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Microstructure and mechanical properties of multi-pass friction stir processed aluminum alloy 6063

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ABSTRACT

The effect of overlapping between consecutive passes of Friction Stir Processing (FSP) was examined on the microstructure, microtexture, and mechanical properties of Al 6063. FSP was carried out at three overlapping (OL) percentages, i.e. 25, 50, and 75, and at constant rotational and traverse speeds of the FSP tool. Microstructural analysis based on grain boundary misorientation distribution, grain size and microtexture were made by Electron Back Scattered Diffraction (EBSD), while mechanical properties were evaluated by microhardness and tensile tests. For the three OL percentages, similar grain refinement (in the range of 3–6 μm) occurred in the processed zone. The microtexture measurements in the OL area show the formation of shear texture, having a stronger intensity of $B/\bar{B}$ component by increasing the OL percentage. On the other hand, the tensile and microhardness tests indicate a reduction in the strength and microhardness of FSP samples with increasing the OL percentage due to the dissolution of the hardening precipitates. The overlapping effect was further evaluated on the thermal stability of microstructure, microtexture, and mechanical properties of FSP samples by applying solution heat-treatment and aging (SHTA). The results show that SHTA led to grain growth with an average grain size of 35 μm. However, it caused limited weakening of the shear texture in the OL area with no sign of recrystallization. In addition, SHTA led to precipitate formation and thus restoring the strength and microhardness to the levels of the base metal.

1. Introduction

Al alloys of the 6000 series are known to have good formability, corrosion resistance, weldability, and high strength-to-weight ratio. They have constituted the highest volume of Al extruded product and been widely used for automobile and aerospace industries, architectural applications, bicycle frames, transportation equipment, bridge railings and welded structures [1–3]. The major alloying elements in the heat-treatable 6000 series are silicon and magnesium. Both elements are required for precipitation strengthening, which is commonly acquired by solutionizing and artificial aging. Strengthening can be enhanced further by refining the grain size to a few micrometers and lower. This can be achieved by Friction Stir Processing (FSP), which is a solid state processing technique developed from the principles of friction stir welding (FSW) and used for microstructural modification by grain refinement [4,5]. In FSP, a non-consumable rotating tool consisting of pin and shoulder is inserted into a plate of metal and traversed along a line to process the region of interest. Friction between the tool shoulder and the workpiece results in localized heating that softens and plasticizes the processed zone. The stirring action of the rotating pin causes intense plastic deformation of the locally heated material. The combination of plastic deformation, mixing and thermal exposure results in a modified microstructure in the stir zone (SZ), which is commonly characterized by fine and equiaxed grain structure with predominant high-angle boundaries. The modification is generally attributed to dynamic recrystallization and break-up of constituent particles [6]. Next to the SZ, a narrow transition region known as the thermomechanically affected zone (TMAZ) is formed, followed by the heat affected zone (HAZ), and finally the unaffected base metal (BM).

Several FSW and FSP works have been devoted to study the microstructural and mechanical properties of 6000 series Al alloys [7–14]. General remarks indicate that frictional heat and intensive plastic deformation during FSW cause dissolution and/or coarsening of strengthening precipitates. Sauvage et al. [10] indicated that achieving ultra-fine grain structure in the weld zone of FSW Al–Mg–Si alloys is difficult due to the instability of second phase particles β''. In such cases, less pinning is exerted by the coarse and less distributed particles on the boundary mobility of recrystallized grains, leading to relatively large grain size in the weld zone. In addition, Woo et al. [13] investigated the influence of the stirring pin and pressing tool shoulder on the microstructural development

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in FSP of 6061 Al. It was found that microstructural softening occurred due to frictional heating by the tool shoulder. The heating resulted in dissolution of fine needle-shape precipitates β'' in the SZ and TMAZ, while dissolution of β'' and growth of coarse precipitates occurred in the HAZ.

The effect of multiple passes on microstructural development during FSP has been investigated on different aluminum alloys [14–20]. Johannes and Mishra [15] demonstrated the effectiveness of multiple passes in creating large areas of superplastic material of 7075 Al with insignificant microstructural differences, having grain size in the range of 3.6–5.4 μm. Ma et al. [16] also showed similar grain refinement in the microstructure of 7075 Al produced by multi-pass FSP and indicated that two-pass FSP samples of 50% overlap have greater superplasticity than single-pass FSP samples. This was explained by the faster grain growth rate that occurred at a testing temperature of 480 °C in the single-pass FSP sample than in the two-pass FSP sample. A recent study by El Rayes and El Danaf [14] on multi-pass FSP of 6082 Al indicated that the increase in number of passes from one to three with 100% overlapping resulted in larger SZ size but more dissolution of the hardening β'' phase. This was found to soften the SZ and reduce its strength.

