Influence of the heat-treatment prior to plastic deformation on the aging behavior and the hardness of the aluminum alloy 6056

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Abstract. Motivated by the improvement of the cost and resource efficiency of the manufacturing process of age-hardening aluminum components, the influence of an initial heat-treatment, prior to plastic deformation, on the artificial aging behavior and the hardness is investigated. Systematic work is done by comparing three initial heat-treatment conditions of the age-hardening aluminum alloy 6056 prior to low-temperature plastic deformation: a solid-solution heat-treated, a naturally aged and a stabilized one. Two plastic deformation processes, linear extrusion and compression, each with two different strains, respectively, were performed and followed by artificial aging. The hardness was measured prior to plastic deformation as a function of the natural aging time, and after plastic deformation as a function of the artificial aging time. Stabilization annealing of the aluminum alloy inhibited natural aging. After plastic deformation and artificial aging, the stabilized conditions showed an increased hardness, as compared to the solid-solution heat-treated, respectively naturally aged, condition. The artificial aging behavior of all tested conditions was only slightly influenced by the respective plastic deformation process. However, the hardness was similar for the extruded, respectively compressed, conditions in their respective initial heat-treatment conditions.

1. Introduction
Age-hardening aluminum alloys stand out for lightweight-applications, not only due to their high specific strength and good machinability, but especially due to their capability to adjust required mechanical properties by aging treatments. Thermomechanical treatment of these aluminum alloys allows to directly affect the precipitation kinetics of the formation of precipitates.

Kim et al. [1–3] developed an effective strategy for age-hardening alloys to achieve high strength and hardness, while preserving a good ductility by a combination of heat treatment and severe plastic deformation. Thereby, equal-channel angular pressing (ECAP) of the alloy leads to a significant increase in hardness and strength due to the introduced strain hardening and the high dislocation density. To compensate for the accompanying loss in ductility, the low-temperature deformation was realized subsequently to a solid-solution heat-treatment of the alloy. During the following artificial aging, the accelerated precipitation kinetics, which is caused by the high dislocation density, results in the formation of fine and finely dispersed precipitations which preserve the high strength of the deformed alloy. Simultaneously, thermal recovery leads to a regain of ductility (which has been
decreased by work hardening). Nevertheless, the mechanical properties are strongly dependent on the introduced strain, the aging time and the artificial aging temperature [4,5]. Hockauf et al. [4] showed, that the strengthening effect of the precipitation hardening is overcompensated by the recovery process during artificial aging when a critical introduced strain is exceeded. Further, low temperatures for artificial aging and short aging times lead to the best resulting combination of strength and ductility [5,6].

The aspired main objective is a transfer of this method into industrial application to improve the cost and resource efficiency of the manufacturing process of components, which require a proper heat-treatment to realize precipitation hardening. The aim is a reduction of heat-treatment times and therefore reduced manufacturing costs by utilization of the accelerated precipitation kinetics due to the low-temperature plastic deformation. As “precipitation engineering” was also successfully performed with cryo-rolling as a severe plastic deformation process [7,8], we want to evaluate the adaptability of this method for the more conventional processes of linear extrusion and compression. To investigate the influence of the heat-treatment prior to deformation on the hardening behavior, a solid-solution heat-treated condition is compared with a naturally aged condition, which represents an industrial process with an interim storage period at room temperature. As a third option for heat-treatment, a stabilized condition is chosen. Stabilization annealing at temperatures below 100 °C for several hours after solid-solution heat-treatment leads to an increased room temperature stability and inhibits natural aging of the aluminum alloy [9].

The purpose of the present study is to systematically investigate the effect of the initial heat-treatment prior to deformation, the plastic deformation process and the artificial aging time on the hardness of an Al-Si-Mg-alloy containing copper. For our investigations, the aluminum alloy 6056 was chosen due to the possibility of natural and artificial aging and its pronounced hardening effect, the good workability and the wide usage in industrial applications.

