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Characterization of the microstructure, texture and mechanical properties of 7075 aluminum alloy in early stage of severe plastic deformation

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ABSTRACT

The present investigation was conducted to study the microstructural, mechanical and texture evolutions of a 7075 aluminum alloy at the early stage of severe plastic deformation. In this regard, three different techniques were elaborated (for just one pass) to ensure maintaining different deformation modes. These were done applying Multi-Axial Forging (MAF), Accumulative Back Extrusion (ABE) and Friction Stir Processing (FSP) under predetermined thermomechanical condition based on the Zener-Hollomon value. The macrostructures of the deformed materials demonstrate a unique flow pattern and distribution of grain refinement zones, especially in ABE and MAF methods. The EBSD characterization results reveal the presence of accumulated micro-shear bands, which have been ended to an outstanding grain refinement. The results show occurrence of both discontinues and continues dynamic recrystallization (mainly in the stir zone) in the FSPed materials. The mechanical examinations display a significant improvement of both yield and ultimate tensile strength values in all methods. Moreover, the tensile tests were applied in different directions to evaluate the mechanical anisotropy of the deformed materials. The results exhibit higher capability of FSP in delivering more isotropic properties in comparison to the other techniques. In addition, the macro-texture results approve the stronger effect of FSP on fading the initial rolling anisotropy out.

1. Introduction

Severe plastic deformation (SPD) is recognized as one of the most effective methods in grain refining of metallic materials. A tremendous amount of strain is applied to a workpiece through SPD, but in the same time it is postulated that its final shape should be similar to its initial one [1–3]. This incident would mainly result in an improvement of mechanical properties, in companion with altering electrical conductivity and corrosion resistance in some alloys [4–7]. Moreover, the microstructural and textural inhomogeneities can be reduced [8]. Hence, the final product would be a multifunctional material due to the combination of aforementioned characteristics [6]. To this end, various types of SPD methods have been designed including HPT (High pressure torsion which was the first SPD method that was scientifically used for material processing by Bridgman) [9], ECAP (Equal Channel Angular Pressing) [10], CGP (Constrained Groove Pressing) [11], MAF (Multi-axial Forging) [12], FSP (Friction Stir Processing) [13], TE (Twist extrusion) [14] , ABE (Accumulative Back Extrusion) [15], etc.

The up-to-date studies related to SPD commonly deal with some limited approaches. Most of which considering post-processing improvements of initial properties in terms of particular mechanical characteristics. Moreover, there are some other researches associated with involved fundamental mechanisms, chiefly the microstructural modification induced by applying SPD methods [16,17]. These detailed micro-mechanisms had been discussed mainly based on the nature of the alloys (crystal lattice or chemical composition), or the process parameters (e.g., temperature, strain rate and strain). In terms of process variables, the strain is known as the most efficient factor and the mode of straining, which can be affected by geometry of the methods, would be an important and influential matter too. Subsequently, the developed SPD routes significantly differ with each other in the resulting deformation mode. Furthermore, the straining mode could range from pure shear to simple shear as well as monotonic loading to cyclic and cross loading in terms of different routes [18,19].

To shed a light into the effect of process variables in SPD, Zener-Hollomon parameter ($Z = \dot{\varepsilon}\exp\left(\frac{Q}{RT}\right)$) has been used by some previous researchers. In this regard, Li et al. [20] used this parameter to clarify the relation between grain size and grain refinement mechanism during quasi-static compression. An almost similar method is performed by

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Brown and co-workers [21] in dynamic severe plastic deformation of a pure copper. Additionally, there are some sporadic researches in which is discussed about the effect of *Z* value on the minimum grain size after a severe plastic deformation route [22–24].

Despite the importance of strain path and Zener-Hollomon parameter there is no comprehensive and clear study on the results of changing the SPD route in affecting final characteristics of the product with Z-parameter taking into account. To be more precise, there are few specific records [25,26] on microstructural and textural evolutions through SPD techniques containing different modes of strain for a definite alloy and in a special thermomechanical scheme. In addition, the influence of this variation on the mechanical properties and microstructural homogeneity of the final product, which is the main goal of SPD, is another lack of knowledge in the open literature.

To redeem this lack of knowledge, a commercial 7075 aluminum alloy is selected as the experimental material in the present investigation. The Zener-Hollomon parameter was considered to synchronize the effects of temperatures and strain rates. Allowing similar Z values in the applied SPD methods may well satisfy this concern. Above all, a range of different SPD techniques (i.e., ABE, MAF and FSP), each holding distinct deformation modes due to their basic concepts, were chosen to magnify the deformation mode effect. In addition, a low amount of strain (just one pass) was applied by each method to well trace the strain accommodation. Finally, mechanical, structural and textural characteristics have been discussed and compared with each other in details, in terms of both macro- and micro-scales.

2. Materials and methods

2.1. Material preparation

A rolled 7075 aluminum alloy in peak-aged T6 condition was chosen as experimental material. The chemical composition of the alloy is given in Table 1. For solution treating, the experimented material was solution treated through isothermal holding at 480 °C for 2 h followed by an immediate quenching. The semi-equiaxed grains are distributed through the initial elongated grains as is shown in optical micrograph Fig. 1. This state of material is implied by ST in the following sections.

