aluminium technologies

15.12.2015
Continuous casting

- Continuous casting offers substantial savings in the production of aluminium sheet.

- Processing cycle is much shorter since the melt is converted into 2-10 mm thick strip that can be cold rolled to sheet gauges without the need for hot rolling.

- However, continuous casting is not suitable for every alloy group. Only those alloys that can solidify in a short time while passing through the caster rolls. Those alloys are the alloys with a rather narrow solidification range.
Strip casting/cold rolling route

**TRC**

- **t = 5 - 6 mm**

**homogenization**

- **$T \sim 500-600 \, ^\circ C$**

**Cold rolling mill**

- **1-2 mm**

**Annealing furnace**

**Softening anneal**

- **$T \sim 250-400 \, ^\circ C$**

**Cold rolling mill**

- **<1 mm**

**Partial anneal**

- **$T \sim 150-250 \, ^\circ C$**

**Annealing furnace**
Structure and properties of strip castings

Main features of all continuous casting technologies are a high solidification and cooling rate, which affect the structure compared to conventional products (DC casting followed by hot and cold rolling).

In particular, the very much higher solidification rates have an effect, as does the formation of two or more solidification fronts.

For example the dendrite spacing and cell sizes are decreasing with higher cooling rate.
Continuous cast products show a supersaturation of alloying elements or impurities, that can have an effect on subsequent thermal treatments.

Other features are a higher density of imperfections (especially dislocations, dislocation loops, vacancies and vacancy clusters), a fine grain size, surface segregation and a centreline segregation.
## Comparison of casting processes

<table>
<thead>
<tr>
<th>Casting process</th>
<th>Cooling rate in K/s</th>
<th>Dendrite arm spacing in µm</th>
<th>Cell size in µm</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>mould casting</td>
<td>0.01 – 0.1</td>
<td>100</td>
<td></td>
<td>Depending on type and temperature of mould</td>
</tr>
<tr>
<td>DC casting</td>
<td>0.5 - 20</td>
<td>12 - 15</td>
<td>50 - 90</td>
<td></td>
</tr>
<tr>
<td>Properzi</td>
<td>0.5 - 13</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Die casting</td>
<td>20 - 80</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Strip casting</td>
<td>200 - 700</td>
<td>1 - 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- twin drum casters</td>
<td>e.g. 450 K/s for</td>
<td>5 – 25</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hunter Engineering</td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>process</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- block and belt</td>
<td></td>
<td></td>
<td>40 – 80</td>
<td></td>
</tr>
<tr>
<td></td>
<td>casters</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Continuous drag</td>
<td>≈ 6000</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>casting</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Structure and properties of strip castings

Strip casting offers several metallurgical advantages due to rapid solidification -
A fine cast structure is obtained with fine dendrites and a fine grain size.
Segregation is lessened. Therefore some alloys could have better properties than conventional produced foil stock.
After the casting the material has to be cold rolled, where a high degree of deformation brings a good quality of the surface.
Cast strip has a light plastic deformation.
Behaviour of cast strip in further processing (rolling, thermal treatment)

In further processing the special features of the material must be taken into account. Due to the rapid solidification the strip can show a significant supersaturation, that influences all processes of rolling and the thermal treatment.

Cold rolling
Strip casting shows essentially the same behaviour as conventional strip under a cold deformation. With an increasing degree of cold work the tensile strength increases, while the elongation decreases.
Recrystallization

- Materials undergo recovery, recrystallization and grain coarsening.
- The RV/RX temperatures for the cast strip are higher than those of the other materials because of the higher supersaturation that delays the RV/RX processes.
- With a homogenisation cycle before cold rolling the supersaturation can be reduced.
- With increasing alloy content the effect of a delayed recrystallization becomes more and more significant.
Recrystallization of commercially pure aluminium Al99,5 and AlMn1Fe1 strip cast materials

Diagram showing the tensile strength $R_m$ in MPa as a function of annealing temperature in °C for AlMn1Fe1-strip cast material (red dashed line) and Al99,5-strip cast material (blue line). The range of recrystallization is highlighted.
Homogenization anneal
Homogenization anneal

\[ x = \sqrt{D \cdot t} \]

**X**: diffusion distance  
**D**: diffusivity (Fe/Al)  
**t**: time

Time required for homogenization is estimated by measuring the dendrite arm spacing, \( x \):

\[ t = \frac{x^2}{D} \]

Homogenization after a cold rolling pass is recommended!
Recrystallization of commercially pure aluminium Al99.5 cold rolled 90% and annealed for 1 h
Wire bar casting

- The continuous casting of wire bars is also of great economic importance.
- As is the case for strip casting some production steps are saved.
- For the alloy content the same limitations apply. That is why mainly commercial pure aluminium is cast.
- Other alloys, eg AlMn and AlMgSi, are produced.
- All these materials are although used in electrical engineering.
Properzi continuous rod casting
Properzi Caster

- The Properzi-Caster (invented by Ilario Properzi, Italy, 1950) has a great importance for industrial production of wire bar from aluminium (or copper) for electrical engineering.

- The usual alloys are electrical conductors grades, for example commercially pure aluminium 1350, alloys of the 3000 series and 6101(AlMg1SiCu), Aldrey (AlMgSi Type).
Properzi Caster

- The mould is formed between the grooved periphery of the rod casting wheel and the endless steel belt.
- The casting wheel is water-cooled.
- The molten metal solidifies between the belt and the casting wheel, whose diameter can be up to 2600 mm.
- The cast bar has a triangular or trapezoidal cross section (up to 3120 mm²) and a temperature of about 350°C after leaving the casting wheel.
- It is immediately hot rolled down to coilable wire stock. The cast, shaped strands are usually rolled and drawn to wire, and then coiled.
Properzi Caster

Properzi rod is usually delivered at 12 mm diameter to be drawn by dry drawing machines to a final diameter of 0.3 mm to 4.0 mm depending on the application.
temper designations for wrought alloys

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXXX -F</td>
<td>as fabricated</td>
</tr>
<tr>
<td>-O</td>
<td>annealed to soft condition</td>
</tr>
<tr>
<td>XXXX -H1</td>
<td>cold worked only</td>
</tr>
<tr>
<td>-H2</td>
<td>cold worked and annealed</td>
</tr>
<tr>
<td>-H3</td>
<td>stabilized with a low temperature anneal after cold work</td>
</tr>
<tr>
<td>-HX2</td>
<td>quarter hard</td>
</tr>
<tr>
<td>-HX4</td>
<td>half hard</td>
</tr>
<tr>
<td>-HX6</td>
<td>three quarter hard</td>
</tr>
<tr>
<td>-HX8</td>
<td>full hard</td>
</tr>
<tr>
<td>-HX9</td>
<td>extra hard</td>
</tr>
</tbody>
</table>

Non heat treatable alloys/hardening only by cold work
H temper designations

H.x.y  x: secondary treatment

1. Cold work - no anneal!
2. Cold work + partial anneal!
3. Cold work + "stabilization"
4. Cold work + baked

3104-H19
Al-Mn alloy/ can body stock
Produced in the extra hard temper by cold rolling!
H temper designations

H-tempers
Non heat tretable aluminium alloys are hardened by cold work.
H tempers are represented by 2 digit codes.

H x y (degree of hardening)

2: 1/4 hard: quarter sert (~%15-20 reduction)
4: 1/2 hard: half hard (~%30-40 reduction)
6: 3/4 hard: 3 quarter hard (~60-65 reduction)
8: 4/4 hard: full hard (~%80 reduction)
9: extra hard (~%90 reduction)
H temper designations

- H1X tempers are produced by cold rolling as the final step with a reduction ratio to ensure the degree of hardening required.
- H2X tempers, on the other hand, are first cold rolled to a full or extra hard temper and then annealed under precisely selected conditions to partially soften the material to achieve the required hardness level.
- Although the hardness levels achieved with the H1X and H2X tempers are the same, the elogation values in the H2X tempers are relatively higher owing to the annealing treatment at the end of the process.
H1X vs H2X processes

Cold rolling

σ

% 30-40 % reduction

H14: half hard

Softening anneal

σ

% 70-80 % reduction

H24: half hard
### Typical applications of rolled aluminium sheet and plate alloys

#### Strain-hardening alloys

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1050, 1060</td>
<td>Chemical equipment, Tankers, Printing (litho) plates</td>
</tr>
<tr>
<td>1100</td>
<td>Cooking utensils, Decorative panels</td>
</tr>
<tr>
<td>1200</td>
<td>Foil (household, packaging)</td>
</tr>
<tr>
<td>8006</td>
<td>Finstock</td>
</tr>
<tr>
<td>3003, 3004</td>
<td>Chemical equipment, Storage tanks, Beverage can bodies, Heat Exchanger Sheet</td>
</tr>
<tr>
<td>5005, 5050, 5052, 5657</td>
<td>Automotive trim, Architectural applications</td>
</tr>
<tr>
<td>5085, 5086</td>
<td>Marine structures, Storage tanks, Rail cars</td>
</tr>
<tr>
<td>5454, 5456</td>
<td>Pressure vessels, Armour plate, Automotive sheet wheels, Chassis parts</td>
</tr>
<tr>
<td>5182, 5356</td>
<td>Cryogenic tanks, Beverage can ends, Automotive panels</td>
</tr>
</tbody>
</table>

#### Heat-treatable alloys

<table>
<thead>
<tr>
<th>Alloys</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>2219</td>
<td>High temperature (e.g. supersonic aircraft)</td>
</tr>
<tr>
<td>2014, 2024</td>
<td>Airframes, Autobody sheet</td>
</tr>
<tr>
<td>6005, 6009, 6010, 6016, 6061, 6063, 6082, 6351</td>
<td>Marine structures, Heavy road transport, Rail cars, Autobody sheet, Bumpers, Crash elements</td>
</tr>
<tr>
<td>7003, 7004, 7005, 7019, 7010</td>
<td>Missiles, Armour plate, Military bridges, Bumpers</td>
</tr>
<tr>
<td>7075, 7079, 7050, 7010, 7150</td>
<td>Airframes, Tooling plate</td>
</tr>
</tbody>
</table>
Aluminium rolled products

- Rolled products, i.e. sheet, plate and foil constitute almost 50% of all aluminium alloys used.
- In North America and Western Europe, the packaging industry consumes the majority of the sheet and foil for making beverage cans, foil containers and foil wrapping.
- Sheet is also used extensively in building for roofing and siding, in transport for airframes, road and rail vehicles, in marine applications, including offshore platforms, and superstructures and hulls of boats.
- Also, while relatively little is currently used in the manufacture of high volume production automobiles, it is expected that the next decade will see an increase of aluminium sheet used for body panels.
# Selection of Rolling Alloys

<table>
<thead>
<tr>
<th>Alloy Designation</th>
<th>Characteristics</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>3004 (No former BS designation)</td>
<td>Al-Mn and Al-Mn-Mg 3000 Series alloys provide a wide range of mechanical properties and very good corrosion resistance, weldability and formability. The strength/formability characteristic is achieved by application of various degrees of strain hardening and by intermediate annealing. Alloy 3004 as well 3104 alloy are the 2 alloy types use for beverage can body stock.</td>
<td>Siding, can stock, packaging, lamp bases. Sheet-metal work, storage tanks, trailer panel sheet.</td>
</tr>
</tbody>
</table>
# Selection of Rolling Alloys

