The Metal Aluminium

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GDA GESAMTVERBAND DER
ALUMINIUMINDUSTRIE e.V.

Contents

This document is intended as an introduction to the fascinating world of aluminium. More detailed information can be found in other Technical Informations published by the former Aluminium-Zentrale, which is now part of the GDA trade association, or Aluminium-Handbook. GDA/Aluminium-Zentrale is able to deal with specific technical questions thanks to an extensive library and literature relating to the subject of aluminium, some in the form of specialist publications.

1. Introduction

Aluminium was first extracted on an industrial scale in 1886 using fused-salt electrolysis. It rapidly developed into one of the most important of the widely used metals. There are several reasons why aluminium is regarded as the most versatile of all metals:

- There is a wide range of standardised and non-standardised casting alloys. Aluminium is suitable for all known mould-casting processes. Particular mention should be made of pressure die casting. Modifications to this casting process, with the aim of achieving improved mechanical properties or a more-rational method of production, have been successfully introduced on an industrial scale.
- Aluminium is well suited to the usual hot and cold metalworking processes such as rolling, drawing, impact extrusion, forging, etc. In addition, aluminium and many of its alloys offer excellent **extrudability**. Thanks to the wide range of possible forms of extruded profile, it is possible to produce cost-effective and elegant design solutions.
- Unalloyed aluminium is very readily formable and can be rolled to very **thin foils**.
- Aluminium alloys are formable, and sometimes even undergo **superplastic forming**.
- A number of aluminium engineering alloys have mechanical strength properties that partially exceed those of construction steels; thus, aluminium opens up a wide range of possibilities in the field of **lightweight supporting** structures.
- Aluminium is suitable as a matrix for high-strength fibre composites.
- In addition to pyrotechnic applications, aluminium powder is used as a pigment for metallic paints and is the starting material for powder metallurgical applications.
- The **surface treatments** made possible by anodising, also in combination with brightening, create a wide variety of durable, decorative and highly reflective aluminium surface finishes (with a natural look or coloured); these surface treatments are in addition to the usual organic and inorganic coatings and other types of surface treatment.

- Refined aluminium and some aluminium alloys that have been optimised for use in electrotechnical applications are better **conductors of electricity** than copper alloys on a weight-for-weight basis.
- Thanks to its very good **thermal conductivity**, aluminium is suitable for making heat exchangers, e.g. for lightweight radiators and oil coolers in motor vehicles and air conditioners.

In addition, aluminium and its alloys are characterised by:

- non-toxicity and absence of potential health risks
- non-magnetic behaviour
- high reflectance, even with untreated surfaces, especially with respect to thermal radiation.

The term 'aluminium' is generally used to describe all aluminium-based materials, including both unalloyed aluminium and aluminium alloys. However, both terms are clearly defined by standards: (unalloyed) aluminium is a metal that contains at least 99.0 wt% Al, with the amount of every other metallic element in the aluminium being subjected to a specific upper limit. Aluminium alloys are split into two groups: **wrought alloys** are used for the production of sheet and strip, extruded products such as profiles, tubes, bars and rods, forgings and impact extruded parts, etc.; **casting alloys** are used for the production of castings.

In standards, the term 'refined aluminium' is used for a metal with at least 99.95 wt% Al. The term 'primary aluminium' is used to describe aluminium produced by the electrolytic decomposition of aluminium oxide. The term 'secondary aluminium' usually refers to aluminium alloys produced from (mixed) used scrap and process scrap; they are usually used as casting alloys for mould casting.

2. Raw materials and deposits

Aluminium does not occur naturally in metallic form. It is the third most abundant element in the earth's crust after oxygen (46.8 %) and silicon (25.8 %), with an 8 % share (iron comprises some 5 %, magnesium approximate 2 %, copper and zinc each approx. 0.01 % and tin approx. 0.004 %). Bauxite is used almost exclusively for the extraction of aluminium. The bauxite used for the commercial extraction of aluminium is a red coloured sedimentary rock, and has the following compositions:

Aluminium oxide	(Al_2O_3)	approx.	60 %
Iron oxide	(Fe_2O_3)	up to	30 %
Silicon oxide	(SiO_2)	up to	5 %
Titanium oxide	(TiO_2)	up to	3 %
Combined water (loss on ignition)		up to	30 %

Aluminium is present in bauxite in the form of hydroxides, either as $Al(OH)_3$ or $AlOOH$. Other raw materials, which are of little interest for extraction commercially, are clay and the silicate-based minerals kaolin, andalusite, nepheline, labradorite and leucite as well as the alkaline potassium-aluminium sulphate alunite. Mined bauxite deposits are located all over the world (Fig. 1).

Seen from today's perspective, economically mineable deposits will meet the demand for some further 200 years.

Bauxite deposits currently being mined worldwide (Fig. 1)

Bauxite production in 1999 in million tonnes
Deposits worldwide 1996: approx. 25bn tonnes*
Total production in 1999: 116m tonnes

Russia 3.4
Europe 2.1
Kazakhstan 3.4
PR China 9.0
USA 0.1
India 5.9   Malaysia 0.2
Jamaica 12.6
Surinam 3.9   Guinea 17.0
Venezuela 4.8   Guyana 2.2   Ghana 0.4
Brazil 11.7
Indonesia 1.0
Australia 44.5

*From today's viewpoint, economically mineable deposits will last another 200 years.

3. Aluminium extraction

Aluminium has a strong tendency to react with oxygen, which means it is not possible to use the usual reduction processes. The production of aluminium on an industrial scale takes place in two stages:

1. Extraction of aluminium oxide (alumina) from bauxite (a clay mineral)
2. Reduction of the oxide using fused-salt electrolysis to produce metallic aluminium

Other extraction technologies have not achieved any commercial significance; they include carbothermic reduction, the electrolysis of aluminium chloride (Alcoa process) and the extraction from aluminium chloride via reaction with manganese (Toth process).

3.1 Extraction of aluminium oxide

The Bayer process is the most important process for producing aluminium oxide (Fig. 2). It involves crushing the bauxite and mixing it in exact quantities with so-called 'digestion liquor' (caustic solution taken from the production loop) having a concentration of 200 to 350 g Na_2O/l and continuously breaking it down in autoclaves at 120 to 230 °C. Aluminium oxide dissolves to form sodium aluminate and the solution becomes more and more concentrated. The sodium aluminate liquor is transferred to a thickener.

The non-soluble components of the bauxite (iron oxide, titanium oxide and most of the silicon oxide) are separated out from the digestion liquor at about 90 °C, washed in counterflow and dumped as 'red mud' or possibly processed further.

After clarification, the sodium aluminate liquor is cooled to 60 °C and 'seeded' with aluminium hydroxide from the production process in precipitators (up to 1400 m^3 in size). This causes aluminium to precipitate out as aluminium hydroxide; most of the aluminium has precipitated out after 60 to 120 hours and the precipitate is separated using a vacuum filter. The remaining caustic solution, which contains the rest of the dissolved aluminium, is subjected to evaporation and returned to the production loop as digestion liquor. The aluminium hydroxide is carefully washed and then calcined to aluminium oxide (Al_2O_3) by heating it to a temperature of 1200 to 1300 °C in a rotary kiln (up to 3 m in diameter and up to 70 m long) or using a fluidised-bed process (the H_2O in the hydroxide is driven off). The aluminium oxide contains Fe_2O_3 and SiO_2 (each about 0.01 to 0.02 %) and up to 0.5 % Na_2O as impurities.

3.2 Aluminium extraction using fused-salt electrolysis

The commercial-scale reduction of aluminium oxide to metallic aluminium is then carried out exclusively using fused-salt electrolysis in a continuous process. The aluminium oxide is dissolved in a bath containing cryolite (aluminium sodium fluoride, Na_3AlF_6) at a temperature of 950 to 970 °C, with a maximum Al_2O_3 concentration of 5 to 7 %. The formation of aluminium leads to the bath becoming diluted in Al_2O_3, which thus has to be replenished at regular intervals to maintain the desired concentration. The metal produced is drawn off regularly.

Extraction of alumina (Fig. 2)

The Bayer process

Aluminium electrolysis (Fig. 3)

The electrolysis cell

Alumina

Electrolytic bath

Molten aluminium

Anode

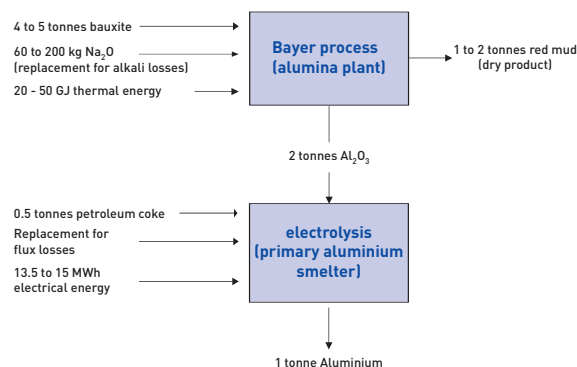Cathode

4 to 5 volts
150 to 170 kA

A large number of individual electrolysis cells, which are also known as 'pots', are connected in series. The voltage of each cell is 4 to 5 volts. The number of cells then determines the direct current voltage needed. The amperage is 150 to 170 kA. The alumina-reduction cells are refractory lined steel boxes, which are lined with graphite (Fig. 3); the power supply to the cathode (cathode = negative pole) is also embedded in this lining. Graphite is used for the anode (positive pole) as well; it is consumed by reaction with the oxygen resulting from the decomposition of aluminium oxide to form gaseous CO_2 or CO. The simplified reaction equation is:

$$2Al_2O_3 + 3\,C \rightarrow 4Al + 3\,CO_2$$

The raw materials, auxiliary materials and energy needed to produce a tonne of primary aluminium (refined aluminium) are shown in Fig. 4. The electrical energy required has a strong bearing on the choice of the location of primary aluminium smelters. Norway has become western Europe's largest aluminium producer because of the widespread availability of water power as a source of low-priced hydroelectricity. In addition to the energy supply, transport considerations also influence the choice of location.

Energy requirement for the extraction of aluminium (Fig 4)

The total energy requirement (thermal and electrical) is 162 GJ/t [*]

4 to 5 tonnes bauxite

60 to 200 kg Na_2O (replacement for alkali losses)

20 – 50 GJ thermal energy

Bayer process (alumina plant)

1 to 2 tonnes red mud (dry product)

2 tonnes Al_2O_3

0.5 tonnes petroleum coke

Replacement for flux losses

13.5 to 15 MWh electrical energy

electrolysis (primary aluminium smelter)

1 tonne Aluminium

[*] Lifecycle Assessment of Packaging Materials. Status as of 1990. Issued by the Swiss Agency for the Environment, Forests and Landscape (SAEFL), Berne 1991

4. Aluminium products and available forms

4.1 Primary aluminium

The aluminium produced by electrolysis is called primary aluminium. It is the starting material for the production of semi-finished products (sheet, strip, tubes, profiles, etc.) from aluminium and wrought aluminium alloys. Primary aluminium is also the starting material for cast alloys used to make particularly demanding products, such as car wheels and chassis parts ('safety components').

In the smelter's in-house foundry, the molten raw metal is treated in order to meet the required specification. It is:

- alloyed, i.e. alloying elements are added either directly or in the form of master alloys (DIN EN 575) to obtain the desired chemical composition. Master alloys contain up to 65 wt% of the alloying elements.
- cleaned (using drossing fluxes or filter)
- degassed
- cast to ingots (or possibly to shapes)
- It might also be marketed as molten metal.

The technical terms used in connection with primary aluminium are:

Remelting ingots (DIN EN 576). These are either cast into open moulds in the smelter's integrated foundry or continuously cast horizontally. The ingots follow one of two different routes:

- They are melted down in the shape-casting foundry in order to make castings.
- Shapes, such as rolling ingots, extrusion billets, etc., are usually cast in the semis plant's in-house shape-casting foundry.

Shapes is the generic term for rolling ingots (DIN EN 487), extrusion billets (DIN EN 486) and cast forging stock (DIN EN 604). They are the starting material for the manufacture of semis and are produced using a (vertical) continuous casting process called 'direct chill (DC) casting' (Fig. 5). Busbars with a large cross-section are usually manufactured using a horizontal continuous casting process.

- **Rolling ingots** have rectangular cross-sections (up to 0.6 x 1.8 m). They can be up to 6 m long and weigh up to 14 t. Some large rolling mills can produce and/or process cross-sections up to 0.6 x 2.25 m, up to 9 m long and weighing up to 30 t. Rolling ingots are the starting material for sheet, strip and foil.
- **Extrusion billets** are the starting material (stock) for extruded products (profiles, bars and rods, tubes, wire). Most extrusion billets have a circular cross-section; the diameter is rarely less than 80 mm and in the majority of cases it is in the range 300 to 500 mm; it is some-

times over 600 mm, and can be up to 1000 mm in the case of forging ingots (see below). Cylindrical hollow billets (e.g. 510 mm external diameter, 160 mm internal diameter) are used to make tubes by forcing the metal over a mandrel. Large profiles with cross-sections up to 800 mm wide and a relatively small cross-sectional height (up to 100 mm) are made from rectangular billets.

