Investigation on the Microstructure and Mechanical Properties of AZ91D Magnesium Alloy Plates Joined by Friction Stir Welding

Nagabhushan Kumar Kadigithala and C. Vanitha

Abstract Friction stir welding (FSW) is an effective technique to join magnesium-based alloys which are difficult to fusion weld. In this work, similar AZ91D Mg alloy sheet of 3 mm thick butt joint was produced via friction stir welding at welding parameters such as rotational speed, welding speed, and tilt angle. The rotational speed was kept constant of 720 rpm, the welding speed varied from 25 to 75 mm/min, and tilt angle from 1.5° to 2.5°. Defect-free weld was obtained under 75 mm/min welding speed and tilt angle of 1.5°. The microstructure of the parent alloy consists of phases, namely primary α and eutectic β ($Mg_{17}Al_{12}$) in the as-received condition (gravity die-cast) which was confirmed by X-ray diffraction (XRD) analysis. Microscopic studies, tensile tests, hardness test, and fractographic studies were conducted. Metallographic studies revealed different features in each zone depending on their thermomechanical condition. A significant increase in hardness was observed in the stir zone of weldment compared to parent alloy due to the recrystallized grain structure. The dendrite grain structure present in weldment was completely disappeared and was transformed to fine grains in stir zone (SZ). The transverse tensile test result of the weld specimen indicated that weldment was about 44.9% higher than the parent alloy. Fractographic analysis of the friction stir welded specimen indicated that the weld specimen failed through the brittle failure.

Keywords AZ91 D mg alloy · Friction stir welding · Microstructure · Dynamic recrystallization

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H. K. Voruganti et al. (eds.), *Advances in Applied Mechanical Engineering*,
Lecture Notes in Mechanical Engineering,
https://doi.org/10.1007/978-981-15-1201-8_109

1 Introduction

Mg-based alloys are transpiring as eminent material in the field of engineering, peculiarly in the automotive and aeronautics field cause of their superior damping strength and reusability, predominant strength-weight ratio, lower bulk density [1]. This material possesses a density of almost about 70% of Al materials, which are auspicious engineering materials to enhance propellant efficiency peculiarly in industries like automobile [2, 3]. Currently, these materials are predominantly utilized to originate cast-based components. Their usability in wrought nature is lesser, and predictions for the future are to advance in forthcoming years. However, the major disadvantage of these materials for structural applications is enormous chemical activity primarily on numerous occasions due to low joining and corrosion resistance [4]. Traditional fusion welding of these alloys involve variety of challenges in obtaining defect free welds [5].

The fusion welding of magnesium-based alloys is unreliable due to the above reasons. Friction stir welding (FSW) is an appropriate bulk form technique to combine Mg alloys that abolish joining imperfections collaborated with traditional fusion joining methods. Weldments originated through FSW route manifest superior mechanical characteristics like elasticity, tensile strength, and hardness with respect to traditional joining techniques. FSW is a bulk form welding process that was innovated at TWI (UK) in 1991 and was preliminarily implemented to combine Al alloys [6]. Because of this dominance, FSW suits as a magnificent strategy for combining divergent metals like Ni-based alloys, Ti and Steel alloys [7]. Contrasting these superior strength alloys, Mg materials have a lesser melting point and low strength that are suitable for FSW like Al materials [1]. Numerous industrial grade Mg materials like AZ31, ZM21 [8–10], and Mg–Zn–Y–Zr [11] are combined utilizing FSW route, producing great outcomes above traditional fusion joining methods.

