## TALAT Lecture 3401

# Forging Alloys

21 pages, 18 figures

Basic Level

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### Objectives:

- to understand how the properties of forgings evolve during the manufacturing process

### Prerequisites:

- general understanding of metallurgy and deformation processes

**Date of Issue: 1994**

# 3401 Forging Alloys

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## 3401.01 Aluminium Alloys for Forging

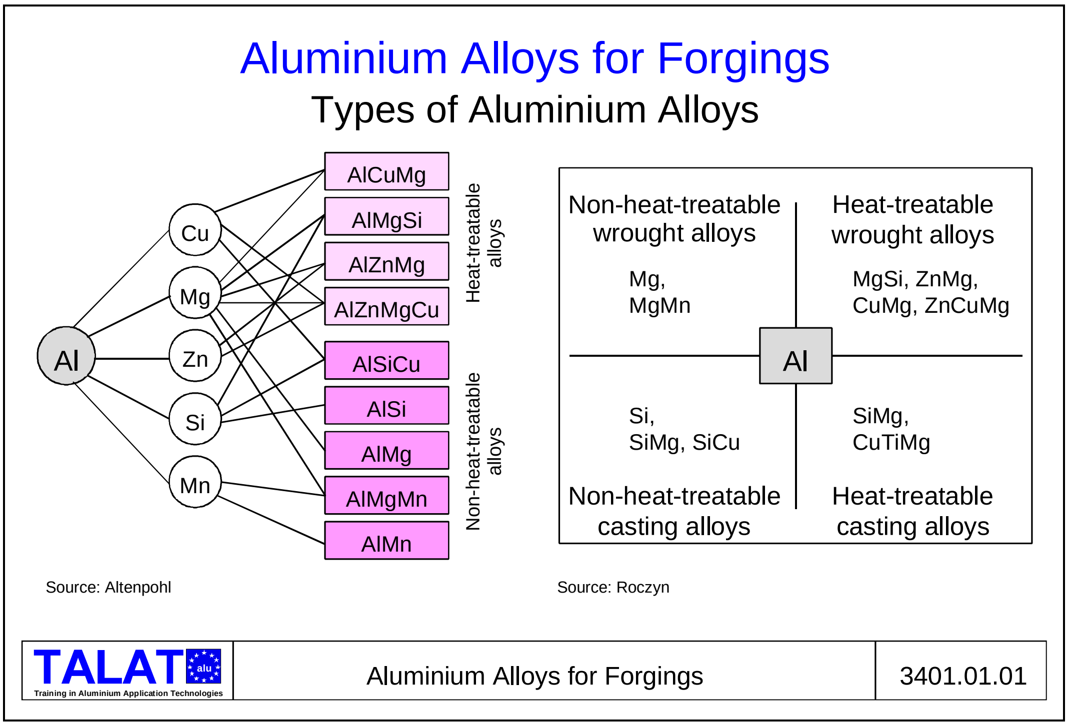
- Non-heat-treatable wrought alloys
- Heat-treatable wrought alloys

Due to its good formability and with the use of modern, efficient presses it is possible, to produce high-precision parts with excellent surface qualities which conform almost completely to end-use requirements with only a minimum of additional finishing still needed.

Aluminium alloys are especially suited for forming operations. It is possible to form aluminium using much higher degrees of deformation in a single forming step than is possible with steel or copper alloys.

With the high-strength aluminium alloys available, it is possible to use aluminium to its full advantage for technological applications beyond those in the classically established packaging sector.

A large number of aluminium alloys, ranging from pure aluminium up to the high-strength aluminium alloys, can be forged effectively (**Figure 3401.01.01**). All alloys standardised in the DIN EN 573 Pt.1 - 4 and DIN EN 586 Pt. 1 - 2 may be used. 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 Forgings

Types of Aluminium Alloys

Al

Cu

Mg

Zn

Si

Mn

AlCuMg

AlMgSi

AlZnMg

AlZnMgCu

Heat-treatable alloys

AlSiCu

AlSi

AlMg

AlMgMn

AlMn

Non-heat-treatable alloys

Source: Altenpohl

| Non-heat-treatable wrought alloys | Heat-treatable wrought alloys |
|---|---|
| Mg,<br>MgMn | MgSi, ZnMg,<br>CuMg, ZnCuMg |
| Si,<br>SiMg, SiCu | SiMg,<br>CuTiMg |
| Non-heat-treatable casting alloys | Heat-treatable casting alloys |

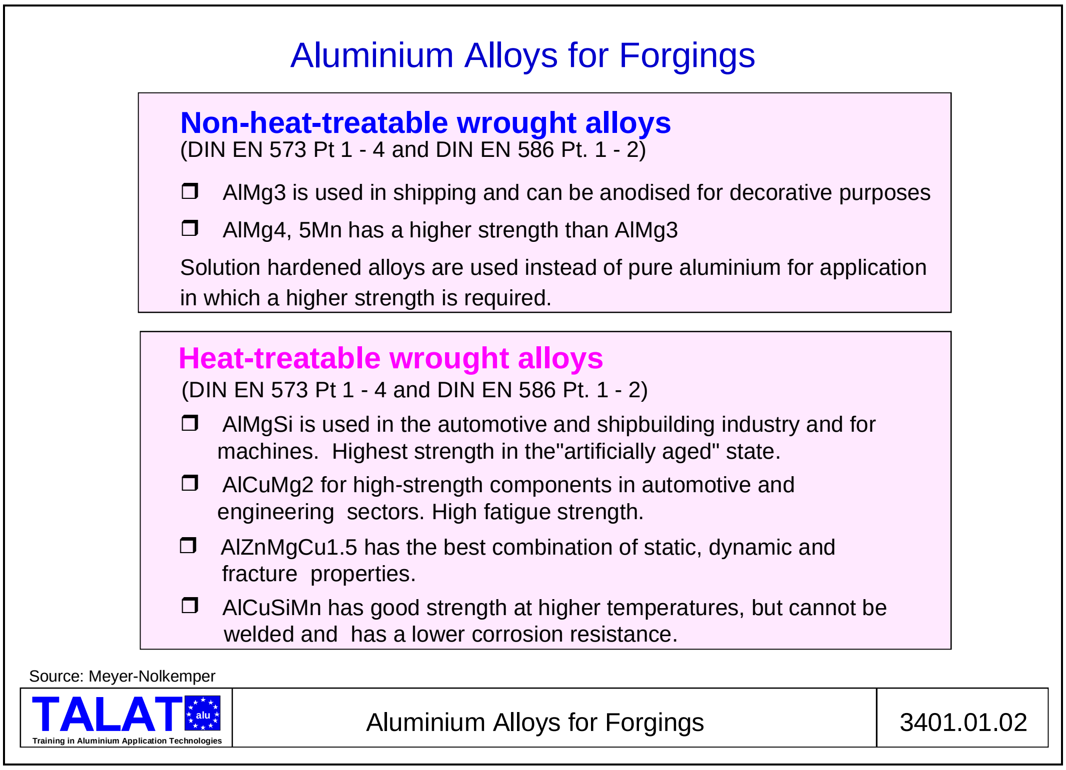
Al

Source: Roczyn

TALAT Training in Aluminium Application Technologies | Aluminium Alloys for Forgings | 3401.01.01

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, i.e. solution treated, quenched and aged, in order to deliver the most suitable service properties.

The strength of pure, unalloyed aluminium Al99,5 is only 65 N/mm² and thus too low for many technical applications. For such purposes one uses aluminium alloys based on Al99,5 with additions of one or more alloying elements. The so-called high-strength aluminium alloys have tensile strengths exceeding 600 N/mm² (**Figure 3401.01.02**).



Aluminium Alloys for Forgings

**Non-heat-treatable wrought alloys**
(DIN EN 573 Pt 1 - 4 and DIN EN 586 Pt. 1 - 2)

❒ 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 wrought alloys**
(DIN EN 573 Pt 1 - 4 and DIN EN 586 Pt. 1 - 2)

❒ 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.

