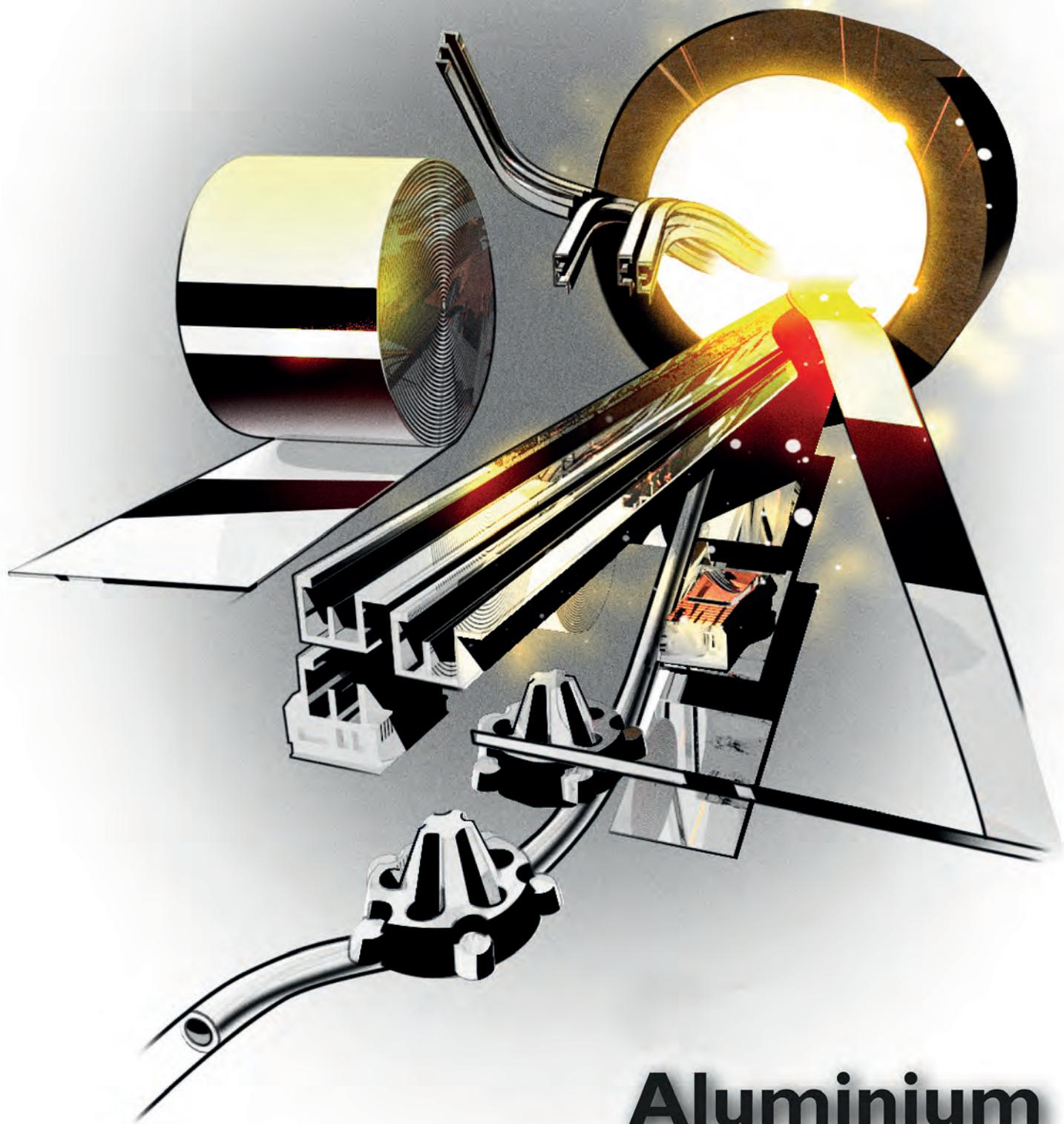


 Svenskt
Aluminium



Aluminium

METALLISKA
MATERIAL



Jernkontoret



Aluminium

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SVENSKT ALUMINIUM
Tel: 070-588 32 07
www.svensktaluminium.se

Realisation:
Hans Frisk, Svenskt Aluminium
Tel: 0705-43 40 86, e-mail: hans.frisk@svensktaluminium.se

Translation and editing:
Staffan Mattson, AluminiumFörlaget
Tel: 0708-45 09 39, e-mail: staffan@alumin.se

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Background

This book is a translation of a Swedish version. Local conditions and geographical locations are, therefore, Swedish. Standard designations are also Swedish and specified as SS-EN. As Sweden complies with the international standard, the SS-EN fully corresponds to the EN standard.

Digit grouping

Since 2003, the use of spaces as separators (for example 20 000 and 1 000 000 for "twenty thousand" and "one million") has been officially endorsed by SI/ISO 31-0 standard, as well as by the International Bureau of Weights and Measures and the International Union of Pure and Applied Chemistry (IUPAC), the American Medical Association's widely followed AMA Manual of Style, and the Metrification Board, among others.

Decimal comma

A decimal comma (,) is a symbol used to separate the integer part from the fractional part of a number written in decimal form.

Aluminium

1.1 Aluminium – a material for many applications

Aluminium combines several useful properties and has, therefore, become the most used metal after iron.

Table 1.1 Data for some important engineering materials¹⁾

	Al	Fe	Cu	Mg	PA6 ²⁾	PTFE ³⁾
Density, kg/dm ³	2,7	7,9	8,9	1,7	1,13	2,15
Melting point, °C	658	1540	1083	650	220	325
Heat conductivity at 20°C, W/(m·°C)	225	75	390	155	0,23	0,25
Specific heat capacity 20–100°C, J/(kg·°C)	900	450	390	1050	1680	1000
Resistivity at 20°C, nΩm	29	105	17	44	∞	∞
Coefficient of linear expansion, ·10 ⁻⁶ /°C	24	12	16	26	85	100
Elastic modulus ⁴⁾ , GPa	70	220	120	44	8	0,4

1) The values refer to clean metals Al, Fe, Cu and Mg.

2) Polyamide plastic (thermoplastic), e.g. Nylon.

3) Fluoro plastic (thermoplastic), e.g. Teflon.

4) Elastic modulus = Young's modulus

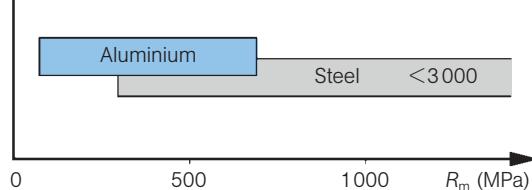


Fig 1.1 Comparison of ultimate strength (R_m) for aluminium and steel.

Some important properties of aluminium are:

- Low weight

The density is 2,7 kg/dm³, which is about one-third compared to iron and copper, respectively. Aluminium is the most common of the light metals, to which also magnesium and titanium belong.

- Good material strength

The ultimate strength (R_m) for aluminium alloys are between 70–700 MPa. Some of them have the same high material strength as some structural steel, Fig 1.1. Aluminium alloys are not brittle at low temperatures but maintain their good toughness down to -200°C.

- Good corrosion resistance

On the aluminium surface, in contact with the air's oxygen, an oxide layer is formed. The layer is very thin and dense and gives excellent protection against corrosion. If the oxide layer is damaged, it reforms immediately and can further grow by surface treatment, *anodising*.

- High conductivity

Aluminium has a high conductivity for electricity and heat. For pure aluminium, the conductivity is about 60% of that of pure copper. The reflection of light and heat radiation is also high.

- Good machinability

Aluminium is well suited for processing, such as extrusion and rolling. Other types of forming such as forging, bending and deep drawing can be performed well. Even cutting, e.g. turning, milling and drilling (subtractive manufacturing) can be achieved. Aluminium can also be welded, brazed, soldered and glued.



Fig 1.2 Aluminium is used in many different building applications, e.g. as house facades.

Fig 1.3 Space-frame for Audi A8, 2018.



Fig 1.4 Benchijigua Express, built by Austal Ships, launched in 2004, is the world's biggest aluminium ship.
Dimensions: 126,7 · 30,4 · 4,2 m.



Fig 1.5 World production of aluminium 1950–2018 (blue), excluding remelted scrap – production for Europe in red.

The production of primary aluminium in EU countries 2002–2015 (green) decreased with 38% as a consequence of fewer smelters in operation. Before the economic crisis in 2009, the EU produced more than 3 Mton of primary aluminium per year. Today, EU countries produce only 2 Mton, while metal imports are increasing. Several of the 16 smelters currently in operation run the risk of being shut down. www.world-aluminium.org

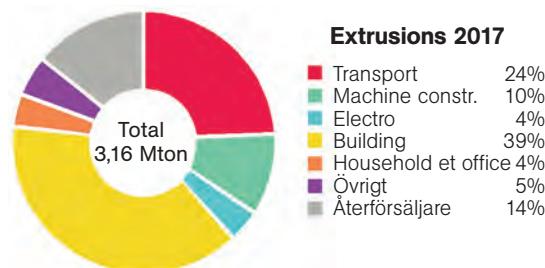


Fig 1.6 Demand for aluminium extrusions in Europe in 2017 by industry. Source: EAA.

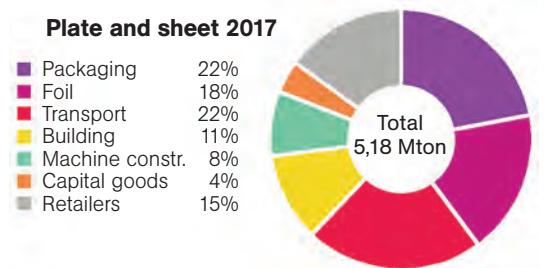


Fig 1.7 Demand for rolled aluminium in Europe in 2017 by industry. Source: EAA.

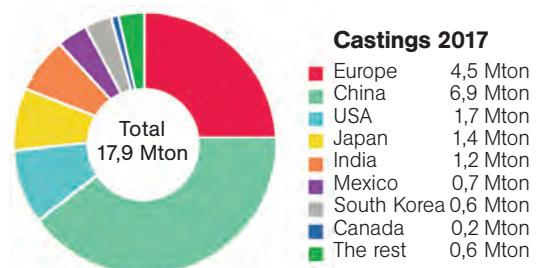


Fig 1.8 Output of global aluminium castings 2017 by countries. Source: Modern Casting.

• Economical production technique

Aluminium's many excellent properties enable efficient manufacturing of semi-finished products and components. Through *extrusion*, profiles can be manufactured and tailor-made for specific products. Different functions can be incorporated into the profile that facilitates design and manufacturing. Sheets can be rolled into various thicknesses and tempers, with a patterned or smooth surface. Gravity casting and die-casting are examples of advanced manufacturing techniques.

• Easy to recover

Aluminium is easy to reuse. Today, large amounts of aluminium are recycled, and the recovery rate is increasingly high. The time between manufacturing and recycling varies for different products. For some, e.g. beverage cans, it is short, only a few months. For others, e.g. an aluminium roof, it can take 100 years before it is scrapped. Recycling aluminium scrap requires only about 5% of the energy used in the production of primary aluminium.

1.2 Extensive application

Aluminium is used in virtually all areas, from small, simple utility objects to large, heavily loaded structures.

Transport

Low weight, high strength and excellent corrosion resistance are the main reasons why aluminium has increased strongly in passenger cars, trucks, buses, trains and ships – the low weight results in lower fuel consumption and thus less environmental impact. Reduced weight in trucks, buses and trains is utilised for higher payloads. Examples of automotive components of aluminium are bumpers, engine blocks, pistons, radiators, fuel tanks, crash boxes, fuel filling pipes, bonnets, doors and luggage compartments. Space-frame is a modern way of building aluminium cars, Fig 1.3.

Mechanical industry

Good formability, low weight, high strength and excellent corrosion resistance make aluminium the most widely used structural metal in the mechanical industry. In addition to sheets and castings, aluminium extrusions are often used as they enable cheap and rational design.

Building industry

The excellent corrosion resistance provides long service life and low maintenance costs, e.g. ceilings, facades, windows and entrance areas. In modern architecture, the share of aluminium is large, e.g. in the combination of extrusions and glass, Fig 1.2.

Electrotechnics

The high electrical conductivity of aluminium is of great importance for electrotechnical products, e.g. high voltage power lines. An aluminium conductor with the same transmission capacity as a copper conductor weighs only half as much. In addition to power lines, aluminium is used in components as chassis and panels. The excellent thermal conductivity is used in cooling fins for electronic parts.

Packaging

For food and pharmaceutical packaging, the requirements of permeability for liquid, gas, aroma and light are high. Aluminium provides a dense barrier layer, which increases the life of the contents and does not require cooling. Aluminium foil is often used in combination with plastic and paper, so-called *laminates*. The beverage can is a known example of an aluminium product. It protects the drink well and weighs less than twenty glass bottles. The recycling system in most of Europe has a very high recycling rate, 85,7% in 2017, according to recycling companies.

1.3 History, production and consumption development

Aluminium has a short history compared to iron, copper, zinc, lead and tin. The name "aluminium" originated from 1807 when the Englishman Sir Humphrey Davy attempted to extract a new metal using electrolysis from a clay mineral. He had previously extracted potassium.



Fig 1.9 Memorial medal in aluminium from the Stockholm exhibition in 1897 with motif by King Oscar II. Natural size.



Fig 1.10 The Danish king Frederick VII wore this general helmet of aluminium from 1853.

um and sodium electrolytically. Now he was so convinced that the clay mineral contained an oxygen-tight metal, so he named it "alumium", which was later changed to "aluminium". ("Alumen" is a Latin term for alum, which was extracted from clay minerals for more than 3000 years). However, Davy never managed to produce aluminium himself.

It was as late as 1825 when the Danish scientist Hans Christian Ørsted found the first traces of metallic aluminium. His disciple, the German chemist Friedrich Wöhler, was in 1845 able to announce that he managed to produce so much aluminium that he could show metal grains as large as pinheads.

The next step in the development came in 1854 when the French chemist Henri Sainte-Claire Deville developed a chemical method for the production of aluminium on a larger scale. However, this method was complicated, and aluminium production remained small. World production amounted to 1,6 ton in 1876.

The breakthrough for industrial aluminium production came in 1886 when the Frenchman Paul T Héroult and the American Charles Martin Hall, independently of each other, invented the electrolysis process for alumina dissolved in molten cryolite, still in use today.

In Sweden, it took until 1934 before the production of aluminium metal started. However, processing of imported aluminium began already in the 1890s and at the World Exhibition in Stockholm in 1897, among other things, Swedish-made "saucers" of aluminium were shown.

Today (2020) there is one Swedish electrolysis plant, Kubal, in Sundsvall, which produces about 140 000 ton per year. Remelting cast houses are found in Finspång, Sjunnen and Älmhult.

For the manufacture of semi-finished products, there is:

- a hot rolling mill and a cold rolling mill in Finspång
- extrusion plants in Finspång, Vetlanda and Åseda

Additionally, in Sweden, there are a large number of plants for sand, gravity and die-casting as well as many companies that process aluminium through, e.g. plastic forming, subtractive manufacturing, surface treatment, welding and assembly.

In 1900, the total world production of aluminium was 5 700 ton. In 2000, it had increased to about 24 Mton, and today (2020) it amounts to approximately 65 Mton. Fig 1.5 shows the global manufacturing development from 1950. Fig 1.6-1.7 show the European production of semi-finished products (plate, sheet and extrusions), and Fig 1.8 shows the global output of castings.

The aluminium use is most significant in countries with high GDP. Sweden occupies a leading position in the world. In total, the aluminium consumption in Sweden is today (2020) around 400 000 ton/year. The output of aluminium castings in Sweden was 45 000 ton in 2017.

Global demand for primary aluminium 2017

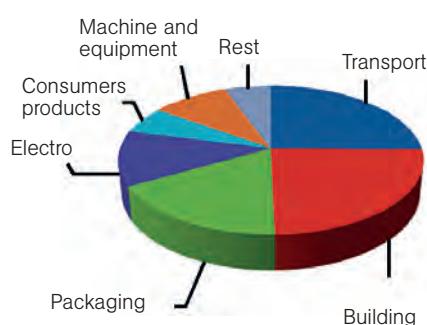


Fig 1.11 The global production of primary aluminium grew by 5,9% in 2017 and 1,5% in 2018.

World production of aluminium 2018

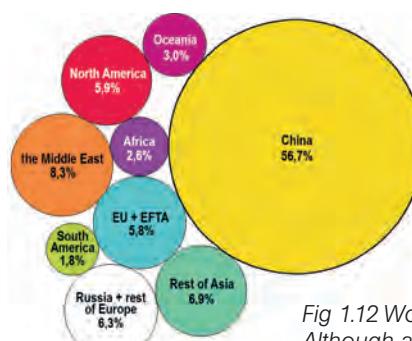


Fig 1.12 World production of aluminium in 2018. Although aluminium is produced in many countries, China now has more than half of the world's smelting capacity. Production in the US fell to almost half 2016, and by nearly 10% in 2017.

Production of aluminium

2.1 Raw materials

2.1.1 Bauxite

Aluminium is produced from *bauxite*, which forms when aluminium containing rocks are weathered under tropical conditions. The average content of aluminium in the earth crust is about 8%. Economically workable bauxite usually includes 20–30% aluminium. Aluminium (Al) is the third most common chemical element on our planet after oxygen and silicon.

Bauxite is usually found as a light mined soil but also appears as solid rock. The colour is often reddish due to the content of iron oxide.

The primary bauxite deposits are found in tropical or subtropical areas such as Australia, Guinea, Brazil, Vietnam, Indonesia and Jamaica. There is no bauxite in Sweden. The world's known supply of workable bauxite is about 30 billion ton (Gton). There are probably more bauxite reserves. Aluminium rich rocks and clays exist in large quantities and are a complement to bauxite. Aluminium from these raw materials, however, can not be extracted with the same process used for bauxite. There is no risk that the raw material for aluminium will run out.

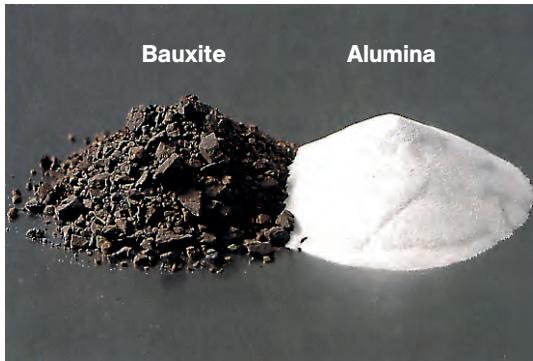


Fig 2.1 Bauxite is converted into alumina.

2.1.2 Scrap

Recycling of used aluminium products steadily increases. Aluminium scrap is today a valuable raw material for the production of new aluminium products. Impurities as paint and oil residues plus pieces of unknown metals, which come from the scrap, is removed in a pre-treatment process. The scrap is sorted according to the chosen alloy before it remelts to get a reasonable economic exchange.

2.2 Production of aluminium from bauxite

Aluminium is produced from bauxite in two steps:

1. Bauxite is converted into alumina (aluminium oxide) through the Bayer process.
2. Alumina dissolves into aluminium metal by electrolysis using the Hall-Héroult process.

The production of alumina takes place in several plants in Europe. Electrolysis plants can be found in many European countries. There is one in Sweden, Kubal AB, in Sundsvall.

2.2.1 Extraction of alumina – the Bayer process

Bauxite contains alumina and hydroxide, but also various iron minerals, aluminium silicate and titanium oxide. During the production of alumina from bauxite, these compounds are dissolved in a 25% aqueous solution of sodium hydroxide. The dissolution takes place in a pressure vessel at an elevated temperature (150–200°C), and with a pressure about 5 bar, sodium aluminate is formed in the process.

The Bayer process

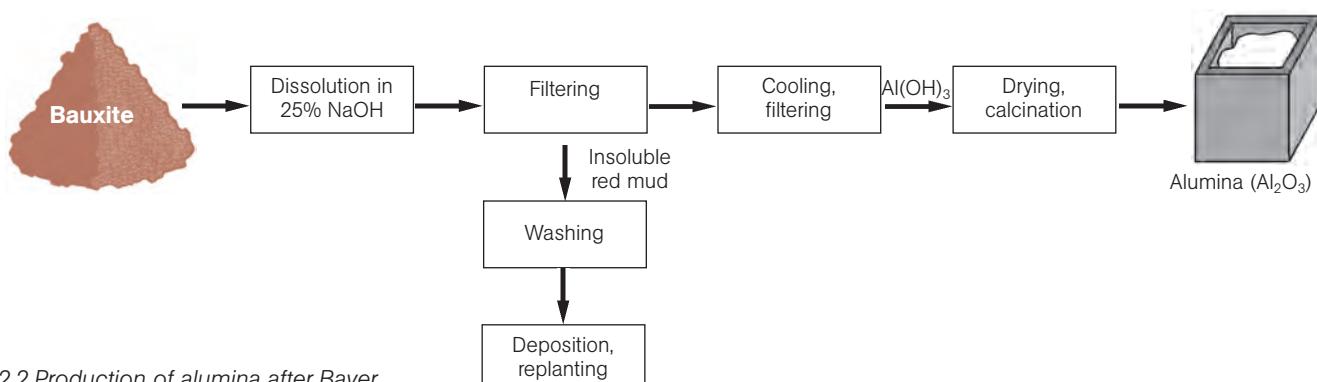


Fig 2.2 Production of alumina after Bayer.

Usually, the unit Joule (J) should be used for all kinds of energy, heat energy, mechanical energy, chemical energy and electrical energy.

For electrical energy, however, the watt-hour (Wh) unit is usually used.

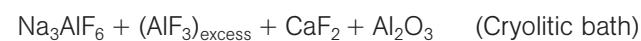
1 kWh = 3,6 MJ

The other compounds in the bauxite are substantially insoluble under these conditions and are removed by filtration. When the filtered aluminium containing solution is diluted slightly with water and cooled to about 60°C, a precipitate of aluminium hydroxide is formed, which separates and dries in a furnace at about 1100°C. The aluminium hydroxide is then decomposed to alumina and water (calcination): – two tonnes of bauxite gives about one ton of alumina. The amount of impurities in the produced alumina is less than 0,1%.

The part of the bauxite that is not dissolved in the sodium hydroxide solution becomes red from iron oxide and is called *red mud*. The sludge also contains silicon oxide, titanium oxide and is strongly alkaline ($\text{pH}=10-13$) and obtained in large quantities. For each ton of alumina, 1–1,5 ton of red mud is generated. Intensive research is underway to find industrial use of the sludge, which else is deposited.

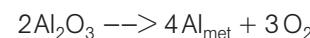
2.2.2 Electrolysis of alumina – the Hall-Héroult process

Aluminium metal is produced by electrolysis of a waterless (anhydrous) alumina melt. When the melting point is high, 2050°C, it is practically impossible to carry out the electrolysis directly on the oxide. Instead, alumina is dissolved in a molten fluoride solvent called *cryolite*.



The temperature of the melt is about 960°C, and the content of alumina in the melt is kept at 3–6%.

In the electrolysis, the alumina is decomposed into aluminium metal and oxygen according to the formula:



The direct current required for the process is supplied through the anodes, which consist of large carbon blocks positioned close to the surface of the melting bath. During electrolysis, the carbon blocks are consumed by reacting with the oxygen ions from the oxide with carbon and carbon oxides are formed. The aluminium ions migrate towards the cathode, a carbon block in the bottom of the furnace. The liquid metal has a higher density than the salt melt and accumulates on the bottom of the furnace. The metal is sucked up to a vacuum ladle. The electrical voltage between the anode and cathode is about 4,5 V, while the current is 80–600 kA per furnace, depending on size.

From the vacuum ladle, the liquid metal is transferred to a *holding furnace* for alloying and purifying the metal before the casting to ingots, slabs and billets in various shapes and dimensions. These are adapted for the processing into semi-finished products like plate, sheet, strip, extrusions, foil etc.

The Hall-Héroult process produces primary aluminium with a purity of at least 99,5%. The residues of iron and silicon that remain in the metal are usually accepted. Higher purity is achieved by repeated electrolysis (99,95–99,99%) or by zone melting (99,9999%). In the

Hall-Héroult cell

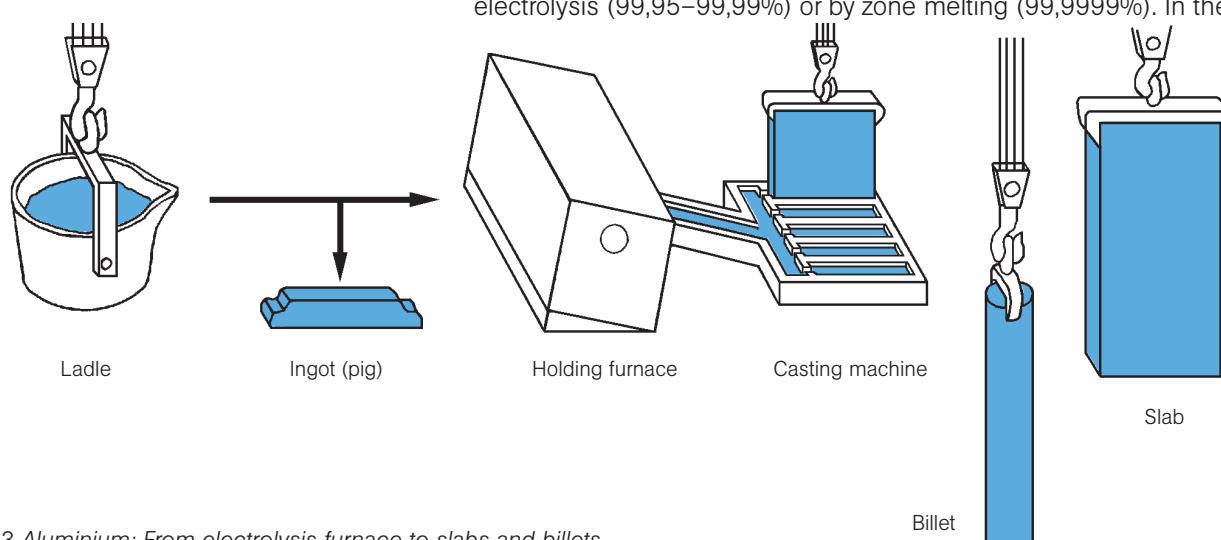
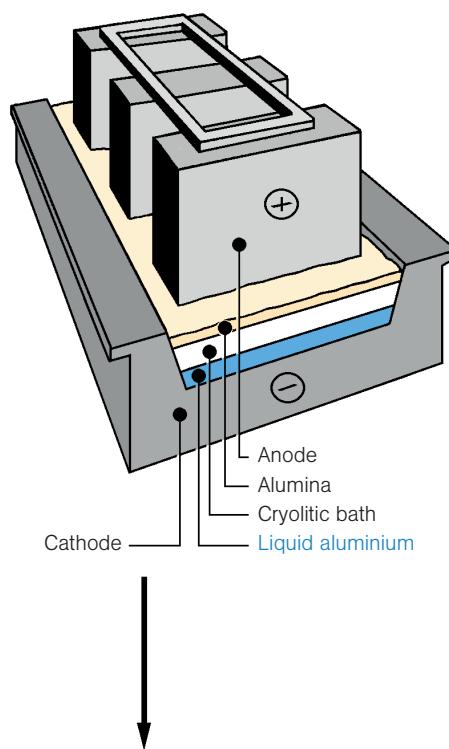


Fig 2.3 Aluminium: From electrolysis furnace to slabs and billets.



Fig 2.4 Electrolysis plant in Kubal AB, Sundsvall.

cast house, various aluminium alloys are produced by adding different alloying elements according to the customer's specification.

The electrolysis requires between 13 000 and 17 500 kWh of electric energy to produce one ton of aluminium.

2.2.3 Environmental processes

The Hall-Héroult process is continuously developed to reduce energy consumption and emissions of carbon dioxide and other greenhouse gases. Attempts to create new methods for the production of aluminium have been made and are still ongoing.

A new environmentally friendly process, *Elysis*, for the production of CO₂-free aluminium is developed today (2020). In addition to aluminium metal, the new process produces only oxygen and eliminates all greenhouse gas emissions from the traditional electrolysis process. However, no process can today compete economically with the Hall-Héroult method.

2.3 Recycled aluminium

Aluminium can easily be reused. Remelting requires only about 5% of the energy needed for the production of *primary aluminium*.

About one-third of the world's aluminium production consists of remelted metal (*secondary aluminium*), which is produced from scrap.

The raw material for the production of secondary aluminium consists of different types of scrap. Partly it consists of cutting, punching, milling and turning chips, from the manufacture of aluminium parts, and partially worn out aluminium products such as, e.g. returned cans, old car parts and utility items.

In the plant, the aluminium scrap is sorted, fragmented, and thermally treated before it is melted. The liquid metal is usually treated with flux, which gives high metal yield and high purity of the metal. Most of the remelted metal is consumed in the foundry industry, but the use of remelted metal for extrusions, sheet and strip increases. Other fields are as deoxidation metal in steelworks to remove oxygen and oxide residues from steel. It is also used in alloying plants for producing high-quality ferroalloys in aluminothermic processes.

Generally, the properties of primary alloys are somewhat better than those casting alloys made from recycled alloys. Primary alloys are used where toughness is of particular importance, e.g. in the aviation and automotive industry. Crash alloys (6000) are made from remelted material.

It is worth noting that beverage cans are part of a separate recycling system apart from normal scrap handling. From recycled boxes, aluminium sheet is often made for the production of new cans.

Aluminium's closed cycle

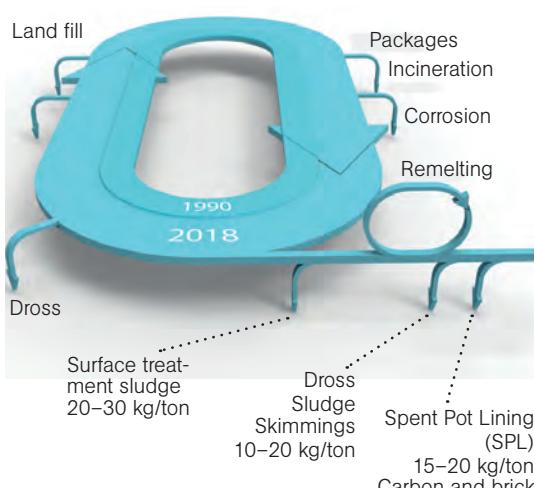


Fig 2.5 Aluminium scrap is a valuable resource, which is remelted and act as an active metal in a closed cycle.

Production of semis

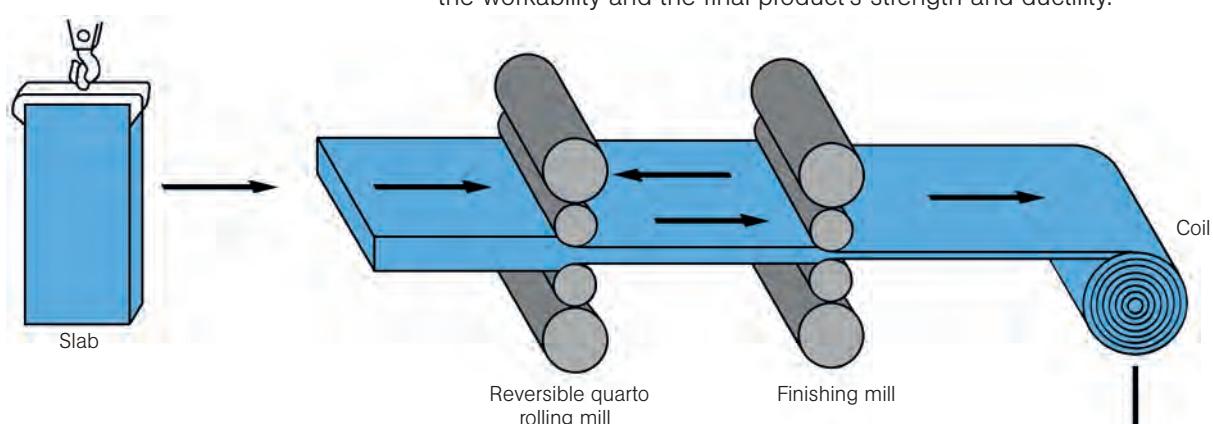
3.1 Slabs and billets

Molten aluminium is cast into slabs and billets in various dimensions and shapes. Slabs have a rectangular cross-section and are the base material for rolled sheets and strips. Billets with a circular cross-section are used for extrusions.

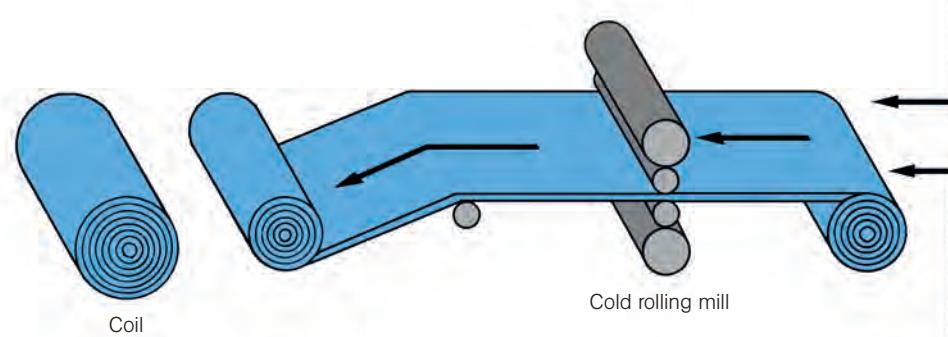
The aluminium ingots (slabs and billets) are treated in different ways depending on the manufacturing process, the alloy and other requirements of the final semi-finished product. As the surface requirements are high on the sheets or strips to be manufactured, usually the "casting skin" on the slabs is removed by milling.

Ingots of special alloys are heat treated, *homogenised*, to equalise the concentration differences of the alloying elements. It improves both the workability and the final product's strength and ductility.

Hot rolling



Cold rolling



Continuous strip casting

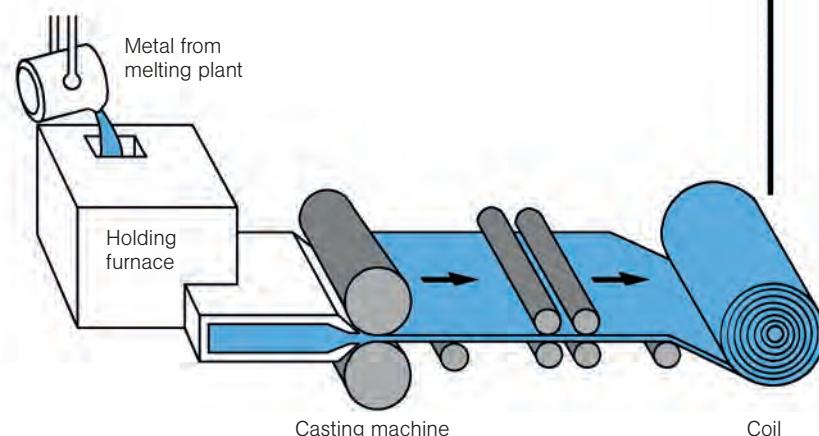


Fig 3.1 Sheet metal strips are made from slabs by hot rolling and subsequent cold rolling. Alternatively, the sheet and strip may be produced by strip casting and cold rolling.



Fig 3.2 Hot rolling of aluminium.



Fig 3.3 Cold rolled aluminium strips (coils).

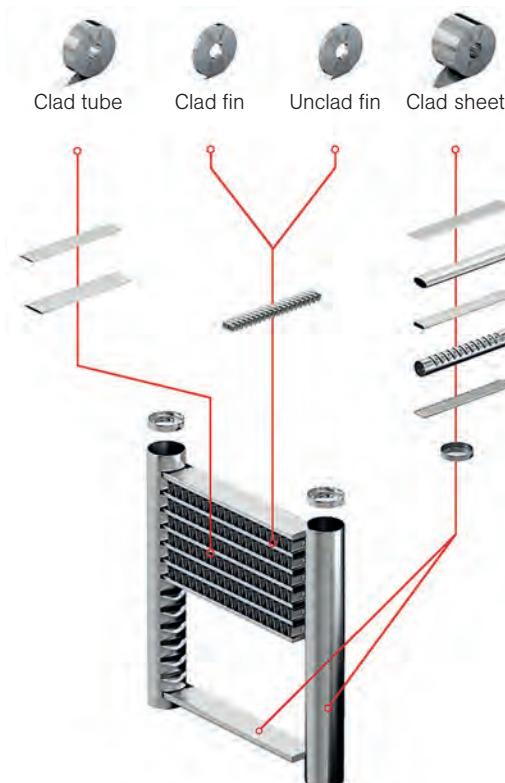


Fig 3.4 Sheets, tubes and fins for coolers.



Fig 3.5 Cladded and slotted strips for coolers.

3.2 Sheet and strip

3.2.1 Hot rolling and cold rolling

Sheets and strips are usually produced by hot rolling and subsequent cold rolling, Figs 3.1-3.3.

Hot rolling starts in the temperature range of 450–550°C. The thickness reduction is achieved by repeatedly passing the slab through the opening (roll gap) between the work rolls of the rolling mill while reducing it for each passage (stick) until the desired end thickness is reached. During the rolling, the metal microstructure is converted into a worked structure.