Nakata [12] had demonstrated numerous FS-joined Mg materials. Scholar delineated that physical characteristics were enhanced above traditional fusion joining route. Lee et al. [13] scrutinized specimen features of FSWed AZ91D Mg alloy weldments and delineated that β intermetallic form was dissolved in stir region, because of frictional heat involved. Cao et al. [14] have scrutinized impacts of probe dimensional length and revolving speed on Friction stir lap weld of AZ31B-H24 Mg material having 2 mm dimensional thickness and demonstrated that by ascending speed of rotation of tool, tensile shear load escalates preliminarily but de-escalates by furthermore extending of rotational speed. Xunhong et al. [15] had scrutinized FS butt joint AZ31 Mg material plates of 4 mm dimensional thickness and delineated that tensile characteristics of the specimen obtained 93% of the metal in bulk form and breakage position was in HAZ region. Afrin et al. [10] explored FSWed AZ31B Mg materials and delineated that grain in stir region and thermo-mechanically impacted region encountered recrystallization and enlargement and the dimensional shape of uniform grains, having tiny values of dual aspect proportion and fractal dimension. Cavaliere et al. [16] has explored the impact of FSP on superplastic behavior of Mg material, i.e., AZ91 and outlined that it manifested superior strength and ductile characteristics because of the tiny composition by processing technique at ambient temperature with respect to bulk metal. Darras et al. [17] scrutinized the impact of FSW on techno-commercial AZ31 Mg material and delineated that uniformity of microstructure and purification of grain are attained in a solo FSP pass over the facet of metal in bulk form. Zeng et al. [18] scrutinized the impact of FSW on AM50 Mg materials and delineated that microstructural homogenization introduce finer size of uniform grains accommodating α-Mg matrix and β phase. Rose et al. [19] scrutinized the impact of length-wise force throughout FSW of AZ61A Mg material and delineated that it has a noteworthy impact on the generation of imperfections, grain size, hardness if tensile strength, and stir region.Cavaliere et al. [20] checked the FS-joined AZ91 fatigue-life cycle and found an improved fatigue-life compared to that of as-cast bulk material. Chai et al. [21] explored immersed FS-processed AZ91 and outlined that after processing larger β $Mg_{17}Al_{12}$ form, grid altered into particles affixed on grain frontiers. Park et al. [22] established texture and movement design in FSWed AZ61 Mg materials and delineated that onion ring form in stir region and nugget form are connected with the availability of (0002) basal plane possess elliptical trace facet. Park et al. [23] explored FSW of thixomolded Mg material AZ91D and delineated that microscopic structure comprising elementary solid fragments is altered to tiny homogenized grains of α-Mg form throughout processing. The toughness of stir region was improved with de-escalating grain dimensional size in correlation with the Hall–Petch equation. Nowadays, welding of dissimilar metals such as magnesium alloys [24, 25] and magnesium to aluminium alloys [26–28] has been getting attention among research groups. Literature survey confirmed that only a limited amount of work has been carried out on the FSW of magnesium-based alloys when compared to Al alloys. The present manuscript reports our primary results on FS-welded AZ91 Mg alloy (gravity die-cast), which is widely used in automobile and aerospace industries.

2 Experimental Procedures

2.1 Base Metal

The AZ91D Mg alloy used in the present work was supplied in the form of as-cast blocks; 3 mm thick plates were prepared from the blocks of dimension 130 × 45 mm using wire cut electrical discharge machine (EDM); and the chemical composition is presented in Table 1.

Table 1 Chemical Composition of AZ91D Mg alloy

Element	Al	Zn	Si	Cu	Ni	Mn	Mg
wt%	8.84	0.59	0.22	0.05	008	0.21	Balance

Table 2 Process parameters used for the present study

Nomenclature	Corresponding processing parameters
Tool details	H13 tool steel tapered cylindrical pin (left-hand metric threads, 0.5 mm pitch) Pin diameter: 7 mm (shoulder end) and 2 mm (tip end) Pin length: 2.6 mm Shoulder diameter: 18 mm
Other details	Rotation speed: 720 rpm, Welding speed: 25, 50, 75 mm/min Tilt angle: 1.5°, 2°, 2.5°
Dwelling time	10 s

2.2 Friction Stir Welding of AZ91D Mg Alloy Plates

Prior to welding, surface oxides of plates are removed by stainless steel brush, and then, the 3 mm thick plates were cleaned with acetone in order to remove any surface pollutant. At a constant rotational speed of 720 rpm, welding speeds varied from 25 to 75 mm/min, and tilt angle varied from 1.5° to 2.5°, the welding operations were performed. Butt joint welds, 3 mm thick, were produced using a commercially available vertical milling machine at IIT, Roorkee. The process parameters used in this study are listed in Table 2.

