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Evolution of microstructure and hardness of aluminum after friction stir processing

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Abstract: The effects of friction stir processing (FSP) on the microstructure, microtexture and hardness of rolled pure aluminum were investigated. The microstructure and microtexture were characterized using electron backscattered diffraction (EBSD) technique on the transversal section. The stir zone (SZ) contains fine, equiaxed and fully recrystallized grains. The texture component of the base material mainly consists of R, S and brass R textures. Miner copper texture component is also determined. In the center of the stir zone, the dominant texture is (111) parallel to about 70° from ND pointing toward RD. The textures of this location rotating clockwise about 30° and anticlockwise about 60° around the ND result in the textures of the areas, which are 3 mm apart from this location on the retreating side and advancing side, respectively.

Key words: friction stir processing; aluminum; EBSD; texture

1 Introduction

As an important method for material strengthening through microstructure refinement, friction-stir processing (FSP) has shown significant microstructural modification and improved mechanical properties for aluminum and its alloys. During FSP, a rotating tool with a shoulder and a pin plunges into the surface of the plates which are processed and moves along the plates [1]. The shoulder contacts with the top surface of the workpiece tightly. The heat generated by the shoulder and the pin softens the material below its melting point around the pin. Severe plastic deformation and flow of this plasticization material occur as the tool is translated along the welding direction.

Four key zones have identified in a friction stir processed material [1−3]. They are: 1) unaffected material; 2) heat-affected zone (HAZ) which is only affected by the heat; 3) thermo-mechanically affected zone (TMAZ) lies between the HAZ and the stir zone (SZ), where material has undergone heat and plastic deformation; 4) stir zone which experiences the most severe deformation and temperature is recrystallized to form fine equiaxed grains. Although FSP has been widely used for material modification, the microstructural evolution to produce the final modified microstructure is still not well understood [4].

SATO et al [5] and SUHUDDIN [6] reported that the dominant texture was simple shear texture with the {111} parallel to the sheet surface after FSP of aluminum alloys. This type of texture was beneficial for enhanced formability. It was studied that the profile of hardness curve and “W” shape was obtained in aluminum alloys [7−11]. YADAV and BAURI [12] reported the effect of FSP on microstructural evolution and mechanical properties of cast aluminum. They proclaimed that the grain size was refined efficiently and the mechanical properties were improved after FSP. There are a number of previous studies characterizing the microstructure, and mechanical properties of various aluminum alloys produced by FSP, few reports are focused on pure aluminum, and studies about crystallographic texture of FSP pure aluminum are much more rare. It is also important to study the microstructure and mechanical properties of pure aluminum after FSP in order to understand the microstructure and mechanical properties developed without the effects of secondary phases. In this work, FSP was used to modify the microstructure of pure aluminum. The evolution of microstructure and microtexture after FSP was examined systematically in order to understand the deformation during FSP.

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Additionally, the hardness of the entire transversal section was also investigated to demonstrate the changes of mechanical properties.

2 Experimental

The base material used for this study was commercial pure (99.00%) aluminum plate containing iron and silicon (0.95%), copper (0.05%−0.20%), zinc (0.10%) and manganese (0.05%) as major impurities. The plate was cold rolled to a thickness of 2 mm. Single-pass FSP was carried out on the aluminum plate. A cylindrical probe was used with diameter of 5 mm and length of 1.65 mm. A cylindrical shoulder without thread was applied with diameter of 10 mm. The tool was operated with a back tilt of 2.5°, using a rotational speed of 800 r/min and a tool transverse speed of 200 mm/min along the rolling direction of the plate. The section of the plane perpendicular to the welding direction was cut and then polished and etched by Keller reagent to obtain an optical macrograph.

Detailed microstructure and microtexture analysis of the entire processed regions across the transversal section was undertaken using electron backscattered diffraction (EBSD). Specimens were cut from the friction stir processed tracks in the plate using electrical discharge machining (EDM). Then, they were mechanically ground and electropolished with a solution of 10% perchloric acid alcohol for 40 s at −20 °C with an applied potential of 20 V. EBSD studies were performed in a FEI Nova 400 FEG-SEM with step size of 0.5 and 0.3 μm for data collection, which were undertaken horizontally from the retreating side (RS) to the advancing side (AS). The regions were indicated by *a*−*h*, as shown in Fig. 1. EBSD maps were used to plot inverse pole figures, misorientation angle histograms and pole figures via the Channel 5 software from HKL technology. A hardness measurement extending across the entire region with a spacing of 0.5 mm was conducted using a Vickers indenter with 25 N load and 10 s dwelling time.

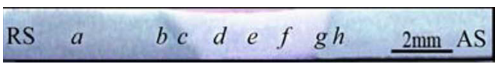

Fig. 1 Macrograph of transversal section perpendicular to RD direction of pure aluminum

3 Results and discussion

3.1 Microstructure

The typical macroscopic overview of the transversal section is indicated in Fig. 1. No defects are found on the processed regions. The basin-shaped stir zone is visible clearly and the SZ width exceeds the width of the probe. Many researchers [1,13] reported that the shape of the SZ is related with processing parameters, tool geometry, temperature of workpiece, and thermal conductivity of the material. The upper surface of the stir zone is wider than the bottom, because the upper surface experiences extreme deformation and frictional heating by contacting with a cylindrical-tool shoulder during FSP, yet the bottom is only affected by the pin. The entire processed zone is not symmetric between the AS and the RS. The slop of the boundary between the SZ and TMAZ is larger in the AS than those in the RS. It is attributed to the 2.5° back tilt of the tool, leading to the different plastic flow pattern between the AS and RS. It was observed that the boundary between SZ and TMAZ is more obvious in the AS than those in the RS, as reported in FSP of AA5182-O aluminum alloy [14].

Figure 2 shows the EBSD (IPF+GB) maps, obtained from the locations *a*−*h* respectively, as marked in Fig. 1. High-angle boundaries (>15°) are designated by black lines, and low-angle boundaries (from 2° to 15°) are designated by white lines. Location *e* is the center of the SZ. Locations *b*, *c* and *d* lie in the RS of the transversal section. Locations *b*, *c* and *d* are about 5.5, 4.5, and 3 mm away from the location *e*, respectively. Location *d* is in the SZ, and location *c* is just outside of the boundary between the SZ and TMAZ, while location *b* is in the HAZ. Locations *f*, *g* and *h* are in the AS of the transversal section. Locations *f*, *g* and *h* are about 5, 4 and 3 mm away from the location *e*, respectively. The specific location is the same as the RS.

The EBSD map of the base material is shown in Fig. 2(a), showing the typical rolled microstructures which are elongated grains with dense sub-structures in the grains. From Figs. 2(d)−(f), it can be observed that the microstructure of SZ is obviously different from that in the base material. The grains in the SZ are particularly small and equiaxed, which are attributed to the dynamic recrystallization during FSP as some researchers reported [15,16]. And the average grain size of locations *d*, *e* and *f* for grains defined by 5° misorientation, are approximately 2.97, 2.61 and 3.11 μm, respectively. The definite dynamic recrystallization mechanism has not been understood. Some researchers [17,18] proposed several typical recrystallization mechanisms including geometric dynamic recrystallization which can explain the phenomenon of this work preferably. The mechanism indicates that plastic deformation occurs in the grains in the form of shearing during FSP, making the BM with small and elongated grains divide into small equiaxed grains, as seen in the SZ. Figure 3 shows the misorientation angle histograms of locations *a*−*h*, and Table 1 shows the fraction of high angle boundaries. By comparing locations *d*, *e* and *f* to location *a*, it can be concluded that a much higher fraction of high angle