Source: Meyer-Nolkemper

TALAT alu Training in Aluminium Application Technologies | Aluminium Alloys for Forgings | 3401.01.02

## Non-Heat-Treatable Wrought Alloys

The main alloying elements for this group of non-heat-treatable alloys are magnesium and manganese added either solely or jointly. With respect to effects on strength the most important alloying element is magnesium, which leads to large increases in strength and hardness. Manganese also increases the alloy strength, but to a much lower extent than equivalent amounts of magnesium additions.

Non-heat-treatable aluminium alloys have a wide range of applications and are used in place of pure aluminium in applications which require higher material strengths. Non-heat-treatable alloys are used for decorative purposes, e.g. for the building and optical sectors, for electro-mechanical components, as well as for components subjected to corrosive environments, e.g. in ship-building and chemical industries as well as for welded structures.

## Heat-Treatable Wrought Alloys

Heat-treatable alloys are obtained by adding alloying elements whose solid solubility in aluminium increases with rising temperature.

The heat-treatable aluminium alloys of technical importance each contain one of the following metal combinations: -MgSi, -CuMg, -ZnMg and ZnMgCu.

By the proper choice of amounts and types of alloy additions as well as degree of straining and heat treating, it is possible to obtain medium and high-strength materials with strength properties superior to those of structural steel.

Heat-treatable alloys are generally used for applications which require materials of high strength. AlMgSi1 is the alloy most widely used for forgings. Characteristic for this alloy is the medium strength of 310 N/mm², the good machinability and weldability as well as the excellent corrosion properties. Consequently, AlMgSi1 is used very frequently for automotive and machine components. In addition, AlMgSi1 is used for parts subjected to a corrosive environment (ship-building).

The remaining alloys AlCuMg, AlCuSiMn and AlZnMgCu are considered as the classical forging alloys. They all have high strengths, good machinability and good dynamical and fracture properties. Among the aluminium alloys, AlCuSiMn has good high-temperature properties but is not weldable and must be protected against corrosion when used in aggressive environments. Components made from these materials are used for parts with the highest safety ratings in the automotive, machine construction and aerospace sectors.

Due to the specific production process used, all parts made of heat-treatable alloys have a certain amount of residual stress. Three-dimensional parts cool at locally different rates, which could cause thin-walled parts to warp. The residual stress can be reduced by post-stamping, overaging to condition T7 or by increasing the temperature of the quenching medium, thereby reducing the cooling rate. At the same time, these methods have a negative influence on the strength properties.

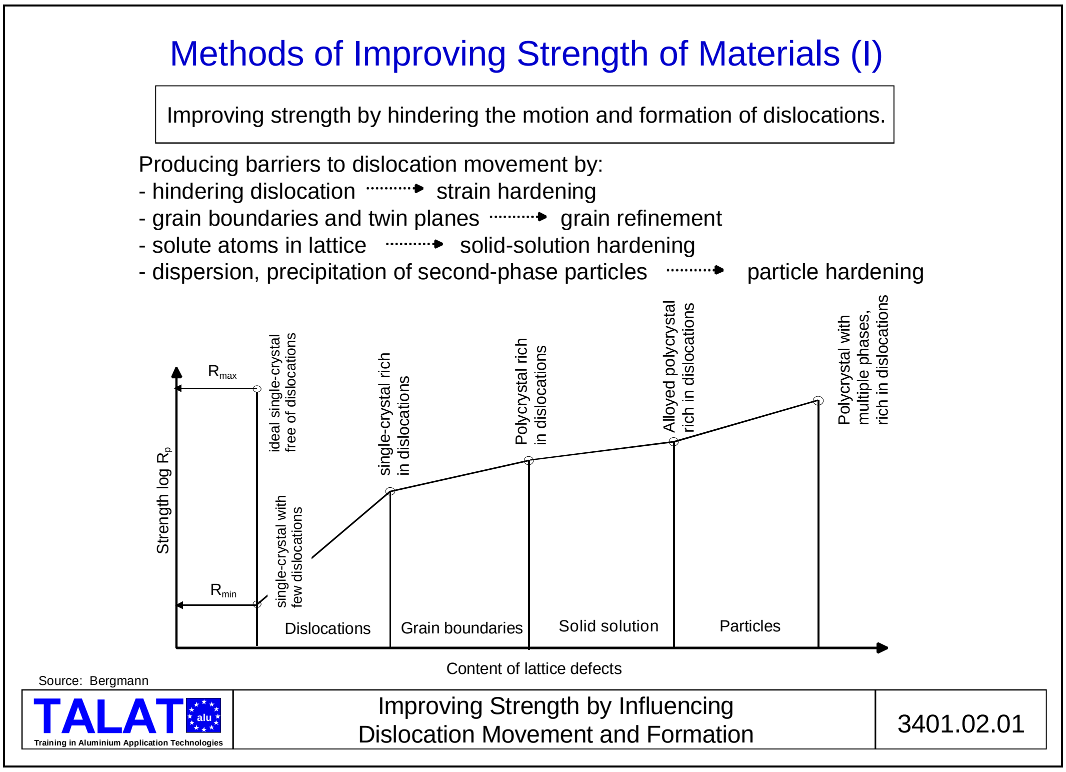
The AlZnMg groups of alloys are an exception, requiring low cooling rates, so that a cooling in forced air is generally sufficient.

## 3401.02 Methods of Improving Strength

- Strain hardening
- Solid solution hardening
- Particle hardening

The final properties of a material do not depend on the chemical composition alone but also on the treatment the material is subjected to, so that it is possible to obtain different states for materials with the same composition.

The state of a material is exactly defined and often possess a standardised strength range with an associated production process.



Methods of Improving Strength of Materials (I)

Improving strength by hindering the motion and formation of dislocations.

Producing barriers to dislocation movement by:
- hindering dislocation ··········▸ strain hardening
- grain boundaries and twin planes ··········▸ grain refinement
- solute atoms in lattice ··········▸ solid-solution hardening
- dispersion, precipitation of second-phase particles ··········▸ particle hardening

Source: Bergmann

| TALAT Training in Aluminium Application Technologies | Improving Strength by Influencing Dislocation Movement and Formation | 3401.02.01 |
|---|---|---|

Compared to other material groups, ductility is the most important property of metallic materials.

Metals have a high ductility and can thus be easily formed and are not susceptible to brittle failure. This advantage is limited by the fact that when the metal is deformed plastically, the ductility decreases. For this reason, the yield strength is the characteristic strength value used for dimensioning statically loaded components. The static strength can only be increased by increasing the resistance to plastic deformation, i.e. the resistance to the movement and creation of dislocations. Consequently, the lattice must be filled with obstacles to dislocation movement. Some such methods are listed in **Figure 3201.02.01:**

- hindering dislocations (cold forming) = $\Delta R_d$
- grain and twinning boundaries (grain refinement) = $\Delta R_{gb}$
- solute atoms in the lattice (solid solution hardening) = $\Delta R_{ss}$
- precipitation of second phase particles (precipitation hardening) = $\Delta R_{ph}$

