In the aluminium-processing industry, several heat treatment process steps that are part of a complex production route are usually necessary to obtain the desired properties of a material. Although more expensive and highly complex, heat treatment processes are absolutely essential in most applications and, if sufficiently understood and properly used, definitely are a key step towards producing the optimum material.

In general, heat treatment is a process of changing the material properties by thermal, thermochemical or thermomechanical means [1]. Heat treatment processes are aimed at optimizing the performance characteristics of an aluminium product. During casting, purely thermal treatment is usually performed, whereas wrought alloys experience an additional forming process to heat treatment; this is what is called „thermomechanical“ treatment of material. Processes such as stress-relief annealing, soft annealing, solution annealing, diffusion annealing, recrystallization annealing, aging and hardening are aimed at deliberately changing the microstructure, bringing certain elements and phases into solution or transforming precipitates of defined types, quantities and sizes [2]. This article describes the processes occurring during these steps and their effects on the resulting material properties, illustrated by carefully selected examples. The underlying physical processes and the great variety of treatment processes are too complex to explain here in full, but we will provide a useful overview below.

It is important to internalize the metallurgical structure in order to understand heat treatment. The aluminium atoms are arranged in a face-centered cubic crystal lattice, which means that they are located at exactly defined sites. That crystal is never perfect, though. The crystal lattice is distorted by defects, which increases strength. Crystal lattice defects may be caused, for example, by foreign atoms with a radius different from that of aluminium. In general, there are zero-dimensional (point), one-dimensional (line), two-dimensional (surface) and three-dimensional (volume) defects. Zero-dimensional defects are, for example, lattice vacancies and foreign atoms located at lattice sites, one-dimensional defects are dislocations, two-dimensional defects are grain and phase boundaries, and three-dimensional defects are precipitates and pores. Such defects lead to a significant increase in lattice energy, and the material is not in thermodynamically equilibrium. To compensate for that imperfection by mass transfer (migration of atoms), the atoms must be mobile and have room to move. Lattice vacancies play a decisive role [3], the number of vacancies existing in the lattice being highly dependent on temperature. In equilibrium, lattice vacancies hardly occur at room temperature. The probability of finding a specific person on earth is 500 times higher than finding a lattice vacancy in aluminium. The higher the temperature, the larger the number of lattice vacancies. Shortly before the metal melts, the probability of finding a lattice vacancy is the same as finding a specific person in Kitzbühel. As the temperature increases, the mobility of the atoms also increases, and the atoms can migrate through lattice vacancies by lattice exchange. This process is referred to as diffusion. Almost all heat treatment processes are based on these two processes, and heat treatment is aimed at exerting a systematic influence on these two processes.

Each finished product that leaves AMAG has a complex thermal history. In order for a rolled product to have the property profile specified by the customer, the alloy composition, forming parameters and all heat treatment parameters must be matched with one another along the entire process chain.

As an example, Figure 1 shows the production route for an AlCuMg-type sheet:

Alloys of the Al-Cu-Mg (2xxx), Al-Mg-Si (6xxx) and Al-Cu-Mg-Zn (7xxx) families are referred to as heat-treatable wrought aluminium alloys. At AMAG, these alloys are continuously cast into slabs. Particularly in high-strength alloys, such as those of the 7xxx family, segregation (inhomogeneous distribution of alloying elements) occurs during metal solidification in addition to extremely high residual stresses as a result of non-uniform cooling due to physical reasons. For this reason, such rolling slabs can burst at room temperature even without external influence. To ensure that the employees can safely handle the slabs, high residual stresses must be reduced by the so-called stress-relief annealing process, in which the material is heated to elevated temperature, where the yield strength and the limiting creep stress are significantly reduced and the stress in the material can be reduced by plastic deformation. The subsequent cooling process must be slow and uniform to prevent new stresses from being introduced [4].

At AMAG, this process is often combined with homogenization to eliminate any local differences in chemical composition, i.e., microsegregation, resulting from solidification without any remelting of the material. Concentration equalization of alloying elements in the grain by diffusion does not occur until very high annealing temperatures are reached that approximate the temperature at which a fused area may begin to form on the material, for which long annealing times are required.

Figure 1: Simplified thermal history of an AlCuMg-type sheet material. Cold rolling is not required for plate products.

**Heat Treatment – A Brief Introduction**

**Heat treatment of heat-treatable aluminium alloys.**

What actually is it and why is it so important for product quality?