- **Cast forging stock** is produced in a continuous casting process to the requirements of the forging plants with diameters up to 1 m. However, most die forgings are made from cut-off lengths of extruded rods.
- **Cast strip** is the starting material for sheet and strip and impact-extruded parts; it is produced on various types of continuously operating casting and casting-and-rolling machines.
- **Continuously cast and rolled rod** (drawing stock, Properzi-type wire) is produced using special casting machines that operate continuously. Like extruded wire, this is also used as the starting material for drawn wire.
- **Aluminium grains** (lentil-shaped up to 15 mm in diameter) are mainly used for deoxidising steel.
- **Aluminium pellets** are metal particles up to 3 mm in diameter. In addition to being used in steel deoxidation they are also used as a reactant in the chemical industry, as a filler for plastics and for aluminothermic applications.
- **Molten metal** (DIN EN 577) is transported to foundries in special vehicle-mounted containers that contain about 3000 kg of aluminium. This approach is becoming increasingly widespread because it saves energy compared with having to remelt ingots.

4.2 Secondary aluminium

New and used aluminium scrap is the starting material for the production of secondary aluminium (or secondary aluminium alloys). So-called 'secondary smelters' process (mixed) used aluminium scrap or process scrap (scrap produced by aluminium processing plants) to secondary aluminium alloys; see also section 12.1.2. These alloys are supplied to foundries as ingots for remelting or as molten metal; the foundries produce castings, which have found widespread use in the automobile industry. Secondary smelters also produce grains.

Schematic representation of the direct-chill casting process (Fig. 5)

A water-cooled collar comprises the mould (chill mould). The cooling water exits the mould via holes drilled on its lower inside edge in such a way that the metal that solidifies on this wall is cooled to room temperature. The mould is closed at the bottom by a loose-fitting base, which is mounted on a retractable stool-cap. Casting several billets or rolling ingots at the same time can increase the economic efficiency. It is also possible to cast hollow billets.
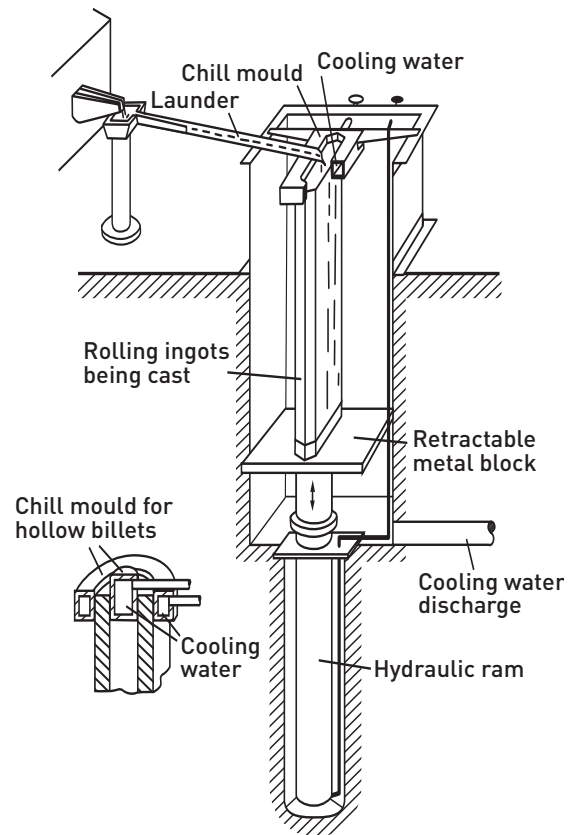
Production of aluminium semis and castings (Fig. 6)
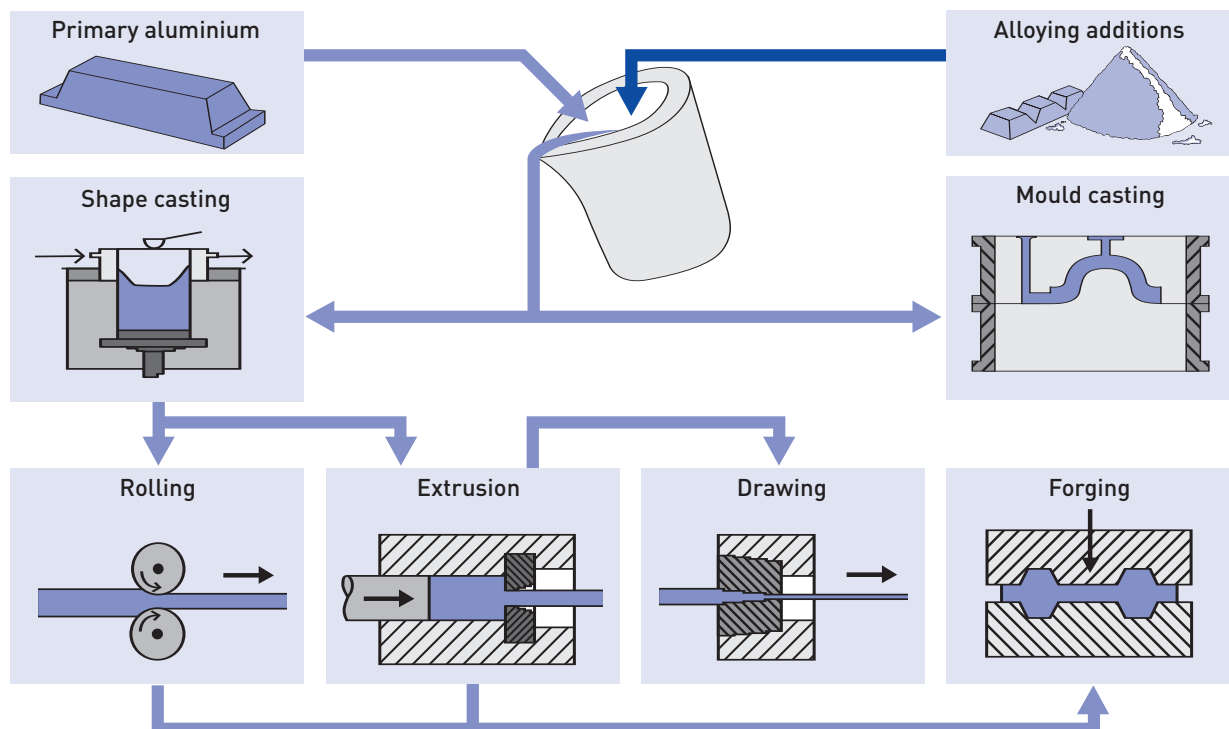
If wrought aluminium alloy scrap is available as carefully sorted fractions, it can be used again directly for semis manufacture. An example of this is the aluminium beverage can, which is recycled in very large quantities worldwide. At least in those countries with high recycling rates and separate collections for used beverage cans (USA, Sweden, etc.), recycling fulfils its prime objective: "A can becomes a can once again."

4.3 Aluminium semis

'Semis' is the term used to describe products made by the hot and/or cold working of shapes (extrusion, forging, hot and cold rolling, drawing). A characteristic of these processes is the way the material is deformed, or worked, so the aluminium alloys that are suitable for processing in this way are called **'wrought' alloys** (DIN EN 573).

Thanks to its excellent workability, aluminium offers the largest range of possible designs. Aluminium semis are the standard material for a vast array of applications. This ranges from foil 6 µm thin and 2 m wide to plates several metres wide for use in the shipbuilding or aircraft industries or in process engineering, and from 0.8 mm thick tubes for the diamond styluses of record players to the 800 mm wide extruded profiles for modern high-speed trains. In particular, extrusion is one of the special features of aluminium because in a single process it facilitates the economical manufacture of the most complicated cross-sections, with excellent surface finishes and high dimensional accuracy.

4.3.1 Rolled products

Rolling is the process commonly used for producing aluminium strip, sheet and foil. Before the metal can be hot rolled, the skin formed during casting has to be removed from the ingot, which is then heated to the rolling temperature in a furnace. An emulsion is used for cooling during rolling and there is a large reduction in thickness per pass. Depending on the requirements for dimensional accuracy and properties, hot rolled strip can be rolled further in a cold mill either to thin strip or foil, or cut into sheet. The properties and technical terms of delivery for aluminium alloy strip and sheet are covered by national and international standards (DIN EN 485).

4.3.2 Extruded products

Unlike any other process for producing semis, the extrusion of aluminium alloys enables the most varied range of shapes to be produced, from simple solid profiles to complicated hollow sections. However, attention must be given to the limitations that result from the process-specific features of the extrusion process. Profiles with large variations in cross-section or wall thickness or those with webs that are extremely thin or wide in comparison to the overall cross-section require considerable effort when preparing the tooling and during extrusion and straightening. The available profile sizes (DIN EN 755 and DIN EN 12020) depend on the material and the diameter of the circumscribing circle. One must adhere to the minimum wall thicknesses and minimum radii for transitions.
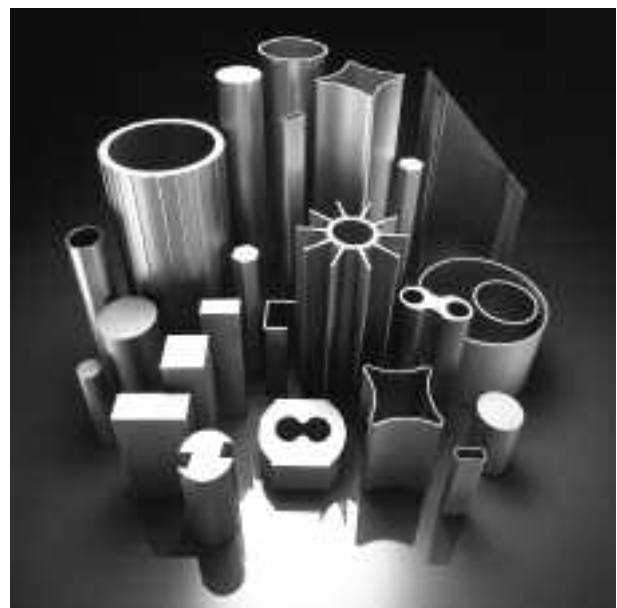
Extruded products (Fig. 7)

4.3.3 Drawn products

The starting material for cold drawing are extruded bars and rods and tubes, or extruded, rolled or cast drawing stock (mostly continuously cast and rolled in the case of refined aluminium and low-alloyed materials). Though it is possible to redraw extruded profiles cold, it is uneconomical and therefore not performed in practice.

Drawn products with details of dimensions are covered by both national and international standards (DIN EN 754).

4.3.4 Forgings

The usual size range for hand forgings is a maximum length of 5 m, with a width of up to 2 m and a surface area of up to 2 m². Die forgings, such as wheels for cars and lorries, or structural parts for aircraft or vehicles, are characterised by high strength and toughness and are thus preferred for highly stressed safety components.

4.4 Aluminium composites

Aluminium can be combined with other materials (metallic or non-metallic) in various non-soluble ways to produce composites. When aluminium is combined with metals such as steel or copper alloys, it is possible, and common practice, to use pressure welding (roll bonding, explosion welding), continuously reinforced extrusion (busbars, Fig. 8) or friction welding.

Two-dimensional combinations of aluminium with a non-metal (e.g. plastic, wood) to form sandwich elements are obtained by adhesive bonding or filling the space between two outer aluminium layers with foam (Fig. 9).

Pistons for diesel engines capable of withstanding high thermal stresses are the best-known example of a composite of aluminium and ceramic fibres or particles used in series production. These pistons are partially strengthened near the bottom of the piston by placing a preformed ceramic-fibre insert in the mould and then filling this with molten aluminium under pressure.

Busbar (Fig. 8)

A composite extruded aluminium busbar with stainless steel cover for Vienna's underground railway; the underside is the area for sliding contact
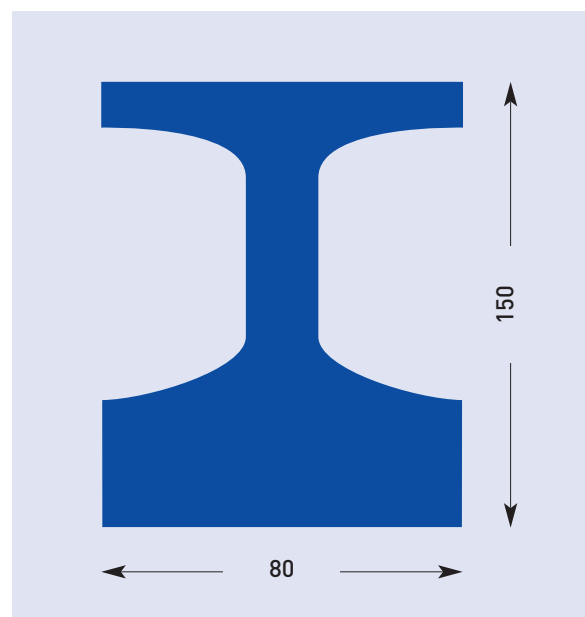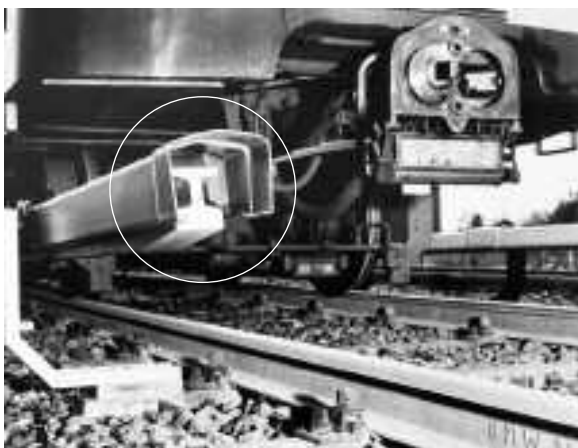
4.5 Aluminium semis-like products

