Influence of rotary swaging and subsequent age hardening on properties of EN AW 6082 aluminium alloy

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Abstract. Mechanical properties and microstructure of EN AW 6082 were investigated. The aluminium alloy was processed by combining the solution annealing, plastic deformation and artificial age hardening, respectively. The initial state of the investigated material was provided in the form of extruded rods with the diameter of 12 mm. For the solution annealing the temperature 530 °C was chosen. The plastic deformation was realized by rotary swaging at ambient temperature and the investigated material was rotary swaged from 12 to 10 mm in diameter. The effect of the age hardening temperature and time was studied at temperatures of 120 and 160 °C and times 1 - 12 hours. The impact of processing parameters on mechanical properties was assessed by tensile testing and hardness measurement. Metallographic examination was carried out by light optical microscopy (LOM) and scanning electron microscopy using electron backscatter diffraction (SEM-EBSD).

1 Introduction
The rising interest in ultrafine-grained (UFG) metallic materials has led to an intensive development of forming methods based on SPD processes [1, 2]. SPD (Severe Plastic Deformation) is a generic term that refers to processes which employ large plastic deformation to achieve notable grain refinement down to the nanometre scale. Grain refinement brings higher strength properties and ductility which surpass those found in today’s conventional materials.

SPD processes have found increased use in the forming of aluminium alloys. This also applies to 6xxx-series aluminium alloys (Al-Mg-Si alloys). They can undergo precipitation strengthening, thanks to varying solubility of the Mg2Si intermetallic phase in aluminium [3]. One of these alloys is the EN AW Al 6082 which is the subject of this investigation.

A number of studies of SPD forming and subsequent artificial age hardening of aluminium alloys have been published in recent years, such as [4-15]. Most of them [4-14] focused on equal channel angular pressing (ECAP) or its modified variants [15]. Only a handful of studies have been devoted to rotary swaging or to combinations of rotary swaging and artificial age hardening.

For instance, the effects of rotary swaging (RS) on mechanical properties and microstructural evolution in commercial purity aluminium are reported in [16]. The authors of [17] dealt with RS and artificial age hardening in EN AW 2024 (Al-Cu-Mg alloy). The present study was carried out to gather information about the effects of RS and subsequent artificial age hardening on the properties of the EN AW Al 6082 alloy.

Plastic deformation was applied by rotary swaging (RS) (Figure 1). RS is an incremental metal forming process for the reduction of cross-sections of bars, tubes, wires or rods. Sets of four dies
perform small, high-frequency, simultaneous radial movements (oscillations). With every stroke of the die, a part of the workpiece is formed. Die movement is generated by means of cams. The kinematics are equivalent to those of a planetary gear. This assembly is completely accessible, which makes it easy to carry out any maintenance work [18].

![Figure 1. Rotary swaging configuration.](image1)

2 Experimental material and procedure

Testing was performed on extruded round bars whose length and initial diameter were 0.5 m and 12 mm, respectively. Table 1 gives the chemical composition of the EN AW 6082 alloy that was used for this testing. The temper of the as-received bars was T6511.

| Element | Si  | Fe  | Cu  | Mn  | Mg  | Cr  | Zn  | Al  |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|
| wt. %   | 1.00| 0.41| 0.11| 0.58| 0.65| 0.13| 0.048| Balance |

Table 1. Chemical composition of EN AW 6082 (wt. %).

The treatment route used for the bars was as follows:

1. Solution annealing at 530 °C for 1.5 hours, and subsequent water quenching
2.Forging in the rotary swaging machine at ambient temperature; reduction of diameter: \( \Phi \) 12 mm \( \rightarrow \Phi \) 10 mm; feed rate of 100 mm/s (6000 mm/min); rotational speed of dies of 24.2 rps (1450 rpm).
3. Artificial age hardening at 120 °C and 160 °C for defined periods:
   - at 120 °C for 1, 3, 6, and 12 hrs.
   - at 160 °C for 1, 3, 6, and 12 hrs.

The schematic profile of the entire experimental route is plotted in Figure 2.

![Figure 2. Experimental route.](image2)
3 Results and discussion

3.1 Mechanical properties

Anisotropy of mechanical properties was evaluated by measuring hardness of the material. HV1 scale was employed. The values were measured using the STRUERS DuranScan tester on transverse sections through the bar, from one edge to the other. The resulting hardness profiles are plotted in Figure 3.

Mechanical properties were analysed with the aid of tensile testing. Specimens of 6 mm diameter and 30 mm gauge length for quasi-static tensile testing were made from samples taken in longitudinal direction of the parts. The samples were tested on a ZWICK Z250 testing machine. The length change was measured with strain gauge clip-on extensometer. The data was evaluated in accordance with the EN ISO 6892-1 standard. The properties (offset yield stress YS, ultimate tensile strength UTS, elongation A, elongation A5, and reduction of area RA) are plotted in Figure 4. The values of mechanical properties are listed in Table 2.

