to 10% in Al-Mg alloys. Magnesium increases hardness, strength and corrosion resistance. It can reduce the melt's flow and increase its oxidation potential.
- **Iron (Fe)** is usually a contaminant in aluminium. But some die-cast alloys may contain up to 1.2% iron because it has the positive effects of reducing both the risk of heat fissures and the soldering of steel dies during the casting process. However, iron also reduces corrosion resistance. High iron levels contribute to the formation of harmful intermetallic phases, which in turn lead to a sharp reduction of the metal's ductility.35 Iron phases can also cause the nucleation of pores.
- **Manganese (Mn)** is normally a contaminant which, together with Fe and Cr, may produce hard particles that can cause machining problems. But Mn also contributes a number of positive characteristics; it reduces the negative effects of iron, for example.

Other additives include:

- **Zinc (Zn)** which may be added in concentrations of up to 1.2%. Zinc increases hardness and strength, but may reduce corrosion resistance. Zinc concentrations of up to 4-5% cause alloys to self-age.
- **Nickel (Ni)** to a maximum level of 0.05% is usually a contaminant in aluminium. But it can be used for such purposes as increasing high-temperature strength, especially with chromium.36

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33 Aluminium
34 Gjutlegeringar
35 Gjutlegeringar
36 Metallurgi för aluminiumgjutlegeringar
Table 2. National notations for alloys meeting EN-1706 standards. 37,38

<table>
<thead>
<tr>
<th>EN</th>
<th>ISO</th>
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<th>NO</th>
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Abbreviations: DK = Denmark, NO = Norway

37 http://www.adc-sweden.se
38 http://www.tremol.com/
Smelting

Aluminium smelting can be carried out by a variety of methods. Large foundries often have a central furnace, heated with electricity or natural gas, which can smelt both ingots and recycled materials. The melt is then tapped into a transport ladle where further treatment of the melt may be carried out. Finally, the melt is tapped into a holding oven near the die-casting machine. It can be a resistance furnace with a crucible for the melt, or an induction furnace without a crucible but with a fireproof lining. It can also be a dosing furnace which is covered over and is not filled from a ladle; instead, the furnace interior is pressurized so that the melt runs into the shot chamber of the die-casting machine. Smelting may also take place in a furnace beside the die-casting machine, in which case it is usually an induction furnace. Long-lived linings are essential for economical smelting and heat retention; they are also important for the work environment. Since aluminium has great affinity for iron, crucibles of steel or iron cannot be used.

Melt treatment

Molten aluminium has a strong tendency to oxidize and to dissolve hydrogen gas, and that tendency becomes stronger with increasing temperature. The molten metal must therefore be purified, which can be done with a variety of methods and fluxes. Melts are treated in order to: improve castability; increase the probability of producing castings that are poreless and pressure tight; reduce defects, increase the ductility, strength and castability of castings and improve heat treatment characteristics.

The most common melt treatments are:

- refining
- cleaning/fluxing
- degassing
- grain refining.

Refining

Refining is a melt treatment that is used by many, but far from all, die-casting foundries.

The use of silicon in aluminium alloys greatly improves their flow and castability; it also increases the strength and hardness of castings. Normally the silicon phase forms disc-shaped structures which in cross-section may resemble thick needles. The disadvantage of silicon is that the alloy’s ductility is sharply reduced, because the thick needle-shaped phase functions as “inner notches”.

Refining with strontium or sodium makes the needle-shaped phase rounder and substantially improves ductility, while also increasing flow.

The use of strontium (Sr), which is a common refining method with die casting, is accomplished by adding a master alloy in the form of small ingots or bars. A suitable Sr concentration for die castings is 200 ppm. Available for purchase are ready-made alloys that include strontium.

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40 Karlebo gjuteriteknisk handbok
41 Metallurgi för aluminiumgjutlegeringar
Strontium refining can also be used with other methods of producing thin-walled castings, since the use of strontium requires rapid solidification. The refining effect of silicon decreases with length of time in the melt; but its effect lasts longer than that of sodium, for example.

Refining advantages of strontium:
- easy to use and to measure out in doses
- does not attack crucibles
- improves melt flow.

Refining disadvantages of strontium:
- requires rapid solidification for maximum performance.
- can increase the number of pores in the casting.