2.3 Metallography

The specimens were prepared by the standard metallographic polishing procedure. The weld specimens were etched with acetic glycol for 10–15 s prior to examination using optical microscopy and scanning electron microscopy.

Microstructural and elemental analysis of the weldments and fractured surfaces was analyzed using a VEGA 3 TESCAN scanning electron microscope.

2.4 X-Ray Diffraction (XRD) Analysis

Phase investigation of the bulk material and joints was explored utilizing an XRD, (X'pert Powder Diffractometer: PANalytical, Netherland) through Cu Kα radiation.

2.5 Tensile Testing

Transverse tensile experiments were executed to diagnose the specimen strength of the weldments. Test samples were assembled following the standard ASTM E8 through a wire cut EDM. The tensile investigations were executed at ambient temperature utilizing Instron Model no. S500 testing machine, at crosshead velocity of 2 mm/min.

2.6 Microhardness Testing

Microhardness was conducted using Shimadzu microhardness tester using a load of 200 g applied for 15 s.

3 Results and Discussion

Defect-free weldment was produced at a rotational speed of 720 rpm, travel speed of 75 mm/min, and tilt angle of 1.5° as shown in Fig. 1. The same has been confirmed through X-ray radiography, and visual inspections are accomplished on the FSW joints to inspect defects generated during the welding process. Microstructure analysis, tensile, and hardness tests were conducted at this weld parameter.A moderate and constant rotational velocity of 720 rpm was maintained throughout the welding process [29, 30] as too low or two high speed results in inadequate and excess heat generation, respectively.

Figure 2 shows the macrostructure of the cross section of the joint which was welded at 720 rpm of rotational speed and 75 mm/min of travel speed. The top

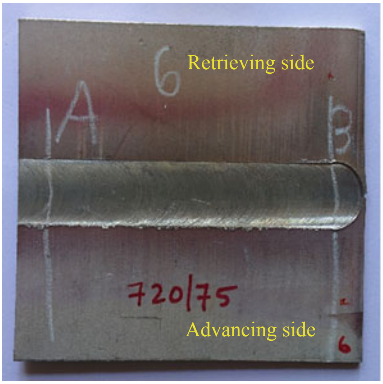

Fig. 1 Surface appearance at welding condition of 500 rpm, 75 mm/min, and 1.5°

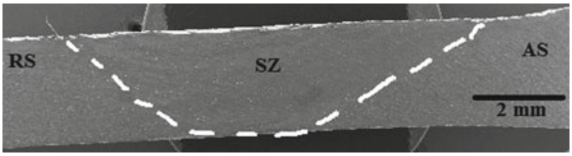

Fig. 2 Macrograph of cross-sectional joint

surface of weld nugget was wider than the bottom surface due to contacting tool shoulder with the top surface has experienced functional heat. The profile of nugget is influenced by tool pin profile, type of material and thermal conductivity. As shown in figure 2 no defects in the weld zone was observed.

3.1 Microstructure of the Weld Zones

The parent alloy consists of a mixture of primary α phase and β intermetallic compound (eutectic β ($Al_{12}Mg_{17}$)) as shown in Fig. 3.

Figure 4 shows the microstructure of the weldment in different zones. The zones named as (a) heat affected zone (HAZ), (b) thermo-mechanically affected zone (TMAZ), and (c) stir zone (SZ), respectively. Each zone exhibits unique features, depending upon thermal and mechanical conditions. In HAZ, due to the thermal effect produced by the tool, the volume fraction of β intermetallic compound undergoes resolution and was reduced to a smaller fraction. In TMAZ, due to combined effects of thermal and plastic deformation, it is composed of partially observed recrystallization grains and eutectic β. The eutectic β is located around the tool rotation direction in TMAZ. In the SZ, the grain structure was transformed into a fine equiaxed grain structure. The stir zone undergoes dynamic recrystallization (DRX).

Figure 5 illustrates the XRD patterns of parent alloy and weldment, and the presence of α and Eutectic β ($Mg_{17}Al_{12}$) phase is confirmed.

