Structure and Mechanical Properties of the Aluminum Alloy 1570C after Multidirectional Forging with Decreasing Temperature and Subsequent Rolling

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Abstract. The effect of multidirectional forging (MDF) with decreasing temperature and subsequent warm and cold rolling on the structure and mechanical behavior of the alloy 1570C (Al-5Mg-0.18Mn-0.2Sc-0.02Zr (wt. %)) was studied. The first MDF step was carried out at a temperature of 325°C to a strain of about 12 and the second step at 250°C to the strain of about 6. Subsequent rolling was performed in isothermal conditions at the appropriate MDF temperatures, as well as at room temperature with reductions of about 80%. The best complex of service and technological properties, involving data on the parameters of strength, plasticity, superplasticity, was obtained in sheets rolled from high-temperature MDF billet. Despite the more significant grain refinement and unique strengthening, the MDF temperature decrease led to almost complete degradation of superplastic properties. The nature of the alloy behavior found was discussed in detail.

1. Introduction

It is known that the strength and ductility of metals and alloys can be significantly improved by processing of ultrafine grained (UFG) structure (the grain size is less than 1 µm) using methods of severe plastic deformation (SPD) [1]. Multidirectional forging (MDF) [1-3] is one of the most efficient SPD techniques that have been developed for the production of bulk UFG workpieces. The key point of MDF is the straining of the billet with changes in the load axis, activating the recrystallization processes and allowing the formation of a homogeneous UFG structure.

Production of sheets with improved technological and service properties is in itself a complicated material science and technological task. This is mostly due to the fact that the overwhelming majority of the industrial sheet rolling processes is characterized by unidirectional deformation, which is of a decisive importance for the structure and property control of sheets, in particular, their anisotropy (e.g. [4]). In addition, due to the limited one-pass and total straining applied in conventional rolling, sheets production from coarse-grained billets tend to have some grain size unevenness both in thickness and length. This challenge can be solved by refining the grain structure before rolling using SPD [5,6]. Number of studies has also shown [2,6] that isothermal rolling of the UFG billets processed by MDF is an effective way to manufacture UFG sheets with the uniform structure and increased strength and superplastic characteristics from some alloys, e.g. based on magnesium, copper, titanium and zirconium. However, these data are still very limited for aluminum alloys [5].

The aim of this work is to analyze the transformation of the grain structure and appropriate changes
in mechanical properties in the commercial complex-alloyed aluminum alloy 1570C, having a high potential for a wide usage in the automotive and aerospace industry, under the treatment based on a combination of MDF and rolling. It is noteworthy that this alloy belongs to the hard-to-deform materials. It can easily be deformed to high strains at elevated temperatures, whereas its cold deformation causes some problems due to high strength and low technological plasticity [7]. Therefore, the processing scheme including warm MDF with temperature decreasing from \( \sim 0.6T_m \) and subsequent isothermal warm or cold rolling (WR or CR), was employed in the present work.

2. Material and procedure

Billets of Ø80x150 mm were machined from the ingot of a commercial alloy 1570C (Al-5Mg-0.18Mn-0.2Sc-0.08Zr (wt. %)), homogenized at 360°C for 6 hours, and subjected to two MDF steps at constant temperatures of a sample and tools - first at 325°C to a total (cumulative) strain, \( e \), of about 12 and then at 250°C to \( e=18 \). Both steps included several deformation cycles of preheated in the air furnace billets, involving successive settings with axes changing after each cycle, according to the scheme, represented in [1,3]. Subsequent isothermal warm and cold rolling with the total reduction of about 80% was carried out after both first and second steps at appropriate MDF temperatures and ambient temperature, respectively. The structure of the billets and sheets was investigated using standard methods of transmission and scanning electron microscopy, including electron back-scattering diffraction (EBSD) analysis. In the EBSD maps, misorientation angles (\( \Theta \)) between neighboring points \( 2^\circ \leq \Theta < 15^\circ \), corresponded to low-angle boundaries (LABs), were marked by light-grey thin lines, whereas high-angle boundaries (HABs) with \( \Theta \geq 15^\circ \), were highlighted by thick black ones. In addition, the highly deformed regions with high stored dislocation density \( (\rho \geq 10^{14} - 2 \times 10^{14} \text{ m}^{-2}) \) were marked by dark color in the EBSD maps [8]. Those were defined as areas composed by crystallites, whose inner lattice-distortion angle exceeded 1.5° [9]. The crystallite size was derived from the EBSD analysis by converting the area measurements into a “circle equivalent diameter” [8]. Tensile tests were carried out at room and elevated temperatures using the dog-bone shaped samples with the gage part of 1.5x3x6 mm³. Microhardness was measured by the Vickers.