**Fig. 1:** Simplified thermal history of an AlCuMg-type sheet material. Cold rolling is not required for plate products.

**Melting**

**Casting and Solidification**

**Homogenization**

**Solution Annealing**

**Quenching**

**Stretching**

**Natural Aging**

**Hot Rolling**

**Cold Rolling**

**Temperature**

**Time**

**50 µm**

**50 µm**

**50 µm**

**Different phases with low melting point (MgZn$_2$, Al$_2$Mg, Zn$_2$Al, CuMg$_4$) occur, for example, in the well-known 7075 aerospace alloy. This alloy also shows a distinct segregation of elements in the aluminium mixed crystal. Additionally, a large number of intermetallic phases occur as a result of the large proportion of alloying elements (primarily Cu and Zn). It is essential to homogenize the microstructure and dissolve particularly the intermetallic phases with low melting point to prevent fused areas from occurring during subsequent hot rolling.**
Figure 2 shows the differences in microstructure (a) prior to and (b) after homogenization. Homogeneously dispersed fine dispersoids are also clearly visible.

After homogenization, the slabs are sawn and milled, and heated to hot rolling temperature in a slab heating furnace. This preheating process varies according to alloy and the required true strain and sometimes can replace separate homogenization. The hot rolling temperature must be high enough to enable the material to be appropriately formed (degree of rolling reduction) but in no case may be so high that fused areas occur. It is absolutely necessary to bear in mind that the energy input during rolling is actually converted into thermal energy and the material may heat up to even higher temperatures during rolling.

The key material characteristics are highly dependent on correct temperature control during rolling. Since variations of ± 5 °C may have a clearly measurable impact on the properties of the finished product, process control as a function of the alloy and continuous process control is a must. Depending on temperature control and composition, dynamic recrystallization may occur as early as in the rolling process.

During dynamic recrystallization, both solidification and softening processes occur at the same time, resulting in subgrain formation in the microstructure. Subgrains can be prevented from forming or coarsening by selective addition of alloying elements. Here, too, it is essential to have in-depth knowledge of the mechanisms of theromomechanical action and of how to manage them. Any process anneals that may be required will soften the material again and allow it to continue to be formed [5].

Prior to solution annealing, sheet materials are cold-formed, by which their strength is significantly increased because new dislocations are formed, whereas elongation after fracture decreases.

Subsequently, heat-treatable materials such as the alloy families mentioned above are solution-annealed. During solution annealing, specific alloying constituents (magnesium, silicon, zinc, copper) in the aluminum-mixed crystal are to be brought into solution and insoluble portions are to be made coalescent in a favorable manner (e.g., silicon). This is performed as near the alloy solidus temperature as possible to achieve fast kinetics during diffusion and avoid long annealing times. At the same time, however, the temperature must be lower than the melting temperature of phases with low melting point of the alloy because fused areas will make the product useless. AMAG has extensive expertise in that area and state-of-the-art heat treatment equipment.

Close cooperation with customers in the aerospace industry has raised our awareness of the issue of accurate temperature control. For example, TUS (Temperature Uniformity Survey) and SAT (System Accuracy Test) certifications ensure the reproducibility of heat treatment in our heat treatment furnaces, which our customers in the aerospace and automotive industries and all customers whose products are treated in our furnaces can benefit from. This technology provides precise measurement to guarantee that the set temperature is correct and maintained throughout the furnace, even in corners and at the furnace entry section.

After solution annealing, the material is rapidly cooled from red heat to room temperature. In this quenching process, the solution annealing condition is “frozen in,” the proportion of dissolved, hardening alloying elements being as large as possible, with a high concentration of lattice vacancies to ensure that the atoms are mobile enough during the subsequent aging process and, consequently, maximum kinetics of the subsequent precipitation processes. Aging is a temperature- and time-dependent process performed at elevated temperature (artificial aging) or at room temperature (natural aging), depending on the material. During aging, the foreign atoms that are dissolved in a supersaturated state migrate through the excess lattice vacancies by diffusion and can form coherent (little difference from the crystal lattice of the alloy), partly coherent and non-coherent precipitates. Most of these particles are metastable, and some of them can change the mechanical characteristics of the product by evolution at room temperature, which must be avoided with a view to the storage life of forming materials by taking special process steps.

Metastable phases affect the storage life and also the behavior of the material when reexposed to elevated temperature after storage: The so-called T6 treatment is the classical heat treatment for the highest possible strength at good elongation. In this process, particles of optimum size are precipitated. This process is shown in Figure 3. If the material should have maximum formability, it is not artificially aged prior to processing, but delivered to the customer in the soft T4 temper, which means that it is solution-anneled only (Figure 3).

