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Structure, strength and superplasticity of the bulk 1570C alloy subjected to high-temperature multidirectional isothermal forging

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Abstract. The structure and mechanical properties of the cast non-age-hardenable complex-alloyed 1570C alloy (Al-5Mg-0.18Mn-0.2Sc-0.08Zr, wt%) were studied after multi-directional isothermal forging at 325 °C up to accumulative strain e ≈ 12 and subsequent annealing in the temperature interval from 325 to 500 °C. It is shown that even amid the absence of substantial alloy hardening, high-temperature multi-directional forging is an effective method for processing bulk billets, resulting in a stable and homogeneous (ultra)fine-grained structure with a grain size of about 2 μm, which provided improved ductility and extraordinary high superplastic properties.

1. Introduction

The non-age-hardenable complex-alloyed aluminum alloy 1570C is one of the advanced structural materials for aerospace application [1,2]. It can be easily hot-worked and demonstrates superior superplasticity in the ultrafine-grained (UFG) state (grain size less than 1 μm) [2], while the cold deformation of coarse-grained counterparts is limited due to the high yield stress and low ductility [1]. One of the crucial issues for the industrial use of the alloy is the lack of an efficient technology to process bulk semi-products with the UFG structure.

The UFG structures have been produced in different materials, including complex-alloyed aluminum alloys, via the so-called severe plastic deformation (SPD) imparting large effective strains e>1 onto the workpiece [2-6]. Among many other SPD techniques, multi-directional isothermal forging (MIF) has been proven to be quite efficient to produce an industrially scalable amount of UFG bulk billets [3,6]. However, the effect of MIF on the microstructure and properties of aluminum alloys has been just scarcely studied to date.

The aim of the work is to investigate the structure and mechanical behavior of the 1570-type alloy ingot subjected to MIF.

2. Material and procedure

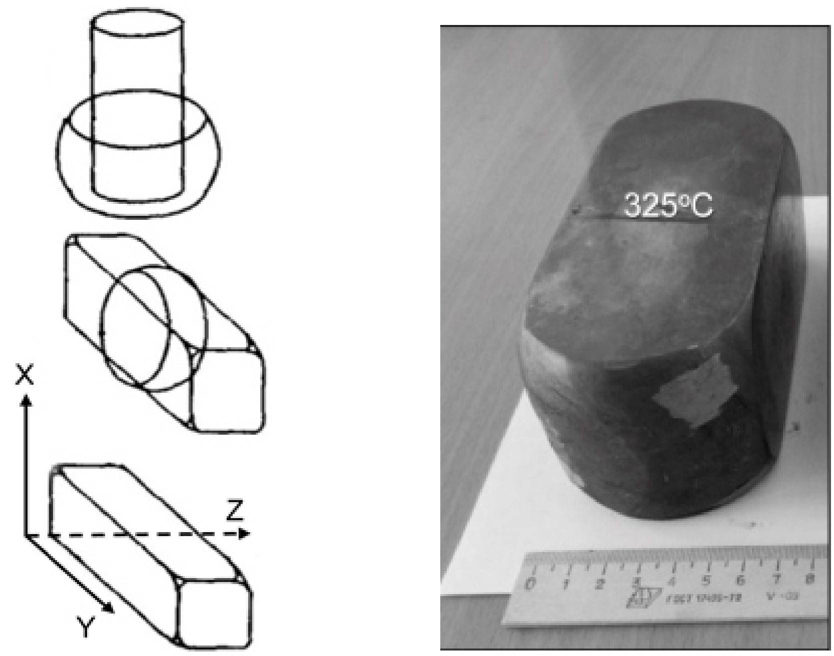
Samples with a diameter of 80 mm and a length of 150 mm were cut from an ingot of the 1570C alloy (Al-5Mg-0.18Mn-0.2Sc-0.08Zr, wt %), homogenized at 360 °C for 6 hours. Then they were subjected to MIF to effective strain of about 12 at 325 °C ($T \approx 0.6T_m$) using a hydraulic press with an isothermal die set. Each MIF cycle consisted of several deformation steps, which involved changing the deformation axis, as shown in figure 1a. Specifically, the first step was compression in the X-direction for a billet preheated in an air furnace, followed by sequential compressions from the sides of the ribs. As a result of a series of steps, the billet elongated in the Y-direction and then in the Z-direction, so that its shape and dimensions were maintained roughly unchanged in each MIF cycle (figure 1b).