Such products are produced from aluminium sheet or strip by cold working. Examples include:

- sheet and strip profiled by roll forming (Fig. 10)
- profiled strip roll-formed or drawn through a die; an example are profiles used for window blinds (Fig. 11)
- profiles made by bending sheet (canted profiles)
- seam-welded thin-gauge tubes (e.g. for heat exchangers)
- slip-joint tubing with longitudinal or spiral joint
- corrugated tubes (flexible tubes)

Alucobond sandwich element with polyethylene core (Fig. 9)

Profile used for window blinds (Fig. 11)
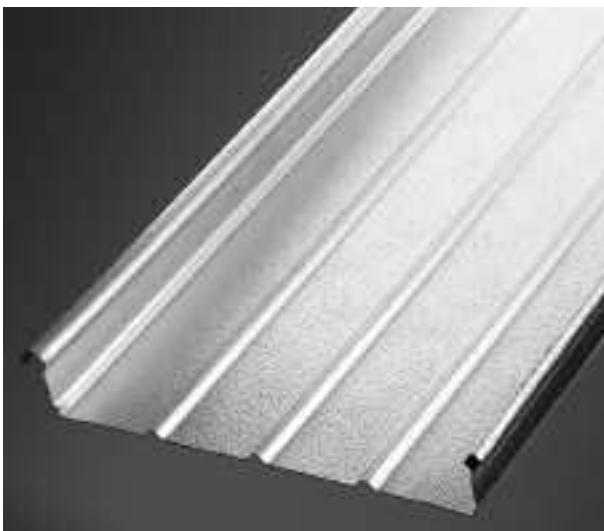
Roll-formed products (Fig. 10)

... and an example of their use

5. Material properties

5.1 Chemical properties

Aluminium is a reactive, easily oxidisable element. Its great affinity for oxygen means that it immediately forms a very thin, natural oxide layer (approx. 0.01 µm thick) with oxygen from the air, and this passivates the underlying metal and protects it against further attack. The oxide layer dissolves in acidic or alkaline aqueous solutions so that aluminium is only chemically resistant over a pH range from 5 to 8. When exposed to the elements, with alternating wet and dry periods, thicker surface oxide layers form (up to 0.1 µm thick), consisting of oxides and hydroxides, and these exhibit increasingly greater protection; however, dust particles can become entrapped in the oxide layer so it can appear somewhat unsightly.

Significantly thicker oxide layers can be formed electrolytically by anodising. These anodically produced oxide layers are practically resistant to any further changes due to the effects of the elements.

The chemical properties of the pure metal also apply to most aluminium alloys, as long as they do not contain any copper as an alloying element.

5.2 Physical properties

Density, elastic modulus and coefficient of thermal expansion are properties of aluminium that only vary slightly with the alloying constituents in the quantities usually present, for example, in standardised wrought alloys. Design codes use a fixed value of 70 000 N/mm^2 for the modulus of elasticity of wrought aluminium alloys when dimensioning aluminium support structures. As far as its effect on density and modulus of elasticity is concerned, lithium is an exception with aluminium. Wrought Al-Li alloys are now used for applications in the aerospace industry, such as for the Space Shuttle, but their high price limits their use to this industry; they have a lower density and higher modulus of elasticity.

Relatively speaking, thermal and electrical conductivity are strongly dependent on alloy constituents, as is also the case with strength properties and corrosion behaviour (with respect to Cu content). Table 1 compares the density and modulus of elasticity of aluminium with the corresponding values for other commercially important metals. Table 2 compares refined aluminium and wrought aluminium alloys with regards to a number of technically relevant physical characteristics and clearly shows the differing influence of alloying elements in aluminium, even on the melting and solidification range. The upper limit of this range is defined by the liquidus and the lower limit by the solidus. It is characterised by liquid and solid phases existing simultaneously and is known to be always lower than the melting point of the pure metal.

In Germany, the hardness of aluminium alloys is usually expressed as Brinell hardness [HB in N/mm^2]. For all alloys and tempers of aluminium semi-finished products, there is no simple relationship between hardness and a strength property (tensile strength) or between hardness and wear resistance. Hardness is not an acceptance criterion, for example when inspecting material received for conformance. Hardness measurements are used, however, to determine the extent of the heat-affected zone near a weld.

(Table 1)

Density and elastic modulus (Young´s modulus) of commercially used metals
(Reference material: the pure metal)

	Metal	Chemical Symbol	Density [g/cm^3]	Elastic Modulus [N/mm^2]
light metals	Magnesium	Mg	1.7	45 000
	Beryllium	Be	1.8	295 000
	Aluminium	Al	2.7	66 600[2]
	Titanium	Ti	4.5	110 000
heavy metals	Zinc	Zn	7.1	120 000
	Tin	Sn	7.3	44 000
	Iron[1]	Fe	7.9	210 000
	Nickel	Ni	8.9	210 000
	Copper	Cu	8.9	120 000
	Lead	Pb	11.3	19 000

1) steel too
2) with wrought alloys for construction purposes, an approximate value of 70 000 N/mm^2 is used; the shear modulus is obtained using Poisson's ratio (= 0.3): G = 27 000 N/mm^2.

(Table 2) Comparison of the physical parameters of wrought aluminium alloys with the corresponding values for refined aluminium

Parameter	Refined Aluminium Al 99.99	Wrought Aluminium Alloys
Density in g/cm^3	2.7	from 2.64 (EN AW-5019) to 2.85 (EN AW-2007)
Average linear coefficient of thermal expansion (in 10^{-3} mm/m K) over the range 20 to 100 °C	23.6	from 22.8 (EN AW-2014)[*] to 24.2 (EN AW-5083) for comparison: construction steel: ~12
Electrical conductivity in m/(Ohm·mm^2)	37.7	up to 16 (EN AW-5083) up to 15 (EN AW-5019)
Thermal conductivity in W/m K	235.0	up to 110 (EN AW-5083 und EN AW-5019)
Melting and solidification range (solidus-/liquidus) in °C	660/660	643/654 (EN AW-3003) 585/650 (EN AW-6060) 480/640 (EN AW-7075)

[*] Typical value for wrought alloys often found in the literature: 24

5.3 Mechanical properties

Strength usually plays the leading role in the commercial application of aluminium. Thus, whilst still exhibiting adequate ductility, aluminium engineering alloys have minimum tensile strength (Rm) values that range from about 200 N/mm^2 to over 500 N/mm^2 in the case of copper-containing aerospace alloys. Unalloyed aluminium does not exhibit such levels of strength, even though strain hardening (e.g. as a result of cold rolling of sheet, drawing of extruded tubes, etc.) leads to significantly higher values of tensile strength and 0.2 % proof stress (0.2 % elastic limit, $R_{p0.2}$) than can be achieved with the 'soft' temper (Fig. 12).

Typical engineering alloys, such as those used in design codes to determine the dimensions of supporting structures, are the highly alloyed variants of the Al-Mg and Al-Mg-Mn non-age-hardenable alloys and the Al-Mg-Si and Al-Zn-Mg age-hardenable alloys.

There are two hardening mechanisms in aluminium alloys: strain hardening (cold working) and ageing, and these can complement each other. The 'soft' temper is used as the reference point for any increases in strength. Even with the 'soft' temper, strength increases with the number of foreign atoms in solid solution, which means with increasing content of alloying elements. Examples are the Al-Mg and Al-Mg-Mn alloys shown by the lower limiting curve in Fig. 12. Refined aluminium (Al) is shown on left and this curve illustrates what is referred to in the literature as 'alloy strengthening'.

■ Strain hardening: plastic strain, for example due to cold rolling, produces dislocations in the crystal lattice, which increasingly interfere with each other and thus increase the resistance to deformation (and thus strength, etc.), whereby lattice defects, grain boundaries and the like also play a role. Strain hardening manifests itself in a huge increase in the UTS/proof stress ratio, $R_{p0.2}/R_m$, with a corresponding marked decrease in the elongation at rupture.

Any increase in strength due to strain hardening is lost at temperatures above 250 °C as a result of recrystallisation, and the strength goes back to that of the 'soft' temper. Annealing at a temperature below the recrystallisation threshold (which depends on composition and degree of cold working or the deformation ratio) leads to a less dramatic loss in strength due to recovery.

Thermal softening (at a temperature of 200 to 250 °C) is used, for example, to obtain a 'half-hard' temper with a sheet having a 'hard' temper. For a given level of strength, the elongation at fracture is considerably higher than if a 'soft' temper is cold worked.

■ Strengthening by aging. This strengthening mechanism is only applicable to certain types of aluminium alloy, such as Al-Cu-Mg, Al-Zn-Mg or Al-Mg-Si. A prerequisite for this hardening mechanism is that the alloy is first heated to a temperature at which as many as possible of the foreign atoms that cause the hardening go into solid solution (solution heat treatment). The alloy is then rapidly cooled to room temperature (by quenching), which leads to the matrix being supersaturated in foreign atoms of sufficiently low mobility, i.e. they remain in solution under non-equilibrium conditions. Storage for longer periods at room temperature (natural ageing) or at a slightly elevated temperature (artificial ageing) causes the foreign atoms to deposit out and form particles of a critical size. The minimum values for R_m and $R_{p0.2}$ for Al-Mg-Si alloys and AlZn4,5Mg1 as given in DIN EN 485-2, 754-2 and 755-2 are shown in Fig. 12 (age-hardened temper).

(Fig. 12)
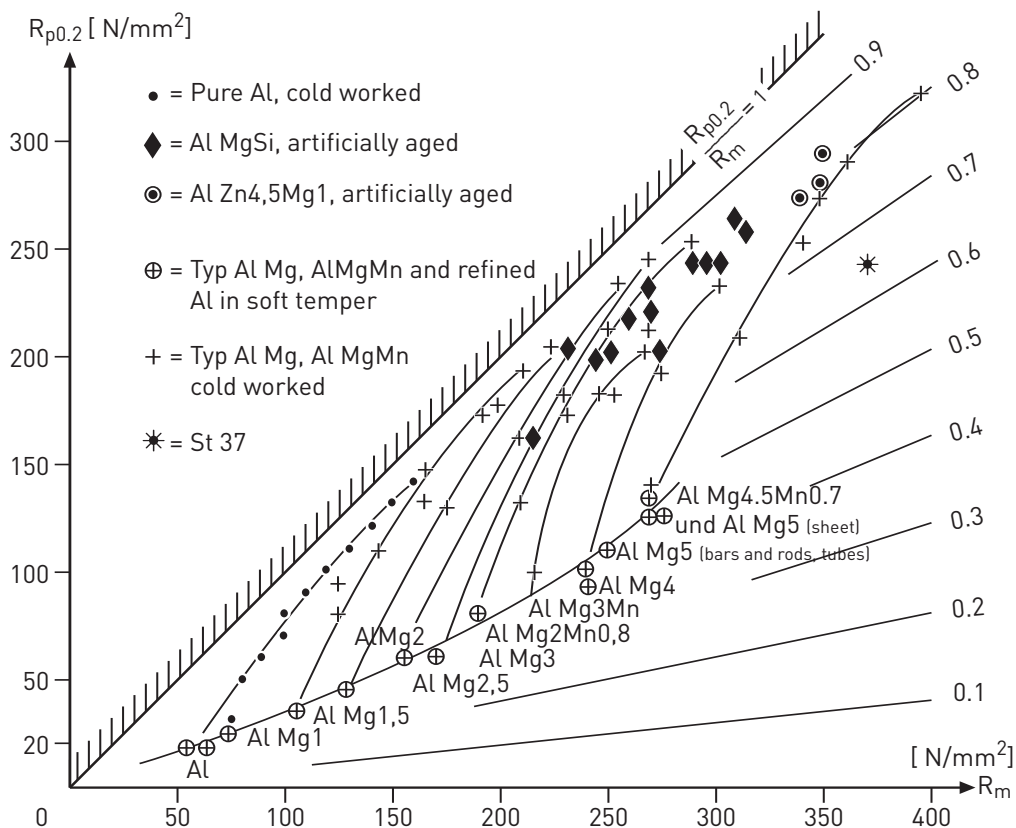
Minimum values of $R_{p0.2}$ and R_m according to DIN EN 485-2, 754-2 and 755-2 for refined aluminium, wrought Al-Mg and Al-Mg-Mn alloys, age-hardenable wrought alloys of the Al-Mg-Si and AlZn4,5Mg1 types, the latter in the 'artificially aged' temper. In the case of refined aluminium and the non-age-hardenable alloys, values are given for the 'soft' temper (lower limiting curve) and for various degrees of strain hardening for each of these alloys (lines that are steeply inclined upwards). For comparison, a value is also shown for St37 (construction steel). The diagram also includes straight lines through the origin showing the proof stress/UTS ratio, $R_{p0.2}/R_m$.

Table 3 shows the minimum strength values for alumin-
ium of 99.5 % purity and a selection of common wrought
aluminium alloys. The figures given are the minimum values
for sheet/strip (DIN EN 485-2) and extruded profiles
(DIN EN 755-2). Tubes and bars and rods (DIN EN 755-2)
are extruded products with standardised strength proper-
ties that are the same or similar.

Tables 4.1, 4.2 and 4.3 contain data on a selection of alu-
minium casting alloys according to DIN EN 1706. The mini-
mum values given are often much lower than the values
that can be achieved in a casting using appropriate casting
techniques and thus only reflect the capability of an alu-
minium casting alloy to a limited extent.

