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Effect of friction stir processing on microstructure and mechanical properties of aluminium

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ABSTRACT

Commercially pure aluminium was subjected to friction stir processing (FSP) to study the microstructure developed and its effects on the mechanical properties. Friction stir processing refined the grain size to 3 μm in a single pass from the starting coarse grain size of 84 μm. Electron backscattered diffraction (EBSD) results showed occurrence of dynamic recrystallization and also revealed existence of different orientations within the stir zone and across the transition zone. Transmission electron microscopy (TEM) revealed fine grains with well defined boundaries. The arrangement and absorption of dislocation into the sub-grain boundaries, formed by dynamic recovery, was also revealed by TEM. The yield strength of the material was improved by a factor of 2.4 after FSP owing to grain refinement. The most important feature of the friction stir processed material was that even after this significant improvement in strength there was little loss of ductility. The hardness also improved by 34% with the peak hardness being observed towards the advancing side.

1. Introduction

The high specific properties of aluminium and its alloys due to their low density make them suitable for variety of applications in aerospace and automotive industries. There has been a constant effort to improve the strength properties of Al in order to meet the ever increasing need of high strength to weight ratio. Grain refinement is a widely accepted method of improving strength of metals and alloys. This has led to the development of ultra fine grained (UFG) or even nanocrystalline (NC) metals and alloys [1,2]. Different severe plastic deformation (SPD) methods have been developed for manufacturing UFG/NC alloys [3]. However, many of these processes have their own limitations to bulk production and this has curtailed their widespread applications. Moreover, retaining the ductility of the material while the strength is increased is a major challenge.

Friction stir processing (FSP) has been developed as a generic tool for materials processing and modification [4,5]. In this technique, a specially designed non consumable cylindrical tool, rotating at high speed is traversed into the material along a particular length at a desired traverse speed. A schematic of the process is shown in Fig. 1. The side in which the tangential velocity of the tool surface is parallel to the traverse direction is defined as advancing side and the anti-parallel one is defined as the retreating side. Localized heating is produced between the rotating tool and the work piece and the temperature increase softens the material below its melting point, where it can be deformed plastically. The material flows around the pin from the retreating to the advancing side. It is essentially a thermomechanical process during which the temperature of the material is taken to a range (typically > 0.5 T_m) where it can be plastically deformed to yield a fine-grained structure [6,7]. The temperature input to the material depends on the ratio between rotation and traverse speeds. It should be, however, noted that FSP is a relative new process and hence, the exact pattern of material flow, and the exact strain, strain rate and temperature the material experiences in the stir zone are not known.

FSP of various aluminium and magnesium alloys have resulted in improvement in their mechanical properties [8,9]. However, since the technique is relatively new there are many outstanding issues which need better scientific understanding [10]. The development of the microstructure during the process is one such issue which needs particular attention. Moreover, most of the FSP studies are on Al alloys where the second phase particles play a role in the microstructure evolution and mechanical properties. It is equally important to study the microstructure of the pure metal after such a process in order to understand the microstructure developed without any secondary effects (from secondary phases or precipitates). Since the microstructure determines the property it is also important to study the mechanical properties and their correlation with the microstructure.

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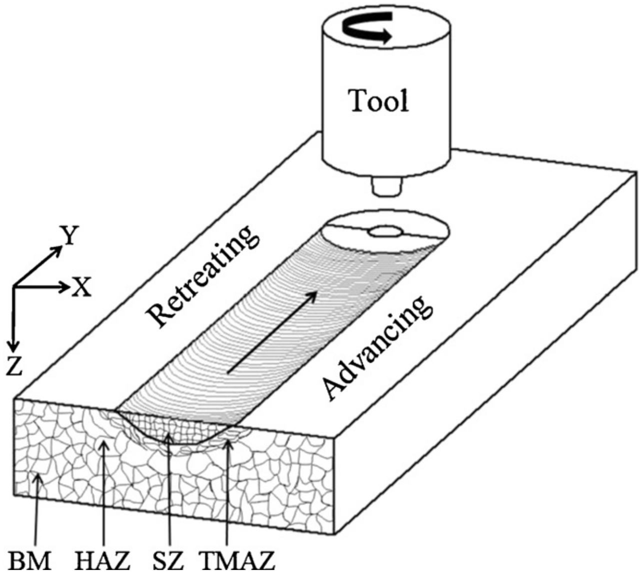

Fig. 1. Schematic of friction stir processing (FSP) showing different regions.

The aim of the present investigation is to develop fine-grained Al by FSP and to characterize the microstructure developed and correlate it with the mechanical properties.

2. Experimental procedure

The commercially pure (99.2%) aluminium plate chosen for the study had iron, silicon, copper, manganese and nickel as major impurities. FSP was carried out on a 12 mm thick plate using a tool made of M2 steel with shoulder diameter of 12 mm, pin diameter of 3 mm and pin length of 2.1 mm. A single pass of FSP was performed on the aluminium plate at a tool rotation speed of 640 rpm and traverse speed of 150 mm/min with a downward force of 5 kN being applied to the tool. This was the minimum ratio (640/150) of the tool rotation speed to the traverse speed needed to get a defect free stir zone. When the ratio was decreased (by decreasing the rotation speed or increasing the traverse speed), it gave rise to defect in the stir zone.