Sodium (Na) is used with refining of thick-walled castings in sand and chill moulds. The effect of sodium decreases more rapidly than that of strontium. The advantage of sodium is that the method in which it is used is rapid. The sodium is usually added in the form of pellets that are forced down into the melt with a ladle. This produces a powerful reaction, including the emission of gas which can irritate human tissues. The turbulence created by the reaction contributes to increased oxide formation.

Refining lowers the eutectic temperature. This results in super cooling which, in combination with sodium or strontium particles, leads to the formation of a fine-grained eutectic.

Cleaning/fluxing
Aluminium has a very strong affinity with oxygen. When molten aluminium comes in contact with atmospheric oxygen, a strong aluminium oxide is formed on the surface of the melt. When the melt is stirred, tapped or ladled out, oxygen is added to the casting. Defects, pores and hard inclusions may develop at the places where that happen.

Fluxing agent is used to remove oxides from the melt and to lower the metal content of the slag that is scraped from the bath surface. When the fluxing agent is added, a slag is formed which is dry, easy to handle and contains about 20% aluminium. If no fluxing agent is added, the slag may contain up to 80% aluminium. Slag formed without fluxing agent is sticky and fastens to the wall of the furnace. 42

Fluxing is carried out by adding an agent in powder, granulated or pellet form. There are two types of fluxing agent — cleansing and covering. They consist of compounds that include such basic elements as Ca, K, Na, Cl and F. 43 In most cases, covering salt is used. Fluxing is used primarily by sand and chill mould foundries, 44 but it is also common with die casting.

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42 Karlebo gjuteriteknisk handbok
43 Metallurgi för aluminiumgjutlegeringar.
44 Metallurgi för aluminiumgjutlegeringar
Degassing
One source of porosity in aluminium castings is hydrogen in the melt prior to casting. Hydrogen gas forms when the melt reacts with water moisture. It dissolves easily in molten aluminium, but its solubility decreases rapidly when the temperature is lowered. When the melt solidifies, the hydrogen forms pockets and bubbles of gas in the metal.

To reduce the formation of gas pores, the melt can be degassed to remove the hydrogen before casting. This can be done with an impeller or degassing pellets that contain nitrogen. When an impeller is used, a carrier gas (nitrogen or argon) is injected into the melt by means of a lance, at the bottom tip of which is an impeller. The lance and the impeller rotate while the gas is injected. Hydrogen and other contaminants are brought up to the surface with the carrier gas. A casting from a degassed melts has a lower proportion of gas pores, and thus has greater strength and ductility.45

With die casting, however, hydrogen gas is not the primary source of pores. Rather, it is air that is trapped in the melt when the mould is filled, a turbulent process. Also, due to the rapid solidification, the hydrogen gas does not separate out in bubbles, as it does with slower processes such as sand moulding. Degassing is therefore not used as often with die casting.

Grain refining
When an aluminium alloy rapidly changes from liquid to solid form, it becomes fine-grained which is often desirable. Fine-grained alloys are harder, and it is comparatively easy to make pressure tight castings from them. Thick-walled castings solidify more slowly, resulting in a more coarse-grained structure. Grain refining may then be necessary. To the melt is added grain refining agent, often a salt preparation containing titanium or boron.46 Grain refining contributes to a more efficient filling process, and also reduces the risk of heat fissures. Grain refining is normally not used with die casting.47

Casting process
The use of die casting has expanded rapidly in recent years. The predominant metals used are alloys of aluminium, magnesium, copper and zinc.48

Die casting is characterized by:

- technologically advanced equipment
- high productivity
- castings with precise dimensions and even surfaces
- capability to produce thin-walled castings
- very little need for post-casting machining
- use of finishing agents can be kept to a minimum
- costly moulding dies whose amortization requires long production runs, usually at least 5000-10,000 pieces.

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45 Gjutlegeringar
46 Karlebo gjuteriteknisk handbok
47 Melallurgi för aluminiumgjutlegeringar.
48 Karlebo gjuteriteknisk handbok
In the die casting process, molten metal is pressed into a steel die. The cavity between the two halves of the die is filled rapidly due to the high pressure. The high pressure-injection speed makes it possible to cast the melt in thin sections and complex geometric shapes. The metal solidifies when heat is transferred from the melt to the die, after which the die is open and the "shot" is removed. There are two basic methods of die casting — cold chamber and hot chamber. For aluminium alloy castings, the cold chamber method is almost always used.