The structure of the deformed billets was investigated in the central parts of the sections parallel to the last compression axis by standard methods of optical microscopy (OM) (using a Nikon L 150 optical microscope), scanning electron microscopy with the electron backscatter diffraction (SEM-EBSD) analysis (using a field emission TESCAN MIRA 3 LMH scanning electron microscope equipped with the Oxford Instruments HKL Channel 5 system), as well as transmission electron microscopy (TEM) (using a JEOL-2000EX transmission electron microscope).

The parameters of the structure, including the average misorientation angle of the intercrystallite boundaries Θ_{ave}, the high angle boundary fraction f_{HAB}, as well as the average size of the fine grains, were derived from the SEM-EBSD analysis [2,5]. The grain size was evaluated from the EBSD data by converting the grain area measurements into the "equivalent circle diameter" (with an average equivalent diameter of each of the individual grains). The Vickers microhardness (HV) was measured at room temperature using a standard procedure at a load of 0.5N. Tensile tests were carried out at ambient and elevated temperatures on an Instron 1185 screw-driven testing machine using dog-bone shaped specimens with the gage part of $1.5 \times 3 \times 6$ mm^3. The thermal stability of the developed structure was evaluated after one-hour annealing in the temperature interval 325-500 °C.

3. Results and discussions

Structural changes. In the initial cast and homogenized state, the alloy possessed an equiaxed grain structure with a grain size of 25 μm (figure 2 a, b) and uniformly distributed coherent precipitates $Al_3(Sc, Zr)$ of about 5-10 nm in diameter (figure 2 c). MIF to e=12 resulted in the development of a rather homogeneous UFG structure with the size and the volume fraction of new equiaxed grains of about 2 μm and 80-85 %, respectively (figure 2 d-f). Moreover, the fraction of high-angle boundaries and the average misorientation angle of intercrystallite boundaries in such a structure were quite high: f_{HAB} = 78% and Θ_{ave} = 31.4°. The formation of this structure was conditioned by the multistep character of the deformation carried out to high strains, occurring in various directions; that provided the uniformity of grain refinement throughout the material volume.



(a) (b)

Figure 1. Scheme of MIF (a) and photograph of the processed billet (b).

