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Short communication

Grain boundary misorientation and texture development in friction stir welded SiCp/Al–Cu–Mg composite

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ABSTRACT

Eight millimeter thick extruded 15 vol.% SiCp/Al–Cu–Mg composite was friction stir welded (FSW) and subjected to subsequent post-weld T4 temper. The grain boundary misorientation relationship in the nugget zone (NZ) was studied by using Kikuchi's-line technique of transmission electron microscopy. Texture development during FSW was examined by using X-ray diffractometry and subsequent orientation distribution function (ODF) analysis. It was revealed that the NZ was characterized by fine and equiaxed recrystallized grains with dominant high angle grain boundaries. Compared to that in the extruded composite, the texture in the NZ was significantly weakened. Post-weld T4 temper did not change the grain boundary characteristics and the texture orientation.

1. Introduction

Friction stir welding (FSW) is a rapidly maturing solid state joining technique that offers significant benefits over conventional joining processes [1]. FSW involves complex material movement and plastic deformation [2]. A combination of severe deformation and heating altered the crystallographic texture and various features of grain structure [3]. The characteristics of the grain structure play an important role in determining various physical and mechanical properties [4].

The dynamic recrystallization during FSW results in the generation of fine and equiaxed grains in the nugget zone (NZ) of the aluminum alloys, magnesium alloys, and copper [2,5]. The high ratio of the high angle grain boundaries (HAGBs) is one of the main microstructural features of the NZ of FSW metallic materials [2]. It was reported that FSW aluminum alloys had a HAGBs ratio as high as 80–95% [6,7]. Electron backscatter diffraction (EBSD) is a very effective technique to characterize the orientation distributions of crystals and has been used to examine the grain structure of the FSW aluminum alloys [8]. However, it is difficult to prepare the composite samples for EBSD examinations due to the existence of numerous SiC particles. Therefore, no information is available so far about the boundary misorientation in the FSW composites.

The textural development during FSW gives important information about the deformation mechanisms and the flow behavior. Texture affects a variety of properties, such as strength, ductility, formability and corrosion resistance [2]. In the past few years, several studies have focused on the texture analysis of the FSW aluminum alloys, magnesium alloys, stainless steel, and titanium alloys [9–14]. It was reported that the texture in the NZ is either weak or present in a complex texture pattern such as the typical shear texture component induced by the shear plastic flow along the pin surface [10,13]. Furthermore, the crystallographic texture is characterized as sharp spatial gradients, not only in the transition from the base metal to the NZ, but also in the NZ itself, which undoubtedly influences the integrity of the weld [12]. However, no information is available so far on the texture development in the FSW metal matrix composites.

In the previous studies, it was reported that 8 mm thick as-extruded SiCp/2009Al composite plates could be successfully welded via FSW at a medium tool rotation rate of 600 rpm with the welds exhibiting good mechanical properties [15,16]. In this study, the FSW SiCp/2009Al composite welds were subjected to detailed microstructural examination under both as-FSW and post-weld heat treatment (PWHT) conditions. The purpose of this work is to investigate the boundary misorientations and texture development during FSW.

2. Materials and methods

15 vol.% SiCp/2009Al composite, produced by powder metallurgy and subsequent extrusion, was used in this study. The chemical composition of the 2009Al alloy was 4.26Cu–1.61Mg–

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0.01Si–0.009Fe (wt.%). 8 mm thick composite plates were cut from the extruded bars and friction stir welded along the extrusion direction at a tool rotation rate of 600 rpm and a traverse speed of 50 mm/min. A tool with a shoulder 24 mm in diameter and a cylindrical threaded pin 8 mm in diameter was used. The FSW samples were kept at room temperature for one month to age naturally. In order to study the effect of the PWHT, part of the FSW samples were subjected to a T4-treatment (solutionized at 502 °C for 1 h, water quenched, and then aged at room temperature for one month).

The microstructure was examined using transmission electron microscopy (TEM). The misorientation between adjacent grains was illustrated based on the Kikuchi's patterns and the crystallographic orientation map, which takes into account the smallest misorientation of the boundaries. Texture development during FSW was examined using a PW3040/60 X-ray diffractometer with Co Kα radiation and subsequent orientation distribution function (ODF) analysis. Incomplete pole figures of {1 1 1}, {2 0 0}, and {2 2 0} planes were measured in steps of $\Delta\alpha = 5^\circ$. The intensity values were then obtained after background deduction and defocusing correction. The ODF calculation was finally carried out using Bunge's series method. The textural development during FSW is illustrated by ODFs, which are represented in Euler's space at constant φ_2 sections.