**Cold chamber method**

With the cold chamber method, the melt is usually kept warm in a holding furnace beside the die-casting machine. A filling device transfers the molten metal from the furnace to the filling chamber of the die-casting machine. After that, the machine’s shot plunger forces the melt into the die. The casting process usually consists of three phases:

**Phase 1.** The first phase begins when the filling device have transferred the melt to the machine's filling chamber. The shot plunger then begins to advance with accelerating speed, up to a maximum speed of 0.5 m/s. The purpose of the plunger’s relatively low speed is to avoid mixing air with the melt. The first phase ends when the metal has filled the entire gating system and its leading edge has reached the cavity inside of the mould.

**Phase 2.** This phase is usually called the mould-filling phase, during this the cavity of the die is filled. The shot plunger moves relatively fast, between 2-6 m/s. Normally, the entire phase takes between 30-300 milliseconds. The time must be kept short in order to fill the mould completely and avoid cold flows. It is important that the speed of the shot plunger increase from slow to fast exactly when the metal reaches the mouth of the mould cavity. The timing of the increase is determined either by measuring the motion of the plunger, or via a pressure sensor in the machine's hydraulic system.

**Phase 3.** This phase begins when the entire mould cavity is filled with molten metal. At that point, the die-casting machine’s hydraulic system encounters powerful resistance because the shot plunger cannot press more metal into the die. Extra hydraulic power is then activated to force the plunger forward a bit further. This compensates for the metal’s shrinkage during solidification and compresses any air bubbles that may be trapped in the melt. The final pressure on the melt is usually between 400-1500 bars, the exact level depends on the requirements for the casting. A high final pressure makes the casting pressure tight and increases its mechanical performance level; but it also increases the wear on the die and the die-casting machine.
a. Moulding die is closed. The melt is poured into the filling chamber (often called cold chamber).

b. The shot plunger forces the melt into the mould cavity at high speed and pressure. The melt is also kept under pressure during solidification.

c. When the melt has solidified, the moulding die is opened and the casting is forced out of the moveable die half by ejector pins.

*Image 1. The three phases of die casting with a cold chamber machine.*

**Vacuum**

Die casting involves a heavy risk of defects such as oxides and air inclusions, due to the fact that ca. 50-90% of the melt comes in contact with ambient air. That risk can be reduced by using vacuum valves that lower the pressure in the mould cavity. Compared with conventional die casting, the volume of trapped air and other gases can be reduced by more than a factor of ten with the vacuum method. This makes it possible to reduce filling time or the machine’s clamping force.  

**Cleaning**

**Burr trimming**

Burr trimming is a relatively new cleaning method. Burrs and sprue remains are removed when cold, by shearing in a press. The method is now used even for small and medium-sized production runs, since the time it takes to change dies has been reduced.

**Grinding**

Grinding is a fast method for evening out a surface. The equipment used to grind aluminium is similar to that used for other metals, but the production rate is usually higher. Machining aluminium with a grinding wheel is fairly uncommon, because the aluminium surface gets sticky and reduces the grinding capacity.  

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Tumbling
This can be done with either dry or wet tumbling. Normally, the castings are placed together with finishing chips, a chemical additive and water in a rotating drum. Tumbling can be used for both grinding and deburring. It can be used as a final treatment or as preparation for some other type of surface treatment.

Blasting
Blasting affects both the structure and cleanliness of a surface. It is a method commonly used with both the production and subsequent maintenance/renovation of products. All hard materials can be blasted, including iron, steel, aluminium, glass and hard plastic. Blasting is used to remove burrs from new aluminium die castings, clean moulds and dies, smooth sharp edges after machining, alter the appearance of surface structure, etc. With blast cleaning of more delicate surfaces, such as those of sheet and light metals, sand is used instead of steel grit.

Other methods
Water-jet cutting is used only to a limited extent to clean castings, due to high investment and operating costs. Robots and CNC machines are often used with various processes.

Heat treatment
Heat treatment is used to make desirable changes in the mechanical properties of castings. It can, for example, increase or decrease breaking point, ductility and yield strength.

Die castings are not heat treated very often, because the casting process often results in the inclusion of air bubbles in the material. With solution heat treatment, such air inclusions may result in surface bubbles. But heat treatment is still possible if the casting’s pore level is low.