Texture development during FSW/FSP can have significant influence on microstructural and mechanical properties. Local variation in the texture during FSW/FSP has been found to occur since distinct microstructural zones (SZ, TMAZ, HAZ, and BS) undergo different thermo-mechanical history [21–29]. The variation in texture is also expected to occur since the processed zone is affected by the mode of deformation and tool geometry. An early work by Sato et al. [21] on the microtexture of FSW 6063 Al indicated that the texture presenting the upper surface of the SZ is affected by deformation through the forging action of the shoulder. In the SZ center, a typical shear texture formed due to the plastic flow arising from the shear stress along the pin surface. In addition, a texture analysis of FSW Al 2519 by Fonda et al. [23,24] showed significant texture variation across the boundary between the TMAZ and HAZ, which was attributed to macroscopic rigid-body rotation of the grains around the stirring pin. Also, Giles et al. [27] indicated in their microstructural study of FSP 2099 Al that a strong B-fiber shear texture is apparent at the surface and center of the SZ, while the bottom of the SZ exhibits weaker shear components and a distinct random component in the texture. It was also suggested that the presence of shear texture in the SZ is consistent with microstructure evolution by dynamic recovery and geometric dynamic recrystallization.

The influence of the overlapping (OL) percentage of multi-pass FSP on the microstructural and mechanical characteristics of the alloy surface has received less attention. The intersection between consecutive passes creates an overlapped region between the processed zones and thus further alters the microstructure and microtexture. Also, there is a possibility of additional dissolution and/or coarsening of strengthening precipitates of Al 6063 at the overlapped region due to the thermal cycle of subsequent pass. This can progress to further weakening of the mechanical properties of the processed zone. Therefore, the first aim of this study is to investigate the effect of the OL percentage produced by multi-pass FSP on the microstructure, microtexture and mechanical properties of AA 6063. Secondly, the OL effect is further examined on the thermal stability of microstructure and the mechanical properties of the processed area after conducting solution heat treatment and artificial aging (SHTA) on the FSP samples. For these purposes, EBSD was employed on FSP and SHTA samples to provide in-depth insight into microstructure and texture evolution at the OL area. Tensile and microhardness tests were also made to evaluate the ultimate strength and microhardness as a measure of the precipitation strengthening in the processed zone. By running multi-pass FSP with different OL percentages, it is also possible to examine whether a specific percentage of OL exists to obtain optimum microstructural and mechanical modifications. Further assessment includes comparative analysis of single-pass and mutli-pass FSP of Al6063, aiding to establish better understanding on the role of overlapping on providing thermal stability against microstructure coarsening and texture weakening during SHTA.

2. Experimental procedure

Aluminum alloy 6063 plates were purchased in hot extrusion condition. FSP specimens were sectioned perpendicular to the extrusion direction. The dimensions of the FSP plates were $150 \times 150 \times 12$ mm, as schematically illustrated in Fig. 1a. The FSP tool material is made of heat-treated H13 steel; it has a shoulder of 14 mm diameter and a 4-mm-long pin with a 4 mm diameter. FSP was conducted using a vertical milling machine with constant tool rotating rate of 600 rpm and travel speed of 145 mm/min. It should be noted that WD, TD, and ND denote the processing, transverse, and normal directions of the plate, respectively (Fig. 1a). Single-pass and multi-pass FSP were carried out. In the case of multi-pass processing, two passes were made with different overlapping percentages: 25%, 50% and 75%. After each FSP pass, the plate was cooled down to ambient temperature and then the next FSP pass was performed to eliminate the effect of accumulative heating. A post heat treatment of solution heat treatment and artificial aging (SHTA) was carried out for the FSP samples. Solutionizing was made by soaking the samples at 530 °C for 2 h and then quenching in a cold-water bath. Artificial aging was carried out at 170 °C for a soaking period of 8 h. The processing details and sample designation are given in Table 1.

To assess microstructure refinement and texture development in the SZ, metallographic samples were prepared for examination by using optical microscopy (OM) and EBSD technique. As illustrated in Fig. 1b, the metallographic samples were cut from the cross-section of FSP plates (ND-TD plane), then ground and polished using standard metallography techniques. The OM studies were carried out using a Ziess (Axio Imager) optical microscope and the samples were chemically etched at ambient temperature for about 6 min with an extended Flick reagent consisting of 1.5 parts of HCl, one part of HF and nine parts of H_2O [30]. The EBSD analysis was conducted with a JEOL 7001F-JSM FE-SEM equipped with HKL5 EBSD system, and the samples were prepared by using Struers (LectroPol-5) electro-polishing unit with an electrolyte containing 700 ml of ethanol, 100 ml of 2-butoxyethanol, 120 ml of water and 80 ml of perchloric acid, operated at 25 °C with an applied potential of 24 V. EBSD measurements were made along multiple lines, as described in Fig. 1b, to evaluate the microstructure (grain structure and size, and grain boundary misorientation distribution) and microtexture (pole figures) at different regions of the SZ. In particular, measurements at line A-A were made horizontally 1 mm below the processed surface to examine the evolution of microtexture of single-pass samples. In addition, line B-B was used to examine microstructure and texture development in the OL region formed by multi-pass processing. The effect of overlapping was also investigated by determining the average grain size at three regions of the SZ using the following measurement lines: line B-B at the middle of the OL region, and lines C-C and D-D at the non-overlapping regions of the SZ located at the first and second passes, respectively (see Fig. 1b). The average grain size was calculated according to ASTM: E112, using an average intercept method program available with the EBSD software. Further examination of the texture development in SZ was also made by X-ray diffraction (XRD), as carried by Siemens D5000 instrument using Cu Kα radiation.