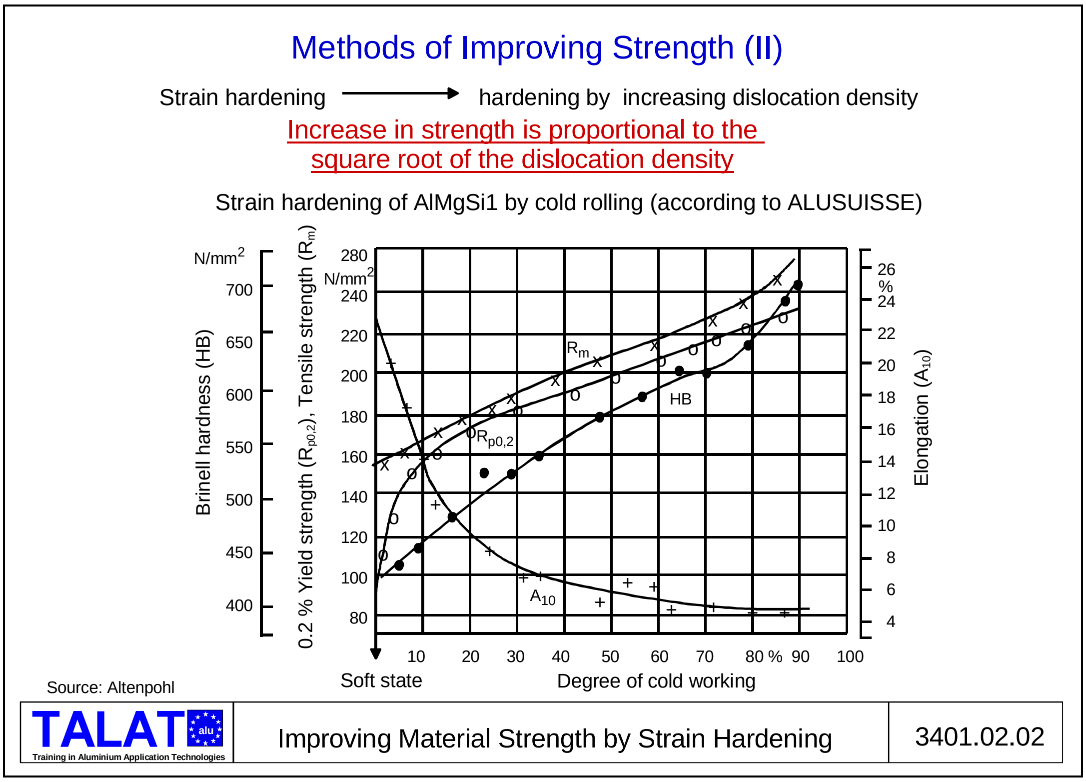
The yield strength $R_p$ of a real material can be calculated as follows:

$$R_p = R_{min} + \Delta R_d + \Delta R_{gb} + \Delta R_{ss} + \Delta R_{ph}$$

$R_{min}$ is the basic strength of the real, plastic but unstrained lattice.

## Strain Hardening

The increase of strength associated with plastic deformation is based on hardening due to dislocations. The hardening effect which increases with increasing dislocation density, is a result of the blocking and hindering actions of the dislocation arrangements. The dislocation arrangements are created as a result of the different opposing dislocation reactions.



Methods of Improving Strength (II)

Strain hardening → hardening by increasing dislocation density

Increase in strength is proportional to the square root of the dislocation density

Strain hardening of AlMgSi1 by cold rolling (according to ALUSUISSE)

Source: Altenpohl

TALAT | Improving Material Strength by Strain Hardening | 3401.02.02

The increase in strength of all metals can be calculated quite accurately using the law based on the square-root of the dislocation density, ρ.

Single phase metals can be hardened only by plastic deformation, if one neglects the effect of changing grain size and the composition.

**Figure 3401.02.02** illustrates that hardness, tensile strength and yield strength increase with increasing degree of cold deformation. This effect is a result of the dislocation multiplication and the following dislocation reactions.

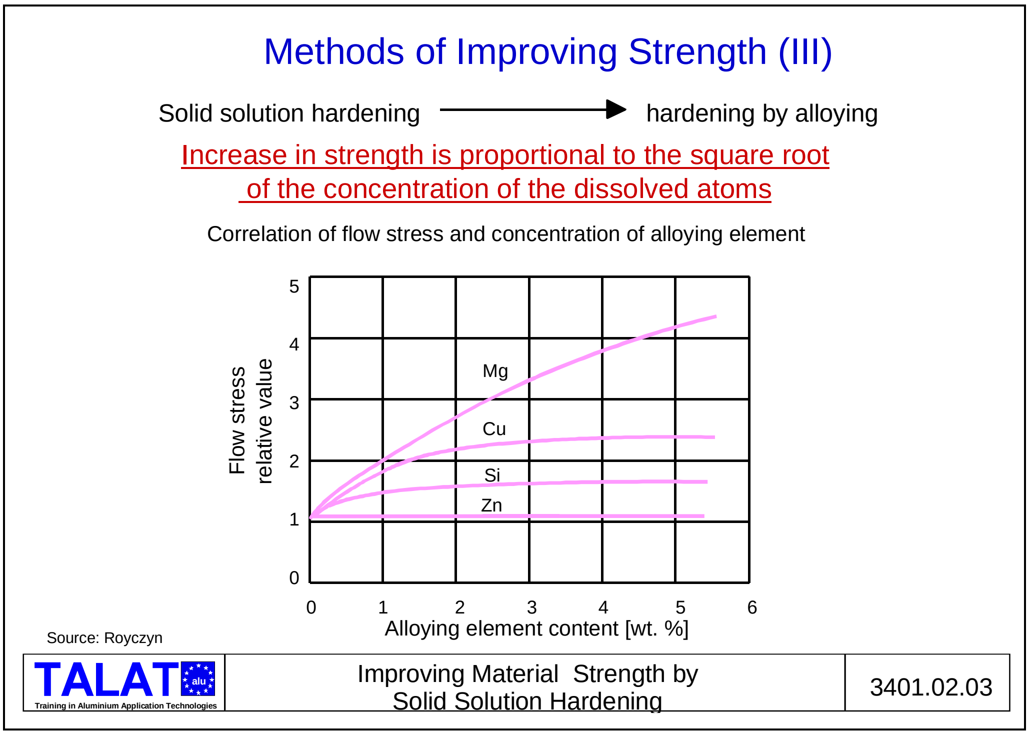
## Solid Solution Hardening

Attractive and repulsive forces interact between dislocations and the solute atoms in solid solution. Thus, foreign atoms that are larger than the matrix atoms are located mostly in the tensile-stressed regions of the dislocations, the smaller foreign atom mostly in the compressively stressed regions of the dislocations. The dislocations are therefore surrounded by "clouds of foreign atoms". A gliding dislocation must drag this cloud along with it  or break free from it, the latter requiring high energy.

The forces interacting between foreign atoms and dislocations depend on the difference in size between alloying and matrix atoms as well as the binding energy between them.

The increase in strength due to solid solution has been found to be proportional to the square root of the amount of solute atoms, c dissolved.

Elements are alloyed to metals mainly to influence such properties as chemical stability, hardenability, toughness, weldability or the creation of hard particles. The increase in strength due to solid solution action is a secondary welcome effect.



Methods of Improving Strength (III)

Solid solution hardening → hardening by alloying

Increase in strength is proportional to the square root of the concentration of the dissolved atoms

Correlation of flow stress and concentration of alloying element

Source: Royczyn

TALAT Training in Aluminium Application Technologies | Improving Material Strength by Solid Solution Hardening | 3401.02.03

**Figure 3401.02.03** illustrates the influence of solute hardening which is due to a difference in the atomic radii between solute and matrix (solvent) atoms. Thus magnesium additions (Δr = 1.7 Å) have a greater strengthening effect than additions of silicon (Δr = 1.32 Å), copper (Δr = 1.5 Å) and zinc (Δr = 0.5 Å).

## Particle Hardening

The most common hardening mechanism is based on the fact that hard particles embedded in the matrix offer a resistance to the motion (slip) of dislocations. These particles are mainly relatively small amounts (up to about 10 volume %) of precipitations of a brittle second phase, b, out of the solid solution and have a coherent, partly coherent or incoherent interface with the matrix phase.

The degree of strengthening resulting from the second-phase dispersion depends not only upon the type and amount but to a large extent on the distribution of the particles in the matrix.

Thus, a more uniform distribution of the same amount of particles can cause a large increase in strength.

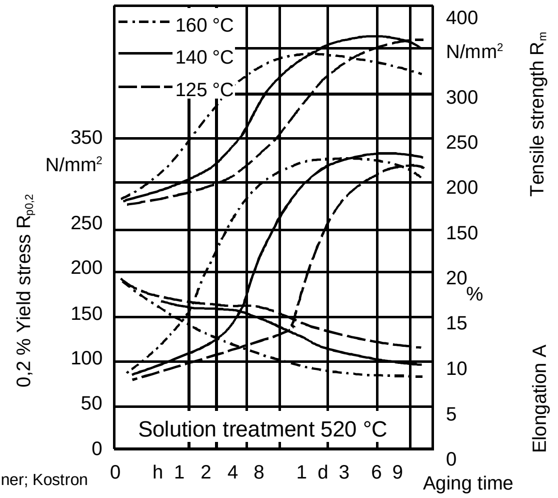
Microstructures with finely dispersed precipitates can be obtained by aging, tempering or dispersion hardening.