3. Results and discussion

Fig. 1 shows the grain structures in the NZ of the FSW composites under both as-welded and T4-treated conditions. Fine recrystallized grains were obtained in the FSW composites. The grain size was determined to be ∼5 and ∼8 μm in the as-FSW composite and T4-treated FSW composite [16]. Based on their corresponding Kikuchi's patterns (Fig. 1b and e), the misorientation between neighboring grains was determined (Fig. 1c and f). It was indicated that the NZ of the FSW composites possessed a high ratio

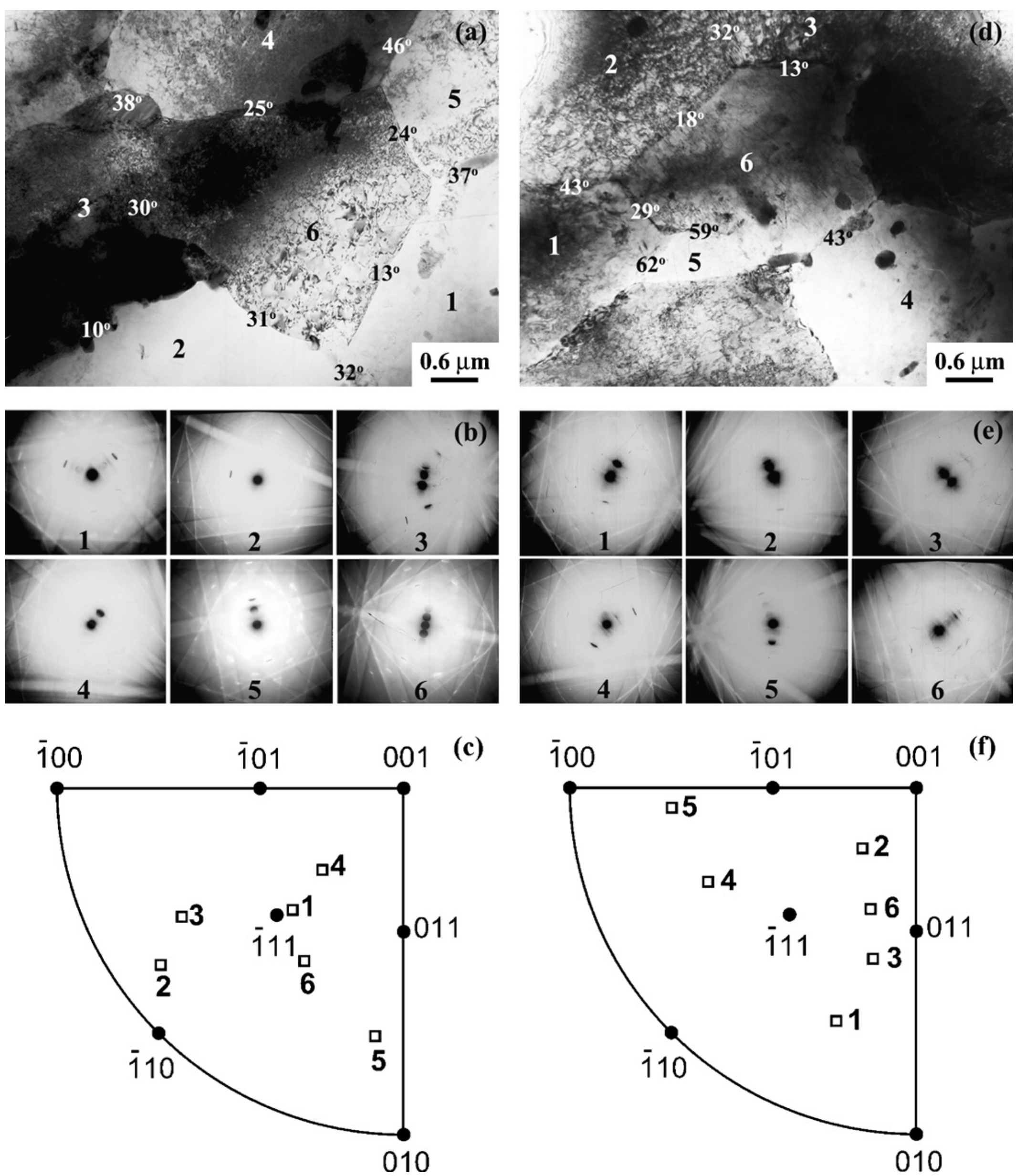

Fig. 1. Dynamically recrystallized grains with dominant HAGBs in NZ of FSW composites under (a) As-FSW condition and (d) T4-treatment condition: (b) and (e) Kikuchi's patterns for (a) and (d), (c) and (f) orientation relationship for neighboring grains in as-FSW and T4-treated composites, respectively.

