

Influence of friction stir processing tool design on microstructure and superplastic behavior of Al-Mg alloys

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ABSTRACT

Friction stir processing is one of the most efficient techniques for microstructure refinement and has a potential for enhancing the deformation behavior of metallic materials at elevated temperature. The design of the tool has been shown to play a decisive role in microstructure modification. In this work, the effect of tool design on superplastic behavior of friction stir processed Al-Mg alloys has been investigated. The alloy was friction stir processed at 400 rpm and 0.42 m/s. Four different tools were used and compared. The pin was right-handed screw type in all cases. Very fine microstructures with grain sizes less than 3 μm were obtained with all the tools. Abnormal grain growth was observed after high temperature exposure using some of the tools. Maximum tensile elongations in the range of 575–810% were achieved with three of the tools. The tool with a larger shoulder area allowed more plastic deformation on the microstructure generating a more suitable microstructure for high temperature deformation.

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1. Introduction

Superplasticity is the ability of a polycrystalline material to exhibit very high tensile elongation prior to failure [1]. This phenomenon has important implications for sheet metal forming industry. The most crucial requirement for a material to show such behavior is a stable fine grain size. Currently, various processes are available for refining the microstructure of as cast Al alloys, with ability to obtain grain sizes in the submicron and nanometer ranges using intense plastic deformation of the material. For instance, thermo mechanical processing (severe cold rolling), equal channel angular processing (ECAP), torsional deformation under pressure and friction stir processing (FSP) have been used. Among these, FSP is particularly attractive because it obtained ultra-fine grain regions without changing the thickness of sheet, with potential benefits for the superplastic forming industry.

Recently, it was found that FSPed Al alloys can produce a grain size less than 5 μm [2–6]. FSP is a severe plastic thermomechanical process originated after the novel friction stir welding (FSW) technique shaped in the early nineties [7]. The welding process consists of a non-consumable rotating tool with a shoulder and pin or probe that is inserted into the interface between two sheets or

plates to be joined and traversed along the line of joint. Frictional heat is generated while tool enters the sheets so as to create a plasticized region facilitating the material flow behind the tool where the welded joint forms. In the case of FSP, the rotating tool is inserted in a monolithic workpiece for localized microstructural modification for specific property enhancement [8]. FSW/FSP tool plays a fundamental role in the joining or microstructural modification. There are several studies on the effect of tool design: pin and shoulder geometry [9–13]. Most of these studies have been focused on the joint strength of the weld. However, very little effort has been made to study the effect of FSP tool geometry on superplastic behavior. Therefore, the aim of this work is to study the effect of four different FSP tools on the microstructure, which influences the superplastic behavior of continuous cast Al-Mg alloys.

2. Experimental procedure

5083 aluminum alloy plate, produced by the continuous belt cast process, was received in the as-cast condition with a thickness of 15 mm. The chemical compositions of the alloy are shown in Table 1. The material was friction stir processed using four different tools of MP159 alloy under the same parameters of 400 rpm tool rotation rate and 0.42 mm/s (1 ipm) traverse speed since these conditions have presented good thermal stability to the

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Table 1
Compositions of the alloy in weight percent (balance Al).

Alloy	Mg	Mn	Cr	Fe	Si
CC 5083	4.72	0.49	0.19	0.16	0.09

microstructure during superplastic tests [14]. Tools used for friction stir processing are shown in Fig. 1, while their main geometric dimensions are summarized in Table 2. The pin was right-handed screw type in all cases. The tool tilt angle and plunge depth were 2.5° and tool height plus 0.4 mm, respectively. Maximum temperature registered over the plate surface next to the tool path for the different tools was measured with a ThermoCAM S40 infrared camera. An infrared image captured during FSP application is shown in Fig. 2.

The microstructure was observed by optical, scanning and transmission electron microscopy on the transverse cross-section of the FSP zone. The samples for optical analysis were mechanically polished then etched using Keller's reagent to reveal grain boundaries, (a heat treatment at 150 °C for 20 h was applied to the samples to decorate the grain boundaries with precipitates). Grain size was measured by the linear intercept method. Large second-phase particles were examined in a Hitachi S-570 scanning electron microscope in backscattered electron mode from as-polished samples. TEM samples were ground and polished, and then thinned by twin-jet electro-polishing at 12 V in a solution of 80% methanol + 20% nitric acid at −30 °C. The samples were examined using a Jeol JEM-2000-FX II transmission electron microscope at 200 kV.

Because of the narrow path of the FSP zone, mini-tensile specimens, with the gage length within this stirred zone, were used for tensile testing. The specimens having a gage length of 1.3 mm, a width of 1.0 mm and a thickness of 0.55 mm were machined from the transverse cross section of the FSP zone while maintaining the gage length in the nugget region having the finest grain size. Elongation-to-failure tests were performed with a custom-built, computer-controlled tensile tester at constant crosshead speeds. It took about 23 min for stabilizing the temperature before tensile tests. The elongation-to-failure tests were carried out in the temperature range of 410–550 °C and at an initial strain rate of $3 \times 10^{-2} \text{ s}^{-1}$ since this strain rate offered good elongations during

Table 2
Main dimensions of four friction stir tools.