After hot rolling, *cold rolling* usually follows. This gives, besides a continued reduction in thickness, also improved surface properties, smaller dimension tolerances and higher strength. During the cold rolling, the material deforms, which can cause the need for intermediate annealing so that the hardness decreases before the continued rolling. The intermediate annealing can also give desirable properties to the final product.

Pattern-rolled sheets are obtained with engraved rolls. Different types of patterns are produced in both hot and cold rolling mills.

Plated material is produced by rolling together two or more aluminium sheet alloys, often with different properties. The outer part of the combination is usually much thinner.

Heat treatment of the rolled product is carried out on materials that are to be delivered soft annealed, hardened or tempered.

3.2.2 Continuous strip casting

Flat products of some alloys can also be produced by *continuous strip casting*, Fig 3.1. The process starts from liquid aluminium, which solidifies into a strip as it passes through the gap between two rotating water-cooled rolls. The strip has a thickness of 3–6 mm and is cast at a speed of about 1 m/min.

After the solidification, the strip is cold rolled to a specified dimension. Homogenising and intermediate annealing can also be performed for the strips.

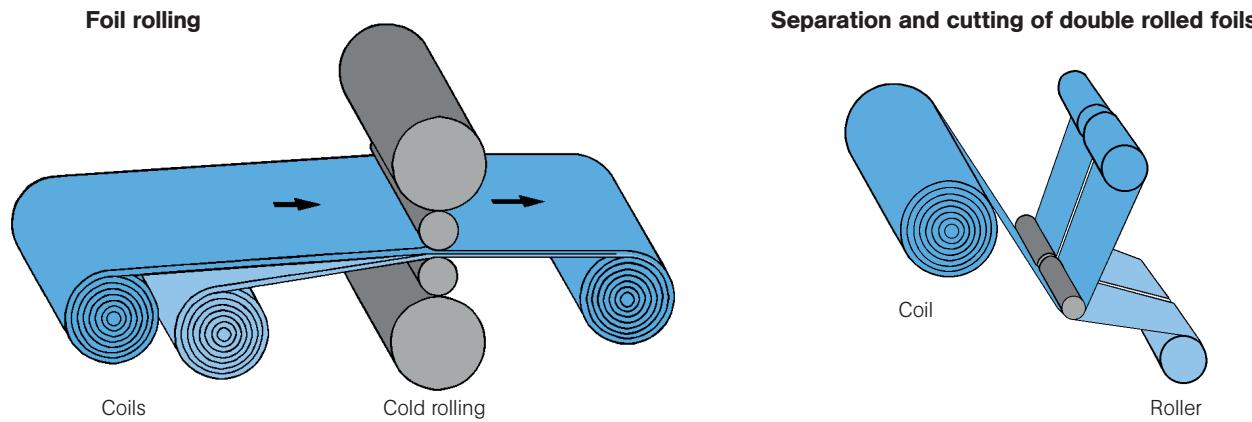


Fig 3.6 Manufacturing of double-rolled aluminium foil (left) plus separation and cutting (right).

3.2.3 Rolling of aluminium foil

Aluminium foil is an extremely thin strip. The foil used in materials packaging has a thickness of only 0,006–0,009 mm (6–9 µm).

The rolling of foil takes place in a specially adapted cold rolling mill, Fig 3.6. The base material is cold rolled and soft annealed strips, usually 0,3–0,7 mm thick. The microstructural breaking down process is performed by repeated rolling passages (sticks) between the rolls. At the last stick, the foil is double-rolled, i.e. two adjacent foil strips pass simultaneously through the roll gap. In the next operation, the two foils are separated from each other and reeled up on separate rollers. As a result, the foil gets a shiny and a matt side.

After the rolling, the foil is hard and covered with a thin film of rolling oil. To make the foil soft and malleable again and to remove the oil, the coils are annealed at 200–300°C for several days.

The foil can be furthered processed in several ways - painting improves corrosion resistance and printability - lamination on paper, cardboard or plastic increase the use of the foil, Fig 3.7.



Fig 3.7 The foil is often used for packaging. Here is a so-called blister pack for pills.

3.2.4 Coil coating and roll forming

Cold rolled strips can be refined in different ways. They can, e.g. be lacquered and roll-formed for roof or facade sheet for buildings, Fig 3.8.

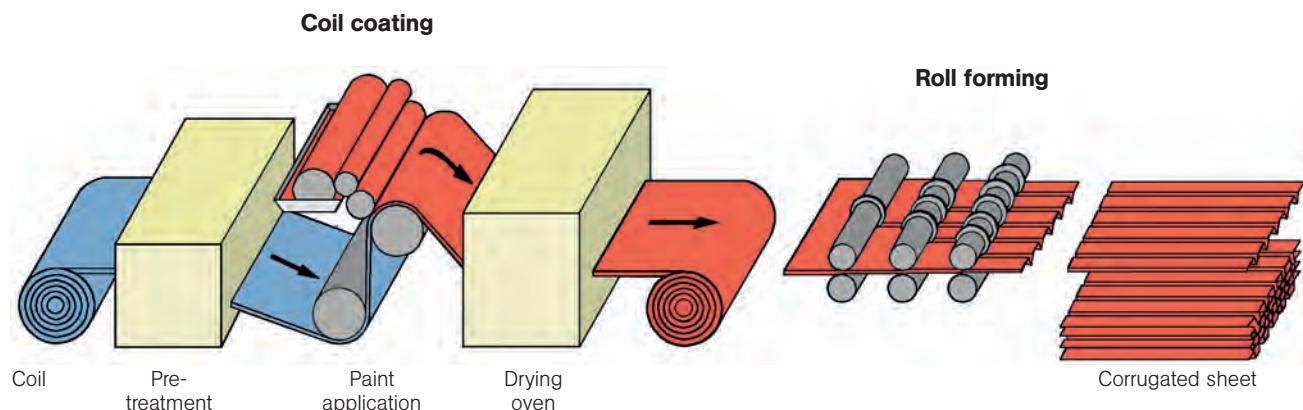


Fig 3.8 Coil coating and roll forming.

3.3 Profiles, bars and tubes

3.3.1 Aluminium extrusions

With the *extrusion* process, aluminium can be formed in almost any way desired. This provides unique structure and design possibilities, which is a good foundation for creating products that contribute to sustainable development, Fig 3.9.

A profile made by extrusion can be precisely adjusted for the intended function. The goods can be placed where it makes the most significant benefit for strength and function. The profile can be provided with screw ports, channels, drill grooves, snap-fit locks, decorative trim, friction patterns, anti-slip surfaces etc. The great freedom in the design of the cross-section of the profile for the intended use also gives low costs for the subsequent machining to finished products.

Fig 3.10 shows the principle of extrusion. The cut-off *billet* is heated to 450–500°C and placed in the *press container*. A hydraulically driven stamp presses the heated billet through a die with a hole. That hole has the shape similar to the cross-section of the desired profile.

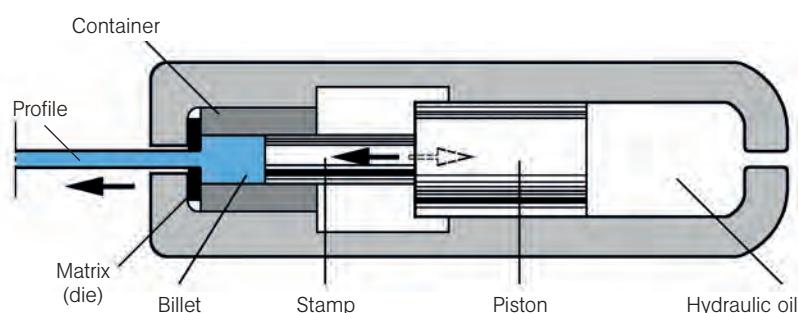


Fig 3.10 Cross-section of an extrusion press.

Large or medium-sized profiles are pressed in tools with only one hole. Smaller profiles are advantageously pressed in multi-purpose tools, up to sixteen holes may be used.

Profiles are usually divided into *massive* and *hollow*. The massive profiles require less complicated tools than the hollow profiles and are therefore easier to manufacture.

Press tools for massive profiles

A press tool for massive profiles consists of a *matrix*, i.e. a disc of tool steel with one or more holes, which corresponds to the cross-section of the desired profile, Fig 3.11.

Press tools for hollow profiles and tubes

For the production of hollow profiles and tubes, a multi-part press tool is used consisting of a *die plate* with a hole, which forms the outer contour of the profile. In front of the die is a *mandrel* with four holes (tunnels), bridges and a *core*, which forms the inner shape of the profile, Fig 3.12. The two die parts are pushed together so the core will be placed in the hole of the die plate and is held in place by the

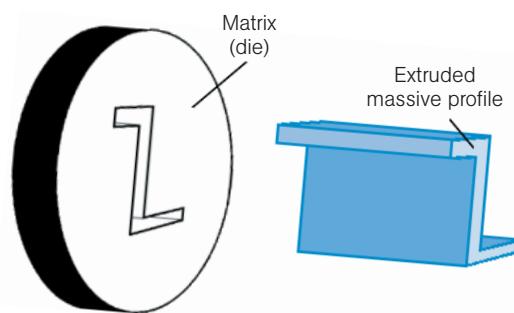


Fig 3.11 Die for a massive profile.

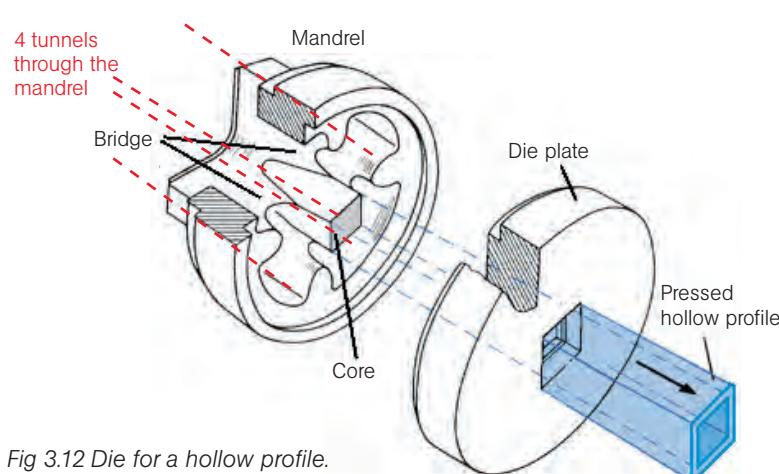


Fig 3.12 Die for a hollow profile.

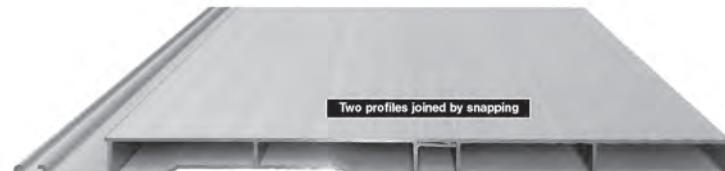
bridges. During the pressing process, the aluminium billet divides into four strings and floats into the mandrel's hole and around the bridges. Before entering the die plate, the four strings meet and are firmly pressed together to one piece before passing through the die hole. The finished hollow profile will now contain *longitudinal welding seams*, which are very strong in comparison to fusion welds. This type of tool is typically used for low and medium strength alloys.

Tubes of high-strength alloys can even be pressed from *hollowed* billets in special presses, whereby the tubes are made free from longitudinal weld seams. In this case, the core is on the press stamp and not in the tool.

Profile dimensions

The largest press in Sweden, Hydro Extrusion Sweden AB's P5 press in Finspång, has a pressing force of 6 500 ton (65 MN). Wider profiles can be produced by either welding together several profiles with, e.g. Friction Stir Welding (FSW) or by using another producer with larger presses than the P5. The advantages of pressing wide profiles are shown in Fig 3.13.

Two profiles joined by snapping



Extruded wide profile

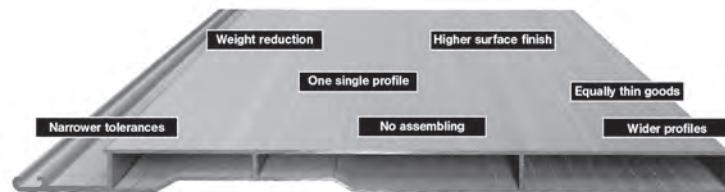


Fig 3.13 The advantages are many with wide profiles.

A unique area for wide profiles is the bodies for railroad cars. There is also a need for unusually wide profiles in the manufacturing of truck flaps and loading platforms.

3.4 Wire

Wires can be manufactured according to several methods. For unalloyed aluminium, continuous casting and rolling with subsequent separate drawing, dominate. Alloyed aluminium wire is usually produced by hot rolling of rods in wire rolling mills and the following drawing to final dimensions. In some cases, hot rolling can be replaced by extrusion. Areas of application include power lines, welding wire and fences, Fig 3.14.



Fig 3.14 Aluminium wire is used, among others, for electric high voltage lines and electrical cables.



Aluminium metallography

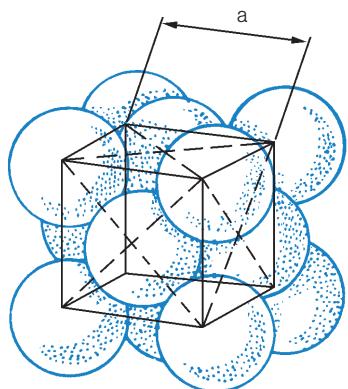


Fig 4.1 The structure of aluminium is fcc. Here the unit cell. $a = 0,4 \text{ nm}$.

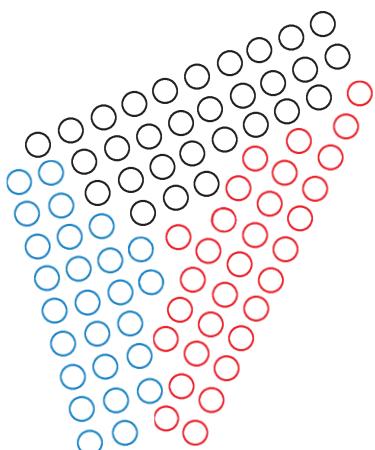


Fig 4.2 Grain boundaries. The atomic lattice has different orientations in different grains. The area between the atoms is called a grain boundary.

4.1 Aluminium structure

Aluminium is a silvery-white metal, the 13th element in the periodic table. It is crystalline, just like most other metals, which means that the atoms are in a regular pattern, a *lattice*. Aluminium has a face-centred cubic lattice (fcc structure), Fig 4.1. A large number of atoms in that regular pattern form a crystal grain. In one crystal there are many planes in different directions. Crystal grains meet in *grain boundaries*, Fig 4.2.

Fig 4.3 shows the grain structure of annealed aluminium. A typical grain diameter is 20–100 μm . In one grain, there may be several hundred billion "cubes" of the type Fig 4.1 shows. 1 mm^3 of aluminium contains about 10^{20} atoms.

Aluminium alloys occur in different *tempers*, i.e. the alloy is given desired properties by processing and heat treatment.

4.2 Cold working

Aluminium can be formed by *plastic deformation*, e.g. rolling, forging, bending, hydroforming and extrusion.

In cold working, the material *strain hardens*. Fig 4.4 shows how the grain structure from Fig 4.3 changes during cold working. The grains thus change their shape, because of different atomic layers in the regular atomic lattice slide against each other. The sliding is resulting from the movements of dislocations (stacking faults). Fig 4.5 and 4.6 show examples of dislocations.

During the deformation of the material, new dislocations are formed. As these increase in number, the dislocations prevent the movements of each other and obstruct further deformation, which means the strength of the material increases.

Fig 4.7 shows an example of how the strength changes due to cold working. With the increased amount of cold working, the ultimate strength, (R_m) and the yield strength, ($R_{p0,2}$) increase, while the elongation, (A) decreases.

By choosing the appropriate degree of cold working (reduction level), the material can get the intended strength.

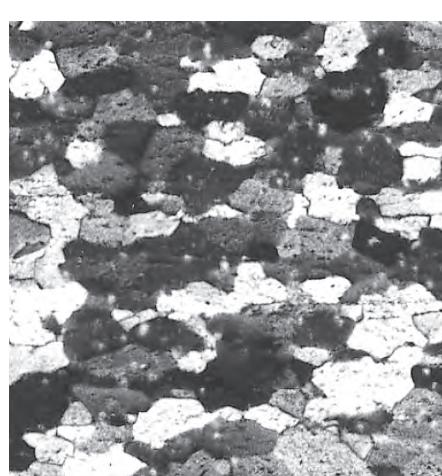


Fig 4.3 Grain structure in annealed aluminium seen in an optical microscope. The structure will be visible if polarised light is used on a polished and oxidised surface. This gives a contrast between different crystal directions. 1 cm in the picture corresponds to $20 \mu\text{m}$.

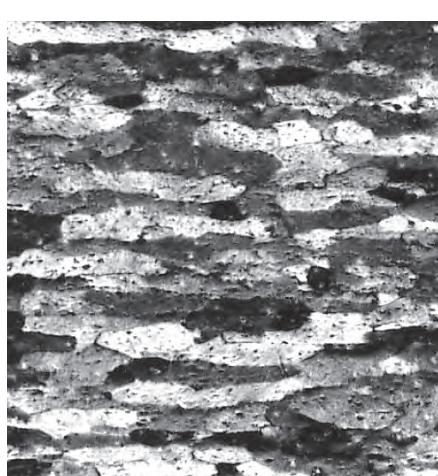


Fig 4.4 Grain structure of aluminium which has been cold worked after annealing. The grains are prolonged in the processing direction. Compare with Fig 4.3. 1 cm in the picture corresponds to $20 \mu\text{m}$.

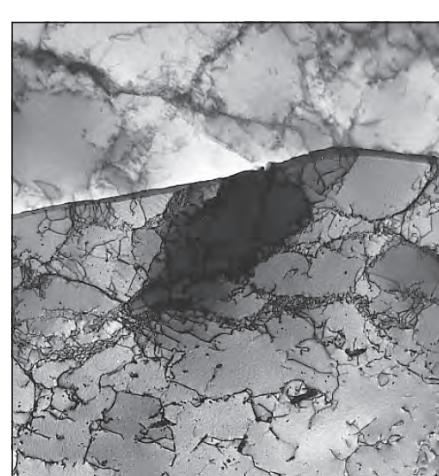


Fig 4.5 Grain boundary (across the image) and dislocations arranged in a cell pattern, seen in a transmission electron microscope (TEM) in high magnification. The material is pure aluminium. 1 cm in the picture corresponds to $1 \mu\text{m}$.

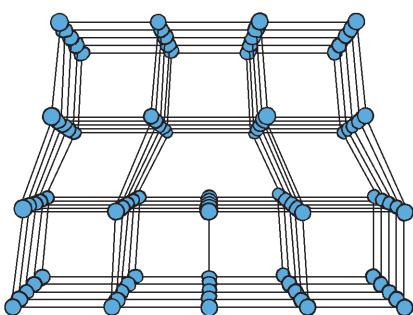


Fig 4.6 Dislocation (edge dislocation) in a single cubic lattice. The dislocation is a disorder in the otherwise regular lattice. Plastic deformation occurs through dislocation movements and formation of new dislocations.

4.3 Annealing

A material that has been hardened after cold working can be softened again through *heat treatment*. The process is called *soft annealing* (recrystallisation annealing) where the material is returned to standard grain structure, as shown in Fig 4.3. The material is now suitable for new forming operations.

Fig 4.8 shows how heat treatment can convert a full-hard material into a semi-hard temper if performed at a temperature slightly lower than for soft annealing. *Tempering* gives higher elongation values for materials cold worked to the same ultimate strength from an annealed temper.

4.4 Alloying elements

Aluminium can be alloyed with metals and non-metals. Thereby, aluminium materials can be given highly various properties.

Iron (Fe) and silicon (Si) occur naturally in aluminium from the bauxite and are therefore found in virtually all technically used aluminium materials. Aluminium containing a maximum of 1,0% by weight of iron and silicon together is called *unalloyed aluminium* or *pure aluminium*.

Unalloyed aluminium has low strength and limited use. Alloyed aluminium, on the other hand, gets elevated mechanical properties and can, therefore, be used in many different applications.

Common alloying elements, besides iron and silicon, are magnesium (Mg), manganese (Mn), copper (Cu) and zinc (Zn).

4.5 Solid solution strengthening

By adding atoms of one element (alloying element) to the crystalline lattice of aluminium (base metal), a solid solution forms which increases the strength of that alloy. These have a different atomic diameter and electron structure than aluminium atoms. The strength is based on the reaction of dislocation lines with foreign atoms.

The most common alloying elements that give a solid solution are manganese and magnesium. Fig 4.9 shows the positions of magnesium atoms that replace aluminium atoms in the lattice. This is called a "solid solution of magnesium in aluminium".

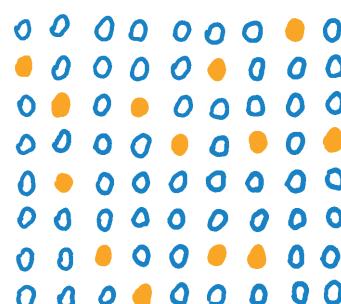


Fig 4.9 Atomic arrangement in a solid solution.

○ Aluminium atom
● Alloying atoms, e.g. magnesium or manganese

Although this way of alloying is called *solution hardening*, the alloy doesn't belong to the heat treatable alloy group. Hardenable alloys only refer to precipitation hardening.

4.6 Precipitation hardening

The strength of some aluminium alloys can be substantially increased by *precipitation hardening*, also known as *age hardening* or *particle hardening*.

If the aluminium alloy has a higher copper concentration than can be dissolved in the aluminium matrix, then the precursors of the Al_2Cu precipitates form during a heat treatment process of the material, Fig 4.10, which have a significant positive impact on yield and ultim-

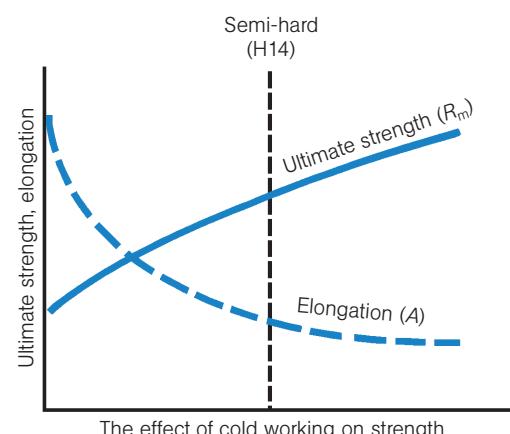


Fig 4.7 The effect of cold working on strength.

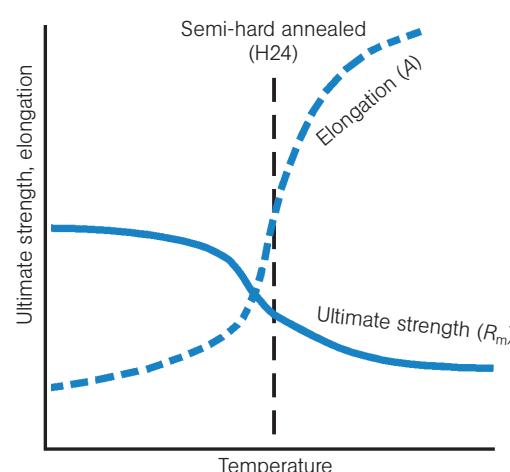


Fig 4.8 The influence of temperature on strength.

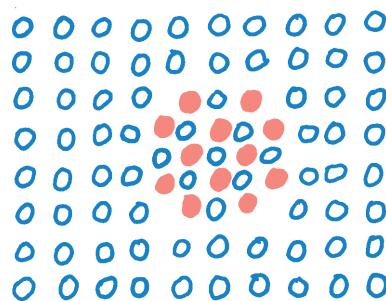


Fig 4.10 Precipitation after hardening.

○ Aluminium atoms
● Alloying atoms, e.g. copper

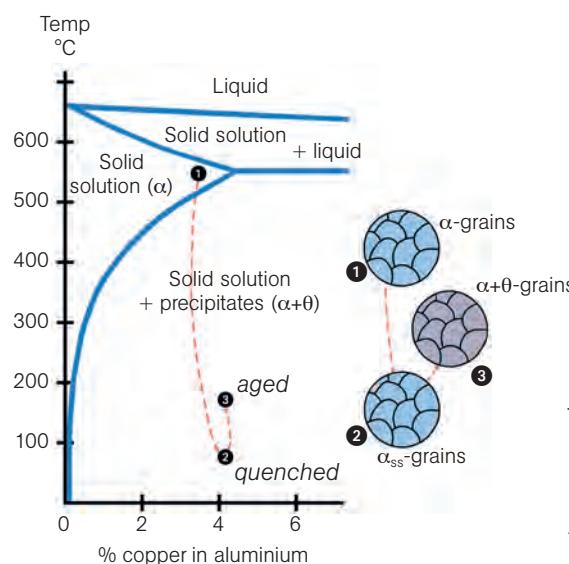


Fig 4.11 Phase diagram Al-Cu showing that the solubility of copper in aluminium increases with temperature.

α = round 4% Cu solved in Al

θ = Al_2Cu

α_{ss} = supersaturated solid solution (Cu in Al)

ate strength as shown. These precursors prevent the movement of the dislocations.

Aluminium-copper is an example of a precipitation hardening alloy. The most common alloy of this type, however, is aluminium-magnesium-silicon (AlMgSi), where the precipitates consist of magnesium and silicon (Mg_2Si).

Precipitation hardening is achieved by heat treatment in three steps, *solution treatment*, *controlled quenching* and *ageing*. The material is heated to 465–530°C, depending on the alloy. Then, the previously separated phases are dissolved and turned into a *solid solution*. The solubility increases as the temperature increases, so higher dissolution temperature is required when the alloy content is increased, Fig 4.11. The resolution ends with a quick cooling in water, mist or air. Afterwards, the ageing process takes place, during which the hardening precipitates form and grow.

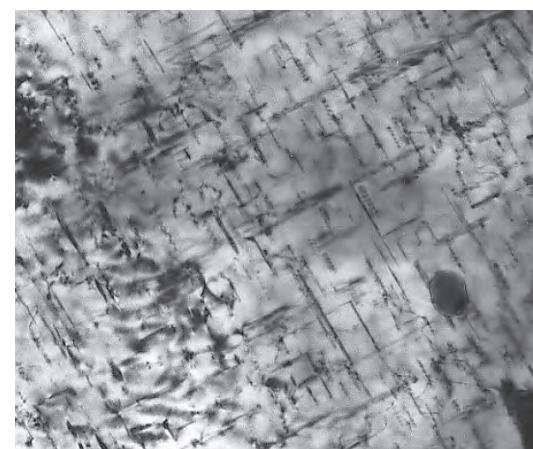


Fig 4.12 Precipitations of needle-shaped Mg_2Si -particles in an AlMgSi alloy after artificial ageing. The image is from a transmission electron microscope (TEM). 1 cm in the picture corresponds to 0,25 μm .

The ageing can be performed in two ways, *natural* (cold) ageing or *artificial* (warm) ageing. When the precipitation process occurs at room temperature (RT), it is referred to as *natural ageing*.

Artificial ageing is performed at 120–200°C depending on the alloy and results in a higher strength than for natural ageing. Fig 4.12 shows precipitations in an AlMgSi-alloy after artificial ageing.

Fig 4.13 gives some examples of how the strength is affected by temperature and time in natural and artificial ageing of AlMgSi-alloys.

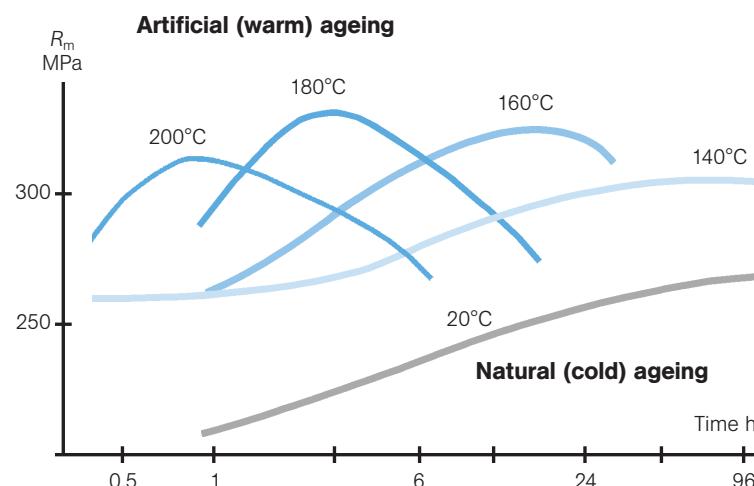


Fig 4.13 The strength is affected by temperature and time in natural and artificial ageing of AlMgSi-alloys.

Aluminium alloys

ISO = International Organisation for Standardisation
CEN = European Committee for Standardisation
EAA = European Aluminium (branch organisation)
AA = Aluminum¹⁾ Association (US trade organisation)
EN = European Standard
SS = Swedish Standard
SIS = Standards in Sweden

1) "Aluminum" is the American spelling of aluminium.

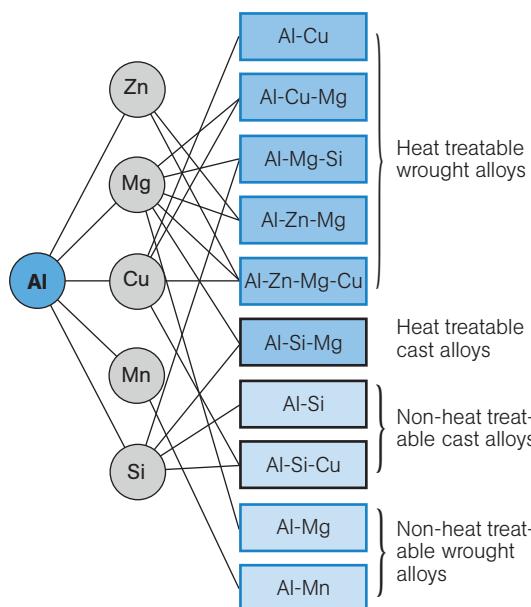


Fig 5.1 The most common alloy systems for aluminium materials.

Wrought alloy (AW) = Alloy for plastic processing (e.g. shaping, machining, bending, rolling)

Table 5.1 Main alloying elements in aluminium according to SS-EN¹⁾

1xxx(x)	Unalloyed (pure aluminium)
2xxx(x)	Copper
3xxx(x)	Manganese
4xxx(x)	Silicon
5xxx(x)	Magnesium
6xxx(x)	Silicon + Magnesium
7xxx(x)	Zinc
8xxx(x)	Other

1) 4 digits are used for wrought alloys and 5 digits for cast alloys.

The internet library "SIS Abonnemang", www.sis.se, holds more than 14 900 standards within materials technology. Furthermore, the database gives answers to many questions on metals and welding technology and offers access to the latest standard versions. The service "The material key – Comparisons between metallic materials" is an excellent tool for comparisons between old and new designations for metallic materials in Sweden and how to find equivalent materials in foreign countries. The service is continuously updated with new standards and newly revised editions of standards published recently.

5.1 Alloy Designation

European standard (EN) in the areas of untreated, processed and cast aluminium and aluminium alloy products is prepared and defined by the CEN and its CEN/TC 132 Committee. Material temper designations and specifications, terms and definitions, technical delivery terms, dimensions and tolerances as well as test methods are discussed. The designation systems within EN are different for different materials such as aluminium, copper, steel, cast iron, zinc and magnesium. In Sweden, the European standard is called SS-EN.

5.1.1 Aluminium Standardisation

For aluminium, there are two designation systems, one *numerical* and one *descriptive*. The first is based on a well-known American system from the Aluminum Association (AA), while the other is based on the chemical composition of the material. Both systems are used in parallel. The numerical system is mainly used, while the descriptive is used to provide additional information. In addition to the systems for alloy designations, there is a separate system for *tempers*.

5.1.2 Numerical designation system

The numerical designation for aluminium material, e.g. SS-EN AW-6063 or SS-EN AC-42000 is composed of three parts:

SS-EN	AW- AB- or AC-	6063 42000
SS = Swedish Standard	A = Aluminium	Alloy Number:
EN = European Standard	W = Wrought Alloys	4 digits for Wrought Alloys
	B = Casting alloys (as ingot)	5 digits for Casting Alloys
	C = Cast component	

In the numerical system, the first digit (6xxx resp. 4xxxx) gives the principal alloying element in the material, see Table 5.1. When an alloy AB (ingot) is cast to a component, it is called AC.

5.1.3 Descriptive designation system

If descriptive designations are used in addition to a numerical system, square brackets [] are used.

Unalloyed aluminium

The designation consists of Al followed by the aluminium content in per cent, with one or two decimals, e.g. [Al99,7]:

SS-EN AW-1070A [Al99,7].

Alloyed aluminium

The designation consists of Al followed by the chemical symbols of the most common alloying elements in descending content order:

SS-EN AW-7020[AlZn4,5Mg1].

5.2 Tempers

Aluminium material is described in addition to the alloy designation also by a *temper designation*. The example shows the structure of it.

SS-EN AW-5052[AlMg2,5]-H24
| Standard | Alloy designation | Temper |

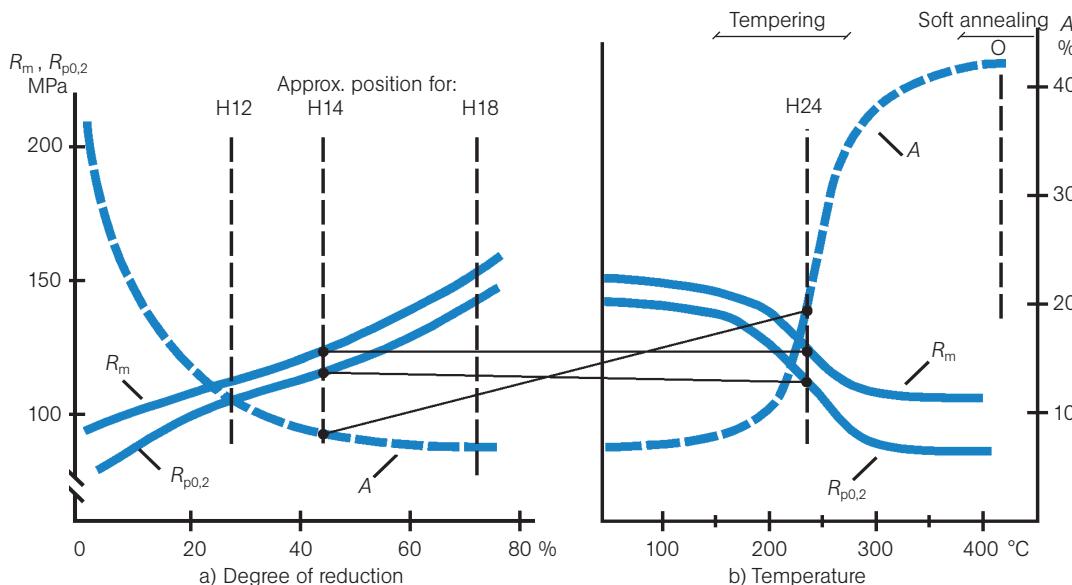


Fig 5.2 Effect of cold working (a), and tempering + soft annealing (b), on the strength for Al99.5 (AW-1050A). The figure gives approximate positions of reduction degree and temperature for different material conditions. The lines connecting points in the two diagrams show the principle difference in strength between conditions obtained by cold working (H14) and by cold working + tempering (H24) only.

Table 5.2 Temper designations

F	As fabricated
O	Annealed
H	Strain-hardened
W	Solution heat treated
T	Thermally treated

All designations are specified in the standard EN 1515:2017, "Aluminium and aluminium alloys – Wrought products – Temper designations".

5.2.1 Basic tempers

There are five basic material tempers, Table 5.2. The designations for them use letters. After a letter, up to five single digits can be specified for certain conditions, depending on how the material is processed.

F-temper (as fabricated) means that the material is coming *directly* from a forming process, e.g. forging or hot rolling, or that it is cast and unprocessed. No requirements for mechanical properties are stated.

O-temper means that the material has been *annealed* to obtain the lowest possible strength. The designation O may be followed by one digit that indicates unique heat treatments, but this is seldom used.

H-temper means that the material has been *cold worked* after the F- or O-temper to obtain specified strength values. Cold working can be followed by a heat treatment called *tempering*. The designation H is followed by at least two digits to indicate, i.e. the strength level. The H-temper can only be used for non-heat treatable alloys.

W-temper means that the material has been *dissolved* and *naturally aged* for such a short time that it is not stable. The designation W is followed by the natural ageing time in hours. W-temper is rarely used.

T-temper means that the material has undergone a complete hardening cycle containing *solution treatment* and *ageing* (natural or artificial) to obtain the intended strength, which also can be combined with cold working. The designation T is always followed by at least one digit. T-tempers are only used for heat treatable alloys.

5.2.2 Strain-hardening tempers

H-tempers are always indicated by at least two additional digits, Hxy. A third digit may sometimes occur. x and y mean the following:

The first digit (x) for H-tempers

H1y	Strain-hardened only e.g. cold rolled from annealed temper – no further heat treatment.
H2y	Strain-hardened and partially annealed
H3y	Strain-hardened and stabilised, (heat treatment used for AIMg-alloys)
H4y	Strain-hardened and lacquered or painted
H1y and H2y	are the most common H-tempers.