of the HAGBs under both as-FSW and T4 conditions. Clearly, the post-weld T4-treatment did not change the grain boundary characteristics, though it resulted in a grain growth from ∼5 to ∼8 μm [16]. The T4-treatment consists of a solution treatment at 502 °C for 1 h and a natural aging at room temperature. Compared to the higher solution temperature of 502 °C, a natural aging at room temperature or an artificial aging at a low temperature of ∼170 °C for 2xxx aluminum alloys, such as 2009Al and 2024Al, could not exert any significant effect on the grained structure of the composite. Therefore, it can be concluded that the high temperature solution treatment caused the grain growth of the fine grains in the NZ of the FSW composite, but did not change the grain boundary characteristics. Generally, the grain boundaries with a misorientaion angle ≥10–15° are considered to be the HAGBs. Compared to the low-angle grain boundaries (LAGBs), the HAGBs exhibit higher surface energy, typically about 0.3–0.5 J/m^2 [4]. In general, the mobility of the HAGBs is much higher than that of the LAGBs.

The dominant HAGBs in the FSW composites indicates that as in the FSW aluminum alloys, the fine and equiaxed grains in the FSW composite were produced by the dynamic recrystallization (DRX). Like any recrystallization process, the DRX proceeds by nucleation and nucleus growth. Proposed recrystallization mechanisms during FSW include: the continuous dynamic recrystallization (CDRX), the geometric dynamic recrystallization (GDRX), and the discontinuous dynamic recrystallization (DDRX) [17].

Fig. 2a shows the ODFs of the as-extruded 2009Al alloy, where the texture exhibited a significant cube orientation {0 0 1}⟨1 0 0⟩ and {0 1 1}⟨1 $\bar{1}$ 1⟩ component, plus a minor copper {1 1 2}⟨1 1 1⟩ orientation and Goss {0 1 1}⟨1 0 0⟩ orientation. After the T4-treatment, the ODFs of the extruded 2009Al exhibited quite irregular orientation types (Fig. 2b). This is attributed to significant grain coarsening during solution treatment (not shown). A typical specimen for measuring the texture by X-ray technique was a 25 mm × 25 mm square. The description of texture was based on the statistical distribution. The limited number of the grains in the scanned zone resulted in the occurrence of the irregular orientation type in the T4-treated 2009Al.

Compared to the as-extruded 2009Al alloy, the as-extruded SiCp/2009Al composite exhibited the same orientation types, but lower orientation densities (Fig. 2c). In addition, the Goss {0 1 1}⟨1 0 0⟩ orientation appeared at $\varphi_1 = 0°$, $\phi = 45°$, $\varphi_2 = 0°$. This indicates that the addition of SiC particles weakened the texture by disturbing the slip pattern in the matrix. The particles affect the recrystallization texture in two ways [18]. First, large (>1 μm)

