Extrusion: Second Edition
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CHAPTER 5

The Production of Extruded Semifinished Products from Metallic Materials*

THE HOT-WORKING PROCESS extrusion is, in contrast to other compressive deformation processes used to produce semifinished products, a deformation process with pure compressive forces in all three force directions. These favorable deformation conditions do not exist in other production processes for semifinished products. Even in rolling, which is the most important compressive working process for producing semifinished products, tensile forces occur in the acceleration zone of the roll gap as well as in the cross rolling process used to pierce blanks in the rolling of steel tubes. These tensile forces cause problems in the rolled product if the deformation conditions are not optimized. The benefits of this three-dimensional compression in terms of deformation technology, which have already been discussed in this book, can be clearly seen in Fig. 5.1 based on experimental results for face-centred cubic (fcc) aluminum and zinc with its hexagonal lattice structure.

The extensive variations in the extrusion process enable a wide spectrum of materials to be extruded. After rolling, extrusion can be considered to be the most important of the hot-working processes.

Extrusion of Materials with Working Temperatures between 0 and 300 °C

Günther Sauer*

5.1 Extrusion of Semifinished Products in Tin Alloys

Tin is a silver-white, very soft metal with a stable tetragonal lattice in the temperature range 20 to 161 °C. The pure metal has a density of 7.28 g/cm^3 and a melting point of 232 °C.

The material can be easily worked with its recrystallization temperature below room tem-

*Extrusion of Materials with Working Temperatures between 0 and 300 °C, Günther Sauer
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Materials, Günther Scharf
Extrusion of Semifinished Products in Copper Alloys, Martin Bauser
Extrusion of Semifinished Products in Titanium Alloys, Martin Bauser
Extrusion of Semifinished Products in Ziroconium Alloys, Martin Bauser
Extrusion of Iron-Alloy Semifinished Products, Martin Bauser
Extrusion of Semifinished Products in Nickel Alloys (Including Superalloys), Martin Bauser
Extrusion of Semifinished Products in Exotic Alloys, Martin Bauser
Extrusion of Powder Metals, Martin Bauser
Extrusion of Semifinished Products from Metallic Composite Materials, Klaus Müller

perature. Consequently, the softest condition develops rapidly in tin materials after cold working. Work hardening by cold working is not possible.

Tin is very stable at room temperature and is not poisonous. Unlike lead, it can therefore be used in contact with food. The metal is used as the base material for soft solder, anode materials as well as bearing materials and for tin plating steel sheet (tin plate).

Soft solders are the main application for tin. Lead, silver, antimony, and copper are used as alloying elements. Special soft solders also contain cadmium and zinc. Aluminum is used as an alloying component for soft solders used to join aluminum alloys. Bearing metals based on tin contain antimony, copper, and lead as the alloying elements as well as additions of cadmium, arsenic, and nickel.

The production of semifinished products in tin alloys by extrusion is limited today to the production of feedstock for the manufacture of soft and special soft solders on transverse extrusion presses and to the direct extrusion of feedstock for the manufacture of anodes with solid and hollow cross-sectional geometries for electrochemical plating. Tin is also used for the production of rolled strip, as the feedstock for the manufacture of high-capacity electrical condensers, as well as for roll cladding of lead-base strips for organ pipes, wine bottle caps, and Christmas ornaments (tinsel).

In general, tin-base materials have good bearing properties and are consequently used as the base material for bearing metals. Very little friction occurs in direct extrusion between the billet surface and the container inner wall because of these good bearing properties. Tin-base extruded alloys, therefore, tend to flow largely according to flow pattern A (Fig. 3.11) in direct extrusion.

The flow stress k_f that has to be overcome for the deformation of very soft pure tin is significantly higher than that of pure lead, as can be clearly seen in Fig. 5.2. It is, however, extremely low at 20 to 32 N/mm^2 for logarithmic strains φ_g up to 0.7 [Sac 34]. Therefore, a specific press pressure of maximum 400 N/mm^2 is sufficient for the direct extrusion of tin alloys when the low friction between the billet and the container liner surface is taken into account.

Tin-base alloys for the production of soft solders are generally extruded transversely at billet temperatures of 50 to 60 °C and a container temperature of approximately 100 °C. It is often sufficient to heat the front third of the billet to this temperature so that, on one hand, the billet upsets from the front to the back to prevent air entrapment and, on the other hand, the optimal welding conditions for the resultant transverse weld in the extruded product are obtained. This transverse weld in soft solders has to be capable of withstanding the drawing loads during the reduction in diameter of the extruded wires on multispindle drawing machines.

Semifinished products in tin materials including bar, wire, tubes, and sections are produced on direct extrusion presses. For productivity reasons, higher extrusion speeds are desired in this process than those used in the transverse extrusion of soft solders, which are typically 4 m/min. It is therefore advantageous to heat the billets to 100 to 150 °C. Again, it is beneficial to have a temperature profile with the temperature decreasing toward the back of the billet. In automatic fully integrated extrusion plants complete

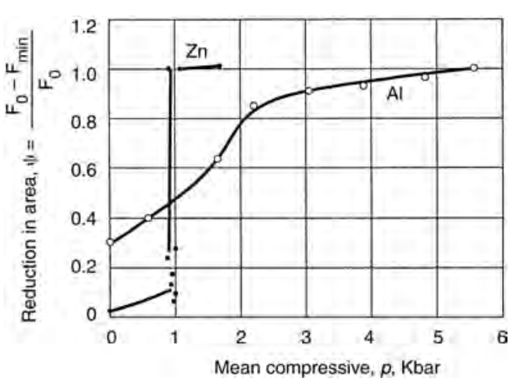


Fig. 5.1 Improving the workability of aluminum and zinc with a hydraulically produced increasing mean compressive stress p measured by the increase in the reduction in area at fracture φ in tensile tests at room temperature

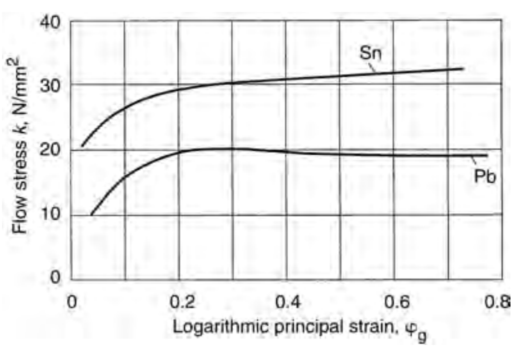


Fig. 5.2 Flow stress k_f as a function of the logarithmic strain of pure lead and pure tin (Source: Rathjen)

with melting furnaces and mold casting machines, as shown in Fig. 5.3, the cast billets retain the heat from the casting process to assist the deformation process. Care has to be taken to ensure that the heat from the casting process, when combined with the deformation heat, does not result in excessive temperatures at high extrusion speeds in the deformation zone of the extrusion tooling. The solidus of the lead-tin eutectic at 183 °C has to be taken into account in the tin alloys containing lead. If melting occurs in the solid tin matrix, transverse cracks will definitely be produced in the extruded products. Controlled cooling of the extrusion tooling improves the situation. In addition, the billet surface is sometimes brushed with a lubricant to improve the product surface.

Tin alloys will weld during the extrusion process under suitable deformation conditions including the extrusion load and temperature. They can, therefore, be used with porthole and bridge dies as well as for billet-on-billet extrusion with feeder chamber dies. These extrusion tools are, in principle, similar to those used in aluminum extrusion. Their design is simpler in detail and the dies are nitrided.

Simple two-column horizontal oil-hydraulic extrusion presses are used. Figure 5.3 shows a typical two-column extrusion press for tin and tin alloys with a maximum press load of 5000 kN.

5.2 Extrusion of Semifinished Products in Lead Materials

Lead is a soft metal, matte blue in appearance with a fcc lattice structure. The pure metal has a very high density of 11.34 g/cm^3 and a melting point of 327 °C. Lead alloys can also be easily worked. Work hardening after cold working at room temperature, for example, from 40 to 120 N/mm^2 disappears within a few minutes because the recrystallization temperature of the base material is about 0 °C. Cold working of lead-base alloys can be approximately compared in its effect to hot working of other metals. Work hardening by cold working is not possible.

Pure lead is very soft and ductile. Soft lead has a very low flow stress k_f as shown in Fig. 5.2. It is, therefore, not possible to draw pure

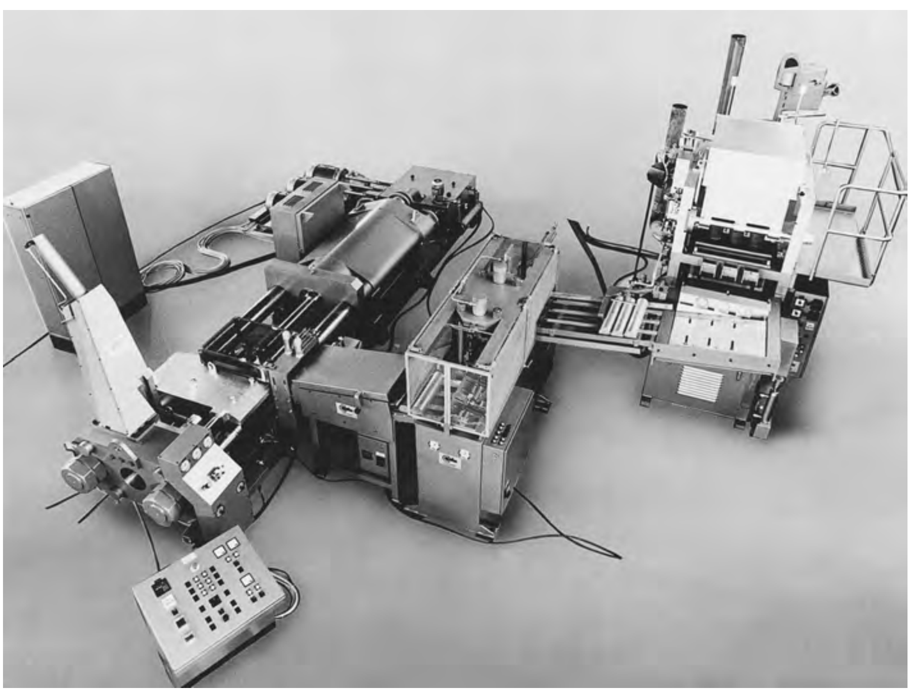


Fig. 5.3 Modern integrated fully automatic 5000 kN extrusion plant for the production of bar, wire, tube, and sections in lead and tin alloys complete with casting oven, triple billet casting plant, hot-billet shear, and oil hydraulic long-stroke extrusion press (Source: Collin)

lead to wire. However, lead alloys have higher flow stresses. Additions of antimony and tin produce solid-solution hardening of the lead, increasing both the base strength and the work-hardening capability. This raises the recrystallization temperature. The loads needed in deformation processes also increase. Antimony and zinc are the main alloying elements for lead, although small amounts of arsenic and cadmium, as well as copper nickel and silver, are also used.

Lead antimony alloys are referred to as hard lead because the antimony significantly hardens the soft lead. Alloys of this type with antimony contents up to 3 wt% also age harden. For example, the Brinell hardness of an alloy with 2 wt% antimony increases from 56 to 130 N/mm^2 within 100 days after quenching from 240 °C. The toughness and the fatigue strength, as well as the corrosion resistance of these alloys, can also be improved by the addition of specific amounts of tin. This is important for the mechanically fatigue loaded sheathed cables on, for example, bridges. Lead forms a eutectic with 11.1% antimony at 253 °C. This has to be taken into account when determining the deformation temperature for the extrusion of PbSb alloys with eutectic, low-melting point phases on grain boundaries.

Lead-tin alloys with their low solidus and liquidus temperatures are particularly suitable for the production of soft solders. Lead forms a eutectic with 38.1% tin at 183 °C. These soft solders can be used to solder steel and copper alloys. Organ pipes are produced from lead-tin alloy strips with similar tin contents. Tin contents from 45 to 75 wt% are used depending on the timbre. Lead-tin-antimony alloys with additives of arsenic, cadmium, and nickel are very important as bearing metals.

Table 5.1 gives recommended lead alloys for the extrusion of rod, wire, tubes, sections, and cable sheathing. Lead alloys are extruded with deformation temperatures in the range 100 to 260 °C, depending on the composition, to obtain economic extrusion speeds of typically 50 to 60 m/min. On the other hand, lead-base soft solders are extruded at significantly lower temperatures of approximately 55 °C and slower speeds of 2 to 4 m/min. When determining the billet and container temperatures, care must be taken to ensure that any eutectics on the grain boundaries do not melt as a result of excessive deformation temperatures in combination with the deformation and friction heat during extrusion. A liquid metal phase on the grain boundaries of a solid metal matrix in extrusion will unavoidably produce transverse cracks in the extruded product. Lubricant is added to the billet surface with a controlled brush stroke.

Lead has even better bearing properties than tin. Lead alloys, therefore, also flow mainly ac-

Table 5.1 Lead-base extruded materials

Material	Abbreviation	German Standardization Institute (DIN)	Alloy constituents and permitted impurities, wt%	Application
Fine lead	Pb 99.99 Pb99.985	1719	Permitted impurities, max 0.01 Permitted impurities, max 0.015	Tube and wire for the chemical industry
Copper fine lead	Pb 99.9 Cu	1719	Cu, 0.04–0.08 Permitted impurities, max 0.015 Pb remainder	Pressure tube
Primary lead	Pb 99.94 Pb 99.9	17641	Sb 0.75–1.25.2006 As 0.02–0.05 Pb remainder	Pressure tube
			Sb 0.2–0.3 Pb remainder	Waste pipe
Cable lead	Kb–Pb Kb–Pb (Sb)		. . .	Standard cable sheath
	Kb–PbSb0.5 Kb–PbSn2.5 Kb–PbTe0.4	17640	Sb 0.5–1.0	Cable mantle sheath resistant to fatigue failure resulting from severe vibration
			Sn ≥ 2.5 Te ≥ 0.035	
Hollow anodes	PbSn10	. . .	Sn 8–12	Anodes for electrochemical coating of bores of bearing shells and bushes for bearing production Anodes for corrosion protection of bearing shells

Source: Laue/Stenger

cording to flow type A in direct extrusion as shown in Fig. 5.4 where the variation of the extrusion load over the container cross-sectional area A_0 is plotted as a function of the stem displacement and the extrusion ratio [Sac 34, Hof 62].

Lead alloys will weld during extrusion at suitable temperatures and extrusion pressures similar to tin alloys and certain aluminum alloys. Tubes and hollow sections can, therefore, be extruded with porthole and bridge dies. Feeder chamber dies have also proved successful for the extrusion of these materials and are required for billet-on-billet extrusion. The tools used for the extrusion of tin and lead alloys are in principle similar to those used for aluminum extrusion, although the designs are simpler because of the significantly lower thermomechanical stresses. All extrusion dies are nitrided.

Extrusion plants consist of integrated automatic complete plants with horizontal, hydraulically operated two-column presses and maximum extrusion loads of 5000 to 10000 kN, as shown in Fig. 5.3. A specific extrusion pressure of 400 N/mm^2 is similar to tin-base extruded materials, adequate for the extrusion of lead-base alloys.

Large tubes with internal diameters up to 300 mm in lead alloys are sometimes extruded on old vertical indirect extrusion presses over mandrels and charged with liquid metal. These extrusion presses can have loads between 5000 and 15,000 kN. Cable sheathing with lead alloys is carried out on special cable sheathing presses as shown in Table 5.1 (see the section on cable sheathing in chapter 3).

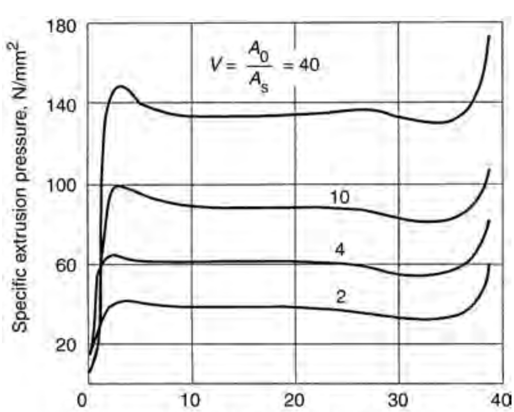


Fig. 5.4 Specific extrusion pressure in N/mm^2 as a function of the stem displacement and the extrusion ratio $V = A_0/A_S$ in direct extrusion of soft lead (Source: Siebal/Fangmeier)

5.3 Extrusion of Tin- and Lead-Base Soft Solders

The standard soft and special tin solders in DIN 1707, as well as nonstandardized special soft solders, are extruded as solid bars, solder threads, solid wire, and hollow wire (tube solder) filled with flux mainly on small hydraulic automatic extrusion presses. The maximum extrusion loads are usually 2500 kN with a maximum specific pressure of 600 N/mm^2, which is required because of the extreme metal flow. The billet-on-billet process is used on transverse presses. Extrusion is usually followed by drawing to the finished diameter of 5 to 0.5 mm on multispindle drawing machines. The majority of finished diameters fall in the range 1 to 2 mm. Special soft alloys with low cold-working capacities sometimes have to be extruded as multiple strands to the finished diameter using the direct extrusion process. Economic wire solder presses operate completely automatically in the same way as large extrusion plants with automatic billet feed called by the press during the extrusion cycle and automatic removal of the extruded semifinished product. Figure 5.5 shows a fully automatic plant with an integrated melting furnace and a chill mold billet casting machine.

Cored solders are hollow wire filled with flux by a special tool during extrusion as shown in Figures 5.6 and 5.7. The extrusion tool system needed for the extrusion of hollow wire with flux filling, which includes the die head with the hollow mandrel, the extrusion die, and the welding chamber, and, in particular, their relative arrangement is similar to that for cable sheathing. Figure 5.6 depicts the construction of a die head. The application of "transverse extrusion" combined with "billet-on-billet" extrusion is an essential requirement for the production of continuous cored solder. Cored solder has, similar to the cable sheath, both longitudinal and transverse welds from this production method. The billets are usually produced by the chill casting process using casting machines and are normally processed with the cast skin forming the billet surface.

Typical widely used solders are the soft solders L-PbSn40, L-Sn50Pb, L-Sn60Pb and L-Sn60PbCu2, the special soft solders L-SnCu3

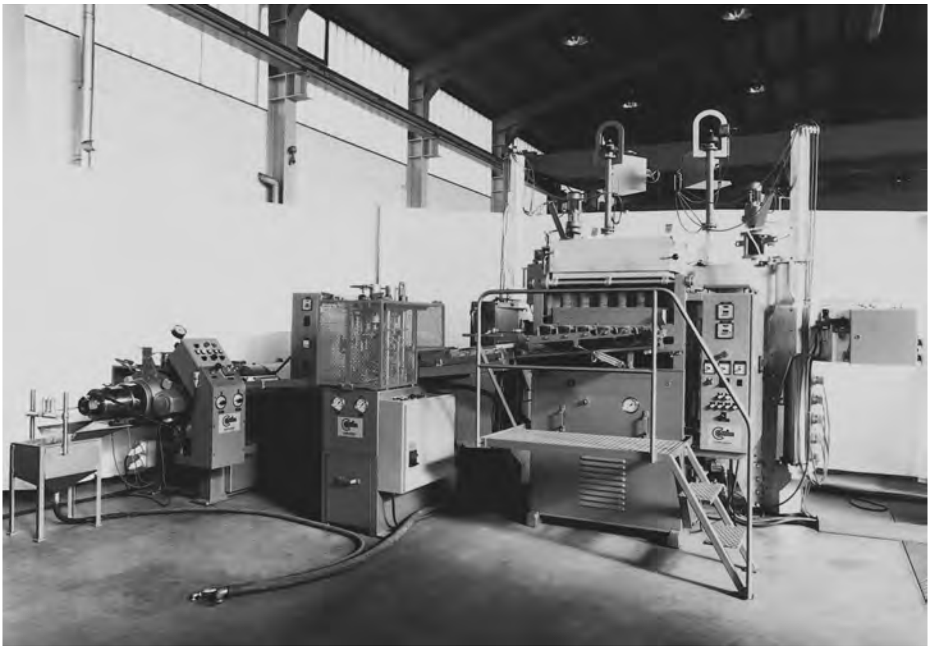


Fig. 5.5 Modern fully automatic extrusion plant for the production of soft solder with casting oven, chill mold billet casting plant, hot-billet shear, and oil hydraulic 2500 kN extrusion press. The extrusion press is fitted with a fixed dummy block on the stem. (Source: Collin)

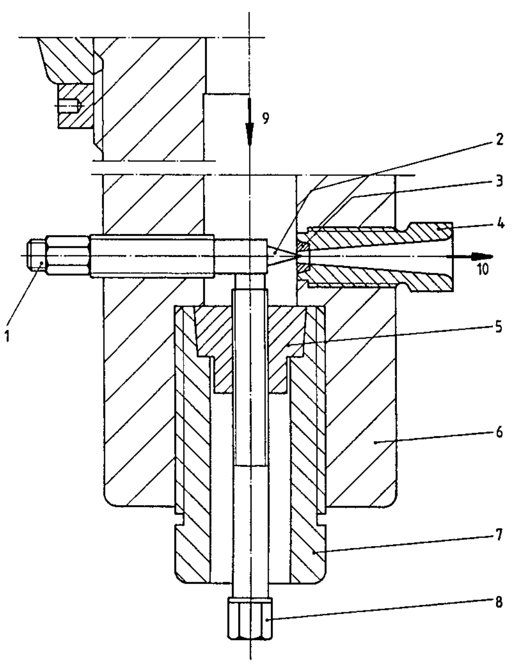


Fig. 5.6 Extrusion tooling for the extrusion of hollow solder. 1, connection to the flux container; 2, hollow mandrel; 3, extrusion die; 4, extrusion die holder; 5, pressure nut; 6, one-piece die head with the container; 7, front nut; 8, hollow mandrel screw adjustment; 9, extrusion stem direction during extrusion; 10, direction of extruded product (Source: Collin)

and L-SnAg5 to DIN 1707 and, as an example of a nonstandard solder, the special soft solder L-SnCd25Zn5.

The easy and moderately difficult to extrude soft solders are usually worked with a temperature of 55 to 60 °C. Heating of the front third of the billet is sufficient. To avoid air entrapment the billet should upset under the influence of the extrusion load and the temperature from the front end to the back and readily weld to the previously extruded billet. The container temperature is set to 90 to 110 °C. With automatically operating integrated extrusion plants for solder wire that include a melting oven and chill mold casting machine, as shown in Fig. 5.3, the cast billet must be transferred with sufficient heat for deformation retained from the casting heat. Equally, an automatic extrusion plant for solder wire need not include a melting oven and chill mold casting machine. Plants with a large number of program changes and small production batches also operate economically without these facilities. The extrusion plant is then equipped with a billet magazine and an induction furnace in line with a hot billet shear. This is used to heat either the entire billet volume or the front third to the deformation temperature.

Special soft solders need to some extent lower the more difficult-to-extrude alloys' higher deformation temperatures, which can be as high as 400 °C. The container temperature has to be set correspondingly high to avoid excessive heat transfer between the billet and the container during extrusion.

The wires are usually extruded to a diameter of approximately 15 mm and then draw on multispindle drawing machines to diameters between 5 and 0.5 mm. The transverse and longitudinal welds formed in the welding chambers of the extrusion die are able to withstand the drawing deformation loads without any problem. Good extruded surfaces are achieved by lightly lubricating the surface of statistically uniformly selected billets with a special lubricant. The quantity applied of this lubricant must be controlled extremely accurately; otherwise, the lubricant can enter the extrusion welds and prevent perfect welding. The wires would then break at the welds during drawing and have to be scrapped.

The extrusion process for the production of feedstock for solder wire commences with the billet call from the extrusion press. The extruded wire passes continuously through a multispindle drawing machine in line with the press corresponding to its capacity. The drawing machine controls the extrusion press. The billet is transferred either directly from the chill molding machine as shown in Fig. 5.8 or from a billet magazine via an induction furnace, depending on the plant specification. The billet end faces are sheared in a hot shear and thus cleaned of any oxide [Lau 76]. This is necessary to ensure perfect transverse welds. After this operation the billets collect in a magazine in front of the container and fall one by one into the centerline of the press when the stem is fully withdrawn. When the stem moves forward, the billet enters the container and is pushed against the previously extruded billet and the contacting material volumes weld together. The extrusion emerging from the die is automatically fed into a multispindle drawing machine and heavily reduced in diameter in one operation using a large number of drawing dies. The extruded wire usually passes through a water cooling system before reaching the drawing machine.

The production plan given subsequently for the manufacture of solder wire with a flux core (hollow solder) explains the solder wire manufacturing process in more detail.

Production of 1000 kg hollow solder with a diameter of 0.8 mm from the soft solder L-Sn60Pb according to DIN 1707 filled with a flux of type F SW32 according to DIN 8511 with 2.5% by weight:

1. Casting in a chill mold casting machine or heating of 168 billets with dimensions: 72 mm diam. × 175 mm long (initial billet weight: 6.05 Kg) using an induction rapid billet heating furnace to 50 °C.

Fig. 5.7 Die holder, left, and hollow mandrel, right, as well as the front nut of the container with the pressure nut for adjusting the hollow mandrel (See Fig. 5.6) (Source: Collin, Alchacht)

2. Shearing of the billet end faces using the double shear visible in Fig. 5.5 during the transfer to the extrusion press.
3. Extrusion into air with subsequent water cooling after the press—one extruded bar per extrusion with the dimensions 14.7 × 6.7 diam. using the billet-on-billet process and transverse extrusion with simultaneous addition of flux using an extrusion tool system shown in Fig. 5.6 from a container: 75 mm diam. on a 2500 kN extrusion press—container temperature: 100 °C; exit speed: 3.02 m/min; extrusion ram speed: 5.5 mm/s; extrusion ratio $V = 32.86$.
4. Drawing to: 6 mm diam. in one operation with 14 drawing dies on a roughing multispindle drawing machine. This drawing machine controls the extrusion press according to the wire requirement via a dancing roll.

Fig. 5.8 Oil-operated 2500 kN solder wire extrusion press as shown in Fig. 5.5 with extruded hollow solder emerging transverse to the press longitudinal axis. The vessel on the left-hand side is filled with flux and linked by a tube to connection 1 on the hollow mandrel 2 in the extrusion tool in Fig. 5.6. The container is located above the hollow mandrel, and the usually very liquid flux heated to approximately 60 to 120 °C flows under hydrostatic pressure to the hollow mandrel.

5. Drawing to: 1.35 mm diam. in one operation with 40 drawing dies on an intermediate multispindle drawing machine
6. Drawing to: 0.8 mm diam. in one operation with 40 drawing dies on a fine multispindle drawing machine.
7. Coiling the wire on bobbins. This operation is frequently combined with operation 6. Quality control of the wire surface is also carried out.
8. Control and labeling

Solder threads are produced by multiple drawing of extruded solid wire approximately 15 mm diam., depending on the final dimensions on the multispindle drawing machines and automatically cut transversely after drawing.

The work hardening of the solder material produced during the cold working is countered by the continuous softening from recrystallization during the multispindle drawing process. The process is helped by the heat of the drawing lubricant in the sump of the drawing machine, in which the entire drawing process takes place. Soft solder usually recrystallizes at room temperature following work hardening. Therefore, intermediate annealing is not needed to achieve the soft, i.e., recrystallized material, state required for further cold working.

5.4 Extrusion of Zinc Alloy Semifinished Products

Pure zinc has a density of 7.13 g/cm^3 and a melting point of 419.5 °C. The metal crystallizes with a hexagonal lattice structure, which, at room temperature only permits material slip on the (0001) basal plane. Consequently, polycrystalline zinc alloys at room temperature and below, in particular, are brittle. Deformation of this material is possible only after heating to temperatures between 150 and 300 °C. Twin formation during the deformation improves the plasticity. Zinc alloys do not have any great work-hardening capacity because the recrystallization temperature of these alloys is at room temperature or just above. The main alloying elements of zinc are aluminum and copper. Aluminum improves the mechanical properties of zinc alloys particularly when combined with hot working by extrusion. Copper also improves the mechanical properties of zinc-base alloys but not to the same extent as aluminum. However, copper improves the fatigue strength and machinability of zinc alloys.

Typical zinc-base extrusion alloys are ZnAl1Cu and ZnAl4Cu1. Bars, wires, tubes, and sections are produced from ZnAl4Cu1. The material can also be drawn. ZnCu is an alloy that is used for the production of sections and hot-stamping components. Car tire valves are produced from the alloy ZnAl15.

After hot rolling, extrusion is the most important deformation process for zinc-base alloys, although the main application of zinc alloys is pressure die castings. The extrusion of these alloys has lost a lot of its importance. Zinc alloys are extruded only to a limited extent mainly because the limited workability associated with the hexagonal lattice structure also affects the hot workability. Zinc alloys are extruded at deformation temperatures of approximately 150 to 300 °C. Only very low extrusion speeds of approximately 3 to 6 m/min can be achieved because of the limited extrudability of the extruded materials at high specific pressures [Sac 34, Lau 76, Schi 77, Schu 69].

Extrusion of Materials with Deformation Temperatures between 300 and 600 °C

Günther Sauer*

5.5 Extrusion of Semifinished Products in Magnesium Alloys

Magnesium is a metal with the low density of 1.74 g/cm^3, which is approximately 40% below that of aluminum. The densities of magnesium alloys fall in the range 1.76 to 1.83 g/cm^3. The modulus of elasticity of pure magnesium is approximately 41,000 N/mm^2 and that of magnesium alloys between 45,000 and 47,000 N/mm^2, i.e., on average about 66% of that of aluminum alloys. Pure magnesium has a liquidus temperature of 650 °C and crystallizes with a hexagonal lattice structure. Metals with the hexagonal lattice structure can only slip on the (0001) base plane at room temperature. Consequently, magnesium alloys are very brittle at room temperature. However, temperatures above 200 °C permit the activation of other slip planes as well as the formation of deformation twins enabling these materials to be hot workable. The narrow temperature range between the brittle and the plastic deformation behavior of magnesium alloys is of interest and is illustrated in Fig. 5.9 for the alloy MgAl6Zn [Sac 34, Bec 39]. Whereas this material clearly has a limited workability at 208 °C as can be seen by the shear stress cracks running at 45°, it can be readily hot worked at 220 °C; i.e., a temperature increase of only 12 °C produces significantly better deformation properties in this alloy. The formation of twin lamellae is associated with the improvement in the plastic workability.

Only magnesium alloys are used as structural materials and in structural applications, the high notch sensitivity has to be taken into account. This also has to be allowed for in the cross-sectional geometry of extruded sections. In addition, magnesium alloys have a very elastic behavior in compression because of their low elastic moduli between 45,000 and 47,000 N/mm^2, but this also increases the sensitivity to buckling.

Specific alloy additions can raise the static and dynamic materials properties of magnesium by a factor of two or three. The principle alloying elements of the wrought alloys are aluminum with contents up to 10 wt%, zinc up to 4 wt%, and manganese up to 2.3 wt%. Zirconium, cerium, and thorium are also added. More recently, lithium has been increasingly used as an alloying element.

Fig. 5.9 Deformation behavior of the magnesium alloy MgAl6Zn in hot-compression tests in the temperature range between 200 and 220 °C (Source: Schmidt/Beck)

*Extrusion of Semifinished Products in Magnesium Alloys, Günther Sauer

Aluminum is the most important alloying element for magnesium, which forms a solid solution with aluminum at low contents and the intermetallic phase Al_2Mg_3 at higher contents. A eutectic occurs at 436 °C at an aluminum content of 32.2 wt%. Crystal segregations can occur in wrought alloys at aluminum contents above 6 wt%. They can be dissolved and thus removed by homogenization of the cast in the temperature range of 400 to 450 °C for correspondingly long times. The solid-solution formation at aluminum contents of 2 to approximately 6 wt% increase the fracture toughness and hardness of magnesium alloys as shown in Fig. 5.10. At higher aluminum contents, the fracture strength and, in particular, the hardness can be further increased by the formation of the hard γ phase, but with a reduction in the ductility of the material as can be clearly seen in Fig. 5.10 [Schu 69]. Magnesium-base wrought alloys have aluminum contents up to 9 wt%. Magnesium alloys can be hot rolled at aluminum contents up to 7 wt% and hot worked by extrusion at aluminum contents up to 9 wt%. The magnesium alloy becomes increasingly more brittle at aluminum contents $>$ 9 wt% as shown by the elongation in Fig. 5.10. This also shows that magnesium alloys with contents $>$ 7 wt% can be age hardened after solution heat treatment. At the same time, the alloy suffers a drastic loss in ductility [Schu 69].

Zinc readily dissolves, depending on the temperature, in magnesium by the formation of solid solutions with the phase MgZn. An addition of up to 3 wt% increases the fracture strength and the fatigue strength of magnesium. Zinc contents more than 3 wt%, however, result in a drastic reduction in the elongation to fracture. Zinc containing magnesium alloys can be age hardened. This can increase the fracture strength of magnesium alloys by 30 to 40%.

Manganese dissolves in magnesium by, depending on temperature, up to 3.4% at 645 °C. At this temperature magnesium forms a eutectic with manganese. Manganese is dissolved by magnesium with the formation of solid solutions and the phase MgMn. It increases the strength of magnesium at contents $>$ 1.5 wt%. Manganese containing magnesium alloys have better corrosion resistance than other magnesium-base alloys. Manganese contents of between 0 and 0.5% are therefore added to all magnesium alloys to improve the corrosion resistance.

Additions of zirconium form finely dispersed zirconium oxides that act as the nuclei for a fine-grain structure and thus increases the tensile strength of magnesium alloys with no reduction in the elongation.

Cerium also increases the fine-grain structure and improves the hot strength.

Thorium improves the hot strength even more than does cerium. This has resulted in the development of magnesium-thorium alloys with particularly high resistance to softening. Thorium also significantly improves the fatigue strength and specifically the creep strength [Tech

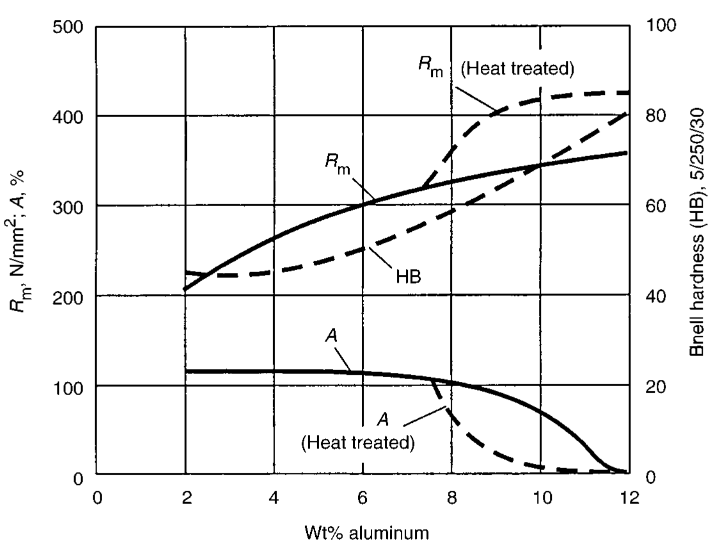


Fig. 5.10 The influence of aluminum on the mechanical properties of extruded magnesium alloys (Source: Spitaler)

96/97/98]. However, in England, alloys with more than 2 wt% of thorium are classified as radioactive. In the United States, use of magnesium-thorium alloys is very restricted because thorium-free magnesium alloys have been substituted.

Magnesium alloys are very susceptible to corrosion compared with aluminum alloys because they are electrochemically less noble. Additions of nickel, iron, copper, and so forth promote the corrosion of the material. Therefore, these additions are held in the range ppm by using purer starting materials as well as improved melt refining processes. This enables the corrosion sensitivity to be significantly reduced. High-purity-based magnesium alloys today have corrosion resistances comparable to aluminum alloys.

This has been one of the factors that has increased the interest of the automobile industry in magnesium-base alloys and provided the incentive to improve the existing alloys and to develop new ones with the intention of:

- Improving the static and dynamic materials properties, including elongation and toughness
- Improving the temperature resistance
- Further reducing the density
- The development of alloys with self-healing surface passive films

The coarse cast structure is transformed into a fine grain elongated structure by hot working in the extrusion process. This structural transformation is associated with a significant improvement in the mechanical properties of the magnesium alloys in the same way as aluminum alloys. The mechanical properties that can be achieved improve with increasing extrusion ratio, i.e., with increasing working during extrusion. Figure 5.11 illustrates this process, which is of considerable importance for the supply of

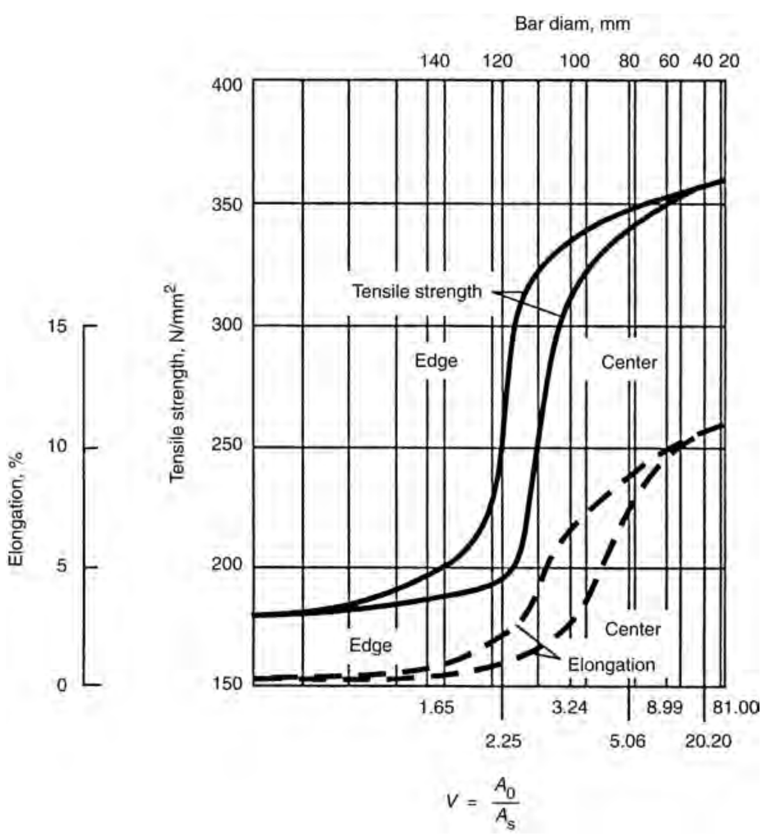


Fig. 5.11 Tensile strength R_M and elongation to fracture A as a function of the extrusion ratio determined on single cavity extruded round bars in the alloy MgAl10. Billets 175 mm diam were used for the experiments with a container diam of 180 mm (Source: Beck)

extruded semifinished products [Bec 39]. The extrusion ratio $V = A_0/A_S$ should not fall below 5, and it is better to specify the minimum at 7. A fine-grained extruded structure with good mechanical properties can be achieved with extrusion ratios of 25 [Har 47].

Magnesium alloys are mainly extruded using the direct extrusion process. Indirect extrusion is possible and is used. Magnesium alloys flow more uniformly in direct extrusion than do aluminum alloys. The discards can be reduced in thickness because of the lower distortion in the region of the billet surface and the resultant flatter dead metal zones in the deformation zone of the container. Magnesium alloys can be welded in the extrusion process. Therefore, porthole dies and bridge dies can be used to produce tubes and hollow sections. Similar to aluminum alloys, large-diameter tubes are extruded over mandrels. It is also possible to use billet-on-billet extrusion with magnesium alloys. However, the weldability is reduced by increasing aluminum contents.

Typical magnesium alloys for hot working by extrusion are given in Table 5.2. There are other wrought magnesium-base alloys in addition to those listed, particularly abroad, for example alloys of the MgAl family. The working temperatures for extrusion are at 250 to 450 °C, depending on the alloy and are higher than those used for hot rolling the same magnesium alloys. Extrusion ratios $V = A_0/A_S$ similar to those for aluminum alloys can be achieved. The extrudable magnesium alloys belong to the category of difficult-to-extrude alloys mainly because of their hexagonal lattice structure. The extrusion speeds fall in the range of moderate- to difficult-to-extrude aluminum alloys. According to [Har 47], the extrudability of magnesium alloys decreases with increasing aluminum content as do the extrusion speeds. Only the alloys MgMn and MgMn2, as well as MgAl1Zn, can be extruded at speeds up to a maximum of 30 m/min [Zol 67]. The predominantly slow extrusion speeds naturally result in long extrusion cycles. Therefore, the extrusion container temperature has to be set so that the billet does not lose any heat to the container during the extrusion cycle; otherwise, the billet will freeze in the container. In

Table 5.2 Extruded magnesium-base alloys

Material designation						Properties		
Symbol	No. (DIN standard)	ASTM	Composition, wt%	Billet, °C	Shape and condition	$R_{p0.2}$ N/mm^2	R_m N/mm^2	A_S/A_{10} %
Mg 99.8H	3.5003 (DIN 17800)	. . .	Cu: 0.02 Si: 0.10 Mn: 0.10 Ni 0.002 Fe: 0.05	250–450	Bar, wire, tube, section	. . .	. . .	. . .
MgMn2	3.5200 (DIN 1729)	M2	Mn: 1.20–2.00 Mg: remainder	250–350	Bar, tube, section Extruded and straightened Drawn and straightened	150–170	200–230	10–15
MgAl2Zn	. . .	. . .	Al: 1.20–2.20 Zn: 0.5 Mn: 0.1 Mg: remainder	300–400	. . .	. . .	. . .	. . .
MgAl3Zn	3.5312 (DIN 1729)	AZ31	Al: 2.50–3.50 Zn: 0.50–1.50 Mn: 0.05–0.40 Mg: remainder	300–400	Bar, tube, section Extruded and straightened	130–200	240–260	3–12
MgAl6Zn	3.5612 (DIN 1729)	AZ61	Al: 5.50–6.50 Zn: 0.50–1.50 Mn: 0.05–0.40 MG: remainder	350–400	Tube and section Extruded and straightened	180–200	250–280	6–10
MgAl7Zn	. . .	. . .	Al: 6.50–8.00 Zn: 0.50–2.00 Mn: 0.05–0.40 Mg: remainder	300–350	Bar Extruded and straightened Age hardened if required	200–230	280–320	3–10 (A_5)
MgAl7Zn	3.5812 (DIN 1729)	AZ81	Al: 7.80–9.20 Zn: 0.20–0.80 Mn: >0.12 Mg: remainder	300–420	Bar and section Extruded and straightened Age hardened if required	200–230	280–320	6–10 (A_5)
MgZn5Zn0.6	3.5161 (DIN 1729)	. . .	Zn: 4.80–6.20 Zr: 0.45–0.80	300–400	Bar, tube, section Extruded and straightened Age hardened if required	200–250	280–320	4–5 (A_5)
MgTh3Mn2(a)	. . .	. . .	Th: 2.50–3.50 Mn: >1.2	. . .	Bar, tube, section Extruded and straightened	180	270	4 (A_5)

(a) Experimental material Fuchs Metallwerke. Source: Schimpke, Schropp, and Konig

Table 5.3 Dependence of the specific extrusion pressure for the extrusion of tubes 44 × 1.5 mm in the alloy $MgAl_3$ on the homogenization treatment and the heating conditions of the billet 48 × 150 mm

Thermal treatment of the cast before heating prior to extrusion	Heating before extrusion		Specific extrusion pressure, N/mm^2
	Temperature, °C	Time, h	
Not carried out	380–350	1	250–300
Not carried out	380–350	3	210–260
Not carried out	380–350	6	180–220
Not carried out	340–300	1	320–400
Not carried out	340–300	3	250–300
Not carried out	340–300	6	200–250
350 °C–12 h	340–300	1	190–250
350 °C–12 h	340–300	3	170–200
350 °C–12 h	340–300	6	150–180
350 °C–12 h	340–300	1	170–220
350 °C–12 h	340–300	3	160–200
350 °C–12 h	340–300	6	130–170

Source: Zubolob and Zwerev

addition, good soaking of the billet during heating is required. Magnesium alloy extrusion billets are normally extruded with the cast skin.

Heat treatment such as homogenizing improves the hot workability of the magnesium-base extrusion alloys. The effect of homogenization on the extrusion loads needed for hot working of the alloy $MgAl_3$ is shown in Table 5.3 [Zol 67, Lau 76].

Extruded magnesium alloy semifinished products exhibit extreme anisotropy because of the hexagonal lattice structure of the metal. For example, tensile tests on extruded semifinished magnesium alloys in the longitudinal direction, i.e., the extrusion direction, have significantly higher values for the 0.2% proof stress, tensile strength, and elongation than in the transverse direction.

If the ratio of the tensile strength transverse/longitudinal is taken as a measure of the anisotropy of a material, magnesium alloys have values in the range 0.6 to 0.7.

The nitrided dies used for the hot working of magnesium extruded alloys have, in principle, the same design features as those used for the extrusion of aluminum alloys. Only the shape-forming regions of the die are matched to the specific properties of magnesium alloys by having longer bearings and larger radii. The typical hollow section die used for aluminum alloys can in principle be used for these alloys because of their ability to weld during extrusion. In addition, in contrast to aluminum alloys, magnesium alloys have a significantly lower affinity for iron alloys [Tech 96/97/98]. This property results in a slower buildup of an intermediate layer of the extruded material on the die bearing surfaces compared with aluminum alloys, even though the formation of a layer cannot be avoided with magnesium alloys even when nitrided dies are used.

Cold working by drawing to improve the mechanical properties is practically impossible for wrought magnesium alloys because of their limited cold workability associated with their hexagonal lattice structure.

Drawing in the form of a calibration draw is, however, of interest, as a means of improving tolerances.

Extrusion of Semifinished Products in Aluminum Alloys

Rudolf Akeret*

5.6 General

Of all the materials processed by extrusion, aluminum occupies the predominant role in terms of both production volume and value. Based on the annual volume of production of primary and secondary metal, aluminum is placed directly after iron. The majority are al-

*Extrusion of Semifinished Products in Aluminum Alloys, Rudolf Akeret loyed to produce wrought alloys and formed into semifinished products of which 25% are extruded. The majority of all extrusion plants, three quarters in Germany, for example, process aluminum alloys [Bau 82], 465,000 t in 1995.

The physical metallurgical properties of aluminum alloys make them particularly suitable for the extrusion of products very close to the finished shape and with attractive properties. The face-centered cubic (fcc) structure with 12 slip systems combined with a high stacking fault energy is a requirement for good cold and hot workability. Corresponding to the melting point of 660 °C, the hot-working temperature of aluminum alloys falls in the range of 350 to 550 °C, which can be easily withstood by tools made from suitable hot-working steels. In this temperature range the flow stress is reduced to values that require relatively low specific press pressures for processing. The natural oxide skin gives aluminum an attractive appearance and a good corrosion resistance in the natural state. Increased surface protection is given by anodic oxidation. Aluminum forms age-hardening alloys with low-alloying additions that combine good hot workability with a high strength after a simple heat treatment.

Sections with an extensive range of function specific cross sections can be extruded within narrow tolerances from aluminum alloys. Hollow sections in the form of rectangular tubes and hollow engineering plates offer a high bending and torsional stiffness. The extensive variety of aluminum sections used today in a wide range of technologies is described in detail in Chapter 2.

The selection of the extrusion process is largely determined by the physical metallurgical properties of the aluminum alloys. The high affinity to steel and thus the tendency to adhere to all extrusion tools has to be included in the material properties in addition to low extrusion temperature and the good extrusion weldability.

Direct hot extrusion without lubrication and without a shell is used for the majority of extruded products, including solid and hollow sections from the easily and moderately difficult alloys. Direct extrusion can be used for practically the entire spectrum of products, from the simple round bar to complicated sections with a circumscribing circle close to the container cross section. Flat dies are used for solid sections and porthole dies for hollow sections.

Indirect extrusion comes into consideration for compact cross sections in hard-to-extrude alloys. Cold and hot extrusion with lubrication of the container and the die is also used for bars and tubes [Ake 73].

5.7 Extrusion Behavior of Aluminum Alloys

5.7.1 Flow Stress

The extrusion temperature range, the flow stress variations, and the friction across the tooling determine the extrusion behavior of aluminum alloys. Alloy and quality requirements determine the necessary exit temperature for the extruded product and the temperature range for the deformation. In the range 350 to 550 °C, the flow stress of aluminum alloys is very dependent on the temperature and the composition [Ake 70, DGM 78]. The increase in the flow stress with increasing content of the most common alloying elements is shown in Fig. 5.12 [Ake 70].

The dependence of the flow stress on temperature and speed is described in the context of the basics of metallurgy in Chapter 4. Figure 5.13 shows for some non-heat-treatable alloys that reducing the temperature by approximately 100 °C results in an almost doubling of the flow stress providing the alloy additions stay in solution [Ake 70].

With age-hardening alloys similar to AlMgSi1 the variation of the flow stress is dis-

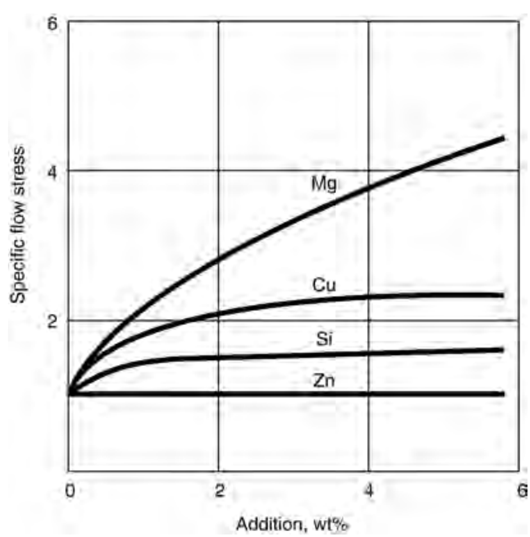


Fig. 5.12 Increase in the flow stress of aluminum in hot working with different alloying additions [Ake 70]

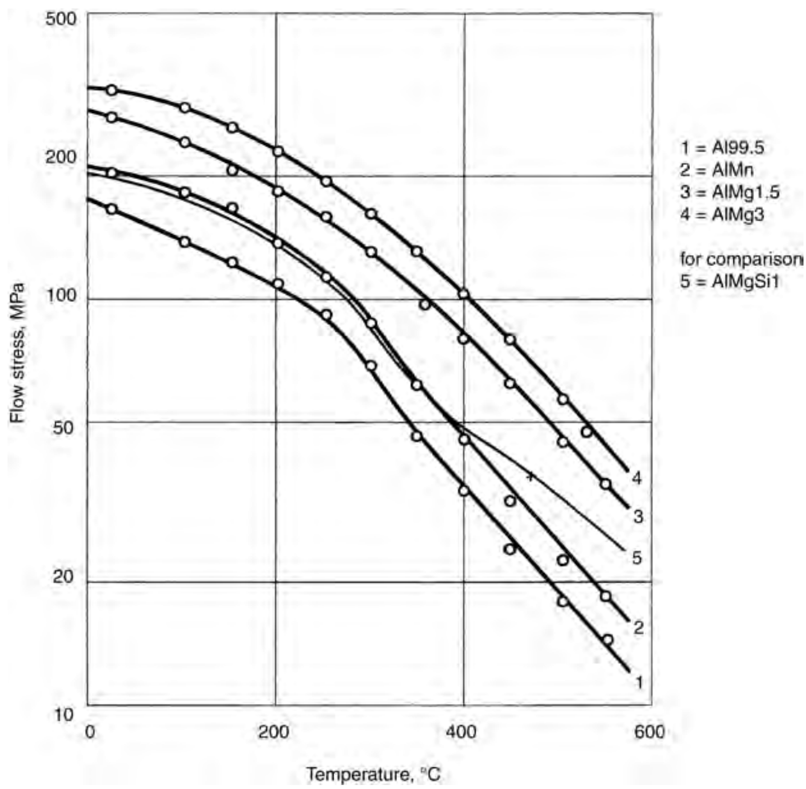


Fig. 13 Flow stress of some non-age-hardening aluminum alloys as a function of the deformation temperature (maximum of the flow curve in torsion tests with $\dot{\varphi}_g = 0.655\ s^{-1}$) [Ake 70]

placed by solution and precipitation processes according to the content of alloying elements in the matrix.

5.7.2 Flow Process

The aluminum alloys are almost always extruded in direct contact with the container and die manufactured in hot-working steel. However, aluminum exhibits a significant chemical affinity and adhesion tendency with iron [Czi 72]. Even in the solid state it tends to adhere to tool surfaces. At face pressures above the flow stress, Coulomb's laws of friction lose their validity if the shear distortion of the peripheral layer requires less force than the slip along the surface of the harder frictional party [Wan 78]. The face pressure at the inner face of the container is of the order of 10 times the flow stress. Therefore, aluminum alloys flow in direct extrusion according to flow type B1 as shown in Fig. 5.14 [Val 96].

5.7.2.1 The Dead Metal Zone

The billet surface is stationary relative to the container inner wall, and the shear distortion is at a maximum immediately below the surface (Fig. 5.15) [Gat 54].

