Experimental Studies on Friction Stir Processing of Magnesium Alloy

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Abstract. Friction Stir Welding (FSW) belongs to the solid state joining technique. In the present study, the effect of FSW parameters such as rotational speed and tool pin diameter on the weldability of ZK61A Magnesium alloy was investigated and the mechanical and micro structural characteristics of the welded specimens were analyzed at room temperature. Further, the tool wear was estimated with constant shoulder diameter. Radiographic tests were done to identify defects in the weldments.

Keywords—Friction Stir Welding, Magnesium alloy (ZK 61A), shoulder diameter, metallurgical characteristics.

1. Introduction

Friction stir welding (FSW), as a solid-state joining method by narrowly preceding frictional heats and plastic flow via turning the welding tools, FSW process generates four distinct micro structural zones: unaffected material or Base Metal (BM), Heat Affected Zone (HAZ), Thermal Mechanically Affected Zone (TMAZ) and Nugget zone [1]. Friction stir welding process consists of a rotating tool pin which extends up to the edge of the work material when forced. The schematic illustration of FSW process is shown in Fig.1. The plastic flow in material was induced by the heat input provided and the stirring action of the tool. The tool rotates about its own axis [2]. Magnesium alloys are light weight materials, due to this property they are considered as energy savers in structural applications.. In addition magnesium alloys have recycling capability which makes them economical and environmental friendly material [3]. Some of the Magnesium alloys are not prone to fusion welding techniques; if fusion welded they would produce defects and reduce the mechanical properties of the weldment this lacuna is rectified by friction stir welding [4]. Alloy ZK 61 A, is holding high creep resistance and high-grade tensile characteristics at both room and high temperatures. This combination is usually used in T6 tempers and is sensitive to micro porosity. Utilization includes aircraft fixtures, gears and shafts, missile parts, controlling valve elements, worm gears, keys, and various other commercial aircraft, aerospace and defense facilities.
Xianjun et al. investigated the shear localization model on FSW found that in order to form continuous banded structure per pin revolution inconsecutive manner; shear band width ($\delta$) formed within one revolution must be equal or larger than the maximum material flow layer width $W_{\text{max}}$ [6]. Jayaraj et al. on his study about the electro chemical corrosion on stir zone of Al-Mg dissimilar joints found that joining of Aluminium (Al) alloys with Magnesium (Mg) alloys by fusion welding process is very complicated.

Friction stir welding (FSW) is a feasible method to join these two dissimilar alloys. Mixing these two metals together in stir zone (SZ) leads to poor corrosion resistance [7]. Long et al. On his analysis about the effect of tool tilt angle on Friction stir welds using Finite Element Models found that tilt angle could increase the peak temperature in the surrounding region of the welding tool, which will significantly soften the material in weld nugget region [8]. Shrivastava et al. on his attempt to create a new non destructive technique to detect subsurface discontinuities on friction stir welds found that the rotational frequency of the tool and its traverse speed plays a major role in creation of sub-surface voids while performing colder welds [9]. Zhu et al. on his investigation about the friction stir welding of CoCrNiAl$_{0.3}$ high entropy alloy found that the equi-axed microstructure was seen at the stir zone which attributes to high hardness of stir zone due to grain refinement during crystallization [10]. Mironov et al. on his investigation about the friction stir welding of Ti-6Al-4V alloy analyzed the critical parameters of FSW process like Temperature, tool design, tool wear, process window etc. From the above literatures it was found that the evidences found for friction stir welding of magnesium alloys. Yong et al. investigated the microstructure and mechanical characteristics of friction stir welded dissimilar materials 5052 Al alloy and AZ31 Mg alloy. They found that the microstructure of stir zone is highly refined compared to base materials [11]. Afrin et al. examined tensile properties of friction stir welded AZ31B-H24 magnesium (Mg) alloy and observed that the yield strength significantly increased with increase in welding speed [12]. It is found that very few literatures are available for the friction stir welding on Magnesium alloys. Hence, the present work attempts to characterize the microstructure and mechanical properties of friction stir welded ZK61A Magnesium alloy.
2. Experimental procedure