![Figure 3. Hardness profiles](image)

*Figure 3. Hardness profiles (artificial age hardening temperature: 120 °C – left, 160 °C – right).*

![Figure 4. Representative tensile test results](image)

*Figure 4. Representative tensile test results (artificial age hardening temperature: 120 °C – left, 160 °C – right). Note: Artificial age hardening time 0 hrs represents the initial state*
Table 2. Mechanical properties (YS, UTS, \(A_g\), \(A_5\), and RA) before (i.e. as-received condition) and after the experimental treatment, \(t = \) artificial age hardening temperature, \(\tau = \) artificial age hardening time.

| \(t - \tau\) (°C - hrs) | YS (MPa) | UTS (MPa) | \(A_g\) (%) | \(A_5\) (%) | RA (%) |
|--------------------------|----------|-----------|-------------|-------------|--------|
| Initial state            | 303.4    | 321.9     | 4.8         | 13.8        | 46.7   |
| 120 °C – 1 hr            | 352.3    | 396.2     | 5.2         | 9.3         | 34.9   |
| 120 °C – 3 hrs           | 432.1    | 469.4     | 7.7         | 13.5        | 29.6   |
| 120 °C – 6 hrs           | 455.1    | 476.5     | 7.0         | 13.6        | 33.3   |
| 120 °C – 12 hrs          | 472.5    | 483.4     | 6.3         | 11.4        | 27.6   |
| 160 °C – 1 hr            | 435.1    | 451.2     | 4.9         | 10.7        | 35.2   |
| 160 °C – 3 hrs           | 443.8    | 445.6     | 4.2         | 11.1        | 40.6   |
| 160 °C – 6 hrs           | 426.7    | 427.1     | 4.0         | 9.7         | 37.9   |
| 160 °C – 12 hrs          | 410.8    | 410.9     | 3.5         | 11.4        | 41.8   |

3.2 Microstructure

The microstructure analysis was first performed under the Carl Zeiss – Observer.Z1m light microscope. The specimens were ground, polished, and etched on longitudinal and transverse cross-sections. For this purpose, all samples were cold-mounted. After polishing, anodization (\(J = 0.2\,\text{A/cm}^2; 60\,\text{s}\)) in Barker’s reagent (200 ml H\(_2\)O + 5 ml HBF\(_4\)) was performed. Polarized light mode was used for observation. Figure 5 shows the relevant optical micrographs.

Figure 5. Micrographs of etched specimens after artificial age hardening taken under polarized light illumination; transverse section (left) and longitudinal section (right). Artificial age hardening conditions: 120 °C – 12 hrs (top), 160 °C – 12 hrs (bottom).
The micrographs of the etched sections show grains elongated in the longitudinal direction. The surface layer contains coarse grains. This was caused by the as-received condition of the material (T6511). During solution annealing, recrystallization took place in this region. Using optical microscopic observation, no difference was found between specimens age-hardened at different temperatures and/or for different times.

Subsequently, an analysis by electron backscattered diffraction (EBSD) was performed to evaluate grain size, and detect boundaries and misorientation on selected longitudinal sections. The JEOL JSM-7400F scanning electron microscope equipped with the Oxford Nordlys EBSD camera was employed. Specimens were prepared by ion polishing to avoid the surface deformation. EBSD maps were acquired across 500×500-point grids with a step size of 0.1 µm.

Three specimens were chosen for EBSD analysis: the as-received material, the material treated at 120 °C – 12 hrs, and that treated at 160 °C – 12 hrs (artificial age hardening conditions). Neither this analysis revealed any significant differences in the grain shape or size. The reduction of cross section was reflected in the traces of slip bands within grains inclined 45° to the direction of deformation.

![Initial state](image1.png) ![120 °C / 12 hrs](image2.png) ![160 °C / 12 hrs](image3.png)

**Figure 6.** EBSD maps of longitudinal sections through selected specimens.

## 5 Conclusion

The objective of this study was to identify the effect of rotary swaging and subsequent artificial age hardening on mechanical properties and microstructure of the EN AW 6082 aluminium alloy. The experimental treatment route led to an increase in strength properties (YS, UTS, HV1), and to reduced ductility properties (A5 and RA).

Artificial age hardening at 120 °C resulted in decreasing hardness on the transverse section from the core towards the surface. This is probably due to recrystallized grains in the surface region of the bar. On the other hand, this decrease was not seen in the material treated at 160 °C, which is why this effect will be studied with respect to this temperature.

Optical and electron microscopy were insufficient for revealing changes in the microstructure. The morphologies of grains were similar in all specimens. Hence, one can assume that the key strengthening mechanism which led to differences in the mechanical properties of specimens upon artificial age hardening was precipitation strengthening.

Transmission electron microscopy should be able to reveal the associated changes. It will be part of the follow-up study on this material.
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