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On the effect of non-isothermal annealing and multi-directional forging on the microstructural evolutions and correlated mechanical and electrical characteristics of hot-deformed Al-Mg alloy

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ABSTRACT

Specimens of hot-extruded AA5056-H38 aluminum alloy were subjected to multi-directional forging (MDF) and non-isothermal annealing. The combined effects of imposed strain and post-annealing on the microstructural evolutions, mechanical properties and electrical conductivity were investigated. Optical microscopy observations showed that consecutive passes of MDF resulted in grain refinement and non-uniform strain distribution created lamellar structure right after the second pass. According to the SEM micrographs, increasing the processing strain led to severe fragmentation of initial coarse intermetallic particles into ultrafine dispersoids and redistributed them within matrix. Meanwhile, during the annealing stage, recrystallization started from stress concentrated locations while asymmetric strain distribution eventually caused bimodal microstructure. Mechanical properties were evaluated using hardness and shear punch tests since results were in good agreement with microstructure transformations. Four-point probe electrical resistivity test outputs indicated that electrical conductivity had inverse relationship with dislocations density and grain boundaries volume.

1. Introduction

Al-Mg alloys have notable potentials for mechanical properties enhancement through deformation processes and became adequate alternatives for ferrous alloys in transport and industrial applications [1]. Magnesium has poor ductility at room temperature and its addition to aluminum alloys makes them to be more brittle under mechanical loadings. Hence, hot-deformation would be an appropriate choice for production of Al-Mg plates/sheets from their cast ingots [2–8].

Nowadays, severe plastic deformation (SPD) techniques are developed as applicable processes for production of ultrafine-grained structures with high strength-to-weight ratio. In this regard, such diverse methods were introduced as accumulative back extrusion (ABE) [9], twist extrusion (TE) [10], high pressure torsion (HPT) [11], tubular channel angular pressing (TCAP) [12], repetitive corrugation and straightening (RCS) [13], constrained groove pressing (CGP) [14, 15], accumulative roll bonding (ARB) [16], equal-channel angular pressing (ECAP) [17], simple shear extrusion (SSE) [18] and multi-directional forging (MDF) [19]. MDF as a SPD technique is applicable to large bulk samples [20]. Schematic design of process is shown in Fig. 1. Effect of MDF and post-annealing on the mechanical properties and microstructural transformations during processing of Al and Mg alloys were investigated separately before [21–28]. Mao et al. [29] investigated the microstructural changes during hot-rolling of Al-Mg alloys. They reported that increasing the Mg content in an Al alloy resulted in conversion of dominant restoration mechanism from dynamic recovery to dynamic recrystallization. Recrystallization kinetics of Al-Mg alloys after hot-deformation was surveyed by Raghunathan et al. [30]. It was expressed that grain size was considerably affected by various parameters such as initial grain size, total strain, strain rate and annealing temperature. Therefore, recrystallization might be controlled by different parameters in Al-Mg alloys.

The focus of prior works were on the studying the materials properties at the terminal stage of thermal and mechanical processes; however, from authors' point of view, it seemed that it

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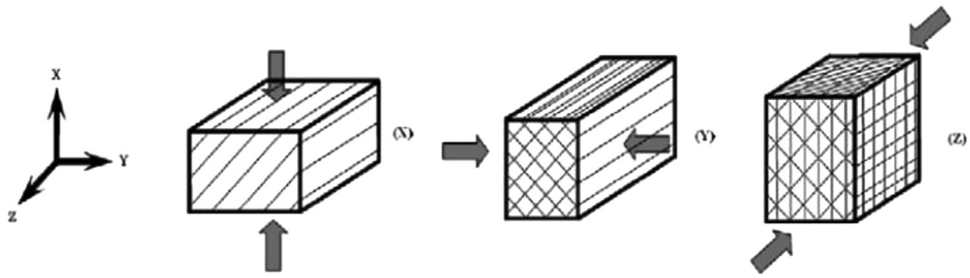

Fig. 1. Schematic design of the MDF process.

would be an attractive approach to investigate the microstructural transformations during non-isothermal annealing of SPDed Al-Mg alloy. Meanwhile, in the current research, the correlations of processing parameters with the mechanical and electrical characteristics were investigated as its novelty.