2. Experimental and materials
For this study, the age-hardening aluminum alloy 6056 (AlSi1MgCuMn) was used. The wire-casted material with a diameter of 5.26 mm was provided by EJOT GmbH & Co. KG (Bad Berleburg, Germany). The chemical composition and the mechanical properties of the tested alloy are given in table 1 and table 2.

| Table 1. Chemical composition of the aluminum alloy 6056 (AlSi1MgCuMn). |
|-------------------------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|---------------|
| Element | Si | Mg | Cu | Mn | Fe | Cr | Zn | Ti | Zr | Al |
| wt-% | 1.06 | 0.89 | 0.78 | 0.59 | 0.16 | 0.01 | 0.19 | 0.04 | 0.13 | balance |

| Table 2. Mechanical properties of the wire-casted aluminum alloy 6056. The standard deviation is given in absolute values. |
|---------------------|----------------|----------------|----------------|
| Wire diameter in mm | Yield strength $R_{\text{p0.2}}$ in MPa | Ultimate tensile strength $R_{\text{m}}$ in MPa | Elongation $A_{100\text{mm}}$ in % |
| 5.26 | 173 ± 1 | 188 ± 2 | 6.3 ± 1.3 |

For analyzing the natural aging behavior of the tested alloy, a solid-solution heat-treated and a stabilized condition were compared. The solid-solution heat-treatment was done at 530 °C for 1 h and quenching in water to room temperature (RT) afterwards. For stabilization annealing, the solid-solution heat-treated condition was heat-treated at 80 °C for 5 h, subsequently.

To examine the influence of the deformation process and the introduced strain on the artificial aging behavior, the tested aluminum alloy was extruded for $\varphi_E = 1.2$ and $\varphi_E = 0.8$, respectively compressed for $\varphi_C = 0.55$ and $\varphi_C = 0.7$. The deformation processes were carried out on three different heat-treated conditions: a solid-solution heat-treated, a condition which has been naturally aged for
7 days, and a stabilized condition. The parameters for the respective heat-treated and deformed conditions are given in table 3.

The extrusion process was carried out at EJOT GmbH & Co. KG (Bad Berleburg, Germany) at room temperature. The introduced strain by the extrusion process \( \varphi_E \) is defined by the diameter reduction of the wire-casted material and is calculated from the ratio of the wire cross-section area before \( (A_0) \) and after \( (A_1) \) extrusion:

\[
\varphi_E = \ln \frac{A_0}{A_1}
\]  

(1)

The compression process was performed at room temperature and at a strain rate of \( 10^{-3}\text{s}^{-1} \) in a Zwick Roell servohydraulic testing machine (Zwick Roell, Ulm, Germany). To minimize friction during the compression process, the cylindrical specimens (5 x 5 mm) were lubricated with molybdenum disulphide. The introduced strain by the compression process \( \varphi_C \) is specified by the height reduction of the wire specimens and is calculated from the ratio of the specimen height before \( (h_0) \) and after \( (h_1) \) compression:

\[
\varphi_C = \ln \frac{h_1}{h_0}
\]  

(2)

To prevent natural aging of the aluminum alloy, the extrusion, respectively the compression, and the following artificial aging treatment were done immediately after the respective initial heat-treatment. Otherwise, the specimens were stored at -7 °C, if a continuous route was unrealizable.

All plastically deformed conditions were artificially aged at 120 °C, with annealing times ranging from 1 to 600 min. Vickers hardness was measured on the cross section of the wire specimens with 20 indentations from edge to core. For the compressed conditions, an automatic hardness tester KB250BVRZ (KB Prüftechnik GmbH, Hochdorf-Assenheim, Germany) with Vickers hardness HV0.5 was used. The extruded conditions were measured at EJOT GmbH & Co. KG (Bad Berleburg, Germany) using an automatic hardness tester DuraScan 70 G5 (EMCO-TEST Prüfmaschinen GmbH, Kuchl, Österreich) with Vickers hardness HV0.1.

**Table 3.** Heat-treatment parameters for the initial material conditions of the wire-casted aluminum alloy 6056 used for the respective plastic deformation process.

| Deformation process | Solid-solution heat-treatment | Natural aging | Stabilization annealing |
|---------------------|-----------------------------|---------------|------------------------|
| extrusion           | 530 °C for 50 min           | 7 days        | 80 °C for 7 h          |
| compression         | 530 °C for 1 h              | 7 days        | 80 °C for 5 h          |

