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Evaluation of the mechanical anisotropy and the deformation mechanism in a multi-pass friction stir processed Al-Zn-Mg-Cu alloy

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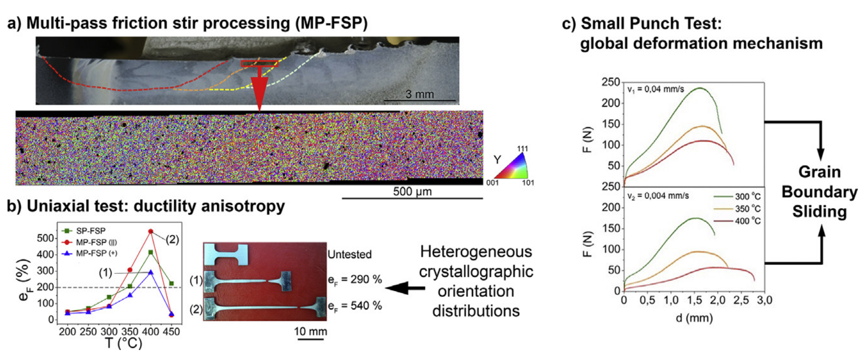
HIGHLIGHTS

- An overaged Al 7075 alloy was single (SP-FSP) and multi-pass (MP-FSP) friction stir processed.
- Different crystallographic orientations distributions were observed in parallel (||) and transverse (+) MP-FSP directions.
- Crystallographic induced superplastic elongation anisotropy was observed: eF=540, 290 % in (||) and (+) at 10-2 s-1, 400°C.
- The biaxial small punch test allowed identifying grain boundary sliding as the global operative deformation mechanism.

GRAPHICAL ABSTRACT



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ABSTRACT

Multi-pass friction stir processing (MP-FSP) can produce extensive bulk nanostructured areas in various metallic materials, such as the Al 7075 alloy (Al-Zn-Mg-Cu), providing fine and highly misoriented grains. This allows obtaining superplastic deformations by the activation of grain boundary sliding (GBS) mechanism at certain strain rate and temperature window, crucial for performing a further superplastic forming (SPF). The superplastic performance of the MP-FSP Al 7075 alloy in two uniaxial testing directions was evaluated and compared to that of a single pass FSP (SP-FSP), reporting a mechanical anisotropy in the MP-FSP attributed to the heterogeneous crystallographic orientation distribution along the transverse testing direction. The operative deformation mechanism was determined by uniaxial tensile test and small punch test (SPT), the former a test with biaxial with radial symmetry. GBS was corroborated as the main operative deformation mechanism in the SP-FSP and MP-FSP, reporting high strain rate superplasticity in the temperature range 350–400 °C at 10^{-2} s^{-1}, and maximum elongation values between 290–540% at 400 °C depending on the testing direction. The Al 7075 alloy processed by MP-FSP showed a great potential for a further SPF as GBS remains as the global deformation mechanism under biaxial testing conditions.

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1. Introduction

Superplasticity is known as the ability of a polycrystalline material to exhibit, in a general isotropic manner, very high tensile elongations prior to failure thanks to the activation of the grain boundary sliding (GBS) mechanism in a determined strain rate ($\dot{\varepsilon}$) and temperature range, known as the "superplastic window". The operation of this mechanism requires equiaxed, fine (<15 μm) and highly misoriented grains and is characterized by low flow stresses (σ) and low stress exponents ($n \sim 2$) [1,2]. Eq. (1) is the constitutive equation for this mechanism,

$$\dot{\varepsilon} = K\left(\frac{\sigma}{E}\right)^2 \left(\frac{b}{L}\right)^p \exp\left(-\frac{Q}{RT}\right) \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, K is a constant, σ is the flow stress, E is the elastic modulus, b is the Burgers vector, L is the grain size, p is the grain size exponent, Q the activation energy, R is the universal gas constant and T is the temperature. Ruano and Sherby [3] performed an experimental review for a wide group of alloys undergoing GBS. They observed that the constitutive equation (Eq. (1)) for this mechanism depends in general on the diffusion coefficient, which depends on temperature. At approximately $0.4T_m < T < 0.6T_m$, $p = 3$ and $Q = Q_{GB}$, while when $T > 0.6T_m$, $p = 2$ and $Q = Q_L$, being Q_{GB} is the activation energy for self-diffusion along grain boundaries and Q_L the activation energy for lattice self-diffusion. It can be predicted from Eq. (1) that the finer the grain size (L), the higher the strain rate ($\dot{\varepsilon}$) and the lower the temperature for which GBS can operate. Additionally, high strain rate superplasticity (HSRSP) is usually considered as obtaining elongations to failure $e_F \geq 200\%$ at strain rates $\dot{\varepsilon} \geq 10^{-2}\ s^{-1}$ [4].

One of the main applications of materials with microstructures able to undergo superplastic deformations is superplastic forming (SPF). SPF is a promising processing technique where pieces with complex shapes and homogeneous thickness can be easily obtained using lower flow stresses than in conventional forming processes, with the corresponding energy saving [5–9]. There are several configurations to carry out the SPF, being the gas pressure forming the most widely used [10]. Nevertheless, in order to perform SPF it is necessary a prior thermomechanical treatment to obtain an appropriated microstructure prone to the operation of GBS as the main deformation mechanism.