The MAF and FSP samples are prepared from ST material using electro discharge machine (EDM). The MAF workpiece was a cube with 10 mm × 10 mm × 16 mm dimensions, and the FSP one was a plate with 10 mm thickness. Moreover, the ST material was machined into cylinder with 18 mm diameter and 8 mm height for ABE test.

2.2. Principles of experimental methods

The MAF and ABE experiments were carried out using a Gotech-AI7000 universal testing machine equipped with electrical resistance furnace. According to Fig. 2a, in MAF procedure, the cubic workpiece is twisted 90° between each individual compressive step. The MAF tests were carried out at 200 °C at nearly constant strain rate of 0.01 s^{-1}. Very thin mica flakes and solid MoS_2 were used to reduce the friction and inhibit the adhesion of the workpiece to the anvil. The ABE experiments were also carried out at 200 °C with a constant ram speed of 1 $mm \cdot min^{-1}$. The principle of ABE method is shown in Fig. 2b. The cylindrical workpiece is placed into the die cavity and pressed by the inner punch. Subsequently, the workpiece is back extruded into the gap between the inner punch and the die. Finally, the extruded part is forged by the outer punch to shape the workpiece into the initial dimensions. The MoS_2 spray is applied to decrease the friction. Moreover, the process strain rate by traveling speed of 1 $mm \cdot min^{-1}$ is 0.01 s^{-1} [27,28]. Ultimately, the FSP was done at the rotational speeds of 400 rpm and traveling speed of 50 $mm \cdot min^{-1}$. An H-13 tool with 8 mm diameter and 3° tilt angle was used to stir and process the workpiece. Furthermore, the atmosphere was neutralized by Argon shielding gas, using a Plexiglas box around the rotating tool and the workpiece to minimize the oxidation. In order to record the maximum temperature a fixed K-type thermocouple is devised to the workpiece according to Fig. 2c. Considering a certain level of rotation lagging effect, the strain rate can be estimated based on a torsional-approach to the deformation using Eq. (1) [22,29]:

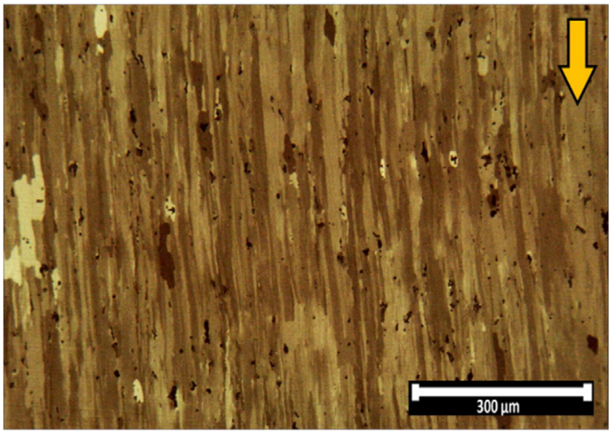

Fig. 1. The microstructure of as-rolled Al7075 experimental alloy after solution treatment.

$$\dot{\varepsilon} = \frac{R_m 2\pi r_e}{L_e} \tag{1}$$

where R_m is the average material flow rate assumed to be almost half of the rotational speed i.e. R_t. r_e and L_e describe the effective radius and depth of the recrystallized zone, respectively; also, r_e is about π/4 of the shoulder radius. The strain rate was estimated as 41.8 s^{-1} and the recorded temperature was 260 °C.

It is noteworthy to mention that the strain distribution had been calculated using FE-simulation in the employed methods. Accordingly, the shear strain of grain refinement zone, which equals to the maximum strain imposed to the sample after one pass, reached approximately ~10 for FSP [30], ~10 for ABE [27] and ~9 For MAF [31]. Also, the distributed strain in these methods is quite different which is drastically returned to die design and geometry of the specimen causing the different distribution of grain size.

2.3. Post-process characterization

To examine the microstructure and texture evolution, the processed materials were sectioned perpendicular to the processing directions. The microstructures were characterized using Barker's (5 g HBF_4, 200 ml H_2O) and Keller's (95 ml H_2O, 2.5 ml HNO_3, 1.5 ml HCl, 1 ml HF) reagents. Moreover, macro-texture measurements were conducted using a Philips X'Pert diffractometer furnished with a close Eulerian cradle. For this, Cu-Kα radiation was used at 50 kV with tilt angle ranging from 0 to 90°. The (111) pole figures were calculated using the X'Pert Texture software. After being ground, the samples were mechanically polished in a sequence of 6 μm, 3 μm and 1 μm diamond and subsequently electropolished in a 30% nitric acid (HNO_3) and 70% methanol

Table 1
The chemical composition of experimental 7075 aluminum alloy.

Zn	Mg	Cu	Fe	Si	Cr	Mn	Ti	Pb	Ni	V	Sb	Zr	Al
5.11	2.46	1.22	0.523	0.45	0.14	0.104	0.063	0.021	0.006	0.006	0.002	0.001	Bal.