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# Selection of Rolling Alloys

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<tr>
<th>Alloy Designation</th>
<th>Characteristics</th>
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</thead>
<tbody>
<tr>
<td>7075 (Former BS designation 2L95)</td>
<td>Heat treatable very high strength alloy with a strength slightly lower than 7010. Very high fatigue strength. Joining preferably by rivets, adhesives or screws. Corrosion protection is recommended also in outdoor atmosphere.</td>
<td>Usually in plate form. Aircraft and military highly stressed structural components. Rolling stock for machine parts and tools (for rubber and plastics). Ski poles, tennis rackets, screws and bolts, nuts. Rivets. Nuclear applications.</td>
</tr>
</tbody>
</table>
Rolled aluminium is widely used in many industries including:

**Aircraft:** Structural members, cladding and many fitments.

**Aerospace:** Satellites, space laboratory structures and cladding.

**Marine:** Superstructures, hulls, interior fitments.

**Rail:** Structures, coach panelling, tankers and freight wagons.

**Road:** Car chassis & body panels, Buses, truck bodies, tippers, tankers, radiators, trim, traffic signs and lighting columns.
Building: Insulation, roofing, cladding and guttering.
Engineering: Welded structures, tooling plate, cladding and panelling, and heat exchangers.
Electrical: Transformer windings, busbars, cable sheathing, and switchgear.
Chemical: Process plant, vessels and chemical carriers.
Food: Handling and processing equipment, and hollowware.
Packaging: Cans, bottle caps, beer barrels, wrapping, packs and containers for a wide range of food and non-food products.
Printing: Lithographic plates
aluminium forging
Forging aluminium alloys

The forging of aluminium alloys is the process of converting a uniform blank shape into a final product by hammering the material between shaped or flat dies.

This process may take place in one stage or in several stages.

The great majority of aluminium forgings are made from the heat-treatable alloys, but forgings in pure aluminium and in some of the non-heat-treatable alloys find application in certain fields.
Forging aluminium alloys

- Precision forgings are used for many highly stressed parts, such as in aircraft undercarriage gear, internal combustion engines and other power units.
- Forged components have an advantage of near net shape, minimising further machining.
- The process encourages increased ductility and decreased pore size.
forging process

- Blanks are cut from extruded stock or from ingot and, before forging, are preheated to temperatures in the range of 400-500°C.
- In the production of hand forgings the blank is hot worked between flat dies, usually on a pneumatic hammer or a press.
- Care is taken to ensure that the degree of deformation is sufficient to provide adequate breakdown of the original cast microstructure.
- The rough outline of the component is developed, with the grain flow or fibre of the material in the direction of stressing.
Hand forgings are usually associated with small quantity requirements or prototypes which do not warrant the cost of dies. Since these forged pieces are produced without shaped dies they cannot be subjected to strict dimensional accuracy.
forging process

- Die-forgings, i.e. pressing and drop-forgings or stampings, are usually subjected to open die forgings.
- Simple components may be pressed or stamped directly from extruded stock.
- Die forgings are produced using shaped dies, giving a product with a high degree of dimensional consistency which considerably reduces the machining to the finished form.
- Such forgings have the advantages of good mechanical properties and structural integrity.
The technology of die forming has advanced to produce close-to-form forgings with higher standards of dimensional accuracy.

In the non heat treatable alloys where mechanical properties depend on the degree of cold working it is possible to cold forge.

Hydraulic presses of up to 12,000 tonnes capacity and hammers weighing as much as 20 tonnes are in use for the largest forgings.
Aluminium forgings

- combination of good mechanical properties, dimensional accuracy and surface finish means that aluminium forgings are used in highly stressed parts where structural integrity is of paramount importance.

- The alloys commonly used for these highly stressed applications are from the 2000, 6000 and 7000 series.

- The aerospace industry is a major end user.
Forging aluminium

High performance and strength

- used in applications where performance and strength are critical.
- Forged components are commonly found at points of stress and shock.
- Pistons, gears and wheel spindles in high performance automobiles and aircraft are often made from forged aluminium.
Forging aluminium

Forged aluminum perfect for aerospace

- challenging and harsh environments in space necessitate lightweight structures that are strong and durable.
- Forged aluminium’s low density relative to steel makes it an ideal candidate for aerospace applications.
Forging aluminium

Forging tools

- Hammers, presses and upsetters are the basic types of equipment used in the forging process.
- Hammers can apply a driving force of up to 25 tons where presses can exert a force of up to 50,000 tons.
- Upsetters are basically presses used horizontally to increase the diameter of a work piece by reducing its length.
Forging aluminium

Mark of quality

- "Forged" is the mark of quality in hand tools and hardware.
- Pliers, hammers, wrenches, garden implements and surgical tools are almost always produced by forging.
Forging is a massive forming process!

- The temperature of the workpiece is increased to such an extent that the deformation forces required are considerably less than would be needed to cold work it.