(Table 3) Mechanical properties (minimum values) of some standardised wrought aluminium alloys

	Alloy No. According to DIN EN 573	Alloy Type and Temper According to DIN EN 573	DIN EN 515	Product Form	R_m N/mm²	$R_{p0,2}$ N/mm²	A_{50mm} %	Temper	Gauge in mm
Refined Al	AW-1050A	Al 99,5	O/H111	strip up to	65	20	35	soft	6 to 12.5
			H12	3 mm thick;	85	65	7	cold rolled	3 to 6
			H22	sheet	85	55	11	recovery heat treated	3 to 6
			H19[*]		150	130	1	cold rolled	1.5 to 3
			F,H12	profiles	60	20	23	extruded	all gauges
Non-age-hardenable alloys	AW-3003	Al Mn1Cu	O/H111	strip up to	95	35	24	soft	6 to 12.5
			H12	3 mm thick;	120	90	7	cold rolled	6 to 12.5
			H19[*]	sheet	210	180	2	cold rolled	1.5 to 3
	AW-3004	Al Mn1Mg1	O/H111	strip up to	155	60	15	soft	1.5 to 3
			H12	2 mm thick;	190	155	4	cold rolled	1.5 to 3
			H22	sheet	190	145	6	recovery heat treated	1.5 to 3
			H19[*]		270	240	1	cold rolled	0.2 to 1.5
	AW-5049 and AW-5754	Al Mg2Mn0,8 and Al Mg3	O/H111	strip up to 3 mm thick;	190	80	18	soft	3 to 6
			H12	sheet	220	170	9	cold rolled	6 to 12.5
			H22		220	130	10	recovery heat treated	6 to 12.5
			H18[*]		290	250	2	cold rolled	0.5 to 3
	AW-5754	Al Mg3	F, H112	profiles	180	80	12	extruded	up to 25
	AW-5454	Al Mg3Mn	O/H111	sheet	215	85	18	soft	6 to 12.5
			H22/H32		250	180	10	recovery heat treated	6 to 12.5
			H28/H38[*]		310	250	3		0.2 to 3
	AW-5083	Al Mg4,5Mn0,7	F/	profiles	270	110	10	extruded	all gauges
			O/H111	sheet	275	125	16	soft	6 to 12.5
			H12		315	250	7	recovery heat treated	6 to 12.5
			H16[*]		360	300	2		0.5 to 4
Age-hardenable alloys	AW6060	Al MgSi	T6	profiles	190	150	6	artificially age hardened	up to 3
			T6		170	140	6		3 to 25
			T66[*]		215	160	6		up to 3
	AW-6063	Al Mg0,7Si	T6		215	170	6	artificially age hardened	up to 10
					195	160	6		10 to 25 mm
	AW-6005A	Al SiMg(A)	T6	profiles	260	215	–	artificially age hardened	solid profiles > 50 to 100
			T6		255	215	6		hollow profiles up to 5
			T6		270	225	6		hollow profiles up to 5
	AW-6082	Al Si1MgMn	T6	profiles	295	250	6	artificially age hardened	solid profiles up to 20
			T6		310	260	8		hollow profiles > 5 to 15
			T6[*]	sheet	310	260	6		0.4 to 1.5
			T6[*]		310	260	7		1.5 to 3
			T6[*]		310	260	10		3 to 6
			T66		300	255	9		6 to 12.5
	AW-7020	Al Zn4,5Mg1	T6	profiles	350	290	8	artificially age hardened	up to 40
			T6	sheet	350	280	10		3 to 12.5
	AW-7075	Al Zn5,5MgCu	T6	profiles	530	460	4	artificially age hardened	up to 25
			T62	sheet	490	390	–		80 to 90
			T6[*]		545	475	8		3 to 6

R_m= tensile strength; $R_{p0.2}$= 0.2 % proof stress; A_{50mm}= elongation at rupture. Values according to DIN EN 485-2 (sheet/strip) and DIN EN 754-2 and 755-2
(profiles) O / H 111 = soft, H xx = strain hardened, T x(x) = age-hardening temper, whereby x is a digit

[*] Material temper at which an alloy has its maximum strength

Mechanical properties of European standardised alloys according to DIN EN 1706

(Table 4.1) Aluminium die casting alloys; values for test bars cast separately

Alloy Group	CEN Designation	Alloy Designation	Tensile Strength Rm N/mm² min.	0.2 % Proof Stress N/mm² min.	Elongation at Rupture A %	Brinell Hardness HB	D = alloys commonly used in Germany
Al Si10Mg	EN-AC 43400	Al Si10Mg(Fe)	240	140	1	70	D
Al Si	EN-AC 44300	Al Si12(Fe)	240	130	1	60	D
	EN-AC 44400	Al Si9	220	120	2	55	
Al Si9Cu	EN-AC 46000	Al Si9Cu3(Fe)	240	140	<1	80	D
	EN-AC 46100	Al Si11Cu2(Fe)	240	140	<1	80	
	EN-AC 46200	Al Si8Cu3	240	140	1	80	
	EN-AC 46500	Al Si9Cu3(Fe)(Zn)	240	140	<1	80	
Al Si(Cu)	EN-AC 47100	Al Si12Cu1(Fe)	240	140	1	70	D
Al Mg	EN-AC 51200	Al Mg9	200	130	1	70	D

(Table 4.2) Aluminium sand-casting alloys; values for test bars cast separately

| Alloy Number EN AC-	Alloy Designation EN AC-	Non-heat-treated				Heat-treated				
		Tensile Strength N/mm² min.	0.2 % Proof Stress N/mm² min.	Elongation at Rupture % min.	Brinell Hardness HB min.	Temper	Tensile Strength N/mm² min.	0.2 % Proof Stress N/mm² min.	Elongation at Rupture % min.	Brinell Hardness HB min.
21000	Al Cu4MgTi					T4	300	200	5	90
21100	Al Cu4Ti					T6	300	200	3	95
						T64	280	180	5	85
41000 x	Al Si2MgTi	140	70	3	50	T6	240	180	3	85
42000 x	Al Si7Mg	140	80	2	50	T6	220	180	1	75
42100	Al Si7Mg0,3					T6	230	190	2	75
42200 x	Al Si7Mg0,6					T6	250	210	1	85
43000	Al Si10Mg(a)	150	80	2	50	T6	220	180	1	75
43100 x	Al Si10Mg(b)	150	80	2	50	T6	220	180	1	75
43200	Al Si10Mg(Cu)	160	80	1	50	T6	220	180	1	75
43300	Al Si9Mg					T6	230	190	2	75
44000	Al Si11	150	70	6	45					
44100 x	Al Si12(b)	150	70	4	50					
44200	Al Si12(a)	150	70	5	50					
45000	Al Si6Cu4	150	90	1	60					
45200 x	Al Si5Cu3Mn	140	70	1	60	T6	230	200	<1	90
45300 x	Al Si5Cu1Mg					T4	170	120	2	80
						T6	230	200	<1	100
46200	Al Si8Cu3	150	90	1	60					
46400 x	Al Si9Cu1Mg	135	90	1	60					
46600 x	Al Si7Cu2	150	90	1	60					
47000	Al Si12(Cu)	150	80	1	50					
51000 x	Al Mg3(b)	140	70	3	50					
51100	Al Mg3(a)	140	70	3	50					
51300	Al Mg5	160	90	3	55					
51400	Al Mg5(Si)	160	100	3	60					
71000 x	Al Zn5Mg					T1	190	120	4	60
x: Not common in Germany; can be replaced by other suitable alloys.										

(Table 4.3) Chill cast aluminium; values for test bars cast separately

| Alloy Number	Alloy Designation	Non-heat-treated				Heat-treated				
		Tensile Strength N/mm² min.	0.2 % Proof Stress N/mm² min.	Elongation at Rupture % min.	Brinell Hardness HB min.	Temper	Tensile Strength N/mm² min.	0.2 % Proof Stress N/mm² min.	Elongation at Rupture % min.	Brinell Hardness HB min.
EN AC-	EN AC-									
21000	Al Cu4MgTi					T4	320	200	8	95
21100	Al Cu4Ti					T6	330	220	7	95
						T64	280	180	8	90
41000 x	Al Si2MgTi	170	70	5	50	T6	260	180	5	85
42000 x	Al Si7Mg	170	90	2.5	55	T6	260	220	1	90
						T64	240	200	2	80
42100 x	Al Si7Mg0,3					T6	290	210	4	90
						T64	250	180	8	80
42200	Al Si7Mg0,6					T6	320	240	3	100
						T64	290	210	6	90
43000	Al Si10Mg(a)	180	90	2.5	55	T6	260	220	1	90
						T64	240	200	2	80
43100 x	Al Si10Mg(b)	180	90	2.5	55	T6	260	220	1	90
						T64	240	200	2	80
43200	Al Si10Mg(Cu)	180	90	1	55	T6	240	200	1	80
43300	Al Si9Mg					T6	290	210	4	90
						T64	250	180	6	80
44000	Al Si11	170	80	7	45					
44100 x	Al Si12(b)	170	80	5	55					
44200	Al Si12(a)	170	80	6	55					
45000	Al Si6Cu4	170	100	1	75					
45100 x	Al Si5Cu3Mg					T4	270	180	2.5	85
						T6	320	280	<1	110
45200 x	Al Si5Cu3Mn	160	80	1	70	T6	280	230	<1	90
45300 x	Al Si5Cu1Mg					T4	230	140	3	85
						T6	280	210	<1	110
45400 x	Al Si5Cu3					T4	230	110	6	75
46200	Al Si8Cu3	170	100	1	75					
46300 x	Al Si7Cu3Mg	180	100	1	80					
46400 x	Al Si9Cu1Mg	170	100	1	75	T6	275	235	1.5	105
46600 x	Al Si7Cu2	170	100	1	75					
47000	Al Si12(Cu)	170	90	2	55					
48000	Al Si12CuNiMg					T5	200	185	<1	90
						T6	280	240	<1	100
51000 x	Al Mg3(b)	150	70	5	50					
51100	Al Mg3(a)	150	70	5	50					
51300	Al Mg5	180	100	4	60					
51400	Al Mg5(Si)	180	110	3	65					
71000 x	Al Zn5Mg					T1	210	130	4	65
x: Not common in Germany; can be replaced by other suitable alloys.										

Impact extrusion process (Fig. 13)

Impact extrusion against the movement of the ram
(reverse impact-extrusion)
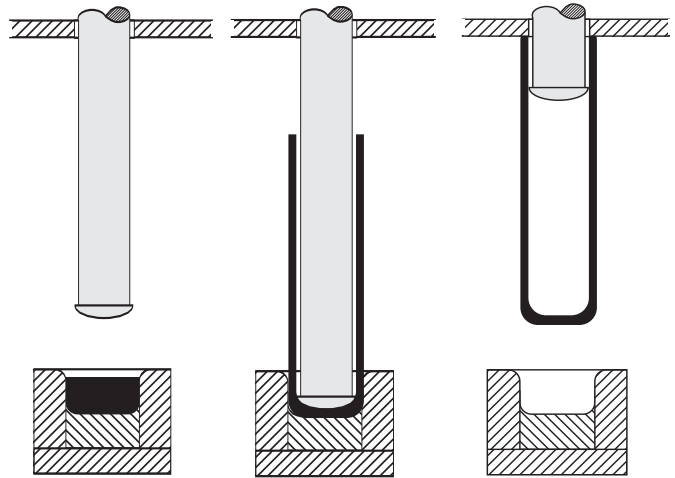
Impact extrusion with and against the movement of the ram
(combined impact-extrusion)
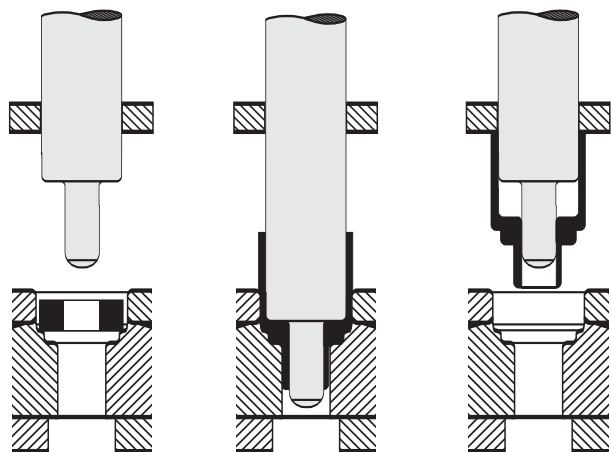
Impact extrusion with movement of the ram
(forward impact-extrusion)
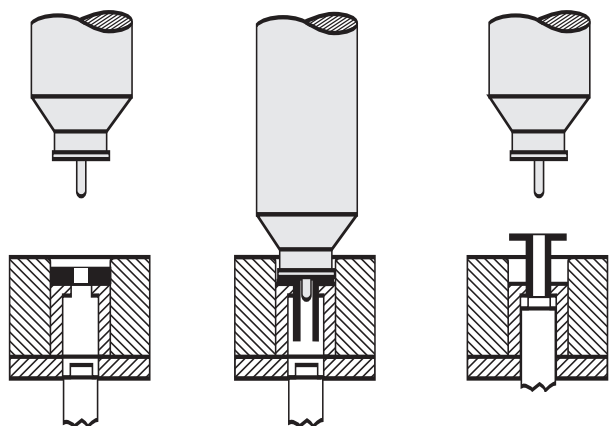
6. Shaped parts

Shaped aluminium parts can be produced using all of the common master-pattern and forming processes used in metal processing:

6.1 Master-pattern processes

Master-pattern forming is the manufacture of a solid body from a formless material, e.g. a material that is in a liquid, mushy or paste-like state, by creating coherence. One has a certain control over the resultant material properties.