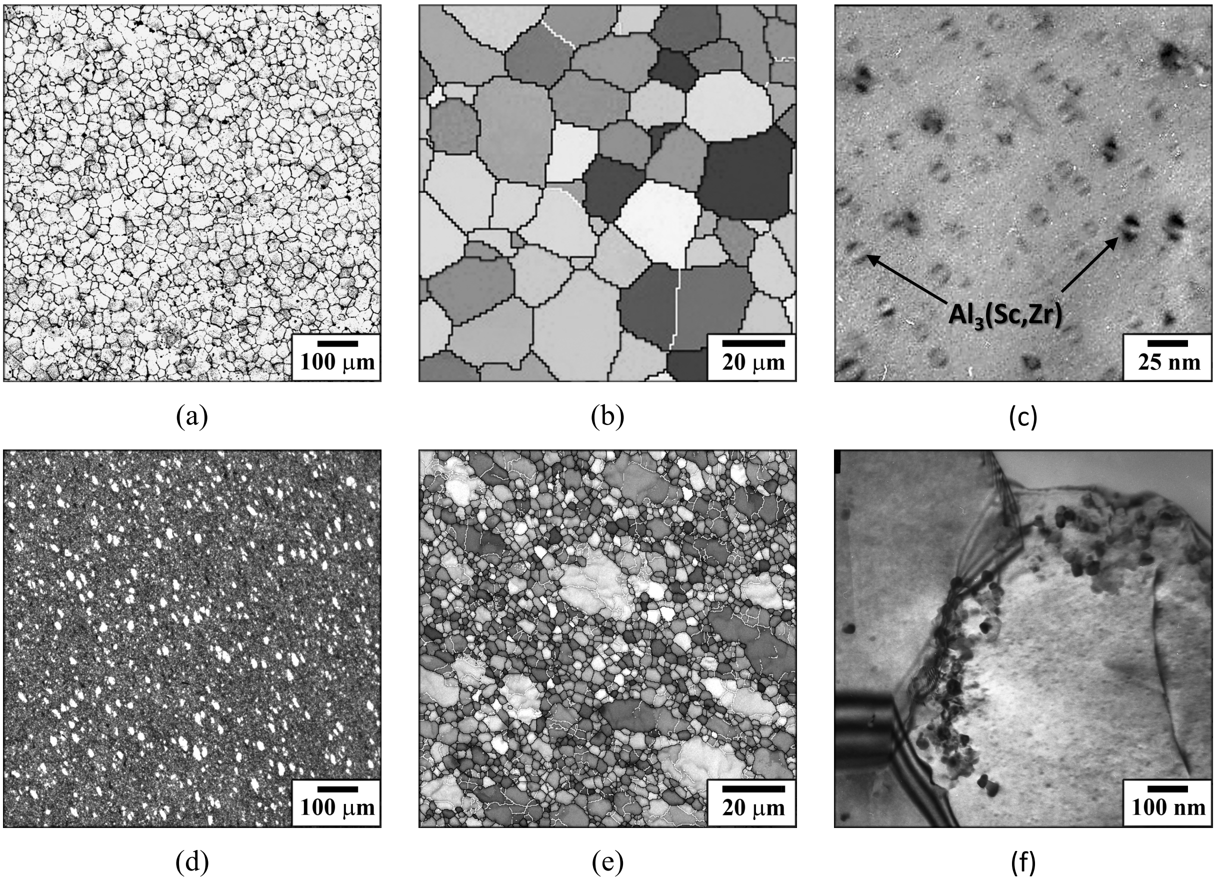


Figure 2. The microstructure of the alloy 1570C before (a-c) and after (d-f) MIF: (a, d) OM; (b, e) SEM-EBSD and (c, f) TEM.

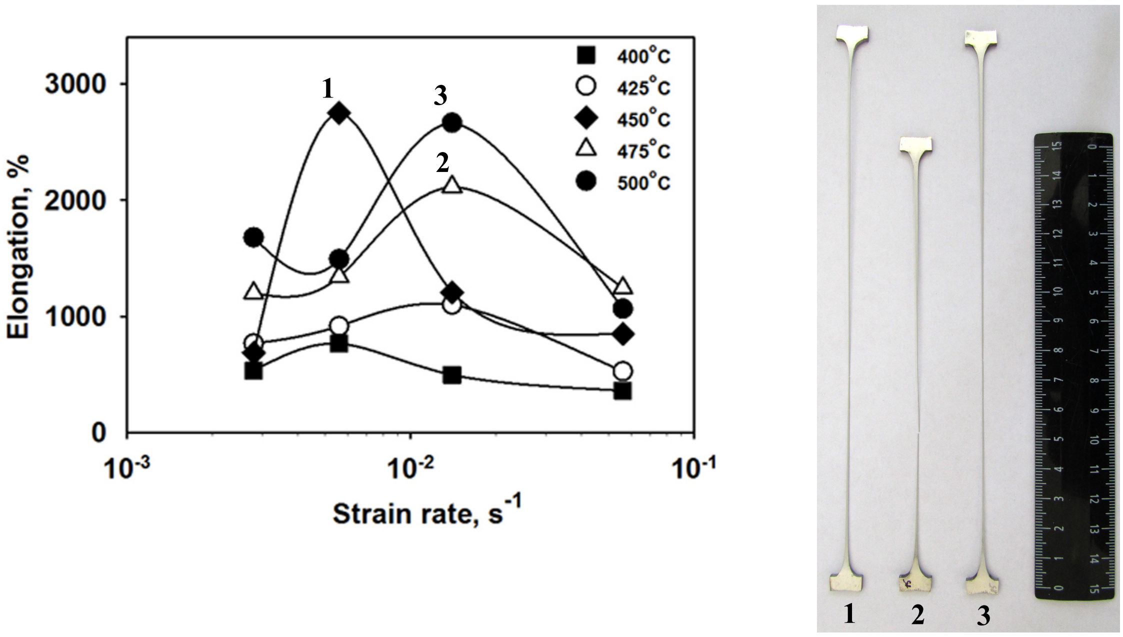
Room-temperature hardness and tensile strength parameters of the alloy before and after MIF are represented in table 1. Besides, the data for the same alloy, which was processed by equal channel angular pressing (ECAP) to e=8 at 325 °C [4], are shown in table 1 for comparison. It is seen that, in contrast to ECAP, the processing of the alloy by MIF at the same temperature did not result in its strengthening, while the ductility after MIF increased to a greater extent. This behavior was conditioned by several reasons. The absence of a significant difference in the strength of the alloy before and after MIF was caused by the fact that its structural (Hall–Petch) strengthening due to the grain refinement (figures 2 a, d) was almost completely compensated by a nearly equal strength drop owing to the coarsening of Al_3(Sc, Zr) precipitates under processing at the high temperature (figure 2 c, f) [5]. Meanwhile, a much more prominent alloy strengthening after ECAP than after MIF was reasoned by a higher (on about two orders) strain rate during ECAP [6] and, hence, by a higher defect density, as well as twice as smaller ultra-fine grain size (about 1 μm), developed in ECAP [5]. Therewith, the higher ductility was predictably exhibited by the material with a more uniform and equilibrium UFG structure processed by MIF.