**Figure 3401.02.04** illustrates the characteristic mechanical and technological values for AlMgSi1 (6082) as a function of ageing time and ageing temperature after solution treatment at 520° C.

### Methods of Improving Strength (IV)

Precipitation hardening → hardening by particles (second-phase precipitation)

Strength of AlMgSi1 as a function of aging time



Increase in strength is proportional to the type, amount and distribution of the particles

Source: Brenner; Kostron

TALAT Training in Aluminium Application Technologies | Improving Material Strength by Precipitation Hardening | 3401.02.04

**Figure 3401.02.04** indicates that the peak strength values are obtained at shorter ageing times when higher ageing temperatures are used. Thus, the ageing time decreases with increasing ageing temperature. If ageing is carried out beyond the peak value, the strength falls (“overageing“).

## Short theory of ageing of aluminium alloys

**Prerequisites:**
The composition of the alloy must be such that at room temperature the α-phase is in equilibrium with a second phase (β) (alloy type: see **Figure 3401.01.01**).

**Solution heat treatment:**
The temperature for solution heat treatment must be below the eutectic temperature in order to prevent melting of any eutectic phases which may be present. The coarse ß-phases go into solution during solution heat treatment.

**Quenching:**
The very rapid cooling from the solution heat treatment temperature down to about 70 °C prevents diffusion processes so that an supersaturated condition is obtained.

**Ageing:**
Controlled by a time and temperature dependent diffusion process β-rich particles precipitate within the supersaturated aluminium matrix. Depending on the ageing conditions these precipitates may be either coherent, semi-coherent or incoherent within the aluminium lattice with corresponding effects on the properties.

## 3401.03 Microstructure

- Influence of fiber structure
- Defects due to non-uniform flow

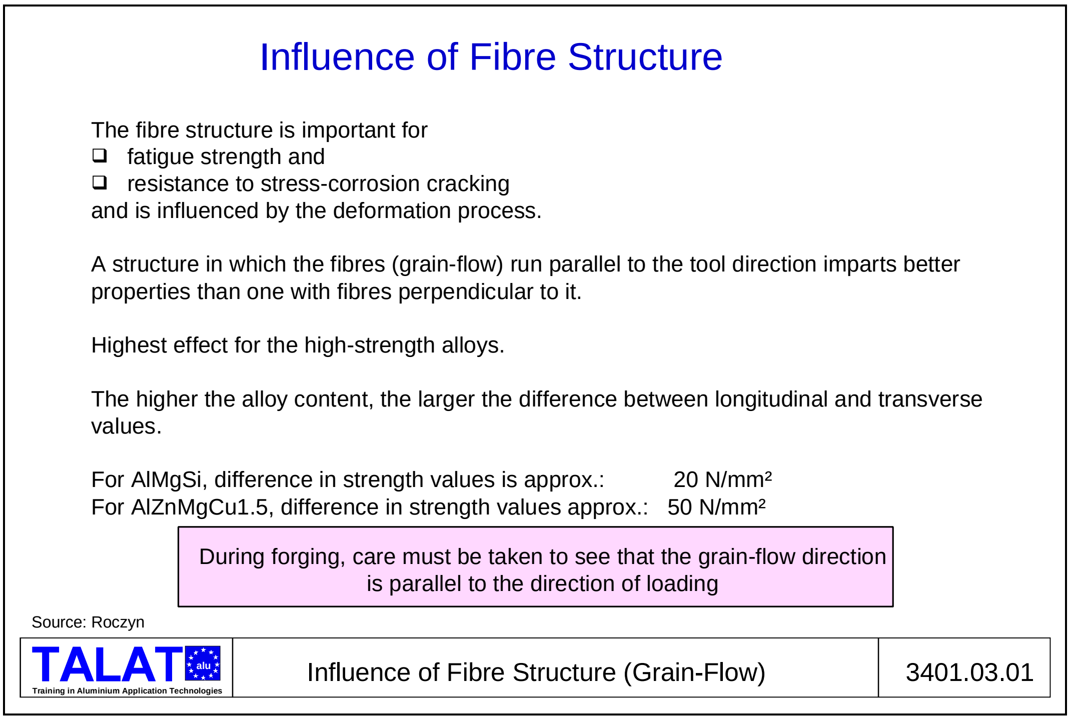
### Influence of Fiber Structure (Figure 3401.03.01)

Characteristic for forgings is that strength values are not isotropic over the bulk of the 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. 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.

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 Fibre 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

Source: Roczyn

| TALAT Training in Aluminium Application Technologies | Influence of Fibre Structure (Grain-Flow) | 3401.03.01 |
|---|---|---|

### Defects due to Non-Uniform Flow

In order to obtain a uniform, undisturbed fibre structure, the metal must be able to 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 (see Figure 3403.06.03 and Figure 3403.06.05).

# 3401.04 Forging Process Data and Forging Properties

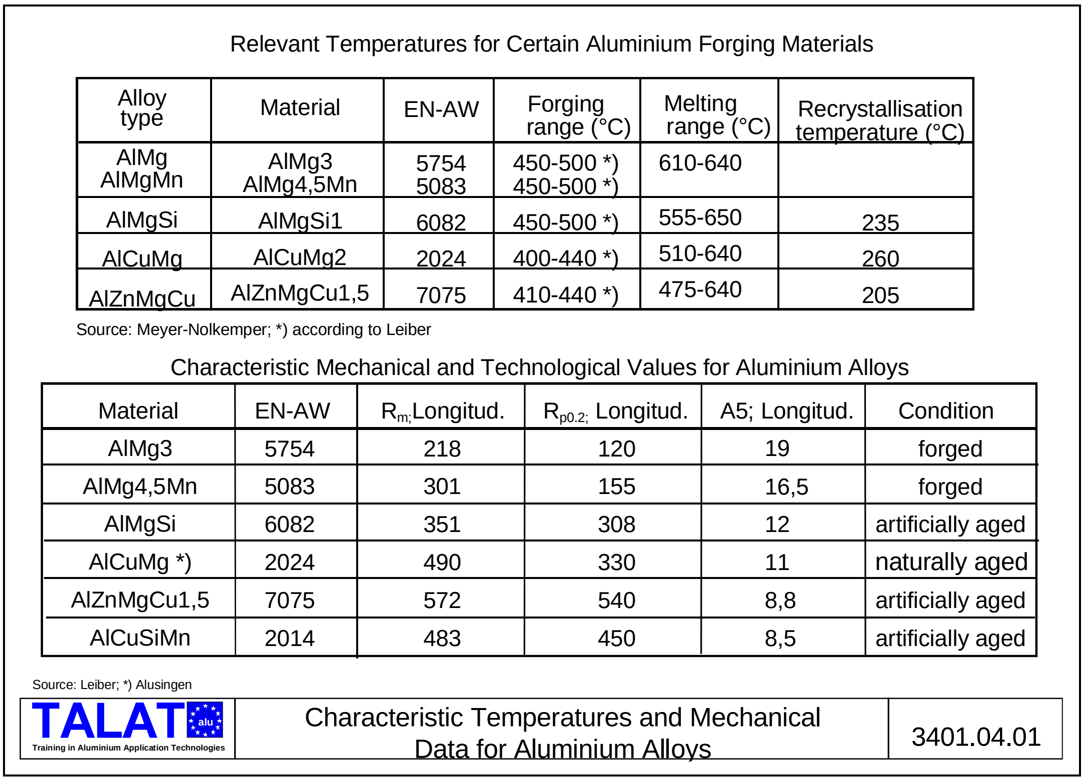
- Characteristic temperatures for certain aluminium forging alloys
- Characteristic mechanical property values for some forged alloys
- Forging temperature and die temperature
- Influence of temperature and forming rate on flow stress

## Characteristic Temperatures for Certain Aluminium Forging Alloys

Forging temperatures depend on melting temperature ranges of the forging alloys as seen in **Figure 3401.04.01**.