6.1.1 Casting

If one allows molten aluminium to solidify in a mould shaped in the form of the required component, this produces a 'casting' or a 'mould casting'. Castings are characterised by a wide variety of possible designs and sizes, whereby the casting process used is also relevant. Although all alloys can be continuously cast into shapes with simple cross-sections without any difficulty (Fig. 5), mould casting places considerably higher demands on castability. Thus, it is only possible to use those alloys for castings that are expressly classified as casting alloys (see DIN EN 1706). Casting alloys usually have a significantly higher content of alloying elements than wrought alloys. This takes into account the solidification and shrinkage processes to which the metal is subjected when it cools down in the mould. One differentiates between different types of casting depending on the casting process used:

- Sand castings: the mould is made in sand using a wooden pattern. The maximum weight depends on the facilities available, typically approx. 4 000 kg.
- Chill castings: the mould is a permanent metal die. Weight of casting: up to about 100 kg.
- Pressure die casting: the mould is a permanent metal die into which the molten metal is injected at high speed. Weight of casting: up to about 50 kg.
- Investment castings: to produce the mould, a wax pattern is first embedded in a special ceramic moulding compound and firing is then used to melt the wax out again. Investment castings have high dimensional accuracy. Weight of casting: up to about 25 kg.

6.1.2 Sintering

Aluminium powder or powder mixtures are mixed cold with special binders and pressed into a metal die at high pressure to form a pre-pressed part or non-sintered slug; the part is subsequently sintered under pressure at an elevated temperature. The density is about 98 % of that of the comparable wrought alloy. Sintered preforms are more dimensionally accurate than die forgings; their properties are similar to wrought alloys of the same composition.

6.2 Forming

6.2.1 Hot working

- Hand forgings:
  The starting shape is a continuously cast billet or a section of an extruded profile.
- Die forgings:
  The starting shape is usually a section of an extruded profile; in the case of larger dimensions it can also be a hand forging.

6.2.2 Cold working

- Parts made by cold impact extrusion for packaging (tubes, small tubes, cans, aerosol cans).
- Technical impact-extruded parts up to about 120 mm diameter and 360 mm high. Minimum wall thickness approx. 1 % of the diameter. Rectangular shapes and shapes with ribs and stiffeners are possible (cold impact extrusion is shown schematically in Fig. 13).
- Deep drawn or hollow embossed sheet components; in the case of cylindrical components, it is possible to taper the cylinder casing by drawing and ironing.
- Stampings (including oval ones); in the case of cylindrical or spherical parts it is possible to taper the wall thickness by spinning (Fig. 14). Rotationally symmetrical parts can be bellied out, drawn in, crimped or flanged.
- Bent sheet metal parts; produced using bending tools or on bending presses.
- Parts formed by bending tube or wire.
- Bellied-out, flanged and crimped deep-drawn parts or tubes.
- Tube bends.

Spinning (Fig. 14)
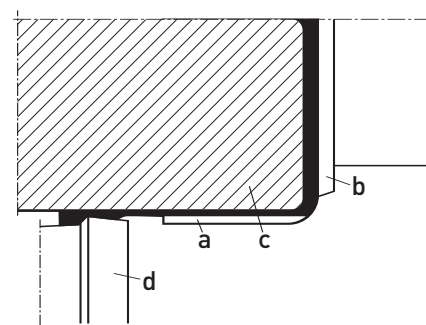
Spinning process:
a) Preform, b) Tail block, c) Chuck, d) Spinning roller

7. Machining

The machining of aluminium is carried out at considerably higher cutting speeds than when machining steel. Rotational speeds of between 20 000 and 35 000 rpm are possible with high-speed milling if a suitable spindle bearing arrangement is used. Materials with a cold worked or aged temper are easier to machine than those with a soft temper. Free-machining alloys (drilling and machining grade) with chip-breaking alloying additions enable the chips to be removed without difficulty even at high levels of chip production. Generally speaking, casting alloys are more suitable for machining than wrought alloys. The use of hard-metal tools is recommended for casting alloys with Si contents in excess of 7 % because of the presence of hard silicon crystals.

8. Cutting

Aluminium alloys can be cut with hacksaws, band saws or circular saws using blades that have well-spaced teeth and a smooth, well rounded tooth gullet. When cutting aluminium, for example using metal shears, the tools (shears, cutting tools) should have a small shear gap. Polishing and greasing possibly using a solid lubricant (the faces of the cutting stamps) helps prevent metal wear. Such wear can cause welding of the cut surface in soft materials and thus produce rough cut surfaces – and in the case of thin stamps even to the stamp breaking.

With the exception of gas cutting, all well-known thermal cutting processes can be used.

9. Joining

9.1 Mechanical joining techniques

The common mechanical joining techniques such as rivets, screws and forming can also be used for aluminium structures. In addition, the freedom to design the cross-section afforded by extrusion makes it possible to join aluminium parts using snap-fit, push-in or hinged connections, etc. When mechanically joining different materials it is absolutely essential to consider their compatibility. Table 5 gives an indication of the risk involved in joining aluminium parts to other metals in different atmospheres.

Even when joining aluminium with non-metallic materials, such as wood or concrete, one should ensure that a separating layer is used when materials are unknown or contain constituents or ingredients that pose a risk for aluminium.

9.1.1 Rivets

Rivets form a joint that cannot be undone non-destructively. The main stress should be at right angles to the axis of the rivet to ensure shearing off or making a folded seam on the edge of the hole; thus, two-part connectors are beneficial. Aluminium, steel and stainless steel are common rivet materials. The riveted joint should have at least the same strength and the same corrosion resistance as the parts to be joined. Riveting with solid rivets, which are made as a single piece and necessitate access from both sides of the joint, are being replaced more and more by joints that can be made from one side using blind rivets, which comprise a mandrel (pull stem), stem head and hollow shaft. The three main types of blind rivets are shown in Fig. 15. When joining with blind rivets, the grip length and diameter of the drilled hole specified by the manufacturer must be followed precisely.

Types of blind rivets (Fig. 15)

| Open-type blind rivet | Closed-end blind rivet | Grooved blind rivet |

(Table 5:)
Risk of contact corrosion for aluminium parts when they are joined together with components made of electrolytically different metals
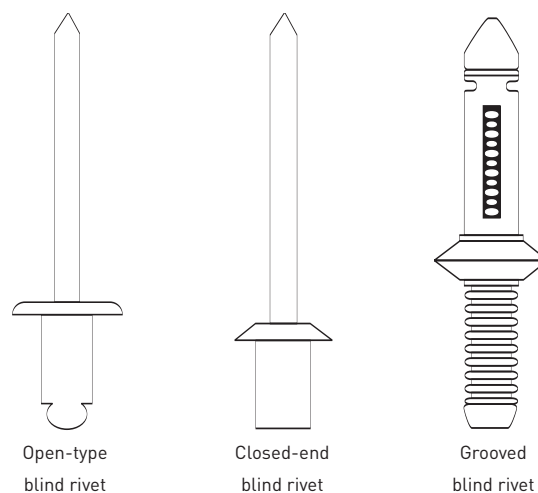
| Level of Risk	Atmosphere Country	Town/ Industrial Area	Coastal
none	lead, zinc, stainless steel	lead, zinc, stainless steel	zinc stainless steel, lead
medium to large	unprotected steel copper	unprotected steel copper	unprotected steel copper

■ Special types of rivets are available: locking-ring bolts require accessibility from both sides and the closing head is replaced by a retaining ring; riveting nuts only require access from one side and other parts can be attached to the nut.

■ Piercing rivets do not require pilot drilling.

9.1.2 Screws

Screwed joints are joints that, in principle, can be undone; they either require access from both sides, as in the case of bolts with nuts, or from one side, as with thread-forming or thread-cutting screws or threaded inserts. Aluminium is particularly suitable for use of the latter type of screw because screw channels (Fig. 16) or similar features can be designed into the extrusion. However, these screws should not be screwed into the same thread in thin sub-structures more than once.

Depending on the area of application, the nature of the mechanical loading and the requirements for corrosion protection, one can use surface treated (to all intents and purposes galvanised) steel screws, screws made of austenitic Cr-Ni stainless steel and aluminium screws (mainly wood screws) to join aluminium components. Care should be taken to ensure that when aluminium structures are exposed to a corrosive environment, the screwed joint does not become a weak point. Attention should be given to sealing the joints, insulating the parts to be joined when they are made of different materials, ensuring the screws and the parts to be joined have at least the same corrosion resistance. Some types of screws that are also suitable for joining thin sheet are shown in Fig. 17. One should follow the manufacturer's recommendations concerning the diameter of the drilled hole and the thicknesses of the parts being joined.

Thread-forming screws in screw channels of aluminium profiles (Fig. 16)
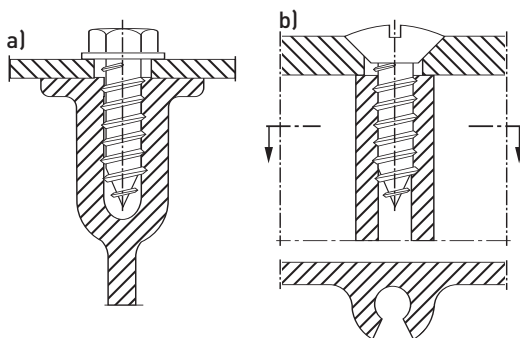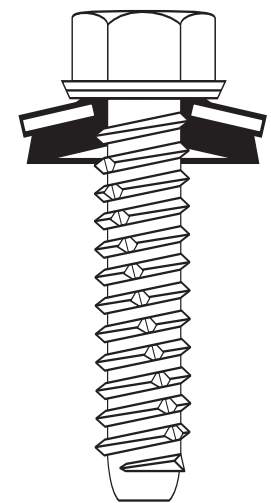

a) Perpendicular to the direction of extrusion of the profile
b) In the direction of extrusion

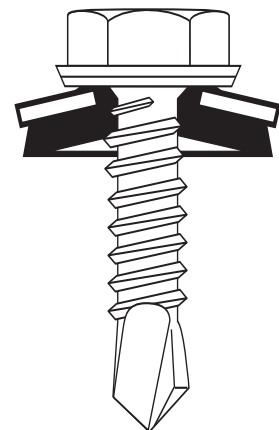**Types of thread-forming screws (Fig. 17)**
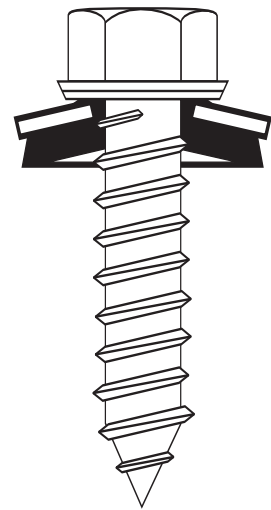
Thread-forming screw
A thread similar to the thread of wood screws

Thread-forming screw
B thread according to DIN 7970, shape BZ

Self-tapping screw

Threaded inserts in the shape of wound spring wire or bushes are suitable for repairs or for frequently undoing or tightening the screws. They improve the effectiveness of the joint with respect to the loads that can be transmitted.
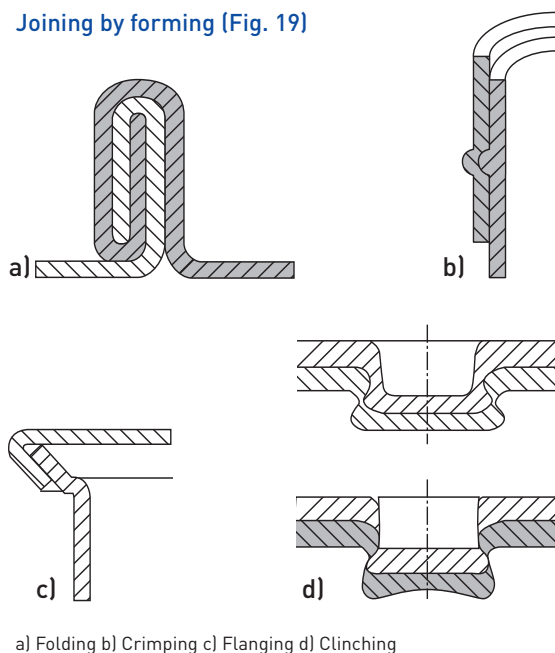
9.1.3 Snap connections

With this type of fastener, which is typical for extruded aluminium profiles, use is made of the springiness of the material over the range where its behaviour is elastic. For the most part, the joints can be undone again. Depending on the environment, consideration should be given to crevice and contact corrosion. Some types of snap connection are compared with other typical ways of joining profiles in Fig. 18.

9.1.4 Joining by forming

Every method of forming can be used to make a joint, whereby essentially one differentiates between manual skills, such as folding, crimping and beading, and techniques used on an industrial scale, like expanding, flaring, rolling in, encapsulating and clinching. Some of the techniques are particularly suitable for sheet (e.g. folding and clinching); the others are better for tubes and profiles. These joints cannot be undone non-destructively. The need for plastic deformation means that certain material properties are required (no hard or age-hardened tempers); when joining different materials together, attention should be given to avoid possible crevice or contact corrosion. Fig. 19 shows typical joints produced by the forming of thin-gauge components.