- The two most important forging processes are open-die forging (in which forming of the workpiece takes place locally and mostly using simple dies) and closed-die forging (where the workpiece is fully enclosed in a die whose form determines the shape of the forging).
Types of forging

Open-die forging

- Ideal for processing large pieces of aluminium,
- open die presses do not constrain the aluminium billet during the forging process and utilize flat dies free of pre-cut profiles and designs.
- Aluminium blocks weighing up to 100 tons and 30 m in length can be open-die forged to create large aluminium components with optimal structural integrity.
- While welding and joining techniques are useful in creating large components, they cannot match the strength or durability of a forged part.
- Open-die forgings are limited only by the size of the starting stock.
Open die forging

http://aluminium.matter.org.uk/content/html/eng/default.asp?catid=198&pageid=2144416773
Closed-die forging

- Closed-die forging, also known as impression-die forging, can produce an almost limitless variety of shapes that range in weight from mere ounces to more than 25 tons.
- As the name implies, two or more dies containing impressions are brought together as forging stock undergoes plastic deformation.
- Because the dies restrict metal flow, this process can yield more complex shapes and closer tolerances than open-die forging.
- Impression-die forging accounts for the majority of aluminum forging production.
Closed die forging
Types of forging

Rolled-ring forging

- Employed when industrial applications call for a high strength, circular cross section component.
- The process typically begins with an open-die forging to create a ring preform, shaped like a doughnut.
- Next, several rollers apply pressure on the preform until the desired wall thickness and height are achieved.
- Configurations can be flat, like a washer or feature heights of more than 2 meters.
- Rings can be rolled into numerous sizes, ranging from roller-bearing sleeves to large pressure vessels.
Rolled-ring forging
General principle of forging

- For large-scale production, closed-die forging is usually used because it is a very reliable process.
- Thanks to the superior mechanical properties obtained, the process can compete with the most advanced casting processes.
- Compared with casting, however, the range of possible shapes that can be produced is more limited.
- In particular, it is difficult to produce sharp corners, undercuts and cavities by use of forging.
General principle of forging

The forging process usually consists of the following steps:

- sawing the extruded or continuously cast feedstock,
- heating the blank
- upsetting or bending
- forging (rough and final forging)
- deburring and, if necessary, punching
- heat treatment
- pickling or blasting and
- final inspection.
Aluminium Forging

Aluminium Forging features

- High level of strength
- Porosity elimination
- Lightweight
- Surface finish that can be easily enhanced
- Low material costs
Aluminium Forging

Strength
- When forged and heat treated, aluminium alloys exhibit some mechanical properties comparable with many grades of steel. (SG=7.8).
- The strength to weight ratio is therefore far superior. For example, the alloy 2014-T6 has a typical UTS of 485 MPa, exceeding that of many grades of steel, and all commonly used Al and Mg casting alloys.
- Unlike some casting processes, forging is always porosity free thus allowing relatively straightforward heat treatment processes that significantly improve selected mechanical characteristics.
Aluminium Forging

Lead-Time

- A typical forging die can be designed and manufactured in about 6 weeks.
- Some alternative light metal fabrication techniques require more complex tooling, which require upwards of 10 weeks for tooling design and manufacture, and often much longer.
- “Time to market” is a common catch-cry, and the forging industry is well positioned to provide quick lead-time solutions.
Aluminium Forging

Surface Finish

- A wide range of surface finishes can be produced with forging, from very smooth surfaces to relatively sharp serrations, and this may facilitate further surface finishing or be a functional attribute of the part design.

- Some alloys, like 6061, have desirable anti-corrosion characteristics without any further surface treatment at all.
Aluminium Forging

Cost

- In applications where several fabrication options are viable from the functional perspective, cost will be a major driver.
- Forging tooling is generally cheaper than, for example, high-pressure die cast tooling, and the production rate is higher.
- Offsetting this is generally higher raw material costs, associated with the necessary alloying of raw materials to provide desirable heat treatable characteristics. Consequently, many aluminium forgings are used in highly stressed applications.
Aluminium Forging

Design Flexibility

- not all shapes can be forged, As with all fabrication options, it is important to review the “manufacturability” of a proposed design as soon as possible in the design process to ensure that optimum contours are suggested.

- The increased use of 3D modelling packages and related 2D drawings allow a client to electronically transfer models to a forging business early in the design phase to have suggestions on, for example bend radii and parting-line position to provide optimum strength and die life.
Aluminium Forging

Design Flexibility

● if a product is migrating from a steel equivalent, then a review of fatigue stresses may be desirable so that all performance criteria are met with a new aluminium part.

● Although most aluminium forging in Australia is “closed-die”, the history of aluminium forging sees a large number of very large “open die” forgings used in the aircraft industry.

● Consequently the physical size of the component may not restrict the use of a forged component although initially it may appear a daunting task.
disadvantages of aluminium forgings

- Possible atmospheric reactions
- Warping or variations may develop in cooling process
- Additional machining may be necessary
Aluminium forgings are used in many automotive and aerospace applications due to their favorable weight to strength ratio.

A variety of commercial tools and medical implements are created using aluminium forgings as these products are strong, lightweight, offer resistance to corrosion, and can be polished to an aesthetically pleasing finish.
High performance with forged components

Wheels Built for Speed, Performance and Safety

- forged aluminium wheels are a great choice for the punishing conditions of competitive racing.
- Built for speed and performance, forged wheels are extremely lightweight, very strong and exceptionally stiff.
- Forged aluminium wheels are found off the racetrack too.
- High performance sports models from Porsche, Lamborghini and Audi can all be outfitted with these sleek and high performance wheels.
Characteristics of automotive forgings

**Aluminium forgings** are used to save weight of components which require
- high functional durability,
- high structural integrity,
- high fatigue resistance, and
- high toughness and ductility.

Aluminium forgings in **automotive applications** are, therefore, generally chosen for components which are essential for the safety of the vehicle:
- system components of front and rear axles: e.g. control arms, knuckles, wheels,
- components of the brake system: e.g. caliper, hydraulic system components.
automotive forgings

Concentric slave cylinder, alloy EN AW-6082-T6

Control arm, alloy 6082-T6

Couplings for drive shaft, alloy 6082-T6
automotive forgings

Control arm
alloy 6082-T6

Control arm
alloy 6082-T6
Forging alloys

While in principle all wrought aluminium alloys can be die or hand forged, only a limited selection of alloys is commonly used. The preferred alloys include:

- Non-age-hardening alloys:
  - EN AW-5754-H112 (AlMg3)
  - EN AW-5083-H112 (AlMg4.5Mn0.7)

- Age-hardening alloys:
  - EN AW-2014-T6 (AlCu4SiMg)
  - EN AW-2024-T4 (AlCu4Mg1)
  - EN AW-6082-T6 (AlSi1MgMn)
  - EN AW-7075-T6, -T73 (AlZn5.5MgCu)
Forging alloys

For reasons of strength, age-hardening alloys are used for structural applications. Due to its excellent corrosion resistance alloy EN AW-6082-T6 is almost exclusively used for automotive suspension and chassis components.