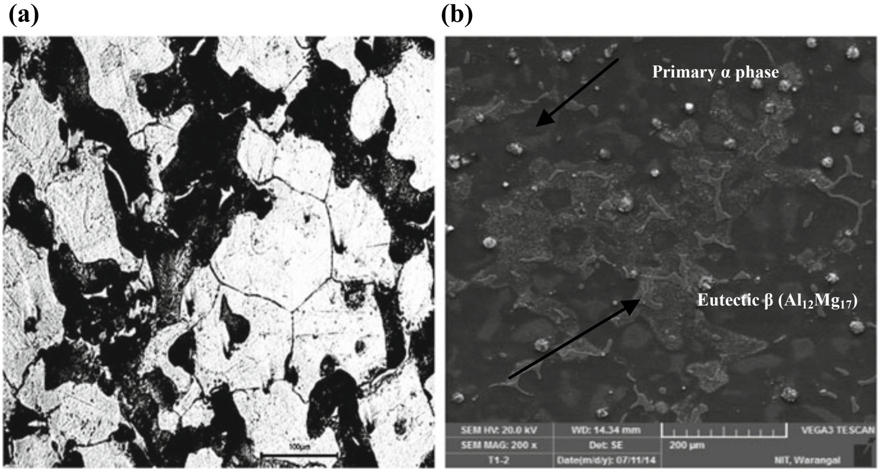

Fig. 3 Showing micrograph of AZ91D Mg alloy **a** optical microscopy image at 100 X **b** SEM image at 200 X

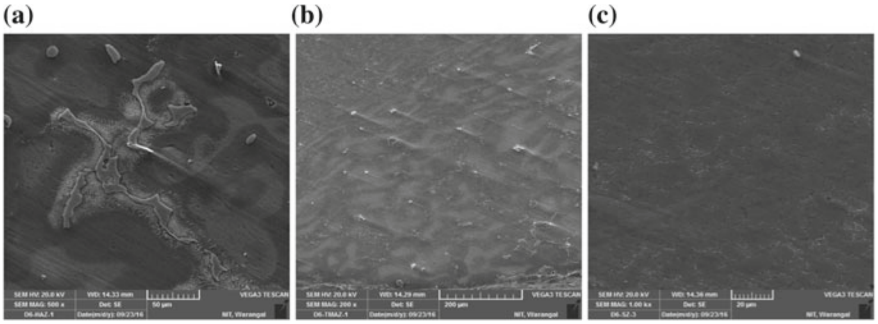

Fig. 4 SEM micrographs of AZ91D Mg alloy weldment of condition 720 rpm, 75 mm/min at **a** HAZ, **b** TMAZ, **c** SZ

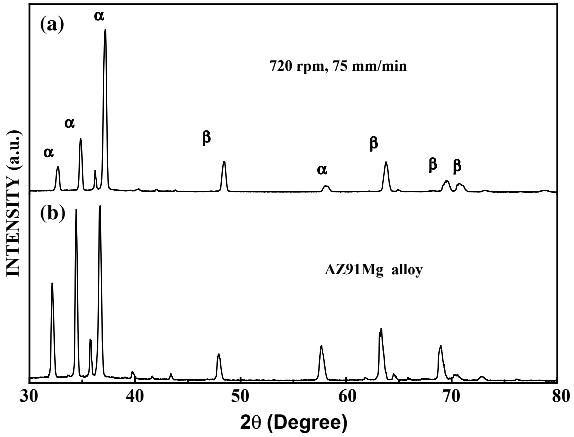

Fig. 5 XRD patterns of **a** parent alloy **b** weldment

3.2 Microhardness Testing Results

Figure 6 shows the microhardness result of the weldment. The hardness of parent alloy was about 68 HV. The hardness of SZ is improved significantly due to the recrystallized grain structure. The stir zone undergoes dynamic recrystallization (DRX) compare to the SZ, and the TMAZ and HAZ showed lower hardness.