T4
Solution heat treatment, only. Performed by rapid heating to solution temperature which is determined by alloy composition; often around 500-530 °C. Treatment time is a function of alloy composition and casting size. Solution heat treatment is used to dissolve as much as possible of the alloy additive (usually Mg) into the matrix and to distribute it evenly in the elementary matter. Immediately after solution heat treatment, the casting is rapidly cooled in water whose maximum temperature is 50°C. The casting must be fully immersed in the cooling water within 30 seconds. The rapid cooling ensures that alloy additives are retained in solid solution. Some castings are deformed by the cooling process, and therefore need to be straightened out. This must be done immediately, because the material starts to age at room temperature. T4 treatment increases the metal’s ductility.

51 KMC ytbehandling AB
52 Vigen@varmzink.se
53 Karlebo Gjuteriteknisk handbok
T5
Direct thermal ageing, which is done without any prior solution heat treatment. The casting is usually heated to 150-170°C for 8-10 minutes, and is then left to cool in the air. After some time in the furnace, the material acquires maximum hardness which thereafter decreases. Thermal ageing contributes to the separation of hardening particles.

T6
Complete age hardening, which is achieved by a thermal treatment in three stages: solution heat treatment, cooling and ageing. The solution heat treatment is usually conducted at 520-530 °C for three hours or more, depending on casting thickness and the type of alloy. The heat treatment is followed by rapid cooling, then by natural ageing for 24 hours. After that, the casting is thermally aged at 150-170°C for ca. 5-15 hours, depending on casting thickness and the type of alloy; during this period, age-hardening particles are formed. Thermal ageing is followed by cooling at room temperature.

T7
Solution heat treatment and averaging, i.e. thermally aged beyond the point of maximum hardness.\textsuperscript{54}

F
As cast.

Stress-relief annealing
Stress-relief annealing is often carried out in connection with machining, which often results in deformation due to the release of internal tensions in the casting. Annealing usually occurs at 315-345°C for 2-4 hours.

Die casting alternatives
Under certain circumstances, it is also possible to increase strength and ductility/elongation in die castings. Direct thermal ageing (T5) is a simple method for increasing yield strength and breaking point without risking the formation of surface bubbles on die castings. If solution heat treatment (T4, T6, T7) is to be carried out, it is important to conduct tests to determine the maximum time and temperature that are possible without giving rise to surface bubbles.\textsuperscript{55}

\textsuperscript{54}Introduktionskurs i pressgjutning
\textsuperscript{55}Gjutlegeringar
Surface treatment
Aluminium is used in many contexts without any surface treatment. Given the material's strong corrosion resistance, there is seldom any need for surface treatment to improve that property. But surface treatment can be used to improve other properties, including surface structure, colour, hardness, wear resistance, tolerance for high temperatures, reflectivity and electrical insulating capacity. There are some difficulties associated with surface treatment of die-casting aluminium alloys, due to the fact that they often have relatively high concentrations of silicon; additives of Cu and Mg can also be problematical. Different alloy additives affect the results of surface treatment in different ways; for example, the thickness and hardness of an anodized coating is affected by Si level.

Mechanical surface treatment
Mechanical surface treatment removes or redistributes metal so that the surface becomes smooth or even shiny. Metal is removed by grinding, polishing, calendering or blasting. Brushing and polishing redistribute metal by levelling out high points. Mechanical surface treatment can be used as the final step in a finishing process, or as preparation for chemical or electrochemical treatment.

Chemical surface treatment
Methods of chemical surface treatment include pickling, glazing, phosphatizing, chromating and chemical plating. However, pickling processes can be difficult to apply due to the high Si concentrations of most aluminium alloys. Phosphatizing and chromating are used to produce a surface with good adhesion and corrosion resistance. Chromating may also be performed for aesthetic reasons.

Electrochemical surface treatment
Anodizing, hard anodizing, glaze anodizing and hard chrome plating are examples of electrochemical surface treatments. Anodizing increases the thickness of the natural oxide layer. The new layer increases the corrosion resistance of an aluminium surface. However, anodizing is seldom used on die-cast products for decorative reasons, as it tends to darken surfaces. Electrical insulation and good abrasion resistance are properties that result from anodizing. Hard anodizing results in an extra thick oxide layer which increases hardness and corrosion resistance. It is possible to achieve a high degree of surface smoothness with anodizing. Hard chrome plating is used to produce a hard, abrasion resistant surface; the method is also used for decorative purposes.