A dead metal zone forms in front of the face of the flat die. The surface of the extruded section is not formed from the surface of the billet

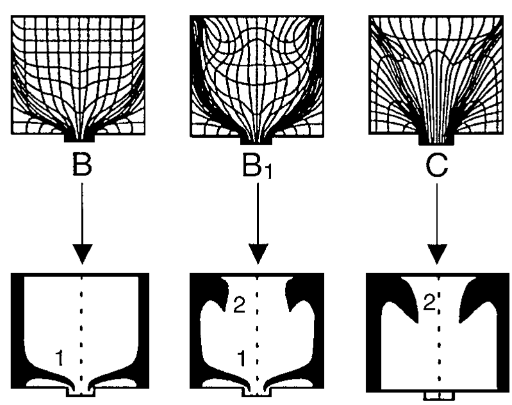


Fig. 5.14 Flow types B, B1, and C and the flow inward of the billet peripheral layer along the dead metal zone (path 1) and from the dummy block edge into the interior of the billet (path 2) [Val 96]

but from the interior of the billet by shearing along the dead metal zone [Ake 88, Lef 92]. The outermost layer of the billet surface initially adheres to the inner wall of the container and is shaved off by the advancing dummy block. The material that is compressed together in front of the dummy block and that contains oxide and exudations from the billet surfaces ends up well below the surface of the extrusion following the path shown in Fig. 5.14, No. 2, and forms an incompletely bonded intermediate layer referred as the piping defect. Material located farther below the surface is compressed at the upper edge of the dead metal zone and follows path 1 of the dead metal zone into the region of the surface of the extruded product. Adhesion of the material also occurs in feeder chambers and in the ports of porthole dies where there is a high pressure [Ake 88].

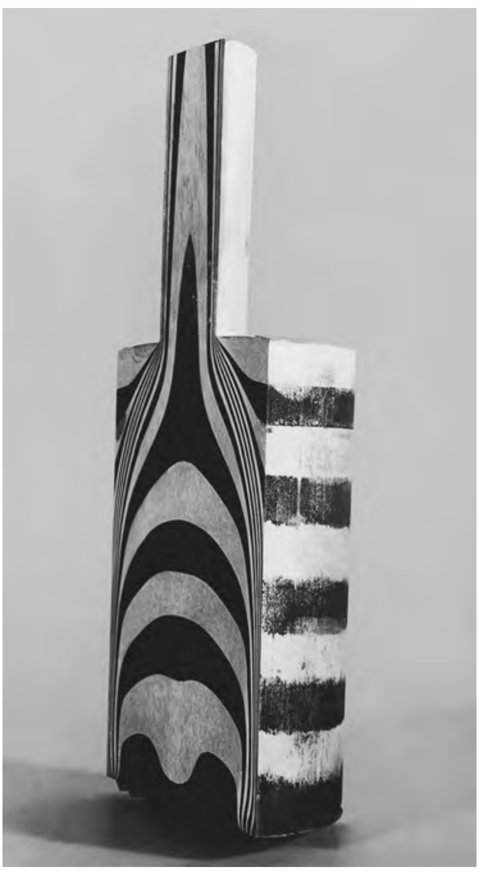


Fig. 5.15 Adhesion of the billet surface to the container wall and the shear deformation of the peripheral layer [Gat 54]

5.7.2.2 In the Shape-Producing Aperture

The pressure conditions in the die aperture are different. The axial pressure at the exit is zero, or there can be a small tensile stress—if a puller is used.

The face pressure, which determines the friction, cannot be easily calculated because it straddles two boundary cases. If the section can slide as a solid body through the die aperture, the face pressure, and thus the friction, is low. If the section undergoes a reduction in thickness through a narrowing die aperture, the face pressure is at least equal to the flow stress. The large adhesion affinity of aluminum increases the friction stress to the same order of magnitude as the shear stress [Ake 88, Ake 85].

The friction in the die opening is responsible for the increase in the axial pressure against the flow direction.

Slip with Coulomb friction is impossible in the extrusion of tubes over a mandrel because of the high radial pressure between the billet and the mandrel. If the extrusion is carried out over a stationary mandrel, relative movement with shear friction takes place between the billet and the mandrel from the start of extrusion over the entire billet length. The relative speed is therefore of the order of magnitude of the stem speed. The billet material is only accelerated to the exit speed of the tube as it crosses the deformation zone and at the same time the pressure on the mandrel surface falls rapidly. The transition to slipping friction of the finish extruded tube over the mandrel tip takes place in the region of the die aperture.

When a moving mandrel is used, the zone in which relative movement occurs between the billet and the moving mandrel is only the length of the deformation zone. The shear zone moves toward the back of the billet as the extrusion progresses [Rup 82].

5.7.3 Thermal Balance and Extrusion Speed

The theoretical background to the thermal balance in extrusion is discussed in chapter 3 (see also Fig. 3.22).

In the direct extrusion of aluminum alloys without lubrication, two to three times the mechanical work is needed than would be required for an ideal loss-free deformation. The work carried out by the press on the material being extruded is practically completely transformed into heat, which is partly transferred into the tooling and partly removed in the emerging extrusion. In the adiabatic limiting case, each MPa of average extrusion pressure corresponds to an average increase in temperature of 0.3 K.

The magnitude involved is shown in Fig. 5.16 for the case of an easily extruded material with a flow stress of 25 MPa in which a billet of length $l_0 = 4D_0$ is extruded as quickly as possible with an extrusion ratio of 30 to avoid any heat losses. When a material volume corresponding approximately to the volume of the deformation zone is extruded, there is initially a steep increase in temperature. With loss-free deformation, which approximately occurs in the core of the extrusion, the material is initially heated by 25 K.

The shearing of the material flowing through the deformation zone along the dead metal zone requires approximately the same amount of work as the pure deformation [Ake 72, Sah 96]. An additional contribution, which cannot be ignored, is the friction in the die aperture, the magnitude of which depends on the angle and the length of the bearings [Ake 85, Moo 96, Mue 96]. The shear takes place in a surface layer approximately 10% of the diameter of the deformation zone, and the friction heats an even thinner surface layer of the section. A peripheral layer approximately one-third of the cross-sectional area is therefore heated to a significantly higher temperature than the core of the section [Ake 72]. This temperature difference is very short lived and is practically completely equalized on the way from the die to the press platen. Experiments with sheathed thermocouples in the die land have shown that the maximum surface temperature can be 60 to 100 K higher than the mean section temperature [Joh 96].

With sections, the maximum temperature, which governs the onset of tearing, occurs during the passage through the die opening usually at an edge where the longitudinal stress is the highest and the temperature probably at the maximum.

The possible working range of the press, i.e., the "window" in the temperature-speed field, is limited by the following thermal and mechanical conditions:

- The surface temperature cannot exceed the maximum value that results in excessive scoring or even transverse cracks at any point (limit curve 1 in Fig. 5.17). The temperature equalizes to some extent during the crossing of the deformation zone.
- The average section temperature has to be high enough to ensure adequate solution heat

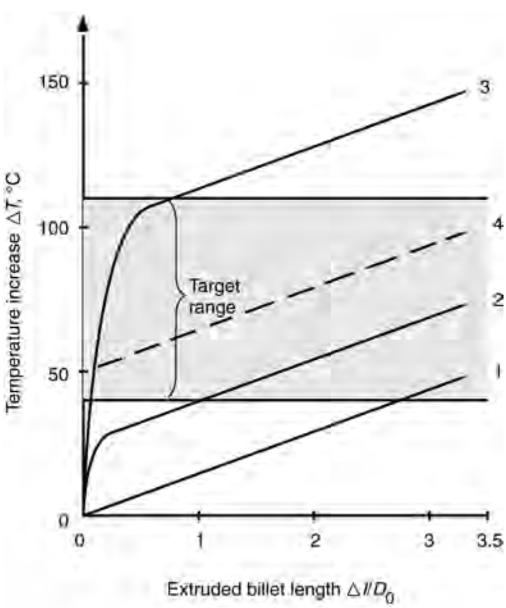


Fig. 5.16 Heating from deformation and shear deformation of the peripheral layer in the adiabatic limiting case (example, AlMgSi0.5: flow stress 25 MPa, billet length: billet Ø = 4, extrusion ratio 30). 1, temperature increase up to the entry into the deformation zone; On exit from the die: 2, temperature increase of the section core; 3, temperature increase of the section surface; 4, mean temperature increase of the section

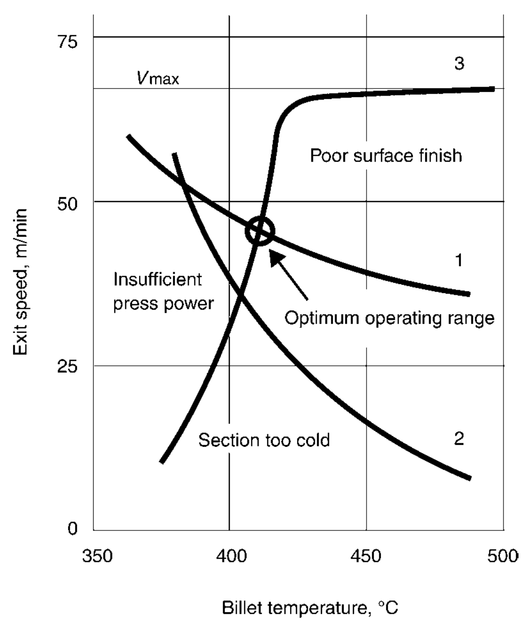


Fig. 5.17 Limit diagram for maximum surface and minimum mean section temperature

treatment with AlMgSi alloys and to reduce the tendency of AlCuMg and AlZnMgCu alloys to recrystallization (limit curve 2).

- The press and its power source, on the other hand, determine the maximum extrusion load and the ram speed. The latter decreases with increasing extrusion load (reduction in billet temperature) because of the increasing slip loss (limit curve 3).

In the literature there are several different proposals for depicting the process limits [Joh 96, Hir 58, Ste 73, She 77].

The range of extrusion speeds that can be practically obtained with aluminum alloys is shown in Fig. 5.18 [Ake 71] plotted against the flow stress at the extrusion temperatures used in practice.

The exit speeds V_A are scattered around a line with a steep negative gradient that can be approximated by the expression:

$$V_A \sim k_f^{-2}$$

This empirical equation [Ake 68] can be explained by the laws of heat penetration [Lag 72].

5.7.4 Section Surface and Surface Defects

In all stages in the production of aluminum extruded sections, the plant and process technologies are influenced mainly by the need to avoid defects that would impair the mechanical properties or the decorative appearance [Bry 71, Fin 92, Par 96]. The following defects are particularly important:

- Uneven color tone (bands or flecks)
- Coarse recrystallization
- Excessive roughness (scoring or pickup)
- Imperfectly bonded brittle contact areas between material streams flowing together (piping, defective welds)
- Material separation in the form of transverse cracks, blisters, and flaking
- Subsequent mechanical damage or corrosion

The cause of these defects can be found in the structure of the billets, the flow process, and the extrusion temperature, in a subsequent heat treatment or defects in the logistics (handling, transport, and storage of the finished sections).

To determine and eliminate the causes of these defects, correct diagnosis and an accurate knowledge of the process technological relationships are necessary. The results obtained from more accurate analysis of the flow processes and the temperature field contribute significantly to the understanding of these relationships. Mention should also be made of the extrusion defect catalog produced by the "extrusion" working party in conjunction with the Institute for Material Science of the RWTH Aachen University.

5.7.4.1 Section Surface and the Peripheral Layer

Microgeometric surface defects and structural-related tone variations (banding, flecks) are related to the method of formation of the section surface and the additional through working and heating of the peripheral layer compared with the section core. Using high resolution marking and evaluation processes, it is possible to localize the exact source of the peripheral layer in the billet [Val 88, Val 92, Val 92a]. Only a small material volume located between the dead metal zone and the deformation zone is involved in the formation of a 50 μm-thick peripheral layer, and this can be extended by a factor of more than 1000 [Val 92a]. This extreme working of the peripheral layer deforms a cast grain to a strip that is thinner than the subgrain size corresponding to the deformation conditions. The subgrains then grow by recovery through the original grain boundaries, as shown in Chapter 4 in the section on metallurgical basics.

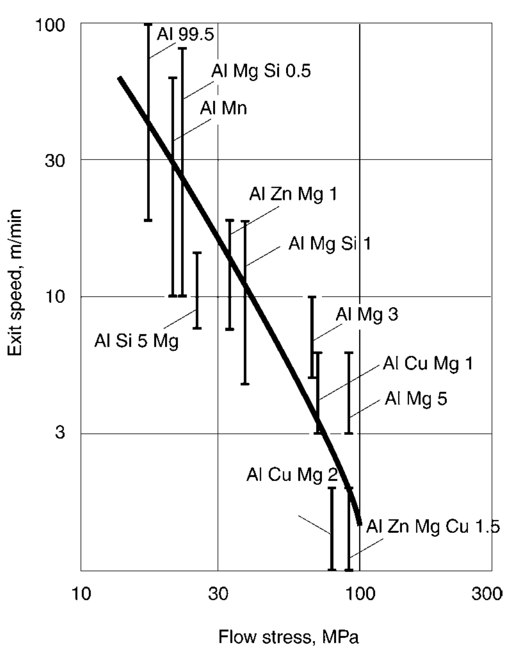


Fig. 5.18 Flow stress and extrudability [Ake 71]

The peripheral layer therefore has a subgrain structure without defined grain boundaries, providing the heat from extrusion or subsequent solution heat treatment does not result in static recrystallization. This high deformation of the peripheral layer does not produce any higher hardness in the as-extruded condition [Moe 75].

An additional feature of the highly deformed peripheral layer is its ⟨001⟩ {211} shear texture, which differs from the ⟨111⟩ + ⟨100⟩ double fiber structure of the core zone [Moe 75, Auk 96].

Rows of precipitates are pulled apart by the extreme deformation and moved closer together in the transverse direction so that the particles appear to be irregularly arranged. The recrystallization retarding effect of layers heavily decorated with particles is then lost. This results in undesired coarse grain recrystallization of the AlCuMg and AlZnMg alloys, particularly at the end of extrusion where the peripheral layer forms up to 90% of the cross section.

5.7.4.2 Cast Structure and Anodizing Capability

Knowledge of the relationship between the location of the volume element in the billet and in the section is the key to explaining and overcoming linear and banded tone variations in anodized sections [Ake 88, Bau 71, Lyn 71, Sta 90].

The formation of the cast structure of the billet is discussed in Chapter 4, in the section on metallurgical basics. From the point of view of the uniformity of the anodized surface, the following regions of the billet surface are important:

- The oxide skin (10–100nm)
- The segregation zone (up to ~600 μm)
- The impoverished peripheral zone
- The periodic cold shut (up to several mm)
- The columnar solidified crust (up to 15 mm)
- The primary solidified regions scattered over the entire billet cross section

Differences in the brightness of the oxide layer are primarily caused by differences in the number of depressions from the initial alkaline etching. The etch attack does not occur uniformly but preferentially at all types of particles at grain boundaries. The brightness is affected, in particular, by the depressions that form at all AlFeSi particles. Particularly deep craters develop at the locations where the Mg_2Si equilibrium particles are nucleated on AlFeSi. Experiments on the etching kinetics have shown that it is these craters that have a strong effect on the matte finish [Sta 90].The number of particles per unit area depends on the average dendrite spacing (cell size) in the cast structure and also on whether a region is normally elongated or highly deformed during extrusion. The impoverished peripheral zones and the primary solidified regions appear bright after anodizing, whereas the oxide skin and the segregation zones matte. The controlling factors for the frequency of nucleation of Mg_2Si and AlFeSi are the temperature changes during billet heat treatment and during cooling or quenching after extrusion.

Pits form during etching along the grain boundaries. The shape of the pits depends on the formation of the age-hardening β-MgSi phase. In general, different cooling conditions (influencing the pit width) as well as different grain size (influencing the pit length) can result in significant variations in brightness.

An orientation-dependent face etching occurs on the surface during etching and this consists of small cube faces with an edge length less than 0.5 μm. The deformation texture of the section with the {011} ⟨211⟩ principle components can form to different extents in different parts of the extrusion die. This results in an inhomogeneous distribution of the cube faces and thus in different reflection properties. This is how some of the undesired leg marks can occur.

Investigations on a hollow section [War 95] have shown that different die designs for the same profile cross section can result in completely different decorative appearances. Feeder chambers and splitting can affect the magnitude and direction of the local strain of the surface layer. The die design therefore has a strong influence on the texture, precipitate distribution, and grain size.

The three mechanisms just described for the roughening of the surface (depressions, pits, texture) have approximately equal importance for the decorative appearance of the anodized section. In addition, precipitates of the base metal, which can neither be dissolved nor removed during etching, end up in the oxide layer, giving it a cloudy or colored appearance.

The external oxide skin in single-cavity extrusion follows path 2 (Fig. 5.14) and finishes in the interior of the sections forming a brittle layer (piping defect). In multicavity extrusion, sections with reentrant angles, and hollow sections, the side adjacent to the center of the die consists of normally elongated material, whereas the external side, particularly at the end of extrusion, can consist of highly deformed material [Ake 88a] (Fig. 5.19).

If the distance between two die openings is large, a dead metal zone can form so that the section surfaces extend into highly deformed material. Within a short distance the central dead metal zone disappears and the section surface extends partly into the normally wrought fibrous material [Ake 88, Val 96a]. In between the oxide and segregation layer of the billet appears on the surface.

Cold shuts, which can extend several millimeters into the billet peripheral zone, can finish up in the peripheral layer of the section following path 1 (Fig. 5.14). If the defects are deep, and if they occur in the front part of the billet, the entire section can be unusable [Bag 81].

In addition, other variations in the material flow and in the through working with subsequent static recrystallization can result in variations in the size and orientation of the recrystallized grains and thus to undesired contrasts in brightness on anodized section surfaces. Known examples include the side opposite to a branch in the profile cross section and the highly deformed material in the area of a weld (see also section 5.7.6.5). In the extreme case variations in the billet structure and in the through working occur as regions with different tones on the same flat polished surface of a section.

5.7.4.3 Surface Roughness

In contrast to most deformed surfaces, extruded section surfaces of aluminum alloys in particular are not formed by the extension and dissipation of the surface of the starting material [Kie 65, Mie 62]. Instead, the section surface is newly formed from the interior of the material by a cutting process between the deformation zones and the dead metal zones.

Two shear zones meet during this cutting process. In one, the flowing material is sheared along the dead metal zone; in the other, it is moved into the exit direction.

The extremely severe deformation of the outermost surface layer in the region of the entry edge can result in cavitation defects in heterogeneous materials. Hollow spaces form by the separation of nonplastic particles from the matrix or by the fracture of these particles without the matrix metal filling the space between the fracture pieces. If the hollow spaces bond together in the direction of extrusion and the hard particles separate from the matrix, microgrooves form on the surface [She 88, Clo 86].

The surface formed in the region of the entry edge undergoes a change by adhesion wear as it passes through the die aperture. The roughness of the section is therefore usually higher than that of the die bearing.

In the same way as the friction load as an integral value is strongly dependent on the

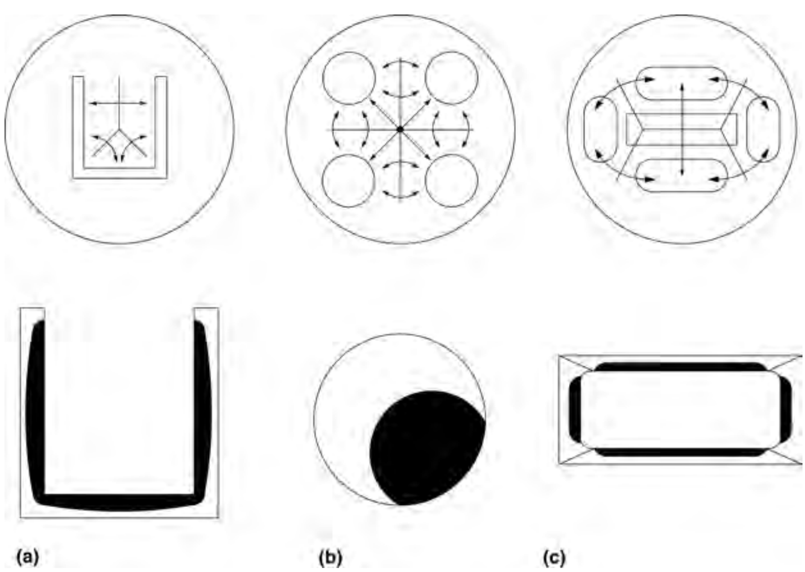


Fig. 5.19 Highly deformed peripheral zone material (light) and normally elongated core material (dark) at the end of extrusion [Ake 88a]

length and the angle of the bearing surface, the locally effective mechanisms of friction and wear of the surfaces of the section and die vary along the die bearing.

The following possibilities have to be considered, as shown in Fig. 5.20:

- Slip of the section as a solid body with a sudden speed increase at the steel surface
- Formation of a coherent layer of aluminum adhering to the bearing surface and slip of the solid section with a sudden speed increase between the section and the bonded layer
- Adhesion of the section peripheral layer on the bearing surface, parabolic speed distribution across the section thickness

Slip exactly corresponding to "the first point" is not seen in hot extrusion of aluminum without lubrication.

A friction "a + b" with adhesion of discrete aluminum particles on the bearing surfaces corresponds most closely to the experience of die correctors and with the nitriding of bearing surfaces. Microscopic investigations on split die inserts confirm that aluminum particles bond to the bearing surfaces to an increasing extent and size in the extrusion direction and determine the microgeometry of the section surface. The aluminum nodules that adhere to the bearing surfaces form grooves on the section surface. The formation of layers of aluminum, which can be interspersed with oxide, increases the number of adhesion points opposing the extrusion direction [The 93]. The nodules are finally torn off with the section and appear as particles ("pickup") on the surface [Tok 88, She 88, The 93, Abt 96].

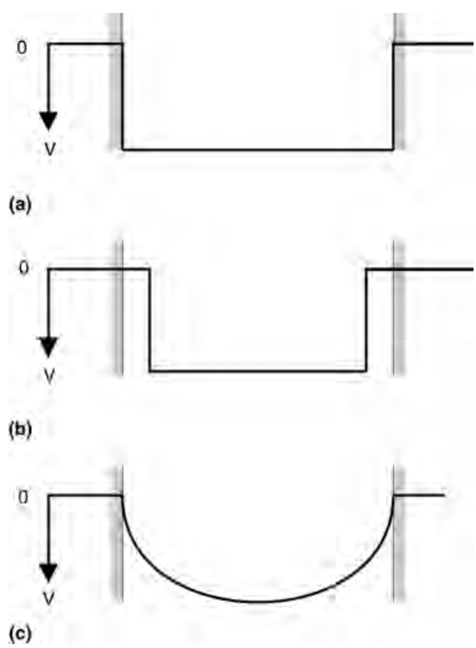


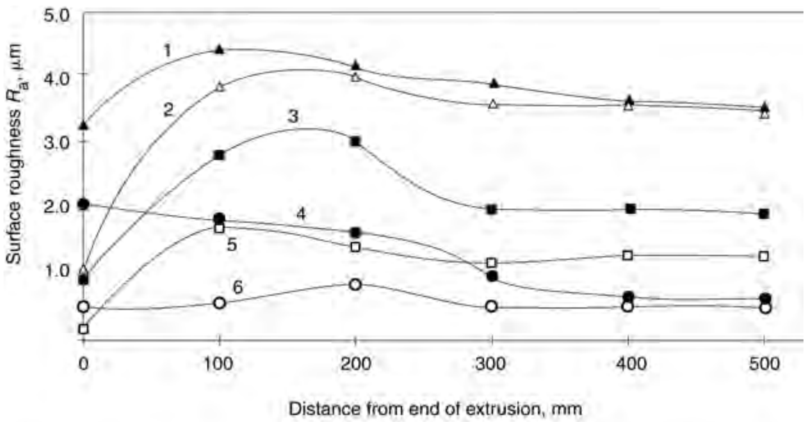
Fig. 5.20 Velocity distribution transverse across the die aperture

In the majority of cases, die bearing lengths are less than the section thickness. If the bearing surfaces are parallel, mixed friction occurs over the entire length. The surface roughness of the extruded product is governed by the adhered layer, i.e., by the tendency for the material to adhere to the die [Mue 96, Mie 62, The 93]. This adhesion tendency cannot be completely suppressed by nitriding the bearing surfaces, but the aluminum layer builds more slowly on nitrided die bearings. In the absence of lubrication, the aim for a high surface quality is not the maximum possible undistorted slip of aluminum over steel (slip process (a) in Fig. 5.20) but the most uniform buildup of a thin adhered layer of aluminum on the die bearing surface. This aim is best fulfilled by die bearings ground perpendicular to the extrusion direction. Die surfaces ground or polished parallel to the extrusion direction or polished favor an irregular buildup of the adhered layer in the form of long elongated and correspondingly wide and high ridges. Figure 5.21 [Tok 88] shows the roughness variation over the length of a flat section on a small research press.

The surface roughness of the extruded product decreases as the bearing length increases between $l_k = 0$ and $l_k = 1$ to 3 mm because with increasing back pressure the adhesive layer regresses at the entry edge. As the bearing length increases, the roughness increases again as a consequence of higher temperatures [Wel 96] and possible mechanical activation processes [She 88] (Fig. 5.22). The optimum has been found to be bearing lengths of the order of half the thickness for flat sections [Mie 62, Tok 76, Tok 88, She 88, The 93].

As the number of extrusions increases, the fine aluminum nodules combine to form a layer that ultimately completely covers the die bearing surface. The relationship between the surface roughness of the extruded product and the buildup of the adhesive layer on the slip surface is shown in Fig. 5.23 [The 93].

In the initial region 1, no aluminum adheres to the bearing surfaces so that section roughness is governed by the surface finish of the die. In



No.	Finish	Roughness, µm	Billet temperature, °C
1	Ground parallel in direction of extrusion	1.50–1.75	450
2	Ground parallel in direction of extrusion	0.50–0.75	450
3	Polished	0.50–0.75	500
4	Ground perpendicular in direction of extrusion	1.50–1.75	450
5	Polished	1.50–1.75	450
6	Ground perpendicular in direction of extrusion	0.50–0.75	450

Fig. 5.21 Influence of the finish of the bearing surface on the quality of the section surface [Tok 88]

region 2, the aluminum adhesive layer builds up and the section roughness increases rapidly. When the bearing has been completely covered, dynamic equilibrium develops in region 3 between adhesion and tearing away of aluminum particles so that the surface roughness remains almost constant. The section roughness is significantly lower than the roughness of the adhered layer. A reduction in the section roughness was periodically observed in trials involving 180 extrusions, and this was attributed to a partial or complete detachment of the coating.

The angle of the die bearing has a significant influence on the friction force and results in a different formation of the coating [Mue 96]. However, it has only a small influence on the section roughness. Hand-filed bearing surfaces close up at the entry and open up at the exit. Mixed friction dominates on bearings that are not too long, yet the changes in the face pressure and the angle result in a different formation of the coating. In the opening exit area loose adhesions form and damage the section surface by die lines and pickup [Clo 90].

As the billet temperature increases, the tendency for adhesion between the section surface and the bearing surfaces increases [Mie 62, Tok 88, Clo 90].

For a given billet temperature, the roughness, the degree of pickup, and the scatter of the gray scale (as a measure of the degree of streaking) increase to a maximum with increasing extrusion speed and then decrease at even faster speeds. This is explained by the hypothesis that at higher speeds the section surface slides over a thin layer of almost liquid metal [Par 96].

Alloy type, alloy content, and differences in the thermal pretreatment of the billets can have a significant influence on the extrusion speed that can be achieved for given surface finish re-

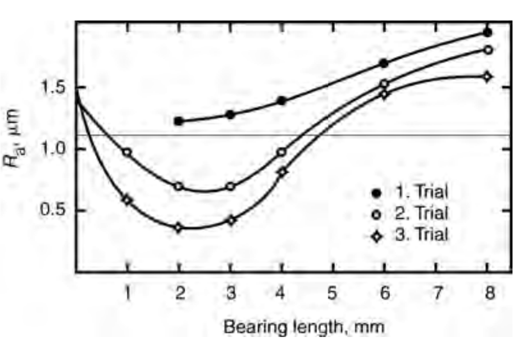


Fig. 5.22 Influence of the bearing length on the roughness R_a of the section surface [She 88]

quirements. Precipitates of alloying constituents have the worst effect.

5.7.4.4 Transverse Cracks and Peeling

The tensile stresses produced in the peripheral layer by the friction on the bearing combined with the considerably higher temperature [Moo 96, Joh 96] and the correspondingly lower flow stress result in defects, which can penetrate deep into the section from the surface. Figure 5.24 (a–d) shows the qualitative variation in the velocity and the stress at the entry to the die aperture.

The material being formed flows from the deformation zone into the die aperture. The profile core flows faster than the surface section, which is retarded by the friction at the surface. The core remains in compression, but a tensile stress prevails in the peripheral zone. If this stress is too low to produce plastic strain, the section can flow as a solid body through the die aperture (Fig. 5.24a). Higher tensile stresses can result in an elongation of the hotter and at the entry slower flowing peripheral layer. This is seen particularly on thin ribs and internal legs of hollow sections (Fig. 5.24b). The elongation of the peripheral layer after the removal of the dominating high mean compressive stress in front of the die results in various types of material defects, depending on the structure and the peripheral layer temperature. Lubricant residues that inadvertently have reached the inner wall of the container can flow into the section following path 1 in Fig. 5.14 and form an interface parallel to the surface. The surface layer can break away during extrusion (peeling) (Fig. 5.24c). In other cases, the material of the interface can break up during a subsequent heat treatment, and the surface layer bulges out in the form of a row of blisters. Peeling is also caused by the melting of isolated eutectic regions resulting from unfavorable casting and homogenization conditions [Rei 84, Lef 96].

A classic defect process is the formation, growth, and the amalgamation of voids resulting in transverse cracks that penetrate deeply into the section (fir tree) (Fig. 5.24d), The propagation and expansion of the cracks occur at the location of the plastic elongation of the peripheral layer. At the same time the transfer of the tensile stresses into the billet is prevented so that less material flows into the peripheral layer. The volume deficit in the peripheral zone is therefore considerably larger than in the case of plastic elongation as shown in Fig. 5.24(b).

In the common aluminum wrought alloys the melting of individual structural regions, e.g., along grain boundaries, is the defect initiating process (hot shortness). The transient exceeding of the solidus temperature in the peripheral layer is the most common cause of transverse cracks. The average section temperature measured at the exit is naturally well below the solidus temperature.

Another type of transverse crack that can occur well below the solidus temperature occurs in materials with a high fraction (>15%) of non-plastic brittle structural components.

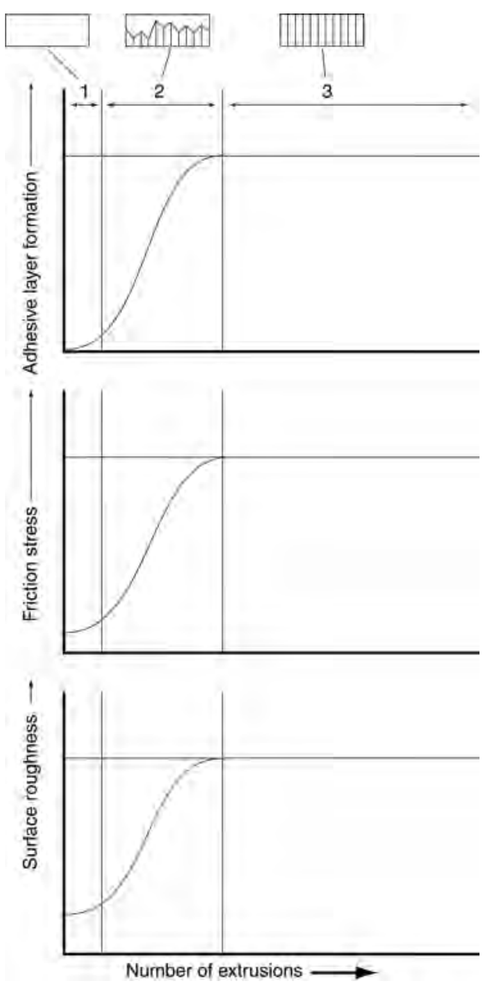


Fig. 5.23 Relationship between adhesive layer formation, friction stress, and surface roughness [The 93]

5.7.5 Procedures to Control the Thermal Balance

As a general rule, the optimal productivity and quality with aluminum alloys can only be achieved by taking the thermal balance of the extrusion process into consideration. The temperature control is optimized by measures that either reduce the amount of heat that has to be removed or accelerate the heat transfer [Ake 71, Ake 80]. These measures have been described to some extent along with the extrusion process (Chapter 3). The technicalities of temperature control are described in more detail in Chapter 6.

5.7.5.1 Material

The heat produced during the extrusion process from the transformation of the mechanical work can be minimized by selecting the most easily extruded alloy from those that meet the product specification (see the section "Materials").

The additional fine adjustment covers the optimization of the composition, the solidification conditions, and the thermal treatment of the billet. Small changes appear to result in considerable differences in the extrusion speeds that can be achieved [Ake 71, Sta 90, Rei 84, Sca 69, Lyn 71, Lan 82, Spe 84, Lan 84].

5.7.5.2 Billet Temperature

The exit temperature is higher than the billet preheat temperature because of the deformation induced heating of the material being deformed; therefore, the billet is usually heated to a temperature below the desired average exit section temperature. The material reaches the desired value only as it passes through the deformation zone. This is described in detail in Chapter 3.

A uniform temperature gradient from the front to the rear of the billet can compensate approximately for the increasing heat from the shear deformation of the peripheral layer. Additional heating of the front of the billet reduces the load needed at the start of the extrusion process and ensures that there is sufficient solution heat treatment effect at the front of the section. This method of achieving "isothermal extrusion," however, requires rapid localized heating or cooling because of the good thermal conductivity of the aluminum. The billet then has to be extruded with minimum delay.

In general, the effectiveness of the procedures in this first group increases as the billet cycle time decreases, for example the extrudability of the alloy improves.

5.7.5.3 Heat Removal

The opposite applies to the following procedures, which require heat flow into the tooling and which are most effective for slow extrusion speeds and long cycle times.

Container. The most important heat sink is the container, which plays an important role in the productivity in the extrusion of aluminum alloys. The container is basically heated to a

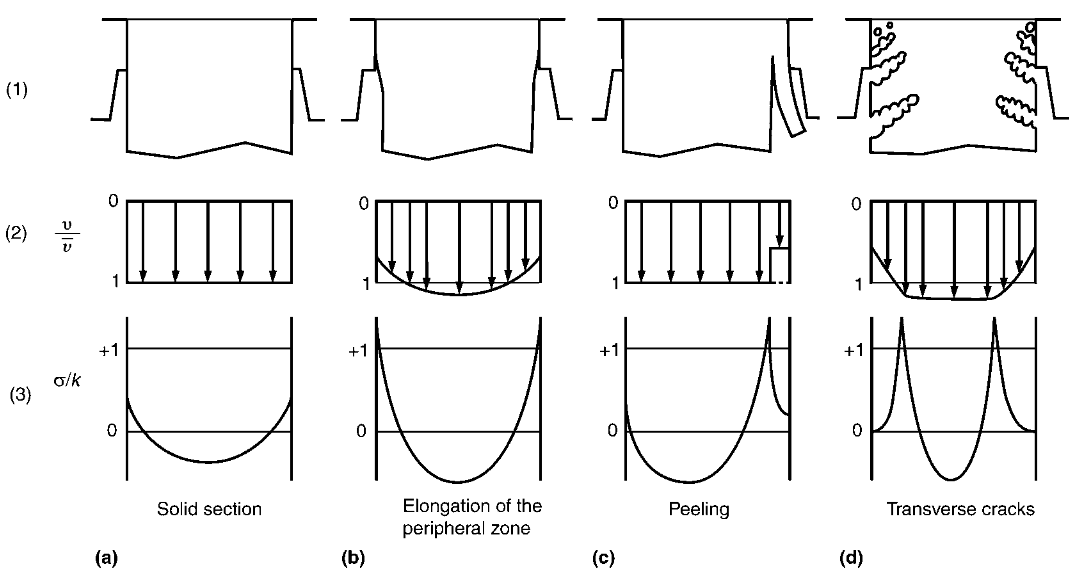


Fig. 5.24 Influence of tensile stresses in the section peripheral layer. 1, appearance of the extrusion; 2, velocity variation across the section; 3, variation of the longitudinal stresses across the section

temperature below that of the specified billet preheat temperature. The temperature difference is usually limited to 50 K in order to avoid the billet sticking in the container because of inadequate press power ("sticker"). The thermal balance in the system container-billet is described in Chapter 3.

The temperature set or recorded on the container heater controller applies only to the hottest location, where, from experience, overheating of the tool steel has to be avoided. The actual temperature field in the container is shown in the example in Fig. 3.19. There are temperature differences of the order of 100 K in the axial and radial direction. The temperature maximum moves during 5 to 10 extrusions from the heating zone to the liner inner face [Ake 71, Ake 72, Sch 79].

The cooling, i.e., the heat flow from the container bore through the wall and into the atmosphere, is determined largely by the thermal conductivity of the container wall. Cooling of the mantle surface by an intensive air blast has only an insignificant effect on the cooling. Blowing onto the container end face has more effect.

Today, combined heating and cooling systems are installed in containers for temperature control (see the section on tooling in chapter 7).

Die. Removing excess deformation heat through the die is helped by the short thermal path from the deformation zone to the location of the cooling channels. Another advantage is that the cooling takes place during the final stage of the deformation so that the load requirement is increased only during the final deformation stage. There is also the possibility of specifically cooling the critical regions, e.g., at the edges prone to tearing.

Because a significant amount of heat has to flow through a relatively small die cross section, it is necessary from the cooling point of view to have an intense heat transfer to a coolant with sufficiently large thermal capacity.

This requirement is more easily fulfilled with liquid coolants than gas. On this basis, the following methods can be differentiated for die cooling:

- Water cooling
- Cooling with liquid-supplied evaporating nitrogen
- Flushing with gaseous nitrogen

Approximate calculations demonstrate that the cooling capacity through a plate 200 mm in diameter is in the range between 2 and 12 kW, depending on the thickness and the coolant. This can be compared with the drive power of a press of up to 400 kW.

The approximate calculations show that with the fast extrusion of alloys with a high extrudability, only a small amount of deformation heat can be removed through a cooled die. With a plate thickness of 50 mm, an aluminum flow of 1 kg/s can at best be cooled by approximately 6 K with water and by only approximately 2.5 K with liquid nitrogen.

A significant reduction in the exit temperature is achieved only with the slow extrusion of the difficult-to-work alloys. In trials it has been possible to increase the exit speed of an AlCuMg alloy by 30% using water cooling. Approximately 15% of the deformation heat can be removed by the water cooling [Bat 79].

The limited resistance of the die materials to temperature fluctuations makes water cooling of a die difficult.

Liquid nitrogen is usually fed through channels machined either in the die itself [Sca 79] or more commonly in the front face of the backer [Wag, Sel 84, Yam 92]. If a separate feeder plate is used, an additional network of cooling channels can be machined in the rear face so that the die is cooled from the front and the back [Ros].

The aim is for the nitrogen fed in as a liquid to evaporate extensively as it flows through the cooling channels. This gives an approximately constant cooling capability, the effect of which is distributed over a more or less large aluminum material flow, depending on the extrusion speed.

In experiments with nine different alloys, the extrusion speed of AlMgSi0.5 could be increased by approximately 8% by cooling, but with the more slowly flowing alloy AlZnMgCu1.5, by a significant 80% [Sca 79].

The dwell time of the deformation material in the die region is short so that the peripheral zone of the section is cooled the most. This reduces the temperature peaks, which are largely responsible for the tearing of the section surface at high extrusion speeds (Fig. 5.25) [Sel 84].

This is the reason why even with limited cooling effect the speed can often also be increased considerably with fast-flowing alloys. The evaporated nitrogen emerges from behind the die aperture onto the surface of the newly extruded section to utilize the protective atmosphere effect (see below).

Gaseous nitrogen is fed through channels in the gap between the die and the backer into the space behind the die exit. The mass flow of the nitrogen stream is usually not more than 1% of that of the aluminum stream because of the low density. The nitrogen flow is therefore not sufficient to cause any serious cooling.

The regularly observed improvement in the section surface must therefore be more attributable to an influence on the dynamic equilibrium of adhesion and tearing off of the aluminum particles on the die bearing by the reaction of the newly formed aluminum surface with the atmosphere.

Mandrel. In contrast to heavy metal extrusion where cooling of the mandrel is unavoidable because of the high thermal loading, in aluminum extrusion, mandrel cooling is not required to compensate for high temperatures. In practice, mandrel cooling is therefore not used. However, temperature measurements on the extruded profile have shown that the specific heat removed by cooled mandrels is at least equal to that associated with die cooling with liquid nitrogen so that it appears to be possible to achieve higher maximum extrusion speeds by extruding over cooled mandrels [Rup 82].

5.7.5.4 Optimization of the Extrusion Parameters

Following the discussion of the different means of influencing the thermal balance their

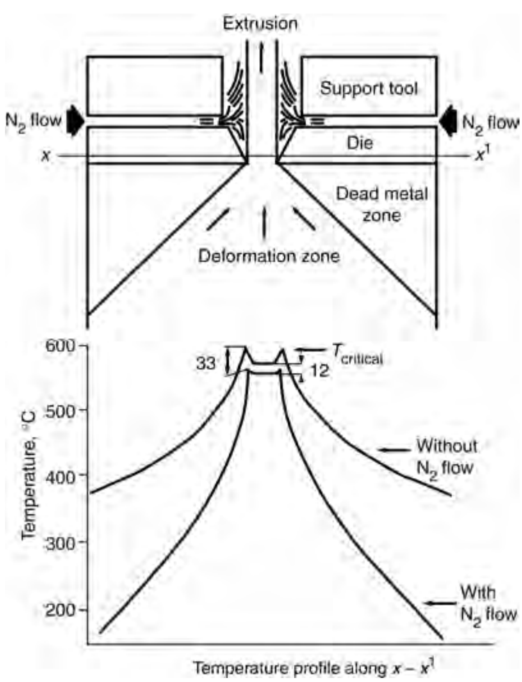


Fig. 5.25 Temperature variation in the die with and without cooling with liquid nitrogen [Sel 84]

application to the optimisation of the extrusion parameters will now be considered. Apart from other limiting additional parameters the extrusion parameters are at an optimum if the exit temperature over the entire cross-section falls within the permitted range for the alloy under consideration, the extrusion speed is as high as possible in the range limited by the equipment, and the extrusion load needed uses the maximum press power of the press within a specific safety factor [Rup 77, Rup 77a, Rup 83].

The parameters that can be set at the press are the ram speed, the initial billet temperature, and the container temperature. The billet temperature and speed can be constant for a heating and extrusion cycle or be decreasing from the front to the back and then be adjusted in subsequent extrusion cycles.

Of all the set parameters, only the extrusion speed can be varied during a single extrusion cycle. The billet temperature and the temperature profile can, in contrast, be set for each cycle before loading into the press. A change in the average temperature or the temperature profile is possible in experimental work and under production conditions in the next billet. The temperature profile in the container with the usual arrangement of heating elements in the container mantle follows a change in the set temperature only after a long delay of several hours. A rapid change in the container temperature can be achieved with heating and cooling systems installed in the liner [Har 94].

The parameter that has to be controlled is the section exit temperature; however, there are numerous difficulties in its continuous measurement, particularly in the case of aluminum alloys:

- The critical maximum temperature occurs in an unknown location in the die aperture that is practically impossible to access for measurements.
- The critical temperature occurs for only a very short time.
- The section surface is soft and easily damaged.
- The radiation is in the invisible infrared range.
- The emissivity of bright aluminum surfaces is very low and also is strongly dependent on the roughness and the wavelength (it is not a “gray” body).
- The measurement area is surrounded by strong sources of additional radiation.

- The display of all temperature sensors is associated with definite delays and with significant measurement scatter.

The original concept of isothermal extrusion assumed a continuous control of the speed based on the measured exit temperature [Lau 60]. This concept is difficult to achieve because of the difficulties mentioned previously, as well as the delayed response of the exit temperature to a change in the speed associated with the heat content of the material in the press. Changing the speed with a rapid reacting control system would result in an unstable reaction in the control loop.

The control systems used or proposed and tested today attempt to cope with these problems associated with exit temperature measurement in various ways. All these control systems are based on optimization concepts with the aim of maintaining the exit temperature within the desired range by suitable combinations of the available parameters and simultaneously maximizing the productivity of the press. One factor to take into account is that every change of one parameter changes all heat sources and heat flows, i.e., the factors that combine to give the exit temperature [Ake 80]. This is described in more detail in Chapter 6.

5.7.6 Joining by Extrusion

The production of complex sections with one or more cavities plays a particularly important role in aluminum alloys. Approximately half the sections produced in the easy to moderately difficult to extrude AlMgSi alloys are hollow sections such as box beams and hollow engineering plates. Compared with the functional corresponding solid sections (I-beams, plates with T-shaped reinforcements) the hollow sections have the advantage of a much higher torsional and bending stiffness. With the exception of tubes in the strictest sense, the hollow sections have *longitudinal welds* where the metal streams split by the supporting legs of the mandrel reunite in a metallic bond.

The joining of the metal from billets extruded one after the other by *transverse welds* is used for products in long lengths and large coil weights. In addition, having a material residue in the die entry or a feeder chamber provides exact positioning of the front of the section, which is essential for automation of the guiding of the front end. The next billet has to join to the residual material in the die.

Special applications of joining in extrusion are cladding or locally reinforced sections of two different materials (two aluminum alloys) (aluminum-copper, aluminum-steel), the compaction and deformation of powder and granular scrap, and the production of composite materials with a metal matrix. This is described later in this chapter.

5.7.6.1 Extrusion Welding

The general metallurgical principles of bonding by extrusion are discussed in Chapter 4. The following section describes how the extrusion process relevant properties of the aluminum alloys influence the technology of extrusion welding and the quality characteristics of the extruded welds.

Aluminum alloys can be extruded in a temperature range at which the tooling is not overheated so that the stability and service life of even complex hollow section dies are adequate. The high adhesion affinity for steel results in adhesive friction in the die at areas with high surface pressures and to the formation of dead metal zones (Fig. 5.26).

After only a short time in air, newly formed aluminum surfaces are coated with an oxide layer that cannot be reduced by any gas atmosphere or removed by diffusion of the oxygen into the parent metal. Aluminum therefore belongs to the group of metals that cannot be joined without macroscopic shape change, i.e., not by mere pressure and heat (diffusion welding) [Jel 79, Bry 75].

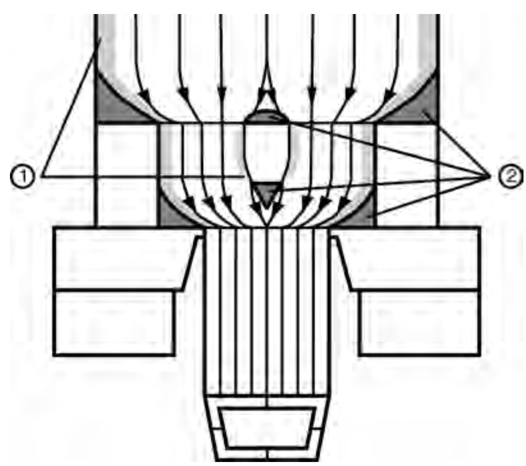


Fig. 5.26 Laminar material flow [Ake 92]. 1, adhesive friction; 2, dead metal zone

In order for two aluminum bodies to join in the solid state, these brittle separating oxide layers require a significant combined deformation to break up the oxide skin and to bring nonoxidized metal to the joint. The generic term *deformation welding* includes roll cladding, composite impact extrusion, and powder extrusion, as well as extrusion welding. It is possible from observations of these processes using general metallurgical basic principles to draw conclusions on the processes (previously studied only to a limited extent) that occur during bonding by extrusion.

The influence of the initial unevenness of the surfaces is also important [Ast 75]. The adhesion process is the result of the plastic flow of the metal in the contact zone, the deformation of the rough tips, the formation of slip and shear bands in the region of the contact surfaces, and the movement of the dislocation fields of the individual contacts. Uneven contact areas, however, rarely occur in longitudinal welds and then in conjunction with cavities under the support legs of the mandrel system.

5.7.6.2 Longitudinal Welds in Hollow Sections

When applying these thoughts on deformation welding to extrusion welding, it is assumed that the latter consists of three sequential extrusion processes and the associated transport and deviation processes (Fig. 5.27). In the first stage (Fig. 5.27a), the billet is divided into two or more streams that flow together under the legs (Fig. 5.27b, c). In the deformation final stage (Fig. 5.27d), the hollow section forms by the metallic bonding of the streams.

The processes at the contact areas are related to the material flow (Fig. 5.26). The conditions on the exit side of the leg are critical where either a dead metal zone or a cavity can form.

Normally, the pressure in the welding chamber is so high that the space under the legs is completely filled and a dead metal zone forms. The conditions for the formation of a dead metal zone and for a good weld have been expressed by several authors in the form of ratios that can be deduced from the die geometry and provide a reference point for the magnitude of the total deformation. As well as the size of the welding chamber, the ratio of the welding chamber cross section to the profile cross section is important [Gil 75].

The pressure applied at the point of formation of the longitudinal weld is composed of components for the reduction in cross-sectional area from the welding chamber to the section, for the deviation in the flow of the metal stream and for overcoming the friction in the die aperture.

Oxide can only enter the welding chamber with the first filling of the die when the free oxide coated front faces of the streams meet (Fig. 5.28a) [Ake 92]. The fractured residues of these

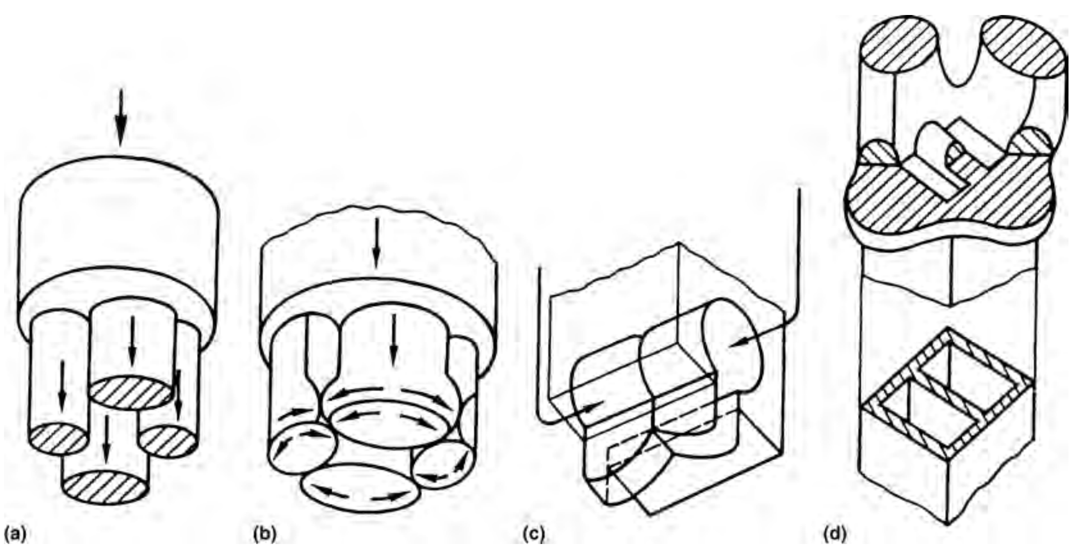


Fig. 5.27 Extrusion of hollow sections. (a) Straight into the ports. (b) At an angle under the legs. (c) At an angle between two mandrel heads. (d) Emergence of the section [Ake 92]

oxide films are largely removed with the front part of the section (Fig. 5.28b). Further bonding occurs between material regions that initially have been upset in front of the legs and mandrels and have then flown along the flanks of the leg with severe shear distortion to collect in the dead metal zone under the legs. The streams that meet together have no free surface and, therefore, no roughness and no oxide film. The welding process then merely consists of the initially small contact area being extended over the total length of the section and thus being enlarged by several orders of magnitude, whereby the subgrains also continuously reform over the original contact areas. This repolygonization is associated with the movement of dislocations but does not require diffusion of atoms.

Die geometries where the cross section of the material flow path is too narrow should be avoided because these result in inadequate feed into the weld chamber and in an inadequate pressure buildup. This can result in cavities forming on the exit side of the leg (gas pockets) [Val 95].

Two-dimensional numerical simulation and experimental semiplanar extrusion both showed the formation of cavity with a section thickness of 25 mm and a dead metal zone with a section thickness of 12.5 mm for the same welding chamber height (Fig. 5.29) [Wel 95].

The contact with the leg is lost under the conditions where a cavity is formed, and it is the free more or less roughened surfaces of the streams that meet in the welding chamber.

The bonding is then restricted to the rough crests [Val 95, Val 96], has little ductility, and is above all very brittle [Ake 92]. Voids in the joint are recognizable in the fracture as bands without fracture dimples and they are preferentially etched in the cross section by alkaline etchants.