The second digit (y) for H-tempers

The second digit following the letter H indicates the degree of strain hardening as identified by the minimum value of the ultimate strength. Numeral 8 has been assigned to the hardest temper usually produced. The minimum ultimate strength of tempers Hx8 may be determined from Table 5.3 and is based on the minimum ultimate strength of the alloy in the annealed temper.

Hx2	Quarter-hard (1/4-hard)
Hx4	Half-hard (1/2-hard)
Hx6	Three-quarter-hard (3/4-hard)
Hx8	Fully-hard (1/1-hard)
Hx9	Extra hard

Table 5.3 Determination of Hx8 minimum ultimate strength

$R_{m, min}$ i O-temper MPa	Increase in R_m to Hx8-temper MPa
<40	55
45– 60	65
65– 80	75
85–100	85
105–120	90
125–160	95
165–200	100
205–240	105
245–280	110
285–320	115
>325	120

Temper between O (annealed) and Hx8 are designated by numerals 1 to 7.

Numerical 4 designates tempers whose ultimate strength is approximately midway between that of the O temper and that of the Hx8 temper.

Numerical 9 designates tempers whose ultimate strength exceeds that of the Hx8 temper by 10 MPa or more.

5.2.3 Thermally treated tempers

The T-tempers are indicated with at least one additional digit Tx.

The first digit (x) for the T-tempers

Tx In European Standards used tempers

- T1 Cooled from an elevated temperature shaping process and naturally aged
- T2 Cooled from an elevated temperature shaping process, cold worked and naturally aged
- T3 Solution heat treated, cold worked and naturally aged
- T4 Solution heat treated and naturally aged
- T5 Cooled from an elevated temperature shaping process and then artificially aged
- T6 Solution heat treated and then artificially aged
- T7 Solution heat treated and then artificially overaged
- T8 Solution heat treated, cold worked and then artificially aged
- T9 Solution heat treated, artificially aged and then cold worked
- T10 Cooled from an elevated temperature shaping process, cold worked and artificially aged

The most commonly used tempers are T4, T5 and T6. One or more digits can be added after the first for operations that affect the properties of the material. Up to five numbers may be present.

5.3 Alloys used for plastic deformation

All wrought alloys can be used for rolling and extrusion. For rolled materials, non-heat treatable alloys (3xxx and 5xxx) are the most common. Extrusions, on the other hand, are usually made of heat treatable alloys, preferably by AlMgSi (6xxx).

5.3.1 Non-heat treatable alloys

During the electrolysis of aluminium, a purity of 99,9% aluminium can be achieved using the purest raw materials. For higher purity, aluminium metal is refined in a second electrolysis. Aluminium with a purity of 99,998% is then obtained, which is used, among others, for electrical purposes in, e.g. electrolytic capacitors. In a chemical or electrolytic way, this high-purity aluminium can provide mirror-bright surfaces without mechanical polishing. It is also used as a coating material on, e.g. vehicle headlight reflectors or mirrors.

In unalloyed aluminium (pure aluminium) there is an original content of iron and silicon. That content must be adjusted to give the material desired properties and may not exceed 1%. Pure aluminium is sold with a guaranteed minimum aluminium content, e.g. Al99,7, Al99,5 and Al99,0. The strength of Al99,5 in the soft annealed condition is low. The material can harden through cold working (strain-hardening). Fig 5.2 shows how the strength of pure aluminium changes with the degree of reduction.

Most non-heat treatable alloys contain manganese and/or magnesium, which raise the strength with increased alloy content, Fig 5.3. The strength can also be increased by cold working, e.g. cold rolling.

5.3.2 Heat treatable alloys

Heat treatable alloys contain one or more added substances which are selected so that the gain in strength is achieved by *precipitation hardening*. Conditions for an alloy to harden is that the solubility of the added elements in the aluminium lattice varies with the temperature.

There are three different types of heat treatable alloy system:

- Aluminium-copper Precipitates of Al_2Cu
- Aluminium-silicon-magnesium Precipitates of Mg_2Si
- Aluminium-zinc-magnesium Precipitates of Zn_2Mg

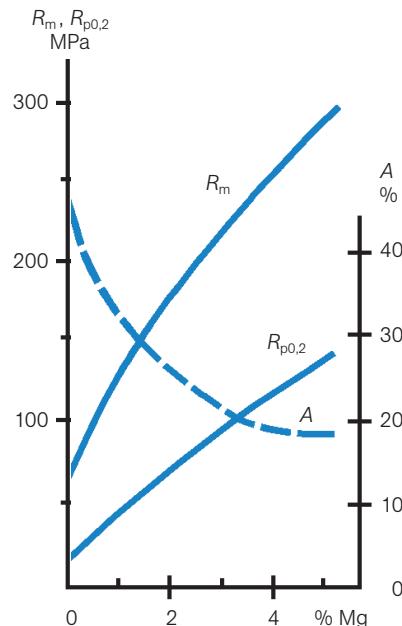


Fig 5.3 The effect of the magnesium content on the strength of an aluminium alloy in a soft annealed temper.

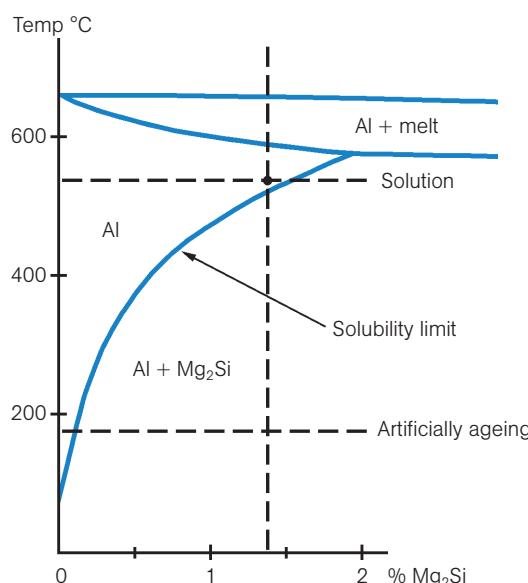


Fig 5.4 Phase diagram for AlMgSi alloys. The figure shows that in an alloy of about 1,4% Mg₂Si, all Mg₂Si is wholly dissolved in the temperature range of 525–585°C. Over this range, the alloy begins to melt, and below 525°C Mg₂Si particles are separated. Temperatures for dissolution and artificially ageing are marked (applies to the AW-6082 alloy).

5.3.3 Composition for wrought alloys

The Swedish standard SS-EN 573-3:2013 regarding wrought alloys, includes more than 170 aluminium alloys. The nominal composition of some of these is given below. For full details, refer to the standard.

Table 5.4 Chemical composition for some SS-EN wrought alloys

Designation according to SS-EN	Al	Si ¹⁾	Fe ¹⁾	Cu	Mn	Mg	Cr	Zn	Notes
Non-heat treatable alloys									
AW-1070A Al99,7	99,7	-	-	-	-	-	-	-	2)
AW-1050A Al99,5(A)	99,5	-	-	-	-	-	-	-	2)
AW-1350 E-Al99,5	99,5	-	-	-	-	-	-	-	2) 3)
AW-1200 Al99,0	99,0	-	-	-	-	-	-	-	2)
AW-3103 AlMn1	rest	-	-	-	1,2	-	-	-	
AW-3003 AlMn1Cu	rest	-	-	0,1	1,3	-	-	-	
AW-3005 AlMn1Mg0,5	rest	-	-	-	1,3	0,4	-	-	
AW-3004 AlMn1Mg1	rest	-	-	-	1,2	1,0	-	-	
AW-4015 AlSi2Mn	rest	1,8	-	-	0,9	0,3	-	-	
AW-4016 AlSi2MnZn	rest	1,8	-	-	0,9	-	-	-	0,9
AW-4017 AlSi1,5MnCuMg	rest	1,5	-	0,3	0,9	0,3	-	-	
AW-4045 AlSi10	rest	10	-	-	-	-	-	-	4)
AW-5005 AlMg1	rest	-	-	-	-	0,8	-	-	
AW-5049 AlMg2Mn0,8	rest	-	-	-	0,8	2,0	-	-	
AW-5052 AlMg2,5	rest	-	-	-	-	2,5	0,2	-	
AW-5754 AlMg3	rest	-	-	-	0,3	3,1	-	-	5)
AW-5083 AlMg4,5Mn0,7	rest	-	-	-	0,7	4,5	0,15	-	
AW-8011A AlFeSi	rest	0,7	0,8	-	-	-	-	-	
Heat treatable alloys									
AW-2011 AlCu6BiPb	-	-	-	-	-	-	-	-	
AW-2014 AlCu4SiMg	rest	0,9	-	4,5	0,8	0,5	-	-	
AW-6060 AlMgSi	rest	0,45	0,2	<0,1	-	0,45	-	-	
AW-6063 AlMg0,7Si	rest	0,4	-	-	-	0,7	-	-	
AW-6063A AlMg0,7Si(A)	rest	0,45	-	-	-	0,75	-	-	
AW-6101 E-AlMgSi ⁶⁾	rest	0,5	-	-	-	0,6	-	-	
AW-6463 AlMg0,7Si(B)	rest	0,4	-	-	-	0,7	-	-	7)
AW-6061 AlMg1SiCu	rest	0,6	-	0,3	-	1,0	0,2	-	
AW-6005 AISiMg	rest	0,75	-	-	-	0,5	-	-	
AW-6005A AISiMg(A)	rest	0,7	-	-	-	0,55	-	-	
AW-6082 AlSi1MgMn	rest	1,0	-	-	0,7	0,9	-	-	
AW-7020 AlZn4,5Mg1	rest	-	-	-	0,3	1,2	0,2	4,5	8)
AW-7021 AlZn5,5Mg1,5	rest	-	-	-	-	1,5	-	5,5	
AW-7075 AlZn5,5MgCu	rest	-	-	1,6	-	2,5	0,25	5,6	
AW-7108 AlZn5Mg1Zr	rest	-	-	-	-	1,0	-	5,0	9)

1) All commercial aluminium alloys contain one or a few tenths of Fe and Si.
These contents are not included in this table.

2) The specified aluminium content is a minimum requirement

3) For electrical purposes

4) Solders for flux brazing

5) (Mn + Cr) 0,4%

6) For electrical purposes

7) Alloy for bright anodising
(extra-low Fe content)

8) (Zr + Ti) 0,15%

9) Zr 0,18%

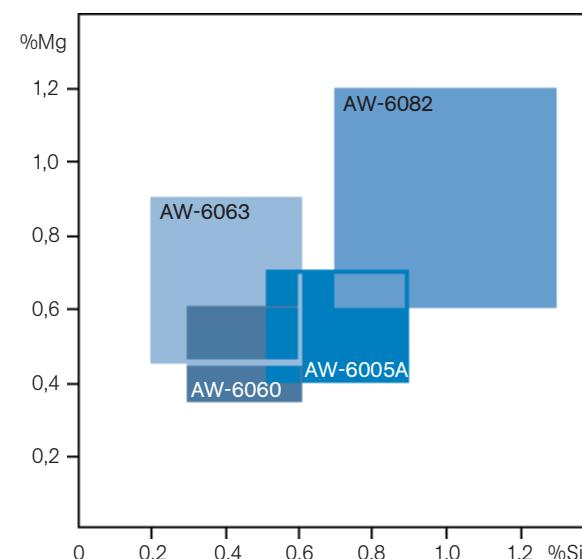


Fig 5.5 Composition window for some AlMgSi-alloys.

5.3.4 Strength for wrought alloys

Table 5.5 shows the strength of the most common sheet and profile alloys.

Plate ≥ 6 mm

A rolled product that is rectangular in cross-section and with thickness not less than 6 mm and with sheared or sawn edges.

Sheet 0,20 – 6 mm

A rolled product that is rectangular in cross-section with nominal thickness less than 6 mm but not less than 0,20 mm and with slit sheared or sawn edges.

Foil 0,006 – 0,20 mm (6 – 200 μm)

Aluminium foil is produced by rolling sheet ingots cast from molten billet aluminium, then re-rolling on sheet and foil rolling mills to the desired thickness, or by continuously casting and cold rolling.

Table 5.5 Typical strength of some wrought aluminium alloys according to www.makeitfrom.com

SS-EN	Temper	Yield strength $R_{p0,2}$ MPa	Ultimate strength R_m MPa	Elongation A %	Hardness HB	Fatigue strength ¹ MPa
Non-heat treatable alloys						
AW-1070A	O	17	73	33	18	20
	H14	79	120	6	32	40
AW-1050A	O	23	77	33	20	27
	H14	90	120	5	34	70
	H24	84	120	6	33	45
	H18	140	140	2	42	50
AW-1200	O	29	87	28	23	33
	H14	100	130	5	37	49
	H18	150	170	3,4	45	55
AW-3003	O	40	110	28	28	50
	H14	130	160	8	42	60
	H18	180	210	4,5	56	70
AW-5052	O	79	190	22	47	110
	H14	200	250	8	69	100
	H24	190	250	8	67	110
	H18	260	300	3,1	83	96
AW-5083	O	140	300	17	75	150
	H24	270	360	4,5	99	140
	H36	320	390	2,2	110	160
AW-5754	O	90	210	19	52	96
	H22/H32	150	240	8,4	63	120
	H12	190	240	5,5	66	140
	H24/H34	190	260	7,8	70	110
	H14	210	260	4	72	100
	H26	220	290	4,7	78	120
Heat treatable alloys						
AW-2011	T4	140	310	16	(95)	75
	T6	270	380	8,5	(115)	100
AW-2014	O	100	190	16	48	90
	T4	270	430	14	110	140
	T6	420	490	6,8	140	130
AW-6060	T4	70	140	16	-	37
	T6	170	220	11		70
AW-6061	O	76	130	20	33	61
	T4	130	230	18	63	96
	T6	270	310	10	93	96
	T651	270	320	11	93	95
AW-6063	O	49	110	21	25	55
	T4	82	160	17	50	65
	T6	210	240	11	73	70
	T8	240	260	9	80	82
AW-6005	T4	100	200	17	-	55
	T6	250	300	11	95	95
AW-6082	O	85	140	18	40	91
	T4	120	230	16	58	66
	T6	270	330	9,8	93	95
AW-7020	O	120	190	14	45	130
	T4	240	360	14	92	120
	T6	310	390	10	100	130
AW-7075	O	120	240	12	59	120
	T6	480	560	7,9	150	160
	T7	410	500	9,3	(150)	160

1) At 10^7 cycles, pulsating load ($\sigma_{min}/\sigma_{max} = -1$).

5.4 Casting alloys

The standard SS-EN 1706:2010 lists the standardised alloys used for casting. The exact requirements for composition and strength are stated in this. Examples of a complete standard designation for a casting alloy in the form of an ingot are: SS-EN 1706:2010 is AB-42000KT6.

Table 5.6 lists designations and suitable casting methods for a large number of casting alloys, while Table 5.7 provides a list of the most common temper designations. Table 5.8 gives the composition for the most common casting alloys, and Table 5.9 presents the strength.

Table 5.6 Aluminium casting alloys, casting methods and tempers after SS-EN 1706:2010

Alloying group	European standard		Casting methods and tempers			Range of application
	Numerical	Chemical	Sand-	Gravity-	Precision-	
AlCu	EN AB-21000	EN AB-AlCu4MgTi	T4	T4	T4	
	EN AB-21100	EN AB-AlCu4Ti	T6, T64	T6, T64		
AISiMgTi	EN AB-41000	EN AB-AISi2MgTi	F, T6	F, T6		
AISi7Mg	EN AB-42000	EN AB-AISi7Mg	F, T6	F, T6, T64	F, T6	AB-42000 (SK) for complicated, pressure-tight and fatigue-stressed castings. Excellent corrosion resistance and high strength after heat treatment. AB-43000 (SK) for complicated, thin-walled, pressure-proof and fatigue-stressed castings. Excellent corrosion resistance and high strength after heat treatment.
	EN AB-42100	EN AB-AISi7Mg0,3	T6	T6, T64	T6	
	EN AB-42200	EN AB-AISi7Mg0,6	T6	T6, T64	T6	
AISi10Mg	EN AB-43000	EN AB-AISi10Mg(a)	F, T6	F, T6, T64		AB-43000 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings. Excellent corrosion resistance and high strength after heat treatment. AB-43100 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings. Decent corrosion resistance and high strength after heat treatment. AB-43200 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings. High strength after heat treatment, but with limited corrosion resistance properties.
	EN AB-43100	EN AB-AISi10Mg(b)	F, T6	F, T6, T64		
	EN AB-43200	EN AB-AISi10Mg(Cu)	F, T6	F, T6		
	EN AB-43300	EN AB-AISi9Mg	T6	T6, T64		
	EN AB-43400	EN AB-AISi10Mg(Fe)			F	
	EN AB-43500	EN AB-AISi10MnMg				
AISi	EN AB-44000	EN AB-AISi11	F	F		AB-43400 (P) for complicated, thin-walled, pressure-tight and fatigue-stressed castings with high strength and excellent corrosion resistance. AB-44100 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings. Good elongation and excellent corrosion resistance. AB-44200 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings. Good elongation and excellent corrosion resistance.
	EN AB-44100	EN AB-AISi12(b)	F	F	F	
	EN AB-44200	EN AB-AISi12(a)	F	F		
	EN AB-44300	EN AB-AISi12(Fe)			F	
	EN AB-44400	EN AB-AISi9			F	
AISi5Cu	EN AB-45000	EN AB-AISi6Cu4	F	F		AB-44300 (P) for complicated, thin-walled, pressure-tight and fatigue-stressed castings with excellent corrosion resistance. Especially for hard, thin-walled castings with decent elongation. AB-44400 (P) for castings with toughness and corrosion resistance requirements.
	EN AB-45100	EN AB-AISi5Cu3Mg		T4, T6		
	EN AB-45200	EN AB-AISi5Cu3Mn	F, T6	F, T6	F	
	EN AB-45300	EN AB-AISi5Cu1Mg	T4, T6	T4, T6		
	EN AB-45400	EN AB-AISi5Cu3		T4		
AISi9Cu	EN AB-46000	EN AB-AISi9Cu3(Fe)			F	AB-44440 (SK) for castings with toughness and corrosion resistance requirements. AB-44500 (P) for complicated, thin-walled, pressure-tight and fatigue-stressed castings with high strength and relatively good corrosion resistance. AB-AB-46000 (P) for versatile use. Also for complicated and thin-walled castings. Especially for high-pressure castings. AB-46100 (P) for versatile use. Especially for thin-walled castings. AB-46200 (SK) for versatile use even for complicated and thin-walled castings. AB-46400 (SK) for versatile use even for complicated and thin-walled castings.
	EN AB-46100	EN AB-AISi11Cu2(Fe)			F	
	EN AB-46200	EN AB-AISi8Cu3	F	F	F	
	EN AB-46300	EN AB-AISi7Cu3Mg		F		
	EN AB-46400	EN AB-AISi9Cu1Mg	F	F, T6		
	EN AB-46500	EN AB-AISi9Cu3(Fe)(Zn)			F	
	EN AB-46600	EN AB-AISi7Cu2	F	F		
AISi(Cu)	EN AB-47000	EN AB-AISi12(Cu)	F	F		AB-46500 (P) for versatile use. Also for complicated and thin-walled castings. Especially for high-pressure castings.
	EN AB-47100	EN AB-AISi12Cu1(Fe)			F	
AISiCuNiMg	EN AB-48000	EN AB-AISi12CuNiMg		T5, T6		AB-47000 (SK) for complicated, thin-walled, pressure-tight and fatigue-stressed castings, but with limitations regarding corrosion resistance and toughness.
AlMg	EN AB-51000	EN AB-AlMg3(b)	F	F		AB-47100 (P) for complicated, thin-walled, pressure-tight and fatigue-stressed castings.
	EN AB-51100	EN AB-AlMg3(a)	F	F		
	EN AB-51200	EN AB-AlMg9			F	
	EN AB-51300	EN AB-AlMg5	F	F	F	
	EN AB-51400	EN AB-AlMg5(Si)	F	F		
AlZnMg	EN AB-71000	EN AB-AlZn5Mg	T1	T1		
	EN AB-71100	EN AB-AlZn10Si8Mg				

Table 5.7 Designations for heat treatment tempers according to SS-EN 1706:2010

F	= As fabricated
O	= Annealed
T1	= Controlled cooling after casting and naturally aged
T4	= Precipitation annealed and naturally aged
T5	= Controlled cooling after casting and artificially aged or over aged
T6	= Precipitation annealed and artificially aged
T64	= Precipitation annealed and not entirely artificially aged (under-aged)
T7	= Precipitation annealed and over-aged (stabilised)

Table 5.8 Nominal composition for some aluminium casting alloys (AB)

Designation acc. to SS-EN	Cast method	Nominal composition (%)						
		Al	Si	Fe ¹⁾	Cu	Mg	Cr	Zn
Non-heat treatable alloys								
AB-44100	AISi12(b)	S, G	88	12	0,6	0,2 ¹⁾	-	-
AB-44300	AISi12(Fe)	P	88	12	1,0	0,2 ¹⁾	-	-
AB-44400	AISi9	P	90	10	0,6	0,2 ¹⁾	-	-
AB-46000	AISi9Cu3(Fe)	P	90	9	1,2	3	-	-
AB-46200	AISi8Cu3	S, G	90	9	0,8	3	-	-
AB-46500	AISi9Cu3(Fe)(Zn)	P	88	9	1,3	3	-	-
AB-47000	AISi12(Cu)	S, G	88	12	0,8	1,0 ¹⁾	-	-
AB-51400	AlMg5(Si)	S, G	94	1	0,5	-	5	-
Heat treatable alloys								
AB-21000	AlCu4MgTi	S, G	95	-	0,18	4,5	0,2	-
AB-42000	AISi7Mg	S, G	93	7	0,5	-	0,3	-
AB-42100	AISi7Mg0,3	S, G	93	7	0,2	-	0,4	-
AB-43100	AISi10Mg(b)	S, G	90	10	0,5	0,2 ¹⁾	0,3	-
AB-71000	AlZn5Mg	S, G	93	-	0,7	0,4	0,7	0,4
AB-71100	AlZn10Si8Mg			8	0,3	0,3	5,5	0,2
							10	0,15

S = Sand casting, G = Gravity casting, P = Pressure die-casting

1) Max-values

Table 5.9 Strength for some aluminium casting alloys (AC)

SS-EN	Cast method	Temper	Yield	Ultimate	Elong-	Hard-	Fatigue
			strength $R_{p0,2}$ MPa	strength R_m MPa	ation A %		
Non-heat treatable alloys							
AC-43400	P	F	160	270	1,1	80	110
AC-43500		F	120–150	250–290	5–11	75–95	80–90
		T5	155–245	275–340	4–9	80–110	
		T6	210–280	290–340	7–12	90–110	
		T7	120–170	200–240	10–20	60–75	
AC-44100	S	F	87	180	4,9	59	64
	G	F	80	170	5	55	
AC-44300	P	F	150	270	1,1	68	100
AC-44400	P	F	110	210	4,1	61	79
AC-46000	P	F	160	270	1,0	91	110
AC-46200	S	F	90	150	1	60	
	G	F	100	170	1	75	
	P	F	130	210	1,1	82	87
AC-47000	S	F	80	150	1	50	
	G	F	97	180	1,7	60	68
AC-47100	P	F	160	270	1,1	80	110
AC-51200	P	F	150	220	1,1	80	100
AC-51400	S	F	100	160	3	60	
	G	F	120	190	3,4	71	85
Heat treatable alloys							
AC-21000	S	T4	240	340	6,7	100	100
AC-42100	S, G	F	90–150	180–240	4–9	55–70	67
	S	T6	200–280	240–320	3–6	80–110	
	G	T6	220–280	290–340	5–9	90–125	70
	G	T64	180–200	250–270	8–12	80–95	76
AC-43100	S	F	80	150	2	50	
	S	T6	180	220	1	75	
	G	F	97	180	2,5	60	68
	G	T64	230	270	2,2	91	76
	G	T6	230	270	1,1	94	71
AC-71100		T1	230	260	1,1	110	150

S = Sand casting, G = Gravity casting, P = Pressure die-casting

NOTE! Pressure die-castings should typically not be welded or heat treated unless special casting techniques are used (e.g. vacuum casting).

NOTE! The strength values for pressure die-castings in the table are only to be considered as guide values for machined test rods taken from substances that are separately cast and not what is to be expected in a finished casting.

5.5 Physical properties

Table 5.10 and 5.11 provide some relevant physical data for some wrought alloys (AW) and some casting alloys (AB). Some of the features are strongly affected by the alloys, while others are relatively unaffected at the most common alloy levels.

Properties that are relatively little affected by alloying elements are density, modulus of elasticity, coefficient of expansion and specific heat. Only if the alloy content is particularly high, as in some casting alloys with high silicon content, the variation becomes more significant than a few per cent. However, melting temperature, resistivity, and thermal conductivity are strongly dependent on the alloy content. Resistivity and thermal conductivity are also strongly dependent on the temper in heat treatable alloys.

Table 5.10 Physical data for some wrought alloys

Designation according to SS-EN		Density (kg/dm ³)	Coefficient of expansion (μm/m·°C)	Specific heat (J/kg·°C)	Melting range (°C)	Modulus of elasticity (MPa)	Temper	Resistivity (nΩm)	Thermal conductivity (W/m·°C)
Non-heat treatable alloys									
AW-1050A	Al99,5(A)	2,70	23,5	899	645–658	69 000	All	29,0	229
AW-1200	Al99,0	2,72	23,4	898	645–657	69 000	All	29,5	225
AW-3003	AlMn1Cu	2,73	23,1	892	640–655	69 500	All	34,0	190
AW-5005	AlMg1	2,70	23,5	897	630–655	69 500	All	33,0	201
AW-5052	AlMg2,5	2,68	23,7	901	605–650	70 000	All	49,5	138
AW-5083	AlMg4,5Mn0,7	2,66	23,8	899	580–640	71 000	All	60,0	117
Heat treatable alloys									
AW-2011	AlCu6BiPb	2,84	23,0	863	540–645	72 500	T4	44,0	152
							T6	38,0	172
AW-2014	AlCu4SiMg	2,80	22,7	869	505–640	73 000	O	34,0	192
							T4	51,0	134
							T6	43,0	155
AW-6005A	AlSiMg(A)	2,71	23,3	892	605–655	69 500	T6	35,0	193
AW-6063	AlMg0,7Si	2,70	23,5	898	615–655	69 500	O	30,0	218
							T4	35,0	197
							T6	33,0	201
AW-6082	AlSi1MgMn	2,71	23,1	894	575–650	70 000	O	31,0	216
							T4	41,0	167
							T6	39,0	172
AW-7020	AlZn4,5Mg1	2,78	23,3	873	605–645	70 000	T6	49,0	140
AW-7075	AlZn5,5MgCu	2,81	23,5	862	475–635	72 000	O	38,0	175
							T6	52,0	134

Table 5.11 Physical data for some aluminium casting alloys

Designation according to SS-EN		Density (kg/dm ³)	Coefficient of expansion (μm/m·°C)	Specific heat (J/kg·°C)	Melting range (°C)	Modulus of elasticity (MPa)	Temper	Resistivity (nΩm)	Thermal conductivity (W/m·°C)
Non-heat treatable alloys									
AB-44300	AlSi12(Fe)	2,65	21,0	960	575–585	75 000	All	50,0	150
AB-46000	AlSi9Cu3(Fe)	2,75	21,0	960	510–610	75 000	All	60,0	155
AB-51400	AlMg5(Si)	2,65	23,0	960	560–630	70 000	All	50,0	125
Heat treatable alloys									
AB-21000	AlCu4MgTi	2,75	23,0	910	540–640	72 000	All	55,0	125
AB-42000	AlSi7Mg	2,70	22,0	960	550–625	75 000	All	50,0	160
AB-71000	AlZn5Mg	2,80	24,0	960	600–650	70 000	All	50,0	125

Heat treatment

6.1 Ovens for heat treatment

For correct heating, especially for solution heat treatment and artificial ageing, a suitable oven and accurate temperature control are required. Air circulation ovens (convection ovens) are commonly used. The oven atmosphere, air, should be completely free from moisture and sulphur to avoid discolouration.

Heating to soft annealing and solution temperatures must be done as quickly as possible. It is an advantage if the oven already has this temperature when inserting the goods.

Gas burners, oxygen cutting torches or welding flames are not recommended for heat treatment of aluminium.

6.2 Soft annealing

Appropriate temperatures for soft annealing are shown in Table 6.1. The holding time at the temperature should be about 30 minutes.

Soft annealing

Soft annealing means rapid heating up to the specified temperature, followed by about 30 minutes of holding time. Cooling, especially for heat treatable alloys, should take place slowly and preferably in an oven down to about 250°C, then free cooling.

When annealing non-heat treatable alloys, the reduction in the nearest previous cold forming operation should not be less than 25% and preferably reach 50% or more, to avoid coarse grain structure. Quick heating is especially needed for AIMn-alloys. Slow heating, too high temperature, or too long holding time can lead to coarse grain formation. Usually, free cooling is used, but water cooling is also adopted.

For heat treatable alloys, excessive temperatures cause undesirable hardening effects or coarse grains. To avoid these effects and obtain maximum softness, the material should cool slowly, preferably in the oven down to about 250°C, then removed to allow free cooling. A high degree of reduction after an earlier cold forming process and rapid heating should be attained for the same reasons as for non-heat treatable alloys.

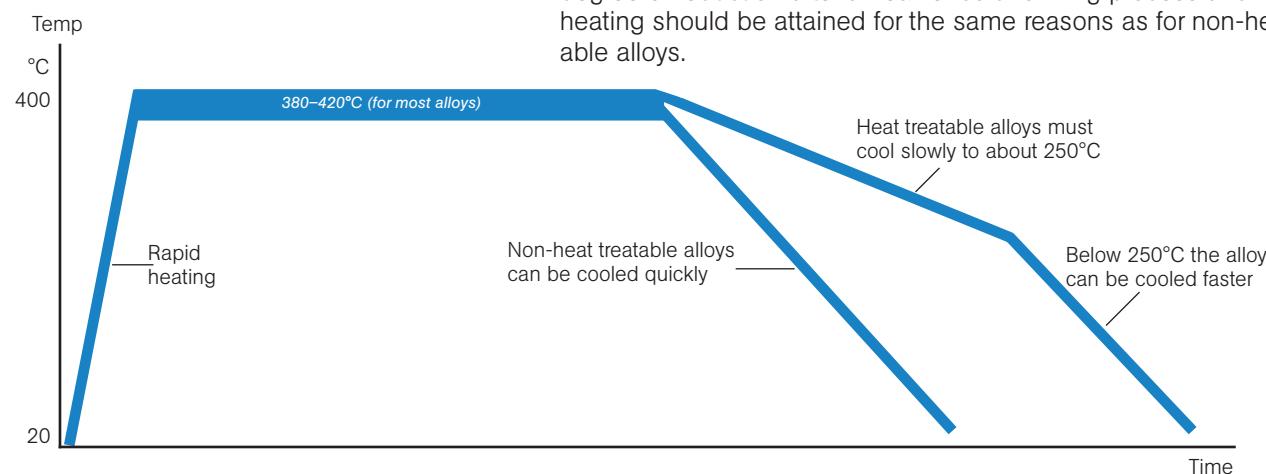


Fig 6.1 The soft annealing process for all aluminium alloys.

6.3 Age hardening

The age hardening process is carried out in three successive steps:

- solution heat treating
- quenching
- ageing

For extrusions, a separate solution heat treatment is often unnecessary, since the freshly extruded profile already has a temper and condition which corresponds to that of a solution heat treated piece. Recommended times and temperatures are given in Table 6.1.

6.3.1 Solution heat treatment

Heating to solution temperatures should be performed quickly. The heating time can vary from a few minutes up to a few hours. The oven capacity and the number of pieces also affect the time. Place the goods in the oven, so the heating and cooling are carried out homogeneously throughout the batch. The guideline value for holding time at the specified temperature is 15–60 min.

Solution temperature limits are essential – too low a temperature results in incomplete solution and low strength. Too high a temperature will cause the risk of discolouration, blistering or incipient melting.

6.3.2 Quenching

The cooling after the solution must be done quickly to avoid unwanted concentrations of alloying elements close to dislocations and grain boundaries. Furthermore, it is not allowed to cool faster than necessary to minimise residual stresses, which can lead to deformation or cracking. The quenching should, therefore, be made in cold water, Fig 6.2.

The cooling rate is alloy dependent. Large forgings can be cooled in warm or boiling water to avoid cracking. The transfer of material from the oven to the water should be quick. For thin goods, the time should not exceed 10 sec. Small details are often cooled with water spray, which reduces the tendency of the material to deform. AlMgSi-alloys can be fan-cooled without reduced strength unless the goods are very thick. For AlZnMg-alloys, fan-cooling is recommended.

The cooling of heat treatable alloys not only affects properties such as strength and ductility but can also cause thermal stresses. These are usually minimised by reducing the cooling rate after the solution treatment. However, if the rate is too low, undesirable grain boundary precipitations will be obtained. If it is too high, there is an increased risk of deformation. Therefore, a big challenge in the cooling process is to select parameters that optimise strength while minimising distortion and ensuring that other undesirable effects are not obtained, e.g. intercrystalline corrosion, which also depends on the cooling rate.

6.3.3 Ageing

After the quenching, the aluminium alloys age spontaneously, and during this process, fine dispersion (small and many) particles precipitates, which considerably increases the material strength. The diffusion process and precipitation kinetics vary with the alloy composition.

The ageing is obtained either at room temperature (RT), *natural ageing* or at elevated temperature, *artificial ageing*. The alloying atoms, which after solution heat treatment and cooling are present in a supersaturated solution, form by diffusion small separated particles which increase the material strength. This process already starts at RT.

Different alloys age differently at RT. The increase of strength becomes markedly higher for AlZnMg-alloys than for AlMgSi. The alloying content is also of great importance – e.g. AW-6082 age significantly faster than AW-6060 due to a higher alloy concentration.

Characteristic of AlZnMg-alloys is that ageing at RT lasts for a very long time (several months) before a stable state is reached. For AlMgSi the ageing is complete already after a few days.

Naturally aged material can be cold formed if the forming is easy. Directly after the solution heat treatment, the formability is best. This can be utilised in complex forming operations, which are best performed shortly after the dissolution. If for practical reasons, the time between dissolution and cold forming is long, the material can be stored at low temperature, e.g. in a freezer at -20°C. For most alloys, a few days at this temperature give a slight natural ageing effect.

Solution heat treatment

Rapid heating to specified temperature. Holding time 15–60 minutes depending on the dimension of the goods. Forced air cooling (fan) if the thickness of the piece is less than 6 mm. For thicker material: Cooling in water. Cooling speed: 1–2°C/s.

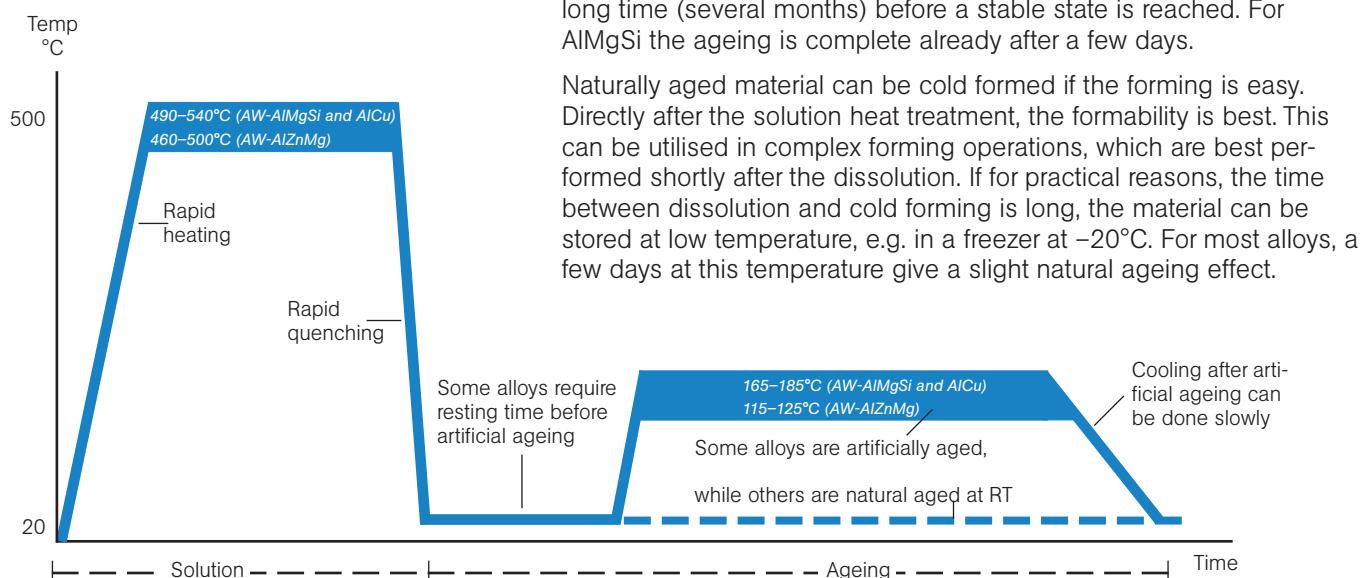


Fig 6.3 The precipitation hardening process for heat treatable alloys.

Maximum strength is achieved after artificial ageing. For best strength, some alloys should be natural aged 1–2 days before artificial ageing, while others should be natural aged shortest possible time, preferably less than one hour. The first group includes AlZnMg-alloys and low alloyed AlMgSi (e.g. AW-6060). The latter consists of higher alloyed AlMgSi (e.g. AW-6005 and AW-6082).