If other characteristic values have to be specifically adjusted in addition to the classical mechanical properties, such as strength and formability, heat treatment may be required prior to or after solution annealing treatment.

For example, fracture toughness and the crack growth rate can be controlled by performing an adapted heat treatment process prior to solution annealing. Figure 4 shows an example of optimized heat treatment of a 2xxx-series aerospace alloy with improved damage tolerance properties. The sheets were produced in two different rolling and heat treatment cycles [6].

Figure 2a: 7075 microstructure prior to homogenization

Homogenizing Furnace
Horizontal Heat Treatment Furnace
Continuous Heat Treatment Line
Heating Furnace
Solution Annealing
Quenching
Artificial Aging
Figure 3: Classical T4- and/or T6-heat treatment process steps.

12
13
AluReport 01.2014
AluReport 01.2014
Condition ‘A’ material was solution-annealed in a continuous heat treatment line at a temperature of just under 500 °C and a holding time of a few minutes, and then quenched to room temperature using cold water. A complete cool of condition ‘B’ material was additionally annealed in a coil furnace at a temperature between 300 °C and 400 °C for two to five hours. After this annealing process, the material was solution-annealed in the continuous heat treatment line in the same way as condition ‘A’ material.

Figure 5 shows a three-dimensional representation of the different grain sizes and shapes of material in the conditions ‘A’ and ‘B’. Condition ‘A’ material has a fine-grained, equiaxed microstructure, whereas condition ‘B’ material has a coarse grain structure that is stretched in rolling direction.

At the measured fracture toughness values, the coarse-grained ‘B’ material has a lower crack growth rate. The better performance of the ‘B’ material is due to its oblong, coarser grain structure. A crack will follow the path of least resistance, which is normally found along the grain boundaries. In fine-grained microstructures, the crack can therefore grow along a relatively straight line. In a stretched, coarse grain, the crack is deflected and must cover a considerably longer distance, resulting in a significantly reduced crack growth rate [6]. Accordingly, fracture toughness and crack growth can be optimized by modifying the grain structure through heat treatment, while at the same time substantially improving the general resistance to corrosion. This is possible by just changing temperature control during the process.

An exceptionally complex sequence of heat treatment processes is performed when manufacturing automotive sheets from 6xxx-series alloys.

Natural aging after solution annealing results in the formation of dispersed clusters of foreign atoms and so-called GP zones in the T4 temper. The GP zones act as nuclei for the beta phase (β phase) during artificial aging, which increases strength. During artificial aging, however, small GP zones partly dissolve and will no longer be available as nuclei. It turned out that it was possible to noticeably improve the size and thermal stability of the GP zones by an additional heat treatment shortly after quenching from solution annealing temperature (Figure 6). This T4 temper describes fast-hardening variants of 6xxx-series alloys, which, after another heat treatment process (nominally performed by the customer), are in the T6 temper.

The increased concentration of nucleating agents leads to a faster response to heat treatment. The heat treatment process can be integrated, for example, into the cathodic dip coating process as is common in the automotive sector, to avoid separate artificial aging. The component has excellent elongation and corrosion properties in addition to high strength. This property is referred to as paint bake response.

Additionally, significantly higher final strength values can be achieved if appropriate material in the T4* temper is used and properly processed (Figure 7).

If sheet for automotive applications is surface-passivated in a strip passivation line, the time-temperature curve of the drying process after T4* heat treatment must also be taken into account.

AMAG’s high-strength 7xxx-series alloy, TopForm UHS, which is used, for example, in automotive structural components, is delivered in the T6 temper and “warm-formed” by the customer at temperatures of approximately 200 °C. In this thermomechanical process, the high-strength material is highly formable and is specifically over-aged (Figure 8). In its T7 temper, the component has excellent elongation and corrosion properties in addition to high strength.

Summary

The examples shown are just a fraction of the heat treatment processes used by AMAG. A separate heat treatment process tailored to the specific alloy is required for each material and each combination of processes requested by the customer. With its abundance of products (from products for aerospace and automotive applications to sports engineering, sheets and plates made of different alloys, with different properties and levels), AMAG, unsurprisingly, sees the greatest potential for developing and improving aluminium for even more efficient use and additional applications in an optimized heat treatment of the material.

LITERATURE