Transverse cracks can also occur in the region of the longitudinal welds. In principle these are no different to the surface and edge cracks that occur on solid sections when the peripheral layer

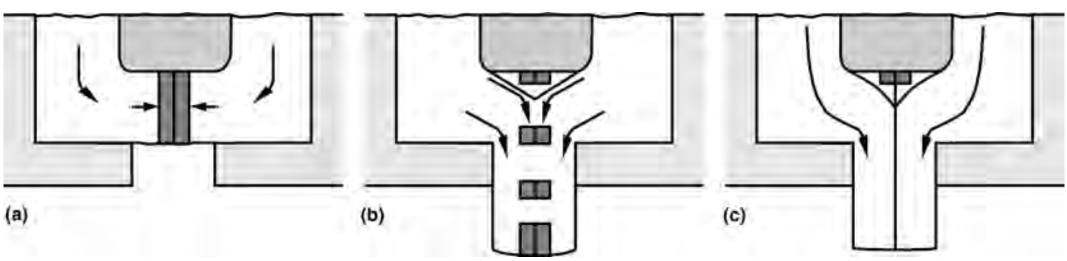


Fig. 5.28 Breakup of the surface layer in longitudinal welds. (a) Meeting under the leg. (b) Breaking apart. (c) Clean longitudinal weld [Ake 92]

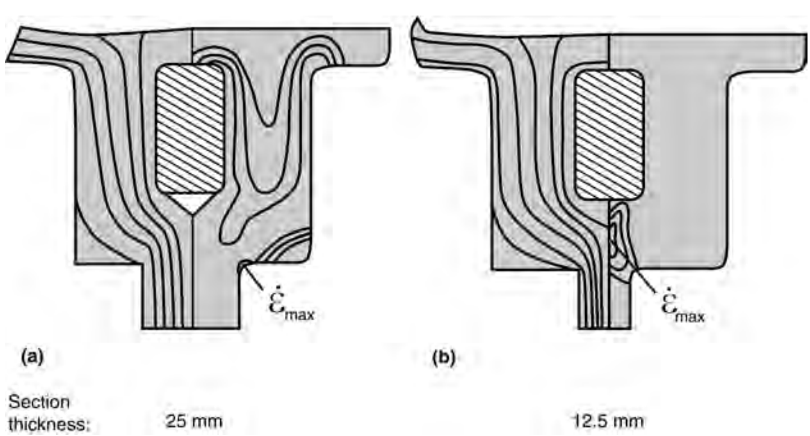


Fig. 5.29 Formation of a hollow space (gas pocket) under the mandrel support leg at a low extrusion ratio (a) and a dead metal zone at a higher extrusion ratio (b). On the left, flow lines; right, lines of equal strain rate [Wel 95]

reaches the hot-shortness temperature [Val 96a]. The fact that the transverse cracks occur preferentially next to the longitudinal welds can be attributed to the severe heating of the peripheral layers of the metal streams, particularly under the legs [Ska 96].

5.7.6.3 Transverse Welds

Transverse welds are usually the severely curved surfaces where the material of the next billet bonds with the residue of the previously extruded billet. This residue can be located in the container, in the feeder chamber of a die for a solid section, or in the entry ports of a hollow die (Fig. 5.30a–c).

The process where the residue is left as a thick discard in the container (Fig. 5.30a) is usually used for the extrusion of cable sheaths and electric conductors in large coil weights. Special measures have to be taken to avoid smearing of the contact surfaces.

The process shown in Fig. 5.30(b) and (c) in which the discard is removed in front of the feeder chamber or in front of the entry ports is common for aluminum sections. Stripping of the discard (Fig. 5.30d) is also possible with aluminum but increases in difficulty with more complex sections.

The originally flat contact surface between the residue and the next billet is deformed to a tongue because of the adhesion of the aluminum to the tool surface. The outline of the tongue approximates to the contour of the corresponding material stream. In the region of the tips of these tongues the contact surface can contract by as much as 50% so that the fractured residues of the oxide layer are more likely to slip over each other than be pulled apart. In the most unfavorable case, there is no bonding [Ake 72], particularly with the current practice considered to be unavoidable of lubricating the dummy block and the discard shear [Joh 96a].

With highly stressed sections, a length long enough to contain the tongue of the transverse weld is removed as scrap from the stop mark. This section usually includes one to two times the content of the entry zones and the welding chambers.

In most of the transverse weld the fractured residues of the oxide layer are extensively pulled apart. These profiles can be supplied with the transverse weld for noncritical applications providing the material surrounding the tongues, which originates from the previously extruded billet, can withstand the stresses from the stretching of the section.

When the method of formation is considered, it is easy to understand that there is a greater risk of transverse welds being impaired by surface coatings than longitudinal welds. When material separations apparently occur in longitudinal welds, usually the transverse welds running along both sides are involved [Val 95].

The most important sources of defects in extrusion welds are [Wei 92]:

- Lubricant or corrosion on the dies
- Impurities on the billet front surface or dirt on the billet surface
- Incorrect die design

Basically, all parts that come into contact with the material being extruded must be clean and, in particular, be free of oil, grease, or graphite. The requirement for perfect separation of the

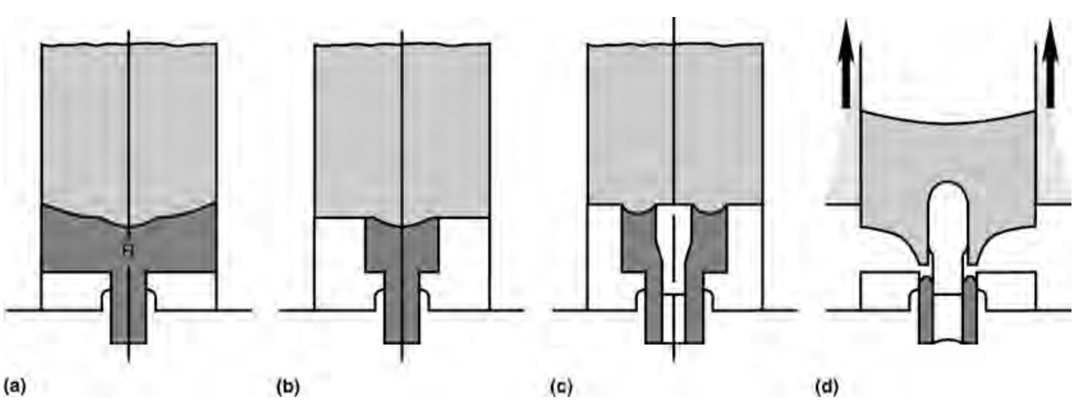


Fig. 5.30 Extrusion of aluminum "billet on billet." (a) Extrusion of a billet on the discard *R* in the container. (b) With feeder die. (c) In the ports of a porthole die. (d) Pulling off the discard in a bridge die to avoid transverse welds [Ake 92]

dummy block and the discard, however, results in practice in compromise solutions in which specific lubricants are considered to be indispensable but have to be used as little as possible and accurately applied.

5.7.6.4 Testing of Extrusion Welds

The extrusion weld has to be considered as a surface of which a fraction f_D is covered with fragments of the original surface coating [Ake 92]. The remaining fraction f_1 consists of metallic ligaments with the same flow stress as the parent material. These ligaments are very short in relationship to their width and can therefore withstand a high three-dimensional tensile stress under tensile loading.

In a tensile test perpendicular to an extrusion weld the specimen can completely neck outside the weld. In the plastic region where the limit of elastic deformation is exceeded many times over, failure in the extrusion weld can still occur. The concentration of fragments of the surface coating on the contacting surfaces facilitates the damage with increasing deformation, i.e., the formation, the growth, and the combination of pores to form microcracks and, finally, failure.

The usual parameters of 0.2% proof stress and the tensile strength from the tensile test have limited relevance to the quality testing of extrusion welds. The increased sensitivity to damage in the region of the extrusion weld compared with the parent material is best expressed by a decrease in the reduction in area at fracture. The quicker the extrusion weld is damaged, the lower is the strain to fracture [Ake 92]. With decreasing extrusion weld quality, the elongation and, in the extreme case, the tensile strength, are also impaired as well as the reduction in area.

Structural Investigation. Because the information from tensile tests is limited, numerous other testing procedures are used for testing the quality of extrusion welds. The location of the longitudinal and transverse welds can be seen in the macrostructure. If a section is cut from an extrusion at an externally visible interface between two billets, it is possible to identify from the structure between neighboring transverse welds whether sufficient material has been cut out to achieve sound material. An extremely intensive etch attack will reveal the inclusion of a lubricant or the peripheral layer.

Ultrasonic Testing, Fatigue Investigations. Ultrasound enables both hidden material separations and laminar enrichments of noncoherent particles to be detected. For example, the tongues of transverse welds can be localized. In fatigue studies the quality of the extrusion welds does not have a significant influence on the total number of cycles but does on the rate of growth of a crack in the extrusion weld at the end of the endurance.

Various Mechanical Tests. A critical mechanical test for extrusion welds requires that the strain is reached at which failure will occur in the parent material or in the weld. This critical strain is strongly material dependent because the energy released from the material separation (“the damage potential”) grows with the square of the elastic limit. Various technological testing procedures [Gil 75] enable the controlled transverse of strains that correspond in tensile tests approximately to the region of uniform elongation up to fracture necking:

- Bending tests on samples taken transverse to the extrusion welds. The limiting bending angle is measured at a section dependent specified bending radius.
- Folding tests along and between the welds up to an internal radius ≈ 0 and elongation of the outer surface of $\approx 100\%$
- Axial compression of a tube section to the point of folding
- Bending of tubes with a roll bending system under longitudinal loading of the extrusion weld
- Expansion with a conical mandrel and measurement of the strain in the circumferential direction

These technological testing procedures are suitable for following quality variations along and between profiles with the same cross section and the same material and for monitoring the maintenance of tolerance limits that have been specified for the individual application. However, they do not supply any characteristic values that could be used for numerical validation of the safety of a design. The “calibration” of a technological testing process from the point of view of a fracture mechanics test value is still an unresolved problem.

5.7.6.5 Influence of the Extrusion Weld on the Surface Appearance

Although it is only a few atomic spacings thick, an extrusion weld can affect the appearance of the anodic film on a visible surface in the form of a band several times wider than the wall thickness [War 95]. Depending on the incidence angle of the light, the area of the same extrusion weld can appear to be lighter or darker than the rest of the surface. The primary cause of this optical contrast between the region of the extrusion weld and the residual material is the heavier working of the peripheral zones of the split streams compared with the core zone. In the region of the weld the section consists of heavily deformed material throughout its full thickness, which results in variations in the size and orientation of the grains and thus the reflection behavior.

5.7.6.6 Suitability of the Material for Hollow Section Extrusion

The selection of the material and the extrusion temperature as well as the die geometry and the avoidance of impurities play an important role in determining the practical applicability of extrusion welding. As a basic rule, all wrought aluminum alloys can be extrusion welded [Ake 72a]. The extrusion pressure, which is already increased by the flow through narrow angled channels, increases with increasing flow stress to values that overload the mandrel. However, hinge sections with a small core (the hole for the pivot) are extruded with bridge dies in the high-strength AlCuMg1.5 and AlZnMgCu alloys [Cre]. Engineering sections with large cores are usually produced in the alloys of the group AlMgSi0.7, AlMgSi1, and AlZnMg.

Only the strength and toughness of the parent metal in the thickness direction is achieved in the transverse direction across the weld because of the fiber orientation in the region of the extrusion weld. In alloys that have a high manganese content to obtain the extrusion effect, transverse sections frequently exhibit lamellar tears along surfaces parallel to the extrusion weld, which are enriched with eutectically precipitated particles. The mechanical properties in the region of the weld can also be impaired by coarse-grain recrystallization of heavily worked material regions. There are alloys available for hollow engineering sections that recrystallize completely and that include peritectically solidifying transition elements instead of manganese [Scw 84].

With the more easily extruded alloys, mainly AlMgSi0.5, a complete fine-grain recrystallization is desired to give the decorative appearance.

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The selection of the alloy for extrusion is usually based on achieving a given property range with specific surface properties at the lowest possible cost. These include the costs for the billet; the actual extrusion; the heat treatment; and the additional operations including stretching, detwisting, and cross-sectional correction.

In contrast to rolling where the strength is increased significantly by cold working, extruded products are hot worked and, therefore, the material condition is practically soft. Cold working can be considered for wires and tubes, which are drawn to their final dimensions. However, aluminum alloys are usually extruded to the final dimensions and the optimal mechanical properties are produced by a suitable heat treatment.

With the exception of the isolated use of silver, the usual alloying additions to aluminum alloys have only a slight effect on the cost of the billets. However, the influence on the cost of extrusion, heat treatment, and correction is much higher.

The influence of the most common alloying additions, magnesium, copper, silicon, and zinc, on the flow stress can be found in section 5.5 and in Fig. 5.12 in section 5.7.

Magnesium increases the flow stress the most followed by copper, whereas silicon only has a small influence and zinc, practically no increase [Ake 70]. The influence of intermetallic phases, in particular of Mg_2Si, has also been extensively studied. This has shown that it is not only the amount of the alloying constituents that increases the flow stress and thus reduces the extrusion speed, but also that the microstructure in which the alloying constituents occur plays an important role [Sca 69, Gru 66, Sca 69b]. Supersaturated dissolved or fine dispersions of precipitated Mg_2Si increase the flow stress and thus make deformation more difficult, whereas coarse precipitates of Mg_2Si phases reduce the flow stress.

The influence of the structure has a particularly significant effect on those alloying elements that tend to supersaturation during solidification and later precipitate during subsequent

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billet heat treatment as a reversible fine dispersion. The influence of manganese, in particular, is strongly dependent on the precipitate state and on the number and fineness of the intermetallic particles [Gru 66]. Intermetallic phases including Al_6Mn, MnFeSi, Al_3Zr, and $FeAl_3$ reduce the extrudability significantly [Sca 67, Sca 69a].

Figure 5.31 shows the product strength of the most common aluminum alloys as a function of the flow stress at the extrusion temperature.

The majority of extruded products therefore are produced in heat treatable alloys with the lowest possible alloy content. The desire to reduce the magnesium content by a tenth or even a hundredth of a percent is due to the strong influence of the flow stress on the cost of extrusion as well as the downstream processes. The extrusion load required is proportional to the flow stress as is the deformation work converted into heat. Another important consideration is that the time needed for this heat to penetrate into the tooling increases with the square of the flow stress, and the extrusion speed decreases accordingly. Apart from the dead cycle time, which is largely independent of the material, the machine costs of the extrusion process alone increase to the cube of the flow stress. The heat

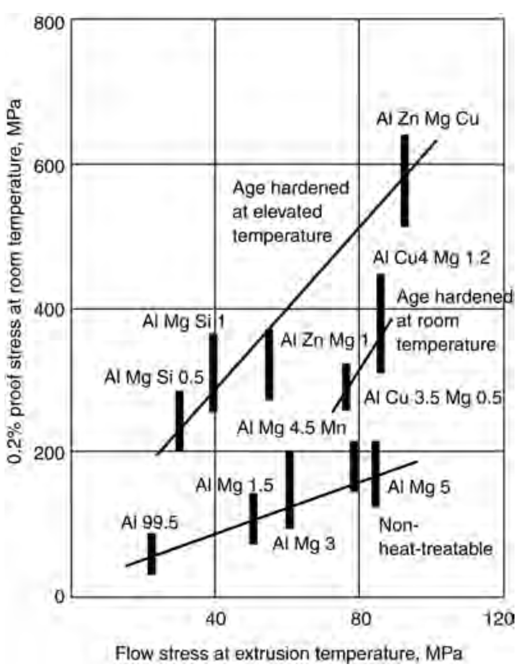


Fig. 5.31 0.2% proof stress of extruded aluminum alloys in the standard as-supplied condition as a function of the flow stress at the usual extrusion temperatures [Ake 71]

treatment costs and correction processes also increase with higher alloy contents.

The heat treatment of age-hardening alloys basically consists of the processes (see also Chapter 4):

- Dissolution of the alloying constituents
- Quenching to retain in metastable solution
- Age hardening, usually hot, in one or more temperature stages

An important simplification is possible if the product leaves the press with a temperature in the region of solution heat treatment and can be immediately quenched to achieve the desired result. This requires that the interval between the solution temperature and the start of melting is greater than the unavoidable temperature error and differences along the length of and across the section. In other cases an optimum solution heat treatment can be achieved only by a separate operation in a very accurately controlled oven. In this case, the material cannot be "press quenched."

As the alloy content is reduced, the precipitation pressure decreases. The section does not have to be quenched so quickly but can be cooled using less drastic means. This has the advantage that distortion resulting from excessive localized temperature differences is avoided. Thin AlMgSi0.5 sections can be adequately cooled in static air or under fans. A more intensive heat transfer is necessary for thick wall sections and higher alloy contents (e.g., AlMgSi0.7). This can be obtained with high air velocities (nozzles) or air water mixtures (mist nozzles) [Kra 93, Str 96]. The cooling requirements provide an additional material-dependent cost factor partly related to the cost of the cooling system but mainly because of the correction costs that rapidly increase with increasing cooling rate.

Because the extrusion load depends mainly on the flow stress k_f, the wrought aluminum alloys are classified according to the flow stress into the groups easy to extrude, moderately difficult, and hard to extrude. Thus

Easy to extrude	$k_f \leq 30$ N/mm^2
Moderately difficult	k_f 30 to 45 N/mm^2
Hard to extrude	k_f 45–57 N/mm^2

On top of this, there is the increasing investment in equipment and the cost of heat treatment and correction as well as the quality control.

The material behavior during plastic working can be derived from high-temperature torsion flow curves. These show the deformation load k_f as a function of the logarithmic principal strain φ. It should be emphasized here that the flow curve is a material parameter for the ideal deformation and depends on the working temperature and, in particular, the rate of deformation.

Figure 5.32 shows the torsion flow curves for the extrusion alloy AlMgSi0.5 at 450 °C and a

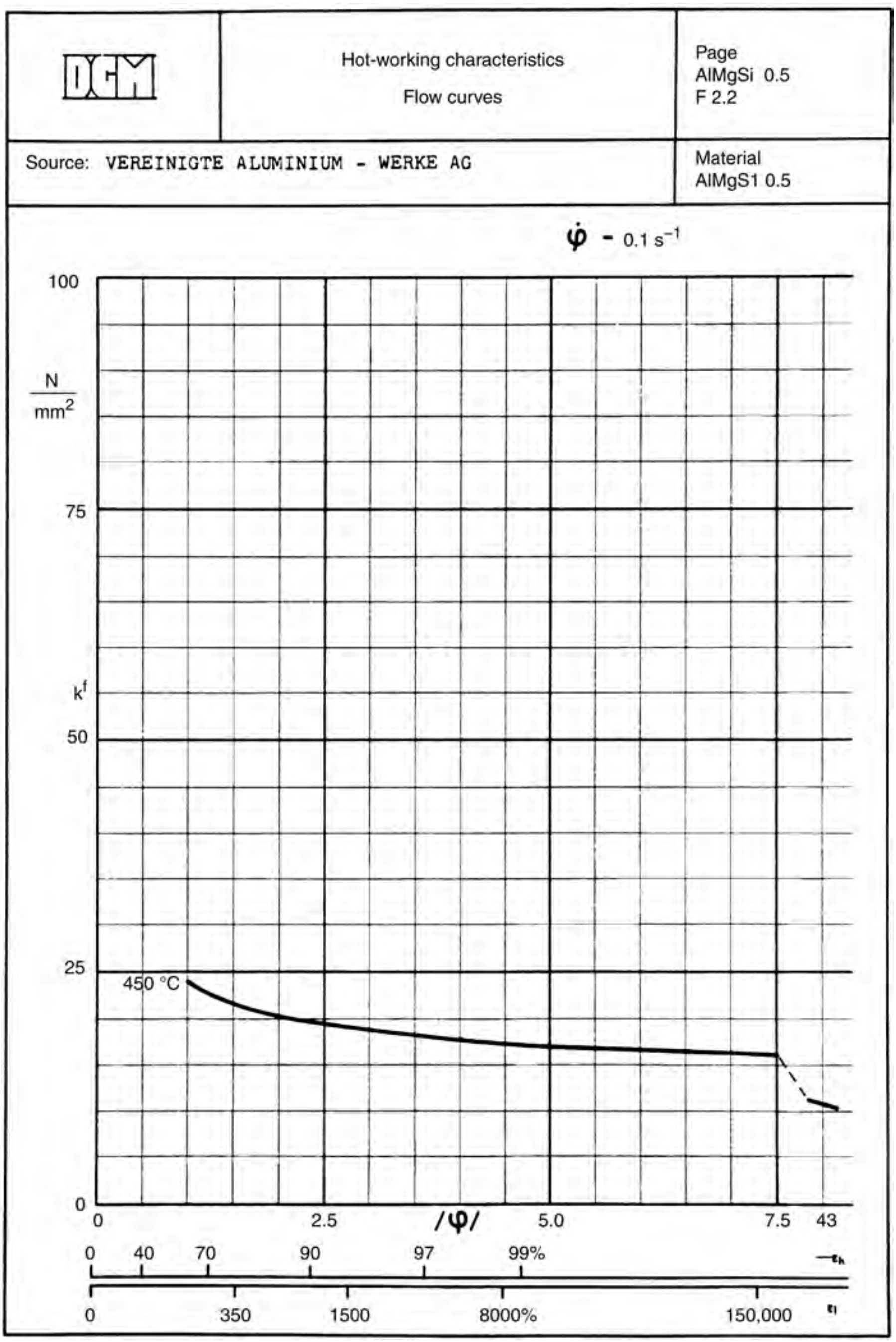


Fig. 5.32 Torsion flow curves of AlMgSi0.5 [DGM 78]

logarithmic strain rate of $d\varphi/dt = 0.1\ s^{-1}$ as a function of the logarithmic principal strain φ_g between 1 and 7.5.

The flow stress of the most important extrusion alloys is shown in Table 5.4 at a logarithmic principal strain of $\varphi_g = 2.7$. This corresponds to an extrusion ratio of 15:1. The k_f values listed illustrate the different deformation properties of the individual extruded alloys. These were obtained from torsion flow curves taken from both the DGM *Atlas of Hot-Working Properties,* Volume 1 [DGM 78], and internal investigations at VAW Aluminium, Bonn, Germany.

The aluminum alloys are designated below by the chemical symbols, which was the custom until recently. Table 5.5 compares the material designation of the old DIN 1712 T and 1725 T with the new DIN EN 573-3.

5.8 Easily Extruded Alloys

Alloys with low k_f values ($k_f \leq 30$ N/mm^2) are usually classified as easily extruded. To a first approximation, the lower the required flow stress the better is the workability. Normally the possible exit speed increases with the workability [Ake 68].

5.8.1 Aluminum Alloys

In addition to aluminum, the naturally hard alloys AlMg1 and AlMn1, as well as AlMgSi0.5 and AlMgSi0.7, are considered to belong to the easily extruded alloys. Because AlMg1 and AlMgSi0.5 are frequently used for anodizing or bright finish applications, care must be taken to ensure that the Mg and Mg_2Si components are dissolved in the solid solution in the as-extruded state. Also, none or, if necessary, very small additions of insoluble or supersaturated dissolved elements such as manganese, chromium, zirconium, or iron may be used. For this reason, AlMg1 and AlMgSi0.5 are produced from a base metal of a higher purity for bright finish qualities. In DIN EN 573-3 the individual alloys are shown based on 99.85, 99.9 and 99.98 Al. If this is not taken into account, secondary precipitates can form during billet heat treatment and these can impair the surface quality of the extruded sections by streaking.

The billet heat treatment—referred to as *homogenization*—of AlMg1 is mainly to reduce crystal segregation and dendritic residual melt-

Table 5.4 Flow stress of different aluminum alloys

Experimental material: homogenized cast billets. Test: torsion flow curves; test temperature 450 °C. Logarithmic principal strain $\varphi_g = 2.7$; deformation rate (log principal strain rate) $\dot{\varphi}_g = 0.1\ s^{-1}$

DIN EN 573-3(a)		
Symbol	No.	Flow stress k_f, N/mm^2
Easy-to-extrude alloys		
Al99.5	1050A	17.9
AlMgSi	6060	19.8
AlMn1	3103	23.6
AMg1	5005A	28.2
Hard-to-extrude alloys		
AlSiMgMn	6082	41.5
AlMg3Mn	5454	43.8
AlZn4.5Mg1	7020	44.2
Difficult-to-extrude alloys		
Al4.5MgMn0.7	5083	46.7
AlCuMg2	2024	48.2
AlCuMgFeNi	2618	51.5
AlMg5	5056A	55.9
AlZn5.5MgCu	7075	56.3

(a) The prefix "ENAW" has been omitted from the DIN EN 573-3 designations. A199.5 is ENAW-A199.5; 1050A is ENAW-1050A.

Table 5.5 Comparison of the aluminum alloys according to DIN and DIN EN

DIN 1712 T3/DIN 1725 T1	DIN EN 573–3(a)	
Symbol	Symbol	No.
Easy-to-extrude alloys		
Al99.5	Al 99.5	1050A
Al99.8	Al 99.85	1085
Al99.98R	Al 99.98	1098
E-Al	E Al 99.5	1350
AlMg1	AlMg1	5005A
AlMn1	AlMn1	3103
AlMgSi0.5	AlMgSi	6060
AlMgSi0.5	AlMg0.7Si	6063
AlMgSi0.7	AlSiMg	6005A
Moderately difficult-to-extrude alloys		
AlMg2.5	AlMg2.5	5052
AlMg3	AlMg3	5754
AlMg1Mn1	AlMn2Mg1	3004
AlMg2.7Mn	AlMg3Mn	5454
AlMgSi1	AlSiMgMn	6082
AlMgSiCu	AlMg1SiCu	6061
AlMgSiPb	AlMgSiPb	6012
AlZn4.5Mg1	AlZn4.5Mg1	7020
AlCuLi(b)	AlCu2LiMg1.5	2091
AlLiCuMg1(b)	AlLi2.5Cu1.5Mg1	8090
Hard-to-extrude alloys		
AlMg5	Al Mg5	5056A
AlMg4.5Mn	AlMg4.5Mn0.7	5083
AlCuMg2	AlCu4Mg1	2024
AlCuSiMn	AlCu4SiMg	2014
AlCuMgPb	AlCu4PbMgMn	2007
AlCuMgFeNi(b)	AlCu2Mg1.5Ni	2618
AlZnMgCu0.5	AlZn5Mg3Cu	7022
AlZnMgCu1.5	AlZn5.5MgCu	7075
AlZn8MgCu(b)	AlZn8MgCu	7049A

(a) The prefix "ENAW" has been omitted from the DIN EN 573-3 designations. Al99.5 is ENAW-Al99.5; 1050A is ENAW-1050A.
(b) Not standardized in DIN

ing and to produce an easily worked cast structure. In contrast, in AlMn1 the manganese exits in a supersaturated solid solution. This nonequilibrium state is activated by the thermal treatment and tries to attain equilibrium by the formation of secondary precipitates. The size of the precipitated particles depends on the temperature and the heat treatment time. The higher the temperature and the longer the heat treatment time, the coarser are the particles. It is known that the degree of dispersion influences the recrystallized grain structure and the workability. It is therefore important with AlMn1 to heat treat at a high temperature of 590–620 °C in order to produce a fine grain during extrusion.

The most common easily extruded alloy is AlMgSi0.5. It differs from the materials described so far in that it achieves its properties by age hardening. AlMgSi0.5 is characterized by good mechanical properties as well as by outstanding workability combined with an excellent surface quality.

As already mentioned, the temperature range for the hot-working process coincides with that for solution heat treatment. In this case, separate solution heat treatment and quenching of the extruded section—as required for the high-strength materials—is not required.

AlMgSi0.5 extruded sections only need to be cooled with moving air because of the low quench sensitivity in order to retain the age-hardening phase Mg_2Si in α-solid solution. A characteristic of this alloy is that Mg_2Si can be retained in supersaturated solution with a cooling rate of only 2 K/s. The desired increase in strength can be obtained by subsequent cold or warm age hardening.

The important requirements for AlMgSi0.5 and AlMgSi0.7 type alloys are small fractions of the principle alloying elements dissolved in the α-solid solution at the press exit temperature and the avoidance of large additions of the recrystallization retarding elements of manganese, chromium, and zirconium because, in the form of fine secondary particles, these significantly increase the flow stress and thus reduce the extrudability. In addition, they act as foreign nuclei for the age-hardening phase. Mg_2Si is deposited at the Al(Mn,Fe)Si containing crystals and in this form can no longer contribute to the age hardening [Sca 64].

The quality of the continuously cast billets has a not insignificant influence on meeting the high quality and productivity requirements of the extrusion plant. It is known that the formation of a smooth billet surface goes hand in hand with the improvement of the internal structure. A fine-cellular dendritic cast structure with little variation in the cell size across the billet diameter is desired [Sca 78] (see also the section "Melting and Casting Processes" in Chapter 4).

During the billet heat treatment (homogenizing), the plasticity of the cast structure can be significantly improved. This occurs by the reduction in grain segregation and the formation of the intermetallic AlFeSi cast phases during the billet heat treatment just below the solidus line. These effects are the more marked the finer the dendritic structure of the cast billet because the initial conditions are then more favorable for the thermally activated processes.

The billet heat treatment cycle involves not only the heat treatment temperature of 560–580 °C and the holding time of 6 to 8 hours, but also the heating and cooling of the billets. The rate of heating is not limited for any metallurgical reasons. With AlMgSi0.5, rapid cooling from the heat treatment temperature is recommended because with slow cooling ($\leq$ 50 K/h), the Mg_2Si is precipitated in a coarse format. With rapid billet heating to the extrusion temperature—in an induction furnace—the heat treatment time can be too short to redissolve the coarse particles. This reduces the mechanical properties after age hardening. In addition, coarse precipitates reduce the surface quality, particularly in anodizing.

5.8.2 Extruded Products

Extruded products are classified as bar, tube, and extruded sections and are standardized in DIN 1746, 1747, and 1748 (See The Aluminum Association, ANSI H35.1).

The range of profile cross sections is almost inexhaustible for the easily extruded aluminum alloys. Profiles with asymmetric cross sections and considerable wall thickness variations can be produced. Reference should be made to Chapter 2, which covers the wide range of applications.

Aluminum and the easily extruded AlMgSi types also have excellent extrusion welding properties. Hollow sections can therefore be produced with extruded longitudinal welds using special dies (bridge, porthole, and spider dies). The wall thickness that can be held with extruded sections is determined by the following parameters:

- Material
- Specific pressure

- Dimensions and type of section
- Degree of difficulty

The problems and limits of hollow section production are covered in section 5.7.6.1.

Extruded AlMgSi0.5 sections are used for façades in high-rise buildings because of their good surface quality, particularly after anodizing. Particular attention has to be given to the design of the die and the location of the extrusion welds. Texture and grain variations in the location of the welds can occur as a result of the material separation as it flows into the die and the bonding of the metal streams in the welding chamber by pressure welding resulting in a different appearance to the other visible surfaces. This is covered in detail in section 5.7.6.5.

With high demands on the brightness of the extruded sections, for example, for trim on household goods, furniture, or automobiles, chemical or electrochemical brightening has to be carried out before anodizing. Because particles of AlFeSi phases impair the brightness alloy variations based on Al99.85, Al99.9 or Al99.99 are used for both AlMg1 and AlMgSi0.5.

Large extruded sections are preferred for rail and road vehicles. It is possible to produce profile cross sections with a circumscribing circle of a maximum of 540 mm and a weight per meter up to 80 kg on presses in the range 72 to 100 MN installed for this application.

Round and flat bars as well as tubes and sections are used as conductors in electrical engineering. The mechanical and electrical properties are standardized in DIN 40501 parts 1 to 4 for the product shapes mentioned. E-Al and E-AlMgSi0.5, which are mentioned in DIN EN 573-3 are used (ASTM Internation Standards for aluminum bus conductors are B 236 and B 317). A special heat treatment in the range of overaging increases the conductivity of E-AlMgSi0.5 without any loss in mechanical properties [Ach 69].

Extruded products are standardized according to the product shape, material, and material condition, the technical delivery conditions, and the dimensional tolerances. Table 5.6 summarizes the standards for bar, tube, and extruded sections.

5.8.3 Extrusion and Materials Properties

The interaction of a suitable alloy, the quality of the cast billet and the correct billet heat treatment, the optimal tool design, the extrusion conditions and the cooling of the extruded section, and the subsequent age hardening is needed to produce a high-value product that completely fulfills all the geometric, chemical, physical, and metallurgical requirements of the extruded section.

The alloys AlMg1 and AlMn are naturally hard alloys in which the mechanical properties are obtained mainly from the solid-solution hardening. Therefore, the extrusion conditions are determined by the material deformation parameters. The extrusion is selected to give the optimal hot-working parameters. This, however, depends on the cast quality and the billet heat treatment (homogenizing), which forms the basis for improving the plasticity. The heating of the homogenized extrusion billets is usually carried out in induction or gas-fired continuous ovens to a temperature that can be found in Table 5.7.

In general, the billet temperature should be as low as possible in order to obtain a smooth section surface at a high extrusion speed. It also depends on the degree of difficulty of the section and the extrusion ratio. With the easily extruded alloys, the extrusion ratio should be between $V = 20$ and $V = 100$, but, if possible, a value of $V = 40$ to $V = 60$ is preferred.

The container temperature is usually approximately 50 °C lower than the billet preheat temperature.

Table 5.6 Comparison of standards for extruded products

Product format	Material/material condition	Technical delivery conditions	Dimensions, permitted deviations	Other comments
Round tube	DIN 1746, part 1 Board 4.6	DIN 1746, Part 2	DIN 9107	. . .
Round-, rectangular-, square-, and hexagonal bar	DIN 1747, Part 1 Board 4.6	DIN 1747, Part 2	DIN EN 755-3 DIN EN 755-5 DIN EN 755-4 DIN EN 755-6	. . .
Extruded section Rectangular tube	DIN 1748, Part 1 Board 4.7	DIN 1748, Part 2 DIN17615, Part 1	DIN 1748, Part 4 DIN17615, Part 3 Board 4.1	Cross-sectional shape DIN 1748, Part 3 Board 5.17

With alloys that do not age harden, the exit temperature and the rate of cooling of the extruded section are not critical for the mechanical properties. Nevertheless, cooling with fans is recommended for economic reasons and to prevent precipitation and grain growth. The guidelines for the extrusion parameters discussed for the individual alloys are given in Table 5.7.

In the production of extruded sections in the age-hardening alloys AlMgSi0.5 and AlMgSi0.7, the combination of special metallurgical and process technological measures enables not only the economic production of complicated profile cross sections but also simultaneously the attainment of favorable mechanical properties. This is possible because with these alloys the temperature range for hot working and solution heat treatment largely coincide. A further positive characteristic of these alloys is that the age-hardening phase Mg_2Si can be retained supersaturated in solution even with a cooling rate of only about 2 K/s and the mechanical properties subsequently improved by precipitation during age hardening.

It is important to set the process parameters to meet both the metallurgical and production requirements. In many cases a compromise has to be found. The exit temperature is determined by two opposing criteria. The lowest possible exit temperature is needed to obtain a smooth surface finish. This is also desired from an economic point of view because higher extrusion speeds are achieved with lower extrusion temperatures. This, however, conflicts with the metallurgical requirement of the exit temperature $\geq$500 °C in order for the age-hardening phase—in this alloy family approximately 1% Mg_2Si—to dissolve in the α-solid solution. If this does not occur, the section cannot be age hardened to the desired values.

The exit temperature depends on the optimized flow stress of the material produced by the billet heat treatment, the billet temperature and the heating conditions before extrusion, the extrusion ratio, and the rate of deformation.

The billet heating in an induction oven requires approximately 4 to 6 minutes. This is significantly faster than a gas-heated continuous oven where approximately 45 to 50 minutes are needed. These differences influence the diffusion-controlled solution processes. It is easy to understand that rapid heating of the billet before extrusion is advantageous where rapid cooling from the billet heat treatment temperature prevents the formation of coarse Mg_2Si particles. If preheating is carried out in a gas-fired continuous furnace, then the opposite applies because the cooling from the billet heat treatment does not play the decisive role.

It should be pointed out here that in the United States in particular, one method of operation is to heat the billets to a temperature above the

Table 5.7 Typical values for billet high-temperature heat treatment and extrusion conditions of aluminum alloys

Alloy	Homogenization, °C	Holding time	Preheat, °C	Container temperature, °C	Typical exit speeds, m/min
Al99.8–99.99	580–600	6	380–450	330–350	50–100
AlMg1	530–550	6	400–460	350–380	30–70
AlMn	590–620	12	400–460	350–400	30–70
AlMgSi0.5	560–580	6	450–500	400–450	30–80
AlMgSi0.7	560–580	6	470–510	420–450	25–65
AlMg2.5	520–540	6	430–490	360–380	5–15
AlMg3	510–530	6	460–490	360–380	5–15
AlMg1Mn1	540–560	16	450–500	380–400	10–30
AlMg2.7Mn	510–530	16	480–510	380–400	10–20
AlMgSi1	480–570	12	500–540	400–420	15–35
AlMgSiCu	540–570	12	500–540	380–400	10–40
AlMgSiPb	470–480	12	450–530	400–420	10–30
AlZnMg1	460–480	12	420–480	370–430	10–40
AlCuLi	520–550	12	400–450	350–400	5–25
AlLiCuMg	520–550	12	400–450	350–400	5–20
AlMg5	500–520	12	440–480	360–410	1.5–3
AlMg4.5Mn	500–520	12	430–480	410–430	2–5
AlCuMg2	480–490	12	400–460	370–400	1.5–3
AlCuSiMn	475–485	12	400–460	380–400	1.5–3
AlCuMgPb	450–480	12	380–440	360–400	1.5–3
AlCuMgFeNi	520–530	24	400–440	360–380	1.5–3
AlZnMgCu0.5	475–485	12	420–480	360–410	1.5–3
AlZnMgCu1.5	475–485	12	420–480	360–410	0.8–2.5
AlZn8MgCu	475–485	12	420–480	360–410	0.8–2.5

subsequent extrusion temperature to achieve complete dissolution of the Mg_2Si phase. The billet is cooled outside the oven to the desired lower production temperature before extrusion. Higher mechanical properties can then be achieved [Sca 64, Rei 88].

As mentioned previously, a wide range of extrusion ratios from $V = 20$ to $V = 100$ can be used for the easily extruded alloys. The selection usually depends on the container diameter. From the point of view of the grain formation, it can be advantageous to change to higher extrusion ratios because the recrystallized grain size depends on the degree of deformation as well as the temperature.

Obviously, the deformation rate should be as high as possible for economic reasons. High deformation rates are also desired for metallurgical reasons because the deformation temperature has a significant influence on the exit temperature, which in turn determines the hardening behavior. Limiting factors are again the specific pressure (stem load over the container cross-sectional area) and the roughening or tearing of the section surface. The effect of die cooling with nitrogen can be found in section 5.7.5.3.

As a guideline, exit speeds of 30 to 100 m/min can be expected with AlMgSi0.5, depending on the degree of difficulty. With AlMgSi0.7, the values are approximately 15 to 20% lower because of the higher amounts of magnesium and silicon, as well as small manganese additions.

Immediately after leaving the press, the sections are cooled with air or an air water mist mixture to a temperature ≤200 °C. This procedure avoids deformation or twisting of the sections. A cooling rate of 2 K/s is sufficient to retain the Mg_2Si in solid solution.

The extruded sections are finally stretched by 0.5 to 1.5% to achieve the straightness specified.

The final operation after cutting to the finished length is age hardening. With the AlMgSi alloys, the mechanical properties are usually reached after 4 to 12 hours at 160–180 °C, depending on the selected temperature (Table 5.8).

Preaging at room temperature has a favorable influence on the properties that can be achieved with alloys with low contents of the main alloying elements [Dor 73].

5.9 Moderately Difficult Alloys

Aluminum alloys with flow stresses >30 to 45 N/mm^2 are classified as moderately difficult. The relative extrudability of these alloys in this category is only 40 to 60% of AlMgSi0.5 if the extrudability of this easily extruded alloy is set at 100% [Hon 68]. This reduction is due to the increase in the main alloying elements, which are added for alloy technical reasons to increase the material properties as well as the addition of manganese to produce the desired hot-working structure.

5.9.1 Aluminum Alloys

The naturally hard materials include the AlMg alloys with higher magnesium contents as well as the AlMgMn alloys. The magnesium contents vary between 1.8 and 3% and the manganese content between 0.3 and 0.8%. The billet heat treatment temperature has to be lowered compared with the easily extruded alloys AlMg1 and AlMn to avoid melting because the solidus line in the phase diagram has a strong temperature dependence (Table 5.7).

Table 5.8 Typical values for heat treatment of age-hardening aluminum alloys

Material	Temper(a)	Quenching at the press exit temperature, °C	Separate heat treatment, °C	Cooling method	Age-hardening temperature/time
AlMgSi0.5	T5	≥ 500	. . .	Moving air	160–180 °C/12–6 h
AlMgSi0.7	T5	≥ 510	. . .	Moving air	160–180 °C/12–6 h
AlMgSiCu	T5	≥ 520	. . .	Moving air	160–180 °C/12–6 h
AlMgSiPb	T5	≥ 520	. . .	Moving air	160–180 °C/12–6 h
AlMgSi1	T6	. . .	530–540	In water	. . .
AlCuMg2	T3	. . .	495–502	In water	. . .
AlCuMgPb	T4	. . .	480–485	In water	. . .
AlCuSiMn	T4	. . .	500–505	In water	. . .
AlCuMgFeNi	T6	. . .	525–535	In water	. . .
AlZn4.5Mg1	T5	≥ 460	. . .	Air	185–195 °C/18–20 h
AlZnMgCu0.5	T6	. . .	475–480	In water	90 °C/10–12h + 120 °C/18–20 h
AlZnMgCu1.5	T6	. . .	475–480	In water	90 °C/10–12h + 120 °C/18–20 h
AlZn8MgCu	T6	. . .	475–480	In water	120VC/20–24 h

(a) Material temper condition according to DIN EN515

The heat treatable materials that belong to the moderately difficult alloys include the alloy AlMgSi1 that is frequently used in Germany and the alloy AlMgSiCu preferred in the United States, the free-cutting alloy AlMgSiPb and the readily weldable alloy AlZn4.5Mg1, as well as the more recent lithium-containing alloys AlCuLi and AlCuMgLi.

AlMgSi1 does not only differ from the AlMgSi0.5 alloy in the higher Mg_2Si content but also in the addition of about 0.4 to 1.0% manganese. From the metallurgical point of view, this results in the recrystallization temperature being increased to a significantly higher temperature and higher strain. It is important to note that both the manganese dissolved in the α-solid solution as well as the precipitated manganese-containing phases have a recrystallization retarding effect and increase the deformation resistance. The size of the manganese-containing phases can be controlled by the temperature of the billet heat treatment [Sca 69a] (see also the section "Extrudability of Metallic Materials" in Chapter 4). Coarse particles that form at a temperature of 560 to 580 °C have a lower recrystallization retarding effect than fine particles that are produced at a heat treatment temperature of 460 to 480 °C.

AlMgSi1 extruded sections do not have a recrystallized grain structure like AlMgSi0.5 because of the recrystallization retarding effect of the manganese additions but an elongated hot-worked structure with deformation texture components (Fig. 5.33). This formation of the grain structure is referred to as the extrusion effect. It is characterized by an increase in the mechanical properties over those of the recrystallized extruded structure, particularly in the direction of extrusion [Die 66]. The formation of a coarse grain recrystallized peripheral layer and an unrecrystallized core is well known in these alloys after age hardening.

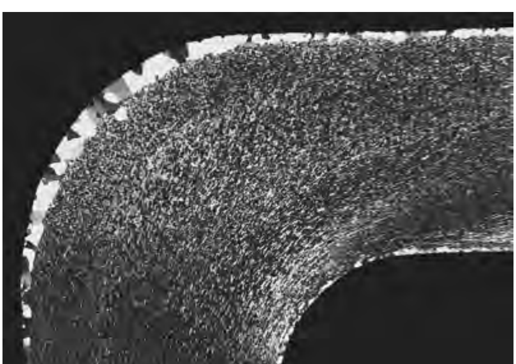


Fig. 5.33 Extruded section (extrusion effect with thin recrystallized peripheral zone) of an AlMgSi1 bar (cross section, Barker anodized, micrograph in polarized light)

The same observations are made in the copper-containing AlMgSi alloy where manganese is partly replaced by chromium, which metallurgically functions in a similar way. The low-copper addition favorably affects the grain formation and the mechanical properties as well as the general corrosion resistance [Sca 65].

Both the alloys AlMgSi1 and AlMgSiCu are significantly more quench sensitive than AlMgSi0.5 because of the manganese addition. Sections in these alloys have to be rapidly cooled immediately after extrusion with a water mist or in a standing water wave. A separate solution heat treatment with water quenching is recommended with thick-walled tubes and bars to maintain the strength and the toughness. The manganese-containing phases of the order of 0.05 to 0.7 μm obtained from low-temperature billet heat treatment and which are uniformly and densely distributed in the matrix have a positive effect on the toughness behavior [Sca 82]. The particle arrangement described displaces the fracture from the grain boundary into the matrix by cavity formation. Manganese-containing AlMgSi alloys therefore are less susceptible to intercrystalline facture and thus have significantly higher toughness values.

Another moderately difficult-to-extrude alloy that should be mentioned is AlZn4.5Mg1. Mechanical properties even higher than AlMgSi1 can be achieved and a structure with the extrusion effect is also needed for this alloy to achieve high mechanical properties. Figure 5.34 shows that only a small recrystallized fraction is to be expected if the billet heat treatment is carried out at 460 to 480 °C and the extrusion ratio is not high. With this alloy a higher billet heat treatment temperature should not be used as otherwise recrystallized grains occur, and there is a tendency toward stress-corrosion cracking (SCC), and the values in the standard are not reached [Sca 73].

AlZn4.5Mg1 is characterized by a significantly lower quench sensitivity than AlMgSi1. Maintaining a cooling rate of 0.5 K/s is not only recommended for process technology reasons but has to be held for metallurgical reasons to avoid SCC.

Since the middle of the 1980s, intensive attempts have been made worldwide to develop new aluminum alloys with improved materials properties. The specific aims for the aerospace industry are a higher component stiffness and weight reduction. Lithium was considered as an alloying element because of its density of only 0.534 g/cm^3 and because it is one of the few elements that increase the modulus of elasticity of aluminum alloys. In addition, the Al-Li phase diagram shows a temperature-dependent solubility so that the requirement for an increase in strength by age hardening is also fulfilled [Web 89].

Age-hardening lithium-containing alloys based on AlCu and AlCuMg have been developed with a 10% lower density and a 15% increased modulus of elasticity. The lithium content has to be approximately 3%. Special melting and casting technology is required because of the high reactivity of lithium-containing melts with oxygen and moisture and the aggressive attack of the lining of the melting furnaces.

The age hardening of the AlLiCuMg alloys is, in contrast to the conventional aluminum alloys, characterized by the partly coherent Al_2CuMg particles that occur in addition to the coherent Al_3Li precipitates during further hardening. These cannot be cut by dislocations and there is an increase in cross slip, which has a positive effect on homogeneous slip distribution. With extended age-hardening, this results in an increase in the elongation to fracture with a simultaneous increase in the flow stress.

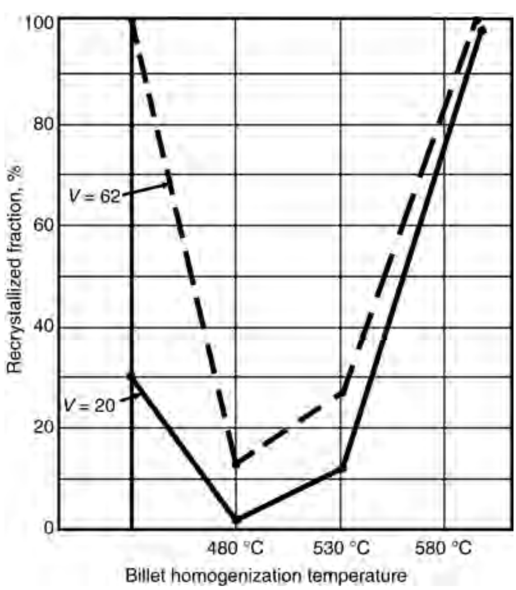


Fig. 5.34 Recrystallized structural fraction as a function of the billet heat treatment temperature and the extrusion ratio (extrusion temperature, 550 °C) [Sca 73]

Mechanical property variations across the cross section are found in lithium-containing alloys because of the nonuniform texture formation [Tem 91].

5.9.2 Extruded Products

With their outstanding corrosion resistance to seawater, the naturally hard alloys are particularly suitable for industrial atmospheres and for pipe systems in the chemical industry. The seamless tubes extruded over a mandrel are further processed by drawing.

The age-hardening materials with their favorable mechanical properties are mainly used for superstructures in rolling stock and as hollow girders for bedplates as well as the manufacture of processing plants.

The moderately difficult alloys can be produced as either solid sections or hollow sections whereby the wall thickness has to be set 20 to 40% higher than the easily extruded alloys, depending on the alloy, for the same circumscribing circle because of the higher deformation stress. The AlZn4.5Mg1 alloy is often used for highly stressed welded structures because of its good weldability and the rehardening in the heat-affected zone. In the "age-hardened" condition (2-stage aging), this alloy has a good resistance to general corrosion and SCC (Table 5.7).

Lead-containing alloys such as AlMgSiPb are available for chip forming machining. They are particularly suitable for the machining on automatic drilling, milling machines, and lathes because they enable fast cutting speeds to be used.

The alloy AlMgSiPb has good mechanical properties, is corrosion resistant, and can be decoratively anodized. The extruded or extruded and drawn products are primarily supplied as round, hexagonal, and octagonal bars. The tolerances are standardized in DIN1769–1799 and DIN 5000-59701 (Aluminum Association H35.2).

Extruded sections in the lithium-containing aluminum alloys are used as stringer sections and floor plate supports in the aerospace industry because of their lower density and increased modulus of elasticity compared with the conventional high-strength alloys. Further applications are limited by the present high billet production costs.

5.9.3 Extrusion and Materials Properties

The flow stress of AlMg and AlMgMn increases with increasing magnesium content, and the melting point decreases. To compensate for the lower extrudability of, for example, AlMg3, the preheat temperature can be set to 30 °C higher than for AlMg1. However, the exit temperature should not significantly exceed 500 °C to avoid the surface turning brown because of increased oxidation. As mentioned earlier with naturally hard alloys, the cooling from the extrusion temperature to room temperature is not that critical. The process parameters for the individual alloys are summarized in Table 5.7.

Higher mechanical properties are obtained with AlMgSi1 and AlMgSiCu by age hardening. However, some compromises have to be made for extrusion. The metallurgical procedures that improve the extrudability (e.g., higher billet heat treatment temperature) have an unfavorable effect on the grain formation and thus on the mechanical properties [Sca 67].

In the production of AlMgSi1 sections, the decision has to be taken in the selection of the metallurgical conditions whether the solution heat treatment and quenching are coupled with the extrusion process or whether these should be carried out as separate operations. For economic reasons it is better if additional operations can be avoided. From the metallurgical point of view, there are advantages in the formation of the grain structure if no additional heat treatment in the shape of solution heat treatment has to be carried out. The decisive factor is whether the age hardening producing Mg_2Si is extensively dissolved at the exit temperature and can be retained in solution during the cooling. AlMgSi1 and AlMgSiCu sections have to be cooled quickly with water because they are quench sensitive due to the manganese content [Sca 64]. Whether this requirement can be fulfilled depends on one hand on the section shape to be produced, in particular, the wall thickness, and on the other hand, on the cooling system installed on the extrusion press. As a general rule, the rate of cooling of AlMgSi and AlMgSiCu in the temperature range 530 to 150 °C has to be a factor of 10 faster than with AlMgSi0.5; i.e., it should be at least 10 to 20 K/s. The required cooling rate can only be achieved with water. Quenching with water after the die can, however, result in uncontrolled distortion of the section that must be kept to a minimum by pullers.

If the solution heat treatment and quenching are to be carried out simultaneously with the extrusion process, care should be taken to ensure that the exit temperature is at least 530 °C. The preheat temperature should, accordingly, be 500 to 520 °C because there is no significant temperature increase from the heat of deformation. On the other hand, with a separate solution heat treatment a lower preheat temperature should be selected, and there is no demand on the exit temperature. The exit speed that can be achieved with AlMgSi and AlMgSiCu is approximately only half that of AlMgSi0.5. The extrusion ratio on the other hand does not differ significantly from that with AlMgSi0.5.

The increase in the mechanical properties of the section is achieved by age hardening for 6 to 8 hours at 160 °C or 4 to 6 hours at 180 °C. However, it should be pointed out that with AlMgSi1, the maximum achievable mechanical properties decrease with increasing room temperature intermediate storage. The damaging influence of an intermediate room temperature aging can be largely overcome by a preventative heat treatment. The sections have to be heated to 180 °C and held for 3 minutes, which eliminates the cold aging that would otherwise take place by approximately 1 day [Koe 61].

The alloy AlMgSi1 is suitable for sections that have to be color anodized because the manganese content that is embedded in the metallic form in the oxide layer produces the brown tone. Attention must be paid to the grain structure because different microstructures can result in bands on the surface after anodizing. In this case it has proved advantageous to try and obtain a completely fine-grain recrystallized structure. This can be achieved when the recrystallization retarding influence of the manganese is largely excluded by the formation of coarse secondary precipitates and thus the rate of nucleation accelerated and recrystallization promoted [Sca 69]. Billet heat treatment at 570 to 590 °C has proved successful in this respect. The associated simultaneous reduction in the mechanical properties is not important for applications in buildings.

The copper-free age-hardening AlZn4.5Mg1 alloys are very suitable for the production of hollow sections and flat sections because with this material the working temperature in extrusion coincides with the solution temperature range, and this alloy has a low quench sensitivity so that air cooling suffices.