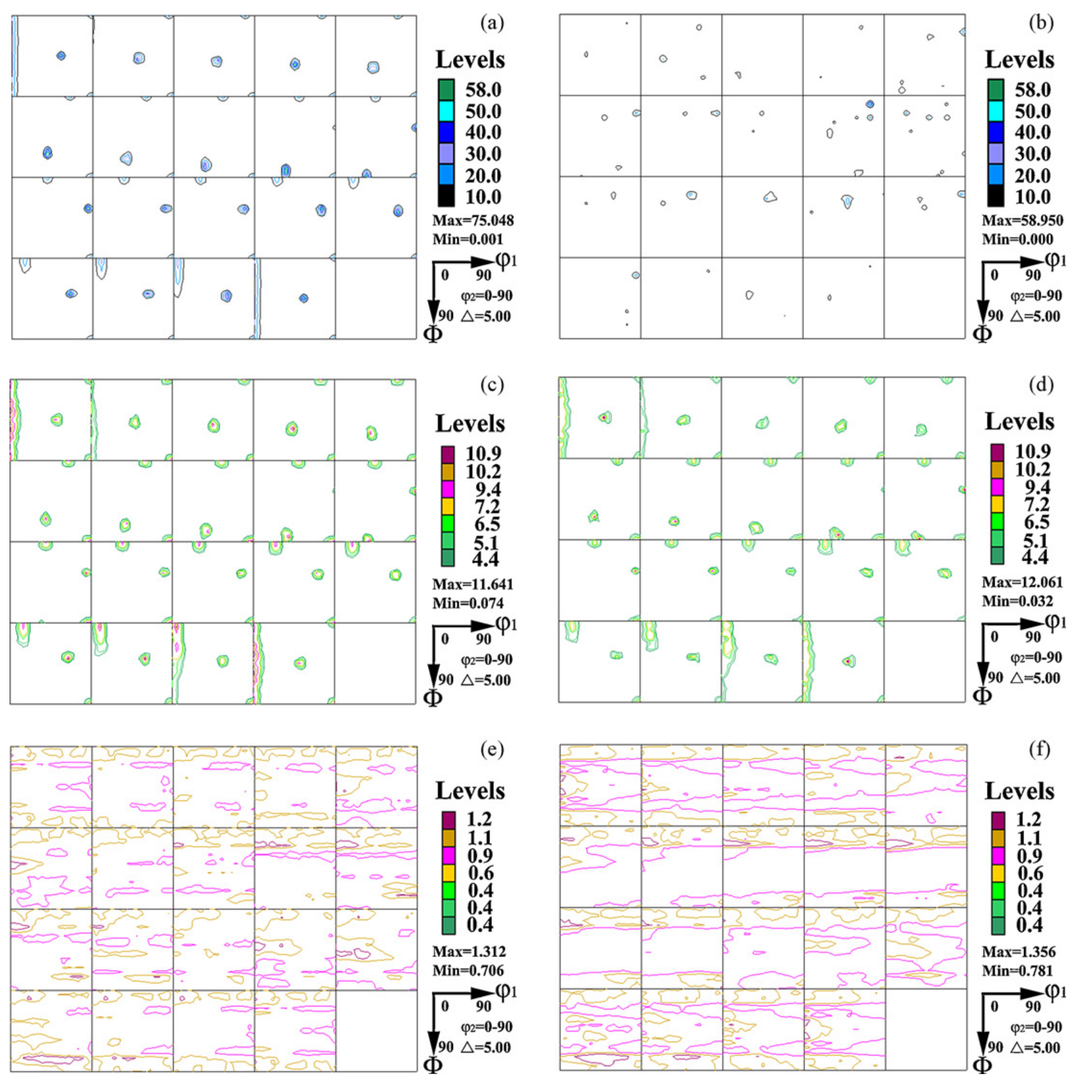

Fig. 2. Orientation distribution functions: (a) As-extruded 2009Al, (b) T4-treated extruded 2009Al, (c) as-extruded composite, (d) T4-treated extruded composite, (e) nugget zone of as-FSW composite and (f) nugget zone of T4-treated FSW composite.

pre-existing particles are favored nucleation sites and highly misoriented deformation zones lead to a wide range of nucleus orientations. Second, if a dispersion of closely spaced particles is present, then pinning (Zener drag) of low or high angle boundaries affects the recrystallization kinetics and texture. After the T4-treatment, the composite exhibited the same orientation types, while accompanied by the disappearance of the Goss {0 1 1}⟨1 0 0⟩ orientation (Fig. 2d). This attributed the fact that the grain coarsening of the SiCp/2009Al composite during the T4-treatment was greatly restricted by the SiC particles. Accordingly, the T4-treated composite exhibited the same orientation types as those in the as-extruded composite.

Fig. 2e shows that the texture of the NZ in the as-FSW composite was essentially random, indicating much weakened texture orientation. After the T4-treatment, only subtle change of the ODFs occurred in the NZ of the FSW composite (Fig. 2f). Generally, the texture in the NZ of the FSW aluminum alloys was weak or present in a complex texture pattern such as the typical shear texture component [10]. Deformation during FSW is largely a shearing process, so the typical shear texture components were observed in the NZ. In this study, the weaker texture component of the as-FSW composite might be associated with the recrystallization in the NZ. During FSW, transient high temperature up to about 500 °C in the NZ with large strain corresponds very well with the continuous annealing and quenching for aluminum [9]. Borrego et al. [19] suggested that the occurrence of particle stimulated nucleation at the SiCw/Al interfaces was responsible for the texture randomization. In addition, if nucleation is dominant, the orientation of recrystallized grains will be random [20]. The static recrystallization subsequent to FSW also influenced the evolution of texture in the NZ of the composite.

4. Conclusions

In summary, the nugget zone of the as-FSW composite was characterized by fine and equiaxed recrystallized grains with dominant HAGBs, as well as weaker texture component. Post-weld T4-treatment did not result in obvious variation in both the boundary features and texture components.

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