<table>
<thead>
<tr>
<th>Element</th>
<th>Weight-%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>0.7 - 1.3</td>
</tr>
<tr>
<td>Fe</td>
<td>0.50</td>
</tr>
<tr>
<td>Cu</td>
<td>0.10</td>
</tr>
<tr>
<td>Mn</td>
<td>0.40 - 1.0</td>
</tr>
<tr>
<td>Mg</td>
<td>0.6 - 1.2</td>
</tr>
<tr>
<td>Cr</td>
<td>0.25</td>
</tr>
</tbody>
</table>
Static properties

- Optimum characteristics are achieved subsequently by a complete heat treatment cycle (solution heat treatment incl. quenching and age-hardening).
- In particular, if the heat treatment is carried out continuously within the production line, the obtained strength levels are significantly higher than the minimum standard values.
- In a batch process with good process control high values above minimum standards can also be achieved.
- The reason for this improvement of strength is the avoidance of room temperature ageing between quenching and artificial ageing.
### Static properties

"L" denotes properties in direction of fibres "T" denotes properties transverse to fibre direction

#### Minimum standard mechanical properties

<table>
<thead>
<tr>
<th>Alloy-Temper</th>
<th>Orientation</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>Elong. [%]</th>
<th>R. A. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6082-T6</td>
<td>L</td>
<td>260</td>
<td>310</td>
<td>6</td>
<td>n.a.</td>
</tr>
<tr>
<td>6082-T6</td>
<td>T</td>
<td>250</td>
<td>290</td>
<td>5</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

#### Typical mechanical properties

<table>
<thead>
<tr>
<th>Alloy-Temper</th>
<th>Orientation</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_m$ [MPa]</th>
<th>Elong. [%]</th>
<th>R. A. [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>6082-T6</td>
<td>L</td>
<td>300</td>
<td>340</td>
<td>15</td>
<td>35</td>
</tr>
</tbody>
</table>
Forging stock

Forged component

- Casting
  - Pre-form
    - Part
    - Cont
  - Round
    - Part
    - Cont
- Extrusion
  - Preform
  - Round

Foundry alloys

Wrought alloys
Process chain for automotive forgings

Die forging process chain for high volume automotive forgings

- Final inspection
- Blast-cleaning
- Artificial ageing
- Quenching (water)
- Solution anneal

Hot forming:
- Trimming/punching
- Finish-forming
- Pre-forging
- Pre-forming
- Pre-forming

Pre-heating to forging temperature

- DC-cast billet
- Forging stock (extruded rod)
- Sawing to length

Temperature control

Surface control

Ultrasonic control
Forging practice

Extrusion

Forging stock

Preheating

Forging

Solution heat treatment

ageing
Forging stock

- Round-the-clock continuous processing
- Reduced production chain compared to Extrusion
- So far produced alloys: 1xxx, 2xxx, 6xxx, 7xxx
- Diameter range: 25-150 mm round bar
forging sequence

- Grain structure development during multi-stage operations:

  - 2-pass reducer rolling
  - Finish forging
  - Microstructure-analysis at indicated cross-sections

![Forging sequence diagram with grain structure development and stages labeled A1 and B1.](image)
forging+T6/ grain structure
extrusion + forging
forging + T6
Extruded forging stock + preheating

<table>
<thead>
<tr>
<th>profile</th>
<th>500 °C</th>
<th>525 °C</th>
<th>550 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
pres çıkış sıcaklığı: 490 °C
dövme sıcaklığı: 500 °C
T6 ısıt işlemi
pres çıkış sıcaklığı: 490 °C
dövme sıcaklığı: 430 °C
T6 ısıl işlemi
section structures

<table>
<thead>
<tr>
<th>forging temperature (°C)</th>
<th>480</th>
<th>520</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-forged</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
<tr>
<td>T6</td>
<td>![Image]</td>
<td>![Image]</td>
</tr>
</tbody>
</table>
section structures

Press exit temperature: 500 °C

<table>
<thead>
<tr>
<th>Forging temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>430</td>
</tr>
<tr>
<td>forged</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>forged</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>T6</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
evolution of grain structure

Ekstrüzyon

Yüzey

Ekstrüde olmuş fiber taneler

Ağır deformasyonlu yüzey tabakasında dinamik yeniden kristalleşme ile çok ince eş eksenli tane yapısı

Dövmé

Yüzeydeki çok ince tanelerin büyümesi ile aşırı iri tane yapısı

Fiberlerin yeniden kristalleşmesi ile eş eksenli ince taneler

İsıl işlem

İri tane yapısı kar

Eş eksenli ince tanelerin büyümesi ile aşırı iri taneler

Yassı tanelerin yeniden kristalleşmesi ile ince eş eksenli taneler

İri tane yapısı kararlı

Eş eksenli ince tanelerin büyümesi ile aşırı iri taneler

Yassı tanelerin yeniden kristalleşmesi ile oluşan eş eksenli tanelerin büyümesi ile iri taneler
Cast forging stock

1

2
Cast forging stock

Profil → dövme → T6
Cast forging stock
<table>
<thead>
<tr>
<th>profil</th>
<th>dövme</th>
<th>T6</th>
</tr>
</thead>
<tbody>
<tr>
<td>ekstrüzyon</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>döküm</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
</tbody>
</table>
Kesit yapısı makul bir kusursuzlukta ise, yorulma hasarı daima yüzeyde başlar! Yorulma ömrünün >%90’ı çatlık başlamasında geçer!
Production of forging stock

- Alcan’s Netcast™ technology - vertical casting of complex shapes
Design of forgings

rules which should be considered in the design of forgings.