Also, the mechanical properties that can be achieved are higher than AlMgSi1. However, with incorrect treatment, a tendency to SCC cannot be completely excluded. Today it is generally recognized that the danger of SCC of extruded sections can be excluded if the production conditions are strictly maintained. These conditions are [Sca 73]:

- The billet heat treatment must be carried out at a low temperature (12 h at 460–480 °C) to suppress the recrystallization by fine manganese, chromium, or zirconium phases.
- The extrusion temperature should be as low as possible (450–490 °C).
- The cooling with air in the temperature range 350–200 °C should be in the range 0.5–1.5 K. Water quenching should be avoided at all costs.
- The age hardening—after an intermediate room temperature aging of at least 3 days—has to be carried out in stages (12 h at 90 °C plus 12–24 h at 120–130 °C) to produce an overaged structure.

The extrusion behavior of the alloy AlZn4.5Mg1 from the point of view of the extrusion speed is comparable to the alloy AlMgSi1. The advantages of AlZn4.5Mg1 are the relatively low solution heat treatment temperature and the use of air even with thick-wall sections to achieve the necessary slow cooling rate.

The extrudability of the alloy AlLiCuMg is comparable with that of the moderately difficult alloys AlMgSi1 and AlZn4.5Mg1. The flow stress of AlCuMgSi is approximately 10 to 15% lower than that of AlMgSi1. The maximum extrusion speed that can be obtained is reduced to a value of only 60% of that of AlMgSi1 because of the low-melting-point copper phase. It is beneficial with the lithium-containing alloy as with the other high-strength materials to pass the section through nitrogen as it leaves the die to avoid oxidation of the surface [Sca 79].

The age hardening of the lithium containing alloys is carried out by solution heat treatment at 530 to 540 °C and quenching in water. Cold working (stretching) of 1.5 to 2% before aging at 185 °C has proved to be beneficial to both the magnitude of the strength and the elongation [Tem 91].

5.10 Difficult-to-Extrude Alloys

The highest mechanical properties in the aluminum alloys can be achieved with the age-hardening alloys of the AlCuMg and, in particular, the AlZnMgCu systems. Alloy technological procedures have to be followed, however, that can be disadvantageous from other perspectives. The addition of up to a few percent copper results in the formation of low-melting-point intermetallic phases. They also have an unfavorable effect on the general corrosion resistance. Recrystallization retarding elements, including manganese, chromium, and zirconium, also have to be added in order to obtain a hot-worked structure in the extruded sections that contains elongated grains in the longitudinal direction. The mechanical properties in the longitudinal direction are higher than in the transverse direction. This is referred to as the *extrusion effect* [Sca 69c]. The alloy technological measures described do fulfill the mechanical property requirements but have serious hot-working disadvantages. The additions of the main alloying elements magnesium and copper and the additions of manganese and chromium increase the flow stress significantly so that AlCuMg2 and AlZnMgCu1.5 have to be classified among the difficult-to-extrude alloys. The difficulty is increased by the low-melting-point phases, which severely limit the extrusion temperature range, and if the latter is exceeded, hot cracking occurs. These alloys have a marked quench sensitivity and a severely limited solution range so that in most cases they have to be solution heat treated and quenched in a separate operation.

In addition to these alloys, the AlMg and AlMgMn alloys with 4 to 5% magnesium are included in the difficult-to-extrude alloys. The flow stress of 47 to 56 N/mm^2 is attributable to the high magnesium content and the manganese secondary precipitates, particularly if these occur in a fine format and a high density in the matrix.

It should be pointed out here that new production processes are being used to develop new aluminum alloys for extruded sections with improved materials properties. These include alloys produced by powder metallurgy and particle reinforced conventional alloys [Web 89] (see the section “Extrusion of Powder Metals” in this chapter).

5.10.1 Aluminum Alloys

There are various types of alloys with copper as the main alloying element. They differ in special material properties. These alloys are usually cold age hardened to give the most favorable properties. AlCuMg2 has the highest mechanical properties and a good toughness. It is very important in the aerospace industry. The alloy AlCuMgFeNi has the best high-temperature mechanical properties of all the conventional alloys. The alloy AlCuSiMn is characterized by high mechanical properties at room temperature and elevated temperatures. Because this alloy also has excellent forging properties, preforms are extruded and then forged in dies. Bars for drilling, milling, and turning are made from the alloys AlCuMgPb and AlCuBiPb.

The billet heat treatment of these alloys is usually carried out at 480 ± 5 °C. Only AlCuMgFeNi is heat treated at 525 ± 5 °C because of the additions of nickel and iron. The heating should not significantly exceed 50 °C/h to avoid melting. After the heat treatment, slow cooling to approximately 360 °C is recommended, preferably in the homogenizing furnace. The cooling can then be carried out in air. These measures help avoid quenching stresses, which can produce cracks in the billets in these alloys.

The following AlZnMgCu alloys are the most common: AlZnMgCu0.5 and AlZnMgCu1.5, which are both standardized, as well as alloys with higher zinc contents in which manganese and chromium are replaced by zirconium. This reduces the quench sensitivity of these alloys. The highest mechanical properties measured on extruded sections are typically $R_{p0.2}$ 580–610 N/mm^2 and R_m 610–640 N/mm^2 and approximately 8–10% for A5.

The billet heat treatment of these alloys is particularly important because of the complexity of the cast structure. Structural rearrangements occur during heating, holding at temperature, and cooling, and these have a significant influence on both the mechanical properties and the extrudability. Cast billets have a lower melting point than homogenized billets. The melting point is increased by 70 to 90 °C by reducing the residual melt bands and segregations as well as dissolution during the billet heat treatment. On the other hand, the supersaturated dissolved fractions of the peritectic phases are precipitated in a fine form in the matrix by thermal activation. In the billet heat treatment—usually 12 h at 480 ± 5 °C —the cooling of these alloys has a decisive influence on the extrusion speed [Fin 96]. If the cooling is not fast enough, coarse particles can form during the cooling. These do not dissolve completely during heating and then melt in the extrusion process, resulting in surface cracks in the section.

The high-alloyed alloys AlMg5 and AlMg4.5Mn are particularly suitable for low temperature applications. The mechanical properties increase as the temperature falls; this also applies to the elongation to fracture. If the magnesium content exceeds 3%, some of the magnesium exists preferentially as intermetallic phases on the grain boundaries and some in the matrix. This applies in particular if the material is held for a long period in the temperature range 250 to 150 °C. Intercrystalline corrosion susceptibility can occur under unfavorable conditions if the application temperature is $>$80 °C. The magnesium phase can be precipitated by suitable thermal treatments during production so that no coherent precipitates form and intercrystalline corrosion can be practically eliminated.

5.10.2 Extruded Products

The high-strength materials are mainly used in the aerospace industry, military applications, and machinery. The products include solid sections, bars, and seamless extruded tubes. AlCuMg2 and AlZnMgCu1.5 are normally not suitable for the production of hollow sections with extrusion welds because of the low-melting-point phases and the high extrusion pressures required [Wei 78]. Simple, thick-wall tubular components are, however, occasionally extruded with bridge or porthole dies.

Whereas AlCuMg2 is usually used in the room temperature age-hardened condition for high-stress applications, AlCuSiMn and AlCuMgFeNi as well as AlZnMg alloys are mainly used after hot age hardening. AlCuSiMn is used in the as-extruded or annealed state for subsequent processing to forged components.

Only the alloy AlMg4.5Mn of the difficult-to-extrude naturally hard alloys can be extruded as a hollow section with extruded welds. However, this is possible only with a large wall thickness because of the high deformation loads. The applications are primarily chemical equipment and machinery.

5.10.3 Extrusion and Materials Properties

Only extrusion ratios of $V = 10$ to $V = 40$ are used for the difficult-to-extrude alloys because of the high flow stress of over 45 to 57 N/mm^2. The extrudability is less than 10% of the easily extruded alloys.

Indirect extrusion of high-strength alloys has been used to an increasing extent in recent years. This has clearly confirmed the advantages of the indirect extrusion process for the high-strength and difficult-to-extrude alloys AlCuMgPb, AlCuSiMn, and AlZnMgCu1.5 [Eul 75]. Indirect extrusion has a higher productivity compared with direct extrusion. Significant advantages include the higher extrusion speed at lower temperatures (340–360 °C) and the use of longer billets (3–7 times the container diam). The different material flow in indirect extrusion produces a homogeneous structure and thus more uniform properties. However, indirect extrusion places higher demands on the casting quality. Only defect-free turned or scalped billets give a good extruded surface finish. The distance between the die and the cooling section at the press exit is greater because of the design of indirect extrusion presses. This makes the quenching of quench-sensitive alloys at the press more difficult. In addition, quenching at the press requires a sufficiently high exit temperature to achieve complete age hardening. In direct extrusion, the extrusion speed of difficult-to-extrude alloys is increased by 20 to 40% by die cooling with nitrogen. This is demonstrated with the copper-containing alloys, which have a relatively low melting point. Die cooling enables some of the deformation heat to be removed so that the critical melting temperature, which results in section cracking, is reached at a higher exit speed [Sca 79].

The solution heat treatment of the high-strength alloy AlZnMgCu1.5 is usually carried out separately after extrusion. The reason for this has already been discussed. This is then followed by age hardening. Room temperature intermediate aging for 3 to 5 days has proved beneficial. The age hardening is carried out in one or two stages (Table 5.8) and depends on the customer specifications. If the maximum mechanical properties are required, age hardening is carried out at only 120 °C to the maximum of the age-hardening curve. However, a slightly overaged condition is recommended because this significantly improves the stress-corrosion resistance for only a slight loss in mechanical properties. A two-stage age hardening is used to achieve the T73 designated properties. The sections are initially aged for 12 to 24 hours at 120 °C and then for 3 to 5 hours at 170 °C [Dah 93].

The alloy AlCuMg2 is usually aged at room temperature after quenching in water as hot age hardening has a negative influence on the corrosion properties; a tendency toward intercrystalline corrosion can be detected. Hot age hardening is the standard process for the AlCuSiMn and the AlCuMgFeNi alloys to achieve the desired high mechanical properties. The age-hardening parameters are given in Table 5.8.

Finally, the difficult-to-extrude alloy AlMg 4.5Mn is a naturally hard alloy where the increase in mechanical properties is not obtained by heat treatment but by solid solution and work hardening. For this reason, the extrusion ratio should not be too high; otherwise, the fraction of recrystallized structure increases to such an extent that the specified values are not reached. This occurs, in particular, when a higher extrusion temperature has to be used because of the limited specific pressure of the extrusion press.

Extrusion of Materials with Deformation Temperatures of 600 to 1300 °C

5.11 Extrusion of Semifinished Products in Copper Alloys

Martin Bauser*

5.11.1 General

5.11.1.1 Copper, Bronze, and Brass—A Long History

The knowledge and application of copper and some of its alloys extends back into prehistory (Bronze Age). They were used up to the beginning of our technical era mainly for jewelry and household goods. The good workability of copper and copper-zinc alloys combined with the attractive appearance is responsible today for their use for metal wares, including containers, lamps, and trays as well as brass instruments.

5.11.1.2 Advantageous Physical and Chemical Properties

Copper is the commercial metal with the highest electrical conductivity (58 m/Ω mm^2 at 20 °C). The additions to some low-alloy copper ma-

*Extrusion of Semifinished Products in Copper Alloys, Martin Bauser terials only reduce the conductivity slightly but significantly improve the mechanical properties. The high thermal conductivity corresponds to the high electrical conductivity. Copper is located close to the noble metals in the electrical chemical series and has a natural resistance to numerous corrosive effects.

The good corrosion resistance and the ease of working make copper one of the most important materials for water supply pipes. It is also particularly suitable for heat exchangers because of its good thermal conductivity. The property of copper used most is the excellent electrical conductivity, which secures its very wide application in electrical engineering and electronics—naturally also in the form of rolled products.

5.11.1.3 Importance of Extrusion in the Processing

Pure copper melts at 1083 °C. The melting point is only increased by the addition of nickel (continuous solid solution). All other element additions lower the melting point, sometimes to less than 900 °C (Table 5.9). The recrystallization temperature falls in the range 350 to 650 °C depending on the composition. Copper alloys are extruded at temperatures between 550 and 1000 °C corresponding to the melting temperature. Along with aluminum alloys, they belong to the group of materials where long semifinished sections are mainly produced by extrusion.

According to the statistics in Europe in 1988, 1.4 million tonnes (metric tons) of extruded

Table 5.9 Extrusion data for copper alloys

Material	Melting interval, °C	Billet temperature, °C	Maximum extrusion ratio	Maximum extrusion speed, m/min
Copper				
E-Cu	1080–1083	780–950	250	300
Low alloyed copper				
CuCrZr	1070	930–980	100	150
CuNi2Si	1040–1070	750–900	75	100
CuNi3Ni	1030–1050	850–950	50	75
CuZn (tombac and brass)				
CuZn10	1015–1035	825–875	150	100
CuZn20	950–990	750–850	60	100
CuZn30	910–935	720–800	150	150
CuZn37	900–920	710–790	200	150
CuZn38Pb1	880–900	650–750	250	250
CuZn40Pb2	875–885	650–750	300	300
Special brass				
CuZn28Sn2	890–930	750–780	75	100
CuZn31Si1	930–950	720–760	150	150
CuZn35Ni2	880–890	700–800	200	300
CuZn40Al2	880–890	600–700	250	250
CuZn40Mn2	880–890	650–700	250	250
CuSn (tin-bronze)				
CuSn2	1020–1070	800–900	100	150
CuSn6	910–1040	600–700	100	50
CuSn8	860–1015	650–720	80	30
CuAl (aluminum-bronze)				
CuAl5As	1050–1060	750–850	75	150
CuAl8	1030–1035	740–780	100	150
CuAl10Fe3Mn2	1030–1050	750–900	100	200
CuAl10Ni5Fe4	~1050	750–900	50	100
CuNi (copper-nickel)				
CuNi10Fe1Mn	1100–1145	850–950	80	50
CuNi30Mn1Fe	1180–1240	900–1000	80	50
CuNi30Fe2Mn2	1180–1240	900–1000		
CuNiZn (nickel-silver)				
CuNi12Zn24	~1020	900–950		
CuNi12Zn30Pb	~1010		80	50
CuNi18Zn20	~1055	850–920		
CuNi18Zn19Pb	~1050		50	30

Source: Lau 76, Moe 80

products were produced in copper alloys by 70 companies and approximately 120 presses [Zei 93]. In Germany there are 14 companies with 37 presses in the range 10 to 50 MN press power.

Sixty percent of all extruded products are bar, wire, and section of which the majority are produced in copper-zinc alloys (brass). The remaining 40% are tube—usually in copper.

5.12 The Groups of Extruded Copper Alloys—Their Important Properties and Applications

5.12.1 Alloy Groups

The DIN standards cover 81 wrought alloys in seven groups that can be extruded under specific conditions (Table 5.10).

The conversion to European standards had not been completed at the time of publication. Only product standards and not individual alloy groups, as is the case in DIN, are included in the European standards. Each EN then usually applies to all alloy groups (Table 5.11). ASTM International Standards cover alloys, product shape, and specific applications.

In addition to these alloys produced from cast billets there are a few composite materials and powder metals discussed in the sections "Extrusion of Powder Metals" and "Extrusion of Semifinished Products from Metallic Composite Materials."

5.12.2 Tooling Temperatures in Extrusion

With extrusion temperatures between 500 and 1000 °C, the tooling is subjected to significantly higher temperatures than with aluminum alloys. However, as copper alloys can usually be extruded at much higher speeds than aluminum, the contact time with the tooling is so short that heating of the tools over the limit of 500 to 600 °C can be avoided. The tooling wear is, however, naturally much higher than with aluminum alloys (see the section "Tools for Copper Alloy Extrusion," in Chapter 7).

5.12.3 Structure

Copper and numerous copper alloys, e.g., copper-tin (up to 8% Sn) and copper–zinc (up to 37% Zn) have a pure face-centered cubic (fcc) α structure up to the melting point and therefore have good cold workability but only moderately good hot workability. On the other hand, the body centered cubic (bcc) β phase, e.g., copper-zinc over 40% zinc, has excellent hot workability but is difficult to cold work.

5.12.4 Typical Extruded Semifinished Products and Applications

The section "Copper Alloy Extruded Products" in Chapter 2 describes typical extruded semifinished products and their applications.

Whereas bar and wire are produced over the entire alloy range, tubes are mainly in SF-Cu for water supply, brass for plumbing fittings, and in special brasses and copper-nickel alloys for corrosive media. Large quantities of free-machining brass are machined to fittings and turned components, including bolts.

In contrast to aluminum, the production of sections is no longer important. The higher extrusion temperature results in higher die temperatures and thus greater wear and more severe tool defection than with aluminum alloys. The

Table 5.10 Copper alloy groups and the associated composition DIN standards

Alloy groups	No. of DIN standardized alloys	ASTM standard
DIN 1787: copper	6	B 133
DIN 17666: copper wrought alloys—low alloyed	20	E 478
DIN 17660: copper-zinc alloys (brass, special brass)	31	B 371
DIN 17662: copper-tin alloys (tin bronzes)	4	B 505(a)
DIN 17665: copper-aluminum alloys (aluminum bronzes)	8	B 150, B 359
DIN 17664: copper-nickel alloys	6	E 75
DIN 17663: copper-nickel-zinc alloys (nickel-silver)	6	B 151

(a) For continuous casting

Table 5.11 Euro standards for extruded copper alloy semifinished products

Standard	Designation
EN 1057	Seamless round copper tubes for water and gas supplied for sanitary installations
EN 12735	Seamless round copper tubes for air conditioning
EN 13348	Seamless round copper tubes for medicinal gases
EN 12449	Seamless round tubes for general applications
EN 12451	Seamless round tubes for heat exchangers
EN 12163	Bar for general application
EN 12164	Bar for machining
EN 12165	Feedstock for forged components
EN 12166	Wire for general applications
EN 12167	Section and rectangular bar for general applications
EN 12168	Hollow bar for machining

extrusion tolerances of copper alloys are wider than with aluminum and it is also not possible to produce thin profile cross sections (see DIN 17 674, page 3). With few exceptions the sections have to be subsequently drawn. Section production is usually limited to copper and low-alloy copper materials as well as the easily extruded α-β brasses.

The most economic production of readily cold-worked alloys to tubes, bar, and section depends on the equipment available at the individual companies. Depending on the type of press, the size, and the number and size of the drawing machines, the most suitable extruded dimensions vary for the same finished product.

5.13 Extrusion Properties of Copper Alloys

Numerous authors have covered the extrusion of copper alloys [Tus 80]. Only the work relevant to practical applications is included here.

5.13.1 Extrudability of Different Materials

Table 5.9 gives the extrusion temperatures, the maximum extrusion speeds, and the maximum extrusion ratios. The data were obtained from practical experience in various extrusion companies. These can differ from plant to plant.

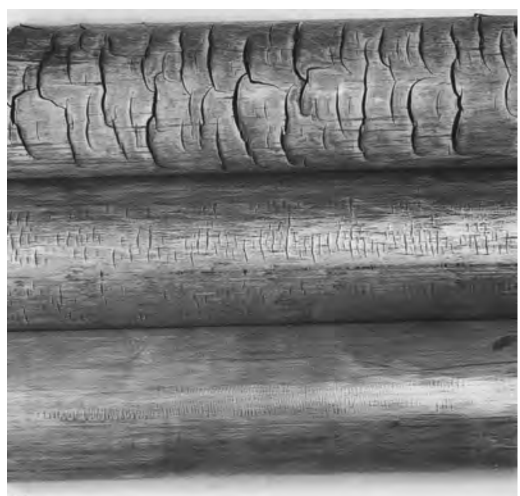
5.13.2 Temperature and Speed—Structure of the Extrusion

The temperature dependence of the workability of different copper alloys is shown in the following section in the form of hot-strength curves. Data obtained from tensile tests only have limited application in calculating the forces needed for extrusion. However, if they have all been measured using the same method on soft specimens, they are suitable for comparing the materials (see also Chapter 4). Values of the flow stress k_f obtained from torsion tests, which are often described in the literature, are more suited to calculating the load. Strains comparable to those in extrusion can be achieved. The *Atlas of Hot-Working Properties of Non-Ferrous Metals*, Volume 2, *Copper Alloys* [DGM 78] gives these k_f values as a function of the logarithmic principal strain φ_g and the logarithmic principal strain rate $\dot{\varphi}_g$. Unfortunately, not all the important alloys are included. In addition, as different authors have used various methods of measurement these data are not suitable for comparison.

Up to the extrusion temperature, copper and low-alloy copper materials have the face centered α-structure, which does not have good hot-working properties.

Brass in the α-β range (free-machining brass) has very good hot workability. The extrusion of brass bars was the first large-scale application of this process (A. Dick, 1890, see the section "Historic Development of Extrusion" in Chapter 1).

With difficult-to-extrude alloys, the flow stress, depending on the press size and the extrusion ratio, places a lower limit on the extrusion temperature and an upper limit on the susceptibility to hot shortness [Lau 76]. Aluminum bronzes and lead-containing nickel silvers are particularly susceptible to hot shortness. The cracks can range from light surface cracks to fir tree defects (Fig. 5.35). It is not only on eco-



(a)

(b)

Fig. 5.35 Hot shortness cracking at excessive extrusion temperature. (a) CuSn8 extruded tube with coarse, moderate, and fine hot shortness cracks. (b) Extruded round bar in CuSn6 with gaping hot shortness cracks [Die 76] nomic grounds that the extrusion speed should be as high as possible and the initial billet temperature as low as possible. The output is higher and the thermal stressing of the tooling during extrusion shorter. The material itself also cools less during extrusion by the conduction of heat into the container, which is at a maximum of 500 °C, which results in a more uniform section exit temperature and structure over the length of the extrusion.

The age-hardening copper-chromium and copper-chromium-zirconium alloys represent a special case where it is possible to quench small sections from the extrusion temperature, which is also the solution heat treatment temperature. In this case, extrusion is carried out at the highest temperature possible (900 to 1000 °C).

The maximum extrusion speed is frequently limited by the equipment, e.g., by the puller system for sections or by the speed of the down coilers for wire.

The extrusion temperature and the deformation are normally so high that the extruded section completely recrystallizes as it leaves the die, usually with a fine-grain structure. However, it is possible to have structural variations from the front of the extrusion to the back. At the start of extrusion the deformation is lower than in the middle and at the end. Depending on the extrusion ratio, the extrudability, and the extrusion speed, the exit temperature can fall or even increase. With multiphase structures the quantity and distribution of the second phase can vary over the cross section and the length of the extrusion. Details are given in the material-specific sections 5.16 to 5.16.9.

5.13.3 Extrusion to Finished or Close-to-Finished Dimensions

Because the α-β brasses are difficult to cold work, brass bar and sections in these alloy groups are extruded close to the final dimensions and then brought to the desired finished dimensions and mechanical properties by a subsequent cold-working operation (usually by drawing). In contrast, the alloys that have good cold workability (copper, low-alloy copper materials, α-brasses) are extruded well above the finished dimensions and then cold worked in several stages. Cold working of sections can be difficult and requires considerable experience in deciding the extruded dimensions, the tool design, and the drawing parameters.

5.13.4 Lubrication

Lubricants based on graphite oil mixtures are well suited for the temperature range in which copper alloys are extruded.

There have been many attempts to introduce other lubricants for the extrusion of copper alloys. These have largely been disappointing. Usually, viscous oil blended with graphite flakes is used. If automatic lubrication systems are used, which is increasingly common on modern equipment, the lubricant has to have a low viscosity. "Lubricant sticks" of graphite containing wax are available for die lubrication. The container is usually unlubricated so that only the die and the mandrel in the case of tubes have to be regularly lubricated. To reduce graphite inclusions and banding on the surface of the section, the minimum of lubricant should be accurately applied. However, too little lubrication will result in wear between the tooling and the extruded material.

5.13.5 Extrusion with a Shell

Materials that are oxide free or have a limited amount of oxide usually bond to the tooling in the absence of lubrication. Brasses, aluminum bronzes, and copper-nickel alloys have to be extruded with a stable shell. At the end of each extrusion the dummy block is pushed out and the shell removed with a cleaning disc. The shell thickness is usually about 1 mm. If it is too thick there is the risk that the material will flow back between the dummy block and the container over the stem. This can occur in particular with alloys that are easy to extrude. An incomplete shell can form if the shell is too thin. A fixed dummy block, which is used for the easily extruded aluminum alloys, cannot be used for copper alloys.

Copper and low-alloy copper materials, as well as bronzes, tend to oxidize. The oxide layer adhering to the hot billet acts as a lubricant [Bla 48, Bei 76, Vat 70]. However, because the billet surface is generally not uniformly oxidized, partial adhesion to the container can occur and extrusion has to be carried out with a shell.

The thin shell in the extrusion of copper and low-alloy copper materials can be easily removed from the container and squashed so that it is possible to operate with a combination dummy block and cleaning pad (see Chapter 7). The front ring of this block has the diameter of the dummy block and the rear the diameter of the cleaning block. In between there is a deep and wide circular recess into which the thin shell folds. Extrusion with a shell is still carried out with the combination dummy block and cleaning pad but the additional cleaning operation is eliminated.

5.13.6 Different Material Flow Behavior

In the direct extrusion of copper alloys with a shell and unlubricated container, flat dies are used. Differences in the hot-working properties and the flow behaviors of different material groups result in different types of material flow. The material flow patterns can be found in Chapter 3.

5.13.6.1 Flow-Type C—Piping Defect

Aluminum bronzes and α-β brasses adhere to the container because of the minimal oxide formation and flow according to type C because the layer close to the surface cools during extrusion and does not flow as readily as the billet core. The danger of the piping defect (see Fig. 5.46) is countered by restricting the billet length. However, the end of the extrusion has to be regularly tested using a fracture test.

It is advantageous with these alloys to change to the indirect extrusion process where there is no friction between the billet and the container and the risk of the piping defect is removed. The material then flows according to type B. Longer billets can then be used, providing the other conditions allow it, and the discard length is reduced [Zil 82].

5.13.6.2 Flow-Type B—Shell Defect

Copper and low-alloyed copper alloys similar to CuCrZr or CuNiSi but also CuNi, CuNiZn, α-brasses as well as CuSn are frequently extruded at temperatures so high that, depending on the material, a more or less thick oxide layer forms that in turn can result in extrusion defects including shell defects and thus blisters on the extruded section (see Fig. 5.39). The material flows according to type B. The dead metal zones when flat dies are used hold back the oxide. Nevertheless, the billet length has to be limited or the discard thickness correspondingly increased to avoid shell and blister defects. This is covered in more detail in Fig. 5.38.

The risk of shell defect is somewhat less in indirect extrusion than in direct extrusion.

5.13.6.3 Back End Defect

If the extrusion ratio is too low (heavy sections), there is the risk of the "back end defect" forming particularly with material that flows according to type C in direct extrusion. The accelerating material in the center of the billet can form a funnel at the end of extrusion. Short billet lengths and large discard lengths can be used to reduce this (see Fig. 5.47).

Back end defect is seen less in indirect extrusion than in direct extrusion and only when the extrusion ratio is too small and the discard too thin.

5.13.7 Discard Length

Discard lengths between 20 and 40 mm are used for copper, α-brasses, and tin bronzes, which also flows according to flow pattern B in direct extrusion.

For α-β brasses and special brasses, which flow following flow pattern C, discard lengths are between 30 and 50 mm.

The lengths should be 40 to 70 mm with the hard-to-extrude aluminum bronzes—also flow pattern C.

These are not always valid. Sometimes—independent of the material and the container—30 to 50 mm discard lengths are used in direct extrusion and the possible defective section ends removed by careful control of cross sections (fracture tests).

The discard length can be significantly smaller in indirect extrusion.

5.13.8 Direct Extrusion with Lubrication and without a Shell

Extrusion is rarely carried out with internal lubrication of the container, which reduces the extrusion load because the friction between the billet and the container is largely eliminated. This process was adopted for the vertical extrusion presses that used to be used when high extrusion ratios were required from relatively low-powered presses. Even today thin-walled tubes and small hollow sections are produced on vertical presses with lubricated containers. On horizontal presses it can be necessary to process difficult-to-extrude alloys, e.g., copper nickel, at higher extrusion ratios than would be possible taking into account the friction between the billet and the container. Lubrication of the container can help in this case.

Blisters on the surface of the extrusion can be avoided on susceptible alloys by extruding with a lubricated container. It is necessary to use a conical entry in the die and to machine the billet surface. The billet surface forms the surface of the section because of the laminar flow and every defect on the billet surface appears on the section.

5.13.9 Extrusion into Water or Air

Alloys that tend to oxidation are often extruded into a water bath or through a water wave. This ensures that the extruded product does not have to be pickled before subsequent further processing. It is also possible with copper tube to restrict the secondary recrystallization observed when extruding into air and thus a coarse grain on the exit from the die [Gre 71]. A fine grain is often required for further processing.

Water cooling should, as a general rule, be avoided for α-β materials because otherwise, as the material leaves the die, the structure consisting mainly of the β-phase is undercooled and it is possible for some of the α-phase to precipitate as needles. Both reduce the workability and increase the strength of the extrusions [Bro 73]. If more rapid cooling than air cooling is required (e.g., with brass wire), the material can only come into contact with water after air cooling (to 500–300 °C, depending on the material) if it is to remain soft. Direct slower cooling with a water-air mixture is possible.

5.14 Extrusion Processes and Suitable Equipment

Whereas earlier extrusion plants were mainly multipurpose plants capable of producing rod and sections as well as wire and tube, today extrusion plants are designed specifically for the production of large quantities of one product [Ste 91]. Specific design details are given in Chapter 6.

5.14.1 Extrusion Presses for Brass Wire and Sections

There are some presses on which large quantities of brass are produced where only wire is extruded onto down coilers and others that are equipped with pullers (up to 4 sections) for the production of rod and sections. In contrast to the extrusion of aluminum sections where several strands can be pulled with a single puller, with copper alloys a specific puller device must be provided for each strand. The exit speeds of the individual sections are not exactly equal so that the slower section would be severely stretched at the high exit temperature.

Indirect extrusion is often used for brass wire and rod because this avoids the piping defect and long billets can be used.

A rod and section press—usually the direct process—has a section cross-transfer system as well as the puller system and frequently a water trough in which the sections can be quickly brought to room temperature after crossing the critical temperature of approximately 300 °C. Wire is also cooled in water after a specific cooling time in air.

If a wide range of materials and dimensions have to be processed, a multipurpose press is still the correct choice.

5.14.2 Tube Extrusion

Tube presses today obviously have a piercer system. Water-cooled mandrels are used that usually move with the stem (moving mandrel). The mandrel that is stationary in the die during extrusion is subjected continuously to a high temperature. The "stationary mandrel" is therefore used only for the extrusion of tubes with small internal diameters and suitable hollow sections.

Copper sections are extruded under water (or occasionally in a protective atmosphere).

In the 1950s and 1960s a large range of vertical tube presses were installed. They were built because the vertical axis simplified the alignment of the mandrel to the container and the die giving a better tube concentricity. On today's horizontal presses the tools can be so easily adjusted and guided that this advantage no longer applies. Horizontal presses need simpler foundations and enable larger section weights to be produced and have therefore almost completely displaced the vertical tube presses.

5.14.3 Drive

Whereas water and accumulator driven extrusion presses were previously exclusively used for copper alloys giving high ram speeds (up to 150 m/s), these are used today only for copper tube and thick sections.

In other cases direct oil drives are used, although these allow only a maximum ram speed of approximately 50 mm/s at an economically acceptable investment; this is usually adequate. The advantages of oil drive (good speed control and regulation over the billet length, simpler maintenance, and smaller footprint) predominate. Exact speed control is particularly advantageous for a linked puller and synchronously operating wire coilers. Variable oil drive also simplifies the automation of the extrusion process.

5.14.4 Die Changing

It must be possible to easily change dies and to control them on copper alloy presses: the high thermomechanical stresses result in such severe wear and deformation of the shape forming dies that dressing can be required after only a few extrusions. Chapter 6 describes suitable die changing systems (rotating arm, slide).

Quick container changing is more important than in aluminum extrusion because of the wear of the liner.

5.14.5 Discard Separation

The discard is normally removed with the saw, in contrast to aluminum extrusion where it is usually sheared. It is important that good swarf extraction prevents damage of the product from swarf.

In indirect extrusion and direct extrusion of small solid sections a powerful shear is, however, preferred [KM 77].

5.15 Billet Production and Heating

5.15.1 Continuous Casting and Homogenizing

Chill cast molds were still used up to the 1960s. They were completely replaced by the continuous casting method developed circa 1930 (see the section "Systems for the Production of Copper Billets" in Chapter 6). Horizontal or vertical casting is used depending on the billet cross section and alloy and usually on continuous plants. Homogenization of the billets is not normally required apart from tin bronze, which is susceptible to severe segregation, where the risk of cracking is reduced.

5.15.2 Billet Length

The length of the extrusion billet is usually determined by the extruded length of the section with rod, sections, and tubes. With coiled wire this is obviously not necessary. In this case the maximum billet length is selected. Alloys that are susceptible to piping are usually limited to 2.5 to 3.5 times the diameter in direct extrusion.

For extruded tubes the traditional rule of thumb is that the billet should not be longer than 5 times the mandrel diameter because of the increasing risk of wall thickness eccentricity as the billet length increases. The billet length also has to be restricted because of the occurrence of shell defects (e.g., with low-extrusion-ratio copper tubes).

5.15.3 Billet Processing

In the case of lubricated extrusion or if the billet surface is defective (particularly with flow type B), the billet has to be skimmed. This expensive operation is, naturally, avoided as much as possible by preferably extruding with an unlubricated container and a thicker shell that collects the casting defects.

In indirect extrusion without a shell and a conical die, the billet surface forms the section surface similar to direct extrusion with a lubricated container. All billets then have to be skimmed. To avoid this, extrusion with a shell and a flat die is also carried out with indirect extrusion so that a dead metal zone forms. Both hinder the flow of the billet surface into the surface of the section. The risk of defects is, however, significantly greater than in direct extrusion and particular emphasis has to be placed on a good, smooth billet surface.

If large-format tubes are extruded from large-diameter billets, the piercing load of the press may not be large enough and the billet has to be prebored. The general rule is that the bore diameter should be approximately 5 mm larger than the mandrel diameter so that the lubricant is not wiped off as the mandrel enters the billet.

5.15.4 Billet Quality Control

The billet quality must in any case be carefully checked before extrusion. This includes porosity and crack monitoring of sensitive material as well as visual inspection of the billet surface.

5.15.5 Billet Heating

Billet heating is described in detail in the section "Billet Heating Systems" in Chapter 6.

The most economic heating in a gas furnace is adequate to heat materials with a relatively low extrusion temperature (e.g., free-machining brasses), even though in terms of the final temperature it is less accurate and less reliable. A temperature profile can be applied, if needed, by subsequent heating in an inline induction furnace with several heating zones and, in any case, the billet temperature can be more accurately controlled. There are also cases in which gas furnaces are used even with higher billet heating temperatures (e.g., copper). In these cases induction furnaces are more common because the risk of overheating is reduced. High billet preheating temperatures are simultaneously close to the solidus temperature and thus there is a risk of the billet melting.

To reduce costs with high billet heating temperatures, the first heating step can be carried out in a gas furnace and the second in an induction oven.

In every case an inline electrically heated equalization chamber can be used in which temperature variations between the billet front and back can be removed and in which billets can be maintained at temperature during press downtime.

5.16 Copper Extrusion

5.16.1 General

Unalloyed copper is mainly extruded to tubes and, to a small degree, to bar and sections. Copper wire is, in contrast, usually cast, hot rolled, and drawn.

5.16.1.1 The Different Grades of Copper, Their Properties and Applications

The different copper grades are standardized in DIN 1787 (see Table 5.11 for the Euro standards). Pure copper with a low oxygen content (less than 0.04%), which bonds the residual impurities, giving the maximum electrical conductivity, is used in electrical technology under the designation E-Cu. In North America a designation beginning "OF" indicate oxygen free. Extruded and drawn sections as well as flat bar are used. Another high-conductivity copper grade that is oxygen free by deoxidation is referred to as SE-Cu in Europe. In North America deoxidized grades, DLP and DHP, are used for nonelectrical purposes. The STP and ETP designations are used for electric bus. The most expensive variation is OF-Cu that is oxygen free without a deoxidation agent.

Oxygen-containing copper is sensitive to heating in a hydrogen-containing atmosphere. The oxygen forms water vapor in the pores of the annealed material with the diffused hydrogen, and this can burst open the structure. If the material has to be suitable for welding, brazing, or annealing, the oxygen has to be bonded, which is carried out by phosphorus in SF-Cu (0.015–0.04%). Water supply tubes are the main application of this copper grade.

5.16.1.2 Hot Workability, Extrusion Temperature

The hot workability of copper is limited by the fcc structure up to the melting point (see the hot-strength curve in Fig. 5.36). The extrusion temperature is accordingly very high (800–950 °C), and a high extrusion ratio is possible only on powerful extrusion presses.

5.16.2 Copper Tube

5.16.2.1 Application

SF-Cu is used exclusively for domestic water pipe, the most common use of copper tubes, because these need to be welded or soldered. However, SF-Cu is also used for underfloor heating or for industrial applications (heat-exchanger tubes in air-conditioning units, for chillers, etc).

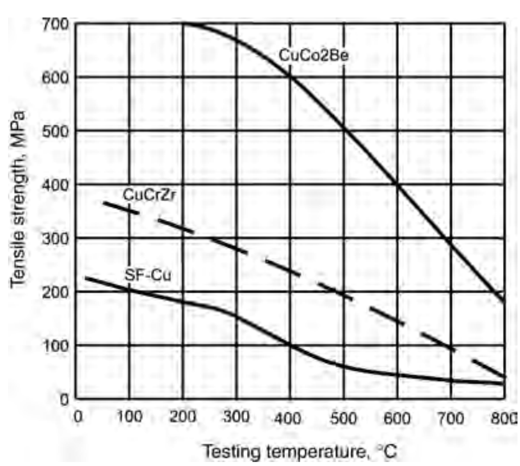


Fig. 5.36 Hot tensile strength of SF-Cu and low-alloy copper materials [Wie 86, Gra 89]

Whereas water supply pipes are available as hard or half-hard pipes or annealed coiled tubes (DIN 1786/EN 1057), industrial tube is usually supplied in annealed multilayered coils (coil weight 60–120 kg). Internal and external finned tubes for heat exchangers are also produced in SF-Cu because of the good thermal conductivity of copper and its excellent cold workability.

5.16.2.2 Production Methods

Numerous modern copper tube plants have been installed specifically for the production of SF-Cu tubes. The combination of the very good cold workability with the reduced hot workability enables hot working to be used to produce a tube larger than the finished dimensions followed by cold working to the finished size by cold pilgering and drawing machines without intermediate annealing. Soft tubes are given a final anneal. Half-hard tubes are lightly drawn after annealing.

Three processes compete for the production of copper tubes [Tus 70]:

- *Production using a piercer, cold pilger machine (tube rolling), and drawing machines:* Heated billets are rolled with inclined rolls over a mandrel to tube blanks. A straight tube up to 150 m long is then produced on a multistage cold pilger machine with a reduction ratio of 10:1 followed by redrawing.
- *Production on an extrusion press, cold pilger machine, and drawing machines:* The usual dimensions of the extruded tube are 80 $\times$ 10 mm with a piece weight of more than 400 kg. As in the first process, the extruded tube is then further processed with cold pilger machines and drawing machines. Schumag machines and spinner blocks are used.
- *Production on an extrusion press and drawing machines:* A so-called thin tube, e.g., 73 $\times$ 4 mm and a length of approximately 50 m but a lower piece weight, is extruded. Without the need for a cold pilger operation these tubes go directly to the drawing machines.

In the first process (with no extrusion press) there is the risk of cracks and thus laps and oxide inclusions, which impair the quality of the tubes if the high demands of the casting process are not fulfilled. In the production of gas and water supply pipe with a minimum wall thickness of 1 mm this does, however, play a minor role. This very economic process is used almost exclusively in the production of gas and water supply pipes.

In the production of industrial tubes with wall thickness down to 0.35 mm and finned tubes, the demands on the starting tube are very high so that only the second and third processes with extrusion are used.

5.16.2.3 Extrusion

The press and the tooling have to be accurately aligned so that a low tube eccentricity ($\pm$7% and under) can be achieved. In spite of careful alignment of the centerline of the container, stem, and mandrel as well as the die, movement of the mandrel during extrusion is almost impossible to avoid. Therefore, to achieve a low eccentricity it is usual to limit the length of the unmachined billet to 5 (up to 8) times the mandrel diameter.

The tube is usually extruded at high speed under water within a few seconds, which reduces the risk of mechanical damage and produces the fine grain needed for extensive cold working.

Only direct extrusion presses are used.

To avoid water getting inside the tube, controlled mandrel movement is used at the start and the end of extrusion to give a tube closed at both ends (Fig. 5.37). The extruded tube is then oxide free internally and externally and can be passed to the cold pilger machine or drawing machine without pickling.

5.16.2.4 Oxide on the Billet Surface, Shell and Blister Defect

As mentioned previously, there is the risk with copper flowing according to type B that the oxide produced on billet heating acts as a lubricant between the billet surface and the container and flows along the dead metal zone that forms in front of the flat die: extrusion shell defects are the consequence (Fig. 5.38). They produce blisters when drawn tubes are annealed (Fig. 5.39).

Fast induction heating is recommended (at least as the final stage) to ensure that the minimum of oxide forms on the billet surface. The oxide on SF-Cu copper does not adhere strongly to the surface—in contrast to the oxide on oxygen-rich qualities. It can be largely removed by a strong water spray at the furnace exit. At the same time the billet hardly loses any heat. Hot scalping of the oxidized billet surface, which is mentioned in the literature, is now rarely used [Vat 70].

In conventional extrusion with a shell, the aim is for the oxide layer to be retained on the container liner. This does not occur completely. Because, as shown in Fig. 5.38, the oxide first arrives at the die toward the end of extrusion, the risk of lines of blisters is reduced by the selection of a large extrusion ratio, which increases the distance between the billet surface and the surface of the extrusion. If the billet is short enough, the flow of the oxide is stopped in time in front of the die.

As already mentioned, the extruded shell is so thin and ductile that a combination dummy block and cleaning block can be used in extrusion.

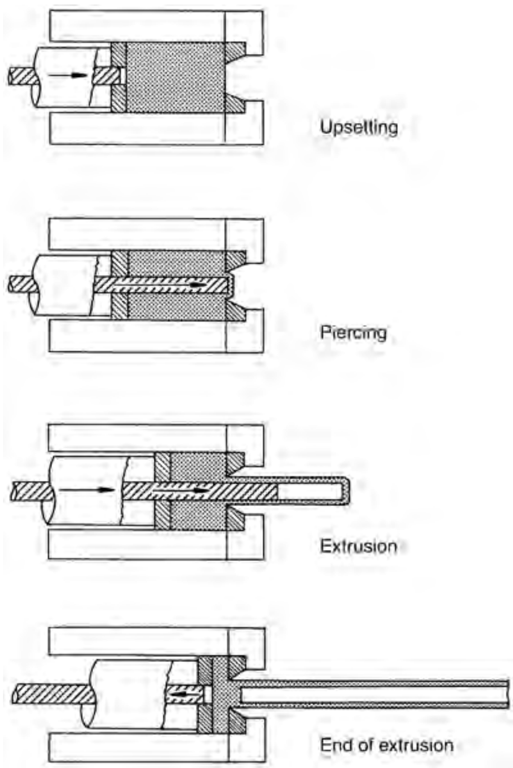


Fig. 5.37 Extrusion of copper tubes [Bau 93]

5.16.3 Copper Rod and Section

5.16.3.1 Dimensions and Shape, Further Processing

The high extrusion temperature of copper prevents the production of thin-wall complex and sharp-edged sections. Extruded shapes therefore have to be brought to the finished dimensions by one or more cold deformation steps—on draw benches. The good cold workability of copper makes this relatively simple. This also produces the preferred hard state. Figure 5.40 shows examples of extruded and drawn copper sections.

As described in section 5.16.2.3 for copper tubes, rods and sections in copper are also extruded underwater to achieve oxide-free, damage-free products with a fine grain. Small cross-sectional areas can be extruded in long lengths through a water wave and then coiled.

5.16.3.2 Hollow Sections

Hollow copper symmetrical sections for internally cooled bus bars in electrical engineering

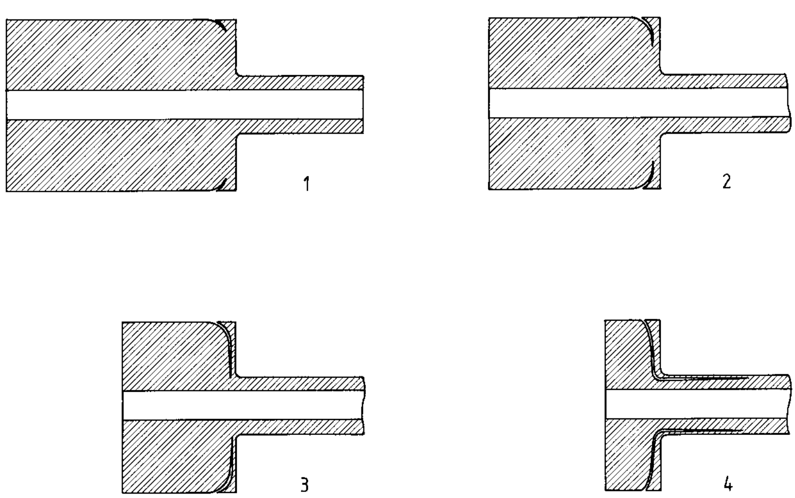


Fig. 5.38 Extrusion shell formation in the extrusion of copper tubes [Bau 93]

are, if possible, extruded from large billets pierced in the press and, for small openings, over the mandrel tip (fixed mandrel). With difficult shapes, prebored billets can be necessary. The shape of the mandrel tip and the exact location in the die require considerable experience.

Hollow sections have to be extruded through bridge dies if the openings are asymmetrical or if the section has several openings. This process is similar to that for aluminum alloys. However, with copper, deformation and cracking of the very expensive dies can occur along with the oxide flowing into the weld seam. This can be avoided only by good technical knowledge and experience. The extrusion of copper through bridge dies is therefore rarely used.

5.16.4 Extrusion of Low-Alloy Copper Materials

5.16.4.1 The Materials, Properties, and Applications

Low-alloy copper materials are covered by the standard DIN 17666 (UNS C-10100–

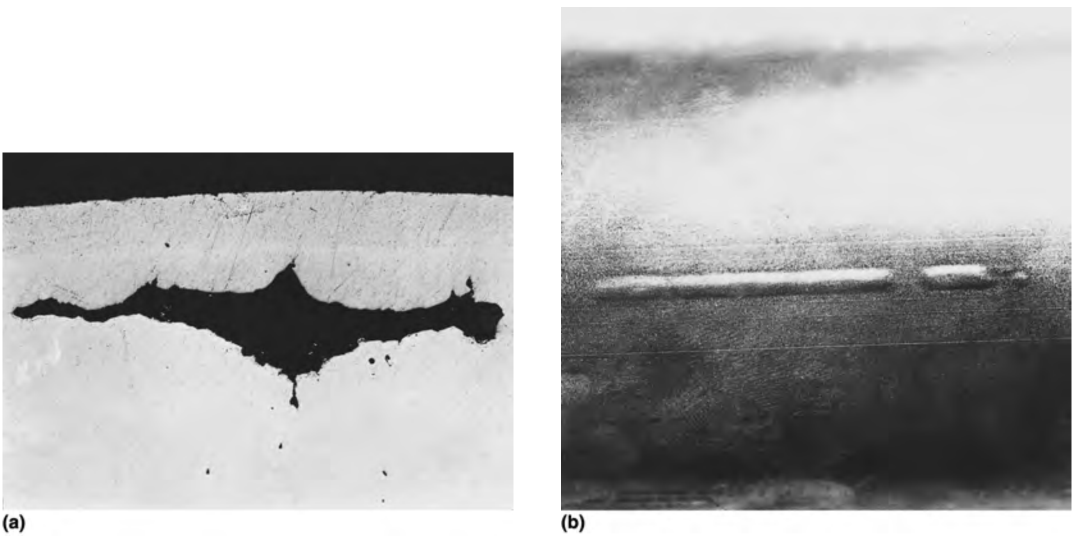


Fig. 5.39 Blisters on the tube surface of a SF-Cu-tube after annealing. (a) Transverse section. (b) External surface with line of blisters [Die 76]

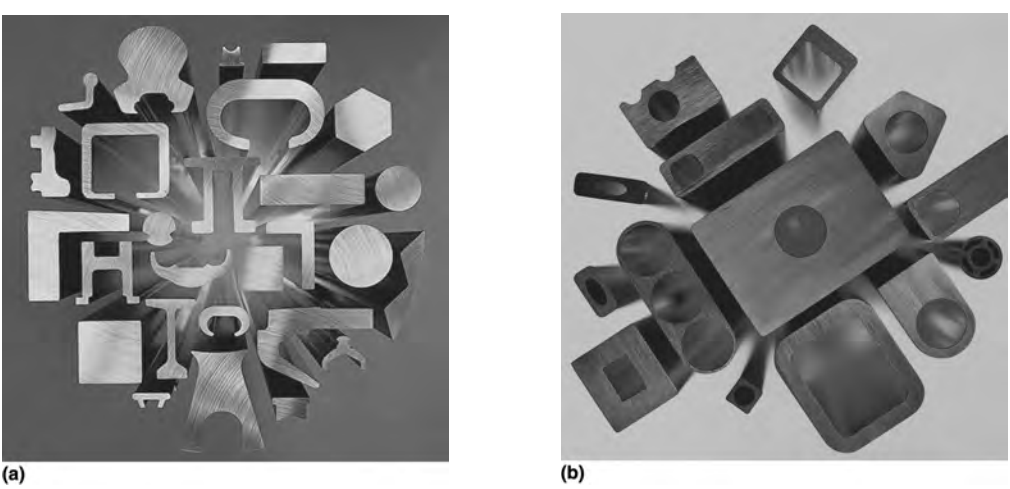


Fig. 5.40 Example of extruded and drawn copper sections. (a) Solid section. (b) Hollow section (Source: Kabelmetal Osnabruck)

C15815). The composition, properties, and applications of the different alloys are described in detail in the DKI information sheet 8 [DKIa].

In the non-age-hardening alloys, additions of silver, cadmium, magnesium, and iron increase the mechanical properties and, in particular, the softening temperature without reducing the conductivity significantly. Tellurium and lead improve the machinability. Additions of beryllium, nickel, silicon, chromium, and zirconium produce age-hardening alloys that have high mechanical properties and simultaneously high electrical conductivity after solution heat treatment and age hardening.

Application examples of the low-alloy copper materials are found mainly in electrical technology and chemical plant construction, e.g., contacts and spring elements as well as (CuCr, CuCrZr) welding electrodes (see also the section on copper alloy extruded products in Chapter 2).

Alloy development in recent years has resulted in some nonstandard age-hardening materials for elements of electrotechnology and electronics. The majority are used only in the form of strip, and extruded and drawn products are rarely used.

5.16.4.2 Extrusion

The low-alloy copper alloys have similar extrusion properties to unalloyed copper. The risk of flaking and blister formation by the inflow of oxide into the funnel behind the dead metal zone is usually even higher than with copper because of the greater tendency to oxidation [Moi 89]. The oxide thickness also increases when a higher extrusion temperature has to be used for the same extrusion ratio because of the higher hot strength. It is advisable in such cases to blow off the oxide from the hot billet using a water spray.

Figure 5.36 shows some hot-strength curves. Extrusion data are given in Table 5.9.

5.16.4.3 Solution Treatment at the Press

The mechanical and electrical properties of the age-hardening alloys are obtained by solution heat treatment followed by hot age hardening. If the cross section is not too high, the solution heat treatment of CuCr and CuCrZr can be carried out on the press. This process is well known from the low-alloy aluminum materials. Because, however, in this case the solution heat treatment has to be carried out at approximately 1000 °C, the stresses in the container and the die are extremely high as is, as described previously, the risk of flaking and blistering [Hes 82]. As a general rule, only relatively short billets can be extruded (length:diameter = 1 to 1.5:1). The billet heating time in the induction oven can sometimes be too short to completely dissolve the second phase and to achieve the maximum mechanical properties.

The section has to be cooled in water to freeze the solid-solution state. Above a specific section thickness (60–70 mm diam) water quenching at the press is no longer sufficient. In this case the section has to be solution heat treated after extrusion in a special oven and then quenched. In this case a lower extrusion temperature can be used because the extrusion process and the solution heat treatment are not combined.

The hot age hardening following solution heat treatment (e.g., 475 °C for CuCr) is carried out before or after the cold working, depending on the properties required.

