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# Friction stir welding of as-extruded Mg–Al–Zn alloy with higher Al content. Part I: Formation of banded and line structures

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ABSTRACT

6-mm-thick extruded Mg–Al–Zn (AZ80) alloy plates were subjected to friction stir welding at a welding speed of 100 $\mathrm{mm \cdot min^{-1}}$ and tool rotation rates of 400–1200 rpm, and the highest joint efficiency of 92% was achieved at 800 rpm. Friction stir welding resulted in the dissolution of coarse β-$Mg_{17}Al_{12}$ particles, with fewer and smaller β particles distributed at the grain boundaries in the nugget zones; meanwhile, banded structures resulting from different Al concentrations were observed in the nugget zones. As the rotation rate increased, the grain size of the nugget zones increased, but the β particles showed little variation in the quantity and size. At low rotation rates, uniform microstructures were produced in the joints, and during tensile testing the joints failed in the nugget zones where was the lowest hardness region of the joints. However, a line structure containing the β particles was observed at the boundary of the nugget zone at the highest rotation rate, which resulted in a decrease in the tensile properties. The results indicated that higher rotation rates would not be suitable for the friction stir welding of wrought Mg–Al–Zn alloys with higher Al content.

## 1. Introduction

Mg alloys are very attractive in structural applications of aerospace and automobile industries for weight reduction and energy saving. The structural application of Mg alloys inevitably involves welding and joining during manufacturing. However, defects such as porosity, thermal cracks, and oxidization often occur in the fusion welding of Mg alloys.

As a novel solid-state joining technique, friction stir welding (FSW) can effectively avoid the drawbacks of the fusion welding and has been successfully used for welding Al alloys [1]. Although Mg alloys show poor deformability at room temperature, the deformability would be greatly improved at high temperatures for the activation of non-basal slips [2], and this is important for the FSW. By altering welding parameters such as pin and shoulder sizes, welding speed ($\nu$), and rotational rate ($\omega$), high-quality FSW joints can be obtained. Recently, FSW has been successfully used to join various Mg alloys, such as Mg–Al–Zn, Mg–Al–Mn, Mg–Al–Ca, Mg–Zn–Zr, and Mg–Zn–Y–Zr [3–18].

Among various kinds of Mg alloys, AZ series alloys were the most fully developed and widely used in manufacturing production for low cost and good properties. For the AZ series alloys, most FSW studies were focused on lower Al content alloys, such as AZ31 and AZ61 [3–9]. It was reported that increasing FSW heat input such as the tool shoulder diameter and the rotation rate could increase the tensile strength of FSW AZ31 joints [3,19]. At tool rotation rate as high as 3500 rpm, a joint efficiency as high as 95% was achieved in the FSW AZ31 joint. This phenomenon is quite different from that observed in FSW Al alloy joints [1]. Besides, much research has been focused on the deformation behaviors of FSW joint, and basal slip and twinning have been proven to be the main deformation mechanism [19,20].

By comparison, FSW studies of the Mg alloys with higher Al content (AZ80 and AZ91) are limited with the main focus on the as-cast alloys which exhibited low strength and ductility due to the coarse grains and coarse network grain boundary β phase ($Mg_{17}Al_{12}$) [10–12,21]. It was reported that FSW could effectively dissolve the coarse eutectic β phase and refine the grains in cast AZ91D alloy with the hardness of the nugget zone (NZ) increased greatly [10]. Thus, the FSW joint of as-cast AZ91 alloy could show a similar UTS to that of the parent material (PM) [11].

However, for the wrought (rolled or extruded) Mg alloys with higher Al content, their strength and ductility are significantly improved due to smaller grains and fewer coarse β phases [22]. In this case, the weldability, the mechanical properties and fracture behavior of resultant FSW joints might be quite different from those of the as-cast counterparts. However, investigation in this aspect is lacking.

The present investigation aims to (a) study the effect of FSW parameters on microstructures and tensile properties of the Mg–Al–Zn alloy with high Al content and (b) evaluate the effect of the β precipitates on the weld properties of this alloy. Part I is presented in this article, while Part II will be described in a companion article.

In this article, as-extruded AZ80 plates were subjected to FSW investigation in a wide tool rotation rate range of 400–1200 rpm at a constant

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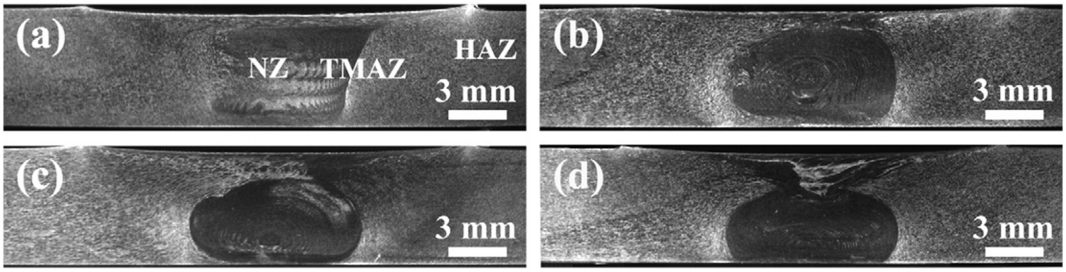

**Fig. 1.** Cross-sectional macrographs of FSW AZ80 joints at different rotation rates: (a) 400 rpm, (b) 600 rpm, (c) 800 rpm, and (d) 1200 rpm (the advancing side is on the right).

traverse speed of 100 mm·min$^{-1}$. The aim is to (a) establish the process window for FSW of as-extruded AZ80 alloy and (b) understand the effect of tool rotation rate on the microstructure evolution and mechanical behavior of FSW AZ80 joints.