Recommended times and temperatures must be followed if best results are to be obtained. In general, if the ageing temperature is increased, the time can be reduced, but followed by lower strength.

6.4 Heat treatment of aluminium castings

Various types of heat treatment are often used to improve the mechanical properties of aluminium castings. For more info see Gjuteriteknisk Handbok, Värmebehandling av aluminiumsgjutgods.

The most common heat treatment of castings is precipitation hardening (solution heat treatment + artificial ageing = T6). Commonly, this treatment only applies to sand and gravity castings. The hardening process is based on the fact that some alloying elements added to an aluminium melt have better solubility in the solid state at high temperature rather than at low temperature. For the most common aluminium cast alloys, magnesium is added as an active agent for the precipitation hardening. Magnesium combined with silicon form Mg₂Si.

Table 6.1 Heat treatment for some wrought aluminium alloys

Designation SS-EN	Temperatures and times				
	Soft annealing °C	Solu-tion °C	Natural ageing days	Artificial ageing °C	Temper h
Non-heat treatable alloys					
AW-1070A	Al99,7	380–450			
AW-1050A	Al99,5(A)	380–450			
AW-1350	E-Al99,5	380–450			
AW-1200	Al99,0	380–450			
AW-3103	AlMn1	450–520			
AW-3003	AlMn1Cu	450–520			
AW-3004	AlMn1Mg1	380–450			
AW-3005	AlMn1Mg0,5	380–450			
AW-5005	AlMg1	380–450			
AW-5049	AlMg2Mn0,8	380–450			
AW-5052	AlMg2,5	380–450			
AW-5754	AlMg3	380–450			
AW-5083	AlMg4,5Mn0,7	410–450			
Heat treatable alloys					
AW-2011	AlCu6BiPb	380–420	520± 5	5	160± 5 14 T8
AW-2014	AlCu4SiMg	380–420	500± 5	5	175± 5 8 T6
AW-6005	AlSiMg	380–420	530±10	2	180± 5 5 T5
AW-6061	AlMgSi				
AW-6063	AlMg0,7Si	380–420	530±10	2	180± 5 5 T6
AW-6082	AlSi1MgMn	380–420	530±10	2	180± 5 5 T5
AW-7075	AlZn5,5MgCu	400–420	465± 5	-	120± 5 24

Materials intended for decorative anodising should not be hot formed, annealed or dissolved, as a poorly anodising result easily will be obtained.

1) For maximum strength recommends 100°C during 4 hours + 140°C during 18 hours.

Table 6.2 Heat treatment for some aluminium casting alloys

Designation SS-EN	Temperatures and times		
	Solution °C	Natural ageing days	Artificial ageing °C h
Non-heat treatable alloys			
AC-21000	AlCu4MgTi	525± 5	4–8 not performed
AC-42000	AlSi7MgFe	525± 5	3–6 160±10 8
AC-42100	AlSi7Mg	540± 5	12 150± 5 12
AC-43100	AlSi10Mg	525± 5	3–6 160±10 8
AC-71000	AlZn5Mg	1)	

1) A solution effect is obtained in the material at the component casting and the subsequent cooling without a separate solution treatment. Natural ageing is then performed at room temperature.

Corrosion resistance

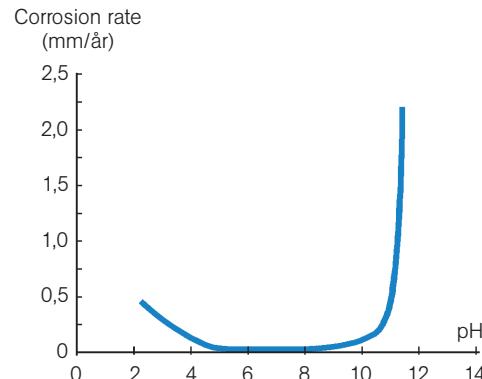


Fig 7.1 Corrosion rate (average corrode depth) of aluminium at different pH values (pH adjustment made with hydrochloric acid and sodium hydroxide, respectively).

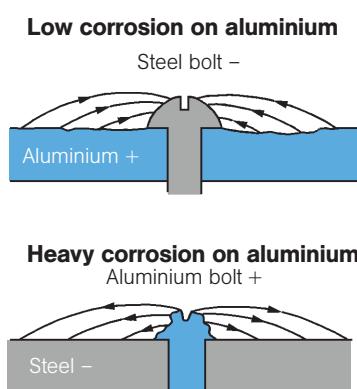


Fig 7.2 The noblest metal becomes the cathode (–) and is protected against corrosion, while the most ignoble becomes the anode (+) and corrodes. A small cathode surface and a large anode surface provide insignificant corrosion. In the opposite case, in severe environments, severe attacks can quickly be achieved.

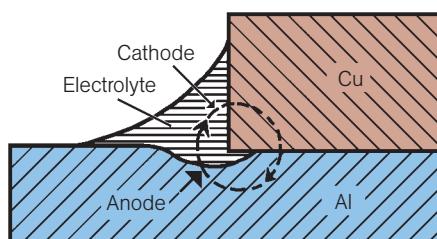


Fig 7.3 Electrolytic cell between aluminium and copper. The most ignoble metal (here aluminium) becomes the anode and corrodes.

7.1 Some terms

Materials attacked by chemical or electrochemical reactions with a surrounding medium are subjected to *corrosion*. The material's ability to withstand corrosion is called *corrosion resistance*.

Corrosion is the reaction of aluminium with water and the subsequent deterioration of its properties. Corrosion, by definition, is a slow process, requiring days or years to occur to a noticeable level, as opposed to similar electrochemical reactions such as etching, brightening, or anodising which occur in minutes or less.

7.2 Corrosion properties

Untreated aluminium exhibits excellent corrosion resistance in most environments, this because aluminium is spontaneously covered with a thin oxide layer which passivates the surface and prevents further oxidation.

Aluminium oxide is dense and, unlike oxide layers on other metals, adheres firmly to the substrate. If the oxide layer is mechanically damaged, it is immediately reformed.

The oxide layer is a fundamental base for the excellent corrosion properties of aluminium. It is stable in the pH range of 4–9. In strongly acidic or alkaline environments, aluminium corrodes quickly, Fig 7.1.

In general, the cleaner the aluminium material is, the more protective the oxide layer will be, which is especially true for highly pure aluminium, Al99,8. However, such material has low mechanical strength and is seldom used. Materials with higher corrosion resistance are only used in exceptional cases.

For unalloyed aluminium of standard quality, like Al99,5 and many other alloys, the corrosion resistance is equally good. It is usually other properties that determine the choice of alloy in constructions. However, Mn-containing materials have slightly increased resistance in an acidic environment, as Mg-alloyed materials show in a weak alkaline, marine environment. Alloys containing more than 0,5% Cu, including high strength alloys of type AlCuMg and AlZnMg (Cu), generally have worse corrosion resistance than other aluminium alloys.

7.3 Most common corrosion cases

Types of corrosion that mainly occur on aluminium are:

- bimetallic corrosion (former galvanic corrosion)
- pitting corrosion
- crevice corrosion
- filiform corrosion

Another, more unique type of corrosion, is *stress corrosion cracking*, SCC. It occurs mainly in high strength alloys, e.g. AlZnMg, if exposed to high tensile stresses for a long time and in a corrosion medium.

7.3.1 Bimetallic corrosion

Bimetallic corrosion can occur when different metals are in contact with each other, while there is a continuous electrolyte bridge between the metals. Figs 7.2 and 7.3 show bimetallic corrosion.

In most combinations with other metals, aluminium is the less noble. Therefore, the risk of bimetallic corrosion on aluminium is higher than for most other structural materials. However, the risk is less than the general belief.

The risk for bimetallic corrosion on aluminium is present:

- only at metallic contact with more precious metals (or other electron conductors, e.g. graphite)
- at the same time as there is an electrolyte (liquid) with good conductivity between the metals

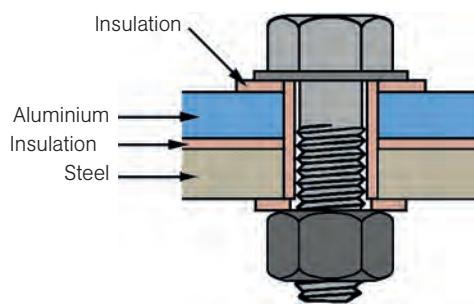


Fig 7.4 Electrical insulation between various metals prevents bimetallic corrosion.

The origin of bimetallic corrosion is often due to inappropriate design of the construction in question. Bimetallic corrosion does not occur in a dry indoor atmosphere. The risk is also low in a rural atmosphere. However, the risk of bimetallic corrosion must always be considered in a chloride-bearing environment, e.g. in sea atmosphere and salted roads. Here copper and carbon steel, but also stainless steel, can give bimetallic corrosion on aluminium.

Zinc-plated steel in contact with aluminium can also cause problems. First, the zinc layer protects the aluminium metal, but once the zinc layer has corroded away, the exposed steel can cause an attack on aluminium. Hot galvanised steel has a thicker zinc layer than electric galvanised steel and thus protects for an extended period. Therefore, when contact on aluminium arises in an aggressive environment, it is best to choose hot-dip galvanised steel.

When different metals come into contact with each other, bimetallic corrosion can be prevented by electrical insulation between the metals. The insulation must completely break the metallic contact. Fig 7.4 shows how this can be done in a bolted joint.

In large structures, where insulation is difficult to carry out, the electrolyte bridge between the two metals can instead be broken by painting or plastic coating. It is usually best to hide the cathode surface (the noblest metal). Another solution is to use spacers of, e.g. plastic film.

Another way to reduce the risk of bimetallic corrosion is to use *cathodic protection* with sacrificial anodes of a less noble metal. That anode will have metallic contact with the aluminium object to be protected – the less noble material sacrifices (corrodes) in this combination. The conditions for obtaining corrosion protection is that there is a liquid contact between the surface to be protected and the anode. For aluminium, sacrificial anodes of Zn or Mg are often used, Fig 7.5.

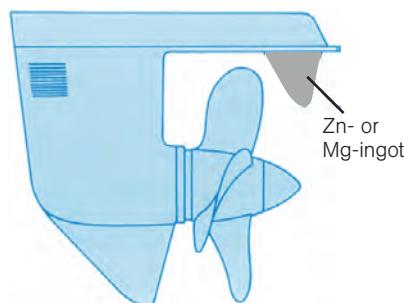


Fig 7.5 Cathodic protection with a sacrificial anode for a cast aluminium outboard engine.

7.3.2 Pitting corrosion

Pitting corrosion is the most common type of corrosion on aluminium. It occurs only in the presence of an electrolyte such as water or moisture with salts dissolved therein, usually chlorides.

The pits formed by random are generally tiny and reach a maximal depth of some tenths of a millimetre ($\approx 100\text{--}200\ \mu\text{m}$) in an outdoor atmosphere. In water and soil, greater depth can occur. The corrosion products often cover the attack sites, which is why visible pits are rarely found in the aluminium surface.

The pitting corrosion is primarily an aesthetic problem that practically never affects the strength and is most significant on untreated aluminium. Surface treatment counteracts pitting corrosion. The treated surface requires cleaning to maintain its attractive appearance and prevent corrosion. Rinsing with water is often enough. Alkaline detergents may not be used.

Pitting corrosion can be prevented with cathodic protection. It is also essential that the structure is designed so that drying can take place.

7.3.3 Crevice corrosion

Crevice corrosion can occur in narrow, fluid-filled gaps, Fig 7.6. The likelihood that this type of corrosion will occur in structures is generally small. However, significant corrosion can happen in a chlorine-containing sea atmosphere or externally on vehicles.

When transporting and storing, in particular, aluminium sheets, water sometimes collects in gaps between opposing surfaces and causes superficial corrosion (water stains). The water comes from rain or condensation that is capillary sucked in between the metal surfaces. This is formed when cold (RT) material is introduced into a warm room.

To prevent crevice corrosion sealants or double-sided adhesive tapes can be used at joining, which prevents water from entering into the gaps. Riveting or bolting can in some cases be replaced by or combined with glueing, which will prevent the formation of crevices.

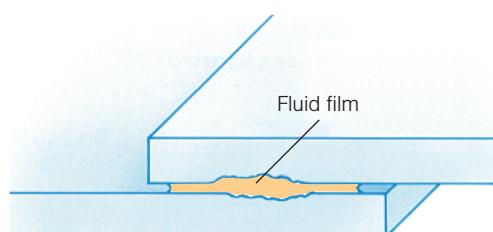


Fig 7.6 Crevice corrosion occurs in narrow areas.



Fig 7.7 Filiform corrosion attack on an aluminium vehicle part. The arrow shows defects in the paint layer where the corrosion started.



Fig 7.8 Filiform corrosion around a scratch on a lacquered aluminium part after ACT-testing (Accelerated Corrosion Test).

7.3.4 Filiform corrosion

Filiform corrosion is a type of corrosion that occurs on the aluminium surface beneath paint, primer and coatings. The breakdown of the aluminium parts is only cosmetic, and the corrosion attack is limited to the surface. This corrosion type appears as thin fibre-like threads filled with corrosion products (white powder) below the coating, Figs 7.7-7.8.

The attack starts around a defect in the coating caused by, e.g. a stone chip, scratch, sharp edge, dent or drilled hole. Filiform corrosion is spread by moisture penetrating the paint/metal interface, which produces corrosion with round or worm-like blisters, often flaking. The corrosion can adversely affect the protective properties of the coating system.

Conditions for filiform corrosion on, e.g. cars, require that all of the following three points will be met:

- Painted or coated aluminium surface
- Damage on the surface coating, which allows the electrolyte to penetrate beneath the layer
- Presence of an electrolyte (saltwater)

Filiform corrosion typically occurs in humid/warm environments and is noticeably more common in coastal and industrial areas.

Protective measures to prevent filiform corrosion

- Clean the surface thoroughly before coating
- Follow recommendations for corrosion protection and repainting
- Eliminate the surface defects (e.g. pores, scratches, air bubbles, lack of coverage)

Painted aluminium parts that have got filiform corrosion can be repaired by removing the coating and the corrosion products plus grinding and repainting with a recommended coating system.

7.4 Aluminium in different environments

7.4.1 Aluminium in the atmosphere

In a typical rural atmosphere and a moderately sulphur-polluted atmosphere, the corrosion resistance of aluminium is excellent. In a severe sulphurous atmosphere, superficial pitting attacks can occur.

The presence of salts, mainly chlorides, in the atmosphere deteriorate the corrosion resistance but is lower than for most other structural materials. The growth rate of the pits decreases with time, and the maximum pit depth for aluminium generally becomes only a fraction of the material thickness. Therefore, strength properties remain virtually unchanged.

Field experiments with untreated metals in different types of outdoor atmospheres have been carried out by the Swedish Corrosion Institute, Fig 7.9. The weight loss of uncoated sheets after eight years of exposure is shown in Table 7.1. The average value of the deepest corrosion pits of the aluminium sheet was 70 µm after the eight years.

The corrosion rate decreases rapidly with distance from the sea. Already about 1 km from the sea, aluminium behaves like in a rural atmosphere.

7.4.2 Aluminium in water

Corrosion of metals in water is strongly dependent on the water composition. For aluminium, it is mainly the presence of chlorides and heavy metals that affect the corrosion resistance.

In natural freshwater and drinking water, pitting corrosion can occur. However, if the material can be washed off and dried, the risk of harmful attacks is little. The probability of attack increases if the water is stagnant and the material is wet for a long time.

The pitting corrosion is obstructed by:

- design solutions that reduce the risk of water pool forming
- use of cathodic protection (with sacrificial anodes)



Fig 7.9 Corrosion testing samples exposed in a marine environment on the Swedish west coast.

- chemical additions of so-called *corrosion inhibitors*, which prevents corrosion (used in, e.g. aluminium heat exchangers)

The rate of growth for pits in natural freshwater decreases with time. In seawater, mainly AlMg-alloys with more than 2,5% Mg show excellent corrosion resistance. Copper-containing alloys should be avoided but can be used if provided with adequate corrosion protection.

With proper design, especially when coupled with other materials, aluminium is an excellent material in seawater. An example of this is the extensive use of aluminium in boats, Fig 7.10. Besides, cathodic protection is often used here to prevent corrosion.

7.4.3 Aluminium in soil

Soil is not a uniform material but varies widely in terms of mineral composition, moisture, pH-value, oxygen content, electrical conductivity and the presence of organic material. Besides, sometimes other factors can affect the corrosion resistance, e.g. leakage currents from direct voltage sources.

The corrosion properties of aluminium in soil depend primarily on moisture, resistivity and pH-value. Unfortunately, knowledge about the corrosivity of different soils is insufficient. When using aluminium in the soil, protective *surface treatment*, e.g. asphalt coating or the use of cathodic protection, is recommended.

7.4.4 Aluminium and alkaline building materials

Splashes of wet alkalis, such as mortar and concrete, provide superficial but apparent stains on aluminium. These are difficult to remove. On aluminium, which is cast into concrete, similar attacks occur, which increases the adhesion between the materials. After hardening of the concrete, no more corrosion attack occurs.

However, if the moisture remains, the corrosion can proceed, whereby the volume of the corrosion products increase, which can cause cracks in the concrete. This can be effectively counteracted by coating the aluminium surface with asphalt or painting it with a varnish that can withstand an alkaline environment. However, anodising does not improve the hardness, as the oxide layer is not stable in an alkaline environment with a high pH.

7.4.5 Aluminium and chemicals

Aluminium has excellent resistance to many chemicals thanks to the protective properties of the natural oxide layer. However, at low and high pH-values ($\text{pH} < 4$ or > 9), a dissolution of the oxide occurs, and aluminium corrodes rapidly. Inorganic acids and strongly alkaline solutions are therefore highly corrosive to aluminium. Concentrated nitric acid and ammonia solutions are exceptions as they do not attack aluminium, but instead are passivating the surface.

In moderately alkaline aqueous solutions, corrosion can be damped by the use of silicates as a corrosion inhibitor (decreases chemical reaction rate). Such inhibitors usually are included in machine dish-washing detergent.

7.4.6 Corrosion behaviour of aluminium – a summary

In a majority of applications, the protection offered by the natural oxide layer is sufficient to suppress the corrosion processes completely. Despite its thinness, that layer is surprisingly resistant and reforms immediately if removed. If aluminium is exposed to wind and weather, the oxide layer continues to grow for one or two years until the thickness is sufficient to prevent further attack.

In summary, it may be said that the application possibilities for aluminium with or without artificially applied oxide layers are far from exhausted. The vast scale of strongly adherent oxide films or differing resistance has led to expanded use of aluminium.

Table 7.1 Weight loss in g/m² after eight years of exposure

Sea atmosphere	
Aluminium	7
Copper	57
Zinc	133
Carbon steel	933
City atmosphere	
Aluminium	2
Copper	31
Zinc	61
Carbon steel	676



Fig 7.10 High-speed motorboats are built mainly of aluminium and are used because of their excellent ability to withstand saltwater.



Fig 7.11 Painted aluminium sheets give both excellent corrosion protection and a decorative appearance.

Surface treatment

Usually, aluminium does not need a surface treatment, but sometimes the surface can be changed to:

- obtain a different aesthetic expression or structure
- increase the resistance to corrosion
- achieve decorative surfaces with permanent colour and shine
- get contact-friendly and dirt-repellent surfaces
- reduce or increase friction
- obtain smooth and/or abrasion resistant surfaces
- increase or decrease the electrical conductivity
- obtain electrically insulating surfaces
- get a sound basis for glueing and painting

A large number of surface treatment methods are available for these requests, Table 8.1 and 8.2. All with great opportunities to change the appearance and properties of the surface.

Table 8.1 Surface treatment methods

Method group	Treatment technology	Result of the treatment
Mechanical methods	As manufactured surface	Unprocessed surface after rolling, pattern rolling, forging, profile pressing or casting
	Grinding	Fine grooves in grinding direction, the finish depending on the grain size of the grinding paper
	Polishing	Smooths the surface and removes grinding grooves
	High gloss polishing	Provides a reflective smoothness with high reflectivity
	Glazing	Gives a slightly diffuse and dull surface
	Tumbling	Provides a matte to shiny surface on small mass-produced articles
	Blasting	Provides a matte and grainy texture
	Patterning	Provides patterns or optical effects of unique character
	Hammering	Provides a deeply patterned surface
Chemical methods	Pickling (etching)	Used to clean surfaces or as pretreatment for joining or continued surface treatment
	Bright dipping	Provides high gloss and reflectivity
	Chemical polishing	Smooths the surface and removes grinding grooves
	Surface conversion	Provides protective and decorative layers of oxides, chromates and phosphates
	Plating	Applying metals such as Zn, Sn, Cu, Ni or Cr without electricity
Electrochemical methods	Anodising	Provides clear or coloured hard oxide layers for protection, decoration or functional nature
	Electrolytic gloss pickling	Provides a polished smooth and even surface with high reflectivity
	Galvanic plating	The surface is covered with other metals such as Zn, Sn, Cu, Ni, Cr or Ag with an electric current
Applying methods	Painting and lacquering	Application of thin plastic layers for protective and decorative effects
	Applying plastics	Decorative, protective or functional coatings applied as laminates or by melting
	Enamelling	Glass-like, hard and corrosion-resistant coatings
	Metal layers	The surface is covered with functional metal layers by spraying or dipping
	Ceramic layers	Functional ceramic layers are applied to the surface by spraying or dipping

8.1 Chemical and electrochemical coating

For the chemical and electrochemical methods, the details are dipped into a bath with various compounds. In the case of chemical treatment, liquid can be sprayed on the surface of the components.

One of the chemical methods used is *pickling* in acidic or alkaline baths. Metals such as zinc, tin and nickel can be applied to the aluminium surface without electricity, *electroless plating*. Chemical surface treatment also includes *chromating* and *phosphating*.

In the electrochemical treatment, an electric current is passed between the part to be treated and a counter electrode. The method group includes *galvanic plating*, *glaze pickling* and, not least, *anodising*, the most common surface treatment method for aluminium.

8.1.1 Anodising

Anodising can be applied to all aluminium alloys, including castings. The composition of the alloy affects the appearance and properties of the anodising layer. Of significant importance is the amount of copper, silicon and iron. If the anodising layer is to fulfil an aesthetic function, it should not be exposed to temperatures above 100°C as fine cracks occur in the layer. They can interfere with the visual impression. Forming and welding should generally be done before anodising.

The anodising layer is transparent. Therefore the surface must have the wanted structure before the details go to anodising. It must also be clean and degreased or pickled before.

Table 8.2 Surface treatments methods

Desired property	Anodising in sulphuric acid	Hard anodising	Anodising in chromic acid	Anodising in phosphoric acid	Chromating	Painting, lacquering	Plating with metals	Particle in melting
Appearance, feeling	x					x		
Corrosion protection	x	x			x			
Abrasion resistance		x				(x) Ni, Cr	x	
Low friction		x					+Teflon®	
Electrically conductive						(x) Ni, Ag		
Electrically insulating	x	x						
Foundation for painting	x				x			
Foundation for glueing	x		x	x	x			

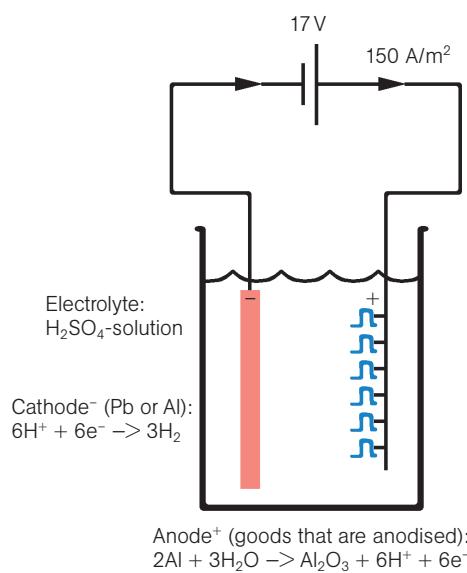


Fig 8.1 Principle for anodising in sulphuric acid.

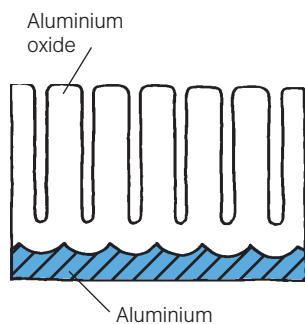


Fig 8.2 Anodising layer made in sulphuric acid.

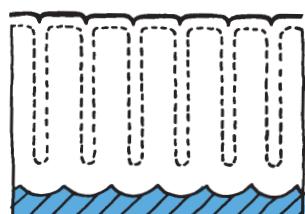


Fig 8.3 Sealed anodising layer with closed pores.

The parts to be anodised are connected as an anode in a DC circuit, Fig 8.1. As cathode, aluminium or lead is usually used. The electrolyte may consist of various acids such as sulphuric acid, phosphoric acid, chromic acid or oxalic acid. Depending on the temperature and acid used, the layers grow in different ways and give different structures. However, dilute sulphuric acid are typically used at RT.

During the anodising process, the natural oxide layer grows, and the aluminium metal is converted into aluminium oxide. Metal and oxide have different volumes, and the product dimensions are therefore changed during the process. As a rule of thumb, the anodising layer "grows outwards" by about 1/3 of its thickness. Typical layer thickness for details used indoors is 10 µm and 20–25 µm for outdoors.

A denser, thicker (100–200 µm) and harder layer can be produced at a lower temperature than RT by *hard anodising*. This layer has excellent abrasion resistance compared to layers made at RT and is more porous and better suited as a substrate for painting. By varying the process parameters, oxide layers with new properties can be obtained, e.g. with anodising and electrolytic colouring create a surface with high absorption of solar energy and low heat radiation, e.g. water-borne solar collectors.

Anodising can be used as a basis for glueing aluminium in structures with demands for high strength, e.g. in aircraft. In this case, very thin oxide layers (only a few µm thick) made by anodising in chromic acid or phosphoric acid are used.

The oxide layer after anodising in sulphuric acid contains narrow pores oriented perpendicular to the metal surface, Fig 8.2. The diameter of the pores is usually 0,01–0,05 µm. The electrical voltage determines the size of the pores. The number of pores is 10^8 – 10^9 per mm². This is utilised, among others, at colouring and painting of the surface by penetrating the dye into the pores. Substances other than colour pigments can also be introduced into the porous surface layer, e.g. fluoroplastics to reduce friction.

The final step in anodising is *sealing*. During this step, the pores in the oxide layer are closed, so they become tight Fig 8.3. The sealing is done by dipping the surface oxide in boiling deionised water or in contact with water vapour. An alternative is *cold sealing* in RT. The oxide layer reacts with a solution containing, among others, nickel and fluorides. Hard anodised layers are generally not sealed.

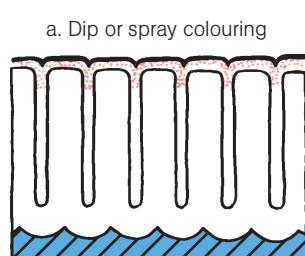
8.1.2 Colouring

Dip colouring

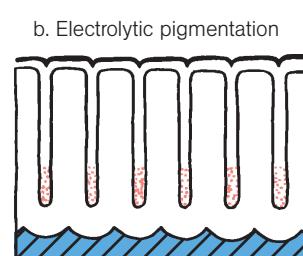
There are many ways to colour an anodised layer. The most common is dipping or spraying on organic pigments, *dip colouring*, Fig 8.4a. The dye only penetrates the outermost parts of the oxide layer, which therefore becomes more sensitive to sunlight. The colour selection is vast, why many colours can be obtained, see Fig 8.5. Dip colouring is most commonly used on short pieces.

Electrolytic pigmentation

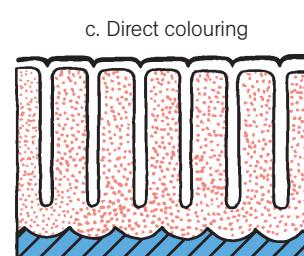
Anodising 6–8 m long extrusions, is carried out in sulphuric acid. Using alternating current (AC), a colour pigment (usually a tin salt) is introduced into the bottom of the oxide pores. The process is called *electrolytic pigmentation*, Fig 8.4b. Then the layer is sealed in boiling



a. Dip or spray colouring



b. Electrolytic pigmentation



c. Direct colouring

Fig 8.4 Anodising layers coloured with three different methods.

Table 8.3 Layer thickness after anodising

Layer	Application
10 µm	Normal load indoors
15 µm	Hard wear indoors and outdoors in dry and clean air
20 µm	Usually intended for heavy wear outdoors, e.g. in transport and construction. Heavy stress under chemical influence indoors, e.g. in the food industry
25 µm	The surface is subjected to heavy loads in the form of a corrosive environment or wear

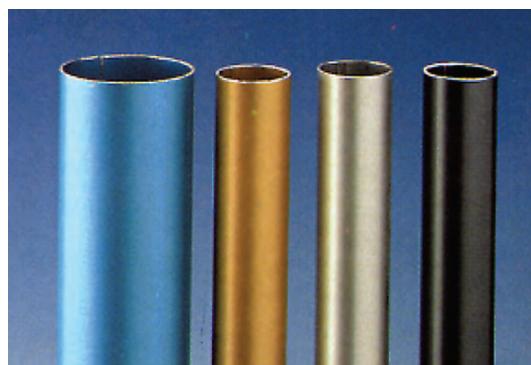


Fig 8.5 High frequency welded, anodised and coloured aluminium tubes.

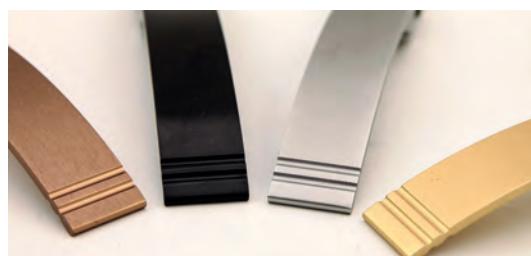


Fig 8.6 Anodised and coloured bottle openers.



Fig 8.7 New fantastic colours can be used for building facades. Here light brown, red and blue.

water. The colour range obtained with tin salts covers shades from light brown (champagne) to black, Fig 8.6. The layers have excellent colour fastness as the pigment is protected in the oxide layer.

Direct colouring

In *direct colouring*, the anodising takes place in organic acids (e.g. sulfosalicylic acid and maleic acid), which gives solid coloured layers, Fig 8.4c. The colour saturation increases with increasing layer thickness, but the choice of colours is limited. The method has limited use. Sometimes different dyes are combined in multi-stage procedures.

Stainless steel effect

A newly developed colouring technique, Alanox®, gives an appearance of stainless steel on aluminium. A specific repeated grinding in combination with particular colouring results in this stainless steel effect, which is in high demand, especially for architectural purposes. The layer thickness is at least 20 µm.

Grey colouring

Grey anodised aluminium, or Granodal® is a new decorative aluminium surface developed by Alutecta. It offers unique opportunities for indoor and outdoor use in architecture and product design. With its subtle shimmering look, varying light impressions and many variations of grey give the surface an unmatched look and feel of aluminium.

8.2 Lacquering

Aluminium can be lacquered (painted) without significant difficulties. The selection of colours is thus considerable, and the technical properties of the lacquers are excellent. Many paints have such a good adhesion and formability that the aluminium product can be formed after the painting, e.g. shaping of building sheet, pressing of coated frying pans, without the paint cracks.

Powder coating and various types of wet coat, e.g. dipping, spraying, rolling or curtain coating is used for aluminium. Most shades, even metallic, can be applied with solvent-free powder coatings. Various types of paints can also be used, e.g. polyester with excellent UV resistance or epoxy lacquer with good chemical resistance. Layer thicknesses for powder coatings are 60–80 µm.

Regardless of the coating method, a suitable pretreatment is required, which includes cleaning and oxide removal. For products used indoors, alkaline degreasing or etching may be sufficient. For outdoor use, a chemical surface conversion, e.g. chromating, is required as well. This is for long-time the most widely used method. However, environmental reasons have led to a switch to chrome-free processes.

8.2.1 HM-white

When anodising and colouring an oxide layer, a large number of colours are available, but not white. An alternative process, HM-white solves the problem. It is an electrophoretic method, according to the Honnystone process.

An anodised, 7–10 µm thick and unsealed oxide layer is dipped in a bath where an acrylic-melamine type lacquer is applied using DC, called *electrophoretic deposition*. Then the paint is cured in the oven at about 180°C to polymerise the paint. The thickness of the surface layer (oxide + paint) is about 30 µm, compared to the powder coating 80–120 µm, Fig 8.8.



Fig 8.8 HM-white, painted aluminium soccer goal.

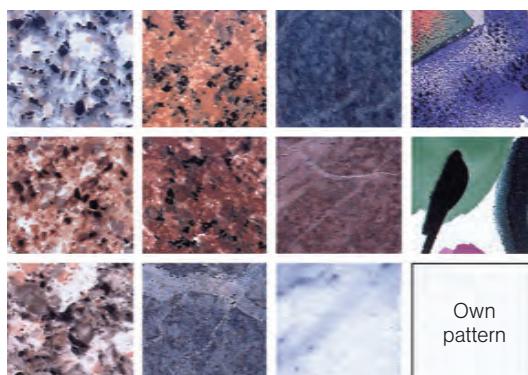


Fig 8.9 New fanciful patterns can be created with the Decoral® method.



Fig 8.10 Decoral treated windows with wood imitation.

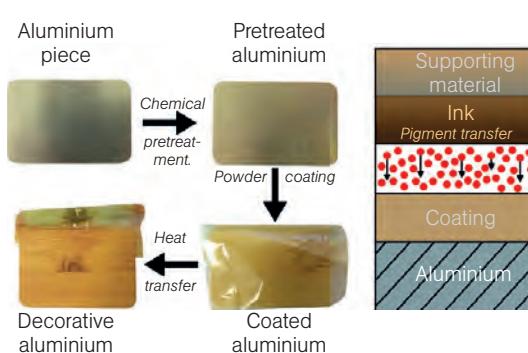


Fig 8.11 Ink transfer for the Decoral-process.

The result is a white, UV-resistant surface with a gloss that does not fade in a hurry. The resistance to corrosion, chemicals and dirt is excellent. Since the colour does not build up on the edges, it fits well for details to be matched in a construction. The paint layer has the same thickness across the entire part.

8.3 Decorative coatings

With new paint technology, exciting decorative and avant-garde surface patterns can be created. The Decoral® process is used on both sheets and extrusions, where decorative surfaces are desired. Many patterns are used, e.g. wood, marble, granite or fantasy, Figs 8.9-10.

In a multi-step process, photo-realistic motifs and metal patterns can be applied, Fig 8.11. A unique powder coat is implemented as a background shadow and supplemented with a motif in a second step. Depending on the technique used, the resulting surface may also have a topographic structure. With this in view, components are wound with a film printed with the desired motif and then heated to 200°C. The ink then bleeds from the film into the powder coating.

The combination of technical advantages and personal component design will open up entirely new applications for aluminium with this method. In this way, coated aluminium can be used for almost any purpose and can, among others, give the appearance and feel of different materials such as wood, steel or glass.

8.3.1 Stripping and recycling

When coated components have reached the end of their service life, the surface decorations can easily be peeled off, and the surface covered again. Typical examples here are aircraft. They can have the paint removed and then used again after repainting.

The surface area is not needed to be recycled anymore. Existing processes can remove all coatings and ensure that the aluminium can be reused and converted into new products, over and over again.

8.4 Other surface treatment methods

There are a large number of different surface treatment methods for aluminium, often with a background in select technical areas, e.g.:

- Rubber can be vulcanised on an aluminium surface.
- Lamination of aluminium foil with plastic or fibre material (paper, cardboard) gives products used for packaging, e.g. food and pharmaceuticals, but also to various building products such as facade elements.
- Improved resistance to abrasive wear can be obtained by melting the aluminium surface with a laser at the same time as hard particles, e.g. chromium carbide, blows into the melt and increases the surface hardness.
- Aluminium can be coated with chemical or electrolytic nickel. Both variants provide improved abrasion resistance and a conductive surface for electricity and heat.

8.4.1 Tufram®

Tufram is a family of surface treatment methods for aluminium materials in six variants. Which option who is the best depends on the application's profile of demands.

The process is based on a combination of hard anodising and fluoroplastic coating, which gives the layer several new properties. High hardness, low friction, corrosion and abrasion resistance, excellent non-stick properties, low seizing tendencies, tight tolerances, good electrical insulation, smooth layer build-up and no need for post-processing are some examples.

Aluminium castings

9.1 Use of castings

The technology for aluminium casting has rapidly developed in recent decades, while commonly used methods have improved. Today's foundry industry has excellent possibilities to satisfy customers' demands for high-quality castings, Fig 9.1. Aluminium casting will continue to be an economical and quality competitive process in the future.

For the manufacturing of castings, there are many different methods. Which method is most suitable from a technical and economic point of view is usually challenging to specify. Guiding the choice of casting method is the total cost and technical quality of the part. For example, relatively high casting costs can be offset by essential savings later in the production chain.

Today computer technology is used both for component design and for simulating the metal solidification. Increased know-how of the casting process leads to improved casting technology. Usually, the entire part is virtually cast in a computer, before it is done in reality.