The material selected for this particular study was Magnesium ZK61A alloy with the tensile strength of 271 MPa it was cut to the required dimension of 100 X 50 mm. Table I shows the base material composition. The tool material selected was high carbon and high chromium steel to withstand high temperature and high resistance to corrosive environment. The tool material composition is shown in the Table II. The welding parameters are welding speed and feed which are selected based on the literature review. The welding speed is selected based on the diameter of the tool pin. For the particular speeds of the experiment the value of the diameter of pin is a minimum so that these two speeds are selected for the welding process. The feed is selected based on the tool.

| Base Material Composition | % by weight |
|---------------------------|-------------|
| Magnesium                | 94.46       |
| Zinc                      | 5.19        |
| Zirconium                | 0.33        |
| Manganese                | 0.0055      |
| Iron                      | 0.0035      |
| Copper                   | 0.001       |
| Nickel                   | 0.003       |
| Aluminium                | 0.0006      |

| Tool Composition | % by weight |
|------------------|-------------|
| Carbon           | 1.54        |
| Chromium         | 12.3        |
| Molybdenum       | 0.987       |
| Vanadium         | 1.32        |
| Manganese        | 0.61        |
| Silicon          | 0.63        |
| Nickel           | 0.32        |
| Copper           | 0.25        |

3. Results and Discussion

3.1. Vicker’s hardness test. The micro hardness of friction stir welded ZK61A sample was measured using Vicker’s hardness test. The cross sections of four welded samples were taken and the average hardness values are plotted in Fig. 2. From the figure it is seen that for different welding speeds and pin diameters the hardness was found to be higher in the weld region than the base metal region.
3.2. Micro structure. To investigate the microstructure development at room temperature, this process was analyzed in the 1000-rpm and 1200-rpm. For the sake of conciseness, the finest results were obtained in the 1200-rpm weld are presented in this paper. The microstructure was observed at the magnification of 100X. From the Fig. 3(a) the microstructure of WZ and HAZ exhibited elongated grains due to the rolling direction. From the Fig. 3(b) formation of pores are observed in HAZ due to insufficient flow of material due to high welding speed [13].

3.3. Macro structure. The macrostructure of the FSW material was measured and analyzed with the base material to welded zone and the welded zone was separately measured with the help of visual inspection machine. The region close to base metal where grain coarsening happened was identified to be the Heat Affected zone (HAZ). Elongation of grains was seen between stir zone and heat affected zone it was found to be Thermo Mechanically Affected Zone (TMAZ). The onion shaped structure was found to be nugget zone where plastic deformation happens due to tool pin. Fig. 4(a-c) shows the macrostructure of friction stir welded specimens [14].
3.4. XRD test. The phase structure and lattice arrangement of base material and welded samples were analyzed using X-ray diffraction technique. The samples were finely grounded to obtain exact phase structure. The welded region gets more identical planes and peaks when compared to the base material by using the hkl planes. Based on XRD result (Fig. 5 and 6) the white phase was considered as $\beta$-Mg$_{17}$Al$_{12}$-an intermetallic compound which was seen in ZK-series magnesium alloys [15].

3.5. Radiographic test. Radiography is an imaging technique used to identify the defects in the welded region which are not found by visual inspection techniques. It uses electromagnetic radiations other
than visible light, mostly X-rays. It can also be used to find the internal structure of a non-uniform or opaque object [16]. Fig. 7(a-c) shows the radiographic image of welded specimens.

![Radiographic image](image)

a) Front view.

b) Top view.

c) Isometric view

Fig.7 Radiographic test.

4. Conclusions

The following are the observations from friction stir welding on ZK 61A

- Taper threaded tool pin profile gives the better welding.
- Magnesium alloy ZK 61A is suitable for solid phase welding also.
- High carbon and high chromium die steel are chosen as a weld tool in the welding process.
- The vast number of parameters changing the mechanical properties of welded joints entails planning characterization tests this decreases time and expense of experiments.
- The dwell time was the most powerful welding parameter and the tool rotational speed was the least significant welding parameter.
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