Joining by forming (Fig. 19)

a) Folding b) Crimping c) Flanging d) Clinching

Snap connections and similar joints between aluminium profiles (Fig. 18)
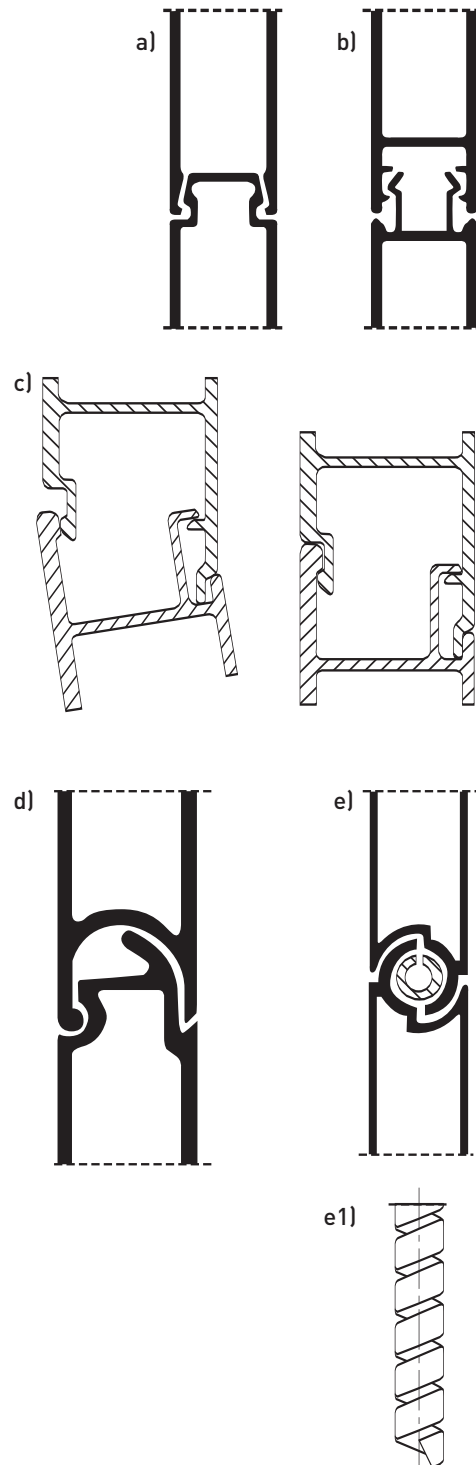
a) to c): Snap connections with or without a prior twisting action. The same load can be applied to both sides of the joint, which cannot be undone, or only undone with great difficulty.
d) Hinged connection; this will only withstand forces on the side away from the pivotal point.
e) Push-in connection with an additional, invisible locking element (spiral coiled spring e1). The same load can be applied to both sides of the joint

9.2 Welding

Welding falls into the category of 'joining materials by uni-fying them', just like soldering or brazing, for example. An important prerequisite for a good welded joint between aluminium components is the removal of the oxide layer, which forms immediately on aluminium surfaces due to reaction with oxygen in the air. This can be achieved in various ways: chemically, using a flux; via an arcing effect when welding under a protective atmosphere; by pressure welding with an increase in the surface area while ex-cluding air (e.g. in overlaps) or by forcibly enlarging the original surface area in the case of butt welding.

9.2.1 Fusion welding

With fusion welding the parts are joined using a filler mate-rial. Metal inert-gas arc-welding techniques are mainly used. Not all aluminium alloys are suitable for fusion weld-ing. This is the case, for example, with wrought Al-Cu-Mg and Al-Zn-Mg-Cu alloys. In principle, die castings produced using the conventional die casting process are unsuitable for fusion welding because of the microporous gaseous inclusions resulting from the casting process. Where alu-minium alloys are suitable for fusion welding, attention should be given to choosing the right weld filler (filler metal). Weld fillers are standardised according to DIN 1732.

The basic types of fusion welding are:

Tungsten inert-gas arc-welding (TIG):
There is an arc between the work piece and a non-consum-able tungsten electrode inside the protective envelope of an inert gas (usually argon). The welding current is alternating current and the filler material is applied without current. The process is suitable for thicknesses from 1 to 6 mm and for welding from both sides simulta-neously up to 12 mm (Fig. 20).

Metal inert-gas arc-welding (MIG) (Fig. 21)

Coiled wire electrode
Wire drive
Protective gas
MIG torch
Wire electrode
Protective gas envelope
+
G
–
Weld pool

Metal inert-gas arc-welding (MIG):
There is an arc between the workpiece and a consumable wire electrode under a protective atmosphere of inert gas (argon, helium or an argon—helium mixture); the welding current is direct current, with the workpiece acting as the negative pole (cathode). The method is suitable for thick-nesses of 4 mm and over; 2 mm and over for MIG welding with superimposed current pulses, Fig. 21.

Special types of fusion welding:

Oxy-fuel gas welding (Fig. 22) using a flux; residues have to be completely removed. Suitable for refined aluminium and non-age-hardenable alloys (up to 3 % Mg) in thick-nesses from 1 to 6 mm. Nowadays the process is of hardly any significance and is not approved by any recognised approval authority (e.g. in the field of building supervision) or any classification society (such as Germanischer Lloyd).

Metal-arc welding (Fig. 23) with flux-coated rod electrodes. Welding is carried out with direct current; the workpiece is connected to the negative pole. It is practically only used for repairing aluminium castings.

Electron-beam welding of aluminium is only possible in a vacuum; its use is limited to special applications.

Tungsten inert-gas arc-welding (TIG) (Fig. 20)

Protective gas
TIG torch
Tungsten electrode
Filler rod
Protective gas envelope
HF
HF

Flame welding (Fig. 22)

weld to left
with aluminium, do not weld to the right
70° - 80°
10° - 20°

Metal arc welding (Fig. 23)

Ultrasonic welding (Fig. 25)

1) High-frequency generator,
2) Ultrasonic probe, 3) Transducer, 4) Horn,
5) Pneumatic cylinder, 6) Pressure piston, 7) Anvil

Laser-beam welding

The specific advantages of this process include low heat input, little distortion of the component and high welding speeds.
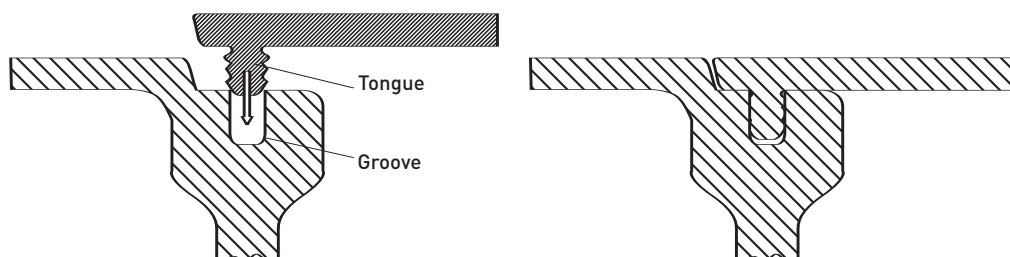
Friction stir welding

In friction stir welding (FSW), two plates are connected by a rotating pin and are 'stirred' mechanically. This process takes place at temperatures below the melting point of the plates.

9.2.2 Pressure welding

With pressure welding, the parts are joined together without using a weld filler material.

Cold pressure welding is carried out at high pressure by enlarging the area of contact and is used for butt and overlapping joints. A patented process enables extruded aluminium profiles to be joined by cold pressure welding along their longitudinal edges. The process is based on the tongue-and-groove principle and can thus only be performed economically on extruded profiles. Cold pressure welding occurs on the surface of the fine fins of the 'tongues', which are oversized and forced into the grooves (Fig. 24).

Ultrasonic welding (Fig. 25) is a variant of cold pressure welding. In addition to the (considerably lower) applied pressure, the parts to be joined undergo relative oscillating movement, which is produced by converting high-frequency oscillations to mechanical movement. Ultrasonic welding can also be used to join aluminium to other metals and non-metals.

Hot pressure welding is only of any significance as friction welding and in the case of roll plating in the manufacture of semis. Resistance pressure welding (Fig. 26) is carried out by locally melting the parts using resistance heating and then immediately upsetting them.

Flash butt welding (Fig. 27). The cross-sections to be joined should have the same shape and the same cross-sectional area. After burn off (heating the point of impact and destroying the oxide skin in the arc) the parts to be joined are pressed together. The loss of strength around the joint is small.

High-frequency welding is used in the continuous production of seam-welded, light-gauge tubes from aluminium strip. The strip, which is shaped to the cross-section of the tube by passing it through a set of rolls, is heated to melting at the edges of the joint by high-frequency currents. Pressure rolls press the heated edges together.
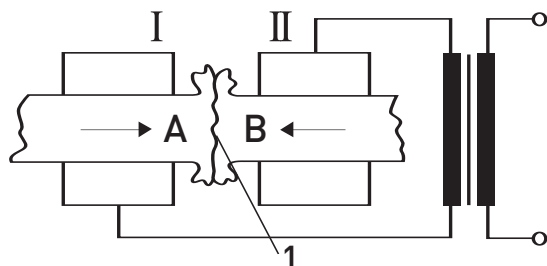
Basic arrangement of the cold pressure welding process (Fig. 24)

Resistance pressure welding (Fig. 26)

a)

b)
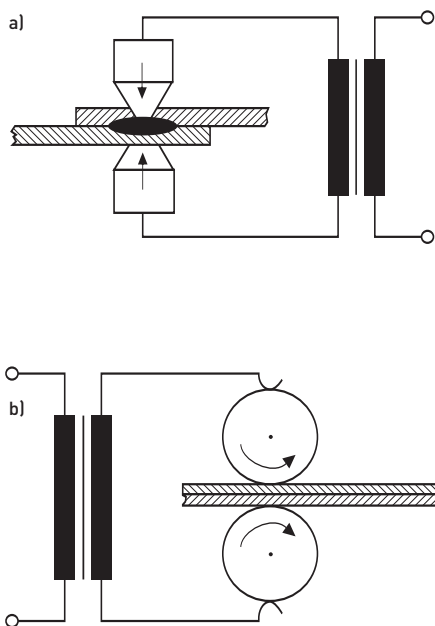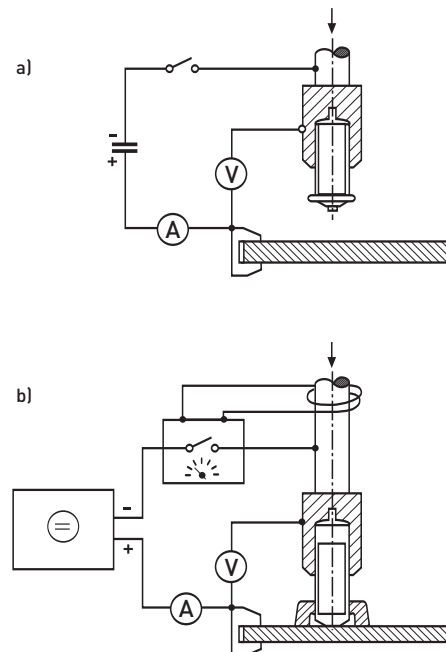
Flash butt welding (Fig. 27)

I and II are the jaws of the clamp;
A and B are the welded parts; 1 is the area of the joint

Arc stud welding

Stud welding is used to join (threaded) bolts to flat surfaces. One differentiates between two processes: stud welding with tip ignition (Fig. 28a), and stud welding with drawn arc (Fig. 28b). Stud welding with tip ignition is an important technique for fastening thin sheet anodised on one side or coated sheet that can only withstand very limited heating. Applications: construction of façades, vehicle manufacturing, white goods industry.

Stud welding (Fig. 28)

a)

b)

9.3 Soldering and brazing

With aluminium alloys one talks of brazing when the melting temperature of the solder is above 450 °C (approx. 600 °C when an L-AlSi12 solder is used) and of soldering when it is below 450 °C.

9.4 Adhesive bonding

Aluminium alloys are very well suited to the use of adhesive bonding techniques. The most important design consideration is that the adhesive-bonded joint should only be subjected to shear forces. One should avoid peel-off forces or tensile stresses. Adhesive-bonded joints are thus mainly overlapping or push-in connections (length of overlap approx. ten times material thickness). Depending on the demands placed on the strength of the joint, one can increase the roughness of the surface, and thus its suitability for adhesive bonding, either by roughening it, thoroughly degreasing it, pickling it or anodising it without compacting. No less effort is required to produce a good adhesive joint than for other joining techniques. The advantages of adhesive bonding are the favourable stress distribution, the fact that the material of the parts being joined is not affected by heat, or only insignificantly so, and that anodised parts can be joined with adhesive without adversely affecting their appearance or the surface protection.

10. Surface treatment, surface protection

Thanks to the formation of an oxide layer, aluminium exhibits excellent self-protection over the chemically neutral range, which is satisfactory for a large number of applications. Additional measures are necessary, however, in order to fulfil the various demands to which aluminium surfaces are subjected in practice: demands such as decorative appeal (metallic, coloured), corrosion resistance or wear resistance. There is a whole range of surface treatments available that allow these properties to be fulfilled, also in various combinations. All processes that produce surface layers or coatings on aluminium or apply a layer of another metal to aluminium have one thing in common: the natural oxide layer interferes with the treatment. Degreasing and pickling produces the necessary bare metal surface with a uniform, thin oxide layer. Carefully carrying out this surface pre-treatment is an essential prerequisite for producing perfect organic or non-organic coatings.