Especially for permanent moulds – gravity die-casting and high pressure die-casting – is a simulation of the filling and solidification process essential for predicting porosity and strength. The tool's thermal image is affected by the former casting cycle, including utilized heat control.

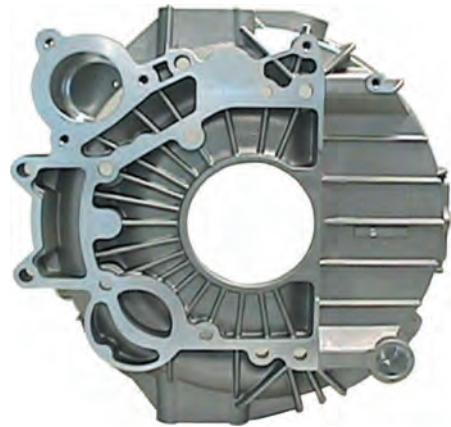


Fig 9.1 Casted flywheel house in aluminium.

9.2 Casting methods

Example of methods for manufacturing aluminium castings:

- *Casting in disposable mould*
 - sand casting
 - plaster mould casting
 - lost wax casting
- *Casting in permanent mould*
 - gravity casting
 - low pressure die-casting (LPDC)
 - high pressure die-casting (HPDC)
 - tilt casting
 - squeeze casting

9.2.1 Sand casting

Casting in disposable moulds of sand, called *sand casting*, Fig 9.2, is the most common method, besides high pressure die-casting, for aluminium. Mould production can be made according to several method variants, which are more or less mechanised. The trend goes towards more automated *flask* and *flaskless forming*.

Despite increased automation, *manual sand forming* is still an essential method for small series and prototypes. Binders and sand are mixed in continuous mixers and added directly to the mould. Improved process control and continued development of binders increase opportunities to meet customers' demands for complicated castings in short series. Models for sand casting can still be made of wood, but more commonly they are made of plastic or metal for long series. 3D printing of sand moulds is a new alternative today.

One moulding technique, which is used for long series, is lost foam casting. A polystyrene model is embedded in vibration packed sand. The casting is executed while the model is still in the mould whereby the hot liquid metal completely gasifies the polystyrene model (lost foam) and replaces it with molten aluminium. One advantage of the method is minimal cleansing work, and that complicated castings can be made. A disadvantage is bad shape correctness of the casting.

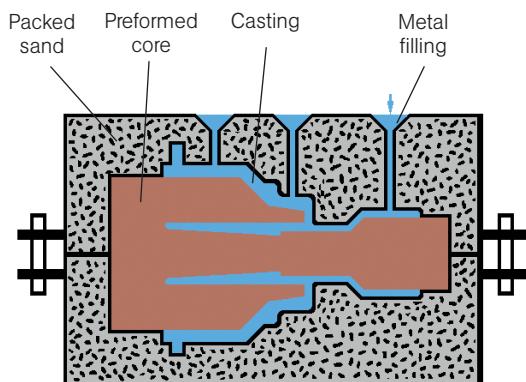
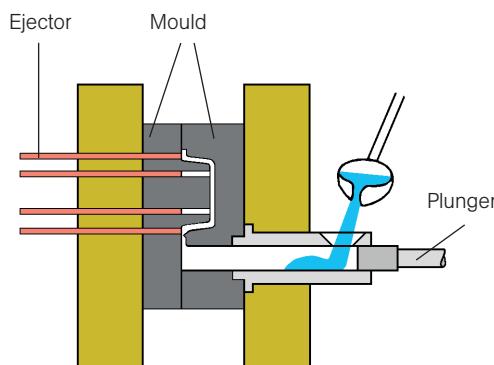


Fig 9.2 Filled mould after sand casting.

9.2.2 Plaster mould casting

The plaster moulding technique has been used in small series and for prototypes. The advantages are good dimensional accuracy and smooth surfaces, which is often comparable to what is obtained in pressure die-casting. Plaster casting, however, gives a slow solidification rate, why it is impossible to compare the strength with those for pressure die-castings.



9.2.3 Gravity casting

In gravity casting, permanent moulds of hot work tool steel are mostly used. In the past, cast iron moulds were used, which had excellent heat conductivity, but was sensitive for cracking. About 100 000 pieces can be cast with the same mould, at 3° draft angle and the alloy AlSi10Mg, while other alloys can reduce the number to 20 000–75 000 pieces. Gravity casting is available in two variants, *static gravity casting* and *low-pressure casting*. Modern computerised process control of various parameters enables gravity casting of increasingly complicated shapes. The cores are made of steel or sand.

A variant of the conventional gravity casting is *tilt casting*. The method involves placing the mould in a cradle. During casting, the cradle is tilted from horizontal to a vertical position, whereby the melt slowly and without turbulence flows down into the mould. By the well-controlled metal filling, technical advantages of the castings are achieved.

Characteristically, low-pressure casting is well in class with tilt casting, since low-pressure casting enables very controlled mould filling.

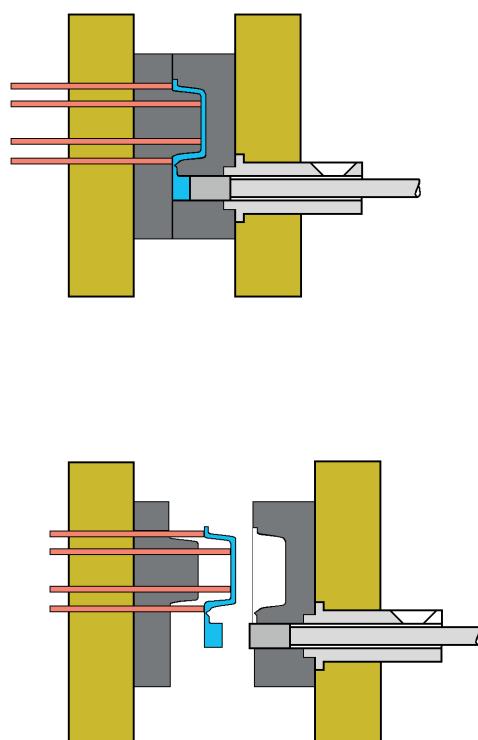


Fig. 9.3 Pressure die-casting.

9.2.4 Pressure die-casting

In pressure die-casting, a dose of molten metal is pressed under high pressure into a hollowed mould made of tool steel, Fig 9.3. In modern pressure die-casting machines, the injection pressure is between 20 and 200 MPa. The device is relatively expensive when casting intricate details, which makes the method best suited for large series. The tool life can be up to 200 000 shots but can vary greatly depending on steel type in the tool, cast alloy, temperature variations and component geometry.

Pressure die-casting technology is developing rapidly. The control systems and monitoring of the various process steps are improved, e.g. has the machine locking force increased, which allows castings to an even bigger size. The method offers excellent possibilities for automation, and today there are production units, which work almost entirely automatically. New technology for fast tool exchanges and metal supply reduces the requirements for long series. Pressure die-casting today dominates the production of aluminium castings.

9.2.5 Squeeze casting

Squeeze casting combines high productivity from pressure die-casting with excellent strength from gravity casting. The process can also be combined with particle or fibre reinforcement in the castings. Casting speed is considerably lower than that of pressure die-casting, which here avoids turbulent metal flow. After filling the mould, a post-feed pressure is maintained until the metal has solidified, giving a material with a minimal amount of pores. Solution heat treatment and artificial ageing can be carried out on the castings.

9.3 Casting of semi-molten material

9.3.1 Rheo casting

Several *rheo casting* methods have been developed in recent decades. However, few of these have reached commercial use outside the research laboratories, which is mainly due to complicated process control and insufficient stability and casting quality.

The RheoMetal process, Fig 9.4, was developed in 2003. It is based on a melt that is cooled with a piece of solid metal, EEM – Enthalpy Exchange Material, which is attached to a stirrer, and which leads to rapid cooling of the melt to the desired temperature and solid fraction when the EEM melts.

The significant advantage of this method is that it is based on internal heat exchange and that the need for external control of the heat flow does not in principle exist. Almost all other rheo casting methods are based on controlling the heat flow, which has proved to be complicated and costly. RheoMetal is used only for aluminium alloys, but it also works for magnesium and brass.

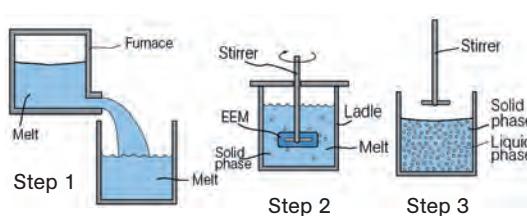


Fig. 9.4 RheoMetal-process with the heat sink EEM.



Fig 9.5 High strength rheo cast component. This unique development of the aluminium casting process enables quality improvements, cost reductions and an apparent weight reduction.

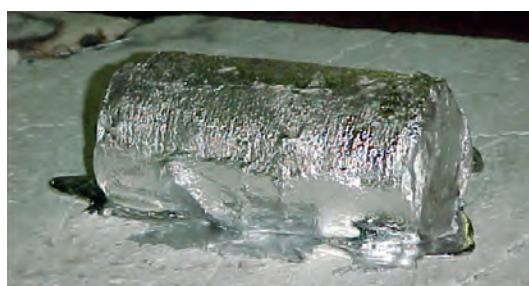


Fig 9.6 A semi-solid metal slug for thixo casting after heating in a furnace. The slug still hangs together after heating to 610°C.

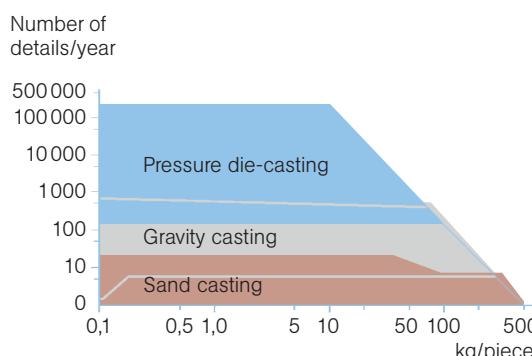


Fig 9.7 Choice of casting method after batch size and component weight.

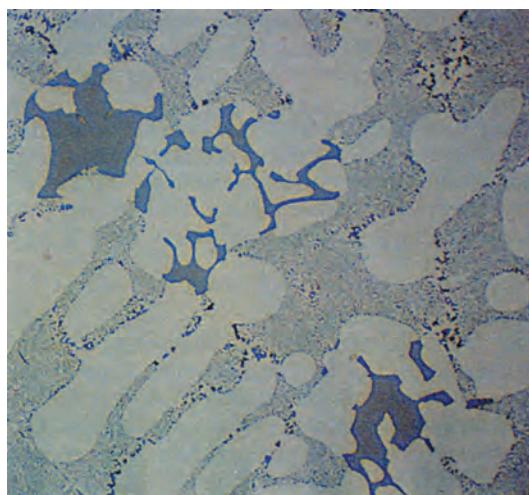


Fig 9.8 The structure of an AlSiCu casting alloy enlarged about 550x.

9.3.2 Thixo casting

One process of producing near-net shaped products with improved mechanical and aesthetic properties is *thixo casting*. Starting with a piece of slug, cut into a suitable length, the slug, which consists of a pretreated alloy, is inductively heated to the semi-solid state, Fig 9.6, and placed in the filling chamber of the casting machine and then pressed into the mould, just like pressure die-casting.

The use of semi-solid metals enables the production of components with complex shapes, thin walls, high mechanical properties, excellent dimensional tolerances and accuracy. Advantages are reduced moulding temperature, clearly lower tool wear, top component precision and efficient production. However, there are several disadvantages, such as the need for a particular starting material with nearly spherical primary crystals, which is expensive.

9.4 Selection of the casting method

When choosing a casting method, the interaction between the process and the alloy used must be taken into account. Available casting methods are more or less well suited to various casting alloys. The batch size is, in many cases, a decisive factor, Fig 9.7.

Table 9.1 Comparison of the properties of casting methods

	Sand casting	Gravity casting	Pressure die casting
Large piece size	1	2	3
Small material thickness	3	2	1
Dimensional accuracy	3	1–2	1
Machining time	3	2	1
Cassation	3	1	1
Handling costs	3	2–3	1
Strength and density	2	1	1
Weldability and heat treatment	1	1	3
Surface smoothness	2–3	1–2	1
Model and forming costs	1	2	3

Comparative figures: 1 = excellent, 2 = good, 3 = less good

With increasing batch size, machine forming becomes a more suitable alternative. A wooden plate model is then used. Wood is still a good model material. For mass production, more durable materials such as fibreglass reinforced plastic or metal are used.

Table 9.1 shows that pressure die-casting has many advantages over sand and gravity casting. However, it also has limitations, e.g. it becomes too expensive when the batch size is too small, or the piece's weight is too high. Details that have many and complicated cavities cannot be pressure die-cast.

9.5 Post-treatment of castings (cleansing)

In recent years, significant efforts have been made to achieve functional technical and environmentally sound solutions for the clean-up of castings (cleansing).

One development way has been to install industrial robots and manipulators for handling castings and various cleansing tools. The robot handles both castings and tools. Another way is the *deburr cutting* technique. At this, burrs, feeder and casting residues are removed in the cold state by shearing in special tools mounted in a press. The method is suitable for automation.

9.6 Fibre- and particle-reinforced castings

The term *composite* is used for materials consisting of two or more components and where the formed structure exhibits mechanical and physical improvements over the individual components. This means that a reinforcing low weight material, usually high-performance particles or fibres, is embedded in a cohesive metallic matrix material, typically aluminium, Fig 9.9. Such materials are called *metal matrix composite*, MMC.

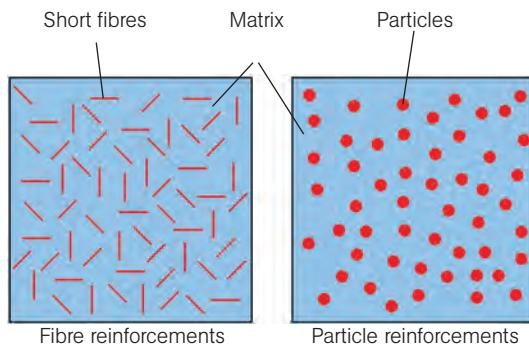


Fig 9.9 Various reinforcement types for aluminium-based metal matrix composites (MMC).



Fig 9.10 2018 Casting of the Year in the USA.
Motorbike swingarm made in alloy AISi7Mg0,3-T6. The mould was 3D printed in a sand model with binder jet technology (BJ) and produced with the low-pressure sand casting process.

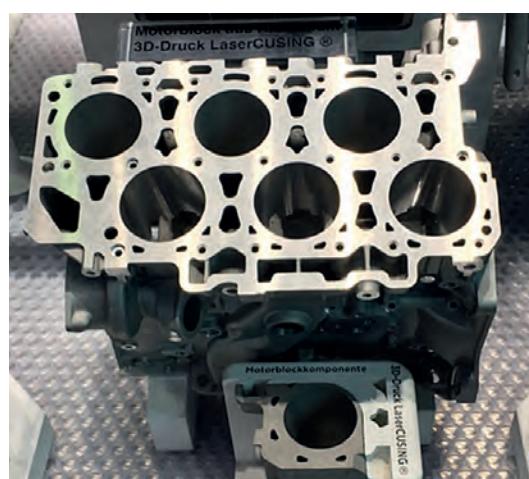


Fig 9.11 Engine block in aluminium for a VW. 3D printed at Robert Hoffmann GmbH. (Foto Sten Farre)



Fig 9.12 Some 3D printed small components.

Examples of MMC-components are brake discs for passenger cars, with an aluminium matrix for lightweight and excellent heat conduction, as well as durable particles for high friction and superior abrasion resistance. Most MMCs consist of relatively inexpensive discontinuous reinforcing materials such as particles, whiskers or short fibres, which have excellent performance.

9.7 Additive manufacturing

Additive Manufacturing (AM) or 3D printing is a way of joining materials to produce complex three-dimensional metallic components, layer by layer, based on data from a digital 3D model. Metal powder or wire is melted locally with a laser or electron beam. The components can have almost any shape or geometry. The method can be compared to the way an inkjet printer works.

To print components in aluminium alloys, some of the AM-variants are more interesting than the others. Those AM-variants are:

- **Binder Jetting (BJ)**, the powder materials are sintered and HIP-ed
- **Powder bed fusion (PBF)**, uses laser and EB technology
- **Direct Energy Deposition (DED)**, laser or plasma is used to join materials to finished components
- **Material Jetting (MJ)**, metal drops are added layer by layer in cold or hot state

9.7.1 Direct production of 3D printed aluminium components

Metal printers for producing parts directly in the printer were launched in the late 1990s and are today dominated by manufacturers mainly from Germany. Sweden has also been successful with Arcam, which uses an electron beam to melt the powder and Digital Metall, a subsidiary of Höganäs, which join metal powder and then sinter and perform HIP (Hot Isostatic Pressing) on the component.

For aluminium, BJ- and SLS (Selective Laser Sintering) technology is mainly used to produce parts, but also DOD (Drop on Demand) is used for small nano-sized components. Limitations in the size of subjects that can be printed exist. Fig 9.11 shows a large part, an engine block for VW. The block of 25 kg took about 300 hours to print, the finishing process then took just as long.

Since 2015, clear progress has been made in AM. New alloys have been developed, especially aluminium-scandium, which better utilise the advantages of rapid cooling compared to conventional manufacturing methods and which provide improved mechanical properties. Commonly used alloys are pure aluminium, AISi12, AISi9Cu3, AISi10Mg and Scalmalloy (AlSc-alloy).

Addalloy is the first high-performance Al-alloy, especially for AM. It is thermally stable up to 350°C. It is also scandium (Sc)- and silicon (Si) free. It has good machinability and is hardenable and weldable. Other qualities are high thermal and electrical conductivity and high density in printed components. $R_m > 390 \text{ MPa}$ and $A_5 > 23,8\%$.

9.7.2 Manufacturing of 3D printed moulds

Both moulds and cores can be printed directly in sand or plaster, without using models. For shorter series, this means cost savings as no model is needed. More extensive series can be produced and evaluated before making models and tools for mass production. The BJ-method is the most common, where the sand first is mixed with a hardener, and then binders are dropped into selected parts of the powder bed.

Another technology is Reverse Engineering, where a 3D scan of an existing product is made, e.g. an old spare part for which there are no drawings. With this technology, a digital substrate is obtained that can be adapted for 3D printing and casting.

Machining

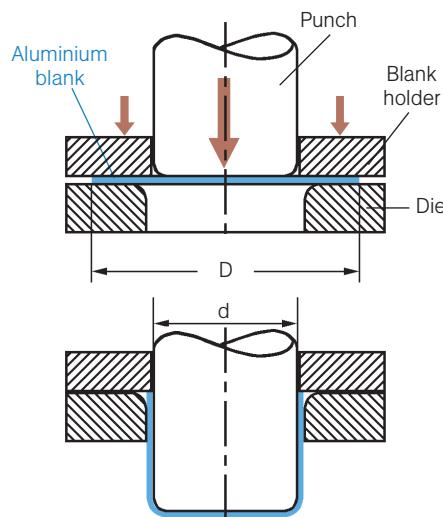


Fig 10.1 The principle of deep drawing. The drawing ratio (D/d) is the quotient of the blank diameter (D) and the punch diameter (d).

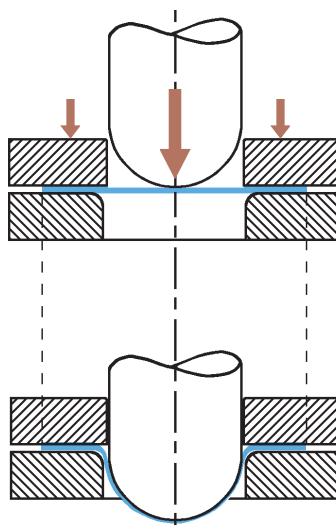


Fig 10.2 The principle of stretch pressing.

10.1 Cold forming

Aluminium has good formability at room temperature (RT) and is therefore suitable for *cold forming*. The formability is different for various alloys and also dependent on the material temper.

Unalloyed aluminium and *non-heat treatable*, low alloyed materials are highly ductile and can easily be formed in soft and semi-hard conditions. Complicated forming operations can be made with small press forces and without intermediate annealing.

For *hardenable alloys*, forming can be performed in different tempers:

- If the forming is not too difficult, it can be done in a naturally aged (T4) temper and followed by artificial ageing (T6) for best strength. T6-material has limited cold formability. AlZnMg-alloys should not be cold formed in T6-temper due to the risk for stress corrosion cracking.

- The formability is best after soft annealing or immediately after dissolution. The advantage of forming in the dissolved state is that solely ageing needs to be executed afterwards to achieve the highest strength. One complication may be that the forming must occur within a few hours after dissolution. On the other hand, after forming in a soft annealed temper, a new dissolution must be performed, which results in a risk of deformations at high temperatures.

For complicated forming operations in several steps, *intermediate annealing* must be used to bring the material back to a soft temper. If the annealing is performed after a slight reduction, there is a risk of coarse crystal grain formation. It is, therefore, essential that the reduction *before* the annealing is as high as possible. A coarse grain structure results in a rough surface, called *orange surface*, which can make subsequent forming complicated.

10.1.1 Deep drawing

Fig 10.1 shows the principle of *deep drawing*. It is used, e.g., in the manufacturing of aluminium cookware and beverage cans. The starting material is a *circular blank*. A punch presses the material through a die whereby the thickness of the blank is only slightly reduced. The cup is often drawn in several steps before it gets its final shape.

The edge of an object that is deep-drawn can sometimes become irregular. This is called *ear formation* (earing) and is obtained because the material has different properties in different directions (anisotropy). To avoid earing, materials specially intended for deep drawing is used.

Table 10.1 Tool radius (r_{min}) at cold bending 90° for some non-heat treatable aluminium alloys

Thickness (t) mm	AW-1050A, 1200				AW-3003, 3103				AW-5052				AW-5083				
	Temper				Temper				Temper				Temper				
	O	H12	H14	H18	O	H12	H14	H18	O	H22	H24	H32	H34	O	H22	H24	
0,2– 0,5	0	0	0	1,0t	0	0	0,5t	1,5t	0	0,5t	0,5t			0,5t	0,5t	1,0t	0,2– 0,5
0,5– 1,5	0	0	0,5t	2,0t	0	0,5t	1,0t	2,5t	0	1,0t	1,5t			1,0t	1,5t	2,0t	0,5– 1,5
1,5– 3,0	0	0,5t	1,0t	3,0t	0	1,0t	1,0t	3,0t	0,5t	1,5t	2,0t			1,0t	2,0t	2,5t	1,5– 3,0
3,0– 6,0	0,5t	1,0t	1,5t	-	1,0t	1,0t	2,0t	-	1,0t	1,5t	2,5t			1,5t	2,5t	3,5t	3,0– 6,0
6,0–12,5	1,0t	2,0t	2,5t	-	1,5t	2,0t	2,5t	-	2,0t	2,5t	3,0t			2,5t	3,5t	4,5t	6,0–12,5

Table 10.2 Tool radius (r_{min}) at cold bending 90° for some heat treatable aluminium alloys

Thickness (t) mm	AW-2014			AW-6061			AW-6082			AW-7020			Thickness (t) mm
	Temper			Temper			Temper			Temper			
	O	T4	T6	O	T4	T6	O	T4	T6	T4 ¹⁾	T6 ¹⁾		
0,2– 0,5	0	3,0t	5,0t	-	-	-	-	-	-	-	-		0,2– 0,5
0,5– 1,5	1,0t	5,0t	7,0t	0,5t	1,0t	2,5t	0,5t	1,5t	2,5t	2,0t	3,5t		0,5– 1,5
1,5– 3,0	1,5t	5,0t	7,0t	1,0t	1,5t	3,5t	1,0t	2,0t	3,5t	2,5t	4,0t		1,5– 3,0
3,0– 6,0	2,5t ²⁾	8,0t	10t	1,0t	3,0t	4,0t	1,5t	3,0t	4,5t	3,5t	5,5t		3,0– 6,0
6,0–12,5	4,0t ²⁾	-	-	2,0t	4,0t	5,0t	2,5t	4,0t	6,0t	5,0t	8,0t		6,0–12,5

1) Cold forming of aged tempers should be avoided due to the risk of stress corrosion.

2) The thickness range is 3,0–9,0 resp. 9,0–12,5.

*) Ductility is a measure of a material's ability to be subjected to plastic deformation without cracking.

Fig 10.2 shows the principle for *stretch pressing*, which starts with a round blank. A holder keeps this in place during pressing, so the thickness of the deformed part diminishes. In practice, pressing of, e.g. a car body part combines deep drawing and stretch pressing.



Fig 10.3 Stretch bending of an aluminium profile.

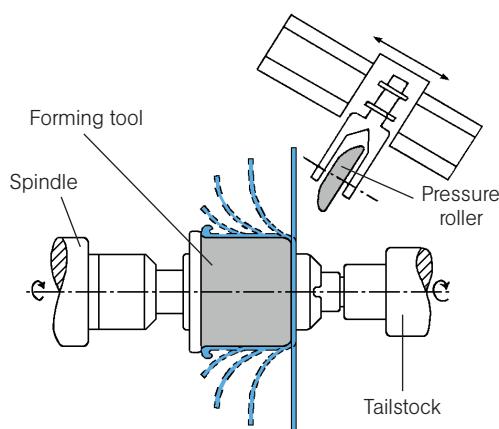


Fig 10.4 The principle of pressure turning.

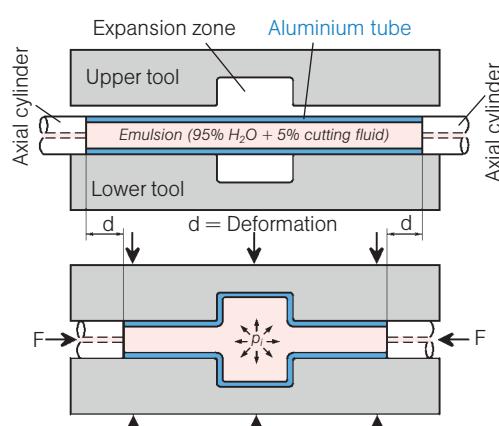


Fig 10.5 The principle of hydroforming.

10.1.2 Bending

Bending of aluminium can be performed both as *edge bending* of sheet metal and as *profile bending* over a template, Fig 10.3. Generally, aluminium requires a more careful bending than steel, where especially the bending radius must be chosen considerably larger.

The spring-back of aluminium during bending is also higher than for steel. The best way to determine the magnitude of the spring-back is to make test bends in each case. Often, during bending, the material is embossed, which results in less spring-back than expected.

Table 10.1 and 10.2 show recommended bending radii for aluminium sheet and strip at cold bending 90° for thicknesses 0,2–12,5 mm. For a minimum bending radius for a given material or the strongest material for a given bend-radius, tests must be done. Local heating to $\approx 150^\circ\text{C}$ during the shortest possible time can simplify the bending.

10.1.3 Pressure turning

Pressure turning is an old artisanal method of manufacturing cylindrical vessels. The technique is still frequently used, because of low costs for the tools and that, contrary to deep drawing, parts can easily be manufactured with a tapered or curved surface. By using modern tool technology, e.g. support-mounted pressure rollers and computer control, the method has undergone high development, Fig 10.4.

10.1.4 Hydroforming

In hydroforming, a hollowed tube of aluminium is placed in a two-part moulding tool, Fig 10.5. The tool halves are closed around the pipe and locked, resulting in a first forming. At each end of the tube, an axial cylinder is sealed against the end. The hollow tube is filled internally with water, which will transmit an internal hydrostatic pressure of up to 400 MPa so the tube will be formed against the cavity (expansion zone) of the tool by the increasing internal pressure and the axial force which feeds the material towards the centre of the tool. The profile is thus "inflated" to its final shape.

Sometimes the profile is formed entirely by the liquid pressure. The axial force then only prevents fluid leakage, which means that the axial cylinders do not feed any material into the expansion zone.

One of the most significant applications of hydroforming is in the automotive industry, where complex shapes for more durable, lighter, and more rigid unibody structures are needed, Fig 10.6.

Advantages of the method are:

- Optimised profile cross-section following the longitudinal stresses
- Increased component stiffness, allowing a reduced weight
- Excellent reproducibility (shape stability)
- A fewer number of subcomponents need to be manufactured
- Possibilities of replacing welded structures

Hydroforming of hollow profiles is a cost-effective method for the production of automotive components with high energy absorption capacity. The process also has high potential in other product areas.

10.1.5 Cold flow pressing

When a stamp is pressed at high pressure against a small aluminium cylindrical blank in a bowl-shaped tool, the material flows out into the gap between the stamp and the tool, Fig 10.7. Small aluminium components such as toothpaste and caviar tubes as well as smaller beverage cans and spray bottles can be manufactured in this way. The material is pressed in a soft or dissolved temper. The method has also been of great importance for making safety parts in cars since excellent material properties are obtained, Fig 10.8.



Fig 10.6 Hydro formed car component.

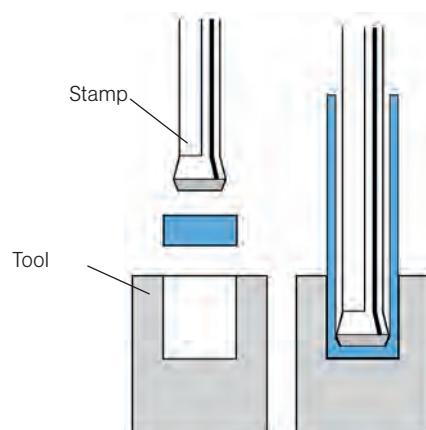


Fig 10.7 Spray bottle made by cold flow pressing.

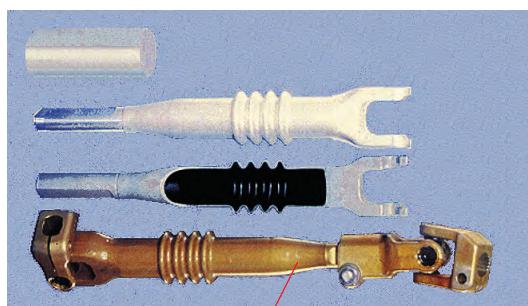
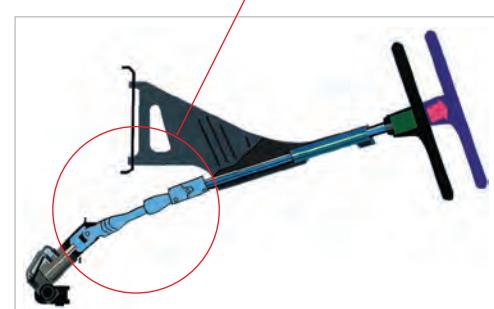


Fig 10.8 Cold flow pressed safety part to a steering wheel axle for a car.



10.1.6 Pressing with rubber tools

When pressed with rubber tools, the material is formed with a rubber pad against a sub-tool. The container pressure can be adjusted during the forming process. The risk of wrinkles is less than in regular deep drawing, and a larger tensile ratio can also be used.

10.2 Hot forming

Aluminium alloys have a low resistance to deformation at elevated temperatures, Fig 10.9. Various types of hot forming such as forging and pressing can therefore usually be carried out with a substantial reduction. The temperature used in hot forming is generally between 400 and 500°C, which is higher than the recrystallisation temperature.

10.2.1 Hot forging

Aluminium details can be *hot forged*. The forging process is carried out between flat tools (free forging) or between shaped tools (drop forging). In aluminium technology, the latter method is also called *hot pressing*. The forging blanks are often "slugs", which are cut from a pressed rod, profile or sheet metal.

By making the forging tool in several parts, the parting line in the component can be oriented to areas of low stress. This gives excellent strength throughout the forging and is often used in the aviation industry.

The choice of alloy for hot forging is done concerning the design of the component and the strength requirements. Common forging alloys are AlMgSi, AlCuSi and AlZnMg. With AlZnMgCu-alloys, forgings with an ultimate strength higher than 500 MPa can be obtained.

10.2.2 Superplastic forming

Very complicated shapes can be produced at elevated temperatures, with *superplastic forming*. The process uses extremely fine-grained alloys and forms them at 450–500°C. Under these conditions, the material exhibits exceptionally high elongation, several hundred per cents. Alloys suitable for superplastic forming are of type AlCu6Zr and AlZn6MgCu.

10.2.3 Hot metal gas forming

Hot metal gas forming (HMGF) is a process to create complex and cost-effective extruded aluminium components. The principle is similar to hydroforming, but the forming process takes place at elevated temperatures around 450–550°C. At those temperatures, material elongation increases significantly, which allows for much sharper bending angles and locally highly deformed areas than compared to hydroforming, Fig 10.10. The material's flow stress is much less than compared to RT, Fig 10.9, which gives low process forces and minimal spring-back.

The hollowed profile is heated in an oven and placed in a forming tool which has a controlled temperature. Then the tool parts are closed, and the pipe is filled with pressurised gas. The tools and metal are heated, not the gas. Then the forming process starts.

The process enables the replacement of multiple components with a single one and with preserved design freedom. This results in:

- Less material consumption
- No joints
- Increased strength and stiffness
- Improved tolerances and appearance
- Simpler integration and assembling

10.2.4 Other hot forming processes

Aluminium can be hot formed even at moderate temperatures, e.g. hot bending at 100–200°C. Choose the lowest possible heat supply for the shortest possible time. Otherwise, the strength of the heated area is affected.

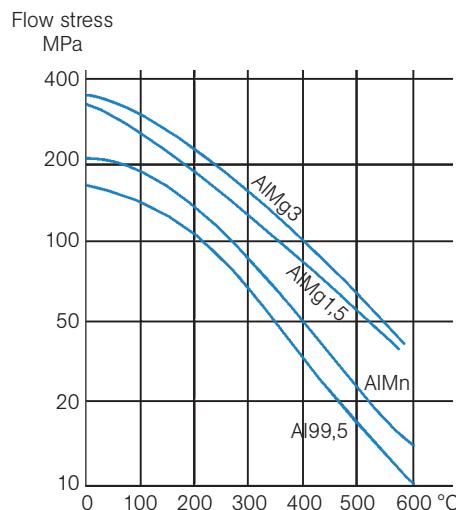


Fig 10.9 The effect of temperature on the flow stress.



Fig 10.10 HMGF-formed component.

Machinability group					
	E	D	C	B	A
Wrought alloys	Pure Al				
	soft tempers	Non-heat treatable		Heat treatable	Hardened tempers
Cast alloys	Pure Al				
		Non-heat treatable		Heat treatable	Hardened tempers

harder to machine → easier to machine →

Fig 10.11 Machinability groups, preliminarily sorted. The meaning of A-E is shown in Table 10.3.

10.3 Thermal cutting

Aluminium material cannot be cut with an oxygen-acetylene torch, which is a standard method for cutting steel. The most common process for cutting aluminium is *plasma cutting*, but *laser* and *water jet cutting* are also widely used.

10.3.1 Plasma cutting

In plasma cutting, an arc with a very high temperature of about 20 000°C is used, which in combination with high gas velocity melts and blows away the metal in a narrow cut. As combustion gas, one of the gases argon, hydrogen, nitrogen or carbon dioxide is used.

The method offers very high cutting speed, but it can be challenging to use the highest theoretical rate for thin materials. The cutting quality is very good with low burr formation.

10.3.2 Laser cutting

Laser cutting of aluminium with oxygen can be done in thicknesses from 0,5 mm. Narrow cuts with high cutting speed and good cut quality are possible.

10.3.3 Water jet cutting

Cold cutting of aluminium can be performed with a jet of water containing abrasive particles. The jet has very high pressure (400 MPa) and top speed (1 km/s). Because the beam is cold, very narrow incisions and acute angles can be produced. Only in exceptional cases, the cutting surface needs to be reworked. Cut width 1–3 mm. Up to 200 mm, thick material can be cut with this method.

10.4 Machining

Aluminium alloys are very suitable for machining. However, material composition and temper affect the machinability. The alloys are divided into five *machinability groups*, Table 10.3, developed concerning chip shape and the possibility of achieving high surface quality.

Table 10.3 Machinability groups for aluminium

Chip shape					
	A	B	C	D	E
A Short chips, low chip volume, easy to attain high surface quality.					
B Little longer chips than for A, but easy to handle. Easy to attain high surface quality.					
C Long chips, but easy to handle. Easy to attain high surface quality.					
D Long and tough chips. Generally easy with suitable tool design and the right choice of machining data attain high surface quality.					
E Long and sturdy, sometimes interlocked chips. For highest surface quality, the best possible tool design and the right choice of machining data are demanded.					

Natural or artificial aged heat treatable alloys have better machinability than non-heat treatable alloys, Fig 10.11. The latter, including pure aluminium, has better machinability in harder tempers.

In *free machining* alloys, additives of low-melting compounds such as bismuth and/or lead provide excellent machinability with short chips. However, according to the RoHS (EU) directive, requirements are set regarding maximum lead content in metals, so new types (lead-free) of free machining alloys must be developed.

Free machining alloys are AW-2007, 2011, 2030, 2111B, 6012, 6023 and 6262. They are used for automated machining in large series, giving components with high-value properties, while the reliability of the machining process has increased considerably. The alloy AW-6026, with bismuth instead of lead, has excellent cutting properties.

10.4.1 Tools

Tools used for machining aluminium are often made of high-speed steels or cemented carbides. Sometimes tools with a surface layer of polycrystalline diamond, PCD, are used when high surface finish or tight dimensional tolerances are wanted.