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.



Relevant Temperatures for Certain Aluminium Forging Materials

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

Source: Meyer-Nolkemper; *) according to Leiber

Characteristic Mechanical and Technological Values for Aluminium Alloys

| Material | EN-AW | $R_{m;}$Longitud. | $R_{p0.2;}$ Longitud. | A5; Longitud. | Condition |
|---|---|---|---|---|---|
| AlMg3 | 5754 | 218 | 120 | 19 | forged |
| AlMg4,5Mn | 5083 | 301 | 155 | 16,5 | forged |
| AlMgSi | 6082 | 351 | 308 | 12 | artificially aged |
| AlCuMg *) | 2024 | 490 | 330 | 11 | naturally aged |
| AlZnMgCu1,5 | 7075 | 572 | 540 | 8,8 | artificially aged |
| AlCuSiMn | 2014 | 483 | 450 | 8,5 | artificially aged |

Source: Leiber; *) Alusingen

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Characteristic Temperatures and Mechanical Data for Aluminium Alloys

3401.04.01

## Characteristic Mechanical Property Values for some Forged Alloys

**Figure 3401.04.01** shows that the heat-treatable alloys in an aged condition have much higher strengths but lower ductilities than non-heat-treatablealloys in the as-forged state.

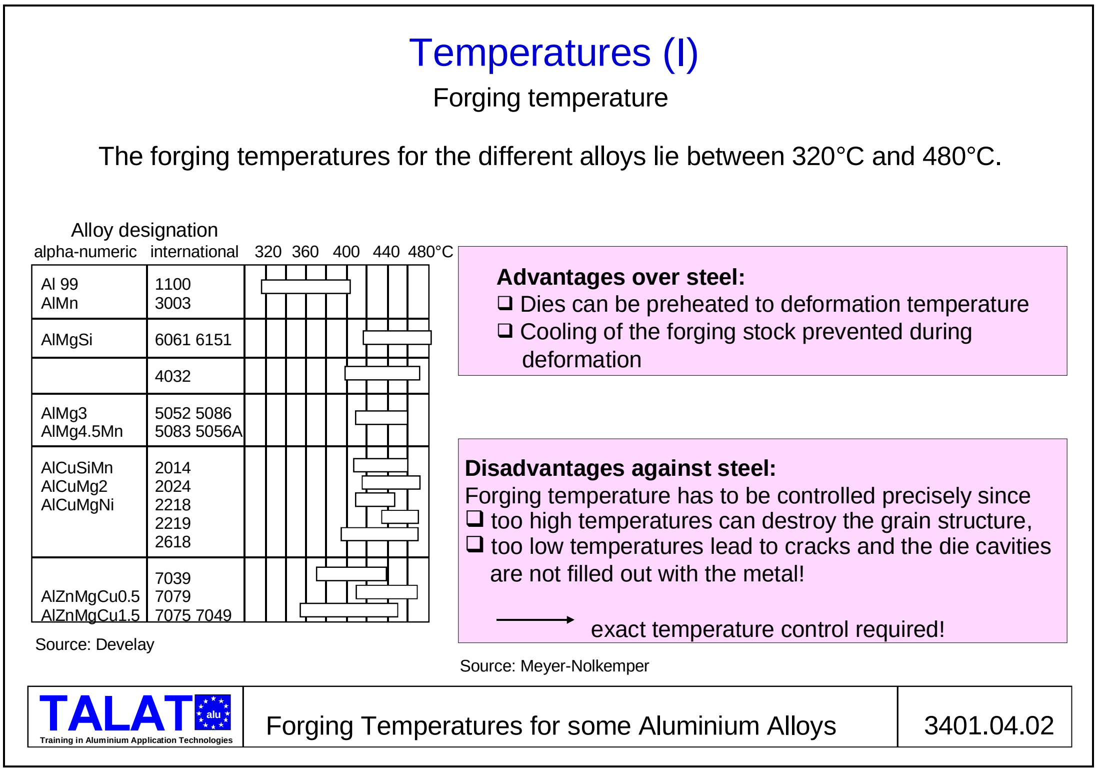
## Forging Temperature and Die Temperature

The forming temperature lies between 320 and 480 °C, depending on the alloy, see **Figure 3401.04.02**. 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.

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.

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 than depicted in **Figure 3401.04.02** 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.



Temperatures (I)

Forging temperature

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

Source: Develay

**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!

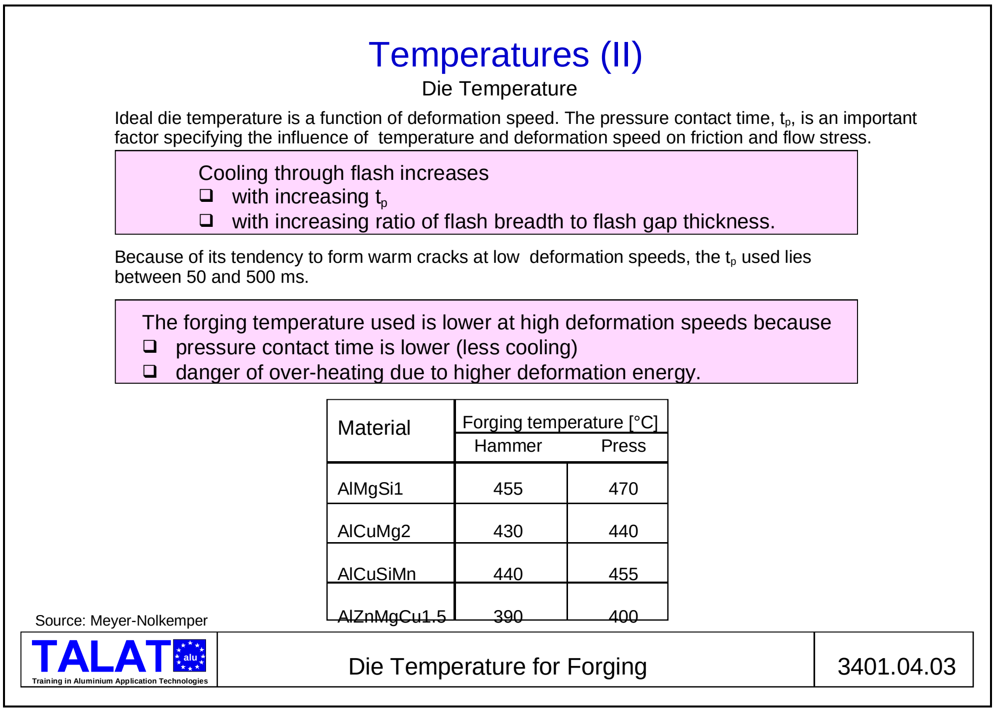
Source: Meyer-Nolkemper

TALAT Training in Aluminium Application Technologies | Forging Temperatures for some Aluminium Alloys | 3401.04.02

## Influence of Temperature and Forming Rate on Flow Stress

Small simple forgings made of alloys with high formability are forged using hammer and mechanical presses. Large, complicated forgings made of alloys with low formability are forged using hydraulic presses.

Forming speeds should be chosen carefully to avoid local overheating. In other words, enough time should be available during forming for the metal temperature to equalise. As a result, the ram velocities and deformation rates can vary within a wide range. The striking speed of a hammer forge varies from 5 to 6 mm/s. The deformation rates in hydraulic forging presses are only a few mm/s, being even lower for so-called creep-forming which leads to low flow stresses (see **Figure 3401.04.03**).



Temperatures (II)

Die Temperature

Ideal die temperature is a function of deformation speed. The pressure contact time, $t_p$, is an important factor specifying the influence of temperature and deformation speed on friction and flow stress.

Cooling through flash increases
- ❑ with increasing $t_p$
- ❑ with increasing ratio of flash breadth to flash gap thickness.

