Investigation on the Microstructure and Mechanical properties of AZ91D Magnesium Alloy Plates joined by Friction Stir Welding

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**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 but 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**0** to 2.5**0**. Defect free weld was obtained under 75 mm/min welding speed and tilt angle of 1.5**0**. The microstructure of the parent alloy consists of the phases namely primary α, and eutectic β (Mg17Al12) in the as-received condition (gravity die cast) was confirmed by X-ray diffraction (XRD) analysis. Microscopic studies, tensile tests, hardness test and fractrographic studies were conducted. Metallographic studies revealed different features in each zone depending on their thermo- mechanical condition. Significant increase in hardness was observed in stir zone of weldment compared to parent alloy due to 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 weld specimen indicated that weldment was about 44.9% higher than the parent alloy. Fractrographic 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.

1. **Introduction**

Mg-based alloys are transpiring as eminent material in 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 almost about 70% of Al materials, 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 future are to advance in forthcoming years. Although, the prominent disadvantage of these material for structural applications is immense chemical activity majorly in numerous occasions to a little joining features and resistance to corrosion [4]. Inevitably, welding of these alloys by traditional fusion joining strategies guiding to a diversity of challenges, comprising porosity, solidification and liquation fissures, erosion of alloying metals, oxide incorporation etc. [5].

Cause of the overhead referred causes, fusion joining of these alloys is undependable. FSW (Friction Stir Welding) 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 bulk form combining process that was innovated at TWI (UK) in 1991 and was preliminarily implemented to combine Al alloys [6].

Because of these dominance, FSW suits as magnificent strategy for combining of divergent metals like Ni-based alloys, Ti and Steel alloys [7]. Contrasting these superior strength alloys, Mg materials have 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], Mg-Zn-Y-Zr [11], are combined utilising FSW route, producing great outcomes above traditional fusion joining methods.

Kazuhiro Nakata [12] had demonstrated numerous FS joined Mg materials. Scholar delineated that physical characteristics were enhanced above traditional fusion joining route. Won-Bae 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] has scrutinized impacts of probe dimensional length and revolving speed on Friction stir lap weld of AZ31B-H24 Mg material having 2mm 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 4mm 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. [16] 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. [17] has explored the impact of FSP on superplastic behaviour of Mg material i.e. AZ91 and outlined that it manifested superior strength and ductile characteristics because of tiny composition by processing technique at ambient temperature with respect of bulk metal. Darras et al. [18] 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. Rong-chang et al. [19] scrutinized impact of FSW on AM50 Mg materials and delineated that microstructural homogenization introducing finer size of uniform grains accommodating α-Mg matrix and β phase. Rose et al. [20] scrutinized the impact of length-wise force on throughout FSW of AZ61A Mg material and delineated that it has noteworthy impact on the generation of imperfections, grain size, hardness if tensile strength and stir region. Cavaliere et al. [21] scrutinized that fatigue life-cycle of the FS joined AZ91 was improved throughout producing comparatively to that of bulk material in as-cast state. Chai et al. [22] explored immersed FS processed AZ91 and outlined that after processing larger β Mg17Al12 form grid altered into particles affixed on grain frontiers. Park et al. [23] 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. [24] explored FSW of thixomolded Mg material AZ91D and delineated that microscopic structure comprising elementary solid fragments is altered to tiny homogenised grains of α-Mg form throughout processing. Toughness of stir region was improved with de-escalating grain dimensional size in correlation with Hall-Petch equation. Literature survey confirmed that only 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 for use 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; 3mm thick plates were prepared from the blocks of dimension 130 X 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 |

***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 constant rotational speed of 720 rpm and welding speeds varied from 25 to 75 mm/min, tilt angle varied from 1.50 to 1.20 the welding operations were performed. Butt joint welds, 3mm 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.

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, 0.5mm 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: 1.50, 20, 2.50 |
| **Dwelling time** | 10 seconds |

***2.3 Metallography***

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

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

**2.4 X-ray diffraction (XRD) Analysis**

Phase investigation of the bulk material and joints were 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 cross head velocity of 2 mm/min.