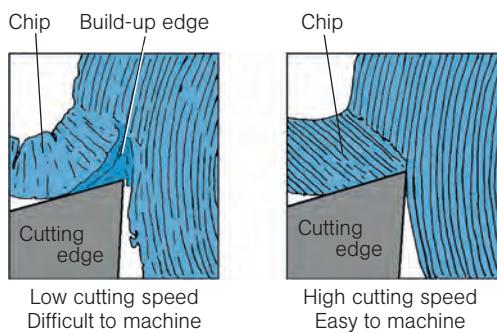


Fig 10.12 Chip shape at low resp. high cutting speed.

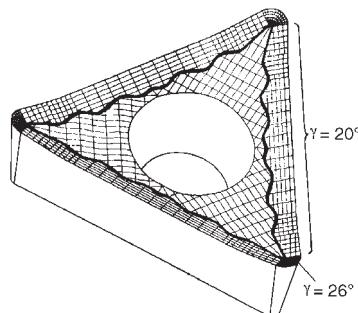


Fig 10.13 The geometry of a modern turning insert with a chip breaker for machining of aluminium.

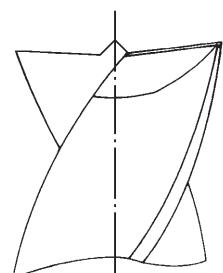


Fig 10.14 Centre point drill for thin sheet metal.

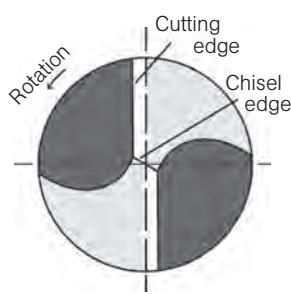


Fig 10.15 4-facet drill with a chisel edge.

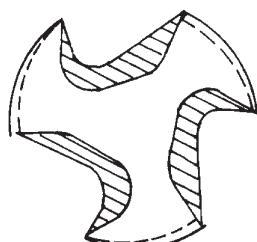


Fig 10.16 Screw tap for aluminium (white surface) and steel (dashed).

Aluminium has a high coefficient of friction in contact with ordinary tool materials. This means that there is a particular risk of aluminium daubing on the tool and sometimes also a build-up edge. Increased cutting speed facilitates machining and the build-up stops, Fig 10.12.

The tools are therefore designed to avoid these troubles. The chip angle is made large, and the edge is sharpened carefully. Chip spaces should be large, more extensive than for steel, and have polished surfaces. It is recommended to obtain an undisturbed chip departure and a chip formation, which requires low cutting effect. Part of this is achieved through appropriate tool design, while others depend on the choice of material and cutting data and the properties of the machine. Tools suitable for machining aluminium are available for turning, milling, drilling, cutting and threading.

Cutting edges for turning long-chipped materials usually have *chip breakers*, which consist of a transverse groove or a step near the cutting edge, Fig 10.13. The chip breaker lifts the chip and breaks it or rolls it in a spiral to a *screw chip*. It also facilitates chip transport and provides a more compact chip scrap.

The total machining cost determines the choice of tool. In most cases, standard tools, often designed to fit machining of steel, achieve acceptable results in the machining of aluminium. But there are exceptions. Fig 10.14 shows a drill with a negative tip angle and with a sharp tip. This drill is intended for through-hole drilling in thin sheet metal and is designed to avoid burrs on the exit side of the hole.

The cutting speed of a drill decreases towards the centre, where the rotation is zero, Fig 10.15. Most often the so-called *chisel edge* is used as it causes about 70% of the necessary penetration force of a standard drill. This force can be reduced by 20–30% with a 3-facet drill and at the same time, improve the chip formation. The accuracy in the centre increases, i.e. the drilled hole becomes straight and has small diameter differences.

Fig 10.16 shows a *screw tap* for aluminium, which has a larger chip space and a sharper edge and therefore receives more support against the hole wall, than a tool for steel.

Many companies today have special tool programs for machining aluminium. These programs optimise the tool shapes concerning breaking, transport, and cutting properties for all cutting operations.

10.4.2 Cutting fluid

Machining of aluminium can be carried out without cutting fluid if the cutting speed is high and the feed is moderate. However, it is often an advantage to use a *cutting fluid*, which has a lubricating and cooling effect and gives the tool longer service life. The cutting fluid also contributes to quickly separation of the chips and better surface quality.

10.4.3 High-speed machining

Through the development of new computer-controlled milling machines, aluminium today can be machined with very high cutting speeds, 2000–4 500 m/min. It is mainly used in milling operations where pins with up to 60 000 rpm provide high cutting speed, low cutting forces, top surface finish and low heat generation. The production of thin-walled products with burr-free edges and unusually high dimensional accuracy is the result. In some cases, up to 90% of the material volume is removed without the method being uneconomical.

The heating of the part decreases with increased cutting speed. In conventional machining, about 80% of the generated heat moves to the detail and 10% to the chips. At high-speed milling, about 10% of the heat moves to the detail and 80% to the chips. It results in a significantly lower temperature in the workpiece and consequently better dimensional accuracy. The used cutting fluid is therefore not for cooling but rather as a chip conveyor.

Joining

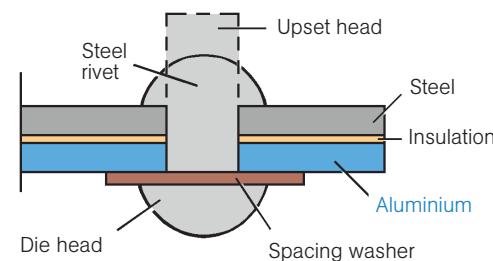
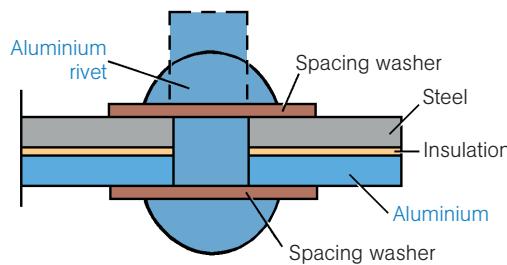


Fig 11.1 Insulation is important when riveting combined joints of aluminium and steel.

11.1 Riveting

11.1.1 Homogeneous rivets

Riveting on aluminium with aluminium rivets is performed with cold rivets (RT) unlike riveting on steel with steel rivets, which usually is performed with hot rivets.

During cooling of the hot steel rivets, a *clamping force* occurs because the rivets shrink. Friction between the rivet skull and the sheet occurs, which significantly impedes sliding. Cold aluminium rivets, on the other hand, give *low clamping forces*, so the entire load is absorbed by the bearing stress between rivets and objects and by shearing. The aluminium rivet must, therefore, fill the rivet hole well for the joint to be effective.

Aluminium rivets with diameters up to 20 mm can be cold pressed. Larger rivets of the heat treatable alloys AlMgSi and AlCuSi are usually pressed immediately after solution treatment. The plasticity is then okay but deteriorates after a few hours of natural ageing. If the rivet is stored in a freezer at a temperature between -5 and -20°C , the formability is kept for around 24 hours.

The aluminium alloy must be of the same type in both rivet and object to prevent corrosion in a humid environment. If aluminium is riveted with steel rivets, the rivets and base material must be insulated from each other, Fig 11.1. Rivets of copper or brass must be avoided.

11.1.2 Blind riveting

In addition to solid rivets, tubular rivets for one-sided mounting in pre-drilled holes can be used, so-called *blind riveting*, Fig 11.2. This rivet type is widely used and available in a large number of variants, both in terms of design and material.

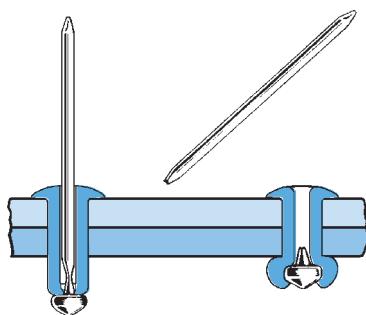


Fig 11.2 One-sided riveting with blind rivets.

11.1.3 Self-piercing riveting

For *self-piercing riveting*, a tubular steel rivet with a flat skull is used for one-sided mounting, Fig 11.3. With a high tool force, the rivet is pressed into the material, which can be aluminium alone or combined with other materials. This technology is common in the car industry.



Fig 11.3 Self-piercing riveting.

11.1.4 Clinching

Mechanical joining methods of thin metal sheets without additional fasteners are becoming more critical for aluminium. *Clinching* uses an upper and a lower tool pressing the sheets together for making a round joint or long tabs. The lower tool is then pressed against the dent or the tab so the sheets will plasticize and expand horizontally and interlock with each other, Fig 11.4 and 11.5. Clinching is based on the plastic deformation of the sheet. The main limitation of the technique is the formability (ductility) of the sheet material.

11.2 Bolting

Bolt with nut and washer can be used as an alternative joining method when there are difficulties in accessing riveting or when the joint must be dismounted.

Aluminium bolts are available to a limited extent. AlMgSi or AlCuMgPb is preferred as bolt material. The latter has reduced corrosion resistance and should be painted if used in a corrosive environment.

Preferably, steel bolts are used, which must be *galvanised* or of *stainless steel* with a washer of corresponding material under both skull and nut. The same demands as for insulation apply to bolted joints as to riveted joints if these will be exposed to a corrosive environment.

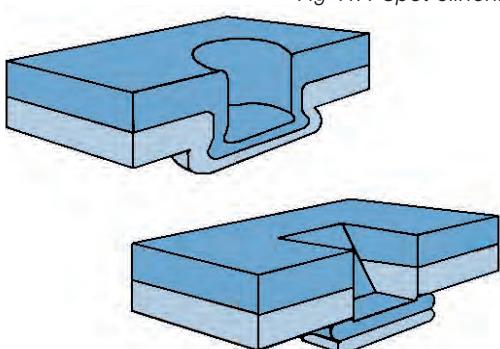


Fig 11.5 Clinching.

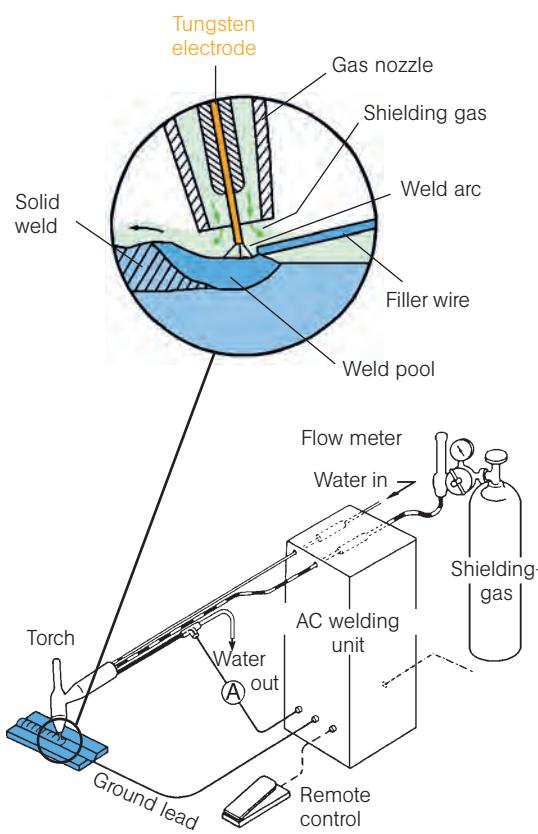


Fig 11.6 The principle for TIG-welding.

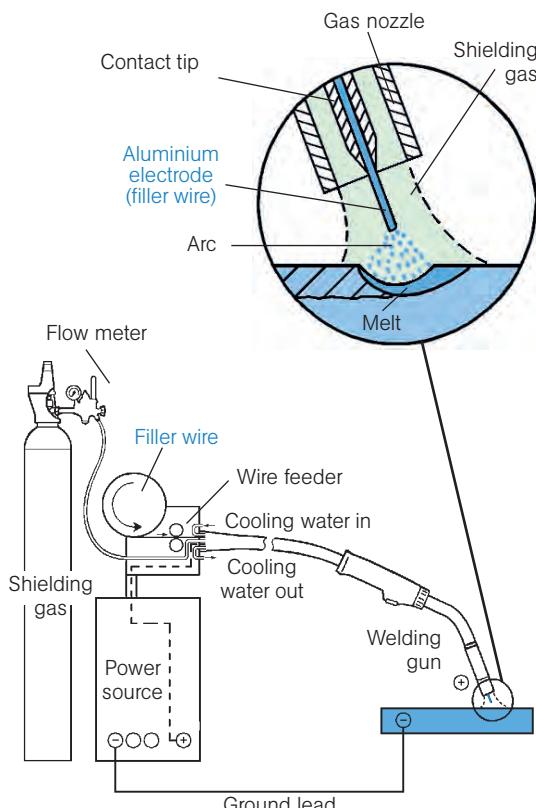


Fig 11.7 The principle for MIG-welding.

In cold riveting, the rivet shaft swells during the riveting operation and fills the hole, which is a prerequisite for the joint to function. In a bolted joint, the corresponding requirements for hole filling are met by drilling and broaching holes and using bolts according to a specific tolerance standard. For smaller joints, the diameter difference between hole and bolt can be 1 mm, under the condition that both the allowed bearing and shear stress is reduced. Then it's enough to drill the holes.

11.3 Welding

11.3.1 Generally

Under the influence of oxygen in the air, an oxide layer forms on the aluminium surface. At elevated temperatures, oxidation occurs faster. Before welding, the oxide must be removed. For gas metal arc welding (GMAW), e.g. MIG, TIG or plasma welding, the arc breaks the oxide layer while the gas protects the melt against the oxygen in the air.

The thermal conductivity of aluminium is about three times that of steel, and the specific heat is twice as high. The melting range for aluminium alloys is 570–660°C, while it is about 1500°C for steel. These properties mean that nearly as much heat must be put in when welding aluminium as welding steel.

Pores can occur in the weld as a result of aluminium dissolving more hydrogen in the liquid state than in the solid state. Hydrogen is formed from moisture or dirt on the surface of the workpiece. It is therefore crucial that the base metal and the filler metal are thoroughly cleaned and that the environment is moisture-free.

The temperature difference that exists between parts in a workpiece can under certain conditions, e.g. in case of inappropriate welding sequence or excessive restraint, cause cracks and deformations.

11.3.2 Fusion welding methods

Gas tungsten arc welding (TIG), Fig 11.6 and gas metal arc welding (MIG), Fig 11.7, are the most basic fusion welding methods for aluminium. Gas welding and metal arc welding with coated consumable electrodes (MMA) are today only used to a limited extent.

TIG-welding is typically performed with alternating current (AC) and with argon as shielding gas. The electrode is of non-melting type. Usually pure tungsten or tungsten alloys are used as electrode material. TIG is suitable for both manual and mechanised welding and is ideal for thicknesses from 0,5 mm and upwards.

MIG-welding is performed with direct current (DC) and with argon or argon/helium mixtures as shielding gas. Unlike TIG, the filler wire is used as an electrode. It melts in the arc, and the drops are transferred to the weld pool as a spray.

The welding speed for MIG is higher than for TIG, 35–70 cm/min for material thicknesses 1–20 mm. Fast welding speed means that the size of the heat-affected zone (HAZ) in the base material becomes smaller than that of other fusion welding methods. As a result, built-in stresses and deformations also become smaller.

MIG is used for material thicknesses from 1 mm and upwards. The high welding speed is a disadvantage when making short welds or welding in challenging positions. Choose TIG instead in that case.

Thanks to modern electronics, the welding equipment and methods have developed tremendously in recent decades. Variants of MIG- and TIG-welding are therefore available for welding with high quality and excellent economy. Plasma MIG and Cold Metal Transfer (CMT) are examples of new welding methods.

11.3.3 Execution of fusion welding

Aluminium melts without colour change, and the welding pool is very fluid. Welding of butt joints requires a great deal of experience so that the melt will not pour down between the edges of the sheet. With



Fig 11.8 Air tank for passenger cars.

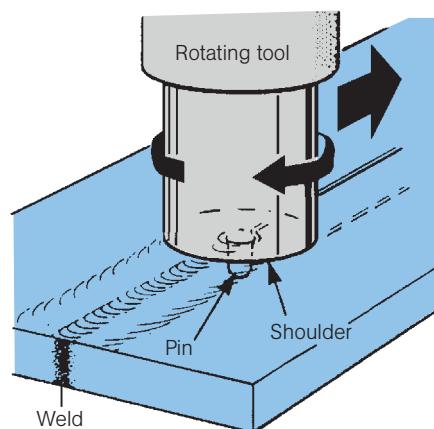


Fig 11.9 Friction Stir Welding (FSW).

Table 11.1 Selection of filler metals for MIG- and TIG-welding of sheet and profile alloys

Example: AIMgSi alloy (see A) should be welded to AIMg3 alloy (see B). The table then shows that AIMg5 is the most suitable filler metal. See the blue boxes.

Base material A type								
Al99,7	Al99,7							
Al99,5 Al99,0	Al99,5Ti Al99,5	Al99,5Ti Al99,5						
AlMn	Al99,5Ti	Al99,5Ti	Al99,5Ti					
AlMg1(Mn) AlMg2,5	Al99,5Ti AlMg5	Al99,5Ti AlMg5	Al99,5Ti AlMg5	AlMg3 AlMg5				
AlMg3	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5	AlMg3 AlMg5			
AlMg4,5Mn	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5	AlMg4,5Mn		
AlMgSi	AlMg5 AlSi5	AlMg5 AlSi5	AlMg5	AlMg5	AlMg5	AlMg5 AlSi5 AlMg5		
AlZnMg	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5	AlMg5 AlMg4,5Mn	AlMg5 AlMg4,5Mn	
Base material B	Al99,7	Al99,5 Al99,0	AlMn	AlMg1(Mn) AlMg2,5	AlMg3	AlMg4,5Mn	AlMgSi	AlZnMg

backings on the root side, e.g. a copper rail with a groove, the work is simplified.

The material volume decreases by about 8% as the welding pool solidifies. This leads to shrinkage in the weld and deformations throughout the workpiece.

Most aluminium alloys can be welded. Copper-containing alloys, e.g. EN AW-2014, are sensitive to crack formation and should not be selected in welded constructions. However, spot welding (resistance welding) is suitable for this type of alloy.

Table 11.1 gives information about the most suitable filler metal for welding alloy combinations. For some alloys, alternative filler metals are specified. These can be selected depending on which property of the weld, is most important, e.g. corrosion resistance, strength or freedom from cracks.

Increased use of the AlSi12 filler metal is found today for MIG-welding within the automotive industry, especially when welding AlMgSi alloys against the casting alloy AlSi10Mg.

The strength of the base material always decreases when welding. The area closest to the weld, called HAZ, has a strength that is almost the same as for annealed material. With hardenable alloys, the loss of strength can be recovered through solution heat treatment and artificial ageing. However, such treatment often leads to deformations, especially when cooling after the solution. For AlZnMg alloys, a specific amount of the lost strength is recovered through natural ageing.

11.3.4 Friction Stir Welding (FSW)

A tool with a pin and a shoulder, Fig 11.9, is rotated at 500–5000 rpm and pressed down into the gap between two aluminium parts. The tool is moved along the gap. The friction heat joins the two components into a weld with homogeneous and oxide-free structure. The weld has excellent properties and contains neither pores nor cracks. However, dimensional variations can be obtained depending on the welding depth and the selected alloy. As the process name indicates, the tool "stirs" the material, but does not melt it. The welding speed is normally 0,5–3,0 m/min for AlMgSi alloys.

Because the material in the weld does not melt, the deformations become very small. FSW is, therefore, an ideal process for welding profiles and sheet metals.

Between HAZ and the weld nugget lies a thermomechanically-affected zone, where the grains of the original microstructure are



Fig 11.10 Side of a railroad wagon, FSW-welded.

retained but deformed. The top surface of the weld has got a different microstructure, a consequence of the shearing induced by the rotating tool-shoulder. Compared to MIG /TIG-welds, the FSW welds exhibit excellent bending properties and superior static and dynamic strength.

The method is ideal for butt joints, Fig 11.10, as no joint preparation is necessary. Overlap joints can also be welded. Machines for welding up to 16 m can be found at Hydro in Finspång.

Since FSW works at temperatures below the melting range of the material, this results in both low heat effects and stresses. The corrosion resistance of the weld is equal to that of the base material.

Like other processes, even FSW has its limitations, e.g.:

- Strong root support is necessary
- Welding fixtures are needed to hold the object parts in place

11.3.5 Friction Stir Spot Welding (FSSW)

Friction stir spot welding (FSSW) is a welding process in solid state that, like FSW, works below the melting range for aluminium. The method provides individual welding spots that occur when a high-force rotating tool is pressed against the upper surface of two overlapping sheets/profiles.

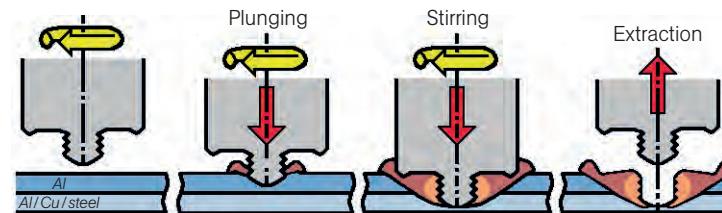


Fig 11.11 The FSSW welding cycle without refilling.

FSSW has four steps. First, the tool is positioned at a right angle to the workpiece surface and begins to rotate, Fig 11.11. The frictional heat and high pressure plasticise the upper sheet and then the lower as the tool pin penetrates them, *plunging*. The tool pin moves into the sheets until it meets the surface of the lower sheet, *stirring*. The high forging pressure joins the sheets metallurgically by stirring the metal without melting. After a short hold time, the tool is pulled out of the sheets, *extraction*. A spot weld can be made every 5 seconds. FSSW is advantageous for welding aluminium to aluminium, copper or steel.

The speed of the device varies depending on the thickness and type of material. For the 5000- (AlMg) or 6000-series (AlMgSi), the rate is generally at 2000 rpm. For other alloys, the tool can rotate as fast as 4500 rpm.

11.3.6 Friction Stir Spot Welding Refill (RFSSW)

Development of the FSSW refilling process, RFSSW (R = refill), has been introduced. It provides a more aesthetic weld than for FSSW.

RFSSW is performed by placing a rotating cylindrical tool on two overlapping sheets/profiles under pressure, Fig 11.12. In the device, there is a central rotating pin (probe) and one outside rotating shoulder plus outside that the non-rotating clamp. The design and dimensions of the tool depend on the material, sheet thickness and the strength requirements for the weld.

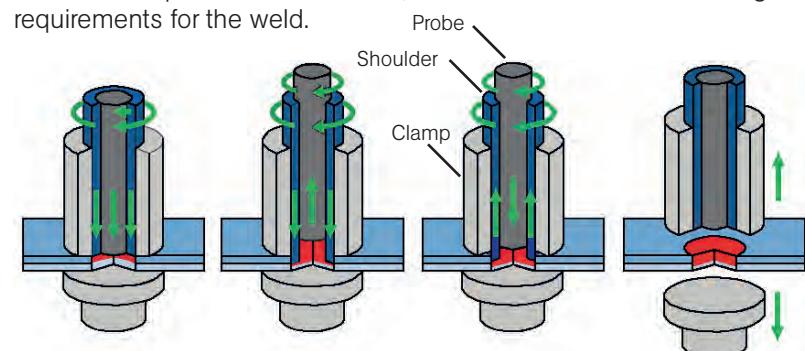


Fig 11.12. Principle and examples for the RFSSW-process. Above is a car component.

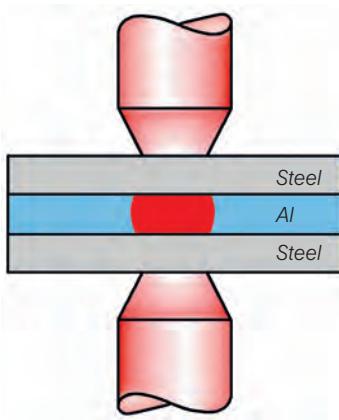


Fig 11.13 Welding of aluminium directly to steel with resistance heating. Bonding between the materials have been obtained with well-adapted welding parameters.

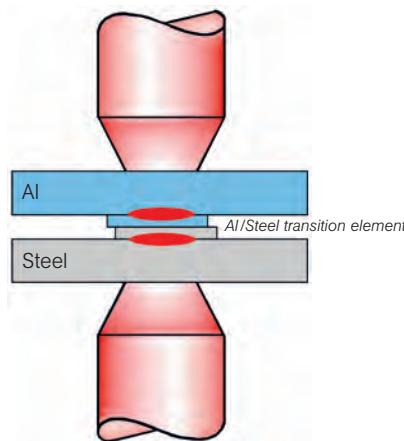


Fig 11.14 RSW of aluminium against steel with a transition element of Al/steel. Two weld lenses are formed at the interface between the respective materials.

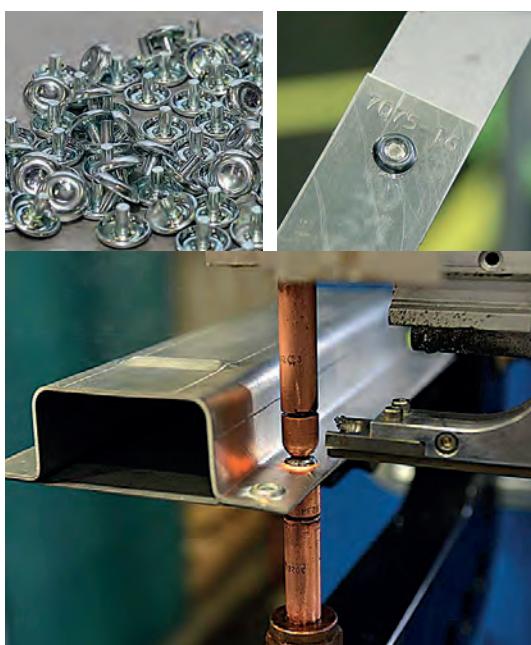


Fig 11.15 RSR technology uses a combination of spot welding and self-piercing rivets for joining different materials, e.g. steel to aluminium. A drawing pin-like steel rivet (top left) is used as a fastener which is pressed through a hole in the aluminium sheet (top right), and spot welded to the steel sheet (bottom).

At the start of the welding phase, all three tool parts act with downward forces on the sheets. Friction from the rotating probe and the shoulder heats the aluminium material and is then pressed down into and through the top layer. After that, the probe is lifted slightly, while the shoulder continues down into the bottom sheet. At a pre-set distance, the shoulder turns upwards, and the probe moves down again. When both the shoulder and the probe are in level with the work surface, the rotation stops, and the tool is held in place to allow weld cooling. A smooth weld (red) has been formed.

11.3.7 Resistance spot welding (RSW)

An electric current of 10–300 kA is transmitted via two water-cooled copper electrodes, which are pressed towards an aluminium/aluminium overlap joint. The ohmic resistance of the material, the current and the time generate the welding heat. The electrical resistance of aluminium is low, and the conductivity is high, so the current must be high, and the welding time short for achieving melting. The weld becomes lens-shaped.

Requirements from the automotive industry have resulted in variants of RSW being developed to weld aluminium to steel. Firstly, attempts have been made to spot weld the materials directly against each other, with some success, Fig 11.13. Secondly, various prefabricated transition pieces, e.g. thin explosion-welded pieces of Al/steel, have been used, Fig 11.14.

11.3.8 Resistance Spot Riveting (RSR)

The American aluminium company Arconic has developed a new method for welding aluminium against several other materials, such as steel, magnesium and composites, Fig 11.15. The company, which is one of the largest aluminium producers in the world, has long been interested in increasing the use of aluminium in the automotive sector.

The RSR method welds different materials together with the same equipment as in conventional spot welding. It offers car manufacturers the flexibility to quickly switch between RSR and traditional welding.

To form a weld, two or more sheets, e.g. aluminium against steel, are placed between the electrodes in a standard spot welding machine. The upper sheet (Al) has a hole for the rivet; the lower sheet (steel) has no hole. A steel rivet is placed in the hole under the upper welding electrode. The electrodes apply a force, and a welding current passes through the rivet and the bottom sheet, creating a weld (steel to steel). The total cycle time is 3–5 seconds, which is comparable to standard spot welding (RSW).

The weld is formed between the steel rivet and the bottom steel sheet. The top aluminium sheet is not electrically involved. Instead, it is mechanically trapped by the broad rivet head. Therefore, the top sheet can be of any material: the same or different, painted or unpainted, conductive or non-conductive. As long as the thickness of the upper sheet corresponds to the shaft length of the rivet, the sheets can be any combination of steel, aluminium, carbon fibre, glass-reinforced composite or plastic.

The system is developed with the car manufacturers in mind, but can also be used in the engineering industry. As multi-material combinations increase in cars, RSR technology is an ideal solution. It can easily be adapted to changes in the assembly line and utilise existing welding robots equipped with automatic feeding systems.

11.3.9 Other welding methods

There are many more welding methods for aluminium, e.g. flash welding, explosion welding, laser welding, friction welding, high-frequency welding, ultrasonic welding, electron beam welding. All methods work well on aluminium but have limited use due to the need for expensive equipment.

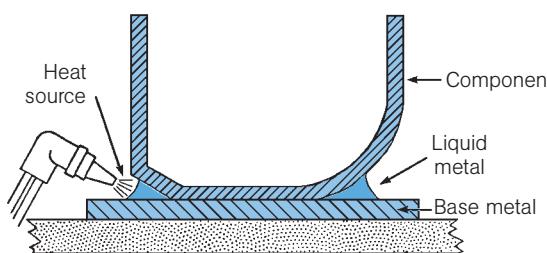


Fig 11.16 The principles for soldering and brazing.

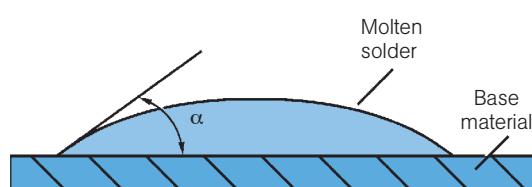


Fig 11.17 A measure of the degree of wetting is the contact angle α of the solder. It should be $<30^\circ$ and will ideally approach 0° .

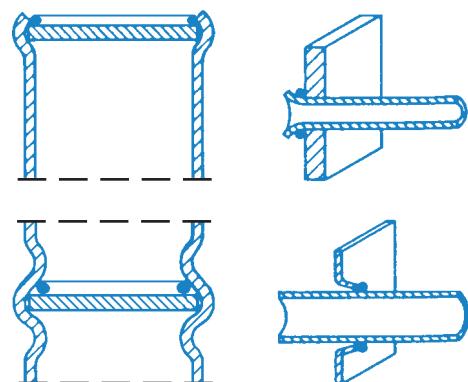


Fig 11.18 Examples of joint types for brazing.

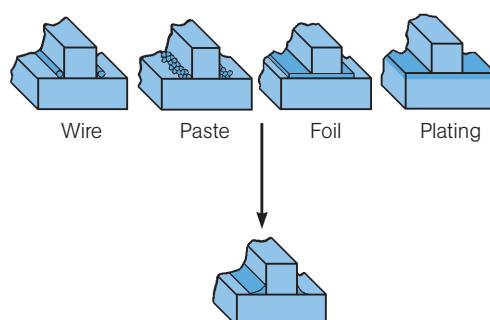


Fig 11.19 Different ways to apply aluminium solder for brazing.

11.4 Soldering and brazing

During soldering and brazing, two metallic materials are joined to each other using a molten metallic additive (solder) and a flux. The solder has a lower melting temperature than the aluminium base material, Fig 11.16. *Soldering* uses solders that melt at temperatures below 450°C . If it melts above 450°C , we are talking about *brazing*. Two unique brazing methods, which are widely used for manufacturing of heat exchangers for cars, are *vacuum brazing* where no flux is needed and *furnace brazing*, which uses a non-corrosive flux.

To obtain an acceptable soldered joint, regardless of method, the molten solder must be able to wet, float on, the two metal parts. A metallic connection is obtained between the solder and the metal, Fig 11.17. The thin, but dense and hard, aluminium surface oxide must be broken and removed so that the solder comes into contact with the oxide-free metal. Oxide breakup is usually done chemically with a *flux*, often combined with mechanical oxide removal. The fluxing agent ensures wetting between solder and base metal by dissolving the oxide and preventing the formation of a new oxide.

Most fluxes are highly corrosive to aluminium, especially in humid environments. The flux residues must, therefore, be removed after soldering/brazing. An adequately soldered joint is secure, pressure-tight, conductive for heat and electricity and corrosion-resistant, which means that soldering is a suitable method in the following cases:

- for thin materials
- when joining aluminium to other metals
- when it is not appropriate to heat to welding temperatures
- when joining large areas
- for serial production of small details
- when a component is complicated and has many joining points

11.4.1 Soldering

Solder on zinc or tin base is most common. The working temperature for zinc solders are $390\text{--}450^\circ\text{C}$ and for tin solders $200\text{--}300^\circ\text{C}$. They are available as:

- **Low-temperature solders.** The melting point for the solders is $150\text{--}260^\circ\text{C}$. They contain tin, lead, zinc and/or cadmium and give joints with the worst corrosion resistance.
- **Mean temperature solders.** The melting point for the solders is $260\text{--}370^\circ\text{C}$. They contain tin or cadmium in various mixes with zinc, plus small amounts of aluminium, copper, nickel or silver and lead.
- **High-temperature solders.** The melting point for the solders is $370\text{--}425^\circ\text{C}$. Zinc-based solders contain 3–10% aluminium and small amounts of copper, silver, nickel and iron to modify their melting and wetting properties. Zinc-rich solders have the highest strength among these solders and give joints with the best corrosion resistance.

When the solder contains zinc, flux isn't necessary. Molten solder is applied to the aluminium surface and with a sharp object, e.g. a glass brush, steel tip or the tip of the soldering iron, the oxide layer is scraped away under the molten metal. The surfaces are pressed together and heated until the solder flows. Finally, it cools and solidifies.

Another flux-free process is *ultrasonic soldering*. In this method, the details to be joined are dipped into a melt of, e.g. ZnAl5 at about 450°C . The melt, as well as the details, are simultaneously vibrated with ultrasound. The oxide breaks up, and the solder wets the metal.

Tin based solders can not be used for capillary joints on aluminium, so soldering is best performed on overlap joints by manual soldering with a gas burner or soldering iron. After soldering with tin solders, it is necessary to remove the flux residues to avoid corrosion attacks.

11.4.2 Conventional brazing

For brazing, aluminium based solders with silicon are used. Solder type AISi12 or AISi10Cu4 are standard. The working temperature is

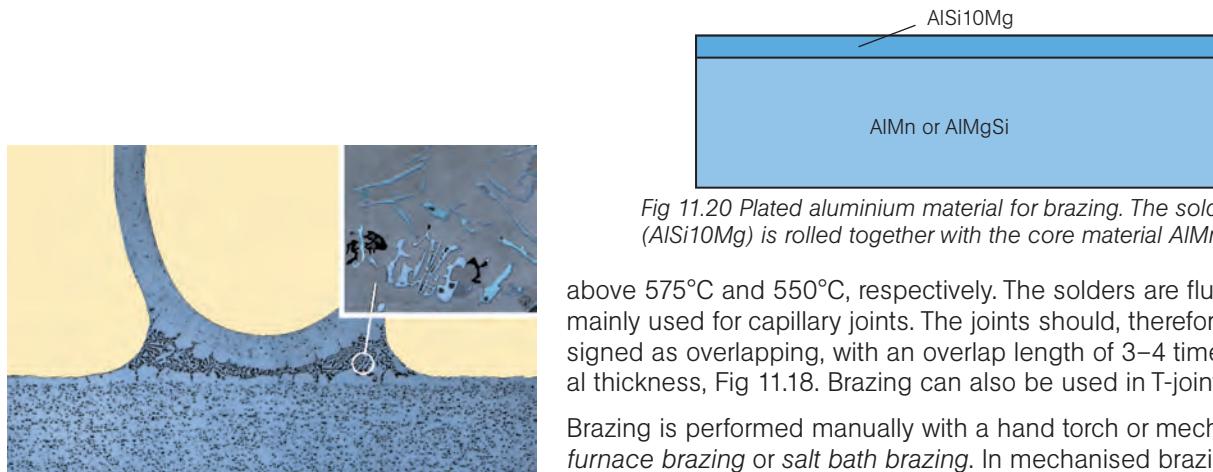


Fig 11.21 Section through a brazed joint for a car radiator.

AISI10Mg

AlMn or AlMgSi

Fig 11.20 Plated aluminium material for brazing. The solder sheet (AISI10Mg) is rolled together with the core material AlMn/AlMgSi.

above 575°C and 550°C, respectively. The solders are fluent and are mainly used for capillary joints. The joints should, therefore, be designed as overlapping, with an overlap length of 3–4 times the material thickness, Fig 11.18. Brazing can also be used in T-joints.

Brazing is performed manually with a hand torch or mechanised by *furnace brazing* or *salt bath brazing*. In mechanised brazing, the solder may be applied in the form of plating, film or paste which fills the joint during melting, Fig 11.19. The solder's penetration into the gap depends on capillary action and is prevented by all kinds of impurities. Careful cleaning before brazing must be carried out. In conventional brazing, chloride-containing fluxes are used. All *flux residues* must be removed after brazing due to the risk of corrosion attacks.