10.1 Mechanical surface treatment

Mechanical surface treatments using grinding, brushing and polishing allow one to obtain aluminium surfaces that not only have different degrees of surface roughness but also differing decorative appearances. Special surface effects are possible. Castings are given a clean, uniform finish using shot blasting. The production of defined metal surfaces by mechanical surface treatment is the basis for a subsequent surface treatment in many processes.

10.2 Chemical surface treatment

Oily or greasy metal surfaces have to be degreased before pickling so that the material can be pickled uniformly during the subsequent treatment. Degreasing is carried out without any significant loss of material using organic solvents, alkaline or acidic solutions or, if a surface with a certain satin finish is required, in special pickling solutions. Chemical brightening is possible with bright alloys (aluminium of 99.9 % purity, aluminium alloys based on Al 99,85). The brightening effect obtained by chemically smoothing out the surface in hot brightening solutions increases with increasing purity of the material. Usually it is necessary to mechanically polish the material first. Polishing is also possible electrolytically. The polished surface is very sensitive so that subsequent anodising is usually carried out. Deep etching can be used to form raised or depressed lettering, lines, areas or symbols by chemically removing aluminium locally.

Parts with intricate shapes can be etched out of thin sheet (contour etching). Chemical milling is used to produce shaped parts with large, flat-bottomed craters parallel to the surface of the sheet (aircraft construction).

10.3 Chemical oxidation

Chromating in accordance with DIN 50939 or EN 12487 leads to chemical oxidation of the pickled aluminium surface. Inorganic layers are formed which as a result of the process consist of oxide hydrates or phosphates of aluminium and chromium: they have a yellow or green colour, and can also be transparent. The layers are some 1 to 3 µm thick; they offer temporary protection against corrosion and serve as a base to which organic coatings can adhere.

Phosphating produces grey coloured layers. These layers can also be used to improve die entry and lubricating properties during forming.

10.4 Anodising

A decorative appearance obtained by mechanical or chemical surface treatment can be given lasting protection by anodising. The anodising process allows oxide layers to be produced in suitable electrolytes that are 200 to 2000 times thicker than natural oxide layers. These anodically produced oxide layers adhere strongly to the aluminium and reproduce the surface structure of the original metal surface without any changes. Depending on the process and alloy used, it is possible to produce transparent or milky opaque oxide layers that are hard and wear resistant, and have good electrical insulating properties. A final compacting process in demineralised water at > 96 °C provides the layers with good corrosion resistance. The fact that they can be coloured is another important property of the layers. The anodised layers, which nowadays are mainly produced using processes that rely on d.c. and sulphuric acid or d.c., sulphuric acid and oxalic acid, are coloured using organic or inorganic dyes (dip dyeing) or electrolytically in a metallic salt solution (electrolytic colouring). Integral colour anodising produces oxide layers with an alloy-specific colouration.

Combined colouring processes enable a wider range of colours to be obtained. DIN 17611 covers the demands placed on anodised semi-finished products with layer thicknesses in excess of 10µm. With transparent oxide layers on polished or brightened surfaces, the amount of specular reflection decreases with increasing layer thickness. Hard anodising produces oxide layers with a thickness of more than 30 µm (cf. 10.6).

10.5 Coated surfaces

Aluminium is coated for decoration and corrosion resistance. Coating materials offer a wide range of possible surface colours. At the same time, they take on the role of corrosion protection because they can withstand more-corrosive chemical environments. The demands placed on the coating dictate the choice of coating system. Before coating, it is necessary to carefully carry out a surface treatment using chromating in accordance with DIN 50939 or EN 12487 or to apply a priming coat containing active anti-corrosive pigments. This produces the necessary bonding, which at the same time provides corrosion protection. The coatings are not impermeable to the diffusion of water vapour. In the absence of the intermediate layer, which affords bonding and inhibits corrosion, this would lead to a reaction between water vapour and aluminium, with the result that the coating would lift away from the surface (blistering).

10.6 Wear-resistant surface coatings on aluminium

Wear-resistant surface coatings have to fulfil special requirements with regard to coating thickness, hardness and wear resistance. Hard anodising can be used for a large number of wrought and casting alloys. The oxide layers produced are 30 to 150 µm thick and have a uniformly high hardness and abrasion resistance over the whole cross-section of the layer. Depending on the layer thickness and material, this leads to a colouration from greyish brown to black. If dimensional tolerances are important, the hard-anodised layers can be ground or lapped.

10.7 Metallic coatings

Other metals, mainly copper, nickel and chromium or even stainless steels, can be galvanically deposited on aluminium for industrial and decorative purposes. A prerequisite for adherent metallic coatings is a pretreatment of the aluminium surface with a zincate or stannate pickling agent. The properties of the metal coating that are attainable are metal specific. Particularly high wear resistances can be obtained by the deposition of dispersion layers. These contain hard materials such as metal carbides, oxides and diamond, which are kept in suspension in the electrolyte and incorporated in the coating when the metal deposits out. Wear resistant, protective surface coatings for highly stressed components can be applied using thermal spraying techniques.

Hard metallic and non-metallic materials such as metal alloys, carbides, silicides and oxides are used for the coatings. Depending on the process used, the spray powder is melted on at different temperatures: flame spraying (1750 to 3100 °C), detonation spraying (approx. 3000 °C), plasma spraying (approx. 25 000 °C). The layer properties attainable must be checked for each specific case.

11. Aluminium applications

Aluminium is a metal that has found its way into many areas of everyday life. The most important applications are shown in Fig. 29. The following is an overview of some common products and areas of application; it makes no claim to completeness.

Transport:
Aircraft and space vehicles, rail and road vehicles, vehicle number plates, radiators, wheels, Space Frames (Audi A2, A8), watercraft, containers, small containers, refrigerated containers, transportation aids, traffic signs, mechanical ropeways (mountain railways)

Building and construction:
Supporting structures for halls and tents, scaffolding, cranes, bridges, masts, façades, roofs, ceilings, windows, doors, building hardware, display cases, lights, reflectors, signs, radiators, composite pipes

Mechanical engineering and precision mechanics:
Cylinder blocks and heads, pistons, bearings, connecting rods, pulleys, hand wheels, guide rails, supporting tables, internal transportation systems, optical equipment, pneumatic cylinders, measuring instruments, office equipment, offset-printing plates

Electrical engineering:
Overhead cables and accessories, ladders and cable sheathing, busbars, squirrel-cage rotors, windings, cooling fins, bond wire, antennae, condensers, casings

Chemical engineering and food industry:
Containers for transport and storage, heat exchangers, fittings, heat regenerators, air-conditioning systems, pumps, work benches

Kitchen, household ware and metal goods: kitchenware and kitchen equipment, household appliances, cutlery, camping equipment, ladders, climbing hooks and carbine swivels

Packaging:
Foil, capsules, tubes, cans, small tubes, bottles, containers, barrels, closures, laminates (Tetra Pack)

Arts and crafts:
Jewellery, art castings, badges, coins

Aluminium powder:
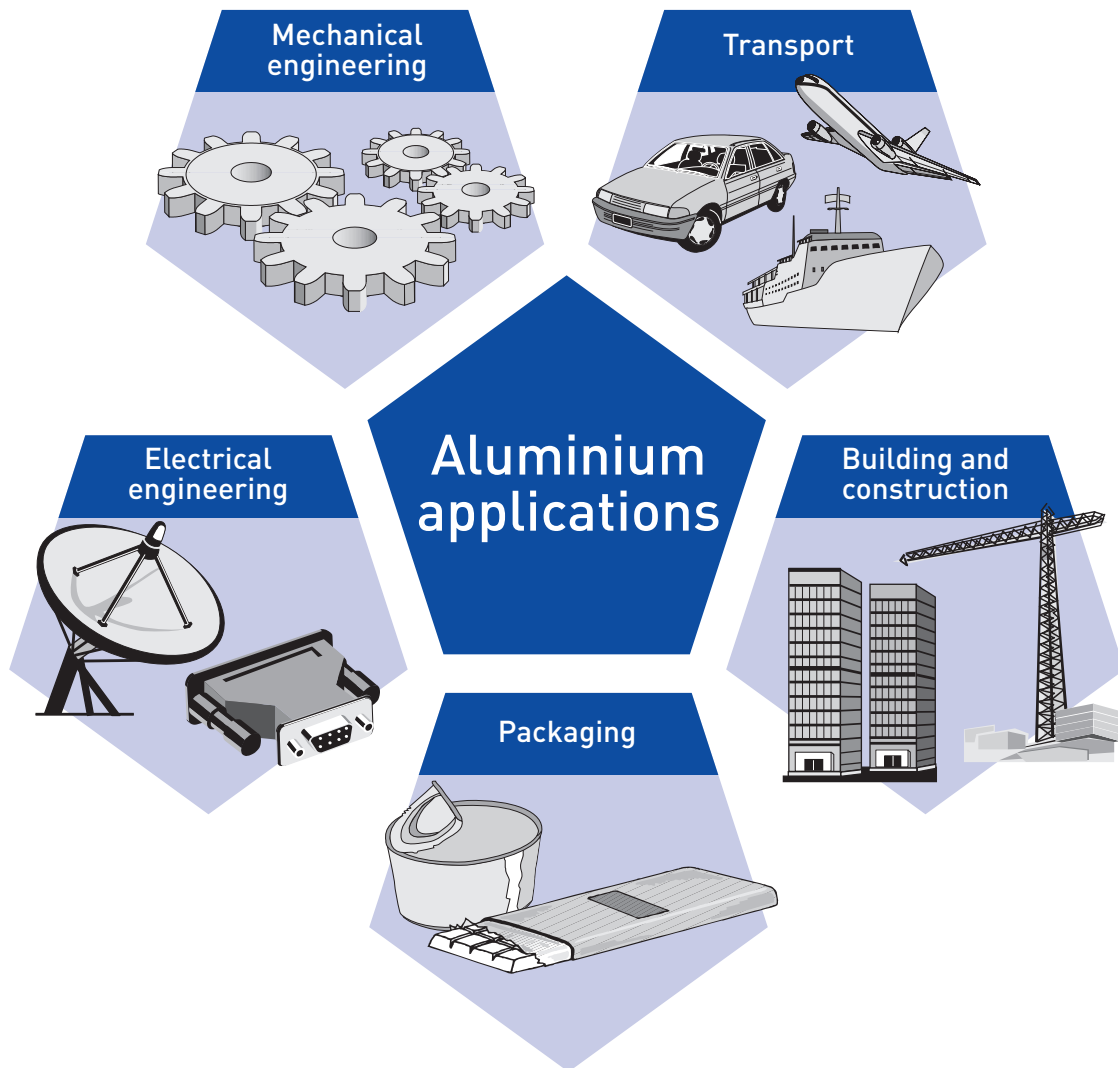As a pigment for paints and plastics, aluminothermic applications and sintered preforms

Aluminium pellets:
Filler for plastics, catalysts for the chemical industry, special products as shot-blasting abrasives
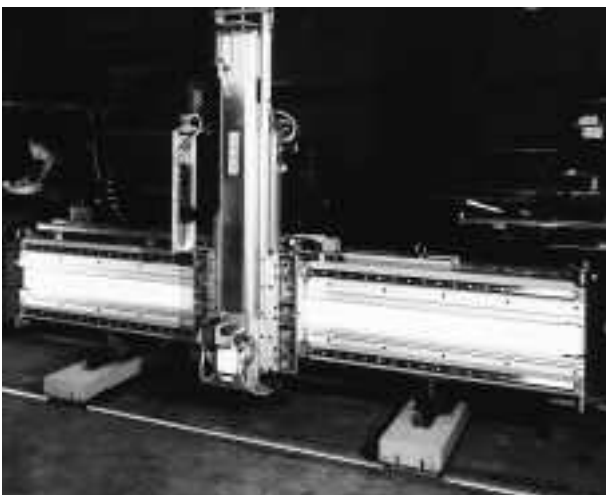
Aluminium grains:
For deoxidation of steel

The most important applications of aluminium in Germany (Fig. 29)

Mechanical engineering

Transport

Electrical engineering

Aluminium applications

Building and construction

Packaging

## Aluminium in mechanical engineering

A prerequisite for the high dynamic capabilities of linear robots is the use of lightweight and stiff extruded aluminium profiles for the axle module. For movement here, there is a system of guide rails made from a round bar fixed in an aluminium retaining profile by two clip profiles.