2. Material and methods

The chemical composition of the utilized commercial hot-extruded AA5056-H38 alloy is listed in Table 1. Primary annealing was carried out at 550 °C (823 K) for 3 h while the obtained grain size reached 74 μm. Rectangular samples with dimensions of 10 mm × 10 mm × 14 mm were cut and prepared by electrical discharge machining parallel to the extrusion direction. Fig. 2 illustrates the applied die which was made of Bohler SPK steel. Samples were processed at room temperature using an Instron mechanical testing frame at an initial strain rate of 10^{-4} s^{-1}. MoS_2 solution was employed as lubricant while processing. Imposed strain (ε) according to Eq. 1 was equal to 0.4 for each MDF pass and the processing was carried out up to the maximum accumulative strain of 1.2 consistent with three passes of forging.

$$\varepsilon = \frac{2}{\sqrt{3}} ln \frac{H}{W} \tag{1}$$

where, H and W were the height and the width of the examined specimens, respectively. In order to investigate the post-annealing effect on SPDed specimens, non-isothermal annealing was performed at 450 °C (723 K) for 10-60 min in an air furnace. Conventional metallography samples were prepared by mechanical polishing on 3000-grit SiC paper and diamond suspension, and then, electro-etched using JE-WorldTech patented etchant [2, 14]. The evolved microstructure was studied on the plane parallel to the ultimate forging axis using polarized-light Olympus PME3 microscope. Average grain size was calculated by the Clemex® software according to the ASTM E112 standard. The intermetallics were characterized by MIRA3 TESCAN field-emission scanning electron microscope (FE-SEM) operated at 15 kV. The Vickers micro-hardness and hardness tests were accomplished by WOLPERT

Table 1
Examined chemical composition of utilized AA5056-H38 alloy.

Element	Percentage (wt%)
Al	Rem.
Mg	5.668
Fe	0.351
Si	0.264
Mn	0.253
Cr	0.112
Zn	0.082
Cu	0.079
Other	< 0.050

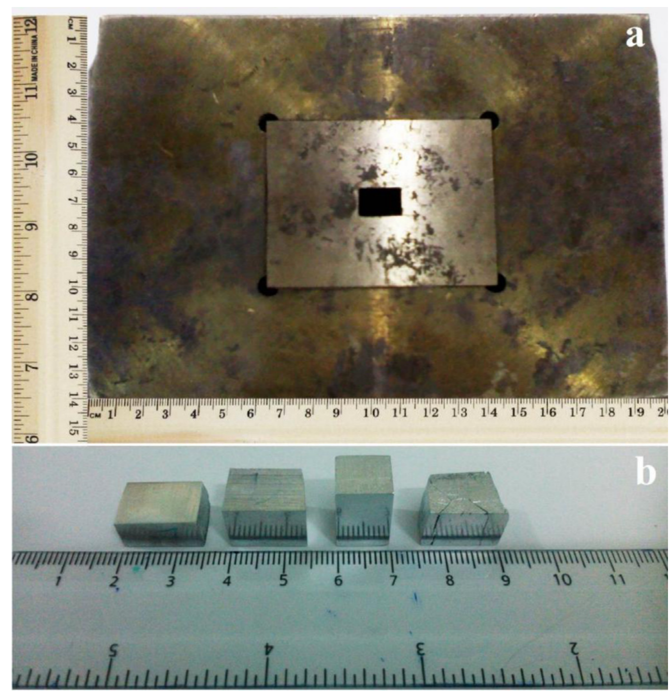

Fig. 2. Illustrations of (a) utilized MDF die, and (b) one-to-four pass MDFed AA5056-H38 alloy specimens.

420MVD universal machine (200 g load and dwelling time of 30 s) and Instron WOLPERT GMBH equipment (25 g load and dwelling time of 20 s), respectively.

Due to the small sizes of examined samples, shear punch test (SPT) was appropriate alternative for tensile testing in order to obtain the mechanical characteristics (Fig. 3). A Hounsfield H10KS tension test machine by constant cross-head displacing velocity of 0.1 $mm.min^{-1}$ was employed to conduct the test while the sample thickness was kept 1 mm. Doing this, cylindrically shaped punch and die with diameters of 2.99 and 3.01 mm were applied, respectively. Displacement was measured using a linear variable differential transformer (LVDT) while the load was measured by a standard load cell. The shear stress could be obtained as follows [31, 32]:

$$\tau = (\mathrm{P} - \mathrm{F})/\pi \ \mathrm{d_{avg}} \mathrm{t} \tag{2}$$

where P is the punching load, F is the frictional load, t is the specimen thickness and d_{avg} is the average of the punch and die-hole diameters. Using lubricant caused the friction effect so negligible and ignored in calculations. Also, the shear strain (γ) and shear strain rate (γ°), at the annular region around the punch circumference, was calculated using the expression for pure-shear condition as follows: