EFFECT OF FORGING TEMPERATURE ON THE FINAL PROPERTIES AND GRAIN STRUCTURE OF ARTIFICIALLY AGED EN AW 6056 ALUMINUM ALLOY

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Abstract

Over the past twenty years, there has been a rising interest in heat-treatable 6xxx series aluminum alloys, primarily due to their impressive strength-to-weight ratio, excellent formability, and outstanding corrosion resistance characteristics [1]. In conventional manufacturing processes, those alloys are solution heat treated and artificially aged following a hot forging process [2]. Besides heat treatment, forging conditions have a major effect on the final properties and grain structure of the forged products. In the current study, effect of the forging temperature on the mechanical properties as well as microstructure of EN AW 6056 aluminum alloy has been investigated. Cylindrical samples with a diameter of 65 mm and length of 160 mm are upset forged with flat dies in their radial direction using a mechanical press. Forging temperature is varied between 150°C and 450°C with 100°C steps. Afterwards, all forged samples are solution heat treated at 550°C for 90 minutes and quenched in water at room temperature. Subsequently, samples are artificially aged at 190°C for 4 hours. Contrary to the common believe, although solution heat treatment is applied at a relatively high temperature, forging temperature had a major influence on the microstructure of samples. Nevertheless, no effect has been observed in the hardness distribution in the forged samples.

Keywords: Aluminum forging, artificial aging, precipitation

1. INTRODUCTION

Over the past twenty years, there has been a rising interest in heat-treatable 6xxx series aluminum alloys, primarily due to their impressive strength-to-weight ratio, excellent formability, and outstanding corrosion resistance characteristics [1]. In conventional manufacturing processes, high strength is obtained after solution heat treatment and artificially aging following a hot forging process [2]. Besides heat treatment, forging conditions have a major effect on the forged products' final properties and grain structure. In the current study, the effect of the forging temperature on the mechanical properties and the microstructure of EN AW 6056 aluminum alloy has been investigated.

6xxx series aluminum alloys are denoted as Al-Mg-Si ternary system alloys where the mechanical strength is attributed to the β˝, β´, β precipitates generated after solution heat treatment followed by quenching and artificial aging [3]. Nevertheless, an addition Cu into the content of 6xxx series alloys as in EN AW 6056 alters the precipitation formation sequence and form significantly. The phase transformation sequence for AlMgSi with copper addition during AA is given schematically below [4].

Super-saturated solid solution → Solute Cluster → β˝→ GP Zones + Q˝ → β´+Q´ → β + Q + Si

By adding Cu to AlMgSi alloys, Q´ precipitates in the lath-shaped structure has been observed which increase the mechanical strength of the alloy [5]. Moreover, when the Cu content of 6xxx series alloys is increased, it is observed that the Q˝ phase is formed instead of β´ and β˝ [6]. Furthermore, it is observed that

Cu addition to AlMgSi alloys reduces the dependency of the mechanical strength increase after artificial aging to the Mg/Si ratio [7].

Although there are multiple studies about the precipitation formation in AlMgSiCu alloys, to the authors best knowledge, effect of the forging conditions on the mechanical properties and microstructure is an understudied field [8]. Therefore, in the current study, the effect of upset forging temperature on the hardness and microstructure has been investigated.

2. EXPERIMENTAL PROCEDURES

EN AW 6056 aluminum alloy in extruded form is used in the study. Its chemical composition is given in **Table 1**.

Table 1 Chemical composition of EN AW 6056 alloy (wt%)

Si	Fe	Cu	Mn	Mg	Zn	Al
0.99	0.24	0.92	0.82	0.93	0.54	balance

Initial material had a diameter of 65 mm. It was hot extruded, quenched and naturally aged. Afterwards, a normalizing heat treatment was applied to the bars. Mechanical properties of the initial material are determined according to the ISO 6892-1 standard. Mechanical strength and hardness of the initial material is given in **Table 2**.