Because of its tendency to form warm cracks at low deformation speeds, the $t_p$ used lies between 50 and 500 ms.

The forging temperature used is lower at high deformation speeds because
- ❑ pressure contact time is lower (less cooling)
- ❑ danger of over-heating due to higher deformation energy.

| Material | Forging temperature [°C] | |
|---|---|---|
| | Hammer | Press |
| AlMgSi1 | 455 | 470 |
| AlCuMg2 | 430 | 440 |
| AlCuSiMn | 440 | 455 |
| AlZnMgCu1.5 | 390 | 400 |

Source: Meyer-Nolkemper

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Die Temperature for Forging

3401.04.03

Temperature and deformation speed have opposing effects on the flow stress. When the temperature increases, softening processes dominate, causing the flow stress to fall. At high deformation speeds, hardening processes predominate, causing the flow stress to increase.

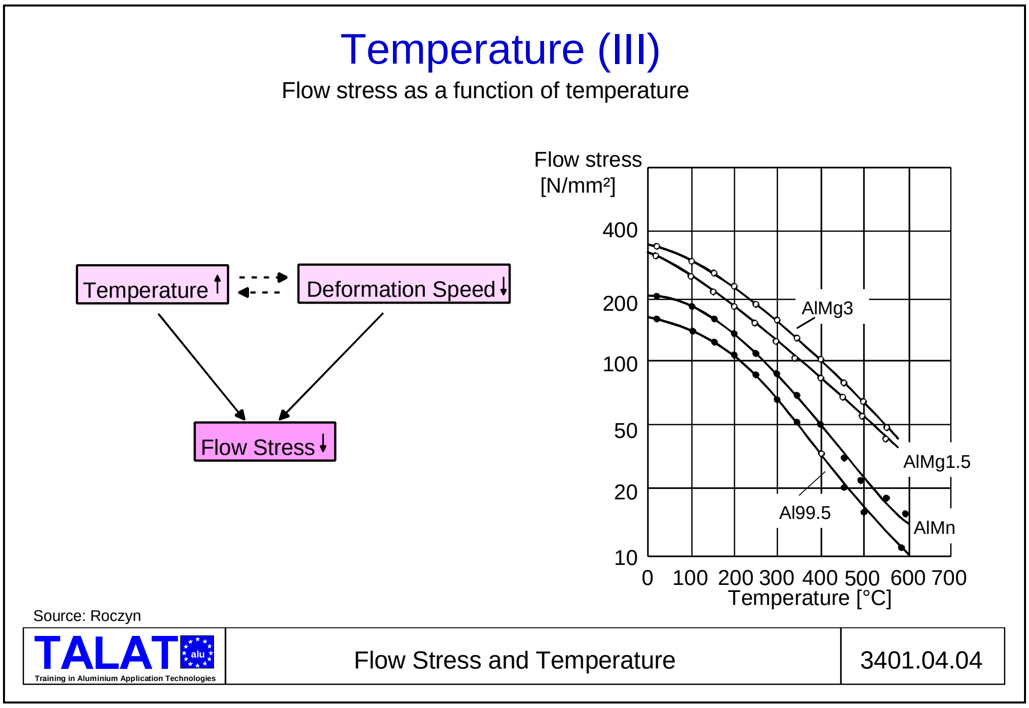
At high temperatures and finite deformation speeds, two opposing processes are in operation. On the one hand, a softening due to recovery and recrystallisation processes resulting from the annihilation of dislocations or from the overcoming of dislocation barriers due to thermal activation, and on the other hand hardening due to dislocation multiplication and dislocation reactions leading to barriers for dislocation motion.

At a given temperature and deformation speed, the dominating process depends on the material and the amount of predeformation already present in the material. This also explains the influence of speed on the flow stress at high temperatures.

The influence of deformation speed on the flow stress is a consequence of the time and temperature dependent recovery and recrystallisation processes. At higher temperatures, these are more intensive, so that time and consequently speed have a greater influence than at room-temperature. The flow stress increases with increasing deformation speed because softening processes are less complete the higher the deformation speed.

**Figure 3401.04.04** illustrates the influence of temperature on the flow stress for 4 non-heat-treatable alloys. This also clearly indicates the influence of magnesium on flow stress.

The flow stress decreases with increasing temperature.



Temperature (III)

Flow stress as a function of temperature

Source: Roczyn

| TALAT | Flow Stress and Temperature | 3401.04.04 |
|---|---|---|

**Figure 3401.04.05**, **Figure 3401.04.06** and **Figure 3401.04.07** illustrate the flow stresses as a function of the degree of deformation (flow curves) and as a function of the deformation speed for three heat-treatable alloys: AlMgSi1 (6082), AlCuMg2 (2024) and AlZnMgCu1.5 (7075). Alloys AlCuMg2 and AlZnMgCu1,5 have considerably higher strengths than AlMgSi1. All alloys, however, behave similarly.

The flow stress increases with increasing deformation speed and decreases with increasing temperature.

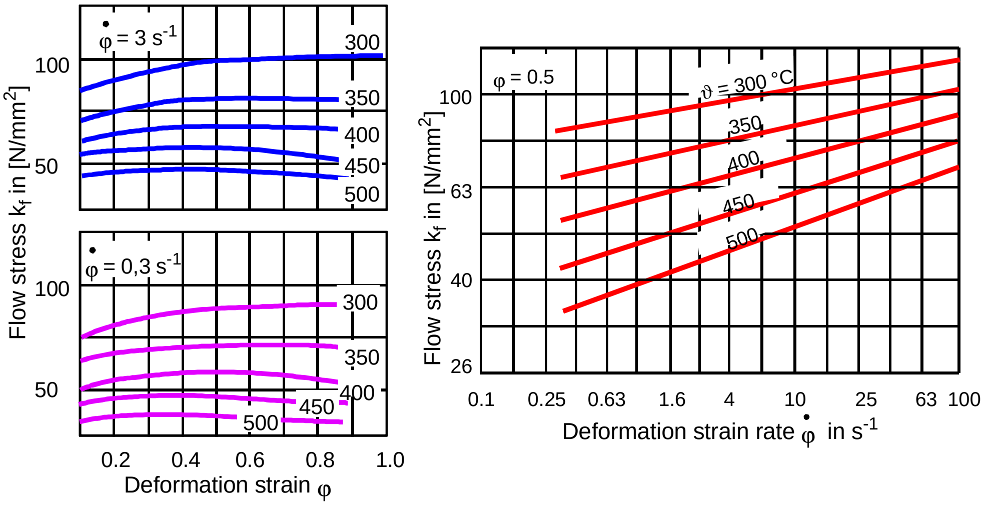
At constant temperature and constant deformation speed, the flow stress increases with increasing degree of deformation (true strain φ) up to maximum value. At higher temperatures, this maximum shifts to lower flow stresses.

The diagram for flow stress as a function of deformation speed illustrates that at usual forming temperatures, a 10-fold increase in the deformation speed changes the flow stress, $k_f$ , by a factor of 1.25. A lower deformation speed requires less force and consequently less deformation energy. Forging at low speeds has a double advantage as far as the temperatures in the forging stock are concerned:

- the temperature increase during deformation is low and
- more time is available for temperature equalization.