5.16.5 Extrusion of Copper-Zinc Alloys (Brass and Tombac)

5.16.5.1 Binary Copper-Zinc Alloys

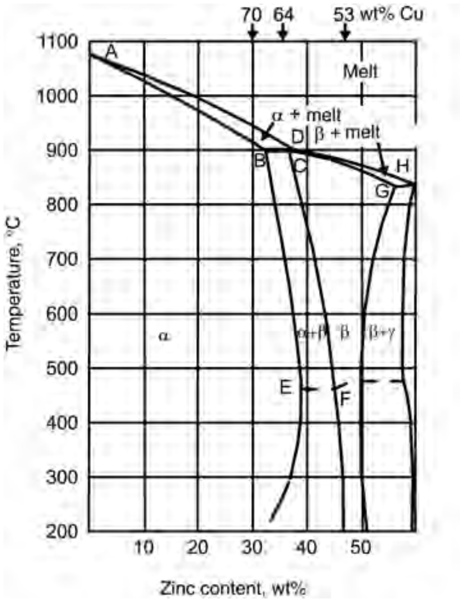
Properties, Structure. Brass alloys are the most commonly used of the copper alloys and long sections are almost completely produced by extrusion. All copper-zinc alloys with a copper fraction more than 50% are referred to as brasses. More than 72% copper, the copper-zinc alloys are also referred to as “tombac.” These are alloys with a reddish color. As the copper content is reduced corresponding to an increase in the zinc content, the color changes more and more to yellow, and at the same time the hardness increases.

The copper-zinc phase diagram is described first because of the marked variations in mechanical properties and structure with the zinc content.

As shown in Fig. 5.41, three alloy groups can be clearly differentiated:

- Single-phase α-alloys with a copper content above 61%
- Binary-phase α/β-alloys with a copper content of 54 to 61%
- Single-phase β-alloys with a copper content of 50 to 54%

The single-phase α-alloys have a fcc lattice similar to pure copper. They can correspond-



Point	Temperature, °C	Zinc content, wt%
A	1083	0
B	902	32.5
C	902	36.8
D	902	37.6
E	454	39.0
F	454	45.0
G	834	60.0

Fig. 5.41 Copper-zinc phase diagram [Ray 49]

ingly be easily cold worked (see structure in Fig. 5.42).

The single-phase β-structure is body centered cubic (bcc) and has very limited workability at room temperature. Between these limits (shown by the lines BE and CF on the phase diagram) there is a region in which the α-phase and the β-phase can coexist. The greater the zinc content, the lower is the α-content. The cold workability reduces in this region corresponding to the increasing zinc content (see Fig. 5.43, α-β-structure).

The Materials, Properties, and Applications. DIN 17660 covers the commercially used copper zinc alloys (See also ASTM B455 for Copper-Zinc-Lead [leaded brass] extruded shapes). The DKI information sheets i.5 and i.15 [DKIb, DKIc] cover these CuZn alloys in detail (See also Copper Development Association web site www.copper.org).

The brasses with a pure α-structure as well as the tombac (low-alloy CuZn) alloys are used predominantly in the form of sheets and strip, less as tubes, and rarely in the form of bar and section. The producers of jewelery and metal ware, brass instruments, lamp bodies, and light-bulbs use α-brasses. Tubes are used for air brake pipes in goods vehicles and for manometers.

The alloys in the α-β field with a β-fraction between 20 and 40% can be readily machined and are therefore widely used as rod material. Chip forming additions—usually between 1 and 3% lead—that are embedded as droplets in the matrix further improve the machinability.

Materials with only a low β-content (Cu Zn36Pb1.5) can be readily machined and cold worked. They are used where stamping or bending is required. The free-machining brasses (mainly CuZn39Pb3) are used in large quantities as hard drawn rods for processing on automatic lathes to turned components of all kinds (e.g., bolts). They can be cold worked only to a limited extent (see Table 5.11, EN 12164). Pure β-brass

Fig. 5.42 Structure of α-brass, etched. Image width is 0.5mm [Wie 86]

(e.g., CuZ44Pb2) is almost brittle at room temperature but is used for extruded sections that do not have to be subsequently cold worked because of its excellent hot workability. Sections in α-β brass can, on the other hand, be cold drawn to a limited extent and therefore be supplied to tight finished tolerances. Figure 5.44 shows some examples of extruded and drawn brass sections. They are covered by the DIN 17674 standard (EN 12167).

Extrusion. At the normal extrusion temperature of more than 600 °C, the β-structure has a significantly lower flow stress than the α-structure. The α-β brasses and especially pure β-brasses therefore have a high extrudability. Figure 5.45 illustrates this by hot flow stress curves.

The workability of the CuZn alloys decreases initially in the normal extrusion temperature range of 600 to 800 °C with increasing zinc content and then increases again from approximately 30% zinc when β-phases occur during extrusion.

The low flow stress of the β-phase at the extrusion temperature enables high extrusion speeds and extrusion ratios to be attained. With free-machining brass extrusion ratios up to V = 900 and exit speeds up to 8 m/s can be reached.

Table 5.9 gives extrusion data on copper-zinc alloys.

Because the phase boundaries α/α-β and α-β/β are displaced to higher zinc contents on cooling, the α-phase fraction extends into the α-β field on cooling (see Fig. 5.41). The α-precipitation can be partially suppressed by quenching (frozen) so that the β-fraction remains higher than would be the case in the equilibrium state. If quenching is carried out after cooling to 500 to 300 °C, depending on the composition, the α-precipitation has stabilized and the structure no longer changes.

By quenching from the deformation heat and aging at temperatures approximately 200 °C, α-β-brasses can be given a substantial hardness increase by the fine precipitation of the second phase [Bro 73]. This is rarely used in practice because it is difficult to maintain the extrusion

Fig. 5.43 Brass with acicular α-β-structure, etched. Image width is approximately 0.275mm [Wie 86]

Fig. 5.44 Extruded and drawn brass sections (Source: Wieland-Werke, Ulm catalog)

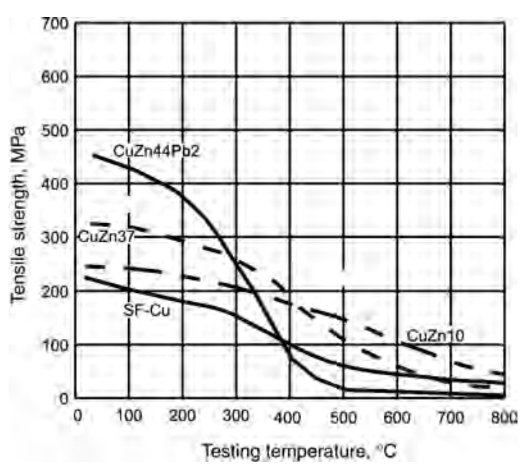


Fig. 5.45 Some hot tensile strength curves for copper-zinc alloys and SF-Cu [Wie 86]

conditions constant from billet to billet, and at the same time the cold workability is restricted.

Possible Extrusion Defects and their Prevention. The high deformation resistance of low-alloy α-brasses requires a high extrusion temperature for a given extrusion press power. This increases the danger of coarse grain formation and in the extreme case, hot shortness. Low initial billet temperatures as well as low extrusion speed reduce the risk of coarse grain formation and hot shortness, as with all materials. However, at the lower extrusion temperature the deformation resistance is higher and the possible minimum extruded cross section for a given press power larger.

With copper-zinc alloys containing more than 80% copper, copper oxide forms on the billet surface during heating in air. With alloys with less than 80% copper, zinc oxide mainly forms and this has no lubrication properties in contrast to copper oxide. Whereas the CuZn alloys with more than 80% copper can still have shell and blister defects, this risk does not occur with higher-zinc-containing materials because the adhesion between the billet and the container is so large that a closed shell is formed when extruding with a shell. On the other hand, the combination dummy block and cleaning disc that can be used in copper extrusion is not suitable because of the large shell thickness. A separate cleaning cycle has to take place after extrusion.

As the zinc content increases, the thermal conductivity of brass decreases and the peripheral cooling of the billet in the container is no longer equalized. Because the β-rich hotter billet core flows more easily than the β-impoverished peripheral zone, the typical flow pattern type C forms (see Fig. 3.11 in Chapter 3) with the risk of the piping defect. Figure 5.46 shows an example.

The billets should have a perfect surface quality to avoid extrusion defects. The difference between the container diameter and the billet diameter should also not be too large to avoid folds forming as the billet is upset in the container. With a good quality liner surface, the shell from the previous extrusion can be completely removed with the cleaning disc [Lot 71].

In direct extrusion, the length of the billet is limited to reduce the risk of the piping defect. As a general rule the billet should not be longer than 2.5 to 3 times the diameter. Routine fracture testing of the end of the sections can remove any sections containing the extrusion defect and ensure that the remaining length is defect free.

Indirect extrusion is recommended for α-β-brasses where there is the risk of the extrusion piping defect forming in direct extrusion because the different material flow excludes this defect. Significantly longer billet lengths can then be used [Sie 78].

As mentioned elsewhere, in direct extrusion, if the extrusion ratio is too low, particularly with brass, the acceleration of the center of the billet can be so severe that cavities can occur toward the end of the section (Fig. 5.47). Their formation in the section can be prevented only by limiting the billet length and leaving a sufficiently long discard.

A further defect, particularly with α-brasses with a low zinc content, is the formation of zinc flakes on the surface of the extruded product. Zinc vaporisation from the newly formed surface immediately behind the die condenses onto cooler parts of the tooling in the form of fine drops, which can be picked up by the passing section. The droplets form zones of high zinc content, containing β phase, on the section surface. These are brittle and can result in defects. These zinc flakes can also be found on the inter-

Fig. 5.46 Extrusion defect (piping) in α-β-brass [Die 76]

nal surface of tubes. In order to prevent them forming it is necessary to ensure that the hot section does not contact the tooling behind the die.

Handling the Section. Because the α-β-brasses and the β-brasses are very soft at the exit temperature and sensitive to mechanical contact, good guiding out of the die (possibly lined with graphite) is needed to avoid damage of the section surface combined with careful handling on the runout table.

Whereas thick bars from single-cavity dies are extruded into air on graphite or steel-lined plates, or onto a freely rotating roller conveyor and then cross transferred until they can be cooled—possibly in a water trough—and cut to length, pullers are usually used for sections and thinner bar. Up to four sections can be simultaneously pulled using independent jaws. The material emerging from the die is very soft and it is necessary to use a defined low puller force to avoid undesired stretching of the sections.

If the cross-transfer conveyor is not large enough, water cooling has to be used at the end before the sections can be cut to length. Figure 5.48 shows the principle of the extrusion of brass sections.

Cu-Zn wires, usually in free-machining brass, are extruded from one or two cavity dies into down coilers, the speed of which are synchronized with the ram speed. Periodic oscillations of the rotation speed (wobble) ensure that the individual layers on the drum are not directly above each other. To avoid damage, the strands are usually extruded into pans, which at the end of extrusion are removed from the coilers and transported on a roller conveyor until the brass

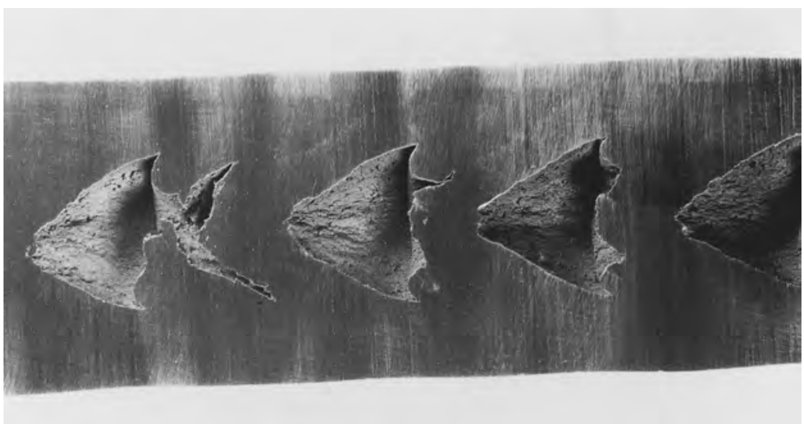


Fig. 5.47 End cavities in a brass bar [Die 76]

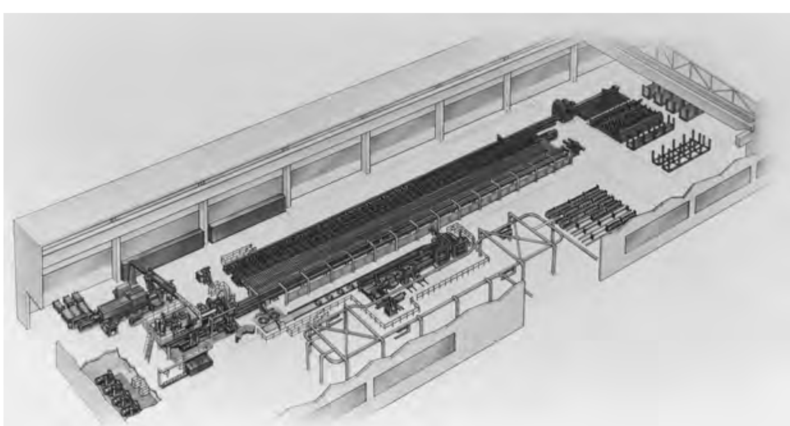


Fig. 5.48 Schematic of a section and wire brass extrusion plant (SMS Hasenclever catalog)

wire has cooled sufficiently and can be lifted out. Further processing is carried out after pickling by a combination of drawing, straightening, and cutting to length.

Straightness—β phase distribution—Further Processing of Bar. The straightness of the bar is very important for machining on automatic lathes with high cutting speeds. Bars that are not clean or straight chatter in the bar feed. If the β-phase fraction and its distribution in the cross section vary over the length of the extrusion, the rectification effect in the combination drawing, straightening, and cutting to length machine changes from the first bar to the last of an extruded coil.

The indirect extrusion process again offers advantages over the direct process. The variation in the size and distribution of the β-phase in the α-β mixed structure between the start of extrusion to the end in indirect extrusion is less than in direct because of the uniform material flow over the length of the extrusion.

In multicavity extrusion the billet no longer flows symmetrically in one strand because the die apertures are arranged asymmetrically. One side of the section surface stems from the outer region of the billet and the other side from the inner region. It is therefore particularly important to ensure a uniform cast structure and good through heating; there are then no disadvantages for the quality of the section and, in particular, for the straightness of the finished bars.

In order to obtain uniform mechanical properties and good straightness, care must be taken to ensure that the degree of deformation in the individual drawing operations is held within narrow limits requiring that the dimensional tolerances of the extruded bar are within tight limits. Suitable selection of the hot-working materials for the die and its design are discussed in detail in the section on tooling for the extrusion of copper alloys in Chapter 7.

5.16.5.2 Copper-Zinc Alloys with Alloy Additions (Special Brasses)

The Different Materials and Their Properties. If additional elements, including aluminum and tin, are added to copper-zinc alloys, properties such as the β-phase fraction, the corrosion resistance, and the strength change significantly. These materials are referred to as special brasses. They are also covered by DIN 17660 copper-zinc-aluminum alloys are known as aluminum bronzes and copper-zinc-tin alloys are tin brasses.

Again, as with brass there are single-phase materials with a fcc α-structure and two-phase materials with an α-β structure. In both groups additional intermetallic phases can occur depending on the type and amount of the additions.

The β-phase fraction in the α-β-mixed structure, which has a strong influence on the extrudability and the cold workability, can be controlled by these additions of alloying elements (see Table 5.12, Fig. 5.49).

Semifinished Products and Applications. The alloys CuZn20Al2 and CuZn28Sn1 are resistant to seawater and corrosion. They are used in heat exchangers and condensers. Because they have a pure α-structure and consequently are difficult to extrude but have good cold workability, the tubes are extruded with large cross sections and brought to the finished dimensions on cold pilger machines and draw benches with intermediate annealing.

CuZn31Si1 is a material with an α-β-mixed structure. Tubes for bearing bushes are produced

Table 5.12 Influence of element additions on the β-phase fraction and the extrudability of special brasses

Alloying element	β-portion	Zinc equivalent(a)	Extrudability
Silicon	Is improved	10	Is improved
Aluminum	Is improved	6	Is improved
Tin	Is improved	2	Is improved
Manganese	Is improved	0.5	Is improved
Nickel	Is improved	−0.9–−1.5	Is improved

(a) 1% the alloying element corresponds to one in the effect on the structure condition one as "zinc equivalent" of indicated multiples of the effect of zinc. Source: Lau 76

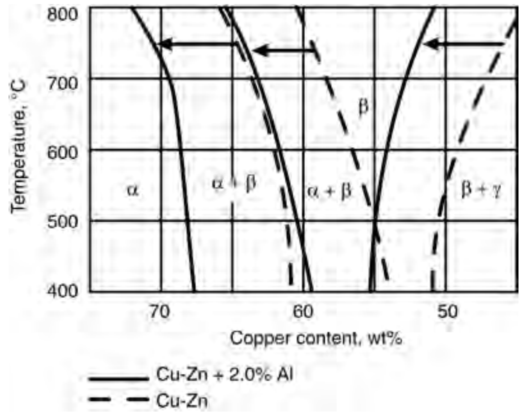


Fig. 5.49 Displacement of the phase limits in the copper-zinc system using aluminum additions as an example [Bar 32]

in this alloy. Other nonstandardized special brasses (with additions of Mn, Ni, Si, and Pb) have proved themselves as wear-resistant bearing materials in special cases.

High-zinc-containing special brasses are construction materials with moderate and high mechanical properties used in the manufacture of chemical plants.

Casting and Extrusion. Casting defects, including porosity and cracks, have to be assumed in special brasses, particularly with aluminum and manganese additions. Careful testing of the billet quality (e.g., using a penetrant such as the Met-L check testing on the cut surface) is necessary. Billets with defects on the mantle surface have to be machined.

In the same way as with pure brasses, the extrudability depends on the amount of the β-phase present at the extrusion temperature. This is shown by the hot tensile test curves in Fig. 5.50. The possible defects and their avoidance follow those described in section 5.16.5.1.

5.16.6 Extrusion of Copper-Tin Alloys (Tin Bronzes)

5.16.6.1 The Different Alloys, Their Structures, Properties, and Applications

The tin content of tin-bronzes can extend to 20%. However, the higher-alloyed materials (more than 10% tin) are extremely difficult to deform and are, therefore, usually used only as cast materials. Complex tin-bronzes can contain additions of zinc and lead.

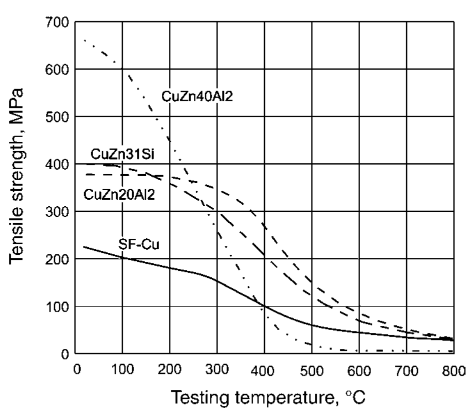


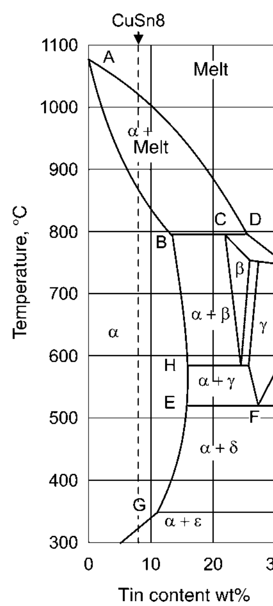
Fig. 5.50 Hot tensile strength curves of special brasses and SF-Cu [Wie 86]

DIN 17662 describes the composition of the common alloys suitable for extrusion with a maximum tin content of 8%. The DKI information sheet i.15 [DKId] describes the copper-tin alloys in detail (See also Copper Development Center. These tin bronzes are also called phosphor bronzes).

Tin-bronzes belong to the oldest known copper alloys. They are still today very important in the chemical industry and ship construction because of their good electrical and thermal conductivity with simultaneous high-strength and favorable corrosion properties. In electrical technology, significantly more tin-bronze strip is used than wire and sections.

CuSn4 and CuSn6 tubes are used for manometers or suction pipes. Highly stressed components, including gear wheels, bolts, and bearings, are made from CuSn8.

The phase diagram in Fig. 5.51 shows that the wrought materials in the equilibrium state have a pure fcc α-structure and therefore behave like copper in hot and cold working.



Point	Temperature, °C	Tin content, %
A	1083	0
B	798	13.5
C	798	22.0
D	798	25.5
E	520	15.8
F	520	27.0
G	320	11.0
H	586	15.8

Fig. 5.51 Copper-tin phase diagram [Ray 49]

5.16.6.2 Casting of Copper-Tin Alloys

Because the cast structure—particularly at the higher tin contents—tends toward segregation because of the wide solidification interval and the billets can exhibit tin sweating as a result of inverse billet segregation, turning of the billets is advised. Homogenization of the billets (630 to 700 °C for several hours) reduces the risk of extrusion defects in the form of longitudinal and transverse cracks in the higher-alloyed materials. With more than 6% tin, the brittle α-β eutectoid that forms on solidification is partly retained in the cooled billet; it can be dissolved only by this homogenization. Some phosphorous is added to the 8% tin-bronze to suppress the tin-oxide formation in melts that have not been completely deoxidized. These tin-bronzes are referred to as phosphor-bronzes.

5.16.6.3 Extrusion of Copper-Tin Alloys

The flow stress of the tin-bronzes is higher than that of copper as shown in the hot tensile strength curves in Fig. 5.52 and increases with increasing tin content. Tin-bronzes are best worked between 700 and 750 °C. The extrusion data can be found in Table 5.9.

Tin-bronzes containing up to 6% tin are moderately difficult and those with 8% difficult to extrude. High-alloyed tin-bronzes are very susceptible to cracking and can be extruded only with slow speeds [Moe 80].

Bars smaller than 25 mm diameter are extruded as several strands and coiled. There is the risk of the billet "freezing" in the container because of the low speed and the large difference between the initial billet temperature and the container temperature. Only short billets can therefore be used.

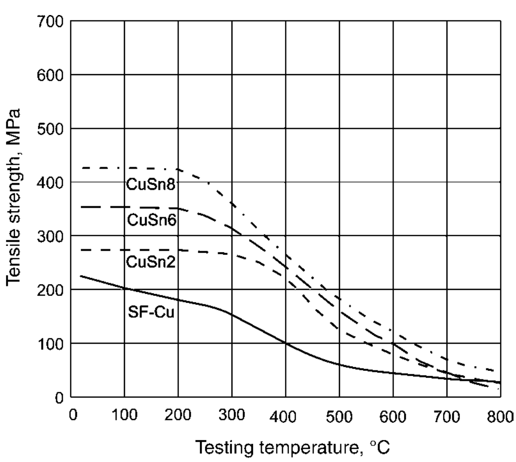


Fig. 5.52 Hot tensile strength curves of copper-tin alloys and SF-Cu [Wie 86]

With the good cold workability of the fcc lattice the section can be extruded above the final dimensions and then worked to the final size in several stages—including where necessary intermediate annealing—by section rolling and drawing. This also produces the frequently required high mechanical properties.

5.16.6.4 Flow Type and Shell Defects

Because tin-bronzes tend to oxidize and this oxide exhibits good lubrication properties, flow type A occurs in the direct extrusion of these alloys, giving the risk of shell and blister defects—particularly with low extrusion ratios, i.e., thick bars [Vat 70]. With large extrusion ratios—thin bars—this risk is reduced. Extrusion is normally carried out without container lubrication and with a thin shell. Care has to be taken in the cleaning cycle to ensure that no residues of the shell from the previous extrusion remain.

5.16.6.5 Competition from Wire Casting

As mentioned previously, only short billets can be used in wire extrusion giving low coil weight. The extrusion process and subsequent downstream processing is correspondingly expensive. Direct continuous casting of wire in large coils has grown in competition to the extrusion of thin bar from which tin-bronze wire is produced by rolling and drawing.

The production of tin-bronze wire today is mainly by this continuous casting process [Bau 76].

5.16.7 Extrusion of Copper-Aluminum Alloys (Aluminum Bronzes)

5.16.7.1 The Different Alloys, Their Properties, and Applications

The composition of copper-aluminum alloys, usually referred to as aluminum-bronzes, is covered by DIN 17665 (see Table 5.11 for the Euro standard). The DKI information sheet i.6 [DKIe] describes aluminum-bronzes in detail (see Copper Development Association).

Binary aluminum-bronzes up to approximately 9% aluminum have a homogeneous structure with the fcc α-phase, as can be seen from the phase diagram in Fig. 5.53. In contrast, complex aluminum-bronzes with aluminum contents of approximately 10% and additions of iron, nickel, manganese, and silicon individually or together usually have a heterogeneous structure.

Aluminum-bronzes are corrosion- and oxidation-resistant alloys because of the formation of Al_2O_3-containing surface layers. They are also very resistant against erosion-corrosion and cavitation and are particularly suitable for seawater applications. Aluminum-bronzes are also found in the chemical industry and in highly stressed machine components.

5.16.7.2 Binary Copper-Aluminum Alloys

Materials and Extrudability. The two standardized alloys CuAl5 and CuAl8 have a fcc α-phase structure. They can be readily cold worked. Their hot workability depends on the aluminum content. Figure 5.54 shows the temperature dependence of the hot tensile strength of the aluminum-bronzes.

The poor extrudability is revealed by the extrusion data in Table 5.9.

The phase diagram in Fig. 5.53 shows that the boundary line α/α-β is displaced to higher aluminum contents with decreasing temperature. The β-content thus decreases during cooling from the extrusion temperature. Even with normal cooling to room temperature from the extrusion temperature, residues of the bcc β-phase are retained with the 8% aluminum-bronze so that only limited cold working is possible. If smaller final cross sections are to be produced from larger extruded cross sections by cold working, then only the 5% aluminum bronzes can be considered.

Extrusion and Extrusion Defects of Copper-Aluminum Alloys. The oxidized billet surface, mainly with Al_2O_3, does not act as a lubricant in the container in contrast to copper oxide. The friction resistance is so high that it is possible to extrude with a stable shell. Because the cast billets frequently have surface defects, machining is recommended. Testing the cross section for cracks and cavities is also advisable.

If the billet heated to more than 750 °C cools during extrusion—it can only be extruded relatively slowly—variations in the α-β-ratio occur over the length of the extrusion along with various forms of the α-phase, resulting in differences in the mechanical properties.

As with all difficult-to-extrude materials, a higher extrusion ratio for the same press power can be attained with the aluminum-bronzes by extruding with a lubricated container without a shell through a conical die. This process is used only in exceptional cases.

If the aluminum content is 8% or more, then the structure at the high extrusion temperature above 900 °C consists of an α-β mixed structure, the flow stress of which is less than the pure α-structure. However, in the direct extrusion of these alloys, there is the risk of flow type C occurring and the formation of the piping defect at the end of extrusion in the same way as with brass. The countermeasures are the same as those mentioned previously; the piping defect can be controlled by a suitable short billet and

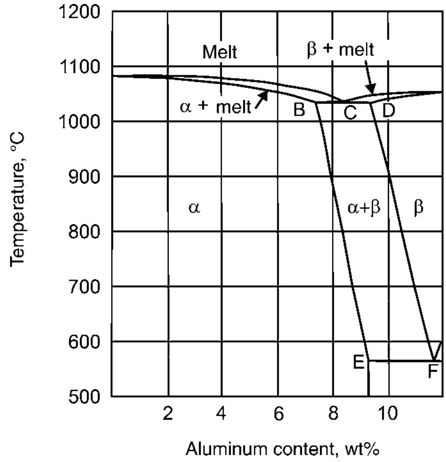


Fig. 5.53 Copper-aluminum phase diagram [Ray 49]

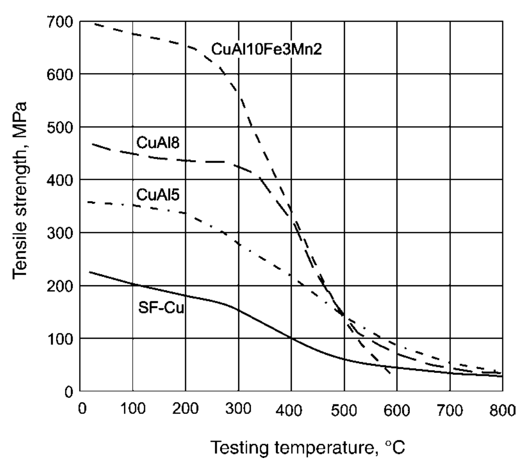


Fig. 5.54 Hot tensile strength curves of copper-aluminum alloys and SF-Cu [Wie 86]

long discard. Fracture tests of the ends of the extrusion are recommended in any case.

5.16.7.3 Copper-Aluminum Alloys with Additions (Complex Aluminum-Bronzes)

Materials, Structure, and Properties. The properties of alloys CuAl8Si, CuAl9Mn, CuAl10Fe, CuAl10Ni, and CuAl10Fe3Mn2 are given in the standards.

The mechanical, physical, and chemical properties of the complex aluminum-bronzes depend on the composition. The aluminum-bronzes with iron, manganese, and silicon additions are usually extruded in the β-phase where they have a lower flow stress than CuAl8 (see Fig. 5.54). On the other hand, CuAl10Ni has an extremely high flow stress (about 70% higher than CuAl8 at 700 °C). This alloy is extremely difficult to extrude.

Extrusion of Complex Aluminum-Bronzes. Complex aluminum-bronzes have a strong tendency to stick to the container wall. In contrast to brass, the shear stress needed to shear away the shell is very high at the extrusion temperature of 600 to 700 °C. The related high stem load needed to shear the shell and the high flow stress result in the complex aluminum-bronzes being very difficult to extrude in spite of the high β-phase component. Often, if small cross sections have to be extruded there is no alternative to working with a lubricated container without a shell and with a conical die entry.

A special case in the complex aluminum-bronzes is the copper-aluminum-nickel-shape memory alloy (about 13% aluminum, 4% nickel) in which the composition, billet pretreatment, and the extrusion conditions have to be exactly maintained to obtain the desired shape memory properties [Don 92].

The sticking of complex aluminum-bronzes to the extrusion tooling can sometimes cause problems in tube extrusion if the mandrel lubrication or the mandrel taper is insufficient. The internal surface of the tube can then exhibit cracks or flaking.

Another almost typical defect with the complex copper-aluminum alloys is the "wood grain fracture" attributable to severe gas porosity of the billet or the inclusion of aluminum oxide films. The billets therefore have to be carefully checked (e.g., by penetrant check) for soundness.

The complex aluminum-bronzes in direct unlubricated extrusion usually flow according to type C similar to CuAl8, so that allowance has to be made for the piping defect.

Further Processing. The cold workability of the complex aluminum-bronzes is very restricted compared with the binary alloys because of the high β-phase component. They are, therefore, normally supplied as extruded.

Similar to special brasses, the complex aluminum-bronzes can be heat treated [Ben 93]. Higher mechanical properties can be obtained with CuAl10Fe and CuAl10Ni by solution heat treatment in the α-β-region followed by quenching and age hardening at 500 to 650 °C. On quenching a β′-martensite forms that partly breaks down on aging. The quenching can take place at the press, but better values are obtained by a separate heat treatment after extrusion.

5.16.8 Extrusion of Copper-Nickel Alloys

5.16.8.1 Materials, Structure, Properties, and Applications

The copper-nickel alloys contain between 4 and 50% nickel, usually approximately 5 to 30%. Nickel forms a continuous solid solution with copper (see Fig. 5.55) so that all copper-nickel alloys are single phase and have a fcc α-structure.

The most important copper-nickel alloys are covered by DIN 17664 (ASTM E 75). They are CuNi10Fe, CuNi20Fe, CuNi30Fe, and CuNi30 Mn1Fe.

The most important alloy technically is CuNi30Fe, which is used for tubes in ship heat exchangers, seawater desalination plants, and air

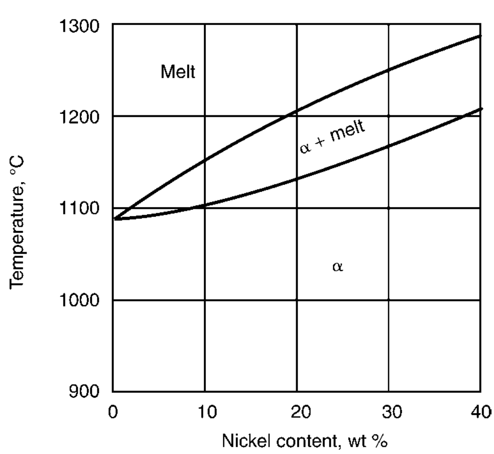


Fig. 5.55 Copper-nickel phase diagram [Han 58]

and oil coolers. However, CuNi10Fe alloys also find applications here. Whereas pure binary alloys are used primarily for the production of coins, the extruded alloys used for other applications, e.g., condenser tubes, have additions of iron and manganese to improve the properties. These elements increase the corrosion and erosion resistance and raise the strength as well as the recrystallization temperature. The DKI information sheet i.14 [DKIf] describes the copper-nickel alloys in detail. (See UNS C/70100 to C/72950 and ASTM B 151.)

5.16.8.2 Extrusion of Copper-Nickel Alloys

The melting point and recrystallization temperature increase with increasing nickel content, and the cold and hot workability decrease. As can be seen in Table 5.9, the extrusion temperature increases with increasing nickel content. The range is between 850 and 1000 °C and is the highest of all the copper extruded alloys. Figure 5.56 shows the hot strength of the copper-nickel alloys as a function of the temperature. It does fall within reasonable limits at the high extrusion temperatures mentioned, but when determining the extrudability, the service life of the tooling plays the decisive role.

Copper-nickel alloys should and can be extruded as quickly as possible because of the high extrusion temperature and the associated thermomechanical stressing of the tooling. Usually, relatively thick-walled tubes are extruded and then further processed on cold pilger machines and by drawing with intermediate annealing because the copper-nickel alloys have good cold-working properties as a result of their fcc lattice.

Extrusion is usually carried out with a shell and without container lubrication through flat dies. This is not possible if small cross sections, i.e., a high extrusion ratio, have to be extruded in these difficult-to-extrude alloys. Container lubrication is then recommended with extrusion through conical dies and without a shell. The resultant significantly lower friction between the billet and the container enables higher extrusion ratios to be produced or lower extrusion temperatures to be used. However, attention has to be paid to having a high-quality container bore and a good billet surface to avoid defects on the surface of the extrusion.

The increase in hydrogen solubility with increasing nickel content and thus the risk of gas porosity with inadequate melt treatment has to be taken into account when casting the billets into water-cooled molds or by continuous casting.

A homogenization heat treatment of the billets is not considered to be necessary in spite of the nickel concentration variations resulting to some degree from the casting process. The billets often have to be machined to remove the cast skin.

5.16.9 *Extrusion of Copper-Nickel-Zinc Alloys (Nickel-Silver)*

5.16.9.1 Material, Structure, Properties, and Applications

Alloys of copper, nickel, and zinc are referred to as nickel-silver because of their silver color. The copper content of the technically most common alloys can range from 45 to 62% and the nickel content 7 to 26%, with zinc forming the remainder. Alloys suitable for turning and drilling with an α-β-phase contain up to 2.5% lead as a chip breaker similar to brass. Small additions of manganese are usual to reduce the risk of cracking at high temperatures ("annealing cracking").

The copper-nickel-zinc alloys are covered by DIN 17663 (see ASTM B 151).

Figure 5.57 shows the copper corner of the copper-nickel-zinc system. The solid lines in the phase diagram show the room temperature state; the dashed lines apply at 850 °C.

In the majority of the commercial nickel-silver alloys, the fractions of nickel and zinc are

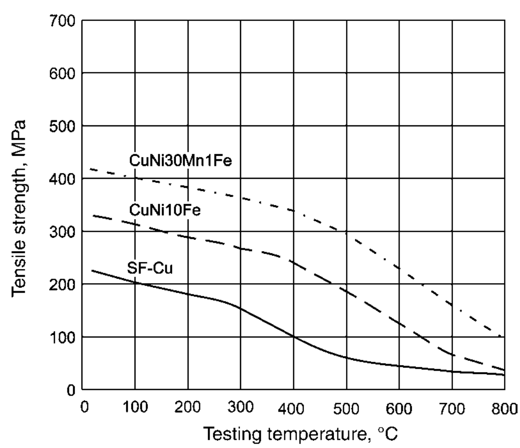


Fig. 5.56 Hot tensile strength curves of copper-nickel alloys and SF-Cu [Wie 86]

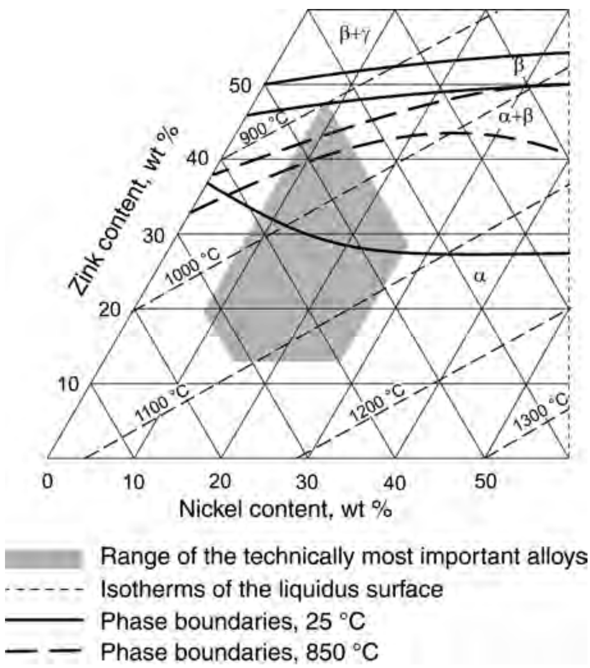


Fig. 5.57 Copper corner of the copper-nickel-zinc system [Sch 35]

completely dissolved in the copper so that only α-solid solution exists. As with brass, only the high-zinc-containing alloys are heterogeneous and consist of α-β mixed crystals.

Tableware and spring elements are produced from lead-free nickel silver. It is also used for frames of glasses and zippers.

The α-β-nickel silvers, also with lead additions, are used for all kinds of turned components and for fine mechanical fittings. The DKI information sheet Nr i.13 [DKIg] describes the nickel-silver alloys in detail (Also refer to ASTM B 151).

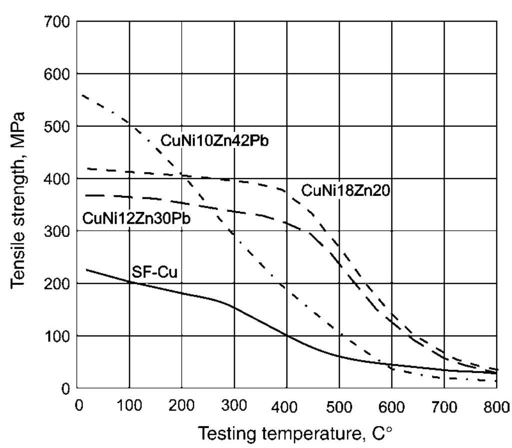


Fig. 5.58 Hot tensile strength curves of copper-nickel-zinc alloys and SF-Cu [Wie 86]

5.16.9.2 Extrusion of Nickel-Silver Alloys

The extrusion data for the nickel-silver alloys is also given in Table 5.9. As with the brasses the β-component determines the hot and cold workability of the different alloys. A lead addition hardly reduces the hot workability of the β-containing nickel-silvers but reduces it significantly in the α-alloys. The hot tensile strength can be obtained from Fig. 5.58 for some Cu-Ni alloys. These alloys can be readily extruded in the temperature range between 600 and 700 °C. In principle, the lowest possible extrusion temperature should be used to avoid oxidation, hot cracking, and a structure with an excessive grain size.

The billet surface of the nickel-silver alloys is usually turned off and extrusion is carried out with a thin shell. Because a defect-free section surface requires the lowest possible extrusion temperature, it is frequently possible to extrude only with a large cross section, i.e., a low-extrusion ratio. Further processing is then carried out by rolling and drawing.

5.16.9.3 Competition from Wire Casting

Lead-free nickel-silver is—similar to tin-bronze—occasionally cast in wire format and then cold worked without hot working. This process is economically superior to the manufacture of wire by extrusion but frequently produces defects in the strand, which reduce the quality [Bau 76].

Extrusion of Semifinished Products in Titanium Alloys

Martin Bauser*

Titanium with a melting point (T_s) of 1668 °C is one of the high-melting-point metals. Although it is the fourth most abundant metal in the earth's crust after aluminum, iron, and magnesium, the high cost, in particular, of the reduction to the pure metal but also of casting and further processing, makes titanium products expensive [Sib 92]. Its low density of 4.5 g/cm^3 compared with iron and, simultaneously, the very high strength of some of its alloys makes it particularly useful where a favorable ratio of strength to density is required, i.e., in the aerospace industry. The very good corrosion resistance against numerous media is attributable to the strongly adhering oxide film that forms even at room temperature. It therefore finds numerous applications in the chemical and petrochemical industries. Titanium alloys can be classified as one of the exotic extruded metals because of the high cost. Because its industrial application only started in the 1950s, all production and application possibilities have certainly not been exhausted.

Special mention should be made of superconductors of titanium-niobium alloys, shape-memory alloys with titanium and nickel as the main constituents, as well as intermetallic phases of titanium and aluminum for high-temperature applications. The book *Titanium and Titanium Alloys* by U. Zwicker gives an overview [Zwi 74].

*Extrusion of Semifinished Products in Titanium Alloys, Martin Bauser

With extrusion temperatures of 850 to 1150 °C, the extrusion process largely corresponds to that of iron and nickel alloys. Titanium alloys are, therefore, usually extruded on steel extrusion presses. An analogous technology is used.

Similar to steels and nickel alloys forging, hot and cold rolling are preferred when possible to the more expensive extrusion process for the production of bar material of titanium. Thin-wall tube in unalloyed titanium is also usually made from strip with longitudinal welding. Extrusion is, however, the most suitable method of production for thick-wall titanium tubes, titanium-alloy tubes, and for sections.

5.17 Materials, Their Properties, and Applications

5.17.1 The Structure and Its Influence on the Properties

The example of the phase diagram for titanium with aluminum (Fig. 5.59) shows that pure titanium has a close-packed hexagonal lattice up to 882 °C, the so-called α-phase. Above this there is the bcc β-phase. In alloys there is a more or less wide field within which the α- and β-phases can coexist.

Titanium alloys are classified into three groups according to the structure at room temperature after the most common deformation and heat treatment processes: α-alloys, α-β-alloys, and β-alloys.

β-alloys in general have a lower strength and elongation as well as an inferior fatigue performance compared with the α-β-alloys. However, the β-alloys are superior to the α-β-alloys in terms of creep strength and fracture toughness [IMIa 88].

The α-alloys are relatively difficult to work at room temperature [Mec 80], whereas β-alloys can still be readily deformed.

The alloying constituents of the technically most important materials are aluminum, which increases the strength and stabilizes the α-phase, as well as chromium, manganese, molybdenum, vanadium, copper, tin, and zirconium. Most of these elements stabilize the β-phase and reduce the α/β transformation temperature and are contained in the precipitates after age hardening. Tin as an alloying element, which slightly stabilizes the α-phase, and zirconium have a high solubility in the α-phase and harden it [Mec 80]. Zirconium increases the hot and creep strengths.

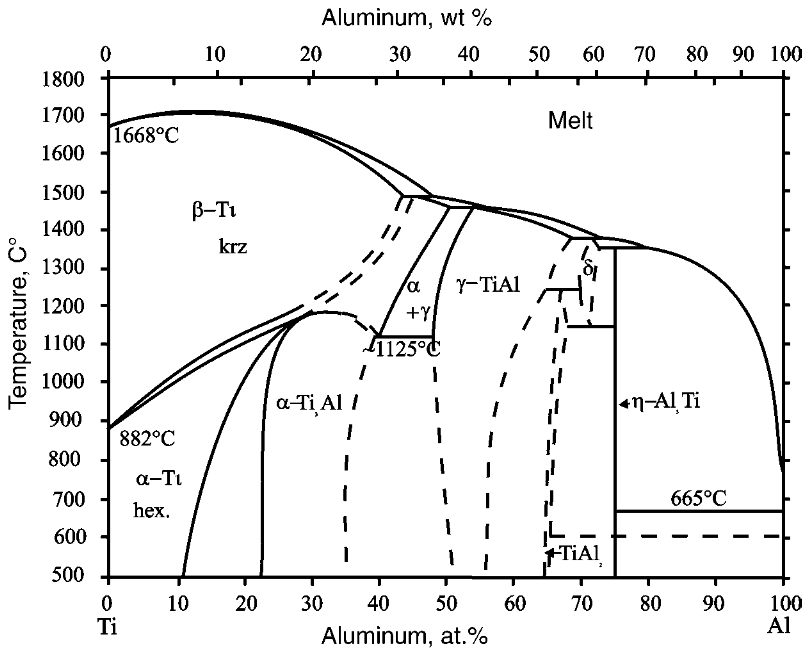


Fig. 5.59 Titanium-aluminum phase diagram [Kum 92]

The undercooling capability of the β-phase and the reducing solubility with the decreasing temperature of numerous alloying elements result in interesting hardening and tempering possibilities. Solution heat treatment is usually carried out in the β-region or just below followed by rapid cooling so that the α-phase or other precipitates can form only in a finely distributed manner after subsequent age hardening. Age hardening cannot be carried out on α-materials [Lam 90].

The often complicated transformation kinetics of the α-β alloys are represented in time-temperature-transformation diagrams similar to steel [Zwi 74].

The lowering of the transformation temperature by β-stabilizing additions is important for hot working because the body-centered cubic β-phase has better forging and extrusion properties than the hexagonal α-phase.

The niobium-titanium alloy with 52% Nb and 48% Ti used for superconductors has a relatively low transformation temperature and can therefore be extruded at approximately 900 °C.

5.17.2 The Most Important Titanium Alloys and Applications

Table 5.13 shows the most important titanium alloys with their properties and application areas.

The strength is not a decisive criterion for thin-wall tube for liquid transport in the chemical or petrochemical industry and, for example, in water desalination plants and power station cooling towers. The requirement is far more for the outstanding corrosion resistance of titanium against a range of media and its oxidation resistance at normal temperatures. In these applications different grades of pure titanium are used that differ from each other only in their oxygen content (Table 5.13).

As with iron alloys the move is away from the production of soft tubes by extrusion, cold pilger mills, and tube drawing. This area has had to be conceded to the more economic longitudinal welding of cold-rolled strip.

Bar and section in commercially pure titanium can be extruded and is produced by this route but the demand is small.

The aerospace industry is the main user of semifinished products in titanium alloys apart from special products, including racing wheels and sports cars. In aircraft, they are used for engine components, fuselage, and wing elements [Pet 92] (Table 5.13). Wherever the strength and mechanical properties of aluminum alloys are insufficient, titanium alloys are used for lightweight fabrications.

Extruded sections, tubes, and bars are produced from the higher-strength materials as well

Table 5.13 Some titanium alloys suitable for extrusion, properties, and applications (IMIa 88, IMIb 88, and personal communication)

Low-temperature alloys

Material	Composition	Structure at room temperature	Strength R_m, N/mm^2	Elongation, A_5, %	Properties	Application
Ti1– Ti3(a)	Unalloyed titanium with min 99–99.5% Ti	α-phase	290–590	30–8	Corrosion resistant, readily worked	Tubes and components for the chemical and petrochemical industries
Ti1Pd–Ti3Pd(a)	Addition of 0.12–0.25% Pd	α-phase	250–590	30–8	Very corrosion resistant	The same areas

Intermediate temperature alloys

Material	Composition: Cu	Al	V	Sn	Mo	Si	Structure at room temperature	Strength R_m, N/mm^2	Elongation, A_5, %	Properties	Application
TiCu2.5 (IMI 230)(c)	2.5	...	...	...	...	...	α-Phase Age-hardening	630–790	>30	Used up to 350°C, soft readily worked	Gas turbines Aircraft components
TiAl6V4(b) (IMI 318)(c)	...	6	4	...	...	...	α-β-mixed structure Quenched and tempered Fine α in β structure	950–1080	>12	Used up to 500°C Creep resistant up to 300°C Suitable for hot-working	Most common alloy, turbines, jet engines, implants
TiAl4Mo4Sn2 (IMI 550)(c)	...	4	...	2	4	0.5	α-β-mixed structure used heat-treated and tempered	1000–1250	>9	Creep resistant up to 400°C	Jet engines Aircraft components
TiAl6V6Sn2(a)	...	6	6	2	...	...	α-β-mixed structure	1000–1300	>8	Creep resistant up to 500°C	Aircraft components

Materials for High-temperature alloys

Material	Composition: Al	Sn	Zr	Mo	Si	Nb	Structure at room temperature	Strength R_m, N/mm^2	Elongation, A_5, %	Properties	Application
IMI 679(d)	2	11	5	1	0.2	...	α-β-mixed structure with precipitates; high-temperature heat treatment; β with precipitates	>1100	>8	Creep resistant up to 450 °C, still suitable for hot working	Aerospace
6242(d) (USA)	6	2	4	2	...	...	Almost α	>900	>10	Creep resistant up to 500 °C	Aerospace
IMI 829(d)	5.5	3.5	3	0.25	0.3	1	Almost α		>9	Creep resistant up to 940 °C	Gas turbines

(a) DIN 17850/17861/17862. (b) DIN 17851/17961/17862. (c) IMI brochure: *Titanium Medium Temperature Alloys*. (d) IMI brochure: *Titanium High Temperature Alloys*.

as sheet and strip. The alloy TiAl6V4 is the most common not only as a construction material because of its high strength, but also in surgery for implants because of its good biocompatibility.

5.17.3 Titanium Alloys Produced by Powder Metallurgy

Titanium alloys produced by powder metallurgy (P/M) are being offered to an increasing extent. This occurs on one hand when high-alloy materials, e.g., with intermetallic titanium aluminide, cannot be produced by melting metallurgy or cannot be or only to a limited extent be hot worked and, on the other hand, if it is dispersion-hardened material in which the dispersoids can only be added to the metal using P/M. These materials are described in Chapter 4.

5.18 Billet Production, Extrusion

5.18.1 Casting, Billet Preparation, Billet Heating

The billet pre-material is usually obtained from vacuum arc furnaces with melting electrodes of titanium foam and recycled material [Kra 82]. If the ingot diameter is too large, it has to be forged to the final billet diameter. This has the advantage that an originally coarse grain structure with low hot workability can be recrystallized with a fine-grain structure by careful selection of the forging temperature intervals.

Mechanical surface processing is the final stage: a smooth billet surface is the requirement for a good product surface in the same way as with steel extrusion because in direct extrusion without a shell, with lubrication and a conical die entry, the billet surface becomes the product surface.

The billets have to be rapidly heated in an induction furnace or a protective atmosphere (argon) because titanium easily oxidizes above 700 °C and can become brittle in hydrogen-containing atmospheres. Very fast heating is opposed by the poor thermal conductivity of titanium. Heating in a salt bath (e.g., with barium chloride as a deoxidant) is less environmentally friendly and is therefore rarely used.

5.18.2 Extrusion, Lubrication

Table 5.14 shows the important data for the extrusion of titanium alloys produced by melting metallurgy.

Titanium alloys are preferentially extruded in the β-phase region where the flow stress is significantly lower than in the α-β mixed region (or in the pure α-phase). The uniform structure, which is obtained by the recrystallization that occurs during extrusion in the β-region, is also advantageous. If the temperature in the β-region is too high, there is the risk of coarse grain formation, which has to be avoided at all costs. With some alloys it is possible to obtain a martensitic structure if the section is not cooled slowly enough from the β-phase. Subsequent annealing is then required.

Because titanium becomes brittle not only in hydrogen but also nitrogen and oxygen atmospheres, the extrusion temperature should be as low as possible without crossing the α/β temperature limit.

If, on the other hand, deformation is carried out just below the α/β phase boundary, the variations in heating during extrusion over the cross section and along the length of the section result in a changing mixed structure that produce variations in materials properties over the cross section and along the length.

Titanium alloys are extruded in the temperature range 850 to 1150 °C. Above 1000 °C, which is in the β-region, it is necessary to use glass lubrication similar to steel and nickel alloys.

The glass film hinders the contact between the titanium material and the extrusion tooling and

Table 5.14 Data for the extrusion of some titanium alloys (Lau 76, Zwi 74, IMI personal communication)

Alloy	β-phase boundary	Extrusion temperature	Structure at extrusion temperature	Deformation at extrusion temperature
Ti 1–Ti	882 °C	700–900 °C	α-phase	
TiAl6V4	995 °C	900–950 °C	α-β-phase	~120 N/mm^2
		1050–1100 °C	β-phase	~80 N/mm^2
TiAl6VSn2	945 °C	800–1040 °C	α-β or β-phase	
TiAl4Mo4Sn2	975 °C	~900 °C	α-β-phase	~160 N/mm^2
		~1100 °C	β-phase	100 N/mm^2
TiAl6Sn3Zr3MoNbSi	1015 °C	1050–1150 °C	β-phase	~100 N/mm^2

thus the destruction of the bearing surfaces by corrosion, to which titanium tends in contact with steel. The molten glass also acts as a thermal insulation barrier and hinders the heat flow from the hot material into the colder tooling. The glasses 4 and 5 for the lower temperature range are preferred from the recommended glass mixtures for stainless steel tubes (see Table 5.18 and [Mar 74]).

The extrusion technology with titanium alloys differs slightly from that for iron-base alloys: titanium alloys are, if possible, coated with a glass powder suspension at 80 to 150 °C. During the subsequent heating to the extrusion temperature, the glass coating can act as a barrier against the reaction of the billet surface with air constituents [Mar 74].

However, the method described for stainless steels, rolling the billet heated to the extrusion temperature over a table in glass powder is common, particularly with tube extrusion and when induction furnaces are available for heating.

Extrusion is usually carried out quickly, directly through a die with a conical entry with a glass disc in front to minimize the cooling of the material during the extrusion process and to ensure that the tooling is subjected to the high temperatures for only a short time. At a high speed the temperature of the emerging section can even increase from the front to the back.