11.4.3 Salt bath brazing (dip brazing)

The heat for this brazing process is supplied from a *liquid salt bath* which also acts as a flux. The aluminium pieces containing solder foils (shims) or solder rings are dipped into the hot liquid which melts the solder and joins the parts together at each interface point. The heat effect on strength is detrimental. Salt bath brazing is suitable for both simple and complicated forms.

The method is very suitable for aluminium. It can be used on thin material without providing deformation and is often combined with high-speed machined components. Salt bath brazing offers high strength, excellent surface finish and high dimensional accuracy.

11.4.4 Vacuum brazing

Vacuum brazing is a *fluxless* method. The solder consists of an aluminium alloy with an addition of silicon, which lowers the melting temperature and of magnesium, which contributes to the oxide breakage. Only *plated* aluminium material is used, i.e. the solder is rolled together with the core material to a sheet or a strip, Fig 11.20.

After assembling the components are placed in a vacuum furnace. The pressure is lowered to 10^{-4} – 10^{-6} bar and the temperature raised to about 600°C. This is 15–40°C below the core melting temperature but above that of the solder. The solder layer melts and forms joints with the core material, 11.21. The method requires extra time for vacuum pumping, and the heating rate is slow compared to shielded gas brazing. Vacuum brazing is used mainly for heat exchangers.

11.4.5 Controlled Atmosphere Brazeing with or without flux

The method Controlled Atmosphere Brazeing (CAB) means using a non-corrosive flux, which is mixed with water to a slurry. Like vacuum brazeing, solder plated material is used. The parts are assembled, dipped in the slurry, dried and then placed in a continuous furnace, where the air is pumped out and replaced by an inert shielding gas, usually nitrogen, Fig 11.22. The temperature is raised to the braze temperature, about 600°C, whereby the flux dissolves the oxide, and the plated layer melts and forms the joint. The flux residues do not need to be removed after brazeing, but gives, on the contrary, some corrosion protection. The method was formerly called Nocolok.

Shielded gas soldering dominates in the automotive industry to produce all types of heat exchangers that occur in modern vehicles in large series. Examples of these are radiators, oil coolers, charge air coolers for turbo engines as well as condensers, evaporators and interior heaters for air conditioning systems, Fig 11.23.

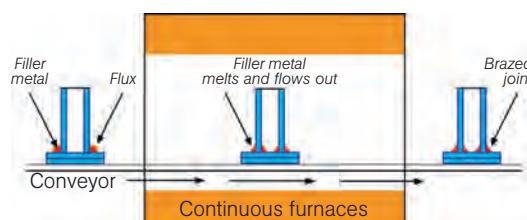


Fig 11.22 Furnace brazing with shielding gas.



Fig 11.23 Brazed heat exchangers of aluminium predominate in today's passenger cars and commercial vehicles.



Fig 11.24 In an aircraft, there are many glued aluminium parts. Primers are often used before painting. Here it has a yellow colour.

In recent years, plated products that contain flux built into the solder or completely flux-free solders have been developed. Consequently, the component manufacturer does not need a separate flux plant, which saves both costs and inconveniences for the working environment. Completely flux-free brazing requires a clean shield gas atmosphere. The solder with built-in flux gives better brazing properties than other brazing methods, which enables new applications and lower requirements for pure shield gas atmosphere.

11.5 Adhesive bonding

Glueing (bonding) with adhesives is an essential complement to the conventional joining methods. Aluminium is by far the most glued metal. Components with high strength requirements in, e.g. aircraft, Fig 11.24, and spacecraft have for a long time been glued. There are many other examples of glueing aluminium, e.g. aluminium boats have been glued to both aluminium (hull) and glass (window).

11.5.1 Conditions before glueing

There are several adhesive types, pretreatments and glueing methods to choose. It is not always easy to select the right combination and also risk-free to glue without knowledge. The distance between the molecules in the material to be bonded and the molecules in the adhesive may not exceed 0,5 nm (almost the same length as between the aluminium atoms) for power transmissions to take place. This distance is attained if the adhesive has a lower surface tension than the material to be glued. Otherwise, the glue would instead form drops than flow out. Different surfaces show different properties. The presence of contaminants and oxides means that the expected forces between adhesives and aluminium materials cannot occur. The joint surface must be well known, clean and reproducible to achieve a satisfactory and uniform glueing result.

11.5.2 Choice of adhesive

The functional mode governs the choice of adhesive and the joint fill factor, heat resistance, toughness, strength, etc. Joints have relatively good load distribution, but still, it is rare to get glued joints with a uniform load distribution over the entire joint surface. The load is usually highest at the edges of the joint. The stronger the chosen adhesive, the higher stress concentration in the joint border.

Inversely, a weaker adhesive gives better load distribution and lower tension peaks. It is advisable to establish a profile of demands for the properties of the intended glued joint and consider how to handle the glueing in production. Such a list makes it easier to describe to a glue supplier which is the best adhesive. In critical cases, the selection of resin should be preceded by extensive tests.

Sometimes during the glueing process, the adhesive must be *liquid* to wet and fill the surface structure. The liquid glue should then *solidify* into a material that can transfer the load. The transition from liquid to solid state can occur in three different ways.

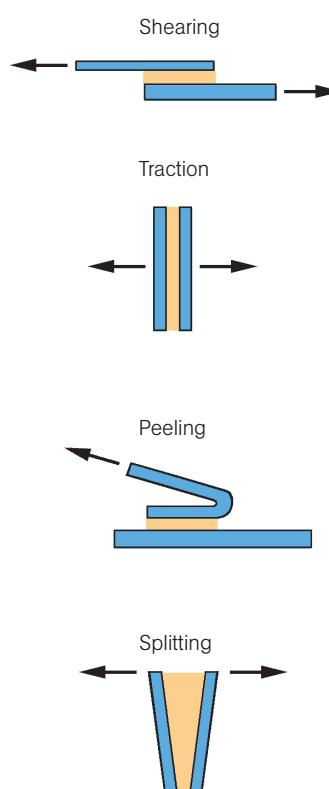


Fig 11.25 Different load cases for glued joints.

Drying	Cooling	Hardening starts by:
Solvents or water which evaporate and gives a solid state	The adhesive is liquid when it is hot and solid when it has cooled down	<ul style="list-style-type: none"> - mixing two or more components - heating (thermosetting) - environmental changes, e.g. moisture, high pH, UV light or oxygen absence

Thermosetting plastics are polymers that irreversibly becomes rigid when heated.

11.5.3 Joint preparation

Glueing means that the joint is made of plastic or rubber. The adhesive always has a lower strength than the aluminium material itself. The joint surface should be enlarged to compensate for the adhesive's lower strength. Glued joints are best suited for *shear loads*, Fig 11.25. Joints in tensile stress are often unsuitable for high loads. Cleavage and splitting load causes high tensions on a small part of the joint surface and should be avoided.

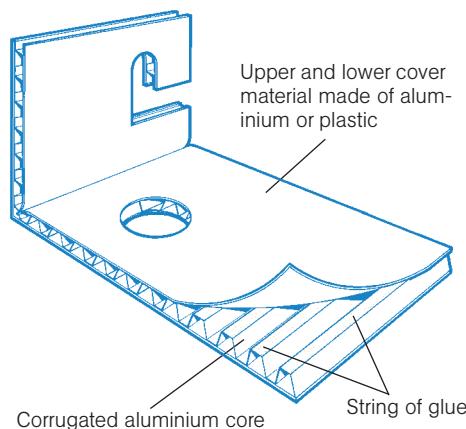


Fig 11.26 Composites can be made by glueing. Light and rigid construction materials are then obtained.

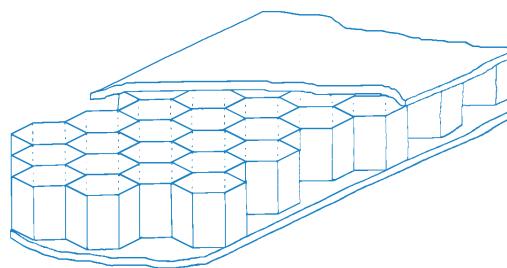


Fig 11.27 In Honeycomb elements, aluminium is often one of the components. The material is made by glueing.

11.5.4 Operating temperature

The practical application temperature for glued joints is for many adhesives in the range of 60–80°C. The highest heat resistance achieves with thermosetting adhesives and adhesive films (150–200°C). However, with silicone adhesives, heat resistance of about 250°C can be achieved without heat treatment.

11.5.5 Long-term strength

The long-term strength and durability of a glued joint to the external environment are mainly determined by the strength and durability of the alumina surface to which it is glued. For use in a dry climate, an untreated aluminium surface can provide excellent glueing results. The same joint outdoors, in coastal climates, can have a short life. It is the total effect of load, temperature and environment that determines the life of the joint.

Usually, it is not the glue or the adhesion that will be ruined or ceased. Still, it is the aluminium material underneath the glued joint that is affected by the environment. However smooth and even a surface seem to be, it always consists of peaks and valleys, seen at high magnification. Therefore, viscous and quick setting adhesives only come into contact with the tops of the surface, which results in a glued joint with pores (air pockets). In a humid environment, this air will eventually be replaced by water which increases the need for surface treatment, e.g. anodising, to obtain improved corrosion resistance of the aluminium surface.

11.5.6 Long-lasting glued joints

The basic principle for producing durable glued joints is well-filled profile depths and resistant oxides. There are a vast number of pretreatment methods for aluminium. The most common and even some unique techniques are described in Table 11.2. The selection of the best glue depends on the environment, load and costs. Best knowledge about treatment and possible working environment risks should be obtained before deciding on a pretreatment method.

Treatment with primer before glueing is mostly executed for filling the surface profile when viscous, and quick setting adhesives are used. The need for primer increases with the corrosive environment or when the surface is not protected at all.

Table 11.2 Pretreatment methods for glueing

Method	Effect	Application (max)
Cleaning /degreasing	Usually, the smallest thing to do to ensure a clean and defined surface to glue on.	For moderately loaded joints in a dry environment.
Smooth grinding /blasting or alkaline pickling	Removes weak surface layers, e.g. oxides. Safer than degreasing.	Highly stressed joints in a dry environment. Unloaded connections in freshwater.
Boiling water (during 5–10 min) after pickling	Provides durable but moderately weak oxides.	Low-stressed flexible adhesive joints, in a moist and corrosive environment.
Phosphating/chromating	Corrosion-resistant, but weak, porous oxides.	Low stressed joints with elastic or very low viscosity adhesives in a corrosive environment.
Hydrochloric acid at 20°C in 30 sec	Quick method, can give darkening of the aluminium surface.	Moderately stressed joints, even in a corrosive environment.
Etching in chromic/sulphuric acid	Thin, stable oxides. (Used by the American aviation industry.)	Highly stressed joints outdoors. Can't stand strong corrosive environments.
Anodising in sulphuric acid	Thick, very resistant oxide.	Low stressed joints in a corrosive environment. Preferably elastic adhesive.
Anodising in chromic acid	Medium-thick, stable oxide. (Used by European aviation industry since the 1940s.)	Highly stressed joints, even in a corrosive environment.
Anodising in phosphoric acid	Porous, very resistant oxide. Used with low viscous primer.	Best pretreatment for highly stressed joints in a corrosive environment.

Rules of Engineering Design

The rules for engineering design presented in this chapter are, where possible, based on a comparison between aluminium and steel. However, such comparisons must be used with caution. It is not always possible in an economically correct steel structure, to replace the steel entirely with aluminium. To be able to calculate and design an aluminium structure, good knowledge about material properties is essential. Even the materials suitability for the intended purpose and the behaviour of the material in operation plus the load situation deserve attention.

Aluminium structures have a low weight due to:

- a low density of the aluminium material
- the possibility to place the goods where it is best needed

It is, to a great extent, the last statement above that determines whether a structure will be economical or not. In the manufacturing of extrusions, a suitable design of the material distribution in the cross-section can easily be performed.

The development of an economically competitive aluminium structure also requires good knowledge of particular design problems, such as buckling and cracking, which occurs at small wall thickness.

Eurocodes

The Eurocodes are ten European standards (EN; harmonised technical rules) specifying how a structural design should be conducted within the European Union (EU). The European Committee for Standardisation developed these upon the request of the European Commission.

EUROPEAN STANDARD · EN 1999-1-1:2007

Eurocode 9: Design of aluminium structures (EN 1999)
Part 1-1: General structural rules (EN 1999-1-1)
Part 1-2: Structural fire design (EN 1999-1-2)
Part 1-3: Structures susceptible to fatigue (EN 1999-1-3)
Part 1-4: Cold formed structural sheeting (EN 1999-1-4)
Part 1-5: Shell structures (EN 1999-1-5)

Addendum: EN 1999-1-1:2007/A2:2013, EN 1999-1-1:2007/A2:2013

EN 1999 Eurocode 9 applies to the design of buildings and other civil engineering and structural works in aluminium. It complies with the principles and requirements for the safety and serviceability of structures, the basis of their design and verification that are given in EN 1990
– Basis of structural design.

EN 1999 is only concerned with requirements for resistance, serviceability, durability and fire resistance of aluminium structures. Other conditions, e.g. regarding thermal or sound insulation, are not considered.

Eurocodes and nationally requirements in EKS

The Swedish National Board of Housing, Building and Planning's (Boverket) design rules, European Construction Standards EKS, specify how the European design standards, the so-called Eurocodes, should be applied. Together with the Eurocodes, EKS constitutes the Swedish rules for verification of load-bearing capacity, stability and durability.

In the EKS, Sweden's Nationally Determined Parameters (NDP) are made for the Eurocodes. For example, the national parameters are based on different conditions regarding geology, climate, way of living and security level. Through these national parameters, the relevant Eurocode parts have been incorporated into the Swedish regulations.

12.1 General structural rules

12.1.1 Low density combined with high strength

The density of aluminium is $2,7 \text{ kg/dm}^3$, i.e. only one-third of that of steel. Common aluminium alloys used for load-bearing purposes have an ultimate strength of up to 350 MPa. If a structural member only is loaded in tension, an aluminium structure can weigh 40–60% of the corresponding steel structure. For systems where the self-weight constitutes the main load, aluminium is an excellent structural material.

The competitiveness of an aluminium structure increases compared to denser material when it is influenced by a given load which does not change with the span as it increases.

Rule

Aluminium's advantage over heavier structural materials increases with an increasing span if the load is mainly tare-weight.

12.1.2 Low elastic modulus in combination with high strength

The elastic modulus for aluminium (E_A) is about 70 000 MPa, i.e. one-third of the corresponding value for steel. Furthermore, aluminium has relatively high strength. The low modulus causes stability problems, e.g. buckling, lateral torsional buckling and local buckling, which occur at lower load levels compared to steel structures with identical geometry. This must, therefore, be taken into account when designing the structure.

Low elastic modulus also causes more significant elastic deflections in aluminium structures than in equivalent steel structures.

12.1.3 In-plane buckling

Rules for the structural design of aluminium are given in the Swedish National Board of Housing, Building and Planning, (Boverket), EKS, which contains national choices for the Eurocode EN 1999 for the design of aluminium structures. EKS 10 (BFS 2015: 6) became valid on 1 January 2016. The design methods used are mostly the same as those used in the design of steel structures. See also Eurocode 9.

When designing for in-plane buckling, the design buckling resistance of a compression member is determined by its slenderness.

The relative slenderness factor λ_c is determined as:

$$\lambda_c = \frac{l_c}{\pi i} \sqrt{\frac{f_y}{E}}$$

where l_c is the effective length factor, i the radius of gyration ($= \sqrt{I/A}$), f_y the specific yield strength of the material and E the elastic modulus. Using the slenderness factor, (λ_c), a reduction factor, (ω_c) is determined. This is given as a function of the slenderness factor in Fig 12.1.

For optimal utilisation of the material, the slenderness factor should be as low as possible, and the reduction factor as high as possible. This is achieved by backing up the column, which reduces the factor (l_c), or by increasing the radius of gyration. NOTE! For slender cross-sectional members, local buckling may be a limiting factor.

Rule

In the case of structural members in compression, it is advantageous to have low slenderness concerning material utilisation. This is achieved by appropriate cross-sectional selection and/or by back up.

12.1.4 Bend loaded design members

For structural members who are bend loaded, aluminium's low elastic modulus gives a more significant deflection than to steel.

The deflection f of a beam of length L and load Q is:

$$f_{Al} = k \cdot \frac{Q \cdot L^3}{E_{Al} \cdot I_{Al}} \quad f_{Steel} = k \cdot \frac{Q \cdot L^3}{E_{Steel} \cdot I_{Steel}}$$

where E = elastic modulus, I = moment of gyration for the beam and k = constant, which depends on the load case.

Where $E_{Steel} = 3 \cdot E_{Al}$ ($E_{Steel} \approx 210$ GPa, $E_{Al} \approx 70$ GPa)

which at the same deflection $f_{Al} = f_{Steel}$ and equal beam length and with the same load gives:

$$E_{Al} \cdot I_{Al} = 3 \cdot E_{Al} \cdot I_{Steel} \text{ and consequently } I_{Al} = 3 \cdot I_{Steel}$$

Thus, the effective second moment of area of the aluminium beam, (I_{Al}), is three times that of the steel beam, (I_{Steel}), for the same deflection and the same load. A rectangular cross-section with equal beam width, (b), but with varying height, (h), gives:

$$I = \frac{b \cdot h^3}{12} \quad \text{which in our case gives } h_{Al} = \sqrt[3]{3} \cdot h_{Steel} \approx 1,43 \cdot h_{Steel}$$

By increasing the height (h_{Al}) of the aluminium beam by 43%, its second moment of area will also increase. The stiffness will then be as high as that of the steel beam, but with only half the weight, Figs 12.2 and 12.3.

Members in compression in bend-loaded structural parts can be secured against instability by suitable profile design and back up.

Rule

Design a beam as high as possible. Place as much material as possible in the flanges of thin webs – watch out for buckling in the web.

Choose statically indeterminate structural forms (e.g., frames, continuous beams, fully restrained beams).

12.1.5 The ratio between ultimate and yield strength

For many structural aluminium alloys, the ratio is:

$$\frac{R_m}{R_{p0,2}} = 1,2 - 1,3$$

This is a relatively low value. Therefore, attention must be paid to structural members in tension with the risk for uncontrollable overloads. The same counts for members in bending, where a substantial transfer of moments can occur when the limit state is utilised.

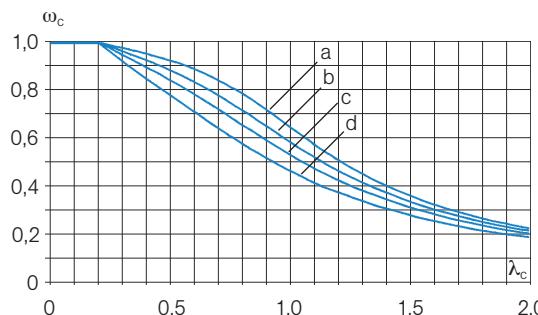


Fig 12.1 The value of the reduction factor ω_c depends on the cross-sectional type and the slenderness λ_c . The cross-sectional type is determined according to Table 12.1.

Table 12.1 Material, cross-section and type for determining ω_c

Material	Cross-section	Type
Heat treatable alloy	Symmetrical	a
Non-heat treatable alloy	Symmetrical	b
Heat treatable alloy	Unsymmetrical	c
Non-heat treatable alloy	Unsymmetrical	d

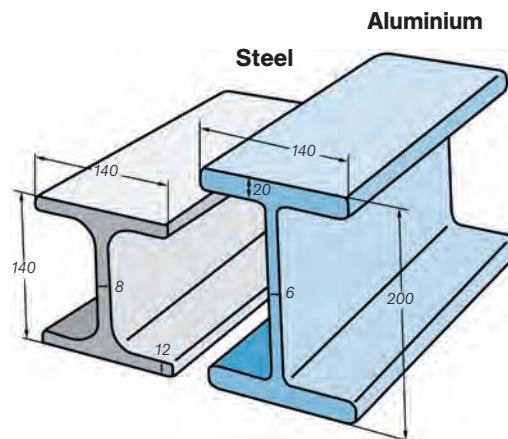


Fig 12.2 One aluminium and one steel beam with the same width and the same rigidity are shown. The aluminium beam has only half the weight of the steel beam.

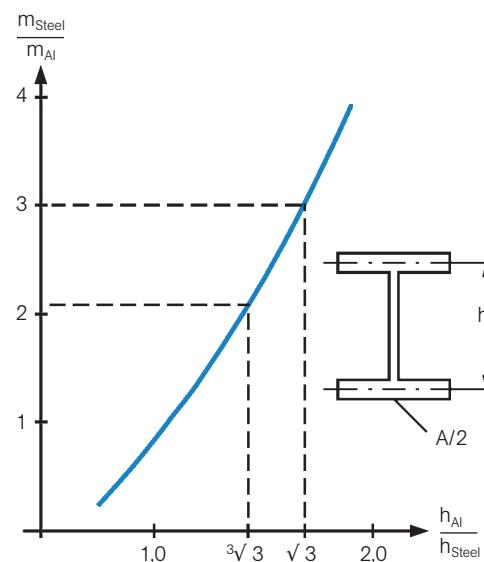


Fig 12.3 Weight relations between a steel and an aluminium beam, as a function of the ratio of the cross-sectional heights, are shown.

Thermal expansion

The elongation is calculated from:

$$\Delta l = \alpha \cdot (T - T_0) \cdot l_0$$

where α is the coefficient of expansion of the metal, T temperature and l_0 original length

Rule

The choice of best structural alloy and temper shall be made concerning the actual stress case. A relatively high ratio of $R_m/R_{p0,2}$ is desired in structures where there is a risk of total collapse in case of unintentional overloads. The same is true for structures where a passive reserve in the load-bearing capacity is wanted.

12.1.6 Thermal expansion

The coefficient of *thermal expansion* for aluminium is $24 \cdot 10^{-6}/^\circ\text{C}$, i.e. almost twice the value for steel. This must be kept in mind if aluminium is to interact with other materials. If the material is prevented from moving freely during temperature variations, coercive forces occur. These are calculated based on the temperature conditions at the time of installation. The reference temperature should always be indicated on the drawings.

Rule

Take into account temperature variations if they can give rise to coercive forces through external movement restrictions. Such limitations may arise from, e.g. stiffening walls or adjoining buildings. For statically indeterminate systems, residual stresses caused by temperature fluctuations must also be taken into account.

12.1.7 Relatively low hardness

Aluminium materials in soft conditions have relatively low *hardness*, which results in the risk of surface damage during assembly and handling. These damages can reduce fatigue strength.

Rule

Protect exposed parts from surface damage during assembly and handling.

12.1.8 Fatigue strength

The characteristic *fatigue* strength of aluminium materials is generally lower than the corresponding *static* strength. A dynamic loading case is considered to be present if the number of cyclic stresses is higher than 10^3 at fluctuating load ($R = 0$). (See Boverket's design rules, EKS or Eurocode 9, Fig 12.4).

Rule

A dynamically loaded aluminium structure shall be designed so that the cross-section where the highest stress amplitude can be expected is made of defect-free base material. Special considerations must be given to the geometric design. Notches, small radii, welds etc. reduce the dynamic strength.

12.1.9 Strength reduction through heat influence

Materials to be used in load-bearing aluminium structures have high strength by cold working (e.g. H14, H18) or heat treatment (e.g. T4, T6), see Chapter 6.

This means that the material only has limited thermal stability. Welding, hot straightening and hot forming can, therefore, give a local decrease in strength. The original strength is difficult to restore.

If there is a risk for instability, the heat-affected zone (HAZ) should be as far as possible from the critical buckling section. The width of the cross-section affected by heat should be restricted.

Rule

If welding or other heat treatment is needed for constructive or manufacturing reasons, the heat-affected structural part should be placed in an area with low stresses.

12.1.10 Corrosion resistance

Aluminium has excellent corrosion resistance because the metal surface spontaneously is coated with a protective oxide layer. That layer is very thin, about $0,01\text{--}0,1 \mu\text{m}$. Aluminium requires limited maintenance in the atmosphere and is suitable for outdoor use.

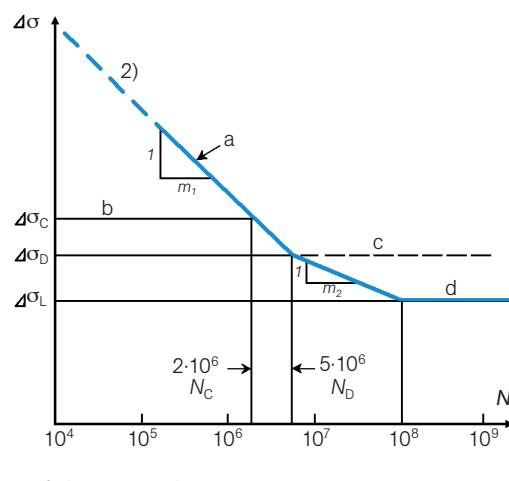


Fig 12.4 Fatigue design curve $\log \Delta\sigma$ - $\log N$, according to Eurocode 9.

Rule

Under normal conditions, aluminium structures can be used outdoors without special surface treatment.

12.2 Economic considerations

To obtain an economical aluminium construction, consider:

- the relationship between material cost and labour cost
- the functional adaptation to other components
- external operating conditions
- transport and assembly costs
- operating and maintenance costs
- adaptation to changed technical requirements

The goal of all project work is to fulfil all demands in the best possible way, i.e. to perform a total optimisation of the design.

The extrusion technology gives great freedom in the design of profiles, and adapt the thickness and dimensions of the material to the power flow and the nodes. It is often worthwhile to design precisely the aluminium profile needed. When it comes to steel profiles, there is a limited selection. Specially ordered steel extrusions are very expensive or cannot be made without more or less extensive welding, milling or other machining processes.

In the following, factors related to design optimisation are discussed.

12.2.1 Members under tension

Often, experience from steel structures is used when designing with aluminium.

At the same yield strength for aluminium ($R_{p0,2}$) and steel (R_{eL}), the weight ratio is 1:3. If the price of aluminium is assumed to be three times higher per kilo than the price of steel, it is often essential to reduce the material consumption and production cost. By designing with extrusions, these factors can be affected and usually reduce the total cost.

Structural members under tension are, e.g. found in truss systems. In these, the cross-section of the profiles is usually determined by the design of the nodes.

Members under compression

A slender aluminium member has a relatively high material usage per unit load capacity. This is because the buckling load is largely controlled by the elastic modulus.

Comparing an aluminium member and one of steel, both with the same cross-section and strength will give:

$$\lambda_{Al} = \sqrt{3} \cdot \lambda_{Steel}$$

λ_{Al} is the slenderness of the aluminium member and λ_{Steel} that of the steel member. This means that the slenderness of the aluminium member is about 1,7 times higher than that of steel. If the buckling length is quite short with $\lambda_{Al} < 0,2$, buckling has no effect, and the aluminium member weighs about one-third of that of steel and has at the same time the same load-bearing capacity, Fig 12.5.

If $\lambda_{Al} > 0,2$ the weight will increase for the aluminium member relative that of steel. If the length is constant, the second moment of area and probably the cross-sectional area must be increased to achieve the same bearing capacity as that of the steel member.

Example: Box-type profile

$$b = 100 \text{ mm}$$

$$l = 2000 \text{ mm}$$

$$N = 315 \text{ kN}$$

An aluminium tube of AW-6082-T6 requires a thickness of 5 mm. The corresponding section in steel requires 3,5 mm, which means that the steel profile has twice the self-weight compared to the aluminium tube.

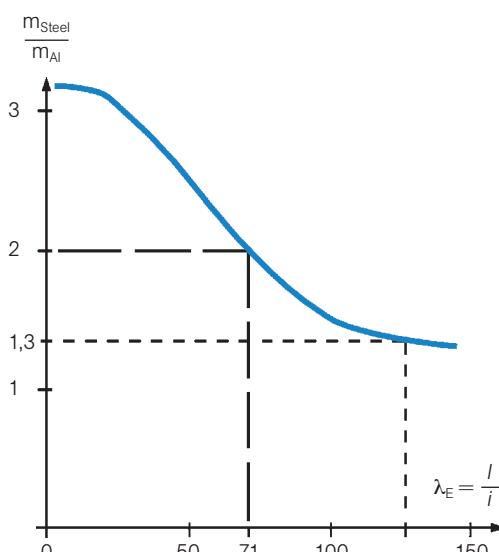


Fig 12.5 Weight comparison at the same slenderness factor λ for aluminium and steel members.

λ is here defined, according to Euler, as the buckling length (l) divided by the radius of gyration (i).

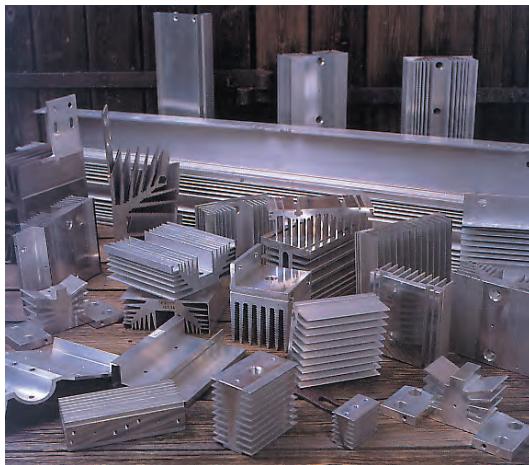


Fig 12.6 Heat sinks of aluminium profiles are often used for cooling electronic components.

For extrusions with open cross-section, e.g. I-profiles, there is a risk of torsional buckling. Here material savings can be achieved by choosing, e.g. an aluminium profile with a closed cross-section. The torsional stiffness of such a cross-section is considerably higher than the corresponding open cross-section, which implies more efficient material utilisation.

12.2.2 Members under bending

When comparing an aluminium and a steel member of equal cross-section and strength, and where the load consists solely of tare weight, the deflection will be identical and the weight of the aluminium member one-third of that of steel. If the tare weight is negligible compared to an external load, the deflection of the aluminium member will be three times that of steel. As compensation for aluminium's lower elastic modulus, the second moment of area can be increased either by redistribution of goods and an increase of the cross-sectional height or by increasing the area of the cross-section. Generally, the weight of an aluminium member is about half the weight of the corresponding member in steel (rule of thumb), Fig 12.2.

12.2.3 Special design

With the help of extrusions, very complicated and intricate cross-sections can be designed, where small wall thicknesses are possible, Fig 12.6. Profiles provide great profit opportunities because the second moment of area can be huge concerning the cross-sectional area. However, there is a risk with aluminium, which must be noticed, the threat of *instability* due to over-optimistic geometric design and relatively low elastic modulus. Instability, i.e. *buckling* or *tilting*, can occur in local parts of the cross-section or in the beam as a whole. The elastic modulus varies very little for different aluminium alloys. Therefore, be observant of fractures and dents when utilising the strength of high strength alloys, since the relationship between material stress and elastic modulus is highest here.

Small changes in the design can often be sufficient, Fig 12.7. The bracket at the top of the figure is made of steel. If the stiffening is thin and the bracket is made of aluminium, another placement of the stiffener can prevent buckling.

Fig 12.8 shows tilting. Here, the stiffness in the vertical plane is significantly high compared to the torsional rigidity. An extra torque can easily occur in asymmetrical profiles. The load then can get an incorrect position relative to the shear centre and give rise to an extra torque on the member. The phenomenon is shown on a simple, asymmetric profile, Fig 12.9. Control calculations should, therefore, be carried out in such cases.

In practice, there are only a few cases for which this type of deformation is relevant since the material stresses usually are moderate.

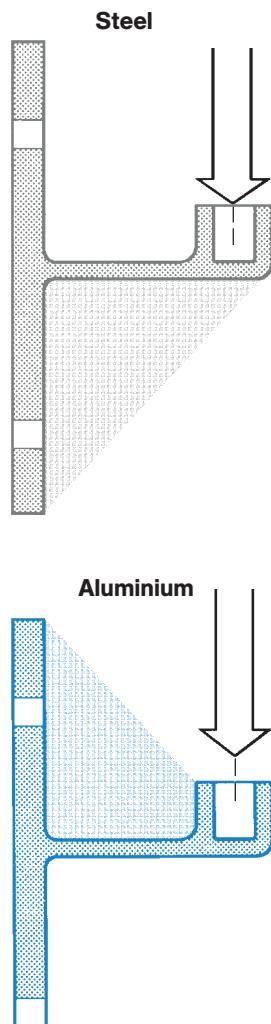


Fig 12.7 Design principles for steel and aluminium.

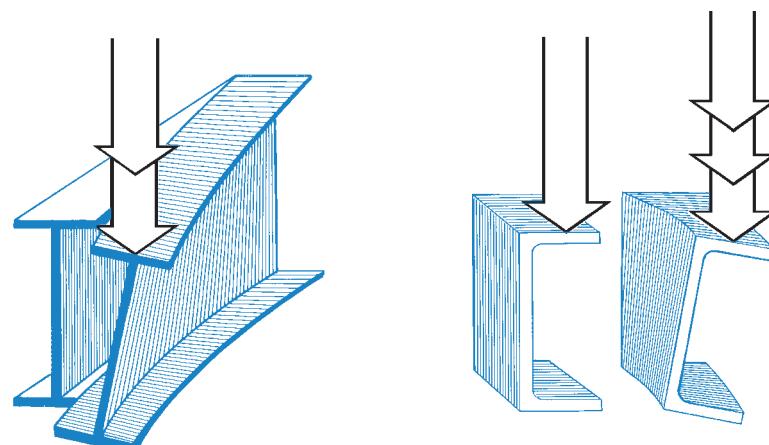


Fig 12.8 Tilting of a beam.

Fig 12.9 Control of the shear centre location.

The extrusion process provides an opportunity to combine bending stiffness of an I-profile and the torsional stiffness of a closed cross-section. This provides an optimal solution that is often economically defensible in small and large series.

12.2.4 Material costs

The costs for the aluminium material vary depending on:

- product type (sheet, strip, foil, profile, casting)
- alloy (heat treatable, non-heat treatable)
- temper (hard, semi-hard, natural aged, artificial aged)
- material thickness

In general, sheet metal in standard thicknesses is cheaper than extrusions, per kilogram.

Price relations

When choosing structural materials, take into account that the price varies for different aluminium grades. The price relationships for sheet metal in the thickness range of 1–3 mm are rough:

Pure aluminium AW-1050A-H14	100
Alloyed aluminium	
AW-5052-H14	112
AW-6082-T6	156
AW-2014-T6	224
AW-5754-F, checker plate	129
AW-5005-H14, anodising quality	129
AW-5005-H14, anodised, natural <20 µm	170–220
AW-3003-H44, lacquered on two sides, with protection foil	170

For sheet metal with particular demands for size and tolerance, price relationships may be different. For extrusions, the price varies with die size, but also with alloy and temper. It varies within broad limits in terms of shape, weight, dimensional tolerance and surface treatment.

12.2.5 Costs for extrusions

Aluminium extrusions are often economically competitive against other types of structural elements. While the price per kg is higher than for steel, this additional cost can be compensated by lower weight per unit volume, lower machining costs, maintenance freedom, longer service life and higher recycling value.

Pressing tools

One reason for using aluminium extrusions is the low cost of the pressing tool, the *die*. The price for new dies today is not higher than many companies order them for their prototypes. It is both cheaper and goes faster than prototype production in a conventional way by machining. Since small modifications can be done in the tool, many times the first die can also be used in serial production.

Typical tool costs are SEK 9 000–200 000 (EUR 820–18 200). Some examples of current tool prices are shown in Fig 12.10. The tool price, which is a one-off cost, includes correction, run-in and replacement tools at wear.

Finished profiles

Factors influencing the cost per meter of the final profile are:

- extrudability (speed m/min, freedom from defects)
- alloy (AlMgSi, AlZnMg etc.)
- weight per meter
- surface requirements, tolerances
- quantity

The designer has excellent opportunities here to affect the first four factors through a constructive design.

Extrudability

The extrudability is a measure of the efficiency, including pressing speed, with which the profile can be produced. It has a high impact on the total price.

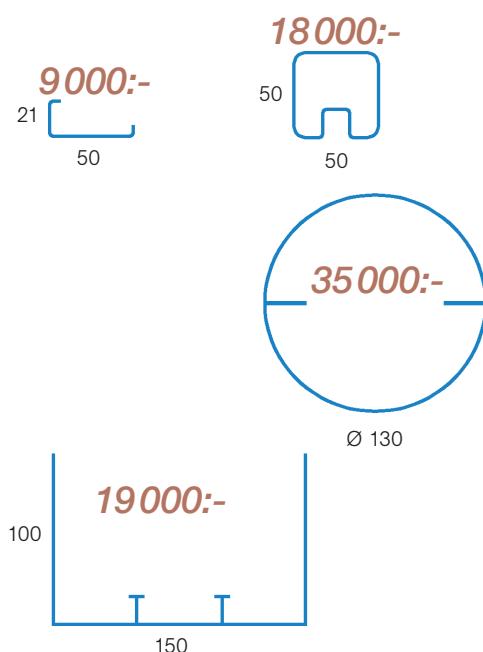


Fig 12.10 Example of tool costs in SEK year 2018.