Alloys belonging to the Al-Zn-Mg-Cu alloy system, such as Al 7075 alloy, present a homogeneous distribution of hardening precipitates that provides high strength to density ratio and excellent mechanical properties [11]. Nevertheless, these alloys have limited formability during conventional forging at elevated temperature. Thus, an optimum thermomechanical processing can lead to a microstructure appropriated for a further SPF.

In this regard, severe plastic deformation (SPD) techniques are a group of metalworking processes, which have been erected as a convenient way to obtain fine and highly misoriented microstructures [12]. The grain refinement is achieved by applying huge plastic deformations without changes in the overall dimensions of the workpiece, which allows repeating the process ideally an undefined number of cycles. The most popular techniques used to produce severely plastic deformed bulk materials are equal channel angular pressing (ECAP) [13,14], accumulative roll bonding (ARB) [15,16] and more recently friction stir processing (FSP) [17–19], the SPD technique used in the present study. FSP is based on the concepts of friction stir welding (FSW) [20,21] and requires a cylindrical rotating tool with a concentric pin and shoulder that is punched in the material and traversed along the line of interest. The friction between the rotating tool and the workpiece produce a localized heating becoming the material easily plastically deformable. The material undergoes intense plastic deformation at elevated temperature resulting in significant grain refinement. FSP allows for a precise control of the required microstructural refinement. In addition, the versatility of the FSP is not only limited to produce deformations along a line [22–25] but to modify the microstructure along extensive sheets as well [26,27] or even being used as a surface modification technique to modify locally the composition [28–33].

Regarding the further superplastic behavior, FSP can produce a microstructure appropriated for SPF when using optimum processing conditions [26,34–37]. Nevertheless, the width of the stir zone in a single pass FSP (SP-FSP), related with the pin diameter, is usually insufficient for engineering applications, becoming necessary to overlap FSP passes (MP-FSP) to produce extensive microstructurally modified areas. However, because of the inherent heterogeneity of the processing, some studies have reported a mechanical anisotropy when uniaxial testing at room temperature in MP-FSP materials, showing that usually the transverse direction possesses less strength and ductility than the longitudinal testing direction [38,39]. This mechanical anisotropy can also be extended to the high temperature deformation behavior [40]. Despite of the mechanical anisotropy, Dutta et al. [18] demonstrated the feasibility of SPF in a MP-FSP Al 7057 alloy, but the high temperature deformation mechanism was determined using uniaxial tests, which are dependent of the testing direction.

The aim of this research is to explore the high temperature mechanical behavior in the SP-FSP and on a MP-FSP Al 7075 sheet using the same processing conditions. Directional anisotropy in the ductility when testing the MP-FSP by means of uniaxial tensile testing was reported [41]. In this approach, we propose to determine the feasibility of the MP-FSP for SPF by studying the global deformation mechanism along the whole surface, independently of the testing direction, using a biaxial geometry test. This characterization, closer to the further SPF conditions, was carried out at the laboratory scale using small punch testing (SPT). SPT can be performed in small samples and turned out to be a convenient and useful method for a pre-industrial scale characterization.

2. Experimental method

The material used in the present study consisted of 3 mm sheets of a Al 7075 aluminum alloy in an overaged state. This overaging treatment was conducted in the commercial 7075-T6 alloy, aging treated at 265 °C for 13 h and furnace cooling. The chemical composition of the alloy is presented in Table 1.

The sheets where then subjected to friction stir processing (FSP) using a rotation rate of 1000 rpm and a traverse speed of 500 mm/min along the previous rolling direction. The processing was carried out using a tool made of MP159 with scrolled shoulder 9.5 mm in diameter and a concentric threaded pin with flutes, 3 mm in diameter and 2 mm in length. Two types of samples were obtained. The first ones consist in one single FSP pass (SP-FSP). The second ones where processed by multi-pass FSP (MP-FSP), with a 50% overlapping on the advancing side along 9 passes. Fig. 1 presents a schematic of the processing and the axis convention used in the present study.

Table 1
Composition of the studied 7075 aluminum alloy (wt%).

Zn	Mg	Cu	Cr	Fe	Si	Ti	Mn	Al
5.68	2.51	1.59	0.19	0.19	0.052	0.025	0.007	bal.

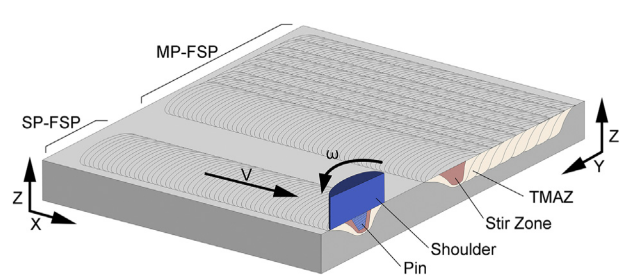

Fig. 1. Friction stir processing (FSP) schematic and axis convention used in this study.