3. Results

To illustrate the natural aging behavior as a function of the heat-treatment condition of the aluminum alloy 6056, figure 1 shows the development of hardness as a function of the natural aging time. The solid-solution treated condition exhibits an almost linear increase in hardness with increasing aging time. Starting at 68 HV0.5 after 90 min of natural aging time, the hardness increases to 91 HV0.5 after 4 weeks. In contrast, the stabilization annealing leads to a more stable, yet higher initial hardness of 80 HV0.5. However, after 3 weeks of natural aging time, the hardness increases as well (up to 86 HV0.5), but remains below the solid-solution treated condition.
Figure 1. Vickers hardness (mean values) of the aluminum alloy 6056 in solid-solution heat-treated and in stabilized condition as a function of the natural aging-time. Scatter bars depict the maximum and minimum values. The stabilized condition shows a more stable hardness within the first weeks of natural aging time, as compared to the solid-solution treated condition.

The artificial aging behavior of the solid-solution treated, the naturally aged and the stabilized condition after extrusion, respectively compression, for the introduced strains is shown in figure 2. In general, the plastic deformation process and the introduced strain have a minor influence on the achieved peak-hardness for the respective heat-treatment conditions.

For all heat-treatment options, stabilization annealing of the aluminum alloy before plastic deformation results in the highest peak-hardness. Artificial aging for 300 min after stabilization annealing and extrusion leads to a peak-hardness of 162 HV0.1 for both introduced strains (see figures 2 a, b). For this aging time, the stabilized and compressed conditions also show a local hardness peak of 152 HV0.5, but the global peak-hardness of 156 HV0.5 is reached later, after 540 min of artificial aging time (see figures 2 c, d). However, the hardness profile of the stabilized and compressed conditions exhibits significant drops: for φC = 0.55 at 420 min of artificial aging time and for φC = 0.7 at 120 min and 360 min (see figures 2 b, d).

As compared to the stabilized conditions, the hardness of the naturally aged, respectively solid-solution heat-treated, conditions remain generally lower.

An acceleration of the artificial aging behavior by an increase in the introduced strain was only noticeable for the solid-solution treated and subsequently extruded, respectively compressed, conditions. Extrusion with φ = 0.8 after solid-solution treatment does not result in a peak-hardness within the chosen time for artificial aging of 360 min. In contrast, an increase in the introduced strain up to φE = 1.2 leads to an accelerated hardening and to a pronounced peak already after 180 min of artificial aging time.
Figure 2. Vickers hardness of the aluminum alloy 6056 as a function of the artificial aging time at 120 °C and dependent on the initial heat-treatment condition: (a, b) after extrusion with an introduced strain of (a) $\phi_E = 0.8$ and (b) $\phi_E = 1.2$, (c, d) after compression with an introduced strain of (c) $\phi_C = 0.55$ and (d) $\phi_C = 0.7$. Scatter bars depict the maximum and minimum values. Stabilization annealing of the aluminum alloy prior to plastic deformation results in the highest hardness values for both deformation processes and both introduced strains.
4. Discussion

The precipitation sequence for Al-Si-Mg-alloys containing copper is described as follows [10–12]:

\[
\alpha/ \text{super-saturated solid-solution} \rightarrow \text{cluster/} \text{GP(I)-zones} \rightarrow \text{metastable } \beta''/ \text{GP(II)-zones} \rightarrow \beta' + Q' \rightarrow \text{stable } \beta + Q + \text{Si}
\]

Guinier-Preston (GP)-zones are nanoscaled precipitates with an ordered arrangement of Mg-, Si- and Cu-atoms which structurally evolve during aging [9,13]. The needle-shaped \(\beta''\) and the rod-like \(\beta'\) are metastable ternary precursor phases to the stable phase \(\beta\) (Mg_6Si). Whereas, for Al-Mg-Si-alloys with Cu, the lath-shaped, metastable quaternary Q’-phase occurs in addition and is a precursor for the stable Q-phase (Al_5Cu_2Mg_8Si_6) [14]. The significant strengthening of these aluminum alloys during artificial aging is attributed in majority to the hardening phase \(\beta''\) (Mg_5Si_6) [15]). The phase Q’ [10,14,17] gives an additional contribution. A very high density of these semi-coherent phases in combination with very fine fully coherent GP(I)-zones leads to major strengthening [15].