3.3 Tensile Testing

The parent alloy exhibited lower tensile strength (109 MPa) and elongation value (3%) when compared to the weldment. The weldment showed the maximum ultimate

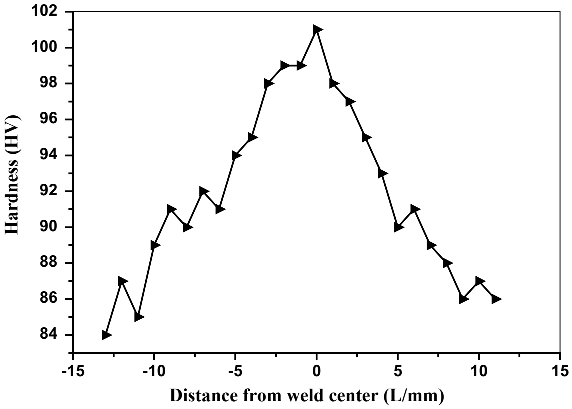

Fig. 6 Hardness profile of the weldment of condition 720 rpm, 75 mm/min

tensile strength of 158 MPa, which is about 44.9% greater and elongation of 4.7% which is about 56.6% higher than the elongation of parent alloy.

3.4 Fractographic Analysis

Figure 7 shows the fractured surface of the parent alloy and weldment. It was observed that fracture occurred at the interface of the weld specimen and image clearly indicates that fracture occurred in the brittle mode. The unevenly distributed eutectic β–$Al_{12}Mg_{17}$ was responsible for preferential crack initiation. Due to this specimen

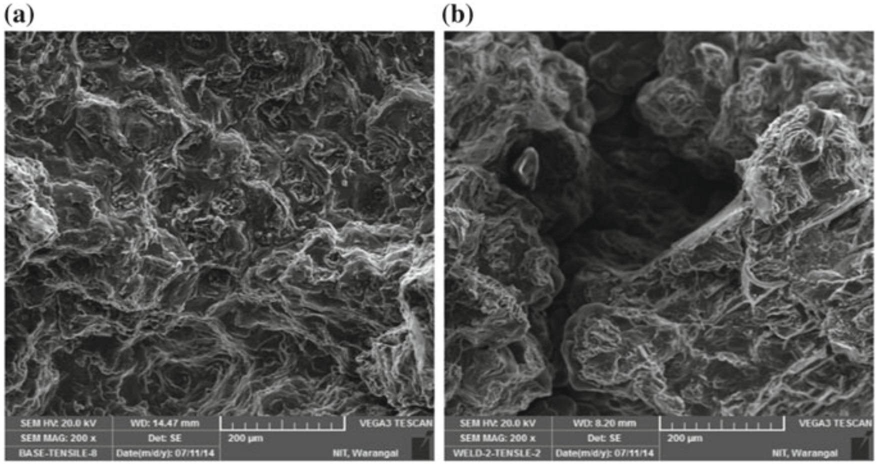

Fig. 7 SEM images of the fractured surface **a** AZ91D Mg alloy and **b** weldment

fractured at weld-base material interface, the existence of quasi-cleavage surfaces in Fig. 7a, b confirms that parent alloy and welded specimen failed through the brittle mode of failure.

4 Conclusion

Similar AZ91D magnesium alloy plates of 3 mm thick were successfully welded at a welding speed of 75 mm/min and tilt angle of 1.5°. The conclusions drawn from the present study are as follows:

1. The original dendritic grain structure present in weldment was completely eliminated in the stir zone. Due to the frictional heat input produced by the tool shoulder in contact with the workpiece, it was replaced with fine grains and β intermetallic phase was dissolved in stir zone.
2. In the stir zone, the grains undergo grain refinement due to dynamic recrystallization.
3. The mechanical properties such as tensile strength of the weldment were about 44.9% higher than the parent alloy.
4. Hardness was improved significantly when compared to other zones due to grain refinement.
5. The mode of fracture in the weldment was observed to be brittle in nature

Acknowledgements Authors would like to acknowledge the National Institute of Technology Warangal for financial support to carry out the experimentation of Mr. K. N. B. Kumar, Research Scholar, Enrollment Number (701251), under the guidance of Dr. C. Vanitha, Associate Professor in Department of Metallurgical and Materials Engineering—NIT Warangal, India.

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