Table 2 Mechanical properties and hardness of initial EN AW 6056 alloy

Yield Strength	Tensile Strength	Elongation at Fracture	Hardness
101 MPa	242 MPa	30%	83.2 HV0.5

All round samples are upset forged in radial direction down to a thickness of 34 mm by a mechanical press. Plastic strain in the formed samples are numerically calculated using finite element simulations. MSC.Marc finite element software has been used for that purpose. An axisymmetric 2D model is generated using 1971 quad elements, type 11. Tools are generated as rigid bodies and displacement of the mechanical press is defined for the upper tool. Coulomb friction coefficient between the specimen and tools are assumed to be constant at 0.1. Whole forging takes place in 0.17 seconds. Material properties of the EN AW 6056 alloy at elevated temperature is modeled with the following Swift isotropic hardening model.

$$\sigma = 85.5 \times (\varepsilon + 0.00022)^{0.05} \tag{1}$$

Plastic strain distribution in the upset forged sample is shown in **Figure 1**. According to the numerical simulations, total strain values in the middle of the forged samples reach up to 1.0. As we move away from the center, total plastic strain values drop gradually.

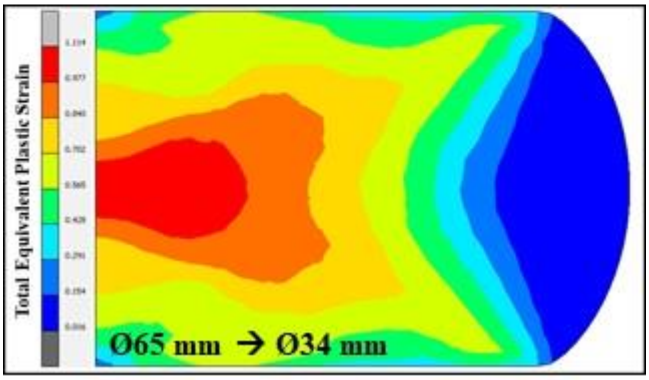

Figure 1 Total plastic strain distribution in the forged samples

In order to reduce friction effects, surfaces of the upset tools are coated with a graphite emulsion before every forming experiment. Both tools are heated to a temperature of 195±5°C to reduce specimen cooling during forging. Four different forming temperature have been investigated, namely 150°C, 250°C, 350°C, and 450°C. Samples are heated in a convection furnace in 30 minutes prior to forging. For each investigation condition, two different samples are formed. Testing set up together with upset forged specimens are shown in **Figure 2**.

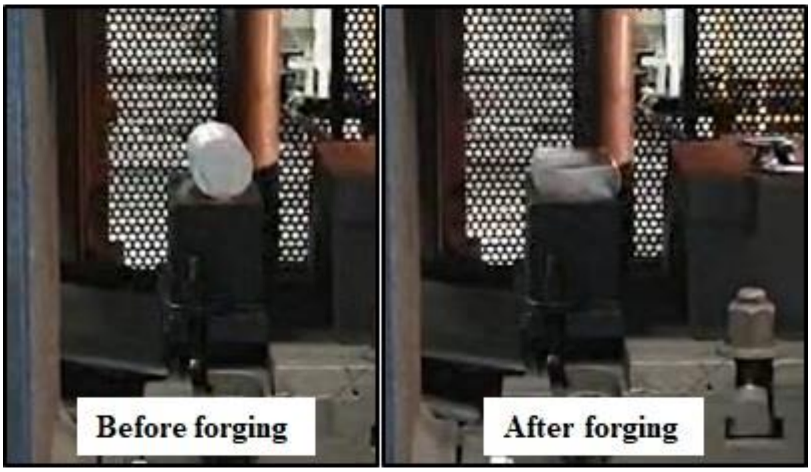

Figure 2 Forging setup as well as samples before and after forging

All upset forged samples are cooled slowly to room temperature. Afterwards, these samples are solution heat treated at 530°C for 120 minutes and quenched in water at room temperature. Subsequently, all samples are artificially aged at 190°C for 4 hours.

Upset forged samples are cut in vertical direction to generate the cross section of the samples. Cut samples are sand papered using grids between P400 and P2500. Vickers hardness of the all upset forged samples is measured using Future-Tech FM-700e Vickers Hardness tester according to ISO 6507-1 standard under a load of 0.5 kg with 15 seconds dwell time. All hardness measurements are taken from the center of the upset forged samples. 11 hardness values are measured in each sample. Arithmetic mean values of these measurements are considered for evaluation.

After hardness measurement, cut samples are sand papered again using grids between P800 and P2500 to remove the indentations on the surface. Subsequently, they are polished with 6μm and 1μm diamond solution. Later, samples are etched with Keller's reagent for 60 seconds. Microstructure is investigated at the center of the forged samples using an Optika IM-3MET inverted light microscope.