- Fibre orientation should follow the principle load direction of the part.
- Fibre orientation is determined by the type of the forging stock, its position in the die and the parting line of the die.
- these factors largely determine costs and properties of the part
Design of forgings

Die partitioning:
Partitioning of the part's cross section into the die halves affects the fibre flow:
Good fibre flow and low tooling costs. However, the relatively deep and narrow cavities are difficult to fill.
Undisturbed fibre flow and good filling of cavities. But there will be higher tooling costs because of protrusion of one die face into the other.
Design of forgings

Mass distribution on metal flow
Mass distribution and plane parting faces:
Symmetric mass distribution over the partition of the die is favourable for good material flow
Design of forgings
Mass distribution on metal flow
Mass distribution and plane parting faces:

However, if this requires broken parting faces, higher die costs, wear and tolerances are to be expected. Large changes in cross section produce high transverse flow (large flash!) with concomitant danger of fold formation, higher tool wear and detrimental effects on mechanical properties.
Effect of radii on metal flow: designing with large radii and soft shape transitions is important. Small radii lead to overshooting of the metal at corners and may produce uncomplete cavity filling and dangerous folds.
Design of forgings

Behaviour of forgings under misuse and crash conditions
Aluminium automotive forgings show a high structural integrity and perform well under conditions of misuse or maltreatment, i.e., they deform without disintegration to a point where the proper function is lost so that the part must obviously be replaced. Furthermore, it is a speciality of aluminium and its alloys that its ductility increases with increasing deformation rate, see diagram below. Aluminium forgings are, therefore, particularly suited for parts which are vital to the safety of the vehicle under critical driving situations.
Behaviour of forgings under misuse and crash conditions

Front axle housing (6082-T6) with linkage arm deformed by "misuse"

Forged front axle housing, alloy 6082-T6
Fatigue behaviour of forgings

Forgings exhibit optimum fatigue strength if the main loading direction coincides with the fibre direction. For a given life time, forged components endure about twice the strain amplitude of cast material.
Fatigue behaviour of forgings

Forgings exhibit optimum fatigue strength if the main loading direction coincides with the fibre direction. For a given life time, forged components endure about twice the strain amplitude of cast material.
Aluminium Alloys for Forging

- With the high-strength aluminium alloys available, it is possible to use aluminium to its full advantage for technological applications.
- A large number of aluminium alloys, ranging from pure aluminium up to the high strength aluminium alloys, can be forged effectively.
- Forgings are mainly used for structural engineering parts, so that aluminium forging alloys are mostly of the heat-treatable type with medium to high strength.
Aluminium Alloys for Forging
After cooling down from a forging temperature of about 400 °C, the forgings are in a soft annealed state. For the non-heat-treatable alloys, this corresponds to the final condition required for the application.

Heat-treatable alloys, on the other hand, are always heat treated in order to deliver the most suitable service properties.

The strength of unalloyed aluminium Al99,5 is only 65 N/mm² and thus too low for many technical applications.

The so-called high-strength aluminium alloys have tensile strengths exceeding 600 N/mm²
Aluminium alloys for forging

Non heat treatable alloys

- AlMg3 is used in shipping and can be anodised for decorative purposes
- AlMg4, 5Mn has a higher strength than AlMg3

Solution hardened alloys are used instead of pure aluminium for application in which a higher strength is required.

Heat treatable alloys

- AlMgSi is used in the automotive and shipbuilding industry and for machines. Highest strength in the "artificially aged" state.
- AlCuMg2 for high-strength components in automotive and engineering sectors. High fatigue strength.
- AlZnMgCu1.5 has the best combination of static, dynamic and fracture properties.
- AlCuSiMn has good strength at higher temperatures, but cannot be welded and has a lower corrosion resistance.
**Microstructure**

**Influence of Fiber Structure**
- Strength values are not isotropic over the bulk of the forged part, being higher in the direction of grain flow (longitudinal) than transverse to it.
- This is analogous to the "press effect" observed in extruded rods.
- The difference between longitudinal and transverse strengths increases with increasing alloying element content and increasing strength.
- The reason for this anisotropy is the textured structure and the geometrical location of the grain boundaries.
Microstructure

- Grain boundaries are regions of lower ductility since they are a preferred location for coarse precipitated phases.
- When a force is applied in the longitudinal (grain-flow) direction, only a small fraction of grain boundaries are exposed to normal stress.
- Conversely, a force applied transverse to the grain-flow direction causes a stress normal to a large fraction of grain boundary area, which can lead to a more brittle behaviour.
Microstructure

- Experienced designers and forging experts use this behaviour to full advantage by fabricating forgings so that the grain-flow direction corresponds to the direction of maximum stressing.
- This increases safety or leads to metal saving.
- Forming in a die leads to an elongation of grains in the direction of flow.
- Grains which were originally equiaxed are now elongated to fibres.
- If, as is the case with extrusions, a fibre structure exists already, this is further enhanced.
influence of fiber structure

The fibre structure is important for
- fatigue strength and
- resistance to stress-corrosion cracking
and is influenced by the deformation process.

A structure in which the fibres (grain-flow) run parallel to the tool direction imparts better properties than one with fibres perpendicular to it.

Highest effect for the high-strength alloys.