Microstructural investigation was carried out by electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). EBSD samples were metallographically polished and then electropolished in a mixture of perchloric acid and methanol at −20 °C and 11 V. EBSD studies were carried out in a FEI Quanta FEG SEM equipped with TSL OIM software operating at 30 kV using a step size of 250 nm. The microstructure was systematically observed moving from the base metal to the stir zone. TEM samples were sliced from the stir zone and thin sections were subjected to twin-jet electropolishing using a mixture of perchloric acid and methanol at −30 °C and 15 V. Observations were made in a Philips CM 20 transmission electron microscope, operating at 200 kV.

Tensile samples (1 mm in thickness and 10 mm in gauge length with 40 mm of overall length) were sliced from the stir zone parallel to the surface along the tool traverse direction by electrical discharge machining (EDM). Tests were carried out as per ASTM E-8 standard on an Instron machine (Model 3367) at a strain rate of 10^{-3} s^{-1}. Vickers hardness was measured across center of the stir zone on a Wilson Wolpert Vickers hardness tester using a load of 300 g and dwell time of 9 s with the distance between the indents being 0.5 mm.

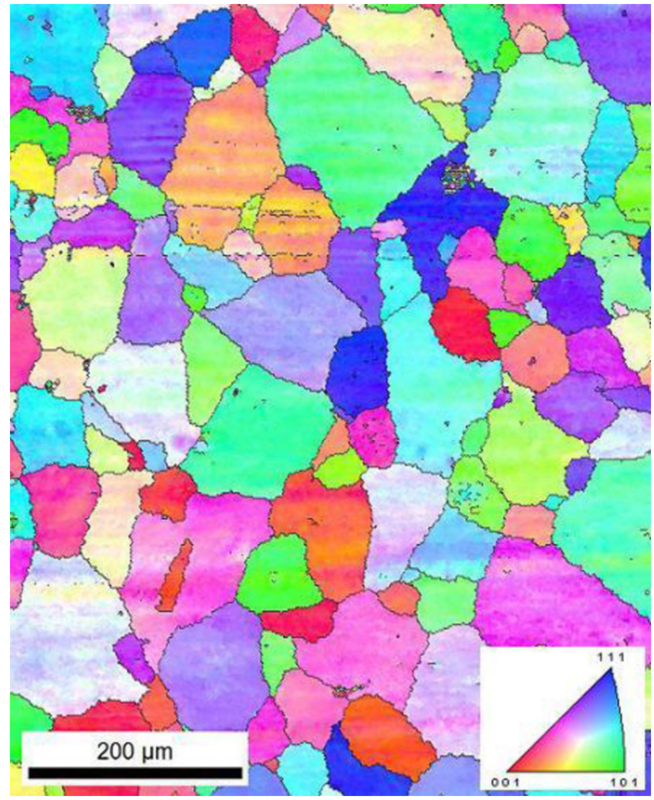

Fig. 2. EBSD (IPF + grain boundary) map of base metal.

3. Results and discussion

3.1. EBSD analysis

The EBSD (IPF + grain boundaries) map of the base metal is shown in Fig. 2. The average grain size was found to be 84 μm with more than 92% of the grain boundaries being high angle (>15° misorientation). As the material flows in different fashions in the advancing and retreating sides during FSP [11,12], the microstructure of the stir zone was observed systematically at the center and at the advancing (4 mm from center) and retreating (4 mm from center) sides. The transition from the stir zone (SZ) to the base metal through thermo-mechanically affected zone (TMAZ) and heat affected zone (HAZ) was also observed carefully.

FSP refined the microstructure to an average grain size of 3 μm. The amount of grain refinement is very significant since it is done in one step. The final grain size after FSP depends on the processing parameters and the tool geometry rather than the initial grain size and grain refinement occurs by dynamic recrystallization process. The EBSD maps (IPF + grain boundary) in Fig. 3(a)–(c) show fine and equiaxed grains at advancing side, center and retreating side of the stir zone respectively indicating occurrence of dynamic recrystallization. The color code corresponds to the orientation of the grains. The {1 1 1} pole figure and [0 0 1] inverse pole figure presented in Table 1 show the orientations developed at the advancing, center and retreating side of the stir zone. The maximum intensity indicated is the times random orientation. It can be seen that there is a strong preference towards (0 0 1) orientation at the center, which is corroborated by the EBSD map in Fig. 3(b). The average grain size, percentage of high-angle grain boundaries (HAGB) (> 15° misorientation) and average grain orientation spread (GOS) values are also given in Table 1. GOS indicate the deviation of each measurement point inside a grain from the average orientation of the grain, which is a measure of strain gradient within the grain.