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# Effect of texture on the mechanical behavior of ultrafine grained magnesium alloy

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Friction stir processing (FSP) improves the mechanical properties of metals by refining grains to submicron scale. It also introduces significant basal texture in ultrafine grained magnesium alloy by tilting the basal poles by various degrees with respect to the depth in the nugget. This texture results in much higher tensile stress and ductility, but lower uniform strain in the transverse direction, than in the processing direction. This paper discusses the effect of FSP-induced texture on anisotropy in mechanical behavior.


*Keywords:* Ultrafine grained microstructure; Texture; Friction stir processing; Anisotropy; Tensile behavior

As one of the lightest metals, magnesium is attractive for structural applications as a potential replacement for steel and aluminum in transportation [1]. The use of magnesium alloys has been greatly limited by their low ductility and poor formability at room temperature [2]. Owing to the limited slip systems available at room temperature, the deformation of magnesium alloys is complicated and texture dependent when a strong texture is present. A basal slip system {0 0 0 2} ⟨1 1 −2 0⟩, which is easily activated in magnesium alloys, alone cannot accommodate general plastic deformation, and other non-basal dislocation slip systems are needed to improve room temperature formability. Microstructure and texture modification can be used to activate non-basal slip systems [3], i.e., prismatic slip systems {1 0 −1 0} ⟨1 1 −2 0⟩ and pyramidal slip systems {1 1 −2 2} ⟨1 1 −2 3⟩.

Friction stir processing (FSP) locally modifies the material structure by refining the grain structure and homogenizing any precipitate particles [4,5]. Various studies have used FSP of magnesium alloys to refine the microstructure [6–12]. Grain refinement enhances the strength of metallic materials according to the classic Hall–Petch relationship. However, some results indicate that ultrafine grained (UFG) and nano-structured materials deviate from this relationship [13–15]. Wang et al. [16] reported that the dependence of yield stress on grain size was weak for friction stir processed (FSPed) AZ31 compared with hot extruded AZ31. This has been ascribed to grain refinement simultaneously inducing texture variation, which strengthens the material in one direction and weakens it in other directions [11].

Park et al. [17] addressed texture evolution in the stir zone of friction stir welded magnesium AZ61 alloy and reported components of texture with a strong accumulation of the basal planes along the surface of the welding pin tool. Woo et al. [9] also reported similar texture evolution using a neutron diffraction method and indicated a 90° rotation of the basal plane in the stir zone compared with the initial rolled texture with the basal planes aligned almost parallel to the rolling plane. Previous X-ray diffraction results showed a different texture for fine grain AZ31, with the basal poles tilted ~45° with respect to the normal direction of the plate after FSP [11]. The current paper seeks to expand understanding of how the detailed local texture evolution in the processed region of UFG AZ31 during two-pass FSP influences mechanical behavior.

A commercial grade AZ31 magnesium alloy in the hot-rolled condition with thickness 6.3 mm was used. To make friction stir passes, a tool with a 12-mm-diameter concave shoulder and a 2-mm conical fluted pin was employed. The shoulder had two scrolls for enhanced downward material flow. Two-pass FSP of AZ31 was carried

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out at a tool rotation speed of 700 revolutions per minute (rpm) and a tool traverse speed of 3.4 mm $s^{-1}$ for the first pass, 500 rpm and 5.9 mm $s^{-1}$ for the second pass with 3° tool tilt for both passes. A copper plate was placed beneath the magnesium plate to achieve a relatively high cooling rate. Tensile properties were characterized using mini-tensile samples with gage length 1.3 mm, width 1.0 mm and thickness 0.5 mm. Samples were machined along the processing direction (PD) and transverse direction (TD) from the center of both the top layer (0–1 mm) and the bottom layer (1–2 mm) (indicated in Fig. 1) of the nugget.

Figure 1 presents the nugget microstructure of FSPed AZ31 at a depth of 1.5 mm. Compared with the as-received material with an average grain size of 9.8 ± 4.5 μm, a finer and more uniform grain structure was achieved by two-pass FSP. The detailed grain size distribution was characterized by statistical analysis of the electron backscattering diffraction (EBSD) results. These indicate an ultrafine structure with an average grain size varying from 0.7 ± 0.3 to 0.6 ± 0.3 μm from the top of the nugget to the bottom. The grain structure evolution of magnesium alloys during FSP is complex and generally accepted as a result of dynamic recrystallization [18–22].