## Flow Curves for AlMgSi1

(Cylinder Compression Test)

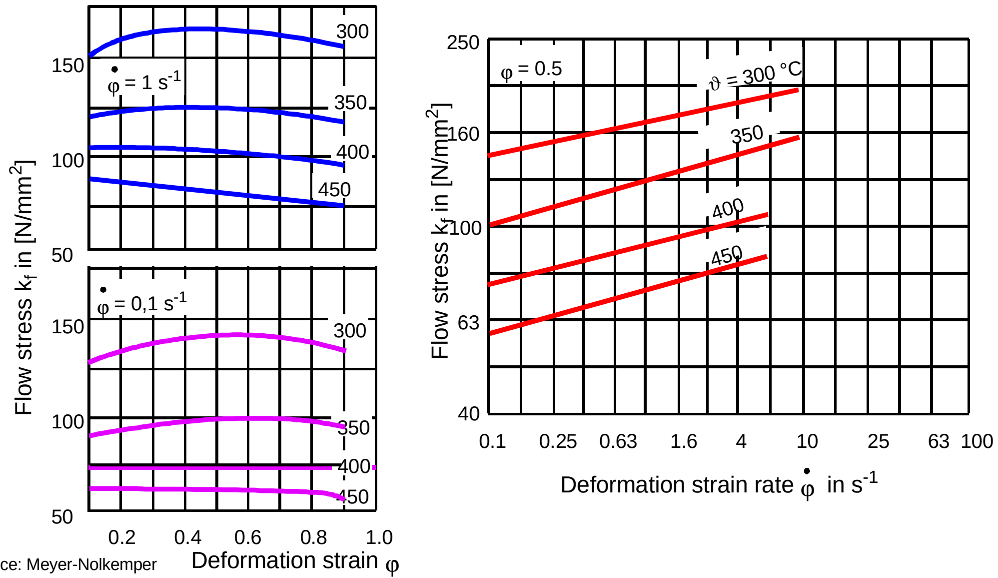


Source: Meyer-Nolkemper

| TALAT alu Training in Aluminium Application Technologies | Flow Curves for AlMgSi1 | 3401.04.05 |
|---|---|---|

## Flow Curves for AlZnMgCu1,5

(Cylinder Compression Test)

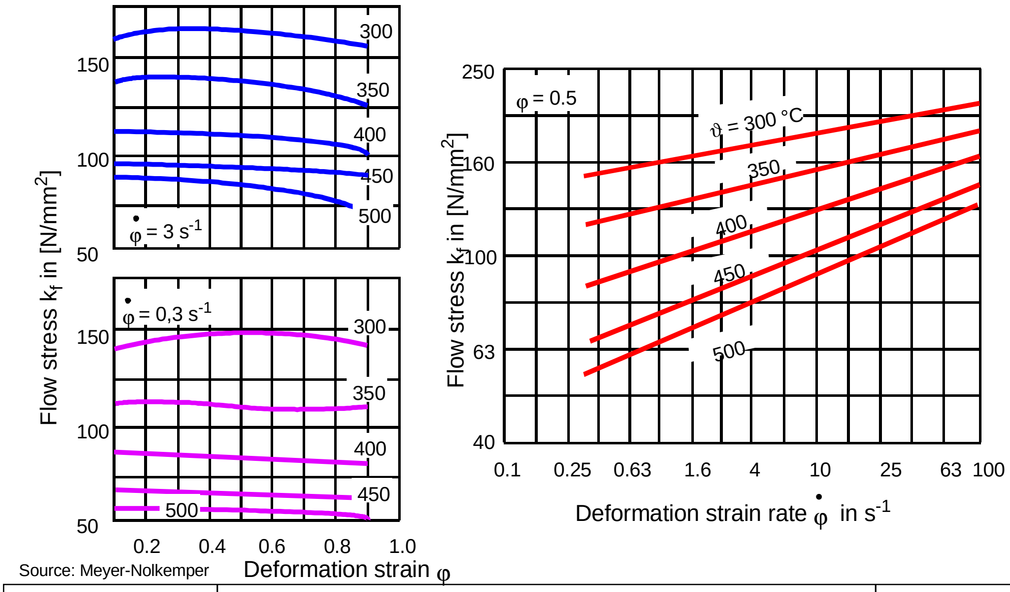


Source: Meyer-Nolkemper

| TALAT alu Training in Aluminium Application Technologies | Flow Curves for AlZnMgCu1,5 | 3401.04.06 |
|---|---|---|

Flow Curves for AlCuMg2

(Cylinder Compression Test)



Source: Meyer-Nolkemper

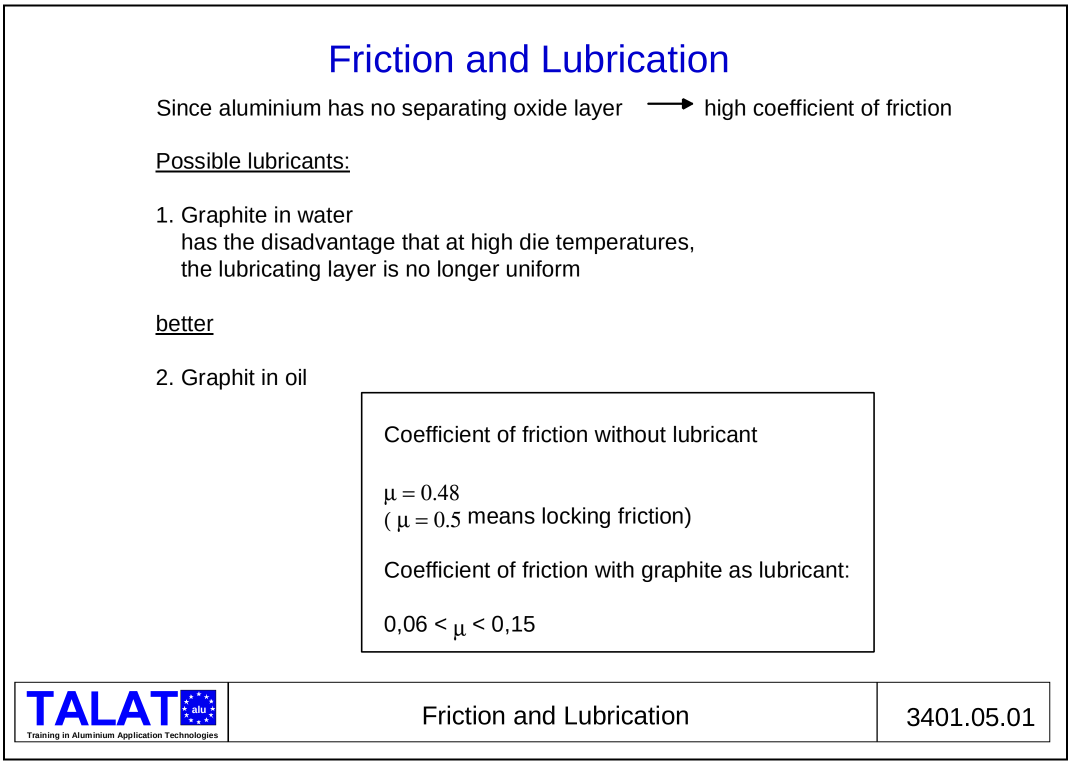
| TALAT Training in Aluminium Application Technologies | Flow Curves for AlCuMg2 | 3401.04.07 |
|---|---|---|

## 3401.05 Friction and Lubrication

Since aluminium does not possess a separating oxide layer during forging, the coefficient of friction is relatively large.

Depending on the die temperature, one uses a lubricant consisting of mostly graphite in oil or in water. For dies are heated to a high temperature, one uses a graphite-oil suspension, since the graphite-water suspension does not deliver a uniform lubrication.

Without the use of a lubricant the coefficient of friction, μ, is 0.48 (μ = 0.5 means locking friction). A graphite lubricant decreases this μ value to between 0,06 and 0.15, which is equal to the coefficient of friction of structural steel forgings using a graphite lubricant. These values are only valid as long as the lubricating film exists during forming. For longer gliding paths, the coefficient of friction can increase (**Figure 3401.05.01**).