Organic coatings
Painting and lacquering, applying plastics, enamelling and applying metals are examples of application methods. Since aluminium has good corrosion resistance to begin with, painting and lacquering are not generally used for corrosion protection, but primarily for aesthetic reasons or to alter surface properties. Other surface coatings can be used for such purposes as reducing friction.

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**Cathodic protection sacrificial anode**

Sacrificial anodes are often used for products to be used in marine environments. They can also be used for products in other wet environments, such as swimming pools and storage tanks, in order to increase the corrosion protection of aluminium. Magnesium and zinc ingots are used to protect aluminium in this way.59

**Final treatment**

**Cutting**

Most aluminium alloys have good cut ability. The per-unit finishing cost is low and the production rate is high. The shearing forces are low. Shavings from die-cast alloys are usually shorter than those of plastic alloys, but wear on cutting tools is usually greater.60 The length of the shavings depends to a large degree on alloy composition; shavings from an alloy with <12% Si are longer and curlier than those from an alloy with >12% Si.

Aluminium materials cannot be cut with an oxyacetylene flame, which is commonly used to cut steel. The most frequently used method for aluminium is plasma cutting; laser cutting is another option.61 Water jet cutting is a method that has been developed during the past 20 years and its use with aluminium materials is increasing.62

**Non-destructive testing**

Non-destructive testing of castings is one method that is used, and some foundries are equipped to conduct it. There is a growing realization that non-destructive testing can help to improve both quality and productivity.

The choice of method for testing castings depends on a number of factors, including type of defect, casting thickness and quality requirements.

There are several different methods of non-destructive testing, but all have their limitations. Accordingly, it is often necessary to experiment in order to determine the most suitable method.63

Some examples of available methods:

- X-ray radiography is used to locate internal defects such as pores and inclusions. This is the most common non-destructive method for testing aluminium castings.
- Ultrasound can be used to locate fissures, inclusions and pores.
- Penetrant testing is used to locate surface fissures, folds and pores.64

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64 Aluminium
Casting defects

The formation of pores is one of the biggest problems of die casting. Shrinkage and gas pores are the principal types of internal porosity in die castings. It is crucial to determine which type of porosity is involved, because the measures required are nearly exact opposites. It is usually possible to determine the type of porosity by magnifying the material by 5-50 times.

Gas pores

Gas pores nearly always take the form of trapped bubbles, which usually look like a series of round holes in the casting. The inner surfaces of the pores are often smooth, with either a shiny or dull finish. If they are dark grey, it is possible that burnt lubricant has vaporized within the pores. Gas pores are formed primarily by trapped gas, water vapour or burnt lubricant.

Shrinkage/suction pores

Shrinkage pores are the result of increases in density that occur when the metal changes from molten to solid form. The metal shrinks both during solidification and cooling. For aluminium, the volume reduction is roughly 4-5%. Shrinkage pores occur in the hottest part of the casting, i.e. the last part to solidify. With die casting, the greater portion of the shrinkage is compensated by the high post-filling pressure that is applied during solidification. It is important that the gating system is properly formed, so that the part near the mouth does not solidify before the rest of the casting; if that happens, the post-filling pressure does not have the intended effect.

Pores can also affect the results of surface treatment if they are filled with fluid during pre-treatment; when the fluid then vaporizes, pores are also formed in the surface coating.

Oxides and hard inclusions

Aluminium reacts very rapidly with atmospheric oxygen to form an oxide film. In melts of pure aluminium, the oxide forms a compact layer that protects against further oxidation. In alloys with high Mg content, the oxide that forms is a mixture that does not provide the same level of protection against further oxidation. Aluminium oxides are transformed by high temperature and increased pressure to corundum which collects at the bottom of the furnace. Corundum is very hard and causes problems if it ends up in the casting. In the die-casting process, the surface of the bath is continually broken by the dosing ladle. When the molten metal is ladled out, films of aluminium oxide follow along. These films often cause problems of pore formation, reduced strength and permeable castings.

Oxide films are formed in connection with various kinds of turbulence, for example when a melt is tapped from a smelting furnace. Oxides can also be added to a melt via ingots and other charging materials that are not clean and dry.