For the precipitation generation, a separate sample is upset forged at 350°C. After solution heat treatment, quenching and artificial aging with previous parameters, a small round sample with a weight of 20 mg is cut from the middle of the specimen using a micro cutter. Differential scanning calorimetry (DSC) test is conducted using a Hitachi DSC 7020 machine between room temperature and 350°C with a heating rate of 10°C/min. Heat flow per weight value is evaluated in order to investigate the precipitation formation.

3. RESULTS AND DISCUSSION

Micro hardness distribution of upset forged samples under different temperatures are given in **Figure 3**. In this figure, average of 11 measurements with corresponding standard deviation bars are shown.

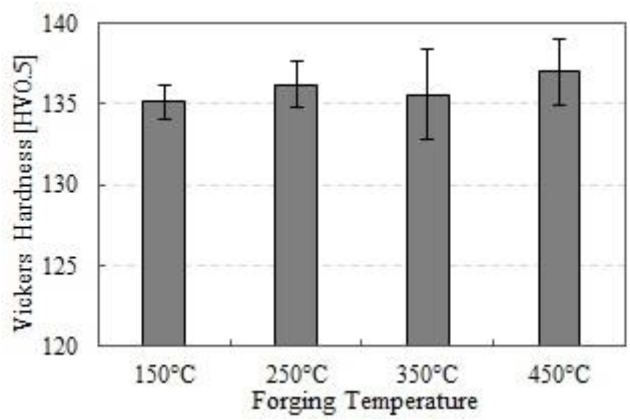

Figure 3 Micro hardness values corresponding to different forging temperatures

When the hardness values are investigated, it is seen that the minimum hardness is measured in sample forged at 150°C whereas maximum hardness is observed in sample forged at 450°C. Nevertheless, the difference is 2.88 and is therefore considered as insignificant. However, as forging temperature increases, there is a clear increase in the standard deviation values. At 150°C forging, this deviation value is 1.07. As the forging temperature rises to 450°C, same deviation rises to 2.04.

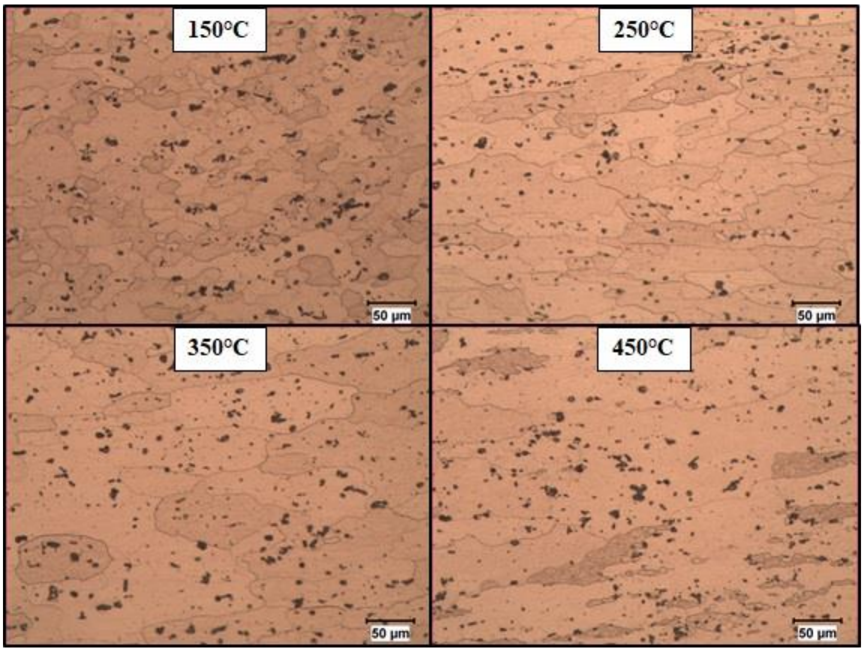

Figure 4 Optical microscopy results of samples forged at different temperatures

Table 3 Measured grain sizes

Forming Temperature [°C]	150	250	350	450
Average Grain Size [µm]	13.11	16.25	28.26	44.48

Optical microscopy results of selected samples as well as the average grain size of formed samples under different upset forging conditions are shown in **Figure 4** and **Table 3**, respectively. It is obvious that the average grains size of the forged and artificially aged samples grows with increasing forging temperature. Although solution heat treatment temperature of 530°C is above the recrystallization temperature of the investigated aluminum material and solution time is 120 minutes, forging temperature still affects grain size significantly.