## Friction and Lubrication

Since aluminium has no separating oxide layer ⟶ high coefficient of friction

Possible lubricants:

1. Graphite in water
   has the disadvantage that at high die temperatures,
   the lubricating layer is no longer uniform

better

2. Graphit in oil

Coefficient of friction without lubricant

$\mu = 0.48$
( $\mu = 0.5$ means locking friction)

Coefficient of friction with graphite as lubricant:

0,06 < $\mu$ < 0,15

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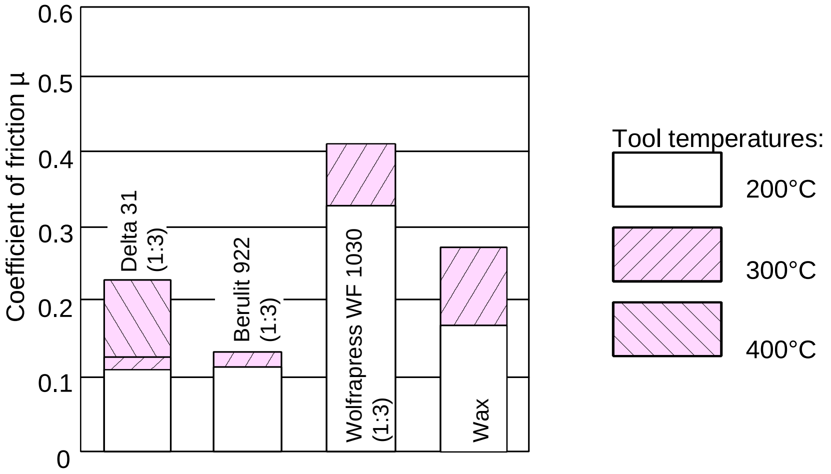
Friction tests have been conducted to test the suitability of different lubricants at forging temperatures commonly used for AlMgSi1 and AlZnMgCu1,5 and die temperatures of 200 to 400 °C.

**Figure 3401.05.02** and **Figure 3401.05.03** illustrate the results obtained for both test materials.

## Friction during Hot Forming of AlZnMgCu1.5



Source: Doege, Schoch

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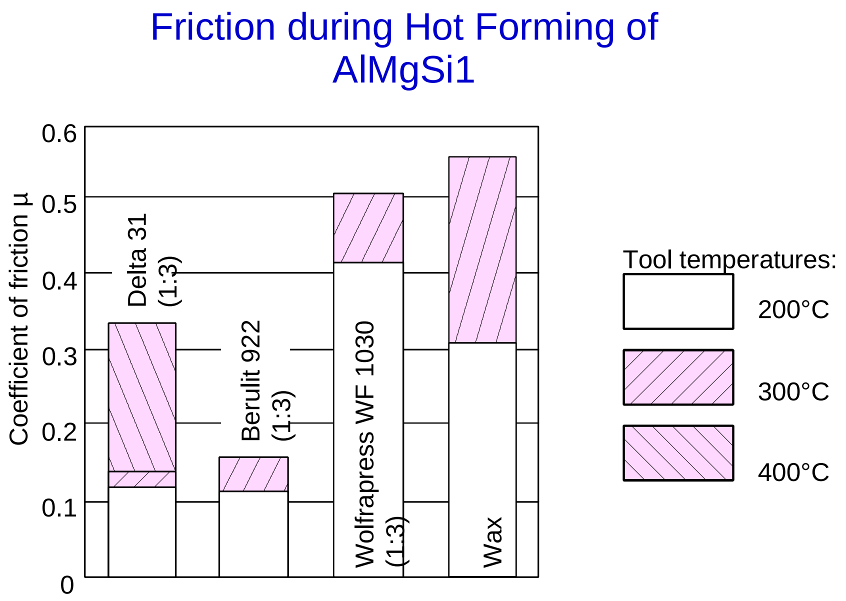
The results show that the graphite-based lubricants Delta 31 and Berulit 992 deliver a better friction behaviour than Wolfapress WF 1030 and wax. At lower die temperatures, the friction behaviour is just as good as for forging steel.

The reduction of friction during lubricating with graphite is based on the gliding action of individual macroscopic layers of graphite consisting of hexagonal rings of atomic carbon.

Increasing die temperature drastically increases friction which can reach as high as the locking friction value. The coefficient of friction for forming AlMgSi1 is clearly higher than for AlZnMgCu1,5. One reason could be the relatively lower strength of AlMgSi1.



Source: Doege, Schoch

TALAT Training in Aluminium Application Technologies | Friction During Hot Forming of AlMgSi1 | 3401.05.03

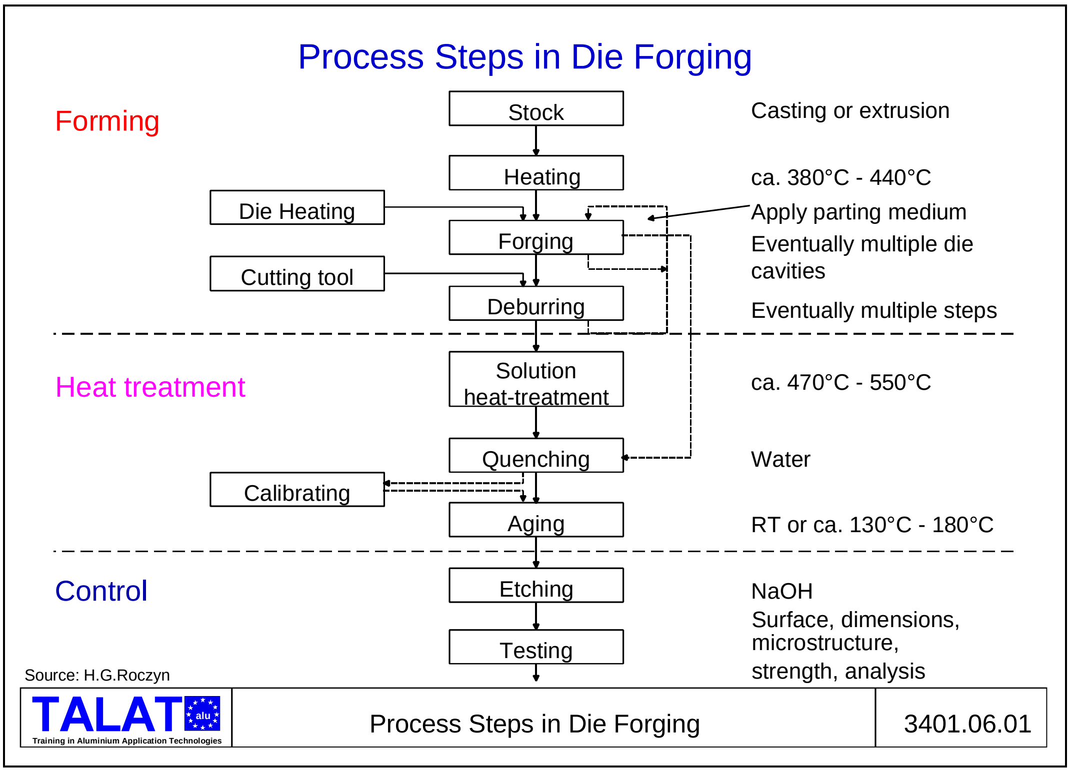
## 3401.06 In-Process Heat Treatment

Forgings made from age-hardening alloys are heat treated after forging in order to obtain the required strength levels and other mechanical, physical and chemical properties. The standard heat treatment procedure for forgings consists of solution treatment, quenching, and ageing.

In the simplified heat-treatment, the material should be formed at solution treatment temperatures which are slightly higher than the usual forging temperatures. The forgings are quenched from the forging temperature immediately after forming and then aged.

For a successful implementation of the simplified heat-treatment process, the temperature must be carefully and exactly controlled since the various aluminium alloys have relatively small temperature ranges for solution treatment ($\Delta T_{sol} < 40$ °C). The upper temperature is limited by the danger that partial melting at grain boundaries, thereby causing irreparable damage to the material. At temperatures below the solution treatment temperature, the required properties cannot be obtained.

**Figure 3401.06.01** gives a schematic view of the full production sequence for aluminium forgings, starting with forging from cast or extruded stock, heat treatment and ending with the necessary quality control. Etching in caustic soda is required for detection of surface folds.



Process Steps in Die Forging

Source: H.G.Roczyn

TALAT Training in Aluminium Application Technologies | Process Steps in Die Forging | 3401.06.01

## 3401.07 Literature

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**Roczyn, H.G.:** Vortrag Schmieden von aluminium am IFU Stuttgart WS 92/93.

**H. Meyer-Nolkemper**: Gesenkschmieden von Aluminiumwerkstoffen (Parts I to IX), Aluminium, 55 (1979) No. 3, 4, 5, 6, 8, 9, 10, 11, and 12.

## 3401.08 List of Figures