Iron-rich particles can form in a melt and give rise to pores and shrinkage effects. The particles can be shaped like discs and contribute to a drastic reduction of the metal's ductility. In order to reduce the iron's harmful effects, alloys should contain as little of it as possible; also, any Fe content should be offset by the addition of Mn.
Everything in an aluminium melt that is not metallic is harmful because the metal cannot bond to it. Every non-metallic inclusion reduces the depth of the material’s cross-section and thereby weakens the strength of the metal. Because such inclusions are hard, they can also have negative effects on cut ability, with wear or breakdown of cutting tools as a result.

**Surface defects**
Most surface defects are visible and result in rejection of the casting. Cold flows comprise the most common type of surface defect. They are caused when the metal begins to solidify as two metal fronts approach each other. In order to avoid such defects, it is important for the gating system be properly formed, and for the metal and the moulding tools to be kept at the correct temperature.

**Laminations**
Laminations are formed when two layers of molten metal do not combine to form a homogeneous solid. This happens when a layer of partly solidified metal with an oxidized surface flows over the upper surface of a similar layer. The layers remain separate from each other, although they may be joined at some places where no oxide film was formed when the two flows came together. The layers may adhere to each other to some extent, but a slight external pressure can cause them to separate. For example, tumbling prior to surface treatment can produce openings in the laminate so that fluid can work its way in and cause bubbles to form between the opposing surfaces. Another problem is that the layers may partially separate and cause measuring errors.

**Flushing**
Flushing in the moulding tool can be the result of several factors. Among them are the high speed that is required at the mouth, the condition of the moulding tool, and the temperature where the melt contacts the tool. The extent of inclusions is also important, and the chemical reaction of the aluminium with the moulding tool may be, as well. The erosion-like effects that can be seen on the moulding tool during the casting process are often combinations of erosion and corrosion, both of which occur at high temperatures.

**Burrs**
Burrs are formed when molten metal flows into a part of the moulding tool where no melt is expected, e.g. at the parting line, under a jaw / jaw back or alongside an ejector pin. Common causes of burr formation are high melt temperature, poor fit between the various parts of the moulding tool, and uneven machine clamping force. Burr formation can also be caused by wrongly calculated clamping force or by tool and machine wear.65

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65 Introduktionskurs i pressgjutning
Energy

Aluminium is extracted from bauxite by means of electrolysis. The process requires a great deal of energy — around 15,000kWh per tonne. Re-smelting aluminium requires much less energy.

Large transport-related energy savings are possible by using aluminium instead of heavier metals in, for example, cars and recyclable containers. By lowering the weight of a car by 25 kilograms, it is possible to reduce CO₂ emissions by 3.0 grams per kilometre. Replacing copper with aluminium in electric wiring also saves energy.66

Health and environment

Aluminium is one of the most common basic elements in nature.67 It is non-poisonous and can therefore be used to package food products. It was previously believed that aluminium causes Alzheimer’s disease, but no causal connection has been demonstrated.68 Nearly all aluminium taken up by a humans being is eliminated from the body via urine within 24 hours.69

Humans can absorb aluminium by inhaling, which can lead to the respiratory illness, aluminosis.70 With long-term heavy exposure, aluminium may accumulate in the skeleton. Elimination from the skeleton is a slow process, with a half-life of several years.

The main environmental issue associated with aluminium production is the generation of digested sludge. Some environmental problems have arisen in connection with the disposal of aluminium materials in rubbish tips; but knowledge of proper handling has improved, and rubbish disposal is now regulated and monitored by public authorities.71

Aluminium concentrations in groundwater are related to pH level and, at levels less than 5.5, seldom exceed 100 ml/l. The solubility of aluminium increases with decreasing pH level.

Bauxite is mined in open pits. Worldwide, the total land area opened annually for bauxite mining is 25 km², of which ca. 8 km² is rainforest. In order to reduce the environmental impact, bauxite mining is often carried out in separate sections, some of which are left undisturbed in order to enable the rapid re-establishment of ecosystems on mined areas. The goal is that, within 10-15 years after mining operations have ceased, the original plant and animal life shall have been restored.72

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67 Gjutlegeringar
68 Metallurgi för aluminiumlegeringar
69 Gjutlegeringar
70 Aluminium
71 Aluminium
72 Aluminium
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