Aluminium in transport

Aluminium Space Frame (ASF) as the supporting structure for an all-aluminium body of a production series car
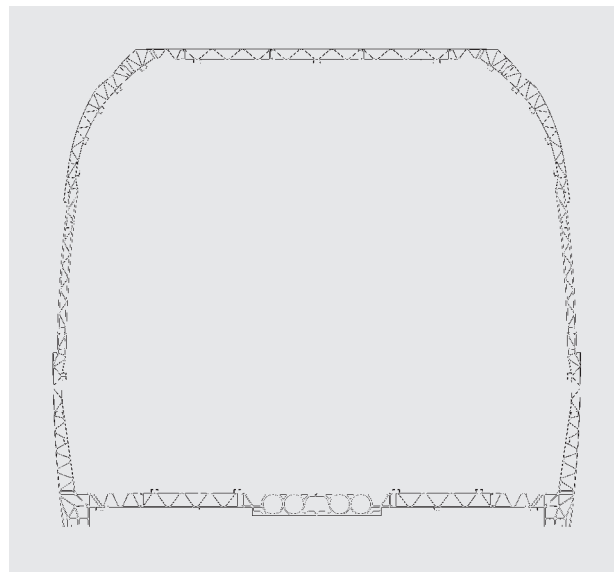
The middle carriages of the ICE train are made from welded extruded aluminium profiles up to 800 mm wide and over 23 m long

Bicycles with aluminium frames, such as the Mercedes-Benz folding bicycle, are frequently standard products nowadays

Lightweight RegioSprinter diesel train

Aluminium in building and construction

Decorative and functional:
Combination of lustrous silvery aluminium façade panel faces and window profiles at the employment exchange in Bremerhaven

Aluminium in electrical engineering

Computer drive

Aluminium control cabinets

Estado do Luz (Stadium of Light) in Lisbon: swung aluminium roofing and upward reaching steel arches look like the way flowers are arranged and convey a playful atmosphere that appeals to the public.

Aluminium in packaging

12. Aluminium in relation to ecology and health

12.1 Aluminium and ecology

Preventive measures to avoid climate change and conservation of resources are the two outstanding environmental objectives of our age. From these one can derive a series of concrete requirements - such as the efficient utilisation of energy, the reduction of emissions and waste, recycling, the development of new environmentally friendly materials, products and production processes that encourage recycling. In the end, the protection of eco-systems and human health are at stake as well as development that is suitable for the future, which safeguards the interests of future generations.

12.1.1 Climate-change protection

The reduction of greenhouse gases is one of the main aims of environmental policy aimed at avoiding climate change and protecting the Earth's atmosphere. Improving energy efficiency and reducing climate-relevant gases is of key importance. The German aluminium industry has been making considerable effort in these areas for many years: e.g. the amount of energy required to produce a kilogram of primary aluminium has been reduced over the last few decades from an average 21 kilowatt hours to its current level of 15 kWh — a saving of almost 30 per cent. There are now electrolysis cells in operation with peak values of less than 13 kWh. As far as the formation of climate-change gases during the production of primary aluminium is concerned, in addition to carbon dioxide these are mainly the trace gases CF_4 and C_2F_6. Here, too, the industry has achieved significant successes. As part of a voluntary self-commitment, the five German primary aluminium smelters have reduced emissions of these trace gases by 85 per cent since 1990. Expressed in carbon dioxide equivalents, this represents a reduction in the year 2000 alone of some two million tonnes compared with 1990. This approach provides market-relevant instruments for ecological progress without the state stipulating how companies should achieve the goals set for them. Such an approach avoids wasting economic resources and at the same time encourages innovation and technical progress. An example of this is the development work being conducted by the aluminium producers on 'inert anodes', which is aimed at using carbon-free, non-consumable materials. According to studies, inert anodes could reduce 60 to 80 per cent of the process-related greenhouse gas emissions and completely eliminate the formation of CF_4 and C_2F_6. Moreover, inert anodes would allow an even greater reduction in fluoride and dust emissions.

Although it is impossible to predict when this technology will be available on a commercial scale, one should remember that something which is a research project today could become tomorrow's 'state-of-the-art'.

12.1.2 Conservation of resources and recycling

The aim of sustainable use of resources is to increase efficiency and ensure that future generations also have access to non-renewable resources. The main themes here are conservation of raw materials, use of renewable energies and improving energy efficiency, recycling, and reduction of waste and emissions.

The raw material bauxite: from today's point of view, the economically mineable bauxite deposits will last for some 200 years.[1] As part of a sustainable, environmentally sound approach, the top soil removed during mining is stored for recultivation at a later date by using it to cover over the area again once mining has finished. About 70 per cent of the area used for bauxite mining is reafforested with the original vegetation and a further 20 per cent is used for forestry and agricultural purposes. The remaining ten per cent is used for recreational, residential and commercial areas and thus supports social or economic development.[2]

Energy: the aluminium industry uses CO_2-free sources of energy to a particularly large extent. More than 50 per cent of the electricity supplied to aluminium smelters worldwide is hydroelectricity, a renewable source of energy.

The quantities of recycled metal in circulation are continuously increasing. This conserves valuable resources and at the same time saves energy, because the energy needed for recycling is up to 95 per cent less than that needed to produce primary aluminium.

An expression of the efficient use of energy, for example, is the district-heating project at the world's largest aluminium rolling mill at Alunorf in North Rhine-Westphalia, Germany. By using the waste heat from the waste-gas cleaning from 13 melting furnaces, 6 500 people in a new residential area a few kilometres away from the plant could be supplied with heating. The measure has led to the substitution of up to 3.9 million cubic metres of natural gas a year, and thus to avoid the formation of some 10 000 tonnes of carbon dioxide annually.

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1) Federal Institute for Geosciences and Natural Resources and National Geological Services in the Federal Republic of Germany: Geological Yearbook (Special Publications). Flows of material quantities and energy requirements during the extraction of selected mineral raw materials - partial study aluminium, 1998 (in German)

2) International Aluminium Institute, Second Bauxite Mine Rehabilitation Survey, London, July 2000

Recycling: aluminium's high intrinsic material value means that it has always been worthwhile returning it to the material recycling loop that comprises metal extraction, processing, utilisation, and recovery. Unlike many other materials, there is no deterioration in properties resulting from recycling. Scrap profiles can be made into new profiles or other high-grade products, aluminium sheet and foil can be made into new material for rolling. The amount of recycled metal in circulation is thus forever on the increase. The aluminium industry can be regarded as recycling on a large scale; as a 'renewable material', aluminium can be put on an equal footing with renewable raw materials. Aluminium is simply 'used' and not 'consumed'.

The conservation of resources starts with in-house closed recycling loops. Where aluminium scrap is produced during processing it is returned completely to the production process. Furthermore, in the aluminium industry, in-house production loops extend to operating and auxiliary materials. For example, recycling includes the core sand used for the sand-casting moulds for engine blocks and cylinder heads, rolling oils used in the production of semis and solvent residues from foil-lacquering processes. The plants even recover the salts used to remove impurities adhering to the scrap in the recycling process itself. In-house recycling loops thus enable resources to be used in a sustainable manner. In this way, they reduce any damage to the environment and alleviate the need for waste disposal.

Regardless of all of this, a well-functioning recycling industry has ensured that aluminium has been recovered from scrap for a good many years - for example from the transport, building and construction, and packaging sectors. With a production of some 620 000 tonnes, or 49 per cent of total production, the German aluminium-recycling industry is one of the leaders in Europe. The recycling rate is about 95 per cent in the transport sector and 85 per cent in the building and construction industry. The recycling of aluminium from packaging increased to a new level following the setting up of the Duales System. This nationwide system for the collection, sorting and use of used packaging has led to some 80 per cent of aluminium packaging now being recycled.[3] Thanks to the use of modern sorting techniques, it is now possible to also recover aluminium from laminates and even coffee packaging. Despite the efforts and successes in this sector, one needs to bear in mind that sustainable development does not always mean one has to have one hundred per cent recycling. The effort needed to collect the very last item of packaging bears no relation to the achievable benefit.

3) Source: GVM -Gesellschaft für Verpackungsmarktforschung

Reduction of emissions and waste: where it is not possible to close recycling loops, and waste is produced, the aim of a sustainable approach to production and consumption is to limit this waste to a minimum, to place as little demand on waste disposal sites as possible and to try to find possible secondary uses for the residues. Spent pot linings are an example of how the amount of mineral waste can be reduced in the primary smelting process: in Germany's largest aluminium smelter, furnace lifetimes have been increased by 150 per cent since 1975 - with the result that significantly less spent pot-linings are produced now than in earlier years.

Environmentally friendly development also demands the reduction from production processes of pollutant discharges that can endanger human health and the ability of the natural environment to adapt. The optimisation of production processes and the installation of pollution control equipment has now reached such a level in Germany that it is an example for the rest of the world. This is also the case with the plant-specific environmental protection in the aluminium industry.

12.2 Aluminium and health

12.2.1 Aluminium compounds and ingestion

Everybody encounters aluminium in its most varied chemical forms, whether they are naturally occurring aluminium compounds, articles of daily use or as mass-produced food additives. Aluminium beverage cans, pots, pans and foil for packaging have long since been taken for granted as part of our everyday life. However, hardly anyone knows that aluminium compounds also occur naturally in practically all animal-based or vegetable-based foodstuffs.

Aluminium is a constituent of nearly all rocks and soils, albeit not in metallic form. In nature, one only finds aluminium combined with other elements, chiefly with oxygen. As a result of soil erosion, aluminium compounds find their way into the air we breathe or are dissolved by surface waters or ground water. This results in aluminium compounds being absorbed by plants and animals, and also reaching human beings via the food chain.

Despite the widespread availability of aluminium in inanimate nature, aluminium is mostly only present as traces in biological systems. According to our current state of knowledge, aluminium is not needed for the proper functioning of our metabolism or growth processes. Various aluminium compounds are used as food additives or in drinking water processing plants.

Some deodorants or medicines contain or consist entirely of aluminium compounds. There is usually no potential health risk associated with the intake of these compounds - even at high dosages.

A range of aluminium compounds is used for a large number of mass-produced foodstuffs and medicines, including painkillers such as Aspirin or medication used for heartburn. They can be found as additives in foodstuffs such as soft cheese and pickled preserves, as well as in toothpaste and deodorants. Aluminium compounds are also used as flocculants in the treatment of drinking water at wastewater treatment plants.

Whenever there is talk of aluminium in the body, this refers to chemically combined aluminium and its soluble fractions - and not to the metal. There is a continuous intake of aluminium compounds into our bodies with food, drinking water and medication, as well as via the inhalation of dust particles. These are mainly insoluble aluminium constituents that are not absorbed by the body. The lungs, skin and gastrointestinal tract are effective barriers against them entering the blood stream.

12.2.2 Products applied externally

Numerous aluminium compounds are applied externally to the skin in the form of ointments, creams or solutions. The cleansing, antiseptic and disinfecting effect of basic aluminium acetate manifests itself in the treatment of skin abrasions, small wounds and burns.

The acidic environment in the stomach helps dissolve certain aluminium compounds. The aluminium content of foodstuffs varies considerably; however, in most dishes it can be regarded as low. Some plants have a distinctly marked tendency to store aluminium; animals, like human beings, excrete nearly all the aluminium so that plant-based foodstuffs usually have higher aluminium contents than animal-based ones.

Even if the foodstuff being consumed has an extremely high aluminium content, the body will only absorb a very small fraction of it. The quantity absorbed by the bloodstream is quickly excreted through the kidneys via the urine. Dialysis patients and premature babies, whose kidneys are not functioning properly for other reasons, are special cases because their ability to excrete aluminium that the body absorbs is limited.

12.2.3 Metallic aluminium products

The use of aluminium packaging and pots and pans only leads to an insignificantly small increase in the aluminium levels of the contents and dishes. Acidic food and drink that comes into direct contact with uncoated aluminium is an exception. These additional quantities can easily lead to the average daily intake being exceeded; the amount will depend on the pH of the contents and the time they are in contact with the aluminium. Examples of acidic dishes are rhubarb, tomatoes, cabbage, apricots, sauerkraut and citrus juices. There is no need to worry about a health risk in these cases either, because the rapid excretion of the aluminium will prevent critical levels in the blood being reached.

12.2.4 Alzheimer's disease

In most cases, Alzheimer's disease first occurs at an advanced age and manifests itself as a continual loss of mental functions, coupled with changes in a person's personality until he or she is totally incapable of organising his or her daily needs.

Based on current scientific knowledge, there is no conclusive evidence to show that aluminium compounds are aetiologically involved in the way the disease develops.

Aluminium is only one aspect among many that is being investigated as part of research into the cause of Alzheimer's disease. Other possible contributory factors include:

■ genetic factors
■ pathogenic agents or virus-like structures
■ toxins
■ metabolic disorders
■ neurochemical disorders
■ the effect of head injuries

Recently there have been many indications that genetic defects play a significant role in the onset of the disease.

The cause of Alzheimer's disease is still unknown. There is no scientific investigation that advises against the use of aluminium products, whether it be in the form of pots and pans or packaging. The use of aluminium for packaging and containers does not have a detrimental effect on people's health. Nor can a low-aluminium diet either prevent the disease occurring or influence it in a positive manner.

Appendix

Further reading
Aluminium Handbook,
Vol. 1: Fundamentals and Materials
First published 1999
ISBN 3-87017-261-4

Vol. 2: Forming, Casting, Surface
Treatment, Recycling and Ecology
First published 2003
ISBN 3-87017-262-2

Aluminium-Taschenbuch
Band 3: Weiterverarbeitung and Anwendung
16. Auflage 2003
ISBN 3-87017-275-4
(in German)

Aluminium-Werkstoffdatenblätter
4. Auflage 2004
ISBN 3-87017-281-9
(in German)

Aluminium-Schlüssel / Key to Aluminium Alloys
6th ed. 2003
ISBN 3-87017-273-8

Details of currently available technical information and brochures relating to aluminium can be found at: www.aluinfo.de.

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