Figure 2 presents room temperature tensile stress–strain curves measured at a strain rate of $1 \times 10^{-3}$ $s^{-1}$ for the as-received and FSPed UFG AZ31 along two orthogonal directions: the rolling direction (RD) for as-received AZ31 or the PD for FSPed AZ31, and the TD. Mini-tensile results of the as-received AZ31 exhibited minor anisotropic behavior, evidenced by slightly higher strength in the TD, which is consistent with the data reported for rolled AZ31 [23]. The FSPed AZ31 exhibited significant anisotropic behavior with significantly higher strength and ductility in the TD compared with the PD. Examination of the data presented in Figure 2 reveals important trends. First, the TD specimens exhibit higher ductility compared with the PD specimens. Secondly, the nature of the stress–strain curves was quite different, in that the PD specimens exhibited almost no post-uniform elongation, whereas the TD did. The yield strength of the sample tested in the PD decreased from 190 to ~130 MPa after FSP. For samples tested in the TD, the yield strength increased from 209 MPa for the as-received to 297 MPa in the FSP TD top layer, and 276 MPa in the FSP TD bottom layer. The ductility of processed material in the top layer was similar to that of as-received material; however, that

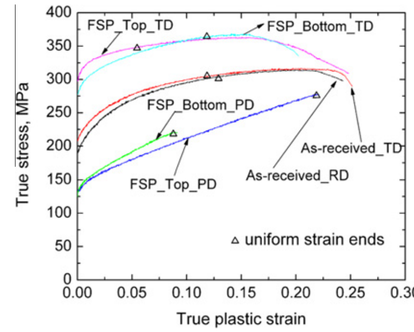


**Figure 2.** Stress–strain curves for the as-received and FSPed UFG AZ31 tested at room temperature with various sample orientations.

in the bottom layer decreased to less than half that of the top layer (from 22% to 9%) in the PD and remained nearly unchanged in the TD.

The significant anisotropy in mechanical behavior was related to the formation of a unique texture component after FSP. Figure 3 shows the {0 0 0 2} and {1 0 −1 0} pole figure plots of FSPed AZ31 in the centerline of the nugget at depths of 0.5, 1.0 and 1.5 mm, as well as for positions 1 mm away to the left and right of the centerline at a depth of 1.5 mm. The initial rolling texture with the *c*-axes of the grains parallel to the ND and a slight basal pole tilt in the RD [11] was modified to a fiber texture with alignment of the *c*-axes of the grains ~37°, 60° and 86° away from the ND after FSP at depths of 0.5, 1.0 and 1.5 mm, respectively. The degree of basal pole tilt with respect to the initial texture increased with depth, becoming roughly parallel to the PD at a depth of 1.5 mm in the centerline of the nugget. At a depth of 1.5 mm, the basal pole tilted outwards asymmetrically as the location was shifted 1.0 mm to the left or right; it rotated about the TD ~30–45°, then rotated about the ND ~10–15°. The prismatic planes exhibited a near random distribution. Park et al. [17] reported that basal planes tend to align with an ellipsoidal surface in the nugget. The discrepancy in direction of basal pole tilt from those of Park et al. [17] is related to the intrinsic difference in material flow. The texture evolution in Ref. [17] indicates the formation of an onion ring structure (reflected by the elliptical shape with alignment of basal planes or shear planes). The onion ring structure is often observed when a threaded pin and finer process pitch (advance per revolution = (tool traverse speed/tool rotation speed)) is used [24–26]. In this work, a conical pin tool and relatively large pitch of ~0.71 mm

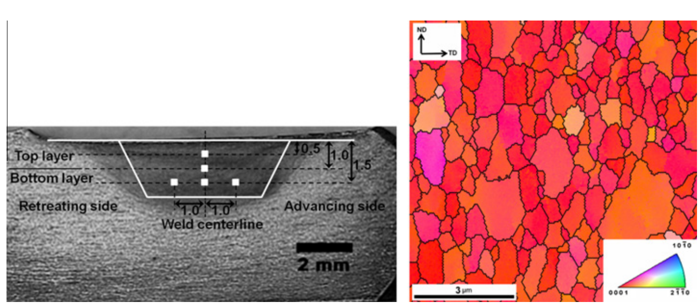


**Figure 1.** Cross section with two-dimension tool profile (indicated by white lines) and EBSD inverse pole figure map for FSPed AZ31 at a depth of 1.5 mm in the centerline of the nugget.