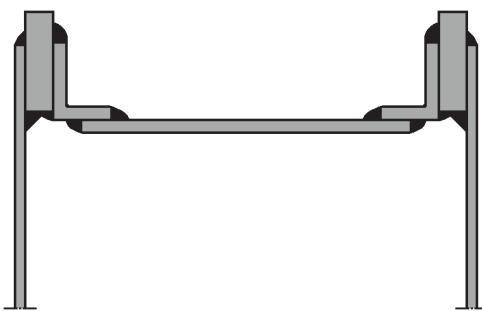


Fig 12.11 Door guide made of steel with 12 welds.

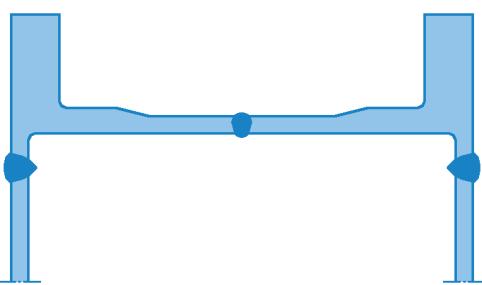


Fig 12.12 A similar guide made of aluminium extrusions. The number of welds is 3.

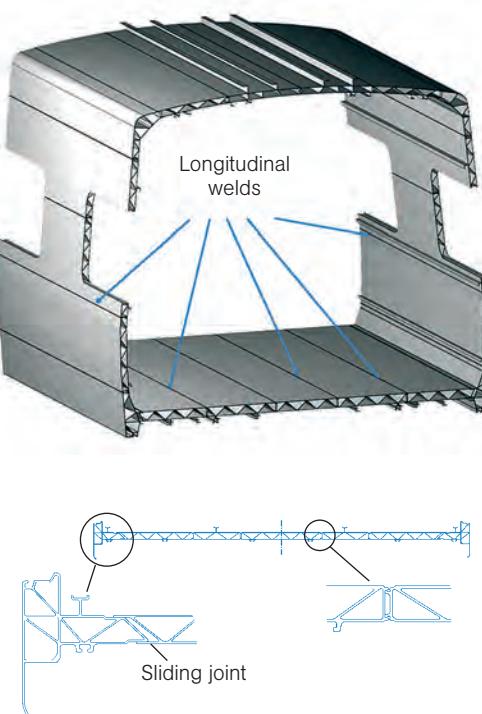


Fig 12.13 Large extrusions in a train wagon.

The wagons are made up of large extrusions that are welded longitudinally with MIG or FSW. Through a unique joint design, which allows the extrusions to slide into each other. Before the last weld is made, the right outer dimensions can be adjusted.

Alloy

Higher alloyed aluminium is more expensive and more difficult to press than, e.g. the lower alloyed AW-6060. Therefore, it is recommended not to choose an alloy with higher strength than necessary. In most cases, it pays to design a profile and press it into a less durable, but more lightly pressed alloy.

Tolerances and surface classes

Tight tolerances and high surface demands require careful control at all stages of the production, albeit resulting in higher production costs. Individual tolerances should thus be limited to the measures most significant for the function of the profile. The highest quality requirements should be carefully discussed with the manufacturer.

12.2.6 Cost comparisons of aluminium and steel structures

The following points can give guidance according to the cost estimations of an aluminium structure compared to a steel one:

- design
- processing costs
- final finished weight
- maintenance costs
- transport
- recycling value and scrap price

Design

A profile with complex shape can often be made directly in aluminium. Fig 12.11 shows a guide to a door. It is made of steel and consists of a large number of fillet welds and a mixture of thick and thin sections. The ready-made door requires a lot of adjusting work after welding. X-ray control of the welds is complicated to perform.

Fig 12.12 shows the same guide made of aluminium profiles. The three welds are butt welds and made of goods with equal thicknesses. The adjusting work is minimal. Control with x-ray, ultra-sonic and crack inspection can be performed easier in this case.

Processing costs

Aluminium has low resistance to plastic deformation compared to many other metals, which often results in lower processing costs.

Aluminium is also easy to machine with cutting tools. Use ordinary machines, e.g. turning lathe, milling cutter, band saw. Practically all chip-cutting devices work faster and cheaper in aluminium than in steel. High-speed machining is today widespread for aluminium. Up to 95% of an aluminium piece can be eliminated for the production of a complex component.

The costs of machining aluminium compared to steel is 30–70% for slightly complicated load-bearing structures. In some cases, they are below 30%. For aluminium, a profile is produced directly by extrusion, while for steel, both welding and machining must be used.

Final weight

The weight of an aluminium structure is usually 40–60% of the corresponding steel structure. The low weight gives cost savings both in transport and assembly, but also in the manufacturing of the object. Smaller trucks, cranes and traverses can be used; sometimes, they may even become unnecessary. In some case, the low weight alone can be the deciding factor for the economy of the construction.

Maintenance costs

Aluminium has excellent corrosion resistance in most environments. The maintenance costs are thus low. Therefore, painting need only to be done for decorative reasons.

Transportation

It is, of course, desirable that all transport vehicles could carry the maximum possible load to the lowest possible price. Examples of such cars in which aluminium is widely used are tank lorries and tank boats, which are used for the transport of liquids (oil, milk, water) or powdered goods (cereals, cement, plastic granules). Cryogenic (low



Fig 12.14 Spherical welded aluminium containers are used in vessels for the transport of liquefied natural gas (LNG) at -163°C or colder.

temperature) liquids are also transported in spherical aluminium tanks at -200°C to -160°C , Fig 12.14. They are mostly carried in aluminium tanks without risk of corrosion. Tank lorries, like other aluminium vehicles, can usually be used *unpainted*. However, some acids and alkalis and some liquid chemicals attack aluminium. For the best corrosion protection, *sacrificial anodes* of magnesium or zinc are used.

The constructive design does not differ significantly between tankers made of different materials. The cylindrical shape gives torsional and bending stiffness which are supported by internal bulkheads, either in the form of baffles or partition walls. The tank is made of welded aluminium sheet with longitudinal stiffening beams on the underside. These beams are made of aluminium extrusions.

The suitability of aluminium for transport vehicles depends, among others, on the strength of the material, the excellent corrosion resistance and the low weight. An example is safety cabins for trucks, which are built on a frame of aluminium extrusions, Fig 12.15.

The economic benefits of aluminium are, of course, the low weight, which means that more useful cargo can be transported per unit.

12.3 Rules of design

12.3.1 Design with aluminium extrusions

By "thinking in profiles", the designer has a unique opportunity to create a product that, from both a technical and an economic point of view, meets high standards.

Some benefits that can be achieved with aluminium extrusions are:

- small dimensions for parts and end products
- reduced number of pieces by integrating multiple functions
- high strength to weight ratio
- free choice of shapes
- great freedom in the selection of joining method
- short process time when machining
- easy and fast mounting
- good product design
- smooth, natural surface, suitable for surface treatment
- low maintenance and repair costs
- long service life due to minor corrosion damage
- high recycling value

Of course, the use of aluminium extrusions has its limitations. Examples of cases where extrusions may not be chosen are:

- the profile is too expensive to manufacture
- weight savings are insignificant
- the dimension tolerances of the profile are too coarse
- the largest dimensions and thicknesses of the profile are insufficient
- the strength of the profile is too low
- the finishing is too expensive
- the forming can be challenging to make
- casting is a more suitable manufacturing method
- The profile quickly solves a partial problem but becomes impractical or uneconomical as part of the final product

12.3.2 Place the goods where needed

To design a product part, it must be clear what functions it should contain. Based on this analysis, it is stipulated:

- where there must be goods
- where material can be saved

An aluminium profile can be designed with the metal exactly where it is needed. Expensive post-processing can largely be eliminated.

Details, which in other materials must be made of several components, can be pressed in one piece at a significantly lower cost and with better dimensional accuracy.



Fig 12.15 A safety truck cabin of aluminium profiles according to the so-called space-frame concept.

In a beam subjected to bending stresses, the goods are concentrated to those parts of the cross-section where it makes the best use, i.e. as far from the bending centre as possible. This compensates for aluminium's lower elastic modulus relative to steel.

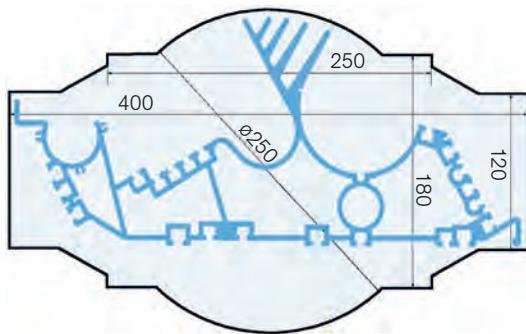


Fig 12.16 Aluminium extrusions can be manufactured in Sweden with the above maximum dimensions (in mm). What can be placed within the frame can usually be pressed.

12.3.3 Dimensional restrictions

The cross-section

In Sweden, extrusions are manufactured whose cross-section fits within the frame of Fig 12.16. For the most massive profiles, difficulties can occur at the pressing, if the cross-section is very complicated.

The thickness of the material

The minimum material thickness is determined by profile size, type and alloy.

The length

Generally, the profile length is maximised to about 17 m. For profiles with substantial weight per meter, however, the total weight of the profile is crucial. Standard delivery length to the customer is 6 m.

The weight

Profiles weighing up to 100 kg/m occur. The total weight of a profile is limited by the maximum weight of the press billet. In Sweden, profiles up to 30 kg/m are pressed.

12.3.4 Production views on the profile design

By carefully specifying which functions are to be built into the profile, the design should ensure that production costs are kept to the minimum.

A profile is easier to press if it:

- has equally thick goods
- have simple, soft shapes
- have a symmetrical shape
- fits in a circumscribed circle with a small radius
- lacks deep, narrow gaps

12.3.5 Profile design

The following pages show some examples of how aluminium extrusions can be designed. More information about design rules can be found in chapter 19, page 166 "Structural calculations" in the book "Design manual" from Hydro.

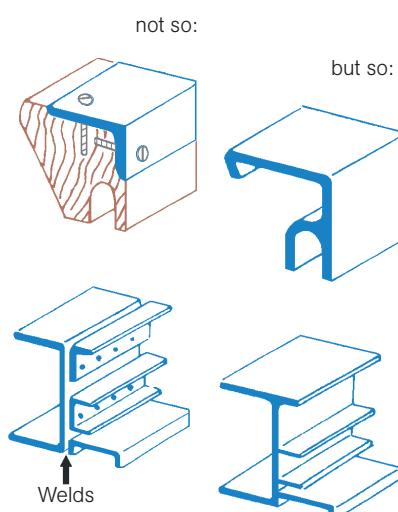


Fig 12.17 Concentrate the goods on the parts of the cross-section where it is most useful.

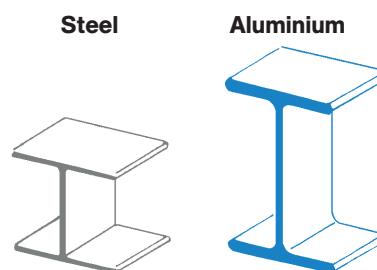
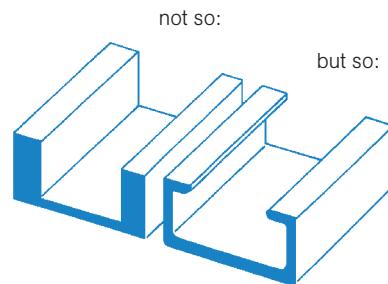
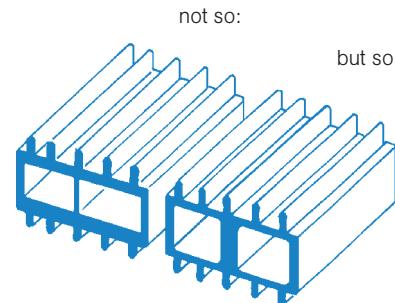


Fig 12.18 Comparison between steel and aluminium beams with the same bending stiffness. The height of the aluminium beam is just over 40% higher than that of the steel beam, but the aluminium beam still weighs only about 50% of the steel beam.

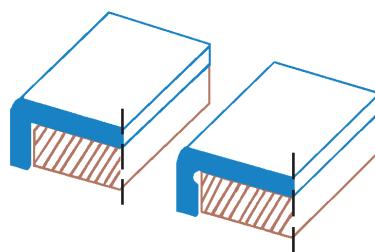
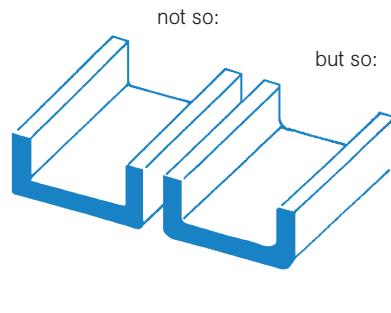
Make the profile walls equally thick



Thick walls are made thinner or thinner parts get more goods. In both cases, extreme loads are avoided locally in the tool.

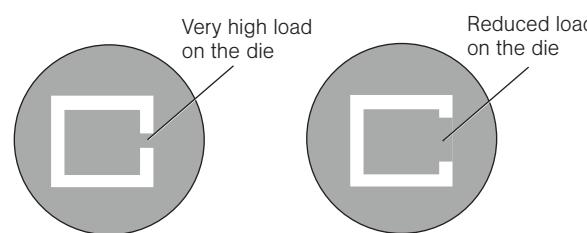
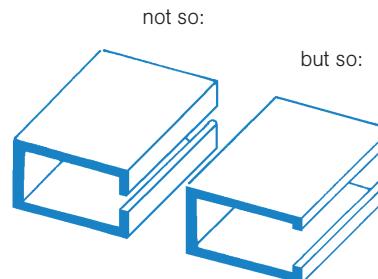


Avoid sharp corners



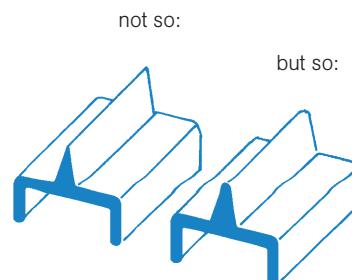
Where sharp corners are not required, the edges should be rounded. This is especially true in transitions from coarser to thinner goods. A radius of 0,5–1 mm can usually suffice. Sharp interior corners can sometimes be required for fitting another part.

Avoid excessive load on the die



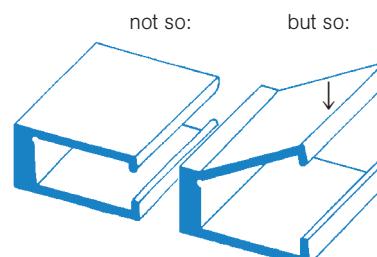
A deep, narrow gap in the profile corresponds in the die with a heavily loaded tongue. The depth-to-width ratio should not exceed the value 3.

Avoid sharp edges



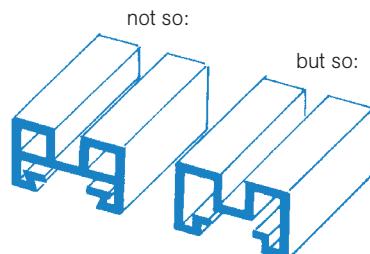
Sharp edges in the profile should be avoided. The tip can quickly become wavy and uneven.

Avoid deep, narrow gaps



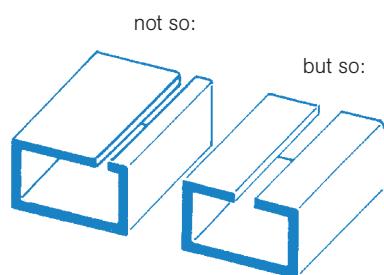
A slight modification of the profile design is sufficient to reduce the load on the tongue. A relatively common method is to press the profile with a larger opening, which after the pressing is rolled down to the desired dimension. The process also gives narrower tolerances on the gap measure.

Avoid hollow profiles



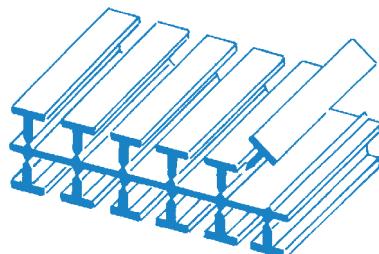
By choosing a massive profile instead of a hollow profile, it becomes cheaper (lower tool cost, less material and more comfortable manufacturing).

Make the profile symmetrical



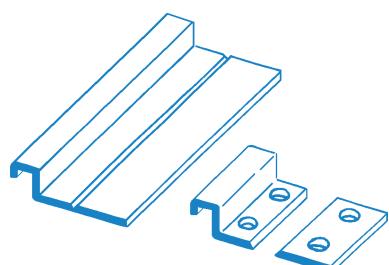
Especially semi-open profiles are easy to produce if they are symmetrical around any of the principal axes.

Profiles with extreme small cross-sections



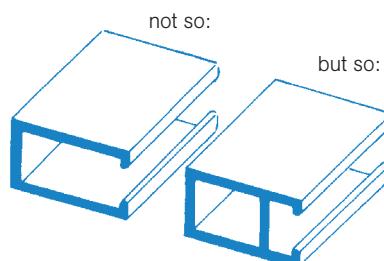
Profiles with a small cross-section result in low capacity utilisation in the press. They are challenging to handle and can easily be deformed and require a great deal of personnel effort at all stages of production. All this contributes to higher costs. Small profiles can advantageously be pressed on a break-off plate. The pressing, surface treatment and a large part of the machining can then be done very rationally. At the end of the manufacturing process, the profile breaks off from the plate, which goes into remelting.

Press two profiles in one with wide dimensions



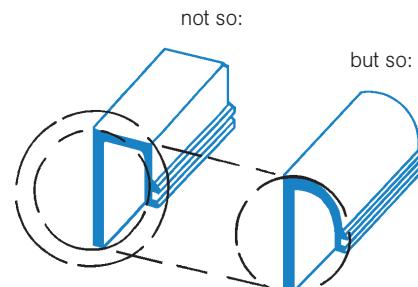
If two or more small profiles with different cross-sections are to be used in equal lengths, they can be pressed as a single profile and then be broken in two. The benefits are the same as in the image above. Besides, the shear plate is eliminated, and the tool costs are reduced, one tool instead of two.

Hollow profiles give better tolerances



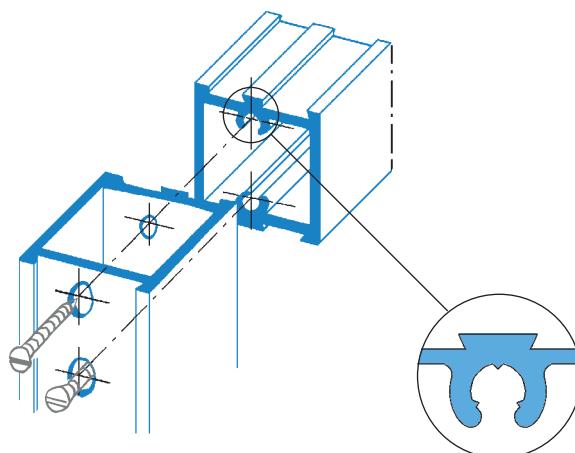
In this case, a transition to a hollow profile gives less load on the die. The support leg also provides smaller gap tolerances.

Decrease the circumscribed circle



With a smaller circumscribed circle, peripheral parts are moved closer to the centre of the die. This makes the profile more easily pressed. In some cases, the tool cost also decreases.

Screw ports



For corner joints in small and medium-sized structures, the screw port is an economical solution. The cost of traditionally drilling and threading a screw hole increases faster with the serial size than the price of the screw port. The port can be threaded in the usual way for machine screws, but can also be used directly for sheet metal screws or self-tapping screws. In the latter case, the port can be provided with three pins, see fig above, which makes it easier to turn the screw while releasing the requirements for individual tolerances.

Energy and environment



Fig 13.1 In addition to replanting during the restoration of mining areas, sowing of seeds collected in the area also takes place before the mining starts.

This chapter mentions a few aspects of aluminium from an environmental and energy point of view. A more detailed description can be found in the reports GeniAl from www.svensktaluminium.se.

13.1 Aluminium – a natural part of our environment

An entire 8% of the earth's crust consists of aluminium in the form of various minerals, primarily silicates (aluminium-silicon-oxygen compounds). Aluminium compounds are thus natural elements in our environment and occur in virtually everything that surrounds us, even in what we eat and drink as well as in our bodies. Aluminium is, after oxygen and silicon, the most common element in the earth's crust and is usually bound to oxygen and is included in, e.g. feldspar, mica and clay. According to the Swedish Environmental Protection Agency, the aluminium content in the Swedish soil is on average 7,1%.

Aluminium is described by the fact that a brick wall contains more aluminium than a wall of corrugated aluminium sheet. 1 m² of 6,5 cm thick brick contains 10–20 kg of aluminium in the form of alumina. 1 m² of 0,6 mm aluminium sheet weighs 1,6 kg.

13.2 Mining of bauxite

The primary material for the production of aluminium metal is essentially bauxite. While the average content of aluminium in the earth crust is 8%, workable bauxite contains 20–30% aluminium.

The access to bauxite is practically unlimited. It is found in a 5–20 m thick layer near the earth surface. 250 000 m³ of bauxite is mined to meet Sweden's annual production of aluminium. By comparison, the Swedish production of peat is more than ten times higher a year.

The annual global need for aluminium metal corresponds to about 50 km² land surface. About 20% of this area consists of rainforest. Mining of bauxite occurs near the ground surface and in climates that promote regrowth. The replanting is often regulated by national laws that ensure this is done in an environmentally sound way. The time for restoration of both plant and animal life is generally 10–15 years.

13.3 Manufacturing of alumina

In the production of alumina, according to the Bayer process, red mud is obtained as a residual product. The red mud sludge is generally stored in large drained basins. Alkaline drainage water is brought back to the process for both environmental and cost reasons. Today, most of the red mud is dried, deposited, and replanting can take place at the dump. Red mud is also used for purification of water and flue gases, for cement and cast iron production and as a soil improver.

13.4 Manufacturing of primary aluminium

Sweden's only plant for producing primary aluminium from alumina (oxide) is Kubal in Sundsvall. Substantial investments to increase energy efficiency in production and to improve the environment around the factory have been made, during the 2000s.

13.4.1 Energy requirements in manufacturing primary aluminium

In the production of aluminium from alumina, electrical energy is needed. About 16 kWh of electrical power and 60 MJ of thermal energy is required per kg of aluminium (from bauxite to metal). These figures also include the energy demand for transport and local heating.

In the social debate, it is often stated that the production of aluminium is "very energy-intense" compared to other materials. This is correct counting per kg, but often wrong if measured per functional unit, e.g. per m² of sheet area. Aluminium has a low density compared to many



Fig 13.2 The bauxite mining area in the foreground, in Australia, has been restored and is beginning to regain its original vegetation state. Already after ten years, the trees are 6–8 meters high thanks to the favourable growth conditions.

other materials, and the same function can often be achieved with a lower weight if aluminium is used.

13.5 Recycled aluminium as raw material

Besides primary aluminium, recycled aluminium from used products (scrap) or manufacturing waste is an increasingly raw material base for new products. The *recovery rate* is high, which is partly because the recycled metal is an excellent raw material with high economic value. Today, one-third of the total aluminium supply is recycled aluminium; in a few decades, it is estimated to be 50%.

The aluminium supply has multiplied many times since the mid-1960s. For some products (e.g. roofing sheets) it may take at least 100 years before they are scrapped and recycled. Today's share of recycled aluminium does not give a real picture of what degree of recycling can be obtained.

A challenge in recycling aluminium is more accurate scrap sorting. Alloying elements are easy to add but difficult to remove from the melt. Therefore, most of the recycled metal goes to the foundry industry, which can receive high alloyed aluminium. More careful sorting is a necessity for the sheet and profile sector to be able to increase the proportion of recycled aluminium in its products, Fig 13.4.

There are many remelt cast houses globally that are remelting both process scrap and end of life scrap of suitable alloys and producing high-quality products for extrusion or rolling mills. Therefore, it is crucial to create a system for scrap sorting by alloy or at least alloy group (first digit according to the alloying system in SS-EN), to let the material be remelted into the same alloy. It is also essential to plan for future recycling already when designing new products.

13.5.1 Low energy demand gives little environmental impact

When remelting aluminium, both energy demand and environmental impact are only about 5% of that of primary aluminium. This fact is, of course, a relationship that drastically affects a product's life cycle. With the help of Environmental Priority Strategies (EPS) system, the automotive industry has compared bonnets of different materials, where it is clear that the recycling of aluminium is of crucial importance.

13.6 Energy recovery

Thin, rolled aluminium foil is often used in packaging, not least in laminates with paper or plastic. Such packaging can, after its end-use, be utilised for energy recovery in a modern waste incineration process. The thin aluminium foil is burned and converted to oxide under strong heat generation. The heat value of aluminium is 30 MJ/kg, which is about the same as for coal, but twice as high as for biofuels, Fig 13.5.

In contrast, aluminium sheets and profiles do not burn because the mass is too large compared to the surface area. Aluminium roofs and walls meet the most stringent requirements of Swedish authorities and are classified as fire-proof surface layers, fire class 1.

13.7 Aluminium and our health

Aluminium is the most prevalent metal in the soil, which means that it is everywhere around us, but in small quantities. Even the food we eat contains aluminium, but usually only in harmless amounts. However, if cooking or storing acid food in aluminium containers, the aluminium content may increase slightly in that food. The human intake of aluminium from staple commodities in Sweden has been estimated at an average of 0,1 mg/kg body weight per week for adults. Knowledge of how much aluminium we get in total from food is inadequate. The "European Food Safety Authority" (EFSA) has set a "Provisional tolerable weekly intake" (PTWI) at 1 mg/kg of body weight per week. The value has been obtained through animal experiments with a safety factor of 300.



Fig. 13.3 In Sweden, 85,6% of all aluminium cans were recovered during 2018. However, this is a decline compared with the peak year 1996, when 92% of the boxes were returned for remelting.

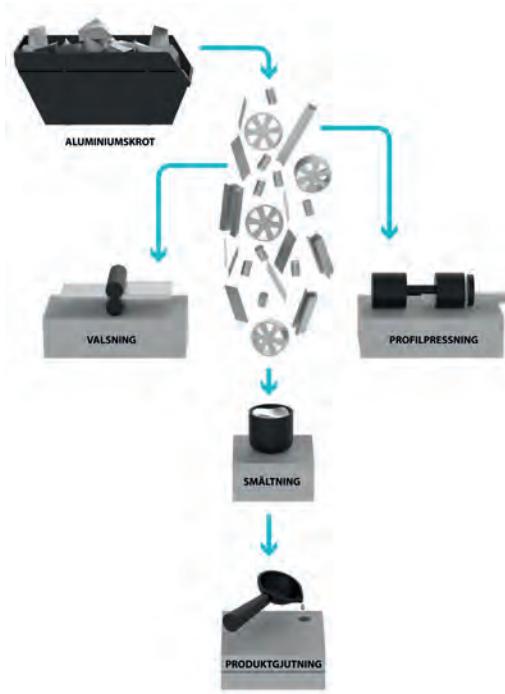


Fig 13.4 Aluminium in the eco cycle society.

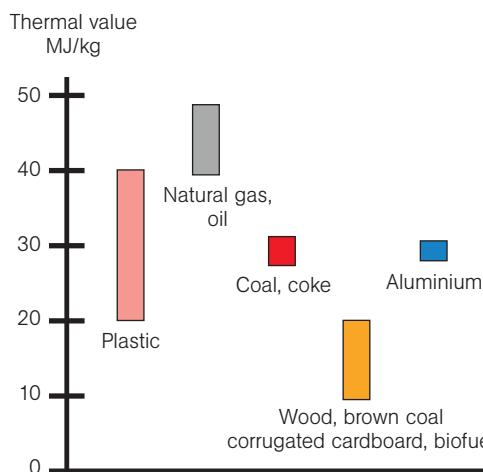


Fig 13.5 In combustion, aluminium provides as much energy like coal and coke and twice as much as paper. Also, no gaseous combustion products are formed. Only ash in the form of alumina is produced.



Fig 13.6 Steel generally has more significant deformation potential than aluminium. Therefore, most aluminium companies have developed "crash alloys" to absorb crash energy best.

Aluminium absorbs the crash energy so well that the material in a unique double hollow profile can be folded together at a collision - without cracking - to what looks like a squeezed accordion. The deformation capability is high. Steel is also deformed, but the exciting thing is the energy uptake per unit weight of the structure. More car designers now know that this is an area where aluminium gives more for the money.

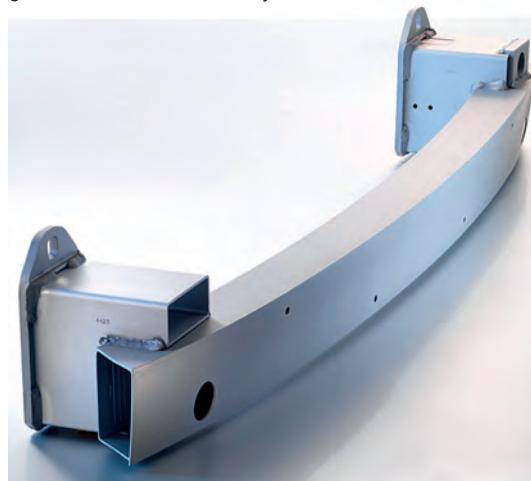


Fig 13.7 Crash-absorbing car bumper made of a customised aluminium profile. The bumper has excellent energy absorption, which protects both the driver and the passengers during a collision.

For millions of years, plants, animals and humans have adapted to our aluminium-containing environment. However, the combustion of coal and oil has disturbed the balance. This has led to an acidification of the 20th century with emissions of sulphur and nitrogen compounds. Increased leaching of aluminium ions into the soil has hurt fish and plants, among other things. But this has nothing to do with the production or use of aluminium products. That comes from the aluminium that is naturally found in our soil.

Research on the possible health effects of aluminium for people with normal kidney function has been concentrated on dementia, especially Alzheimer's disease. An expert group at EFSA in 2008 concluded that aluminium does not appear to be a risk factor for the development of Alzheimer's. In 2007, another international expert group found that the evidence of the relationship between aluminium and Alzheimer's is weak.

Craftsmen's exposure to aluminium-containing dust with microscopic dust particles and smoke from welding aluminium can affect health. This risk is avoided if a suitable respiratory filter or fresh air mask is used at the proper work stages so that the exposure level does not exceed the applicable limit values.

13.7.1 Health effects

Exposure to aluminium can cause lung fibrosis, *aluminous*. In the development of this pneumoconiosis, the exposure has usually been a mixture of aluminium and silicon, so it is unclear if it was only aluminium that caused the lung disease. In aluminium smelting plants, an increased incidence of so-called obstructive pulmonary disease is noted. These problems may also be due to other contaminants in this work environment.

13.7.2 Circulation in the body

When exposed to aluminium, the absorption occurs via the inhalation. The removal of aluminium from the body, after a brief exposure, takes place with the urine. Aluminium has a biological half-life of about 8 hours. For prolonged intensive exposure, aluminium can accumulate in the skeleton. However, the departure from skeletal deposits is slow with a half-life of several years.

13.7.3 Hygienic limit values

The hygienic limit values for aluminium in vocational exposure are set according to the lung effect as a critical effect. The threshold limit value for inhaled aluminium dust is 2 mg/m³.

13.8 Aluminium in passenger cars

The total aluminium content per vehicle will grow from 2016 to 2025. Most of the growth is expected to be sheet metal components, especially for hang-on parts (shutters, doors, bonnets, etc.).

- Based on the forecast, the aluminium share per vehicle increases to almost 170 kg in 2020 and about 195 kg in 2025.
- The use of aluminium car sheet is expected to increase by 110% over the next ten years.
- The difference between optimistic and pessimistic forecasts is mainly due to the rate of introduction and the use of aluminium for hang-on parts, load-bearing parts and chassis plus suspension parts.
- Much of the growth is due to an expected increase in aluminium vacuum die-castings, replacing the steel forging (subframes, shock absorbers) in the body and chassis.
- Aluminium growth will fluctuate according to the ability of car manufacturers to meet emission requirements and with future changes in European carbon dioxide regulation.



Fig 13.8 The amount of aluminium in an average car has increased from 50 kg in 1990 to today's 150 kg. Experts predict that this could increase to 195 kg by 2025. Aluminium in vehicles is an excellent example of the circular economy. More than 90% of the metal is recycled after the car's life cycle and is reused to create new aluminium products.

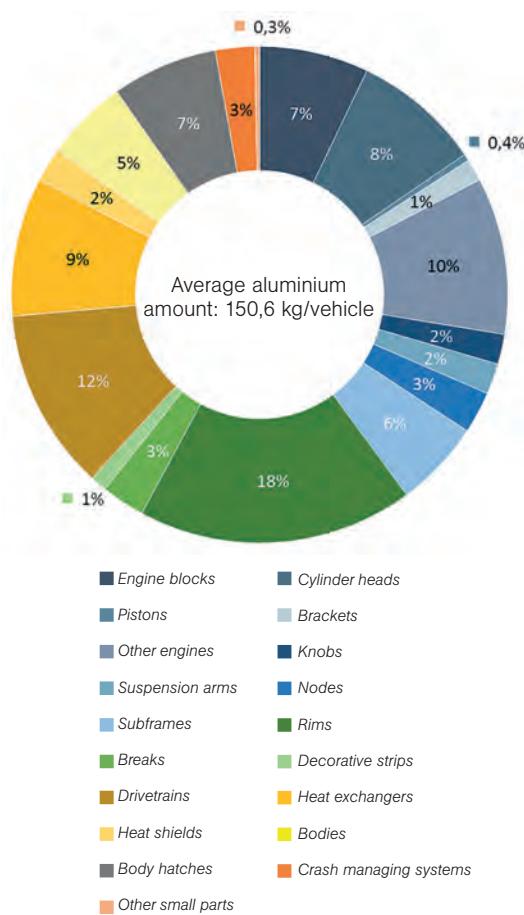


Fig 13.9 European car production - Weight distribution of components.
Although the most strong focus is on an aluminium sheet for body and hatch, the proportion of castings, between drive-line and wheels, is almost 50% of the total aluminium content.

– Forecasts for the aluminium share for a given year are based on information on vehicle production of upcoming models. Changes to updates of one or more models can have significant effects on the average amount of aluminium in a given year.

– If e.g. a car manufacturer plans to convert a specific model to aluminium shortly after 2020, it will not be included in the 2020 forecast but only in the forecast for 2025.

The average aluminium content per vehicle varies from 62 kg for a Smart Fortwo, up to 610 kg for a Range Rover Sport.

Table 13.1 Cost-effective analysis

Aluminium can replace steel in passenger cars. Many modern vehicles include pistons, engine blocks, bumpers, bonnets, luggage lids, doors, radiators, fuel tanks, crash boxes, rims and fuel filler pipes, all in aluminium. Space-frame is a modern way of building aluminium cars.

Suppose a car loses weight by 100 kg due to the use of aluminium, which results in lower fuel consumption. This leads to both a reduction in exhaust emission and a reduction in total energy consumption.

Replace 200 kg steel with 100 kg aluminium. These figures are realistic and based on the automotive industry's experience. The energy contribution will then be:

$$\begin{array}{rcl} \text{Aluminium} & 100 \cdot 94,4^1) = & 9440 \text{ MJ} \\ \text{Steel} & 200 \cdot 30 = & -6000 \text{ MJ} \\ & & 3440 \text{ MJ} \end{array}$$

We assume the following data for the use of the car:

- mileage totaling 200 000 km (15 000 km/year for 13,3 years)
- 100 kg weight loss reduces gasoline consumption by 0,0046 litres/km
- the energy content of the gasoline is 36 MJ/litre

The energy savings during the life of the car will then be:

$$0,0046 \cdot 200\,000 \cdot 36 = 33\,120 \text{ MJ} (2490 \text{ MJ/år})$$

Total energy gain becomes $33\,120 - 3\,440 \text{ MJ} = 29\,680 \text{ MJ}$. The additional energy contribution, 3 440 MJ in the manufacture of the car, takes almost 1,5 years to earn. Then it is a pure energy gain.

Carbon dioxide emissions during production:

$$\begin{array}{rcl} \text{Aluminium} & 100 \text{ kg Al} \cdot 6,0 \text{ kg CO}_2/\text{kg Al} = & 600 \text{ kg CO}_2 \\ \text{Steel} & 200 \text{ kg steel} \cdot 1,8 \text{ kg CO}_2/\text{kg steel} = & 360 \text{ kg CO}_2 \end{array}$$

The carbon dioxide emissions will thus be 240 kg higher when switching to aluminium.

Reduced emissions of carbon dioxide when driving over the lifespan of the car (litres/km · (total mileage) · emission factor²⁾ in kg CO₂/litre):

$$0,0046 \cdot 200\,000 \cdot 2,85 = 2620 \text{ kg CO}_2$$

The profit over the car's lifespan will be:

$$2620 - 240 = 2380 \text{ kg CO}_2$$

With 4 000 000 cars in Sweden, a reduction in CO₂ emission of 0,72 Mton/year is achieved. This is about 1% of the total CO₂ emission in the country.

1) The energy requirement for the production of primary aluminium is 132 MJ/kg and 6,6 MJ/kg for recycled aluminium. Cars include both primary metal and recycled metal, hence the above-average values. Here, 70% of primary metal and 30% of recycled metal have been adopted.

2) The emission factor varies between 2,33 and 2,95 kg CO₂/litre gasoline depending on the most conservative and the most optimistic approach. 2,85 has been used here.

3) If all copper wire were replaced with aluminium-zirconium wire in a car, the weight would be 12 kg less.