The higher the alloy content, the larger the difference between longitudinal and transverse values.

For AlMgSi, difference in strength values is approx.: 20 N/mm²
For AlZnMgCu1.5, difference in strength values approx.: 50 N/mm²

During forging, care must be taken to see that the grain-flow direction is parallel to the direction of loading.
Defects due to Non-Uniform Flow

- In order to obtain a uniform, undisturbed fibre structure, the metal must flow uniformly during forging.

- Defects can occur if dies with sharp radii or unfavorable die separations (partings) are used. When the radius is large enough, the material flows uniformly and continuously filling up the die cavity fully from the bottom to the top.

- If the radius is too small, the material curls away from one side of the wall, is reflected and flows back again.

- In this case, the die cavity is filled from top to bottom, causing forging folds.
Forging temperatures depend on melting temperature ranges of the forging alloys.

High strength alloys, i.e. alloys with high solute contents, have an extended melting range and, therefore, require lower forging temperatures.

Strictly speaking, a defined recrystallisation temperature does not exist, since this is influenced by the degree of deformation and annealing time.
Characteristic Temperatures and Mechanical Data for Aluminium Alloys

<table>
<thead>
<tr>
<th>Alloy type</th>
<th>Material</th>
<th>EN-AW</th>
<th>Forging range (°C)</th>
<th>Melting range (°C)</th>
<th>Recrystallisation temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlMg</td>
<td>AlMg3</td>
<td>5754</td>
<td>450-500 *)</td>
<td>610-640</td>
<td></td>
</tr>
<tr>
<td>AlMgMn</td>
<td>AlMg4,5Mn</td>
<td>5083</td>
<td>450-500 *)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlMgSi</td>
<td>AlMgSi1</td>
<td>6082</td>
<td>450-500 *)</td>
<td>555-650</td>
<td>235</td>
</tr>
<tr>
<td>AlCuMg</td>
<td>AlCuMg2</td>
<td>2024</td>
<td>400-440 *)</td>
<td>510-640</td>
<td>260</td>
</tr>
<tr>
<td>AlZnMgCu</td>
<td>AlZnMgCu1,5</td>
<td>7075</td>
<td>410-440 *)</td>
<td>475-640</td>
<td>205</td>
</tr>
</tbody>
</table>

Source: Meyer-Nolkemper; *) according to Leiber

Characteristic Mechanical and Technological Values for Aluminium Alloys

<table>
<thead>
<tr>
<th>Material</th>
<th>EN-AW</th>
<th>$R_m$ Longitud.</th>
<th>$R_{p0.2}$ Longitud.</th>
<th>A5; Longitud.</th>
<th>Condition</th>
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</thead>
<tbody>
<tr>
<td>AlMg3</td>
<td>5754</td>
<td>218</td>
<td>120</td>
<td>19</td>
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<tr>
<td>AlMg4,5Mn</td>
<td>5083</td>
<td>301</td>
<td>155</td>
<td>16.5</td>
<td>forged</td>
</tr>
<tr>
<td>AlMgSi</td>
<td>6082</td>
<td>351</td>
<td>308</td>
<td>12</td>
<td>artificially aged</td>
</tr>
<tr>
<td>AlCuMg *)</td>
<td>2024</td>
<td>490</td>
<td>330</td>
<td>11</td>
<td>naturally aged</td>
</tr>
<tr>
<td>AlZnMgCu1,5</td>
<td>7075</td>
<td>572</td>
<td>540</td>
<td>8.8</td>
<td>artificially aged</td>
</tr>
<tr>
<td>AlCuSiMn</td>
<td>2014</td>
<td>483</td>
<td>450</td>
<td>8.5</td>
<td>artificially aged</td>
</tr>
</tbody>
</table>
Forging Temperature and Die Temperature

- The forming temperature lies between 320 and 480 °C, depending on the alloy.
- As far as temperature is concerned, the forging of aluminium is simpler than for most other materials. Dies can be preheated to forging temperature without appreciable loss of strength.
- Heating the die prevents cooling of the forging stock. The forging temperature range is, however, very limited.
- Exceeding the solidus temperature leads to irreparable damage caused by melting at the grain boundaries, leading to embrittlement of the material.
Forging Temperature and Die Temperature

- Since the real temperature in the forging stock during forming depends on the cooling and heating effects caused by the conversion of forming energy to heat, the temperature set for the start of forging depends on the logarithm of deformation and the deformation speed.
- Care must be taken that the critical temperature is not exceeded anywhere within the forging.
- Thus, the starting temperatures for hammer forging is lower than for press forging.
Forging Temperature and Die Temperature

- Too low temperatures lead to cracks, unfilled die cavities and high stresses.
- When the temperature decreases, the formability decreases and the flow stress increases.
- In some cases a higher forging temperature is chosen, e.g. 500 to 520 °C for forging AlMgSi1, in order to utilise the forming heat for heat-treatment.
- The forging is quenched immediately after the forging process.
Forging Temperatures for some Aluminium Alloys

The forging temperatures for the different alloys lie between 320°C and 480°C.