If the speed is too high, in particular with sections, there is the risk that the glass film will tear. The instantaneous failure of the tool working surfaces is the result [Mar 74]. The extrusion speed is in the range 0.5 to 5 m/s.

There are also alloys that have to be extruded in the α-β-mixed region with temperatures between 700 and 950 °C, especially if subsequent cold working is not carried out and a fine-grain structure is needed in the as-extruded condition [Zwi 74]. The turned billet is then wrapped in a thin copper sheet and extruded with a lubricated container, in this case, a graphite grease mixture, through conical dies. At the upper temperature range of 850 to 950 °C, an iron foil is recommended as an intermediate layer to avoid a reaction between the copper and the titanium.

With adequate lubrication the friction between the billet and the container is, similar to glass lubrication, so low that a quasi-stationary deformation with laminar material flow occurs, and the surface copper layer at the start and end of the section has an approximately constant thickness. This would be even better with indirect extrusion, but usually only direct extrusion presses are available.

The pickling away of the copper film in a mixture of nitric and hydrofluoric acid is unpleasant and is the reason why cladding in copper is avoided as much as possible. It has been reported that an extrusion in the α-β-mixed region is possible without a copper cladding in spite of the severe adhesion tendency between titanium and the tooling surface if a special graphite grease lubrication is used [Boy 89].

5.18.3 Flow Stress, Extrusion Defects

Compared with many stainless steels, the titanium alloys have a high flow stress at the extrusion temperatures mentioned, and they are therefore difficult to extrude (see Fig. 5.60). This means that on a press usually used for extruded semifinished products in steel, titanium can be extruded only with a low deformation. Extrusion ratios of $V = 10$ to $V = 100$ are used.

The flow stress is—particularly in the α-β-mixed region—very temperature dependent: It increases rapidly with falling temperature as shown in Fig. 5.60. Care must therefore be taken to ensure that the billet is not given time in the container to cool, producing a large radial temperature gradient. Otherwise, the material from

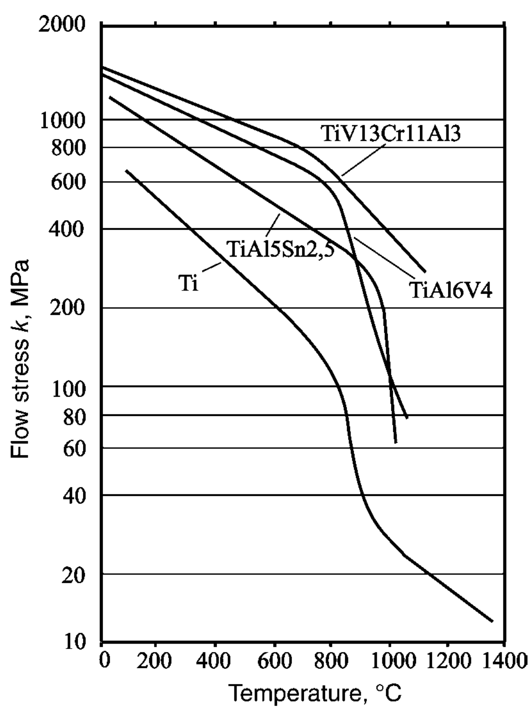


Fig. 5.60 Flow stress k_f as a function of the temperature [Zwi 74]

the billet interior will flow first producing a piping defect at the end of the section. If the extrusion is too slow there is also the risk of the billet's "sticking."

The dependence of the flow stress on the rate of deformation is higher for titanium than for steel. Nevertheless, extrusion has to be carried out quickly for the reasons just mentioned.

5.19 Tooling, Further Processing

The tooling is discussed in Chapter 7 in the section on tooling for the extrusion of titanium alloys.

The tooling loading is similar to the extrusion of stainless steels. When extruding in the β-region with glass lubrication—particularly in section extrusion—only one or two billets can be extruded before the die has to be reworked. The die service life is significantly longer with copper sheathed billets and lower extrusion temperatures. Chapter 7 describes coated section dies that are much more expensive but have a significantly longer service life.

Normally, the lowest limit for the wall thickness of sections is 2 mm. Sections used in aircraft construction often have to have thinner walls (down to 1 mm wall thickness). Because cold working of the common alloys is possible only to a limited extent, drawing and stretching of the extruded sections at a higher temperature is utilized [Mar 74]. However, 350 °C should not be exceeded to avoid undesired structural changes.

Extrusion of Semifinished Products in Zirconium Alloys

Martin Bauser*

5.20 Materials, Properties, and Applications

Pure zirconium and, in particular, zirconium alloys with tin (ZrSn1.5 = zircaloy) and niobium (ZrNb2.5) are used as construction materials in nuclear reactors, especially for the casing material for the fuel rods because of the low absorption of thermal neutrons, good heat transfer, good corrosion resistance, and high hot strength. The chemical industry also uses zirconium-alloy semifinished products for specific critical corrosion conditions.

The production of the very pure metal necessary for processing is costly, and zirconium alloys are therefore correspondingly expensive.

Zirconium melts at 1852 °C and has a density of 6.5 g/cm^3. Pure zirconium has a hexagonal α-lattice up to 862 °C. Above this transformation temperature, there is a bcc β-phase. With alloys—also with small quantities of element additions—there occurs a more or less wide temperature interval with the simultaneous presence of the α- and the β-phases [Web 90]. The structure is similar to that described for titanium alloys, and the properties during hot and cold working are comparable.

5.21 Billet Production, Extrusion

5.21.1 Casting, Billet Preparation

Similar to titanium production, the starting material is melted from zirconium sponge in vacuum or protected atmosphere furnaces with self-consuming electrodes. After forging or rolling the large-diameter cast ingots, the billets for the extrusion of tubes have to be turned on the outside to remove surface defects and also be prebored. Because zirconium has the same property as titanium of readily welding to the tooling during deformation and also reacts with oxygen, hydrogen, and nitrogen at high temperature, the billets are normally externally and internally clad. Copper sheet material is usually used sometimes with an intermediate steel layer when the temperature is high to prevent diffusion of the copper into the zirconium base material. The copper cladding can, however, be applied by plasma spraying. To avoid an expensive zirconium discard, a copper disc can be attached to the back of the billet to form the discard, at the end of extrusion. The cladding of the billet can be avoided by using special lubricants.

5.21.2 Extrusion, Influence of the Structure

If zirconium, for which there is no great demand, is processed on presses installed for steel

*Extrusion of Semifinished Products in Ziroconium Alloys, Martin Bauser or copper alloys, then the technology used follows that for the corresponding main material.

The flow stress of most zirconium alloys is not very high at the extrusion temperature, and the dependence on the temperature is tolerable so that the extrusion temperature and speed can be varied within relatively wide boundaries with no risk.

Because the β-phase has the best hot workability, it makes sense from the deformation point of view to extrude in the temperature range 800 to 1100 °C, where the flow stress is relatively low. This, however, rarely occurs because the billets would then have to be clad in steel. In this case, lubrication is carried out with a glass powder mixture similar to steel and titanium.

In practice zirconium alloys are extruded preferentially in the temperature range 675 to 800 °C to reduce the risk of gas absorption, which severely impairs the toughness of the extruded semifinished product. Just below the α/β transformation temperature and (in the case of alloys) in the α-β mixed phase region the workability is very good [Sch 93].

The best method, but also the most expensive, is cladding the billets in copper. Clad billets can be heated in an induction furnace and lubrication with oil-graphite suffices similar to standard copper alloys. Dies with conical entries are necessary to obtain a predominantly laminar flow and thus to obtain a uniform cladding thickness over the length of the extrusion.

If extrusion is carried out without cladding, it is important that the billets are brought rapidly to temperature and protected as far as possible from atmospheric influences during heating. Salt bath heating is, therefore, preferred over other methods (75% BaCl, 25% NaCl is referred to in [Lus 55]).

Special glass mixtures are used as lubricants when extruding without cladding at approximately 800 °C. They have a low viscosity even at this low temperature and substantially protect the billets from gas absorption.

5.22 Tooling, Further Processing

When selecting the tooling materials and the tooling design, the experience gained from the extrusion of copper alloys and—when extruding at high temperatures—of steels can be utilized.

As a general rule, conical dies ($2\alpha = 140$ to 90 °C) are used to produce tubes and round bars.

If extrusion is carried out with copper cladding, the cladding material has to be removed from the extruded product either mechanically or with nitric acid. Zirconium is not attacked by nitric acid. Coarse grain billet material leaves an orange peel effect on the pickled surface as an image of the grain structure. A fine-grain starting material is therefore preferred.

The subsequent processing of zirconium alloy tubes is carried out on precision cold pilger machines [Jun 93]. Drawing requires careful preparation by bonderizing and lubrication because the material has a tendency to weld to the tooling. More recently, drawing has been carried out using an ultrasonic vibrating mandrel, which improves the internal surface. Zircalloy cladding for fuel rods can be produced from extruded tubes without drawing by multiple cold pilger operations with intermediate annealing (70% reduction per cycle can be achieved).

Extrusion of Iron-Alloy Semifinished Products

Martin Bauser*

5.23 General

5.23.1 Process Basics

The high melting point of iron alloys (pure iron: 1535 °C, density 7.9 g/cm^3) corresponds to a high recrystallization and hot-working temperature. Hot working usually is carried out in the fcc austenite region, depending on the alloy, between 1000 and 1300 °C. This is associated with high tool wear because of the high thermal and mechanical stresses and, depending on the composition, a more or less severe oxide formation. As a result, it was relatively late before these alloys could be successfully extruded.

The oil graphite lubricants known from copper alloys, and which were used for steel extrusion around 1930, were not really suitable. They were initially replaced with mixtures of oil, graphite, and cooking salt, which could be ef-

*Extrusion of Iron-Alloy Semifinished Products, Martin Bauser fective only with very short contact times between the hot material and the shape-forming tooling. This method of lubrication is used only rarely today for the production of mild steel tubes on vertical mechanical presses (see section 5.24).

A significant extension to the application of the extrusion process followed the development of the Ugine-Séjournet process in 1950 in which glass of a specific composition was used for lubrication [Séj 56]. The molten glass not only protects the heated billet from oxidation and acts as a lubricant between the material and the tooling, but also acts as thermal insulation so that the die and container heat more slowly than with the lubricants previously used. It was now possible to produce alloy steel tubes and steel sections on horizontal extrusion presses with a lubricated container.

Steels are extruded using the direct extrusion process with lubricated containers without a shell. With this process it is possible to achieve short contact times with fast extrusion speeds—important for the necessary high extrusion temperatures. The use of conical dies result in a material flow in which the billet surface forms the surface of the extruded product (see Chapter 3, the section on material flow in direct extrusion, Fig. 3.31).

5.23.2 Importance of Steel Extrusion Today

The growth in the extrusion of steel in the 1950s and 1960s was followed by a continuous decline. The production of seamless tubes in mild steels and low-alloy structural steels on vertical presses has largely been replaced by more economic continuous rolling processes. Seamless tubes in these steel grades are now replaced whenever possible by the less-expensive longitudinally welded tubes.

Today, the extrusion of stainless steel tubes and steel sections is used only when the material, the section shape, or the low volume required cannot be produced by other processes or only with significant expense.

The reasons for extruding steel tubes are:

- Crack-free production of long products even in materials that are difficult to hot work and that tend to crack during rolling
- Production of small volumes. If unusual dimensions or materials are involved, then frequently the setting and operation of rolling processes designed for mass production is uneconomic. The tooling costs can also be very high. In contrast, extrusion can be viable for quantities as low as three billets.
- Experimental or pilot production of tubes and sections that will later be produced in large quantities more economically by rolling

Approximately only 30% of all steel tubes are produced as seamless and of these, less than 10% are produced by extrusion [Bil 79].

Three product groups are described in detail subsequently:

- Mild steel tubes
- Alloy steel tubes
- Steel sections

5.24 Mild Steel Tubes

5.24.1 Use of Mechanical Presses

The numerous vertical mechanical presses previously used in the technically highly developed countries are no longer in operation. Carbon steel tubes are usually produced on continuous production lines that have a significant higher productivity. However, these mechanical presses are still used in other countries.

Carbon steels, free cutting steels, low alloy hot and cold working steels and high speed steels can be processed on mechanical presses.

5.24.2 Application of Mechanical Presses

Mechanical extrusion presses are similar to the machines used in the drop-forging industry.

The billets are pierced and extruded in one operation on vertical mechanical presses. The billets are first heated to 1100 to 1300 °C and loaded into the vertical lubricated container. Then, at the upper top dead center the crankshaft is connected to a continuously operating electrically driven flywheel with a horizontal axis. In one revolution the stem and piercing mandrel fall and the billet is extruded down into a curved channel and the stem and mandrel retracted. The discard is sheared with a shearing tool and removed from above.

The high deformation temperature and the extrusion time, which lasts for only a few seconds on the mechanical press, enables extruded tubes in mild and free-cutting steels to be hot reduced directly after extrusion on a stretch reducing mill without reheating.

The glass lubrication used on horizontal presses to protect the tooling (see section 5.25.4.2) is not really applicable for vertical presses because the glass powder does not adhere securely to the billet surface in the vertical position.

The older method of lubrication with a viscous oil-graphite salt mixture has to be used. This partly evaporates and can even burn during extrusion. Today's environmental requirements are difficult to fulfill even with careful extraction.

5.24.3 Dimensional Range and Throughput

Mechanical tube presses are restricted in their press loads because there is a limit to the load that can be economically transferred mechanically. They are, therefore, used only for extrusion loads up to a maximum of 17 MN. Because the upper limit of the billet weight naturally depends on the extrusion load that can be developed, the maximum billet weight that can be deformed is 120 kg with a diameter of 200 mm.

The entire extrusion process lasts no longer than 3 s so that it is possible to have up to 200 working cycles in one hour (average 120 to 130). The mandrel length is restricted to 5 to 7 times the mandrel diameter because longer mandrels can deflect sideways within the press during piercing.

The dimensional range of the extruded tubes extends from 40 to 120 mm external diameter and 2.5 to 5 mm wall thickness [Sar 75].

5.25 Seamless Alloy Steel Tubes

5.25.1 Extrusion in Competition with Other Hot-Working Processes

There has also been a large reduction in the extrusion of seamless alloy steel tubes over the last few decades and numerous presses have had to be closed down. The extrusion of seamless alloy steel tubes has to compete with a range of more economic rolling processes, the production capacity of which can be seen in Table 5.15.

Economic analysis has shown that extrusion is inferior in output to the continuously operating rolling processes because of the low billet weight and the long dead cycle times. The dies for extrusion can be produced relatively inexpensively but wear much more rapidly than the tooling in the rolling process.

Table 5.15 Production ranges for the different methods for producing seamless steel tubes (Man 86)

Process	Tube diameter, mm
Extrusion	35–250
Tube continuous rolling	20–180
Diagonal rolling and Pilger process	160–660
Plug rolling procedure	180–400

The most important method of producing seamless alloy steel tubes in the same dimensional range as the extrusion press is the continuous tube-rolling process in which a forged round ingot formed to a hollow billet in a piercing mill is hot rolled over a mandrel through numerous profiled roll pairs and then brought to the finished size on a stretch reducing mill after reheating. This process has at least 4 times the throughput of an extrusion press [Bil 79].

The extrusion process today is restricted to:

- High-alloy stainless ferritic and austenitic steels
- Heat-resistant high-chromium ferritic and austenitic alloy steels
- High-temperature austenitic alloy steels

The dimensional range of these tubes is between 35 and 250 mm external diameter and a wall thickness of 5 to 50 mm with a minimum internal diameter of 30 to 40 mm [Ric 93]. The extruded tubes are usually processed further by rolling and/or drawing.

To produce the infrequently required dimensions over 200 mm external diameter, an alloy steel tube extrusion press would have to be so massive that the high cost would generally prohibit the use of the extrusion process [Bil 79]. A 55 MN press designed for this purpose was supplied to Russia several years ago.

Horizontal water-driven tube presses and only the direct process without a shell are used. Figure 5.61 shows the extrusion principle.

Alloy steel tubes produced by extrusion are sold as hot finished or further cold worked. Applications are in the chemical industry, plant manufacture, nuclear technology, and the petrochemical industry.

5.25.2 Alloys and Extrusion Properties

5.25.2.1 Alloy Groups, Structure, Properties, and Applications

Table 5.16 shows a selection of the alloy steels currently extruded.

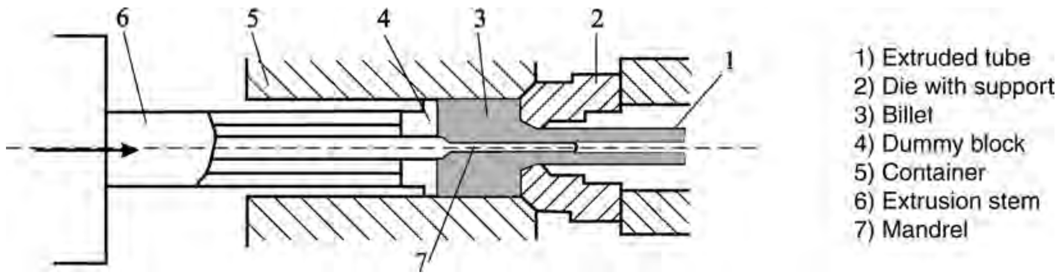


Fig. 5.61 Extrusion of alloy steel tubes on a horizontal press [Sar 75]

Table 5.16 Examples of stainless heat-resistant and high hot strength steels that are processed by extrusion (Ric 93)

	Chemical composition, %					
Material No.	**C**	**Cr**	**Ni**	**Mo**	**Other**	**Similar UNS No./Common Name**
Stainless steel						
Ferritic	...	...	...	...	...	...
1.4016	<0.08	16.5	...	...	...	S43000/430
1.4510	<0.05	17.0	...	...	Ti>4 × (C+N) < 0.8	S43036/430Ti
Austenitic						
1.4301	<0.07	18.0	9.5	...	...	S30400/304
1.4306	<0.03	19.0	11.0	...	...	S30403/304L
1.4401	<0.07	17.5	12.0	2.2	...	S31600/316
1.4404	<0.03	17.5	12.5	2.2	...	S31603/316L
1.4571	<0.08	17.5	12.0	2.2	Ti>5 × %C < 0.7	S31635/316Ti
Heat-resistant steels (austenite)						
1.4845	<0.15	25.0	20.5	...	...	S31000/310
1.4841	<0.20	25.0	20.5	...	Si 2.0	S31400/314
1.4876	<0.12	21.0	32.0	...	+ Al + Ti	
High-temperature steels (austenite)						
1.4910	<0.04	17.0	13.0	2.5	N 0.14	S31653/316LN
1.4961	<0.10	16.0	13.0	...	Nb 10 × %C ~ 1.20	S34700/347
1.4959	0.07	20.0	32.0	...	Al + Ti, V 0.07	...

The heat-resistant materials are covered by DIN EN 10095, the other materials by DIN EN 10216-5 and DIN 17456 (the European standard [EN] has replaced the previous DIN standards).

The following material groups are classified by the hot-working temperature range [Ric 93]:

- *Ferritic steels* with bcc α-iron structure. All ferritic chromium steels over 12% Cr content as well as the steels alloyed with molybdenum and/or titanium belong to this group and have a bcc α-iron structure. They are characterized by a flow stress that decreases rapidly with increasing temperature so that they can be readily hot worked.

  However, this alloy group tends to brittleness due to precipitated phases and to grain coarsening during the hot working of the starting material by rolling or forging before extrusion. The embrittlement reduces the notch impact values. Suitable billets for extrusion are therefore difficult to produce free from cracks in the high-chromium-containing materials.

  Hot-brittle lead and sulfur-containing free-machining steels can only be hot rolled with difficulty. Only piercing and rolling over a mandrel are suitable for processing these alloys apart from extrusion, which is still the most common process used for this material group.
- *Austenitic steels* have chromium contents over 16% and nickel contents exceeding 8%. At the extrusion temperature the structure of these alloys is the fcc γ-iron lattice. The austenite is, therefore, usually characterized by very good hot workability as well as a low tendency to embrittlement. The undesirable coarse grain formation found with the ferritic steels does not occur with the austenitic ma-

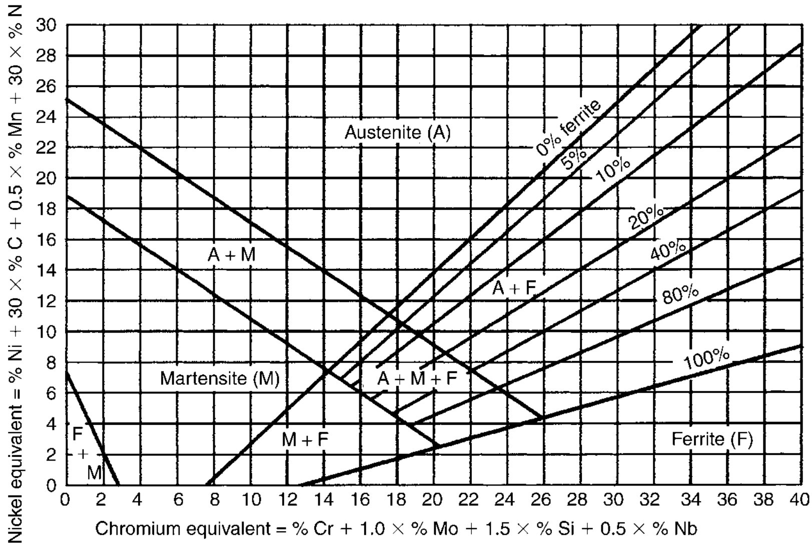


Fig. 5.62 Phase diagram according to Schaeffler-DeLong [Ric 93]

terials so that they can also be readily welded.

The good workability and the good corrosion resistance against many media provide the austenitic materials with a wide range of applications in chemical plant manufacture and in energy production.

The higher the nickel content, the higher is the hot strength of austenitic materials and the more difficult they are to extrude. High-nickel-containing materials can consequently be extruded only at low extrusion ratios.

- *Austenitic–ferritic alloys* with chromium contents of 18–25% and nickel contents of 4–7% are used for a range of applications. They combine to some extent the advantages of both the alloy groups described previously. They have a lower susceptibility to embrittlement than do ferritic materials and are more easily worked than the austenitic materials and also offer advantages in specific types of corrosion attack. The most well-known representative of this group is the material 1.4462 with 22% Cr, 5.5% Ni, and 3% Mo, which is an alloy steel with many applications in the petrochemical industry.

An overview of the structure of the three material groups is given by the phase diagram according to Schaeffler-DeLong (Fig. 5.62), which shows the structure as a function of the chromium and nickel content. The effect of other alloying elements is determined from their chromium or nickel equivalent.

In austenitic steels, δ-ferrite is particularly dangerous because its occurrence limits the extrusion temperature; otherwise, transverse cracking occurs in the extruded section.

5.25.2.2 Extrusion Properties, Defects

The extrudability and extrusion temperature range of the different materials are given in Table 5.17.

The fewer the precipitates, the better the extrudability of ferrite and austenite. Single-phase materials—particularly in the γ-range with a fcc structure—are particularly easy to extrude [Bur 70, Ben 73].

At the normal extrusion temperatures of 1100 to 1350 °C, the flow stress is in the range 150 MPa (materials with high extrudability) to 400 MPa (materials with low extrudability) for austenite and ferrite. The extrusion ratio (V) is usually 8 to 40.

Examples of the relationship of the flow stress and the deformation capability on the composition and the temperature are shown by the curves for different steels in Fig. 5.63.

Whereas the workability of homogeneous structures always increases with increasing temperature, a marked decrease can occur with Cr-Ni steels as a result of the formation of δ-ferrite above approximately 1200 °C. This results in a risk of transverse cracking during extrusion. The limit is considered to be 2 to 3% δ-ferrite at room temperature (corresponding to approximately 8% at the extrusion temperature).

The calculation of the extrusion load is discussed in detail in Chapter 3.

The high extrusion temperature produces a large temperature difference between the material and the container and a rapid loss of heat. It is necessary to extrude quickly to prevent the billet freezing during the extrusion process. This also aids the die life.

In the deformation zone immediately in front of the die, an adiabatic temperature increase of up to 150 °C occurs during extrusion. The higher the flow stress of the material and the faster the extrusion speed, then the higher the temperature increase will be, i.e., the closer the process approaches adiabatic conditions. It is therefore necessary to carefully match the temperature and speed for materials with low-melting-point constituents to avoid melting and thus cracks in the extruded section.

Because the extrusion temperature is above the solution heat treatment temperature of constituents that can form precipitates, the extruded section usually has a fully recrystallized structure.

At low extrusion ratios, i.e., large tube cross-sectional areas, the core region tends to accelerate. The resultant internal longitudinal stresses can result in lamination such as internal cracking within the extruded section that cannot be detected externally. These defects can only be discovered using ultrasonic testing.

In contrast, in thin-wall tubes, these stresses result in cracks originating at the surface.

5.25.3 Billet Production

5.25.3.1 Melting, Casting, Hot Working

Alloy steels are melted today by the following processes [Ric 93]:

- Electric arc melting process with downstream argon-oxygen-decarburization (AOD) or vacuum-oxygen-decarburization [VOD]
- Induction melting in air or in a vacuum
- Remelting using the electroslag refining process (ESR)

Table 5.17 Extrudability of different material groups (examples) (Ric 93)

Group	Characterization	Nominal flow stress k_f MPa	Example, alloy (DIN No.)	Billet preheat temperature, °C
1	Easily extruded	150	410 (1.4006)	
			430 (1.4016)	
			439 (1.4510)	1000–1200
2	Good extrudability	200	304 (1.4301)	
			304L (1.4306)	
			316 (1.4401)	
			316L (1.4404)	
			316Ti (1.4571)	1050–1250
3	Difficult to extrude	250	314 (1.4841)	
			310 (1.4845)	
			. . . (1.4876)	1100–1300

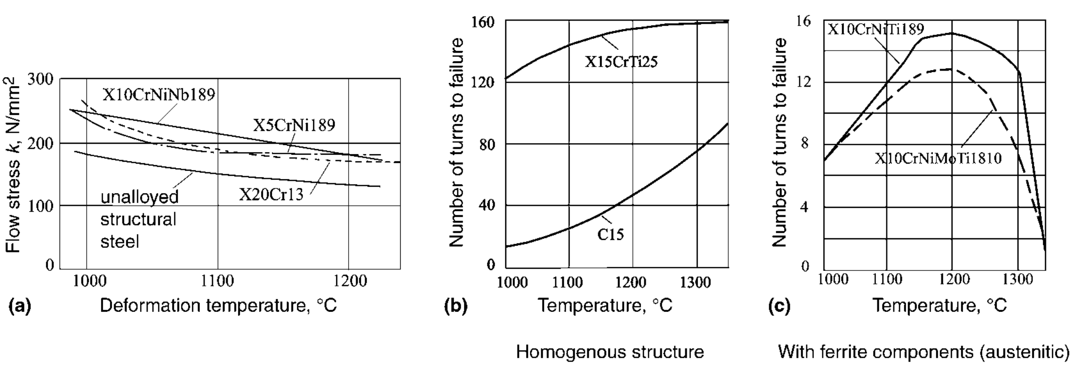


Fig. 5.63 Flow stress and workability of steels measured from the number of turns to failure in torsion tests as a function of temperature. (a) Flow stress. (b) δ. (c) Deformation capacity [Ben 73]

The latter guarantees a high cast purity and an extensively homogeneous distribution of the elements that tend to segregation such as niobium and molybdenum.

Continuous casting is carried out if the charge size permits; otherwise, mold casting is used. Only pure and low-alloy carbon steels can be directly extruded without previous hot working. Higher-alloyed materials have to first be forged or hot rolled to destroy the columnar cast structure and produce a homogeneous structure [Man 91, Bil 79, Bur 70].

5.25.3.2 Homogenizing, Billet Preparation

Homogenizing of the rolled or forged billets is rarely carried out and only when the homogeneity or grain distribution is inadequate for defect-free extruded bars [Ric 93]. The need for homogenization increases with increasing content of the elements molybdenum, niobium, and titanium, which result in the formation of segregations.

Because the billet surface in direct extrusion with lubrication without a shell and using conical dies becomes the surface of the extrusion, the 8- to 12-m-long forged or hot-rolled round bars have to be cross sectioned and carefully machined by turning or peeling. Coarse turning marks result in fish-bone patterns on the extruded tube surface. A chamfer on the front face of the billet simplifies the uniform flow of the glass lubricant during extrusion (see below).

Billet diameters from 200 to 300 mm and billet lengths up to 700 mm are standard.

Whereas in the extrusion of copper alloy tubes large billets are pierced in the press, this process is not possible with alloy steels, which are also processed on hydraulic horizontal presses. The mandrels cannot withstand the severe thermomechanical stresses and would rapidly wear because of the absence of the lubricating film. The billets are therefore bored, although for diameters up to 60 mm, a deep hole without expansion is sufficient. The billet length to bore ratio should not exceed the value of 7:1; otherwise, the bore will deviate. With larger bore diameters, the predrilled billet is expanded in a separate piercing press [Bil 79]. The hole diameter is always larger than the mandrel diameter so that the lubricant spread in the bore is not stripped off by the mandrel.

5.25.4 Billet Heating, Lubrication

5.25.4.1 Billet Heating

Apart from the uniform through heating of the billet, it is important during heating to avoid oxidation and surface decarburization of the heat treatable steels.

Billet heating to the required temperature of 1100 to 1300 °C is carried out in rotary hearth furnaces with protective atmospheres, in induction furnaces, or in a combination of both with a gas furnace for preheating to approximately 700 °C and final heating in an induction furnace.

The slower heating in the rotary hearth furnace with its more uniform through heating can have a homogenizing effect on the structure of some steels.

The cost advantage of gas heating also plays a role, particularly with infrequent alloy changes. The possibility of a rapid temperature change with small batch sizes of different steels is an argument for induction heating.

Induction furnaces are more expensive to operate but heat more quickly, and the temperature can be more accurately controlled, which is the reason why induction furnaces are used in particular for high-alloy steels with exactly specified preheat temperatures. Complex alloy steels often have only a narrow extrusion temperature range. The upper limit is determined by the solidus temperature and the lower limit by the press power.

The temperature of the billet core lags behind during the rapid induction heating, which can result in core cracking in crack-susceptible steels, e.g., heat-resistant ferrites with high chromium contents. In this case the preheating in rotary hearth furnaces mentioned previously is recommended.

Although induction furnaces with the shorter heating times of 5 to 15 minutes largely heat free of oxidation, a protective atmosphere is often passed through the induction coil with the oxide-susceptible steels. This can be necessary, in particular, with furnaces with a vertical axis in which the billets oxidize more severely because of the larger air throughput from the chimney effect.

Salt bath ovens for billet heating are rarely used. Their advantage is the capability of exact temperature control and the avoidance of oxidation. They are, however, unwieldy and expensive and the salt carryover presents a large environmental risk [Sar 75, Lau 76, Kur 62]. The diffusion of nitrogen damages the surface zones of austenite and, as a result, the extruded tubes sometimes have to be ground over.

If the turned billet has to be pierced before extrusion, this process is carried out in vertical piercing presses linked to a vertical single-billet furnace in order to balance out the heat losses and to exactly control the extrusion temperature. In the piercing press, for example, the existing bore diameter is expanded from 35 mm to a range of 53 to 74 mm, increasing the billet length by up to 20%.

Carbon steels and low-alloy steels can oxidize so severely that removing the thick oxide layer with a strong jet of high pressure water after billet heating is recommended. This process is so quick that hardly any heat is lost.

The high billet temperature of high-alloy steels necessitates a fast transport from the oven to the press. Otherwise, the material would cool too quickly, particularly with small billet diameters where there is a large surface to volume ratio.

The use of radiation protective sheaths has been reported in the United States. These have to be removed just before extrusion when the billet is loaded into the container [Lau 76]. However, a thick glass layer, which surrounds the hot billet as a lubricant, also acts as insulation.

5.25.4.2 Lubrication

Similar to other difficult-to-extrude materials, e.g., the nickel alloys, the development of lubrication technology was an important requirement for the economic extrusion of alloy steel tubes. The graphite and salt containing oil suspensions initially used as lubricants would carburize the surface of low-carbon steels, among other disadvantages. Glass lubrication technology was rapidly adopted and had to meet numerous requirements [Ben 73]:

- The lubricant with its good slip properties has to form a closed lubricant film that does not break up even when being extruded through the die aperture. It should prevent contact with the tool working surfaces as well as reduce the load.
- It should form an insulating layer between the billet and the extrusion tooling and thus increase the ability of the tooling to withstand the thermomechanical stressing. A low thermal conductivity is desirable.
- The lubricant applied to the billet surface immediately after heating should protect this and the emerging extrusion from oxidation with a thick film. Thin oxide coatings that have already formed should as far as possible be removed or absorbed by the lubricant.
- Glassy lubricants have a larger volume contraction on solidification and cooling than steel, and the lubricant can readily break off, particularly with rapidly cooled extrusions.

Glasses that are optimally suited for all steels with their different extrusion temperatures and flow resistances do not exist. Therefore, glasses with different compositions and thus a different viscosity temperature dependence are recommended for the various material groups (Table 5.18).

The criterion for the upper limit of the temperature application of glasses in extrusion is the so-called "hemispherical" temperature (see footnote in Table 5.18). The viscosity is then approximately 2×10^4 poise. The lower limit is characterized by the compressive softening temperature (CST) where the glass is extremely tough (approximately 10^{10} poise) but no longer breaks in a brittle manner. The extrusion temperature should be at least 200 to 300° above the CST.

Standardized glasses are available from various manufacturers. Today only a few types are used in extrusion with SiO_2 as the main constituent. They contain oxides of sodium, potassium, calcium, magnesium, aluminum, and boron. Barium oxide is also sometimes added. These

Table 5.18 Glasses used successfully as lubricants for extrusion (Deg 74)

No.	Composition								Extrusion temperature	
	Na_2O	K_2O	MgO	CaO	BaO	Al_2O_3	B_2O_3	SiO_2	Maximum HK(a), °C	Minimum DET(b), °C
1	. . .	. . .	. . .	+	+	+	+	+	1300	765
2	+	+	. . .	+	. . .	+	+	+	1220	690
3	+	+	+	+	+	+	. . .	+	990	645
4	+	+	+	+	+	+	+	+	710	510

(a) Hemispherical temperature (HK) is the temperature at which a specific quantity of the glass powder melted in a heated microscope forms a hemisphere. Viscosity is approximately 2×10^4 poise, i.e., highly fluidic. (b) Compressive softening temperature (DET) is the temperature at which the glass has a viscosity of approximately 10^{10} poise and is extremely tough but no longer brittle.

additions lower the melting point and stabilize the glasses.

The billet from the preheating furnace is rolled over a sloping table covered in the glass powder and also has powder spread in the bore using a spoon. The powder immediately melts and protects the billet from further oxidation and can even dissolve any oxide that has formed. If the billet is not pierced before it is loaded into the press, the procedure for applying the glass powder has to be repeated (after the reheating). Different glasses are sometimes used for internal and external application. The grain size of the glass also plays a role because fine grain-size powder melts more quickly than coarse grain.

In front of the die there is a pressed disc of the same glass powder or fiber glass (with water glass as the binding agent) that slowly melts during the extrusion process and encloses the front of the extrusion. The thickness of the glass layer is of the order of 10 μm.

Careful matching of the type of glass, the extrusion temperature, and the extrusion speed, as well as the quantity of glass is important to produce a perfect glass, coating on the extrusion. If too little glass flows through the die, grooves form; if the quantity is too high, the surface of the section exhibits bulges or a so-called "orange peel surface" corresponding to the individual grains [Bur 70].

It should be mentioned that the removal of the glass film from extruded tubes is expensive and did not have to be carried out with the previous graphite-containing lubricants.

5.25.5 Extrusion Process

A high extrusion speed is possible for the majority of iron alloys. Depending on the material and the extrusion ratio, ram speeds in the range of 20 to 300 mm/s are attained so that the billets are extruded within a few seconds. High extrusion speeds are necessary to keep the stresses on the tooling to a minimum. The tooling temperature should not exceed 500 °C. The melting properties of the glass used for lubrication prevents the use of the maximum extrusion speeds so that in practice, the minimum ram speed is 50 mm/s and the upper limit is 200 mm/s.

High extrusion speeds can be achieved only with hydraulic accumulator drives. In the steel industry, direct oil operating systems are not used.

The construction of the horizontal hydraulic tube extrusion presses are basically similar to those used for copper tube extrusion.

The stem loading is, as usual, restricted to a maximum of 1200 N/mm^2. In order to achieve this, there are presses with several hydraulic cylinders that can be individually switched off to avoid overloading with small billet diameters. The press capacity of these presses is 35 to a maximum of 50 MN. Extrusion ratios (V) of 10 to 40 are standard.

Because extrusion is carried out without a shell the dummy blocks used have to be matched as closely as possible to the container bore; a cleaning pad is not required.

A laminar quasi-stationary material flow is achieved by using dies with a conical entry inlet angle of 120 to 150° or dies with a curved inlet. A fast die-change system is needed to avoid overheating of the dies and to enable die reworking after every extrusion. If a die has to be reused, it is cooled to approximately 250 °C in a water bath.

The container is not heated during extrusion because the heat transferred from the hot billet is sufficient to keep it warm. The container only has to be maintained at approximately 500 °C before starting extrusion and during production interruptions. There are extrusion presses with rotating container devices in which two containers are used in turn: while one container is being used for extrusion, the other can be cooled and cleaned.

The extrusion mandrel moves with the stem during extrusion so that no mandrel cross section has to have prolonged contact with the hot deformation zone in the die. The mandrel is cooled internally as with copper materials or sprayed externally with water between extrusions.

In order to remove the glass lubricant from the tooling, the following operations have to be carried out between extrusions:

- The mandrel is sprayed externally with water.
- The container is cleaned with a steel brush.
- The die is quenched in a water bath.

The discard and tube are separated with a hot saw or a shear between the opened container and the die. The extruded length is restricted to a maximum of 20 m for steel tube extrusion to ensure that the contact time between the material and the die is not too long. Runout tables up to 50 m, which are used for aluminum and copper alloys, are not possible with steel. The runout trough for steel can also be fitted with powered rollers.

In the majority of cases, quenching with water is carried out directly behind the die because most of the alloys produced have to be cooled as quickly as possible to avoid precipitates of carbides and intermetallic phases such as the σ- and χ-phases. Precipitated phases result in embrittlement and in numerous cases, unfavorable corrosion behavior. Water quenching also has the advantage that the glass film breaks up so that it can be easily removed. Quenching should be avoided only with materials where there is a tendency for cracking with rapid cooling and with ferrites where martensite can form [Ric 93].

5.25.6 Tooling

Tooling design and other details are covered in Chapter 7.

The shape-forming tools—die and mandrel—are usually made in steel 1.2343 (H11, UNS T20811). The die with the conical entry is usually located in a die holder with a truncated shaped external face, which mates with the conical container seat. Container liners are also frequently manufactured in the steel 1.2343.

Dies that are removed and cooled can last between 20 and 40 extrusions and can then be opened up to another dimension. The mandrel life is around 400 extrusions and that of the container about 4000 extrusions, with the possibility of reworking.

The use of high-alloy materials for dies and liners in the extrusion of alloy steels has been tried but for economic reasons is not used [Ben 73].

5.25.7 Further Processing, Testing

5.25.7.1 Further Processing

Steel, ball shot blasting (VacuBlast) is used, followed by pickling in nitric acid with hydrofluoric acid additions to remove residual glass lubricant from the internal and external surfaces of the tube. Hot molten sodium and calcium salts are used to some extent for surface cleaning, but they are expensive and environmentally unfriendly because salt carryover is difficult too avoid.

Heat treatment after extrusion is necessary if it is not possible to arrange the cooling of the hot extrusion so that a precipitation-free structure is obtained. The heat treatment after extrusion then has the nature of a homogenization or a solution heat treatment.

Extruded and metallic clean semifinished products can be directly used as hot-finished semifinished products after finishing (straightening and cutting to the finished length). If necessary, the surface has to be ground.

In other cases, the extruded tubes are further processed by cold pilgering and/or cold drawing.

5.25.7.2 Testing

In order to prevent δ-ferrite occurring in austenitic steels, the billets are tested randomly by a magnetic balance. The permitted upper limit is 3%. Crack testing of the billet surface (penetrant testing) is required only occasionally.

As well as the standard visual inspection of the tube surface, ultrasonic testing is required, particularly with high-alloy materials and for some critical applications. This is carried out with either fixed test heads and rotating tubes or with static tubes and rotating test heads. Water is used as the coupling agent.

The danger of internal cracks occurs only with the highest-alloyed materials (molybdenum-containing). Internal inspection with an endoscope is specified only for these.

5.26 Steel Sections

5.26.1 General

5.26.1.1 Extrusion Process, Materials

As with alloy steel tubes, only horizontal hydraulic extrusion presses are used for steel sections. The laminar extrusion takes place with glass lubrication and without a shell. In this case the competing processes, which are economically more competitive for suitable quantities and specific sections, again have a higher market share than the extrusion process.

In principle, all steel grades that can be hot worked can be extruded to sections. Nevertheless, the tool wear increases drastically with increasing extrusion temperature. The higher the flow stress at the extrusion temperature, the lower the possible extrusion ratio will be and also, as a rule, the length of the extrusion.

5.26.1.2 Competition with Other Deformation Processes

The processes used to produce sections are:

- *Hot rolling:* The dimensional range falls within a circumscribing circle of 250 mm diameter. The possible weight per meter is 1 to 7 kg with minimum wall thickness of 3 mm. The minimum wall thickness tolerance is ±0.3 mm. In the hot-rolling process, cross-sectional undercuts are impossible and hollow sections cannot be produced. A relatively large tonnage is required to justify the cost of the manufacture of the profiled roll pairs needed for the sequential tools.

- *Machining from solid material:* The high material loss and the expensive process ensure that this process usually follows a non-machining deformation and only when other methods of producing the final shape have to be excluded.
- *Cold profile forming from steel strip:* This process requires material that can be cold bent and the section must have a uniform wall thickness. The final shape is produced from the flat sheet using several roll sets in the bending machine. The form-shaping tool pairs are expensive, so the process is economic only for large quantities.
- *Joining of part sections by longitudinal welding, riveting, or bolting:* Extruded sections are frequently used to produce more complex sections or larger cross-sectional areas.
- *Extrusion:* The possible dimensional range falls within a circumscribing circle of approximately 250 mm diameter with a weight per meter of 1.5 to 100 kg/m and a wall thickness of at least 3.5 mm. The thickness tolerance that can be achieved is ±0.5 mm. Complicated sections and also hollow sections can be produced (Fig. 5.64).

Obviously, given the severe thermal stressing of the form-producing tooling, the degree of complexity and the range of sections that can be produced cannot be compared with aluminum sections. Sharp edges are impossible because of the risk of tooling failure and the thermomechanical localized stresses. External edges should, therefore, have a minimum radius of at least 1.5 mm and internal edges on hollow sections a minimum of 4 mm (Lin 82). Tolerances that are too wide for the application can often be reduced by subsequent cold drawing.

Extrusion is used even for sections that can be produced by hot rolling when it is not economical to produce the roll sets needed for the multistand mills because of the small volume required. Extrusion can then be used for the production of prototypes and first series.

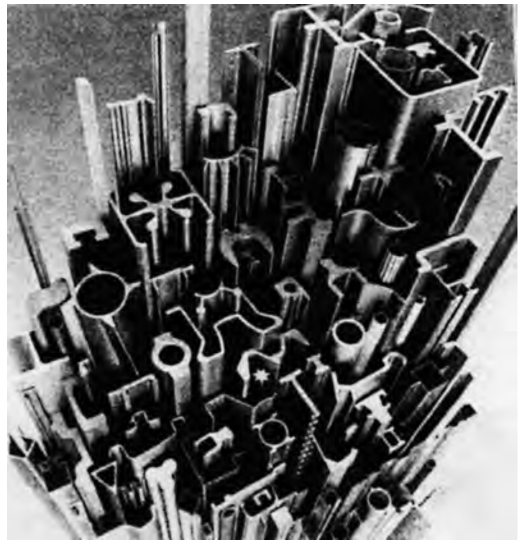


Fig. 5.64 Extruded steel profiles [Hoe 90]

Extrusion is also preferred for sections that can be more economically produced by welding but which cannot have any weld for safety reasons.

The average lot size is 10 billets per order and is therefore generally small. If larger quantities are required, an alternative method of production is usually sought for cost reasons, e.g., hot rolling, even if the shapes have to be slightly modified and simplified.

Of the steel sections produced in a section mill, only 8 to 10% are extruded. Approximately 65% of sections are hot rolled and the others are produced using other processes.

5.26.2 Materials, Starting Material, Process

Extrusion produces the same mechanical properties as hot rolling. In both processes the hot-working temperature is higher than the recrystallization temperature, and a fine-grain recrystallized structure is produced.

Structural steels are processed along with heat treatable steels and alloy steels (stainless, heat resistant as well as tool grades), as well as nickel-base alloys and, more rarely, cobalt-base alloys and titanium alloys.

The starting material for carbon steels is continuously cast and supplied in approximately 10 m lengths from the foundry cleaned by pickling or shot blasting.

The starting material for alloy steels has to be hot rolled or forged in the same way as for tube production for homogenizing and to achieve a fine-grain, crack-free structure.

The extrusion process with a lubricated container and without a shell resembles that described for tube production. The large billets used for heavy sections and, in the case of hollow sections, prebored billets also have to be chamfered on the end surfaces to achieve the uniform flow of the glass lubricant.

5.26.3 Billet Production, Extrusion, Further Processing

5.26.3.1 Billet Preparation, Heating, Lubrication

As soon as an order is passed to production, the bars delivered to billet production are cross-cut, peeled, turned or ground and chamfered. The billets for hollow sections have also to be bored. The hole is larger than the circumscribing circle of the mandrel cross section. The billets are heated to 1000 to 1300 °C in a rotary hearth furnace with a reducing protective gas burner or in an induction furnace similar to steel tubes. Salt bath heating is also used.

After the billets have been removed from the furnace, they are rolled down a table with glass powder. The glass film formed from the molten powder prevents high thermal losses and oxidation of the billet surface and can even dissolve the oxide that has formed. A 4 mm-thick glass powder disc bonded with water glass is placed in front of the conical die. The type of glass used is the same as for the extrusion of steel tubes (e.g., type 3 in Table 5.18 for carbon steels).

Extrusion. The tube and solid extrusion presses used have a capacity of 15 to 25 MN. The diameter of the billets varies from 150 to 250 mm, depending on the section cross-sectional area, and the length can extend to 900 mm. Extrusion ratios up to 100 are possible but rarely used.

Hollow sections are extruded over round or profiled mandrels that are not internally cooled and that move with the stem during the extrusion process. The thickness should be at least 20 mm to be able to withstand the large thermal stresses. It is not possible to use bridge dies as with aluminum and copper because of the high extrusion temperature, the relatively high flow stress, and the resultant thermomechanical stresses on the tooling.

The billet loaded into the container is extruded to a discard length of 10 to 20 mm. After the container has been opened, the discard is cut from the section with a hot saw. The section is pulled back through the die and then removed on a powered roller conveyor. After pushing out the discard together with the dummy block, the die is changed for a new or reworked die using a rotating arm or a slide. The die has to be checked for the dimensional tolerances after each extrusion and, if necessary, reworked because of the high thermomechanical stresses.

The length of the section that is extruded as quickly as possible has a maximum length of 20 m so that the die that is deformed by the temperature effect during the extrusion does not exceed the extrusion tolerances toward the end of the extrusion.

The required high ram speeds of up to 300 mm/s can only be achieved by a water hydraulic system.

The sections cool in free air but bend and twist significantly in the longitudinal direction and deform in the transverse direction because of the different flow behaviors of different cross-sectional areas in the die and the faster cooling of thin legs after extrusion. To avoid accidents from moving sections, the runout table is occasionally covered to form a tunnel.

In multihole extrusion, the extruded sections usually have varying lengths because of the different amounts of lubricant in the die openings.

5.26.3.2 Further Processing

The extruded sections have to be straightened and detwisted by stretching 2 to 3% on stretchers with rotating stretcher heads and capacities of up to 3000 kN. Hot stretching is also used for the higher-strength alloys (alloy steels, Ni, and Ti alloys). This stretching process is sufficient with carbon steels to break off the 10 to 20 μm-thick glass film from the lubrication. Alloy steels, however, have to be pickled and sometimes first shot blasted.

After stretching, it may be necessary to carry out further straightening on a roller correction machine or even on a straightening press with profiled tools. This straightening process adds significantly to the costs of producing steel extruded sections [Lin 82].

If a coarse grain structure or, in the case of alloy steels, excessive mechanical properties are detected, a subsequent annealing treatment is required.

Tight tolerances are obtained by bright drawing. If necessary, sections can also be ground.

5.26.4 Tooling

Information on the tooling for steel sections can be found in Chapter 7 in the section on tooling for the glass-lubricated extrusion of titanium, nickel, and iron alloys.

Extrusion of Semifinished Products in Nickel Alloys (Including Superalloys)

Martin Bauser*

5.27 General

Nickel alloys are used for many applications in machinery, chemical engineering, industrial furnaces, electrical engineering, electronics, and in power stations. Extrusion is used to produce tubes and wire as well as bars for feedstock for the manufacture of turned, forged, and impact-forged components.

High-alloy nickel materials (in particular with iron, cobalt, and molybdenum) are referred to as superalloys and are suitable for applications at temperatures of more than 1000 °C. They are used in gas turbines and jet engines. These multiphase alloys can often hardly be referred to as nickel alloys, but they do not belong to any specific alloy group. Extrusion is important for the production of bars and rods in these high-strength alloys because they are almost impossible to forge [Vol 70].

The extrusion process is largely identical to that described for alloy steel tubes.

Pure nickel melts at 1453 °C and has a density comparable to iron and copper of 8.9 g/cm^3. Nickel and many technically important nickel alloys have a fcc lattice up to the melting point and therefore have good hot and cold workability. The flow stress varies considerably depending on the alloy.

The high-alloy superalloys are very difficult to extrude because of both the high extrusion temperature (up to 1300 °C) as well as the high extrusion loads needed.

*Extrusion of Semifinished Products in Nickel Alloys (Including Superalloys), Martin Bauser

Copper forms a continuous solid solution with nickel. Molybdenum increases the strength by the formation of a solid solution. Intermetallic phases (mainly Ni_3Al) increase the strength as do carbides and carbon-nitrides in conjunction with titanium, niobium, molybdenum, and chromium.

5.28 Materials, Properties, and Applications

Table 5.19 refers to the nickel alloy DIN standards. Table 5.20 shows some important and typical nickel alloys that are processed by extrusion.

Pure nickel and low-alloy nickel materials have properties that are particularly suited to chemical processes and electronic applications. Nickel alloys are corrosion resistant to many reducing chemicals and cannot be bettered for resistance to strong alkalis. The food industry is an important application. Nickel also has a high electrical conductivity, a high Curie temperature, and good magnetostrictive properties. Battery components and spark electrodes are application examples.

Low-alloy nickel materials are often used in heat exchangers because of the good thermal conductivity. Good workability and good weldability mean they can be readily worked.

Monel, i.e., nickel-copper alloys, are the most widely used high-nickel-containing alloys and have been used for over a hundred years. Their strength is higher than pure nickel, but in spite of this, they can be easily worked and possess good corrosion resistance against many environmental factors. Their good resistance to acids is utilized in the chemical industry and the good thermal conductivity relative to other nickel alloys in heat exchangers. The seawater resistance of Monel is useful in ship construction.

Certain nickel-iron alloys have a special coefficient of expansion property, which makes them suitable for use with glasses. The soft magnetic behavior of nickel-iron alloys is also utilized.

Nickel-chromium alloys and nickel-iron-chromium alloys are characterized by their good corrosion resistance, good mechanical properties, and excellent oxidation resistance at high temperatures. Combined with their good workability, these alloys have a wide range of applications in heat treatment furnaces, incineration

Table 5.19 German Standardization Institute (DIN) standards for nickel alloys

Standard	Designation	Comments to DIN	Similar ASTM standard	Title
DIN 17740	Nickel in semifinished products	Composition	B39	Standard Specification for Nickel
DIN 17741	Low-alloyed nickel wrought alloys	Composition	. . .	. . .
DIN 17742	Nickel wrought alloys with chromium	Composition	B167	Standard Specification for Nickel Chromium-Iron Alloys (UNS N06600, N06690, N06025) Seamless Pipe and Tube
DIN 17743	Nickel wrought alloys with copper	Composition	B164	Standard Specification for Nickel-Copper Alloy Rod, Bar, and Wire
DIN 17744	Nickel wrought alloys with molybdenum and chromium	Composition	B335	Standard Specification for Nickel Molybdenum-Alloy Rod
DIN 17745	Wrought alloys of nickel and iron	Composition	B407	Standard Specification for Nickel-Iron-Chromium Alloy Seamless Pipe and Tube
			B408	Standard Specification for Nickel-Iron-Chromium Alloy Rod and Bar
DIN 17751	Tubes in nickel and nickel wrought alloys	Dimensions, mechanical properties	B161	Standard Specification for Nickel Seamless Pipe and Tube
DIN 17752	Bar in nickel and nickel wrought alloys	Dimensions, mechanical properties	B160	Standard Specification for Nickel Rod and Bar
DIN 17753	Wire in nickel and nickel wrought alloys	Dimensions, mechanical properties	B473	Standard Specification for UNS N08020, UNS N08024, and UNS N08026 Nickel Alloy Bar and Wire
			B475	Standard Specification for UNS N08020, UNS N08024, and UNS N08026 Nickel Round Weaving Wire

plants, steam generators, and resistance heating elements.