If grain size results are investigated together with hardness measurements, it is concluded that precipitation hardening is the major mechanism for strength increase in the EN AW 6056 aluminum alloy. Nevertheless, it is already known that hardness measurements cannot represent the true mechanical properties of aluminum alloys. On the contrary, they serve rather a guiding value for further investigations. Therefore, tensile tests have to be conducted on the forged and artificially aged samples in further studies.

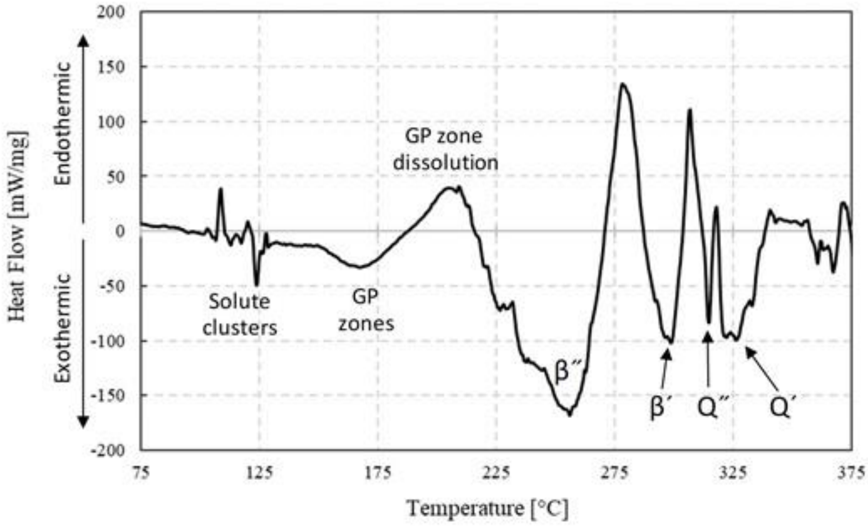

Figure 5 DSC result of forged sample formed at 350°C and artificially aged at 190 °C for 4h

Differential scanning calorimetry (DSC) results of the sample forged at 350°C and artificially aged at 190°C for 4 hours after solution heat treatment is shown in **Figure 5**. This investigation is done to be able to foresee different precipitation formation characteristic to Al-Mg-Si alloys with Cu addition. In DSC results, an exothermic peak predicts formation of a cluster or a precipitation. An endothermic peak following that formation usually depicts the dissolution of the formed cluster or precipitation. The first peak at 125°C dictates solute clusters which consist of partially Mg and Si clusters, or co-clusters of Mg-Si. The second exothermic peak indicates GP zones at 170°C. The 3rd peak shows β˝ precipitation at 255 °C and is the most recognizable exothermic peak in this graph. The formation of the fourth exothermic peak at 298°C is controversial. According to some studies, this is an indicator of β´ precipitation [4, 9]. However, in other studies, it is reported that this peak is an indication for the formation of Q˝ phase [10, 11]. Since there are other exothermic peaks in the results, authors believe that the peak at 298°C is an indicator for β´ precipitates. Two different follow this one. First occurs at 315°C and indicates in the authors opinion Q˝ precipitates formation. The last one at 325°C is a sign for Q´ formation. The endothermic peak at 375°C is a sign of precipitation dissolution.

Formation of Q˝ precipitates is of high importance. Similar to β˝ precipitates, they enable the additional strengthening of the material compared to the conventional Al-Mg-Si alloys [10]. The DCS analysis reveals that a significant precipitation strengthening can be achieved after the forging and artificial aging of samples.

4. CONCLUSIONS

In the current study, the effect of upset forging temperature on the mechanical properties and microstructure of EN AW 6056 alloy has been investigated. Industrial upsetting procedures are used in the sample preparation. Following conclusions are made:

- Although solution heat treatment is applied at a relatively high temperature, forging temperature had a major influence on the grain size,
- As the forging temperature decreased, the grain size of the forged samples also decreased,
- Forging temperature has an insignificant effect on the hardness of forged samples after solution heat treatment and artificial aging,
- Precipitation generation is seen as the major hardening mechanism for the investigated EN AW 6056 aluminum alloy after forging, solution heat treatment and artificial aging.

In the future studies, mechanical properties of the forged and artifially aged samples should be investiagted using tensile tests.

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