Thermal stability. It was found that the MIF processed UFG structure was entirely stable up to temperatures 425-450 °C. At higher temperatures, an abnormal grain growth was noticed. As a result, the UFG structure was transformed into the bimodal one, composed by areas of ultrafine and coarse grains.

Superplasticity. Tensile tests at elevated temperatures have shown that the alloy after MIF demonstrated enhanced superplastic properties with elongations-to-failure of more than 500% in the temperature interval 400-500 °C and at strain rates up to 10^{-1} s^{-1} (figure 3 a). Therewith the maximum elongation-to-failure values of about 2800% were achieved at 450 °C and a strain rate of 5.6x10^{-3} s^{-1} and at 500 °C and a strain rate of 1.4x10^{-2} s^{-1} (figure 3 b). The data obtained testify to the achievement of superplasticity with ultra-high elongations in a wide range of temperatures - strain rates, including high-strain rate superplasticity, which significantly increases the efficiency and potential of commercial application of the alloy.

Table 1. Mechanical properties of the alloy 1570C at room temperature after MIF and ECAP

State	HV	YS, MPa	UTS, MPa	El , %
Initial	105±10	240±3	355±6	28±1
MIF at 325°C	105±10	235±5	360±5	38±3
ECAP Bcz at 325 °C [4]	-	300±4	380±6	31±2



(a) (b)

Figure 3. Elongations-to-failure of the alloy 1570C after MIF (a); photographs of the samples after tensile tests at 450 °C and 5.6x10^{-3} s^{-1} (1), 475 °C and 1.4x10^{-2} s^{-1} (2), 500 °C and 1.4x10^{-2} s^{-1} (3) showing maximum elongations (b).

4. Conclusions

Bulk billets with a fairly stable and uniform structure with a grain size of about 2 μm were processed from the complex-alloyed 1570C alloy by MIF at 325 °C (at about 0.6T_m). The data obtained testify to a high potential of commercial use of high-temperature MIF for obtaining bulk billets with a stable and homogeneous UFG structure from 1570-type aluminum alloys.

In the absence of substantial hardening, the UFG alloy 1570C processed by high-temperature MIF exhibited significantly increased room temperature ductility. Besides, the structural superplasticity with extraordinary high parameters of elongation-to-failure was achieved at elevated temperatures in a wide range of strain rates, including high-strain rate superplasticity.

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