The superalloys contain cobalt, molybdenum, iron, titanium, and aluminum, in addition to chromium and nickel. A wide range of applications are possible at high and very high temperatures. These include gas turbines, jet engines, and nuclear power stations. Hot-working tooling is also produced from these alloys.

There are high-strength dispersion-hardened nickel alloys that have to be produced by powder metallurgy. These alloys are discussed in the section “Extrusion of Powder Metals.”

5.29 Billet Production

Depending on the composition and the material requirements, various routes are used to produce the starting material and these have been described in section 5.41.5 [Ric 93].

High-alloy materials are melted in an electric arc furnace and, if a specific purity is required, subjected to the Vacuum-oxygen-decarburization (VOD) process in an evacuated ladle. This removes the carbon and nitrogen and reduces the sulfur content drastically.

Nickel alloys can be continuously cast. If the charge size is insufficient for continuous casting, chill mold casting with all its disadvantages (coarse, radial columnar, and frequently crack-susceptible structure) is preferred. For this reason, as well as reducing the large chill mold casting to the billet dimensions, they are usually broken down by forging or rolling. This aligns the grains axially and frequently produces a fine-grained recrystallized structure. It is then necessary with the high-alloy materials to follow this with a homogenization heat treatment to minimize the segregation.

The feedstock material supplied to the press as long bars is sawn to length, turned, and chamfered. If tubes are being produced, the billets usually have to be bored. A good billet surface is necessary as is the case with alloy steels because it will form the surface of the extrusion as a result of the glass lubrication (see below) and the resultant laminar material flow.

5.30 Billet Heating

The billets have to be heated in a low-sulfur furnace atmosphere because of the sensitivity of nickel and its alloys to intercrystalline attack by sulfur. It should be weakly reducing in gas-fired furnaces because nickel and nickel-copper alloys in particular tend to intercrystalline corrosion and thus embrittlement in an oxidizing atmosphere even without sulfur [Vol 70].

Because the oxide layer of severely oxidizing nickel-iron and nickel-copper alloys also reduces the effect of the lubricant in extrusion and produces a poor surface quality, these materials should be heated as quickly as possible—at best, in an induction furnace.

With high-alloy, crack-sensitive alloys on the other hand, and with coarse grain cast billets, a slow heating rate is important because if the heating is too rapid the thermal stresses can result in grain-boundary cracking. Some nickel-chromium-cobalt alloys cannot be directly charged into the hot-gas-fired furnace if they exhibit coarse grain or severe segregation but have to be slowly heated from a low temperature to the extrusion temperature so that the temperature gradient remains low in all phases of heating [Pol 75]. Reducing continuous, chamber or rotary furnaces are used for this.

High-alloy materials that are not crack sensitive and those that have been well homogenized and have a fine-grain structure can, however, be heated in an induction furnace that guarantees the exact final temperature. With complex alloys, the exact setting of the final temperature is very important if a low-melting-point eutectic has formed (e.g., with niobium).

To save energy and to ensure the slow heating of crack-sensitive materials mentioned above, a gas furnace can be used for the base heating (up to 1000 °C) and an induction furnace for the final stage [Ric 93]. Salt bath heating cannot be used because of the risk of the diffusion of embrittling elements.

5.31 Extrusion

5.31.1 Billet Preparation, Lubrication

As with alloy steels, prebored or pierced billets are used for the production of tubes to avoid high mandrel wear and to obtain a low eccentricity [Eng 74]. With large internal diameters the billets are again expanded on a separate piercing press and then reheated in an induction furnace.

Whereas nickel, low-alloy nickel materials, NiCu, and NiFe can be lubricated with graphite oil for low extrusion ratios and thus low extrusion temperatures, higher-alloyed material billets are only lubricated with glass using the Séjournet process similar to alloy steels [Pol 75]. Suitable glasses for the corresponding temperature are selected from Table 5.18. The glass with the highest melting point is used for the high-alloy materials with extrusion temperatures of almost 1300 °C. The glass powder is applied even with two-stage heating (gas furnace-induction furnace) only after the billet has left the induction furnace.

5.31.2 Deformation Behavior and Extrusion Data

Figure 5.65 shows the tensile strengths of various nickel alloys as a function of temperature.

The flow stress of pure nickel is low enough for extrusion even below 1000 °C. Similarly, the soft alloys of nickel with copper or with up to 20% Cr have a relatively wide temperature range for hot working. The complex alloys on the other hand have narrow deformation temperature ranges, in particular, the molybdenum-containing and the high-strength nickel-chromium alloys, and these must be accurately maintained to avoid cracking.

The addition of strength-increasing elements to improve the mechanical properties at high

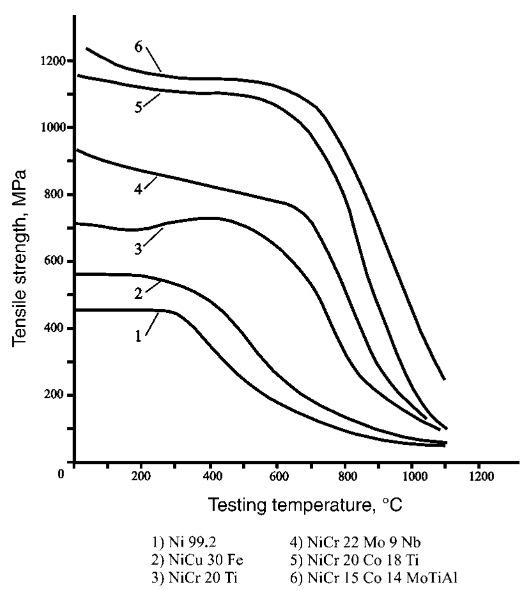


Fig. 5.65 Tensile strength of nickel alloys as a function of the temperature [Inc 88]

Table 5.20 Some important typical nickel alloys that are extruded

(a) Nickel and low-alloyed nickel materials

Material	Standard	British/U.S.	Ni	Fe	Mn	Al	Other	Semifinished product	Strength	Properties	Application
Ni 99.2	DIN 17740 2.4066	NA 11 Alloy 200	>99.2	<0.4	<0.35	. . .	. . .	R, S, D	370–590	High electrical and thermal conductivity, corrosion resistant	Corrosion-resistant components, lightbulbs, electrode tubes
NiMn2	DIN 17741 2.4110	. . .	>97.0	. . .	1.5–2.5	. . .	. . .	S, D	. . .	. . .	Lightbulbs, electrotubes, spark plugs

(b) Nickel-copper alloys (Monel)

	Standard	British/U.S.	Ni	Cu	Fe	Al	Other	Semifinished product	Strength	Properties	Application
NiCu30Fe	DIN 17743 2.4360	NA 13 Alloy 400	>63	28–34	1.5–2.5	. . .	<2.0 Mn	R, S, D	450–700	Good strength, best high-corrosion resistance	Corrosion resistant construction units, ship construction, chemical industry
NiCu30Al	DIN 17743 2.4375	Na 18 Alloy K500	>63	27–34	0.5–2.0	2.2–3.5	0.3–1.0 Ti	R, S, D	600–800	Age hardening	Chemical industry, petrochemical industry

(c) Nickel iron alloys

Material	Standard	British/U.S.	Ni	Fe	Other	Semifinished product	Strength	Properties	Application
Ni 42	DIN 17745 1.3917	Alloy 42	40.0–43.0	Remainder	. . .	R, D	. . .	Low temperature expansion	Glass/metal ceramic bonds, e.g., for integrated circuits
Ni 48	DIN 17745 1.3922/26/27	Alloy 48	46.0–49.0	Remainder	. . .	R, S, D	. . .	Best coefficient of expansion, slightly magnetic	Relay components, transformers

(d) Nickel-chromium (iron) alloys

Material	Standard	British/U.S.	Ni	Cr	Fe	Ti	Other	Semifinished product	Strength	Properties	Application
NiCr20Ti	DIN 17742 2.4951	Alloy 75	>72	18–21	<5	0.2–0.5	. . .	S, P, R, D	650	High oxide and corrosion resistance	Furnace components, heating conductor, gas turbines
NiCr15Fe	DIN 17742 2.4816	NA 14 Alloy 600	>72	14–17	6–10	. . .	. . .	S, R, D	550	Heat resistant, corrosion resistant	Furnaces, chemical industry, spark plugs
NiCr20TiAl	DIN 17742 2.4952	Alloy 80A	>65	18–21	. . .	2.3	1.0–1.5Al 1.9Ti	S, P, R, D	1100	Age hardening, high hot strength	Components subjected to creep loading

(e) Nickel alloys with chromium, molybdenum, and/or cobalt super alloys

Material	Standard	British/U.S.	Ni	Cr	Fe	Co	Mo	Other	Semifinished product	Strength	Properties	Application
NiMo16Cr16Ti	Din 17744 2.4610	Alloy C4	Remainder	14–18	<3	<2	14–17	. . .	S, R, D	690–850	Excellent corrosion properties	Chemical industry, paper industry
NiMo16Cr15W	DIN 17744 2.4819	Alloy C276	Remainder	14.5–16.5	4.0–7.0	<2	15–17	3.0–4.5W	S, R, D	690–850	Excellent corrosion properties	Chemical industry, paper industry
NiCr22Mo9Nb	DIN 17744 2.4856	Alloy 625	Remainder	20–23	. . .	. . .	8–10	3.15–4.15Nb	S, R, D	690–830	High strength without age hardening, corrosion resistant	Chemical industry, aircraft
NiCr23Co12Mo	DIN 17744 2.4663	Alloy 617	Remainder	20–23	. . .	10–15	8–10	Al, Ti	S, R, D	~700	Stable up to high temperature, resistant to oxidation	Gas turbine, petrochemical industry, chemical industry
NiCr20Co18Ti	2.4632	NA19 Alloy 90	58	20	<1.5	18	. . .	2.5 Ti1.5Al	S, P, R	~1100	Creep resistant up to 900 °C	Gas turbine, hot-working tools
NiCr15Co14MoTiAl	2.4636	Alloy 115	51	15	. . .	14	4	4Ti5Al	S, P	~1200	Creep resistant up to 1010 °C	Jet engine

temperatures results, on one hand, in a reduction in the liquidus temperature and, on the other hand, an increase in the flow stress.

These difficult-to-extrude alloys require a high degree of homogeneity in the starting material (see section 5.29), uniform billet heating (see section 5.30), correct lubrication conditions, and exact maintenance of the extrusion conditions. Economic production is, therefore, not possible without an extrusion plant with a correspondingly high extrusion power [Inc 86].

Table 5.21 gives data for the extrusion of some nickel alloys.

In the high-strength nickel alloys, there are some with a low-melting-point eutectic (e.g., with niobium) that can only be extruded with a maximum of 1150 °C and thus with a low extrusion ratio (e.g., Inconel 625).

Some superalloys, for example, the high-molybdenum-containing alloys, have to be extruded above 1400 °C to obtain low flow stresses. Preferably, extrusion is carried out below 1300 °C because of the high tool wear and the low viscosity of the glasses used, and the resultant low extrusion ratio is accepted. This naturally means more expensive further processing.

5.31.3 Defects and Their Prevention

Narrow limits are placed on the extrusion speed, particularly for the complex molybdenum-containing nickel alloys. If the extrusion speed is too slow, the lubricant film breaks up, resulting in a rough surface on the extruded product and/or the extrusion process "freezes." If the extrusion speed is too high, the exit temperature can increase to such an extent that transverse hot cracking occurs or—particularly with thick bars—lap defects occur. Consequently, especially for the slowly extruded complex high-alloy steels with extrusion speeds below 10 mm/s, the extrusion speed has to be controlled to ensure that the exit temperature remains between the two limits. In other words, if the plant is capable, "isothermal extrusion" is required. Extrusion presses built especially for nickel have a suitable speed control system. Oil hydraulic presses are preferred to water hydraulic ones [Lau 76]. A high press power (up to 60 MN) simplifies the extrusion of the high-alloy nickel materials with high flow stresses [Eng 74]. Because the billet rapidly cools at this slow speed with the risk of freezing, only short billets can be used.

Ultrasonic testing of extruded products is recommended for the crack-sensitive materials.

5.32 Tooling, Further Processing

Information on the tooling used and the tooling design is given in Chapter 7.

The dies are, as described for alloy steel tubes, conical to obtain a laminar flow with the glass lubrication.

The further processing is also similar to that described for alloy steel. The glass lubricant film is removed by shot blasting with steel grit followed by pickling. If the glass skin is broken up by quenching at the press (to suppress precipitation), shot blasting and pickling may not be required. Cold pilgering or drawing is then carried out, possibly with intermediate annealing.

Extrusion of Semifinished Products in Exotic Alloys

Martin Bauser*

All the materials described in this section are rarely used in long lengths and are therefore not

Table 5.21 Data for the extrusion of some nickel alloys (see Table 5.20 for examples indicated by (b), (c), (d), and (e) (Lau 7, Vol 70, Ric 93)

Group	Characterization	Approximate K_f value, N/mm^2	Billet preheat temperature	Examples
1	Easily extruded	150	900–1100 °C	All nickel and the low-alloyed nickel materials
2	Good extrudability	200	1050–1150 °C	Monel(b) Nickel iron(c)
3	Difficult to extrude	250	1100–1250 °C	Ni-Cr materials(d)
4	Very difficult to extrude	320	1150–1280 °C	Ni-Cr-Mo materials Super alloys(e)

*Extrusion of Semifinished Products in Exotic Alloys, Martin Bauser extruded in Germany. However, they are included for completeness.

5.33 Beryllium

5.33.1 Properties and Applications

There are special areas of application for beryllium in optical components, precision instruments, and space travel because of its unusual combination of physical and mechanical properties. Selection criteria are the low weight (density 1.85 g/cm^3), a high *E*-modulus, and low radiation absorption.

Beryllium melts at 1283 °C and has a hexagonal lattice. It is characterized by a high thermal capacity and heat resistance combined with good corrosion resistance and high strength and is therefore used in reactor technology. The very poisonous metal can only be melted and processed under the strictest conditions [Sto 90].

5.33.2 Billet Production

Cast beryllium has a coarse grain, is brittle, and tends to porosity. It can consequently be further processed only with difficulty. For this reason, plus the importance of a fine grain for the properties, beryllium is usually prepared by powder metallurgy.

This also applies to extrusion (see the section "Extrusion of Powder Metals"). Usually, beryllium powder with the minimum possible oxygen content is consolidated to billets by hot-isostatic compaction in vacuum [Sto 90].

If extrusion has to be carried out at a high temperature (approximately 1000 °C), a billet clad in a steel jacket has to be used. The compaction of the beryllium powder directly into the jacket with a ram, the subsequent welding of the jacket and the evacuation (to prevent oxidation) has been described [Kur 70].

5.33.3 Deformation Behavior, Extrusion

According to Fig. 5.66, beryllium exhibits two maxima in the elongation to fracture, one at 400 °C and another one at approximately 800 °C. From experience, the elongation to fracture can be taken to be a measure of the workability. Consequently, it is possible to differentiate between "warm" extrusion with billet temperatures from 400 to 500 °C and "hot" extrusion with billet temperatures from 900 to 1065 °C. In the first case, no recrystallization takes place during

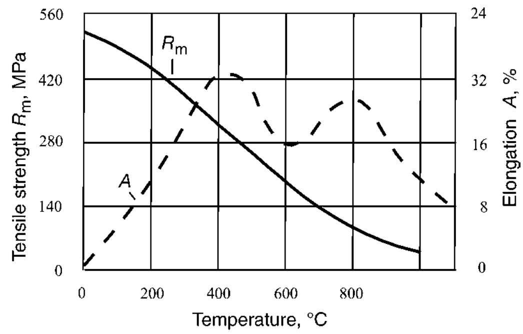


Fig. 5.66 Elongation to failure and tensile strength of compacted beryllium as a function of the temperature [Sto 90, Kau 56, Lau 76]

extrusion and a texture favorable for the mechanical properties is formed. In "warm" extrusion, the compacted and possibly sintered billet can be lubricated with graphite or molybdenum sulfide. Warm extruded bars and tubes can be drawn to the finished sizes.

The "hot" extrusion process is selected for large extrusion ratios because of the lower extrusion loads. The billets sheathed in steel are extruded like alloy steel with glass lubrication. The sections leave the press fully recrystallized and largely texture free.

5.34 Uranium

5.34.1 Properties, Applications

The best-known application is the extensive use of uranium in the form of oxide powder as nuclear fuel in nuclear power stations. Uranium is also sometimes used in other areas as a pure metal and dilute alloys because of the very high density (19.1 g/cm^3, which is 68% higher than lead) and the good radiation absorption. Typical nonnuclear applications are radiation protective shields and counterweights [Eck 90].

Natural uranium contains up to 99.3% of the weakly radioactive isotope U238 and only up to 0.7% of the nuclear fuel U235. Whereas this low radioactivity has little effect on the workability, the poisonous nature and the ease of oxidation of uranium necessitates special measures.

Uranium melts at 1689 °C. It has a rhombic lattice up to 665 °C (α-phase) and a tetragonal lattice (β-phase) above this temperature. At 771 °C this lattice transforms into the body-centered cubic (bcc) γ-phase. Because the tetragonal β-phase is difficult to deform, extrusion cannot be carried out between 650 and 790 °C because of the risk of cracking.

5.34.2 Deformation Behavior, Extrusion

The billets are melted in induction furnaces under a vacuum and cast in molds.

The deformation behavior of uranium is shown in Fig. 5.67. The extrusion in the lower α-region (between 550 and 650 °C) avoids the difficulties of high-temperature extrusion described subsequently but does require a high press power because of the higher flow stress. The extruded sections are fine-grain recrystallized. It is possible to work in this temperature range without cladding with the usual graphite-grease lubrication. Preheating the billets in a salt bath prevents oxidation. They should, however, be subjected to the atmosphere for only a short time at the extrusion temperature.

In the γ-region (between 800 and 1000 °C), where significantly higher extrusion ratios can be used, uranium reacts very rapidly with iron, nickel, and other metals and is very susceptible to oxidation. The billets for this hot extrusion are usually clad in copper, evacuated, and then extruded using graphite grease as a lubricant.

Only a few low-alloy-content uranium alloys with higher mechanical properties and better corrosion resistance are known (with titanium, zirconium, molybdenum, and niobium) that can be melted in vacuum induction melting furnaces or in vacuum arc furnaces. Because the structure is similar, the extrusion is the same as for pure uranium [Eck 90]. Because the β/γ phase boundary is displaced to lower temperatures by these alloying additions and because in the γ-region secondary phases are held in solution, the extrusion of alloys is easier.

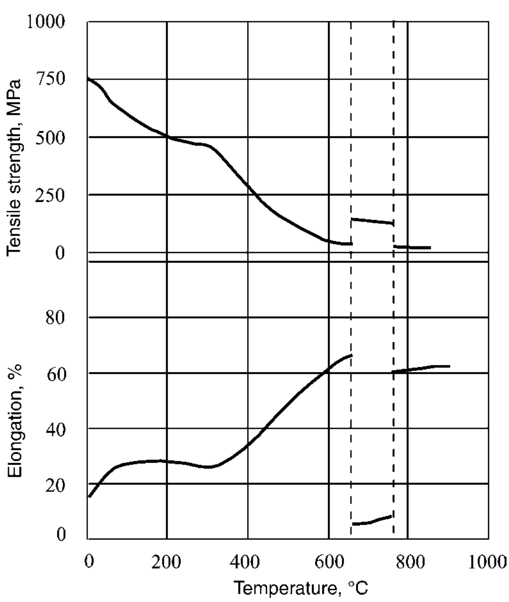


Fig. 5.67 Hot tensile strength and elongation of uranium as a function of the temperature [Eck 90]

5.35 Molybdenum, Tungsten

5.35.1 Molybdenum

Molybdenum is usually used as an alloying element in steels and high-alloyed materials. However, it is also important as a pure metal and a low-alloy material. Tools in TZM (Mo-0.5 Ti-0.17Zr), for example, can withstand temperatures well over 1000 °C. Further application areas are cathodes, electric resistance elements (up to 2200 °C), and high-temperature components in space travel and for rockets. The highest application temperature is 1650 °C. Molybdenum's good resistance to hydrochloric acid is of interest to the chemical industry. The density of molybdenum is 10.2 g/cm^3 [Joh 90].

The high melting point of 2622 °C permits only powder metallurgical processing. The powder is obtained by hydrogen reduction of molybdenum oxide and then cold compacted and sintered. These sintered billets can then be either directly extruded or melted in a vacuum arc furnace.

The bcc lattice of molybdenum is the reason behind the excellent deformation characteristics. This can be deduced from the hot tensile strength curves in Fig. 5.68.

Pure molybdenum is extruded in the range 1065 to 1090 °C and the most common alloy TZM (Mo-0.5Ti-0.1Zr) at 1120 to 1150 °C. The billets are heated in conventional gas or oil-fired furnaces or by induction. Above 650 °C, molybdenum oxidizes as a gas with a weight loss of 1 to 5% without an oxide layer forming. Rapid heating obviously reduces the loss from oxidation. Similar to steel, glass has to be used for extrusion. Bar, tube, and simple shapes can be produced by extrusion [Joh 90]. The glass applied as powder after the billet has left the furnace melts and protects it from oxidation.

5.35.2 Tungsten

Tungsten melts at the extremely high temperature of 3380 °C. The structure and properties

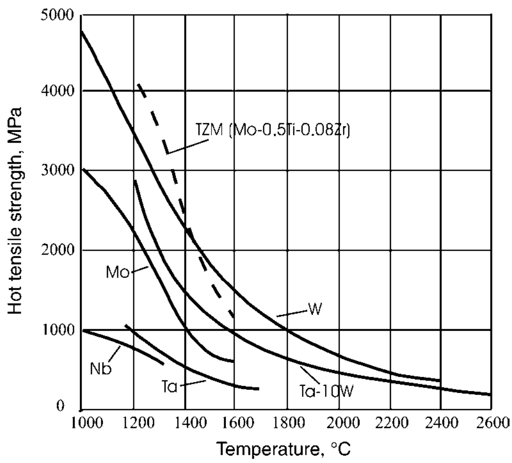


Fig. 5.68 Hot tensile strength of some high-melting-point metals and alloys as a function of temperature [Kie 71]

are similar to molybdenum. With its high density of 19.3 g/cm^3, it dominates where high weight is a main requirement. The high melting point combined with its high electrical resistance makes it the most common material for heating conductors and filaments in lamps [Joh 90a].

In contrast to molybdenum, a significantly higher hot-working temperature of 1500 to 1800 °C is required, as shown in Fig. 5.68, which makes tungsten unsuitable for extrusion. Hot forging of sintered powder billets is preferred [Par 91].

5.36 Niobium and Tantalum

Niobium melts at 2468 °C and at room temperature has a bcc structure with a density of 8.4 g/cm^3. It can be readily worked at room temperature. Niobium alloys have a wide range of applications in space travel because of their relatively low weight and high hot strength. Niobium and its alloys are also in demand in the chemical industry because of the resistance to specific corrosive media [Ger 90].

Similar to other high-melting-point metals, the extrusion billets are made by a powder metallurgical route.

Figure 5.68 shows for niobium a relatively low hot-working temperature. Extrusion temperatures between 1050 and 1200 °C with extrusion ratios of $V = 4$ to $V = 10$ have been described for niobium alloys with zirconium, hafnium, and tungsten [Ger 90]. However, niobium oxidizes severely above 425 °C so that the billets have to be protected from oxidation by cladding and evacuating.

Niobium forms a continuous solid solution with titanium. Niobium with 46.5% titanium is the alloy most commonly used as a super conductor [Kre 90]. Fine wires of this niobium alloy are embedded in a copper matrix (see the section "Extrusion of Semifinished Products from Metallic Composite Materials"). The niobium-titanium starting material is extruded to bars using glass as a lubricant in the same way as steel and titanium. These are then clad with copper and further processed in several stages.

5.36.1 Tantalum

Tantalum has similar structure and properties to niobium. It also has a bcc structure but first melts at 3030 °C and is twice as heavy with 16.6 g/cm^3.

The widest application of tantalum—apart from an alloying element in steel like niobium—is as an anode material in electrolytic cells. In the chemical industry it is known for its resistance to nitric acid, hydrochloric acid, and sulfuric acid. The high melting point ensures applications in the high temperature region [Pok 90].

Processing usually follows a powder metallurgical route. Electron beam cast tantalum is usually too coarse grained for further processing and has to be forged before it can be extruded.

The extrusion of compacted and sintered powders has been mentioned but does not have any great importance because the recrystallization temperature, and thus the extrusion temperature, is very high [Pok 90].

Extrusion of Powder Metals

Martin Bauser*

5.37 General

Oxide-containing aluminum powder was extruded in the 1940s under the name sintered alu-

*Extrusion of Powder Metals, Martin Bauser minum powder (SAP). In the 1950s the advantages of the extrusion of powder was known for reactor materials and beryllium. This process has only recently found a wide application, particularly with aluminum alloys but also high-alloyed and dispersion-hardened materials.

A good overview of powder metallurgy (P/M) can be obtained from the textbook on powder metallurgy by W. Schatt [Sch 86]. The work of Roberts and Ferguson gives detailed information on the extrusion of powder metals [Rob 91].

5.37.1 Main Application Areas of Powder Metallurgy

Processing by extrusion plays an important role compared with other processes in P/M. The most important is the processing of metal powders to near final shape and thus the economic production of molded components with a piece weight below 2 kg, and mainly in iron alloys. The powder is compacted on vertical compaction presses in dies by a stem and then sintered at a high temperature, during which the particles form a solid bond. For large pieces with simple geometries (e.g., forging billets), the compaction is carried out by fluid pressure applied on all sides (cold isostatic pressing, or CIP) before they are sintered. Compaction and sintering carried out in a single operation by hot isostatic pressing (HIP) is also used occasionally.

5.37.2 Advantages of Metal Powder Extrusion

Where long semifinished products can be conventionally produced by casting and extrusion, powder extrusion is usually less favorable because the production of suitably mixed and sieved powders is usually too expensive.

The production of extruded semifinished products by the powder route is worthwhile when:

- The material cannot be processed conventionally by melting and casting.
- An extremely fine grain size and finely distributed precipitates have to be achieved. Rapidly quenched powder can have a significantly extended solid-solution range [Tus 82].
- A uniform distribution of very small inclusions to achieve specific properties is required (dispersion hardening).

This last-mentioned processing of metal powders with mixed or reaction produced nonmetallic particles as dispersions by extrusion is also discussed in this chapter (metal matrix composites, or MMCs). Chapter 4 discusses the physical properties, in particular those at high temperatures, and the processes in the deformation of dispersion-hardened materials. Frequently, metallic or nonmetallic fibers are mixed with the metal powder to achieve certain properties and then extruded [Boe 89]. The resultant so-called fiber composite materials are described in the section "Extrusion of Semifinished Products from Metallic Composite Materials."

5.37.3 Powder Production

Atomization of the melt using water or gas streams is the most common of all the different casting, mechanical, and chemical processes used to produce metal powders. Water gives the fastest cooling rate, but the powder particles are coarser (approximately 500 μm) and in a spattered format. If, however, atomization is carried out in an air or protective gas jet, more rounded shapes and smaller particles are produced (down to a few μm, depending on the process parameters) (Fig. 5.69). The output per hour of atomization plants is relatively low. Because a restricted particle size is usually required and the powder usually falls in a wide particle spectrum, the particles of different sizes have to be separated by sieves. The powder costs are correspondingly high. A desired material composition can be obtained by mixing powders if it does not exist in the atomized melt.

"Reaction milling" in ball mills is a new process that enables the mechanical alloying of metal components. Nonmetallic particles can also be finely dispersed by this method. The powder particles are repeatedly broken down and welded between steel balls. A fine structure is obtained after a certain milling time [Inc 86].

5.37.4 Spray Compaction

In the new process of spray compaction developed by the company Osprey [Cra 88], the gas-atomized material from the melt is sprayed onto a rotating block with a vertical axis ([Man 88] (Fig. 5.70). The slowly sinking block grows layer by layer. This process saves precompaction, encapsulation, and evacuation.

Hard particles can be blown into the spray by an injector and form a dispersion in the finished billet.

The disadvantage of spray compaction is that a considerable part of the spray droplets miss the

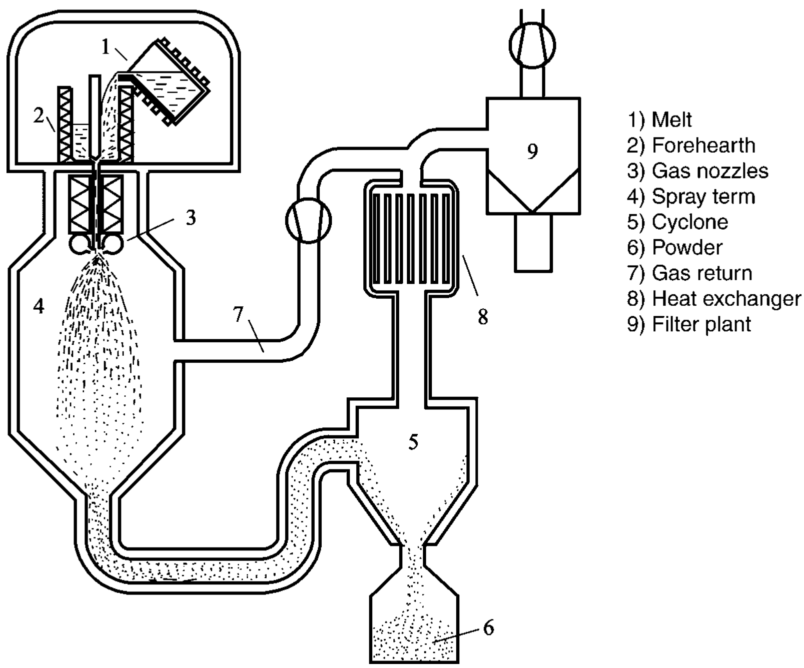


Fig. 5.69 Example of a gas atomization plant for metal powder [Wei 86]

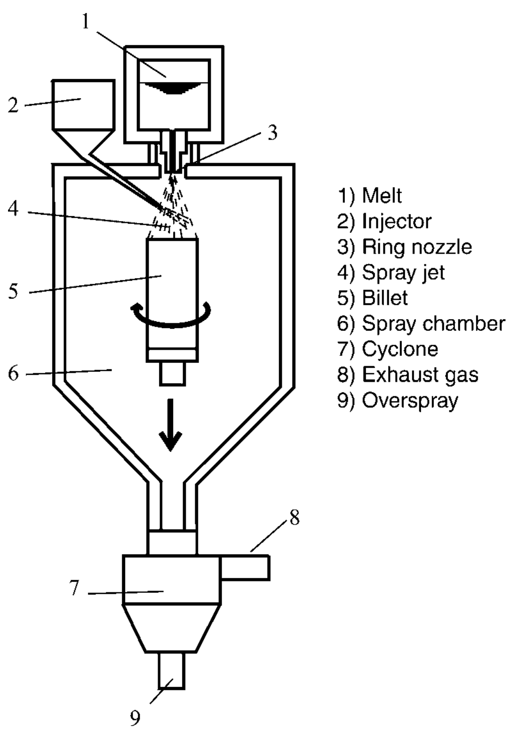


Fig. 5.70 Schematic of spray compaction [Arn 92]

block and fall to the bottom as powder "over spray," which can be remelted or used as a powder.

The powder particles cool on the solidified block so slowly in spray compaction that a structure similar to casting forms, but with significantly better homogeneity and with finely distributed particles and dispersed particles.

Because the billet diameter varies slightly, it has to be turned to the extrusion dimension. The spray-compacted billets can be extruded like cast billets—also to tubes with piercing mandrels. Plants are in operation producing aluminum, copper, and steel.

5.38 Powder Extrusion Processes

5.38.1 General

The individual powder particles are plastically deformed in the extrusion direction during the extrusion of metal powders, usually at the same temperature as cast billets, and the surface area increases. Oxides and other films on the particle surface break up and release new reactive metallic surfaces. The powder is compacted during extrusion and the newly formed surfaces bonded by pressure welding. Even with low-density powders, a complete compaction and porous-free material is obtained by extrusion if the particles can be sheared sufficiently. This assumes that no gas porosity can form, e.g., from moisture.

Several types of powder extrusion are known, including (a) the rarely used shaking of the loosed powder into the vertical container of an extrusion press, (b) the precompaction outside the press, and (c) the encapsulating of the powder before extrusion (Fig. 5.71). The new process of spray compaction is described above.

5.38.2 Shaking of Loose Powder into a Vertical, Heated Container and Direct Extrusion (Version a)

The loosely filled powder has a low bulk density (maximum 50% of the theoretical density), because the large number of interstitial space. Therefore, a relatively long container is necessary. The stem first compacts the powder before the actual extrusion process commences. This apparently economic process has a low throughput if the powder first has to be heated in the container. It can be used only rarely. An example is the extrusion of magnesium-alloy pellets with grain sizes from 70 to 450 μm to rods [Rob 91].

5.38.3 Precompaction of the Powder outside the Press

"Green" compacts can be produced by cold isostatic pressing (CIP in autoclaves), particularly from angular particles or flakes. These are so stable that they do not break up during handling before extrusion. The powder filled into a plastic container is subjected by a pressurizing liquid to a uniformly applied high pressure (2000 to 5000 bar max), which increases the original powder density of 35 to 50% of the density of a cast billet to 70 to 85%. The risk of the fracture of the precompacted billet during handling can be reduced further if necessary (e.g., with round particles) by sintering before extrusion by heating. An alternative to this two-stage process is to carry out the compaction itself at an elevated temperature (HIP). In this case, the powder has to be filled into a thin-walled metal can that does not melt at the pressing temperature (special case of version c).

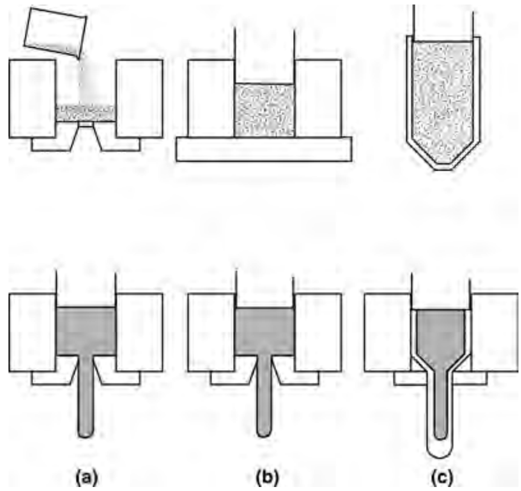


Fig. 5.71 The classic processes for powder extrusion. (a) Addition of loose powder. (b) Precompaction outside the press. (c) Encapsulation before extrusion [Rob 91]

5.38.4 Encapsulation of the Powder before Extrusion (Version c)

Usually the metal powder is compacted in the metal sleeve before sealing. After this it is often evacuated (possibly at an elevated temperature) and then vacuum sealed (Fig. 5.72).

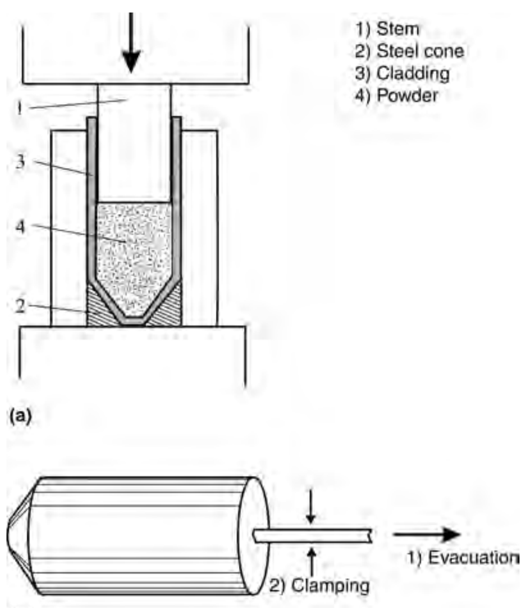


Fig. 5.72 (a) Encapsulation of powder. Cladding sealed at the back and with evacuation tube. (b) Evacuation [Rob 91]

The reasons for encapsulation include:

- Excluding a reactive powder material from air and extrusion lubricants
- Protection from poisonous materials during handling (e.g., Be and U)
- Risk of breaking up of green compacts of round powders or other particles that are difficult to compact in a billet shape
- Improved lubrication and friction behavior and better flow through the die by the correct selection of the container material
- Keeping the base material away from the die and the zone of severe shear deformation. This is important only for materials with low ductility [Rob 91].

With high-purity materials, processing has to be carried out in a clean room with careful cleaning of the can and evacuation at an elevated temperature.

A large disadvantage of this process is that the can material remains on the surface of the extruded product and can be difficult to remove by machining or by pickling. There has been reference to a degassed and hot-compacted aluminum powder in an aluminum capsule, which is removed from the billet before extrusion by machining [Sha 87].

5.39 Mechanism and Flow Behavior in the Extrusion of Metal Powders

If loose powder is extruded (version a), the container first has to be sealed on the die side to ensure good compaction by the stem. The die is then opened.

With precompacted green blanks (version b), a "nose" or a disc of the cast material corresponding to the powder is often placed in front of the die. This compensates for the risk of the surface of the extrusion tearing due to insufficient initial pressure. Indirect extrusion is preferred because of the more uniform material flow. Extrusion with a lubricated container is avoided because of the risk of lubricant penetration of the green blank.

The thermal conductivity in the green blank is relatively low. Too-rapid billet heating therefore results in localized melting with the risk of cracking. Slow heating in a chamber furnace is the most suitable. If heating has to be carried out in an induction furnace, allowance has to be made for an equalization time before loading the billet into the furnace (possibly in an equalization furnace).

Encapsulated powders (version c) are usually extruded with lubricated containers and conical dies (90–120°) or indirectly. This gives a laminar material flow and a uniform cladding material thickness on the extrusion. The selection of the lubricant depends on the cladding material (e.g., aluminum: unlubricated; copper: graphite-oil; iron: glass). Nevertheless, a uniform laminar material flow can be achieved only with round bar or tubes and simple section shapes. Section extrusion is successful only when a suitable die inlet has been developed.

A billet produced from powder usually has a lower density than a cast billet. A longer billet is therefore needed for the same section weight. In extrusion the stem initially pushes together the still not highly compacted powder in the container before the particles are subjected to a shear deformation and friction between each other in the entry (shear) zone to the die and in the die itself. The bonding of the grains on the newly formed surface occurs by friction (or pressure) welding under high pressure and takes place more quickly than the more conventional sintering process used in powder metallurgy.

The extrusion process can produce a better bond between individual particles than sintering. This applies in particular to aluminum alloys, the powder particles of which always exhibit surface films of aluminum oxide because of the high reactivity of the element aluminum. These films are broken up to such an extent in extrusion that the higher the extrusion ratio the greater the number of newly formed surfaces available for particle bonding. An extrusion ratio of at least 20 is often stated to be certain of achieving a perfect bond between the powder particles [Sha 87a]. The resultant structure of the extruded powder corresponds to the structure formed during the extrusion of solid billets.

Encapsulated powder has to be well compacted and degassed. If the strength of the powder material and the encapsulating material differ too severely, or if the can is too thin and the powder inadequately compacted, there is the risk of folds forming during extrusion (Fig. 5.73). Diffusion between the can material and the powder material should be prevented as far as possible, and it should not be possible for a eutectic to form between them. When selecting the can material, consideration should always be given to the fact that it later has to be removed.

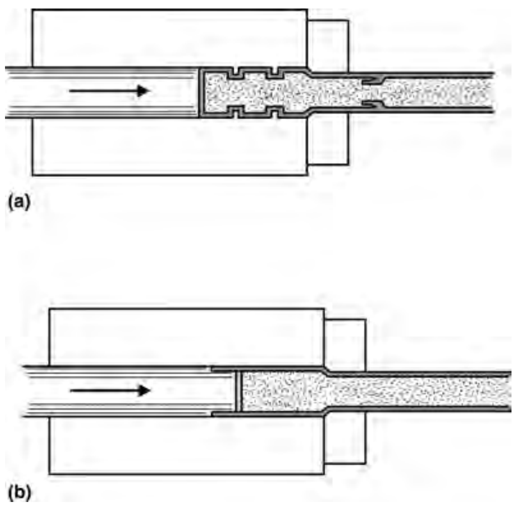


Fig. 5.73 (a) Fold formation during extrusion of insufficiently precompacted metal powder. (b) Avoiding fold formation by advance of the capsule back wall [Rob 91]

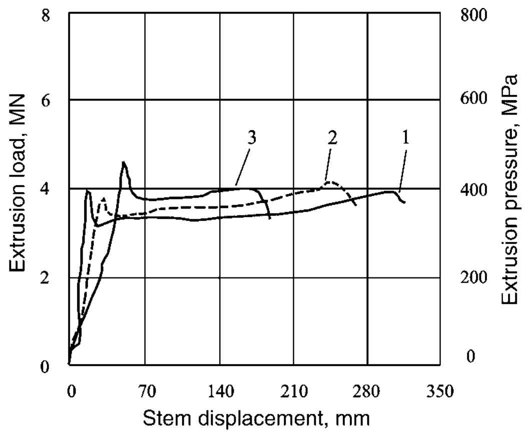


Fig. 5.74 Load variation in the extrusion of powder and spray compacted material compared with cast (Al18SiCuMgNi), indirectly extruded. 1, cast; 2, spray compacted; 3, compacted powder [Mue 93]

An interesting variation of the extrusion of metal powders is the hydrostatic extrusion of silver alloy powders. Presintered billets can be extruded without a can because the pores close during the pressure buildup, preventing the penetration of the pressure medium and the production of defects.

As mentioned previously, spray-compacted billets behave similarly to cast billets—the powder compaction measures then no longer apply.

5.40 Load Variation

The variation in the load in the extrusion of powders differs considerably from that with cast billets because there is a less severe increase in the load during compaction in the first part of the stem movement. The gradient of the load-displacement curve varies with the degree of compaction.

The high load peak often seen with aluminum powders during upsetting can cause problems, and there is still no definite explanation for it (Fig. 5.74).

Additional work also has to be carried out during extrusion to overcome the friction between the grains and for their bonding. It is therefore often assumed that the extrusion load in extruding powders is somewhat higher than in the extrusion of cast billets. In a few cases a lower load has been mentioned [Nae 69]. However, it is rare for exactly the same material to be extruded as a cast billet or as a powder, which prevents exact comparisons.

The use of indirect extrusion has proved beneficial in the extrusion of powders in order to reduce the extrusion load.

5.41 Examples of Powder Extrusion

In almost every powder metallurgically produced material group there are materials with solid insoluble inclusions (dispersoids). These dispersion-hardened materials can be produced only by powder metallurgical processes.

5.41.1 Aluminum Alloys

It is practically impossible to produce aluminum powder without an oxide skin because of the high affinity of aluminum for oxygen. Normal sintering is therefore hindered or prevented with aluminum alloys. Extrusion, therefore, remains as the only practical possibility of producing defect-free dense materials by P/M of aluminum alloys because the oxide skins on the powder particles are torn away to leave oxide-free, easily weldable surfaces. Pure aluminum powder can be bonded to a metallic dense material with at least 80% cold deformation [Gro 73].

The starting material is usually quenched powder from a gas stream atomization plant that is first compacted in a cold isostatic press or, for small dimensions, in a cylindrical compression die to a green blank with 75 to 80% of the theoretical density. In the extrusion press the green blank is almost 100% compressed with an initially closed die and then extruded using the direct or the indirect process at 450 to 500 °C [Sha 87]. Placing a "nose" or a disc of aluminum in front of the powder billet can promote sufficient compaction during upsetting and also prevent the start of the extrusion from breaking up. The abrasive effect of hard particles in a powder mixture on the shape-forming tools is also reduced. Encapsulation with degassing at 500 °C and hot compaction is required only if absolute freedom from hydrogen is specified. The cladding can be removed by machining prior to extrusion.

In practice, the extrusion of aluminum powder materials is worthwhile only if it produces a material that cannot be produced by casting technology. Most attention is paid to the high-alloy materials with high room temperature strength as well as dispersion-hardened materials that have a much higher strength and better mechanical properties at higher temperatures than naturally hard and precipitation-hardened aluminium alloys (Fig. 5.75).

In the 1940s, a process was developed for producing and working an oxide-containing powder from aluminum powder by a milling process. This product was referred to as sintered aluminum powder (SAP) [Irm 52, Jan 75]. Originally, the extruded aluminum material contained 12 to 15% Al_2O_3; today less than 5% Al_2O_3 is used because the dispersed particles are finer and better distributed.

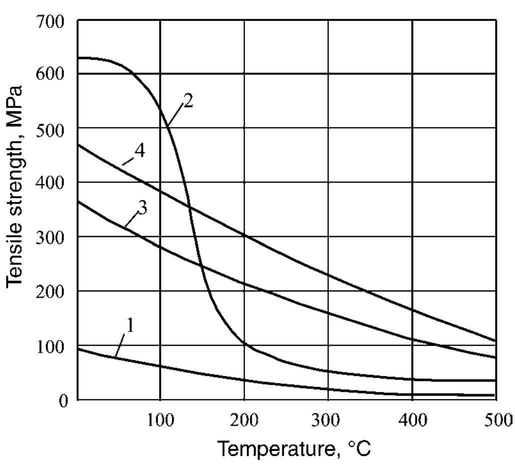


Fig. 5.75 Temperature dependence of the tensile strength of different aluminum alloys. 1, aluminum 99% soft; 2, AlZnMgCu1.5; 3, sintered aluminum powder (SAP) with 10% Al_2O_3; 4, Al with 4% C (as Al_4C_3) [Sch 86]

Milling aluminum powder with electrographite followed by heat treatment for complete transformation of the carbon into Al_4C_3 produces a dispersion-hardened aluminum material with embedded Al_4C_3 and Al_2O_3 particles marketed under the trade name Dispal [Arn 85]. In variations of the material solid-solution hardening AlMg5 or AlSi12 is used as the base material instead of pure aluminum to achieve better mechanical properties even at lower temperatures. Whereas the solid-solution hardening and precipitation hardening are lost at higher temperatures, the dispersion hardening is retained.

Dispal materials with high silicon content are preferably processed by spray compaction to extrusion billets. As well as saving the cost of cold isostatic pressing of powders, the main advantage is the fine distribution of the embedded particles. After extrusion, rapidly solidified aluminum powder with iron and nickel additions contain finely distributed particles of intermetallic phases of the types Al_3Fe and Al_3Ni (metallic dispersoids) [Sha 87]. Alloys based on AlFeCe, AlFeMo, AlCrMnZr, and AlNiFeMn with additions of copper, magnesium, and titanium, which also form intermetallic dispersoids, are used to achieve high hot strengths. This results in alloys that have an approximately 100% higher hot strength in the temperature range 250 to 350 °C, compared with conventional materials. The fatigue strength of such materials can also be significantly improved. The *E*-modulus is also increased by 20 to 30%. These improvements in the mechanical properties are, however, obtained with an increase in density to 2.8 to 3.0 g/cm^3 because of the increased content of heavy elements [Sha 87a]. In powder metallurgically produced aluminum alloys with silicon contents of 10 to 30%, the eutectic and the primary phases are very finely formed in the structure ($<$25 μm). This structure has an advantageous effect on the hot and fatigue strengths [Sha 87a]. The alloys can be readily mechanically worked and are characterized by a low coefficient of thermal expansion. For bearing elements, the extrusion of powder- and spray-compacted materials produces an uneven finer distribution of hard particles than that achieved by casting. The wear properties are significantly improved. Materials that contain other elements in addition to silicon are being tested in engine construction [Arn 92a], where, however, the high manufacturing cost is a major barrier in spite of the significantly better properties compared with conventionally produced components. A breakthrough is high-silicon-containing aluminum tubes for cylinder sleeves that have recently been extruded from spray-compacted billets [Hum 97].

Other aluminum alloys produced by mechanical alloying with oxides and carbides as dispersoids and that contain 1 to 4% copper and magnesium are commercially available. They are hot compacted and then extruded. However, only simple cross sections are available. After extrusion they can be further processed by forging, hammering, rolling, or drawing [Rob 91].

5.41.2 Copper and Noble Metal-Base Alloys

If powders of electrolytic copper and aluminum oxide are cold isostatically compacted, sintered, and extruded to rods, the very fine Al_2O_3 particles (approximately 0.3 μm), which should be finely distributed, prevent recrystallization so that a high strength is retained up to 1000 °C [Zwi 57].

Copper alloys with 1.1% aluminum oxide are supplied as wire and rods and processed to spot welding tips. These tips have a very good electrical conductivity and a high flow stress at the welding temperature. At room temperature the material can be cold worked like copper without intermediate annealing.

The strength-increasing effect up to very high temperatures of the aluminum oxide particles as dispersoids requires extremely fine particles (3–12 nm) and a uniform distance between them of less than 0.1 μm. This is achieved by a so-called internal oxidation of copper-aluminum powders, i.e., an oxidizing annealing in which the oxygen transforms the aluminum to oxide, whereas the more noble copper is retained as a metal.

Dispersion-hardened copper with 0.1 to 0.5 μm large TiB_2 particles (3 vol %) is produced by the following original process.

Two different copper melts are reacted together in a reaction vessel whereby the dispersed phase is produced by a precipitation reaction in situ in the melt. This melt is then atomized to powder, which is filled into a copper can and evacuated [Sut 90]. This material can also be extruded and processed to spot welding electrodes.

CuSn and CuSnNi alloys with high tin contents are known as bearing materials but cannot be extruded because of the coarse δ-phase precipitates. However, with spray compaction, the particles are so finely distributed that the billets can be readily extruded without difficulty to rod and tube. Graphite particles, which improve the slip properties, can be included by an injector during the spray compaction (see Fig. 5.70). A further application of spray-compacted-produced tubes of high-alloy bronze is as super conductors [Mur 96].

Dispersion-hardened silver materials (e.g., with AgNi2 or with cadmium oxide) have better erosion properties, a lower contact resistance, and less tendency to welding than homogeneous materials. Silver and nickel are almost completely insoluble in each other at room temperature. AgNi alloys, therefore, cannot be produced by melting metallurgy but only by powder metallurgy. A uniform distribution of the embedded nickel is obtained by currentless nickel plating of silver powder followed by extrusion [Mue 87].

As described previously for copper, finely distributed particles of cadmium oxide can be formed as a dispersoid in silver by internal oxidation of alloy powders of the noble metal silver, which practically cannot be oxidized, and the base metal additive cadmium. The fraction of cadmium oxide is very high, up to 25%.

Platinum and its alloys, which are used for special heating wires and other high-temperature components, are dispersion hardened whereby they are extruded as powder mixtures with thorium oxide, yttrium oxide, or zircon oxide as dispersoids [Rob 91].

5.41.3 Titanium Alloys

A dispersion-hardened titanium alloy is, for example, a modification of Ti-6242 with 6% Al, 2% Sn, 4% Zr, 2% Mo, 0.1% Si, and 2% Er, which is produced by internal oxidation during the annealing of the powder Er_2O_3, with extremely small particles. Of interest is that the structure obtained by very rapid solidification is not changed by extrusion [Rob 91].

5.41.4 Iron Alloys

The production of chromium-nickel-steels and chromium-aluminum-steels by extrusion of steel powder produced by water atomization was reported in 1969. The process did not go into production [Nae 69] because, normally, even with iron alloys the production, or steels using powder, and compaction is more expensive than by melting and casting.

However, because fewer operating steps are needed than between casting and the production of the bar and a better homogeneity is obtained, powder extrusion is again being promoted for some iron alloys. A Swedish manufacturer offers powder metallurgically produced tubes in stainless chromium-nickel-steels as well as nickel and cobalt alloys [Asl 81, Rob 91]. The melt is atomized under a protective gas and the powder then cold isostatically compacted in an iron can before being extruded over a mandrel. The hollow billet also has to be internally encapsulated to produce tubes. The lubricant is glass, the same as with conventional extrusion, and extrusion is carried out at approximately 1200 °C. The process is supposed to have economic advantages over the conventional one [Tus 82].

Some high-speed and tool steels that are severely segregated when produced by the normal process are extruded as bar from powder to eliminate segregations and to retain elements in solution above the equilibrium value. This is not possible with molten metallurgical production. Because atomization is usually carried out under a protective atmosphere, the round particles that do not readily bond have to be encapsulated for compaction. Water-atomized material can be cold compacted without a can and then sintered before extrusion [Rob 91].

The dispersion hardened iron based alloys MA956 and PM2000 with chromium and aluminium as the main alloying elements and yttrium oxide as the dispersoid are described in the next section.

5.41.5 Nickel and Cobalt-Base High-Temperature Alloys

Alloys with high contents of nickel, chromium, and cobalt are necessary for high-temperature applications, particularly in gas turbines and in the aerospace industries. The high strength is usually obtained by precipitation hardening.

The molten metallurgical production route is the most economic solution when possible. It is, however, accompanied with coarse precipitates and reduced hot workability and is not possible at all with wide melting intervals.

Oxide dispersion strengthened (ODS) alloys are materials in which fine particles, in contrast to precipitates, are also resistant to high temperatures, act as strength increasing dispersions. There is no melting metallurgical alternative to powder metallurgical production. Oxides of yttrium are mainly used [Rob 91].