Tool	Shoulder diameter (mm)	Major diameter of the pin (mm)	Minor diameter of the pin (mm)	Height of the pin (mm)
T1	12.5	6	4	3.5
T2	16	7	5	5
T3	12.5	6	4	3
T4	12.5	6	4	3

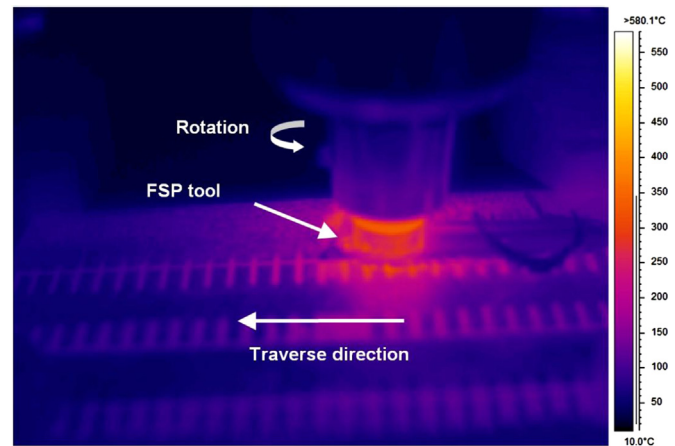


Fig. 2. IR image of FSP tool during processing.

Table 3
Summary of FSP tools used on alloy 5083, along with maximum temperature over the plate surface during FSP and average grain size in the FSP zone.

Tool	Tool shoulder area (mm ²)	Maximum temperature ^a (°C)	Grain size (μm)
T1	114	270	1.17 ± 0.06
T2	198	360	2.15 ± 0.14
T3	114	270	0.92 ± 0.04
T4	114	270	1.36 ± 0.06

^a Maximum temperature was measured over the plate surface next to the tool path.

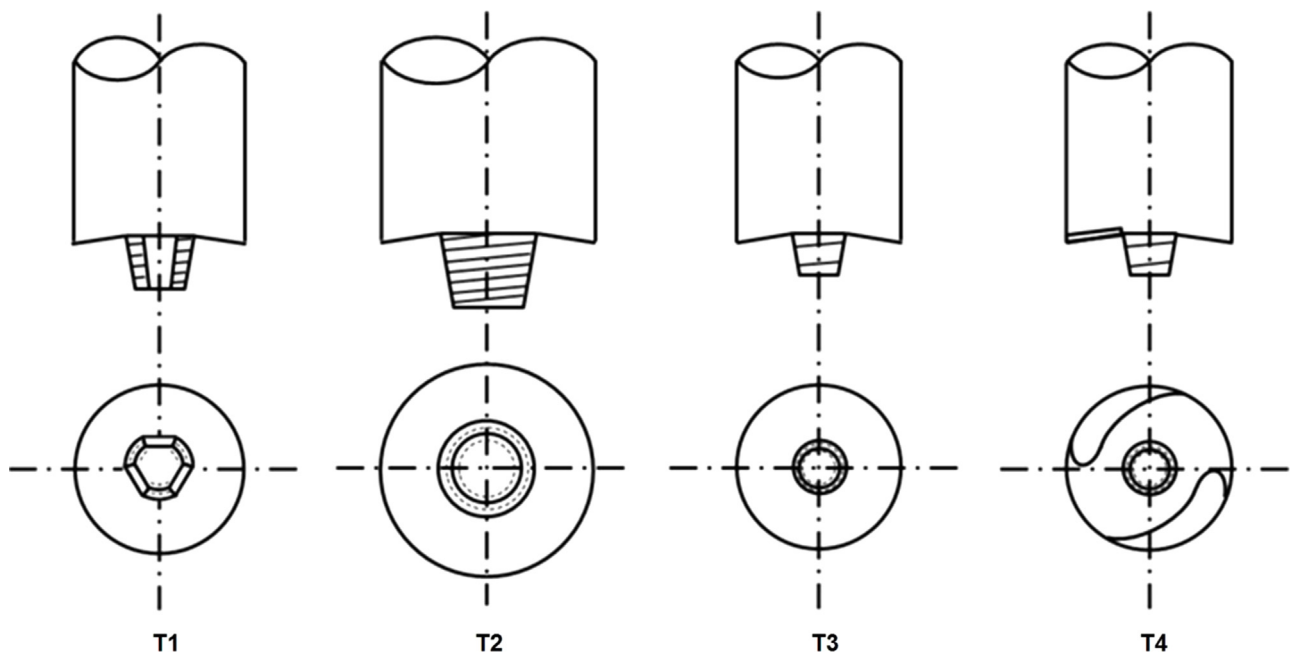


Fig. 1. Friction stir tool profiles used.

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