The significant increase in hardness during natural aging after solid-solution heat-treatment is a result of aggregated Mg- and Si-clusters, which form stable Mg-Si co-clusters, which are also described as GP(I)-zones [11,18–20]. The formation of these co-clusters is mainly controlled by the concentration of mobile vacancies [9,11]. Stabilization annealing after solid-solution treatment and quenching annihilates these vacancies and the diffusion controlled formation of the co-clusters is inhibited [9], which explains the increased room temperature stability (see figure 1). Instead, GP(II)-zones are formed during stabilization annealing [9,10,21–23].

The improved artificial aging response of the stabilized conditions, if compared to the naturally aged ones (see figure 2), is in good accordance to the literature [24]. The reason for this effect are the GP(II)-zones, which form during stabilization annealing and their transformability into \(\beta''\) during subsequent artificial aging due to the similarity in composition, structure and size [10,18,19,22,25]. Further, the high number of GP(II)-zones initiated during stabilization treatment results in an increase in the number of the hardening phase \(\beta''\) in the following artificial aging treatment, as numerous nucleation sites are provided [18,19]. The pronounced drops in the hardness profile during artificial aging indicate the formation of metastable strengthening phases, which lead to a following peak in hardness after the precipitation transformation [12].

In contrast, the hardening response of the naturally aged conditions during subsequent artificial aging is limited. The precipitation kinetics is retarded by the previous natural aging and the formation of GP(II)-zones is suppressed by the formation of Mg-Si co-clusters [11,19,22,25,26].

Of all three heat-treated and subsequently plastically deformed (\(\phi = 0.7\)) conditions, the solid-solution heat-treated condition attains peak-hardness most rapidly during artificial aging. The accelerated precipitation kinetics of this condition is a result of the supported diffusion by the quenched-in vacancies after solid-solution heat-treatment [11] and the high dislocation density due to the plastic deformation [1,4,5,12]. Both effects lead to numerous nucleation sites and an increased nucleation rate of the \(\beta''\)-phase and therefore faster hardening of the aluminum alloy. The precipitation sequence remains unaltered by the plastic deformation [27]. The overall minor hardness of the solid-solution heat-treated condition (if compared to the stabilized condition) is supposedly due to the precipitation formation and the introduced strain. Through artificial aging, the hardening response of the initial GP(II)-zones formed by stabilization annealing predominates the strengthening effect of the combined solid-solution treatment and plastic deformation. The latter strategy is strongly dependent on the dislocation density and it is assumed that the introduced strain was too low to take advantage of the full potential of this method.
5. Conclusions
The influence of the initial heat-treatment in combination with a following plastic deformation process on the artificial aging behavior and the achieved hardness of the aluminum alloy 6056 was investigated. Three initial heat-treatment conditions were compared: a solid-solution heat-treated, a naturally aged and a stabilized condition. Extrusion, respectively compression, were chosen as plastic deformation processes with two different introduced strains and were performed on each of the three initial heat-treatment conditions followed by artificial aging. Conclusions can be drawn as follows:

(1) Stabilization annealing at low temperatures for several hours immediately after the solid-solution heat-treatment inhibits natural aging of the aluminum alloy. This increase in room temperature stability is attributed to the inhibited formation of stable Mg-Si co-clusters/ GP(I)-zones during the stabilization treatment and causes the formation of GP(II)-zones instead.

(2) The artificial aging behavior of the three tested initial heat-treatment conditions after plastic deformation was not influenced by the type of the deformation process. The extruded, respectively compressed, conditions show a similar hardness evolution during artificial aging.

(3) Stabilization treatment before plastic deformation leads to major hardness, if compared to the naturally aged respectively solid-solution heat-treated and plastically deformed conditions. This improved artificial aging response is a result of the formed GP(II)-zones during stabilization annealing, which promote a pronounced nucleation of the hardening phase \(\beta''\) due to their structural and compositional similarity.

(4) The combination of solid-solution heat-treatment and subsequent plastic deformation results in a more rapid hardening of the conditions with higher introduced strain, if compared to the two other initial heat-treatments. The introduced strain hardening and the high dislocation density lead – in combination with enhanced diffusion due to quenched-in vacancies – to an accelerated precipitation kinetics of the solid-solution treated and plastically deformed condition.

In summary, stabilization annealing of the aluminum alloy 6056 is a promising strategy for a resource and cost efficient manufacturing process, as the room temperature stability during interim storage periods is improved and, additionally, the artificial aging response and therefore the achieved hardness is increased.

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