Table 5.22 summarizes the superalloys produced by P/M.

In the ODS process, the rapidly quenched (more than 10^3 K/s) powder produced by atomization in an inert gas stream after sieving and mixing is encapsulated in a steel can, which has to be evacuated at a high temperature to eliminate micropores. If a particularly uniform precipitation-free structure is required, cooling has to be carried out extremely quickly. Special rapid solidification rate (RSR) processes have been developed (up to 10^6 K/s). Extrusion has proved to be the most suitable compaction method with these materials because the large deformation breaks up oxide films as described for aluminum, disperses impurities present, and provides very good compaction. The encapsulated powder is precompacted by HIP or forging to approximately 85% before it is extruded. The bars extruded at an extrusion ratio of 5–7 with glass lubrication at approximately 1200 °C are further processed by forging and rolling after removal of the can. It is possible with extrusion to significantly reduce the residual porosity and thus the notch impact sensitivity. The extrusion temperature with these alloys has to be very carefully controlled to prevent the risk of coarse precipitates forming at high temperature (e.g., carbide in René 95) [Rob 91].

Table 5.22 Composition of some iron and nickel superalloys produced by powder metallurgy (addition in wt%)

Designation	Fe	Ni	Cr	Co	Mo	W	Ti	Al	Nb	Ta	Zr	B	C	Y_2O_3
MA 956(a)	74.0	. . .	20.0	. . .	. . .	. . .	0.5	4.5	. . .	. . .	. . .	. . .	. . .	0.5
PM 2000(b)	73.0	. . .	20.0	. . .	. . .	. . .	0.5	5.5	. . .	. . .	. . .	. . .	. . .	0.5
MA 754(a)	1.0	77.5	20.0	. . .	. . .	. . .	0.5	0.3	. . .	. . .	. . .	. . .	0.05	0.6
MA 6000(a)	. . .	68.5	15.0	. . .	2.0	4.0	2.5	4.5	. . .	2.0	0.15	0.01	0.05	1.1
PM 3000(b)	. . .	67.0	20.0	. . .	2.0	3.5	. . .	6.0	. . .	. . .	0.15	0.01	0.05	1.1
Renè 95(c)	. . .	62.0	13.0	8.0	3.5	3.5	2.5	3.5	3.5	. . .	0.15	0.01	0.07	. . .
Nimonic AP1(a)	. . .	55.5	15.0	17.0	5.0	. . .	3.5	4.0	. . .	. . .	. . .	0.025	0.02	. . .

(a) Inco Alloys International. (b) High temperature metal GmbH. (c) Nuclear Metals Inc. Source: Sch 86, Rue 92

The alloy René 95 and Nimonic AP1 are precipitation-hardening alloys where solid-solution hardening is also effective at moderate temperatures because of the addition of molybdenum. They are used for gas turbine discs.

In the ODS alloys Ma 965 and PM2000 (Fe-Cr-basis), as well as Ma754, Ma 6000, and PM 3000 (Ni-Cr-basis), the Y_2O_3 is worked into the metal powder by mechanical alloying in high-energy ball mills and finely dispersed. The fiber texture obtained by extrusion is utilized by suitable heat treatment (coarse-fiber crystals from zone recrystallization) to achieve a very good fatigue and creep strength.

MA956 and PM2000 with high oxidation and hot corrosion strength up to 1100 °C are used in combustion chambers, in gas turbines, and other cases demanding maximum resistance at high temperatures.

MA6000 and PM3000 are used in the first and second stages of jet engines and can be hot and cold rolled after extrusion.

5.41.6 Exotic Materials

Beryllium tubes are the ideal construction material in communication satellites because of their low density (1.85 g/cm^3), the high *E*-modulus, and their considerable elongation. In order to achieve a fine structure, P/M processing is preferred to melting and casting. The material being processed is encased in carbon steel because of the poisonous nature of beryllium and the susceptibility to oxidation. This can be removed by pickling with hydrochloric acid after extrusion with glass lubrication. The workability in the extrusion direction is increased by the texture formed in extrusion of this hexagonal crystallizing material [Rob 91].

Ceramic uranium oxide powder has to be heated to 1750 to 2000 °C for plastic flow. Because no deformation tooling can withstand this high temperature, experiments have been reported in which the hot powder is filled into relatively cold steel cans at approximately 700 °C and then extruded.

This two-temperature process has also been investigated for the production of chromium tube and bar whereby hot chromium powder is filled into a colder steel can and immediately extruded. The aim is to ensure that the very different deformation behaviors of the two materials at the same temperature are matched to each other.

Intermetallic phases such as Ni_3Al_4 or Ti_3Al_4 can only be deformed at approximately 1100 °C. Because the production of alloy powder would be very expensive, element powders are mixed and cold compacted. The green blanks are encased in aluminum and extruded at approximately 500 °C. This prevents the extreme exothermic reaction from the formation of the intermetallic phases occurring during the extrusion. It takes place—possibly after further deformation steps—in high-vacuum furnaces or in an HIP unit. Another method is "reaction extrusion" at such a high temperature that the phase formation actually occurs during extrusion.

Extrusion of Semifinished Products from Metallic Composite Materials

Klaus Müller*

Metallic composite materials are microscopically heterogeneous, macroscopically homogeneous-appearing materials that consist of two or more components intimately connected with each other and in which at least the component with the highest volume is a metal or an alloy [Rau 78]. Its structure can be matched to the stresses of the component.

Pure metals and alloys have a defined property spectrum so that the determination of a property for a given material also determines all other properties. In composite materials, in contrast, the properties of different components are combined, resulting in a new extended property spectrum. The spatial arrangement of the components in the composite gives rise to typical composite properties, the so-called structural properties. Composite materials can also exhibit properties resulting from interactions between the components, the so-called product properties. Always present are the cumulative properties, i.e., the resultant properties from the addition of the component properties. This is shown in Fig. 5.76 [Sto 86].

The application of metallic composite materials in place of conventional alloys produces in most cases economic as well as technical advan-

*Extrusion of Semifinished Products from Metallic Composite Materials, Klaus Müller

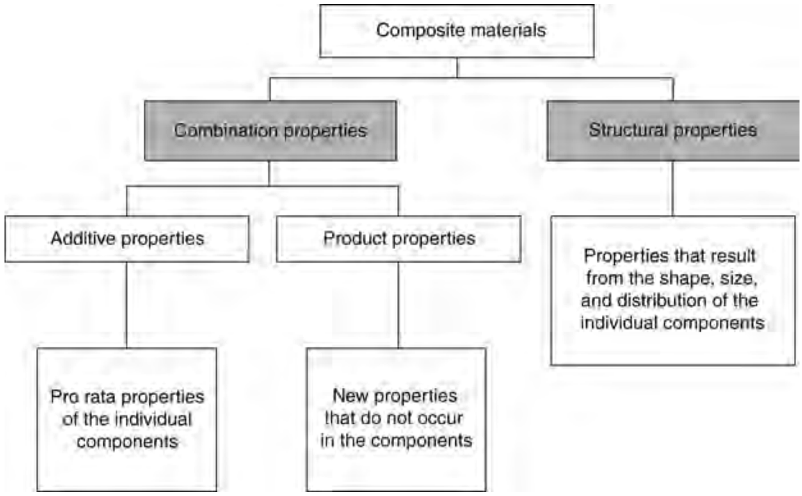


Fig. 5.76 Properties of metallic materials

tages. Composite materials are produced today, the metallic components of which form solid solutions or intermetallic phases corresponding to the phase diagram or are insoluble in each other. The application of the composite materials is determined by the adhesion at the boundary faces of the individual components. The general conditions for a satisfactory boundary surface adhesion with common deformation of heterogeneous materials include:

- Adequate face pressure (compressive stress in the deformation zone)
- Adequate increase in the surface area during the deformation
- A limited inhomogeneity of the flow in the deformation zone that is still sufficient for the structures to conform to each other but, on the other hand, is not so high that the composite material is subjected to unacceptable internal stresses. The composite components have to be capable of flowing together under the process-specific stress conditions.

For longitudinally orientated semifinished products (section, bar, wire, and tubes), the criteria described previously for stresses, surface increase, and flow field formation are fulfilled by the deformation processes rolling, drawing, extrusion, and (to a limited extent) by forging.

However, extrusion provides the most favorable conditions with reference to the three basic requirements:

- Compressive deformation
- Large strains in one operation
- The capability of influencing the deformation zone by die design

Depending on the materials combination, the materials structure, the application, and the extrusion temperature, metallic composite materials can be produced by direct, indirect, or hydrostatic extrusion.

5.42 Terminology and Examples

The metalic composites can be classified according to the spatial arrangement of the components:

- Fiber composite materials
- Particle composite materials
- Penetration composite materials
- Laminated composite materials

Figure 5.77 [Lan 93] shows schematically the geometric structure.

Composite materials in which fibers of the other components aligned or randomly oriented are embedded, aligned, or randomly orientated in the matrix of the predominating component by volume are referred to as *fiber composite materials*. Examples are:

- Directionally solidified eutectics
- Copper-sheathed aluminum conductors for electrotechnology
- Superconducting materials, including NbTi multifilaments in a copper matrix

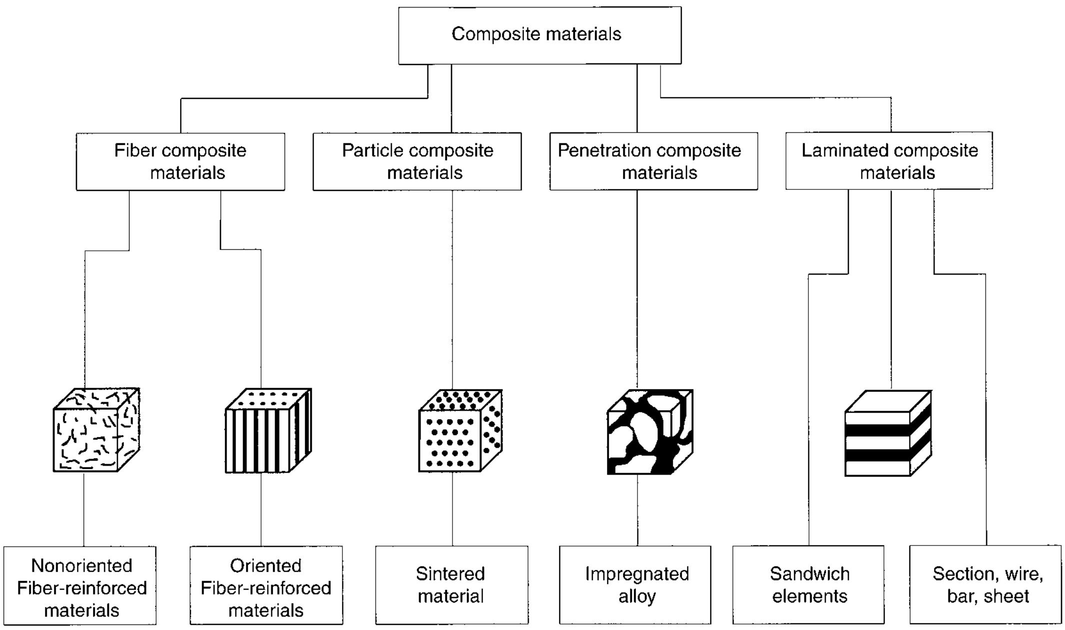


Fig. 5.77 Spatial arrangement of the components in composite materials [Lan 93]

- Electrical contact material, including Ag/C, Ag/Cu/C, and Cu/Pd
- SiC or B fiber-reinforced light metal materials

Composite materials in which the other components are embedded without a marked preferred orientation in the matrix of the predominating component by volume are referred to as *particle composite materials*. They are discussed in the section "Extrusion of Powder Metals."

Composite materials in which the various components form an intermingled structure are referred to as *penetration composite materials*.

Composite materials that have a laminated structure of the composite materials are referred to as *laminated composite materials*.

5.43 Flow Behavior in the Extrusion of Fiber Composite Materials

The following cases can be differentiated from the point of view of the deformation:

- Only one or not all of the components are deformed (aluminum-steel bus bars, metal powder combinations with ceramic additives).
- All the components involved are deformed together whereby different strains can occur within the components.

Because the composite materials produced by extrusion are predominantly metallic fiber composite materials and the production of dispersion composite materials are described in the section "Extrusion of Powder Metals," the basic principles are described using this type of material. The range of possible material combinations, which are not fully utilized today, are illustrated by way of an example in Fig. 5.78 [Mue 91].

Single or multicore wires can be produced as well as wires with solid or powder cores. In some cases, viscous wire fillers (glasses during hot working) can be used. If thermal material influences and diffusion are taken into account as well as the structure along with the associated metallurgical possibilities, the wide range of material technical possibilities is clear [Mue 82].

Metallic fiber composite materials, corresponding to the structure described (outer tube and one or more wire cores), can only be produced, depending on the application, by indirect or hydrostatic extrusion because the outer tube cannot have any distortion relative to the core material resulting from adhesion or friction with the container liner.

Both in indirect extrusion and hydrostatic extrusion there is no friction between the billet and

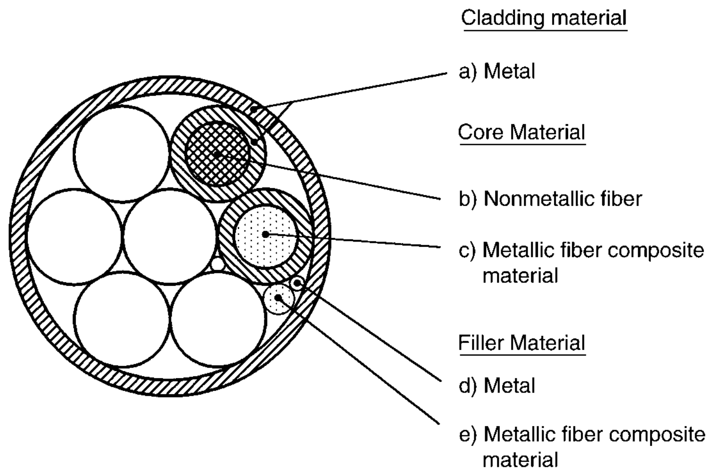


Fig. 5.78 Schematic structure of metallic fiber composite materials

the container. Under comparable stress conditions in the actual deformation zone both processes can be differentiated by the billet upsetting. This is important because the billet used to produce a core filled sheathed tube contains an empty volume of between 15 and 23%. In hydrostatic extrusion, this empty volume is removed by the hydrostatic pressure conditions; in indirect extrusion this occurs by the reduction of the billet length and the increase in the billet diameter. This can result in twisting and buckling processes that can produce defects in the composite material.

The risk of twisting and buckling increases with an increasing length/diameter ratio of the core wire in the tube sheath. The structure can be so severely distorted that further extrusion results in elongated folds and doublings that can initiate cracks and thus render the composite materials unusable [Mue 80].

5.43.1 Criterion for Homogeneous Deformation

In the combined extrusion of metallic materials with different flow stresses k_f, the material flow can take place in different ways. The aim of composite material production by extrusion must be, in addition to pure cladding, to transform the individual components into a compact undamaged material. This requires that the individual components have the same flow stress k_f in the deformation zone. This condition can be achieved by the selection of the following parameters:

- Extrusion ratio
- Volume distribution or volume fraction
- Die opening angle
- Flow stress ratio $k_{f1}/k_{f2}/........../k_{fm}$
- Extrusion speed
- Lubricant (influences the friction conditions in the die in particular)
- Temperature control of the extrusion process
- Bonding quality in the initial billet

These relationships are shown in Fig. 5.79 for the two-component-composite aluminum-copper.

Figure 5.80 represents a homogeneous deformation in which the individual components are subjected to the same reduction for the three-part composite CU/Ni/Cu with the relevant HV 0.1 values in the billet and the extruded section.

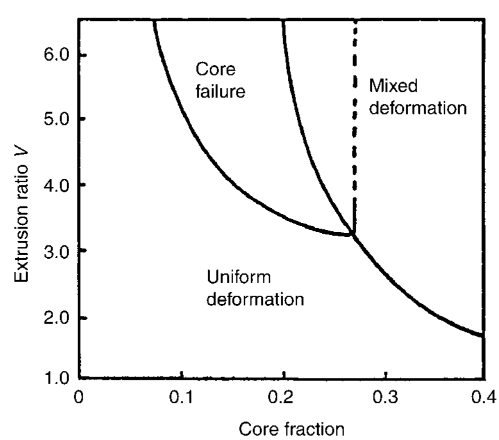


Fig. 5.79 Influence of the extrusion ratio and core fraction on the type of deformation. Material: sheath Al, core Cu, flow stress ratio 2.7, die opening angle 2 alpha (ν = 45°). Area for achieving homogeneous deformation [Osa 73]

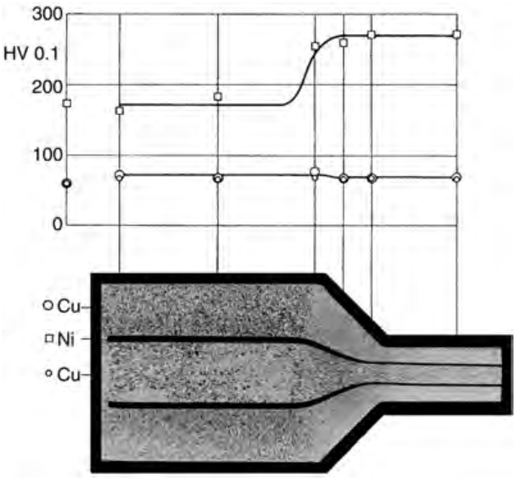


Fig. 5.80 Homogeneous deformation of the composite Cu/Ni/Cu

A nonhomogeneous deformation in which the individual components are extruded with different reductions can result in the failure of the composite with the pure cladding material not being deformed with the core material.

5.43.2 Deformation with Failure of the Composite Material

The most common failures are core and sheath fracture, if defects from undesired reactions during the deformation are excluded. Examples of core failure are shown in Fig. 5.81 for both a two- and three-component composite. However, there is no external visible defect on the extrusion. This type of failure occurs with the combination of hard core material and soft sheath material. Sheath failure can be seen externally at least for the case of the two-part composite with the material composition hard sheath material and soft core material. In a three-component composite, the damage need not be visible at the surface. The innermost core can have core oscillations, i.e., periodic irregular deformation. Figure 5.82 shows examples. The works of [Ahm 78, Rup 80, Hol 78] give various solutions to avoid these failures for the composite Cu/Al.

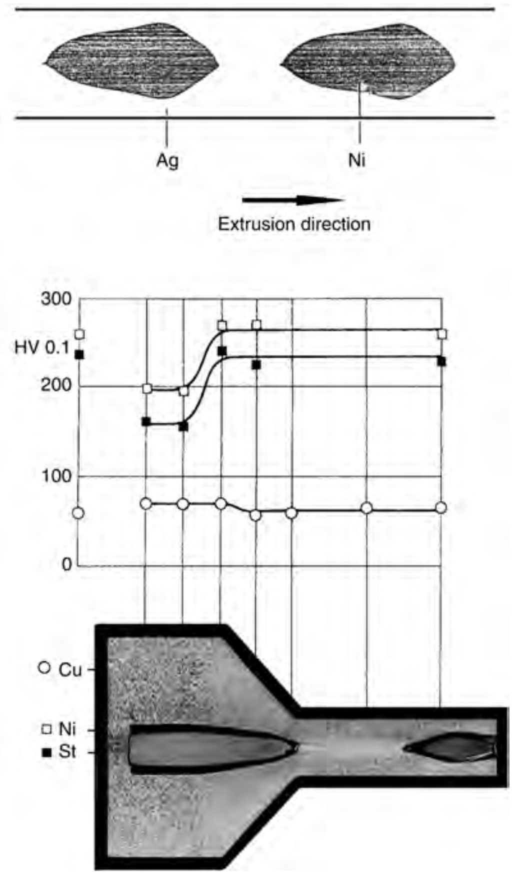


Fig. 5.81 Example of core fracture. The core material used is periodically broken.

5.44 Production of Metallic Composite Materials

Indirect and hydrostatic extrusion offer the following favorable conditions for production:

- It is possible to extrude composite billets with thin casing tubes without the risk of the casing cracking because of the absence of friction between the billet and the container.
- The bonding of the composite components to one another is strongly promoted by the surrounding compressive stress state during the deformation.
- Because the process can be carried out over a wide temperature range, boundary surface reactions can be suppressed by suitable temperature control where they reduce the properties and promoted where they improve the composite material.

Depending on the geometry of the billet used, composite materials with a fibrous, particle and laminated structure can be produced. Figure 5.83 illustrates this for the composite copper-palladium [Sto 87].

The production of a metallic fiber composite material corresponding to the schematic structure shown in Fig. 5.78 and consisting of a cas-

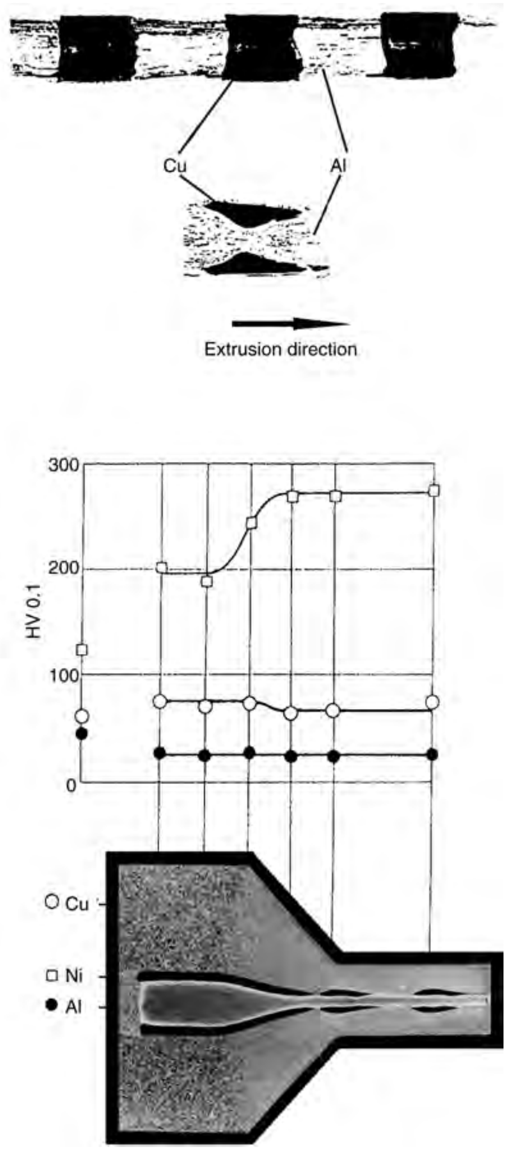


Fig. 5.82 Examples of sheath failure

ing tube and one or more core wires is possible by extruding a number of thin core wires (the number of wires corresponding to the desired number of fibers in the finished product, simple extrusion) or by extruding a less number of thick core wires in a casing to a relatively thick section, a small number of sections of which are then bundled into a common casing and reextruded (repetitive extrusion).

Handling of thin wires can be difficult. It can therefore be assumed that a core wire thickness of approximately 1 mm is the lower limit for acceptable handling. Thus, in simple extrusion, the number of fibers in the end product is determined by the maximum possible internal diameter of the casing tube.

The total production is largely determined by the cost of the production of the casing tube. These include casings in the form of closed cups (produced by drawing and redrawing); casings machined with a solid or hollow tip, the angle of which is matched to the angle of the die; and casings that consist of flanged tube sections. The simplest case from the production point of view is shown in Fig. 5.84.

A tube is used for the casing material, the short inlet of which is conically upset outside the press. The upper and lower closure of the core wire packet is made from embedded stamped blanks (indirect extrusion) or from a stamped blank and an embedded radial plug that simultaneously can act as the guide for the billet in the container (hydrostatic extrusion). With suitable materials selection, this component can be reused.

In the application of composite billets that consist of only two components and thus have almost no volume gaps (e.g., copper-clad aluminum bus bar conductor), there are no additional influences resulting from the geometry of the initial material apart from those described.

This is not the case when multicore composite billets are used (simplest billet preparation, no precompaction of the billets). In the case of hydrostatic extrusion, the billet is radially compacted at the start of extrusion because upsetting cannot occur. Twisting and bending of the wire bundle does not occur from experience; however, with thick wires their contour can be seen in the form of corrugations in the encasing tube. With thin wires, the compaction results in the geometry of the billet deviating from a circular shape.

In both cases there is nonuniform flow in the die and explosive lubricant breakdowns in the die aperture, resulting in the extrusion shattering. In the case of hydrostatic extrusion of noncompacted multicore billets, with simple billet preparation, these problems have to be expected if very small core wires (1 mm diam.) are not used [Mue 81].

Under the stress conditions of indirect extrusion, the composite billet is not radially compacted as in hydrostatic extrusion but upsets with a reduction in length and increase in cross section to the diameter of the container. The re-

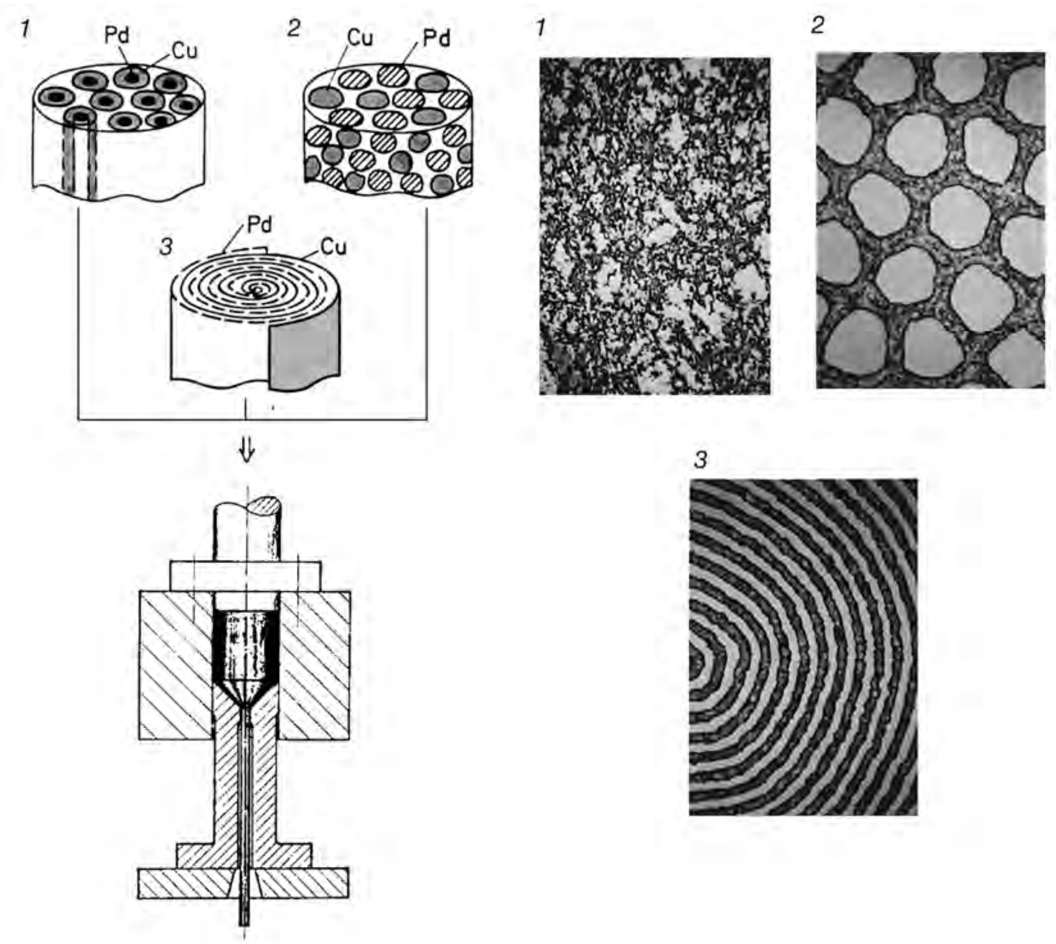


Fig. 5.83 Structure of extruded copper/palladium-composite material. Micrograph image width is approximately 3.6 mm

duction in length of the core wire bundle can take place in three ways:

- Twisting of the core wire bundle
- Buckling of the individual wires or the entire bundle
- Compression of the core wires

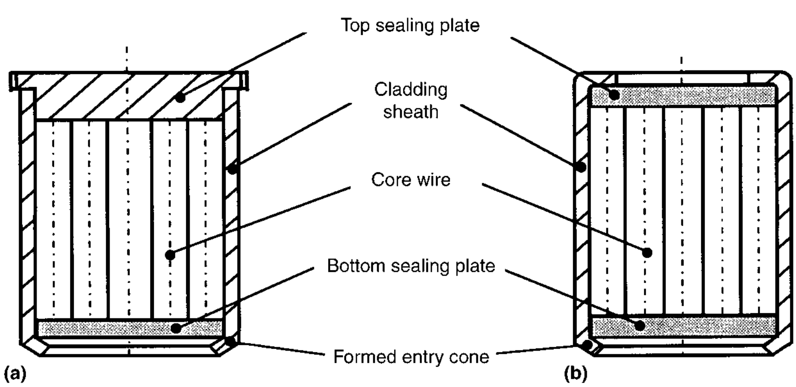


Fig. 5.84 Multicore billet preparation for (a) hydrostatic extrusion and (b) indirect extrusion

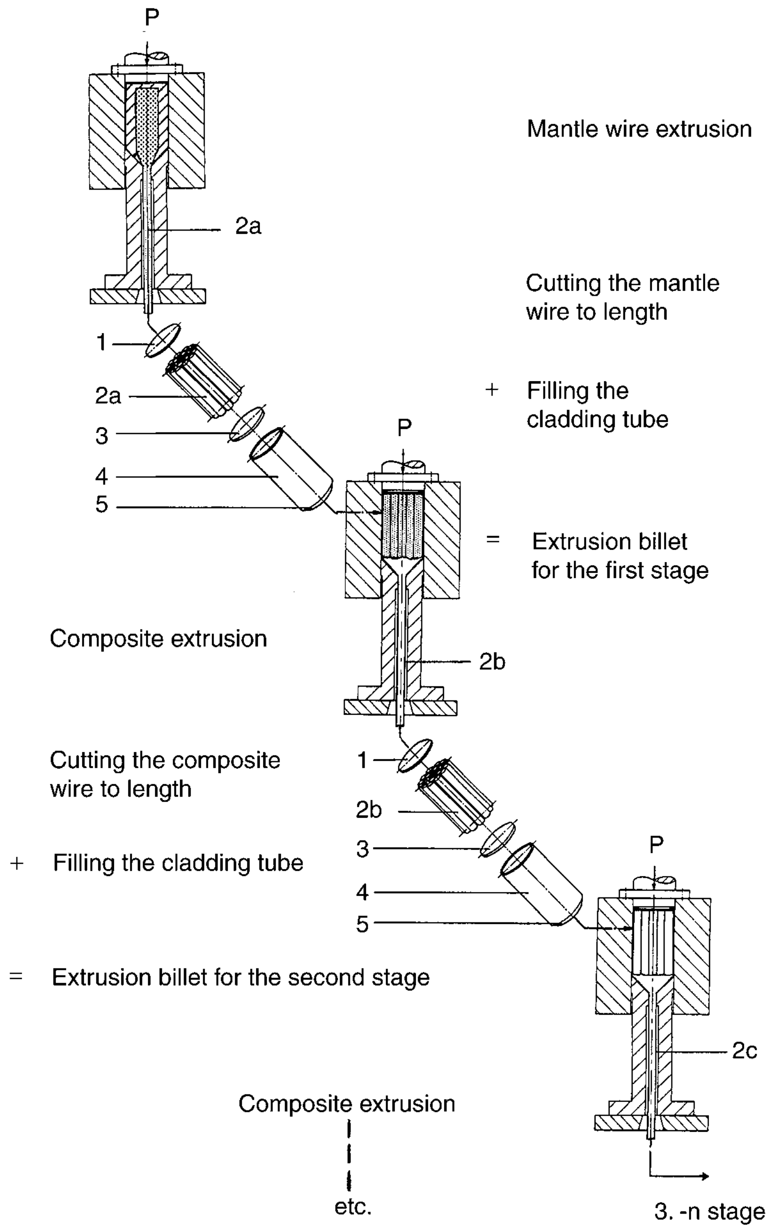


Fig. 5.85 Schematic of indirect repetitive extrusion

The first two mechanisms do not initially contain any cross-section increase of the individual wires. There is the risk of the casing buckling or bending giving rise to extrusion defects. The twisting represents energetically the lowest state and can therefore always be expected. Whether compression or buckling occurs after twisting depends on the length-diameter (*L*/*d*) ratio of the individual rods as well as their mutual support in the rod bundle, the support of the casing, and the mechanical properties of the material.

[Mue 81] shows that twisting and buckling processes can be identified at an *L*/*d* ratio of 20 for a fiber composite material of AlMgSi0.5 wires; however, no material defect occurs. At an *L*/*d* ratio of 100, the casing material exhibits folding and a defect-free product cannot be obtained.

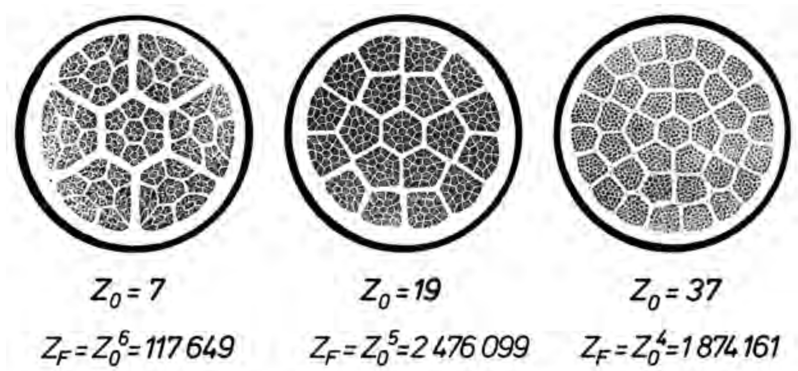


Fig. 5.86 Different structures in Ag/C (billet diam, 30 mm; bar diam, 12 mm). Z_F, number of fibers in sheath tube

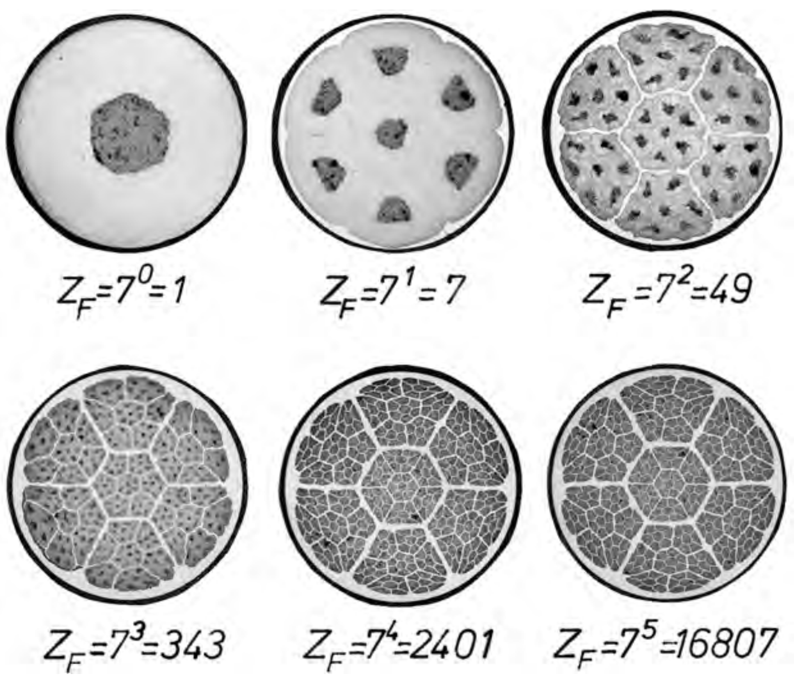
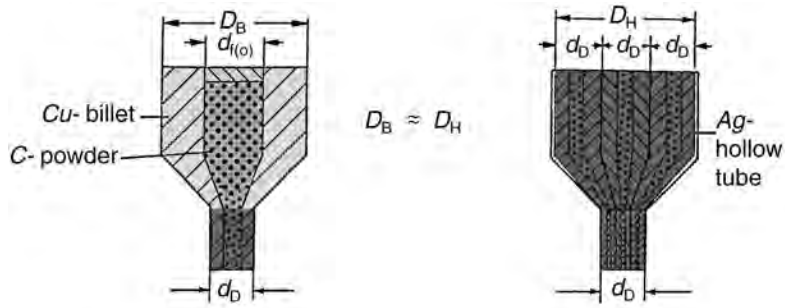


Fig. 5.87 Cross section after progressive extrusion stages (bar diam, 12 mm). Z_F, number of fibers in the sheath tube

Therefore, the so-called indirect repetitive extrusion is a particularly suitable variation of the indirect extrusion for the production of composite materials with complex structures. A billet made from a specific number of core wires (mantle wires) is extruded to a rod, which is then sectioned and the cross sections reextruded. This process can be repeated as often as required to produce the desired structure. The process sequence is shown schematically in Fig. 5.85.

The process for the production of Ag/C and Ag/Cu/C contact materials is described in more detail in this chapter [Mue 85]. Silver or copper billets were drilled and filled with graphite powder for the production of silver/graphite and copper/graphite composite materials. The diameter of the bores was determined by the graphite content that had to be achieved. The billets were sealed, preheated to extrusion temperature, and indirect extruded to bars. After cutting the sections to length, a specific number of the cross sections was arranged in a thin-walled silver or



Diameter ratio	$D_H/d_D = 2n-1$	(n = Total number)
Wires in hollow tube	$Z_0 = 1 + 6 \sum_{1}^{n-1} n$	
Total no. of fibers in the composite	$Z_F = Z_0^a$	
Effective total extrusion ratio of the composite	$\text{Veff(total)} = (2n-1)^2 \times Z_0^a$	(a = No. of extrusion steps)
Fiber diameter after the a. extrusion stage	$d_{F(a)} = d_{F(o)}\sqrt{\dfrac{1}{\text{Veff(total)}}}$	
	$l_g\, d_{F(a)} = l_g\left(\dfrac{d_{F(o)}}{2n-1}\right) - \dfrac{a}{2} \times l_g\, Z_0$	

Fig. 5.88 Geometric arrangements in indirect repetitive extrusion

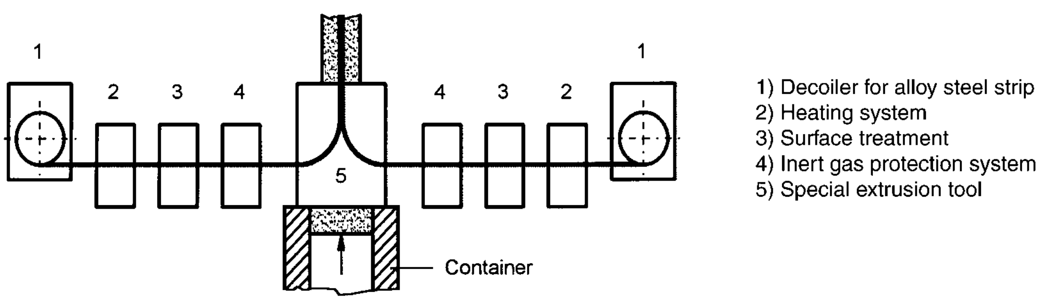


Fig. 5.89 Process principle for the production of Al-alloy steel composite bus bar

copper casing. The number of bar sections depends on the extrusion ratio.

Depending on the extrusion ratio and the number of extrusion stages, different structures can be obtained Fig. 5.86.

The casings were also sealed at both ends and extruded like the powder filled billets. The extruded multicore bars were again cut to length and reprocessed as described previously. The sequential structures can be seen in Fig. 5.87.

The relationship between the casing used, the wire diameter, the extrusion ratio, and the number of fibers in the composite is shown in Fig. 5.88.

5.45 Application Examples

The applications described below subsequently for metallic composite materials produced by extrusion can illustrate only a few areas of the comprehensive range. There has been no attempt to provide a full coverage of all possible and, to some extent, still-experimental materials.

5.45.1 Simple Structures and Coatings

Lead sheathing of electrical cables can be considered as the oldest and also the most well-known example of the production of a metallic composite material. In the mid-1960s, the composite extrusion of bar, tube, and section became technically important [Ric 69], particularly for the processing of reactive metals including beryllium, titanium, zirconium, hafnium, vanadium, niobium, and tantalum. The problem of attack of the extrusion tooling is a major problem in the processing of these metals and their alloys. Technically, this means that the standard lubricants used in extrusion are not able to guarantee reliable separation between the metals being extruded and the extrusion tooling so that localized welding occurs. Billets of reactive metals have to be clad with a metal that provides the lubrication as a “lost shell.” Ti/Cu ignition electrodes are produced this way.

The development of suitable lubricants, and of low-melting-point glasses in particular, enables conventional extrusion without a cladding material to be carried out today in many cases. Cladding with, for example, 18/8 chromium-nickel steel, is used today for the extrusion of cast intermetallic materials including NiAl, Ni_3Al, and TiAl to counteract embrittlement by oxygen absorption at the high extrusion temperature of approximately 1250 °C.

Since 1963, laminated composite materials of copper-clad aluminum for conductors have been developed as a substitute for copper [Hor 70, Nyl 78, Fri 67]. The aluminum core consists of EC aluminum, the copper cladding of electrolytic copper. For technical and economic reasons, the copper cladding is 15% of the cross-sectional area. This material is produced only to a limited extent today because of the changes in metal prices.

In contrast, the process developed by the company Alusingen for the production of composite electrical bus bars conductors in aluminum-steel for high-speed and underground trains is commercially important [Mie 87]. The basic process is that two alloy steel strips are fed into an extrusion die. The steel strips are fed from decoilers. They pass through stations for chemical and mechanical pretreatment to apply corrosion protection. They are then fed into the extrusion die and turned through 90°. Both metals bond together in the welding chamber under the influence of the high extrusion pressure and the increased temperature as well as the relative movement between the steel and the aluminum. In this way, two-mirror image, composite bus bars conductor rails are extruded with a metallic bond between the steel and the aluminum. The reason for simultaneously extruding two composite sections is to avoid friction between the steel strip and the die. In this process the steel band does not contact the die surface but emerges with no wear. This is achieved as the steel strips are completely surrounded by the aluminum and never come into contact with the die bearings. Because the steel strips do not stick to each other, the two sections can be easily separated from each other. Figure 5.89 shows the process principles.

Simple composite structures are also found in the area of steel- and iron-alloy composite tubes and sections [Deg 89, Gut 91, Hug 82, Lat 89, Vil 92], as well as aluminum-clad steel wire [Hir 84] that has excellent corrosion resistance even in marine atmospheres and is used as wire cloth and wire netting.

5.45.2 Metallic Fiber Composite Materials with Complex Structures

Outstanding examples in this area are the industrial metallic superconductors NbTi and Nb_3Sn [Web 82, Bre 79, Hil 84]. Very different complex structures of usually three or more individual components are produced depending on the desired current-carrying capacity. The examples in Fig. 5.90 shows examples of niobium wires embedded in a copper-tin matrix.

Copper forms the core of the composite material and is separated from the CuSn of the superconductor by a tantalum barrier. Structures with up to 10,000 individual filaments and a filament diameter between 3 and 5 μm in wire diameter of 0.4 to 2.0 mm are obtained by multiple combination and followed by multiple extrusion, comparable to the repeated indirect extrusion already described but with a packing density of 95 to 98%, followed by drawing.

After the final operation to produce the required dimensions, the material is heat treated to produce the superconducting compound Nb_3Sn by diffusion of the tin from the copper-tin matrix and reaction with the niobium wires. The copper core remains unaltered (protected by the tantalum barrier). Because the superconducting intermetallic phase Nb_3Sn cannot be deformed, this production route has to be used.

The possibility of influencing the material and properties by changing the structure and by

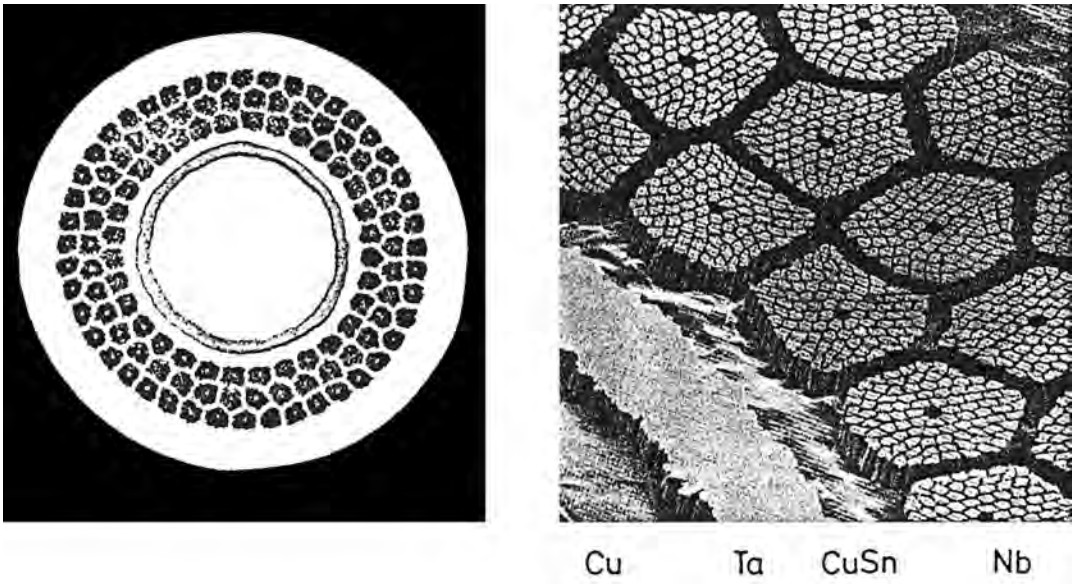


Fig. 5.90 Cross section of a filament super conductor [Web 82]

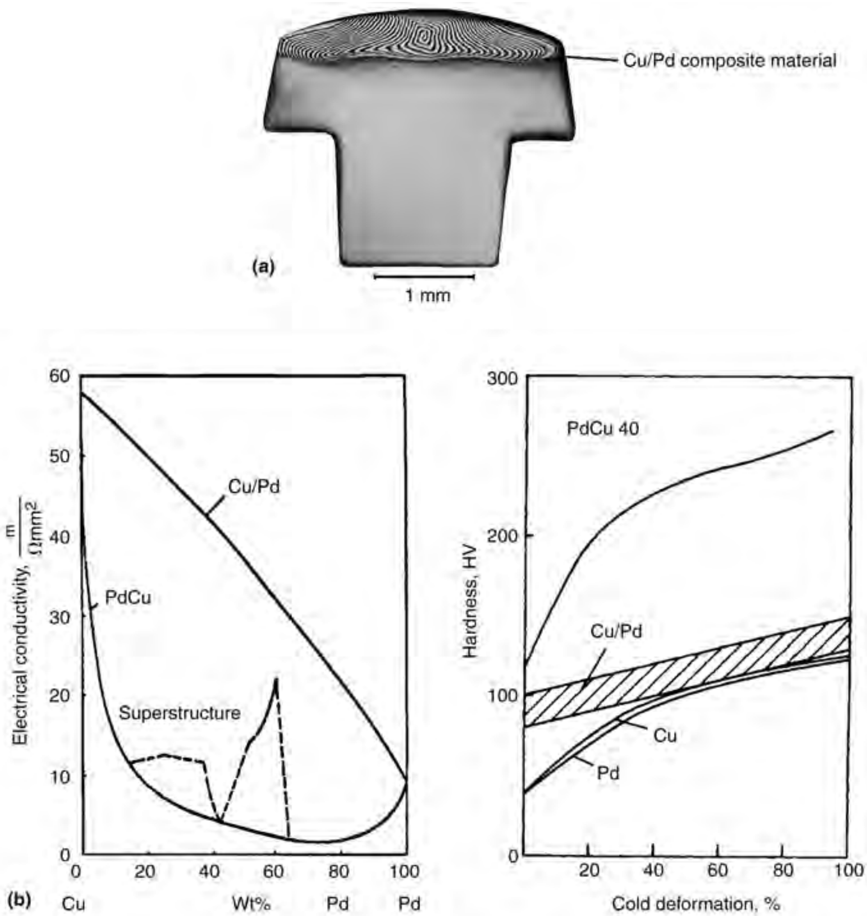


Fig. 5.91 Property comparison between Cu/Pd composite materials (VW) and corresponding Pd/Cu alloys (electrical conductivity and hardness after cold working)

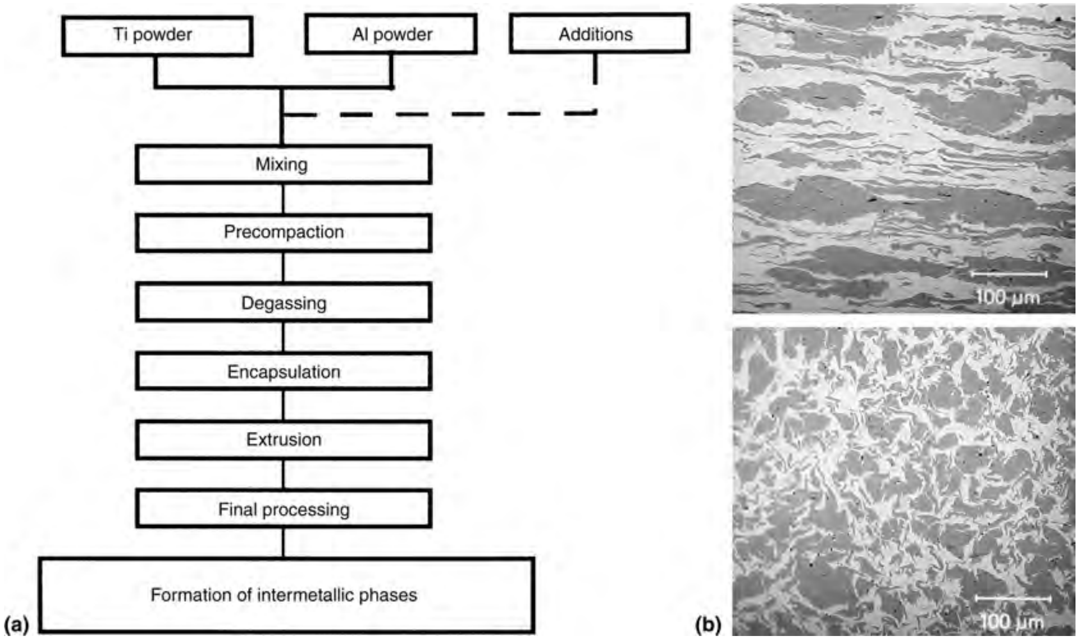


Fig. 5.92 Schematic process for reaction powder metallurgy. (a) Longitudinal and transverse structure of Ti48.5Al, unreacted. (b) Longitudinal and transverse sections in the extruded state

specific heat treatments can be applied to other materials. The work by [Sto 87] and [Mue 86] describes the contact material copper palladium. Palladium-copper alloys with 15 or 40 wt% Cu are used extensively for contact materials for switching direct current because of their high resistance to material movement. Palladium and copper form a continuous solid-solution series with superstructure phases. This governs the electrical conductivity of the alloys. There are significant technical and economic advantages in using Cu/Pd composite materials instead of conventional PdCu alloys. Care should be taken to avoid the formation of solid-solution zones at the boundary surface between copper and palladium in the manufacture of the composite materials. It is possible, by controlling the structure and the temperature in the deformation process, to obtain the microscopic heterogeneous composite structure. The indirect extrusion of coils of copper and palladium strip is particularly suited for this. This produces contact materials that exhibit a completely different property spectrum compared with conventional alloys of the same composition. The electrical and thermal conductivities of Cu/Pd composite materials are up to 10 times higher than the corresponding Cu-Pd alloys. The absence of solid-solution hardening gives the Cu/Pd composite alloys a high ductility (Fig. 5.91). This provides excellent further processing possibilities, providing savings in the noble metals and economic production processes for complex components.

5.45.3 Metallic Fiber Composite Materials with P/M Structures

This application area includes all those fiber composite materials that can be produced from powder starting materials. These are mainly aluminum-base fiber-reinforced materials [Sch 87, Ros 92, Bei 90, Moo 85], metal matrix composites (MMC) [Sta 88], and materials for electrical contacts [The 90]. The production of fibers [Boe 88] also provides a means of materials strengthening.

Alloys based on the intermetallic phase TiAl have a large potential for use as high-temperature, light structural components. The deformation potential of this phase, which is usually brittle under a conventional stress state, is very limited. Semifinished and structural components can be produced economically by reaction powder metallurgy [Mue 90, Wan 92, Mue 93] (see also the section "Extrusion of Powder Metals"). The production of titanium aluminides by reaction powder metallurgy (Fig. 5.92a) includes the following steps:

1. Mixing the initial powders (element and/or alloy powders)
2. Precompaction of the powder mixture (e.g., by CIP)
3. Production of semifinished product by extrusion
4. Finishing of component
5. Reaction heat treatment

Figure 5.92(b) shows longitudinal and transverse sections in the extruded state. Suitable control of the reaction heat treatment produces the phase TiAl expected from the phase diagram.

In the future, it should be possible for starting materials that have been produced by mechanically alloyed powder particles or by a spray compaction process to be used for the application of new composite materials with excellent properties.

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