<table>
<thead>
<tr>
<th>Alloy designation</th>
<th>alpha-numeric</th>
<th>international</th>
<th>320</th>
<th>360</th>
<th>400</th>
<th>440</th>
<th>480°C</th>
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</thead>
<tbody>
<tr>
<td>Al 99</td>
<td>1100</td>
<td>3003</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>AlMn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AlMgSi</td>
<td>6061 6151</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>4032</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>AlMg3</td>
<td>5052 5086</td>
<td>5083 5056A</td>
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<td></td>
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</tr>
<tr>
<td>AlMg4.5Mn</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>AlCuSiMn</td>
<td>2014</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>AlCuMg2</td>
<td>2024</td>
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<td></td>
</tr>
<tr>
<td>AlCuMgNi</td>
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<td>2618</td>
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<td></td>
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<tr>
<td>AlZnMgCu0.5</td>
<td>7039</td>
<td></td>
<td>7079</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>AlZnMgCu1.5</td>
<td>7049</td>
<td></td>
<td>7075</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Advantages over steel:**
- Dies can be preheated to deformation temperature
- Cooling of the forging stock prevented during deformation

**Disadvantages against steel:**
- Forging temperature has to be controlled precisely since
  - too high temperatures can destroy the grain structure,
  - too low temperatures lead to cracks and the die cavities are not filled out with the metal!
- exact temperature control required!

Source: Develay
Process steps in die forging

Forming
- Stock
- Heating
- Forging
  - Die Heating
  - Cutting tool
- Deburring
- Casting or extrusion
  - Apply parting medium
  - Eventually multiple die cavities
  - Eventually multiple steps

Heat treatment
- Solution heat-treatment
- Quenching
- Calibrating
- Aging
- Water
  - RT or ca. 130°C - 180°C

Control
- Etching
- Testing
- NaOH
  - Surface, dimensions, microstructure, strength, analysis

Source: H.G. Roczyn
Fabricating Processes of Forging

- The term forging is used to define a group of processes which are mainly forming processes.
- Additionally included are processes of separating (splitting) and joining, if large or complicated workpieces are built up out of individual parts.
- The exact processes of separating and joining are not listed here in detail.
- According to the characteristic differences in free forming (or unrestricted forming) and die forming (restricted forming), forging can be divided into open-die forging and die forging.
Processes for changing cross-sections

- The processes for changing cross-sections build-up the fundamentals of forging.
- According to the law of constant volumes, changes in cross-section lead to corresponding changes in length.
- The cross-section can be changed by material displacement and material accumulation, whereby the processes of material displacement dominate.
### Processes for changing cross-sections

<table>
<thead>
<tr>
<th>Material displacement</th>
<th>Open-die forming</th>
<th>Closed-die Forming</th>
<th>Pushing through</th>
<th>Rolling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drawing out</td>
<td>Drawing out over a mandrel</td>
<td>Upsetting in a die</td>
<td>Solid forward impact extrusion</td>
<td>Stretch rolling</td>
</tr>
<tr>
<td>Spreading</td>
<td>Radial forging</td>
<td>Radial forging in a die</td>
<td>Backward cup impact extrusion</td>
<td>Ring rolling</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Solid lateral impact extrusion</td>
<td>Cross rolling</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material accumulation</th>
<th>Upsetting</th>
<th>Heading</th>
</tr>
</thead>
</table>

| Combined material displacement and accumulation | Upset die forging |

Source: K. Lange
Processes for changing direction

These processes include bending processes (free bending, die bending) and shear forming processes.
Characteristics of open die forging

**Merits:**
- No special tools (costs, fabricating time)
- Simple forms

**Problems:**
- High machining costs
- Material not optimally used
- Grain flow (fibre structure) not optimal

**Applications:**
- For low production series
- Test samples and prototypes
- Especially large dimensions
- Shortest delivery times

**Alloys:**
- Mainly medium and high-strength
Characteristics of die forging

**Merits:**
- Optimal microstructure
- Grain flow (fibre structure) made to suit
- Complicated forms
- Low amount of machining
- Efficient use of material

**Problems:**
- Tool costs

**Applications:**
- For large production series
- Highest demands on strength + toughness
- Safety parts

**Alloys:**
- Mainly medium to high-strength materials
Special forging processes and their aims

<table>
<thead>
<tr>
<th>Process</th>
<th>Characteristics</th>
<th>Advantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Precision forging</td>
<td>better forging quality</td>
<td>narrower tolerances, better replication of final form</td>
</tr>
<tr>
<td>2. High precision forging</td>
<td>best forging quality</td>
<td>narrower tolerances, better replication of final form, better surfaces</td>
</tr>
<tr>
<td>3. Closed die forging without flash</td>
<td>forging in closed dies</td>
<td>material savings</td>
</tr>
<tr>
<td>4. Powder forging (mostly combined with 3.)</td>
<td>sintered raw parts</td>
<td>material savings, fewer forming process steps, narrower tolerances</td>
</tr>
<tr>
<td>5. Isothermal forging</td>
<td>tool temperature ~ work temperature</td>
<td>better replication of final form</td>
</tr>
<tr>
<td>6. Superplastic forging (mostly combined with 3)</td>
<td>as in 5.; very low forming speeds</td>
<td>material savings, fewer forming process steps, better replication of final form</td>
</tr>
<tr>
<td>7. Squeeze casting</td>
<td>pressing in pasty state</td>
<td>fewer forming process steps, better replication of final form</td>
</tr>
<tr>
<td>8. Partial forging</td>
<td>stepwise fabrication</td>
<td>better replication of final form</td>
</tr>
<tr>
<td>9. Thermomechanical working</td>
<td>combined forging and structure change</td>
<td>better mechanical properties</td>
</tr>
</tbody>
</table>
Closed die forging without flash

= Die forms in closed tools from which no material is lost

- Constant volume of hot starting, intermediate and final form
- Exact mass distribution
- Exact positioning
- No flash

 ↔ Weight savings
 ↔ No flash
 ↔ Shorter production times for finished part
Failure and damaging of forging dies

Damage is a result of:
- the *mechanical loading* (repeated) due to forming resistance and geometrical conditions,
- the *thermal stressing* due to workpiece and tool temperature as well as pressure contact time,
- the *tribological conditions* at the contact zone between workpiece and tool.

- mechanical fatigue
- permanent deformation
- Wear (abrasion)
- thermal fatigue