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The origin of non-uniform microstructure and its effects on the mechanical properties of a friction stir processed Al–Mg alloy

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Abstract

The microstructure of the stirred zone (SZ) resulting from friction stir processing or welding (FSP/FSW) has usually been assumed to be uniform when discussing the mechanical properties. However, numerous works have indicated that the fine-grained microstructures in the SZ were non-uniform, with precipitate, texture and grain size gradients caused by the severe plastic deformation and heat distribution. In this work commercial aluminum alloy 5083-H112 was subjected to FSP and fine-grained microstructures with an average grain sizes of 2.7–13.4 μm were obtained by controlling the FSP conditions. The stress–strain curves exhibited stepped yield point elongation, which was suggested to be associated with these characteristic non-uniform microstructures. Tensile tests indicated that the Hall–Petch relationship held in this FSP alloy when taking account of the average grain size. Toughness analysis indicated that the optimum toughness was anticipated to be obtained around a grain size of ∼1 μm for this FSP alloy.

Keywords: Friction stir processing; Aluminum alloys; Grain refining; Mechanical properties; Yield phenomena

1. Introduction

Friction stir processing (FSP) has been developed as an effective grain refinement technique based on the principle of friction stir welding (FSW) [1]. It is well documented that the intense plastic deformation and temperature rise during FSW/FSP result in the generation of dynamic recrystallization, producing fine and equiaxed grains in the stirred zone (SZ) [2–4]. By changing the FSW/FSP conditions, such as process parameters, tool geometry, vertical pressure, composition of workpiece, temperature of workpiece and active cooling, a wide range of grain sizes from 0.1 to 17.8 μm can be produced by FSW/FSP [5].

When discussing the mechanical properties of FSP samples, as an approximation, the SZ is usually assumed to have a uniform microstructure [6]. However, numerous studies [7–12] have indicated that the SZ exhibits a non-uniform character, e.g. the grain size and texture vary with position. The grain size in the SZ tended to increase near the top of the SZ and to decrease with distance on either side of the center line [7,8]. Such a variation in grain size from the bottom to the top of the SZ is believed to be associated with differences in the temperature profile and heat dissipation.

In the microstructure produced by FSP onion rings, consisting of different scales of grains [9] and periodical microstructure with alternate particle-rich bands [7] have often been observed in cross-sections of the SZ or in horizontal cross-sections along the tool travel direction [10]. In a previous study [11] the flow lines induced by intense deformation also indicated a non-uniform microstructure like onion rings. Field et al. [12] indicated that severe gradients in crystallographic texture existed through the thickness and across the width of FSW joints and the character of local textures appeared to depend on the weld parameters. Also, Prangnell and Heason [10] found that the SZ material (thick 2195 Al alloy plate) had a strong ideal {1 1 2}<1 1 0> texture or strong $B/\bar{B}$ ideal simple shear component, with the shear plane normal and shear

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Table 1
Nominal chemical composition of Al alloy 5083 (wt.%).

Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
0.4	0.4	0.1	∼0.40–1.0	4.0–4.9	∼0.05–0.25	0.25	0.15	Balance

direction being aligned approximately perpendicular to and tangential to the flow lines (surrounding the tool) in the SZ. However, there is still a lack of overall analyses on the origin, characteristics and influence of the non-uniform microstructure produced by FSP, especially for thick plates with a more apparent non-uniformity.

As experimental materials non-heat-treatable Al–Mg alloys have a simple element system and weakly anisotropic properties. Thus the mechanical properties of Al–Mg alloys are mainly determined by grain size and dislocation density. Lüders strain is one inherent feature of Al–Mg alloys with annealed fine grains, generally studied based on relative uniform materials [13], since it is well known that Lüders strain depends markedly on grain size [14]. The magnitude of Lüders strain increases as the grain size decreases. Considering the non-uniformity of FSP alloys, Lüders strain having different characteristics could be anticipated if the SZ consisted of grains which varied significantly. This could give some clues to a better understanding of the structure–property relations of FSP alloys.

In this work a non-heat-treatable Al–Mg alloy 5083 was used to investigate the effect of FSP conditions, such as FSP parameters, tool sizes, tool to workpiece angle and active cooling, on microstructure evolution and mechanical response. Especially, overall microstructure characterization in the SZ, based on grain size measurement and hardness tests, was carried out, and optimization of the material properties through grain refinement is discussed.

2. Experimental

Commercial aluminum alloy 5083 (H112) rolled plate 6.1 mm in thickness was used. The nominal composition of the as-received alloy is given in Table 1. The yield strength, ultimate tensile strength, uniform elongation and total elongation of the alloy are 205 and 337 MPa and 13.2% and 13.7%, respectively. The plates were cut into $6.1 \times 70 \times 400\ mm^3$ and were friction stir processed using a H13 steel tool. The tool was fitted with a threaded pin (right-handed screw). The FSP parameters used in this study and cooling systems are summarized in Table 2. The tool to workpiece angle was 2.5–3.5° from the vertical axis. For sample 9 a copper backplate and two narrow copper plates were placed under and on the workpiece, respectively, to increase the cooling rate. For sample 10, in addition to the copper backplate, fast flowing water covered the whole workpiece. Based on the FSP conditions, there are four main groups of samples for comparison, with differences in the (a) diameters of the shoulder and pin, (b) tilt angles, (c) rotation rates and travel speeds and (d) cooling methods.

Vickers hardness profiles were measured on a transverse cross-section (XOZ plane in Fig. 1) along the center line (OX), with a 200 g load for 15 s. The specimens for optical microscopy (OM), stereoscopy and electron backscattered diffraction (EBSD) were ground and electrolytically polished in a solution of 40 ml perchloric acid and 160 ml ethanol at −30 °C. The specimens for OM were anodized for 100 s at $0.4\ A\ cm^{-2}$ in Barker's solution – 5 ml HBF_4 (48%) in 200 ml water at room temperature. Tensile specimens with a gage length of 26 mm and a width of 4 mm were cut from the SZ along the FSP direction and thinned to 2.5 mm thickness, with the top and bottom parts being removed by an electrical discharge machine (Fig. 1). Tensile tests were conducted in an Instron 8871 tester at a strain rate of $1 \times 10^{-3}\ s^{-1}$.

3. Results

3.1. Microstructure

Fig. 2 shows typical optical microstructures of the SZ in the FSP samples, which were composed of fine equiaxed recrystallized grains. The grain size of the SZ could be adjusted by changing the size of the shoulder and pin, the rotation rate and travel speed of the tool and the angle of the tool to the workpiece or by using different cooling

Table 2
Tool size, FSP parameters and cooling methods used in this study.

Sample No.	Pin diameter (mm)	Shoulder diameter (mm)	Travel speed ($mm\ min^{-1}$)	Rotation rate (r.p.m.)	Tilt angle (°)	Cooling method
1	8	20	150	300	2.5	Air/steel
2	8	22	100	400	2.5	Air/steel
3	6	18	200	400	3.5	Air/steel
4	6	18	200	400	3	Air/steel
5	6	18	200	400	2.5	Air/steel
6	6	18	300	500	2.5	Air/steel
7	6	18	400	600	2.5	Air/steel
8	6	18	500	700	2.5	Air/steel
9	6	18	200	400	3	Air/copper
10	6	18	200	400	3	Water/copper