3. Results and discussion

In the initial state, the alloy had an equiaxed grain structure with a grain size of about 25 \( \mu \text{m} \) and uniformly distributed nano-sized (about 15 \( \text{nm} \) in diameter) coherent precipitates Al\((\text{Sc}, \text{Zr})\) [3]. MDF led to development of fairly homogeneous UFG structures with the new grain/subgrain sizes of 2.2/1.9 and 1.9/1.6 \( \mu \text{m} \), and the volume fractions of new grains of about 80 and 85% after forging at 325°C (figure 1a) and 250°C (figure 1e), respectively. Therewith the fractions of HABs were about 75% after the first- and 80% after the second MDF steps. The homogeneity of the structures formed was attributed to multistage multidirectional deformation, which promoted uniform grain refinement over the billets volume. WR in turn provided an additional refinement of the structures formed by MDF through formation of new (sub)grain boundaries (figure 1b and f). As a result, somewhat finer UFG structures with the fraction of HABs \( \sim 65\% \) and grain/subgrain sizes of 1.8/1.4 \( \mu \text{m} \) and 1.6/1.1 \( \mu \text{m} \) were developed in sheets, processed in billets after the first and second MDF steps, respectively. Therewith, the WR carried out after the second MDF step (i.e. at a lower temperature) expectedly led to the structure with higher dislocation density (figure 1f). As the result of CR, highly deformed UFG structures were formed in the rolling planes after the first and second MDF steps (figure 1c,d,g,h) with the HABs fractions of about 37 and 47% and with average grain/subgrain sizes of \( \sim 2.4/1.2 \) and \( \sim 1.7/0.9 \mu \text{m} \), respectively, containing cells up to \( \sim 300-400 \mu \text{m} \).

The effect of MDF on the mechanical properties is shown in Table 1 and described in detail elsewhere [3]. Compared with MDF at 325°C, subsequent WR led to an increase in the alloy hardness (Hv) on 12%, yield stress (YS) on 30%, and ultimate tensile strength (UTS) on 11% amid a decrease in elongations-to-failure (El) only from 38 to 32%. At the same time, WR, carried out after the second MDF step, increased the hardness on 12%, YS - on almost 40%, UTS - on 15%, accompanied with decrease in El from 33 to 22%. More significant increase in strength was observed in the cold-rolled
sheets. Namely, in comparison with MDF, Hv, YS and UTS increase due to CR was about 1.5, 2.0 and 1.4 times, after the first step and about 1.4, 1.8 and 1.5 times, after the second step, respectively. Note that the strength characteristics obtained demonstrated the unique values for non-age-hardenable Al alloys being typical for sheets out of high-strength 7xxx series Al alloys in T6 condition: YS=430-475MPa, UTS=510-540MPa [10]. At the same time, even after CR the alloy simultaneously exhibited a sufficiently high ductility of about 20%. It can be assumed that the alloy strengthening under rolling was probably conditioned by a combined effect of structural (Hall-Petch) strengthening (due to grain refinement [11]), dispersion strengthening (owing to the homogeneous distribution of nanoscale dispersoids Al3(Sc, Zr) [3,11]), as well as by dislocation strengthening (figure 1) [11], whereas a relatively high level of ductility was, in turn, mainly caused by decreasing the grain size.

The analysis of superplastic characteristics of the sheets processed showed that high-strain rate superplasticity with elongations-to-failure exceeding 1000% and strain rate sensitivity coefficient, m=0.4-0.6, was achieved only in the alloy after the first MDF step (figure 2). Therewith, the alloy after WR exhibited extraordinarily high superplastic characteristics: maximum elongations-to-failure were as high as 3500% at 5.6x10⁻² s⁻¹ and 450°C, and 4000% at 5.6x10⁻³ s⁻¹ and 500°C (figure 2a). After CR, maximum elongation of 1500% was obtained at 1.4 x 10⁻² s⁻¹ and 400°C (figure 2b). On the other hand, after the second step of MDF and subsequent rolling, the alloy demonstrated the mechanical behavior that was typical of ordinary hot deformation, rather than superplastic flow, as evidenced by low values of elongations and m, not exceeding 250% and 0.3, respectively (figure 2c and d).

### Table 1. Mechanical properties of the alloy 1570C at room temperature

| State                  | Hv   | YS, MPa | UTS, MPa | El, % |
|------------------------|------|---------|----------|------|
| Initial                | 105±10 | 240±3   | 355±6    | 28±1 |
| MDF 325°C              | 105±5  | 235±5   | 360±5    | 38±3 |
| MDF 325°C + WR 325°C  | 118±5  | 315±5   | 400±5    | 32±3 |
| MDF 325°C + CR         | 162±6  | 460±6   | 515±5    | 17±5 |
| MDF 250°C              | 115±5  | 260±6   | 370±5    | 33±3 |
| MDF 250°C + WR 250°C  | 129±5  | 360±5   | 425±5    | 22±3 |
| MDF 250°C + CR         | 157±7  | 475±5   | 540±5    | 20±5 |
Figure 2. Elongations-to-failure of alloy vs tensile temperature and strain rate after MDF at 325°C and WR (a), MDF at 325°C and CR (b), MDF at 250°C and WR (c), MDF at 250°C and CR (d).

4. Conclusions

Thus, based on the level and balance of static strength at room temperature and characteristics of superplasticity, the best result was obtained in the sheets processed by the high-temperature MDF and subsequent WR or CR. Lowering the temperature of MDF, despite the more significant refining of grains and subgrains, led to almost complete degradation of its superplastic properties. However, this ensured the strength of sheets after CR, uniquely high for a non-age-hardenable alloy.

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