## 2. Material and Methods

AZ80 extruded plates with a nominal composition of 8.00Al–0.33Zn–0.25Mn–0.036Si–0.0018Cu–0.0012Ni–0.0016Fe (in wt.%) were used in this study. 6-mm-thick plates were friction stir welded along the extrusion direction at a traverse speed of 100 mm·min$^{-1}$ and tool rotation rates of 400, 600, 800, and 1200 rpm, respectively. A tool with a concave shoulder 20 mm in diameter and a threaded conical pin 8 mm in root diameter, 6.2 mm in tip diameter and 5.7 mm in length was used. The FSW was performed under the plunge control model with the plunge depth being fixed at 0.15 mm with a tilt angle of 2.7° for all the welding parameters. The tool was carefully machined and mounted to reduce the eccentricity as much as possible.

The specimens for microstructural examinations were cross-sectioned perpendicular to the welding direction. Microstructural characterization and analysis were carried out via optical microscopy (OM), scanning electron microscopy (SEM), and transmission electron microscopy (TEM). The specimens for OM and SEM observations were prepared by mechanical polishing and etching using a solution of 4.2 g picric acid, 10 ml acetic acid, 70 ml ethanol, and 10 ml water. Thin foils for TEM were prepared by the ion-milling technique. The grain size was measured using the linear intercept method with the measuring direction perpendicular to both the normal and welding directions.

Vickers hardness and tensile tests were conducted in accordance with ASTM: E384-11e1 and ASTM: E8/E8M-11, respectively. The hardness of the welds was measured along the mid-thickness of the plates with a 300 g load for 10 s using a LECO-LM247AT type Vickers-hardness tester. Transverse tensile specimens with a gauge length of 50 mm and width of 10 mm were machined perpendicular to the FSW direction with the NZ in the center of the gauge. Tensile tests were conducted at a strain rate of $1 \times 10^{-3}$ s$^{-1}$ with a Zwick Z050 tester at room temperature. The tensile properties of each FSW joint reported

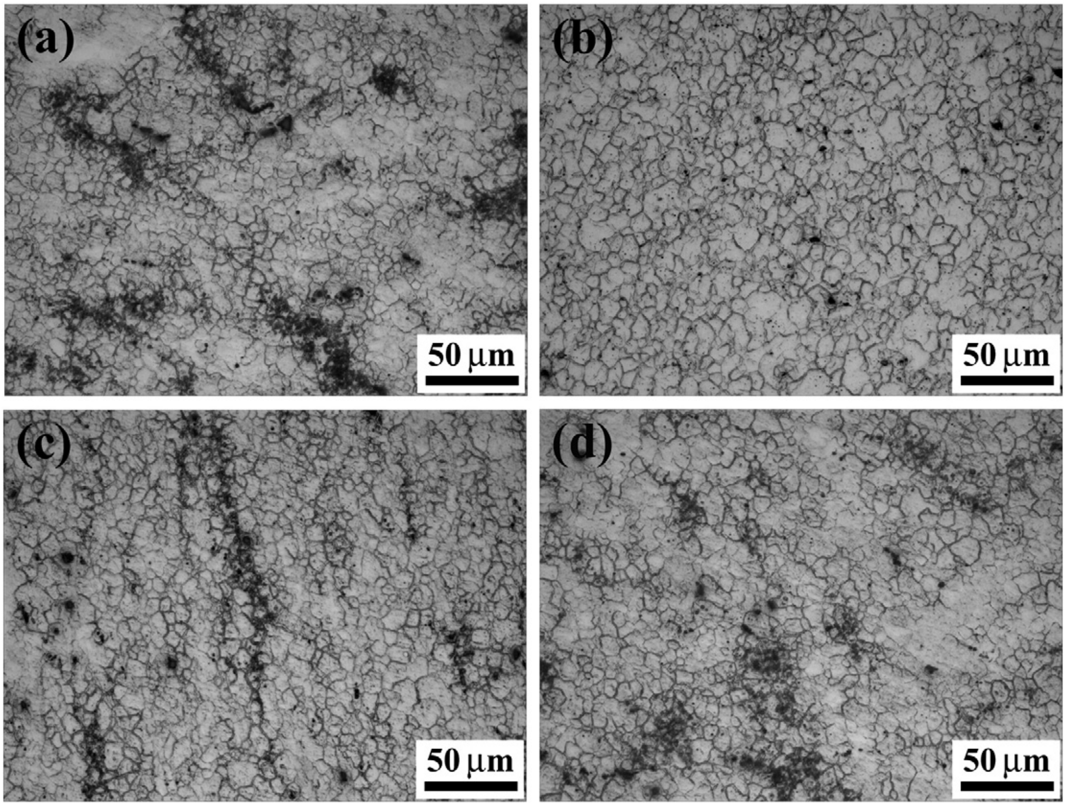

**Fig. 2.** OM microstructures of FSW AZ80 joint at 400 rpm: (a) PM, (b) NZ, (c) TMAZ, and (d) HAZ.