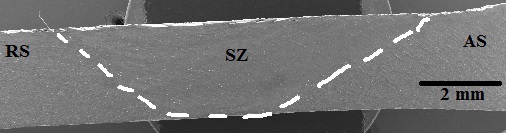
***2.6 Microhardness testing***

Micro hardness was conducted using Shimadzu micro hardness tester using a load of 200 g applied for 15 seconds.

1. **Results and discussion**

Defect free weldment was produced at rotational speed of 720 rpm, travel speed of 75 mm/min and tilt angle of 1.50 as shown in figure 1. The same has been confirmed through X-ray radiography and Visual inspections accomplished on the FSW joints to inspect defects generated during welding process. Microstructure analysis, tensile and harness tests were conducted at this weld parameter.

Figure 2 Show the macro structure 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 surface of is 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, materials to be welded and their rate of thermal conductivity. From the inspection it was observed that for condition has no defect in the weld zone, as shown in Figure 2.

Retrieving side

Advancing side

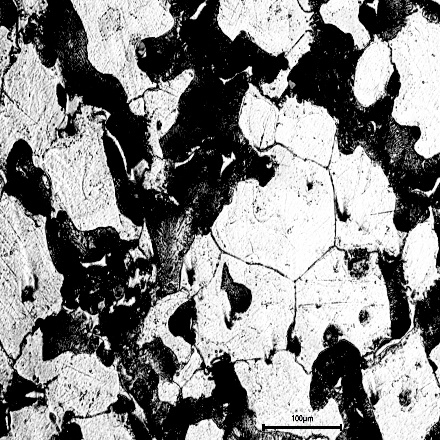
Fig. 1 Surface appearance at welding condition of

500 rpm, 75 mm/min and 1.50. Fig. 2 Macrograph of cross sectional joint

**3.1 Microstructure of the weld zones**

The parent alloy consist a mixture of primary α phase and β intermetallic compound (eutectic β (Al12Mg17)) as shown in Figure 3.

**(a)**

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**(b)**

**Eutectic β (Al12Mg17)**

**Primary α phase**

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

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, depend up on thermal and mechanical conditions. In HAZ, due to thermal effect produced by tool, the volume fraction of β intermetallic compound under goes resolution and was reduced to smaller fraction. In TMAZ, due to combined effects of thermal and plastic deformation, it is composed 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 to fine equiaxed grain structure. The stir zone under goes dynamic recrystallization (DRX).

**(a)**

**(c)**

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**(b)**

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

Figure 5 illustrates the XRD patterns of parent alloy and weldment, and the presence of α and Eutectic β (Mg17Al12) phase is confirmed.



Fig. 5 XRD patterns of (a) parent alloy (b) weldment Fig. 6 Hardness profile of the weldment of condition

720 rpm, 75 mm/min.

**3.2 Micro hardness testing results**

Figure 6 shows micro hardness result of 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 under goes dynamic recrystallization (DRX).Compare to the SZ 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 compare to weldment. The weldment showed the maximum ultimate 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 facture occurred at the interface of the weld specimen and image clearly indicates that facture occurred in the brittle mode. The unevenly distributed eutectic β -Al12Mg17 was responsible for preferential crack initiation. Due to this specimen fractured at weld -base material interface. The existence of Quasi-cleavage surfaces in Figure.7 (a) and (b) confirms that parent alloy and welded specimen failed through brittle mode of failure.

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**(a)**

**(b)**

Fig. 7 SEM images of fractured surface (a) AZ91D Mg alloy and (b) weldment

1. **Conclusion**

Similar AZ91D Magnesium alloy plates of 3 mm thick were successfully welded at welding speed of 75 mm/min and tilt angle of 1.50. 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 work piece it was replaced with fine grains and β intermetallic phase was dissolved in stir zone.
2. In the stir zone the grains under goes grain refinement due to dynamic recrystallization.
3. The mechanical properties such as tensile strength of the weldment was about 44.9% higher than the parent alloy.
4. Hardness were improved significantly when compare to other zones due to grain refinement.
5. It was observed that weldment was fracture thorough brittle- mode of failure.

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