Journal of Manufacturing Engineering, March 2018, Vol. 13, Issue. 1, pp 026-031

EFFECT OF TOOL ROTATIONAL AND WELDING SPEED ON MECHANICAL AND MICROSTRUCTURAL CHARATERISTICS OF FRICTION STIR WELDED AZ31B MAGNESIUM ALLOY JOINTS

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ABSTRACT

In recent times, the greater attention on welding of magnesium alloys has been growing rapidly in aerospace and automotive industries due to their excellent properties such as light weight, high specific strength and stiffness. Fusion welding of these alloys is not preferable due to hot cracking, formation of porosity etc. However solid state welding techniques, such as, friction sitr welding are found to offer solution to the above problems. In this study, an attempt was made to understand the effect of welding speed of FSW process on microstructure and tensile properties of AZ31B magnesium alloy. Fabrication of FSW joints were completed using different levels of tool rotational between 1400 rpm and 1800rpm and for different welding speed between 0.4 mm/sec and 0.6 mm/sec. Tensile properties of the welded joints were evaluated and correlated with the weld zone microstructure and hardness. From this investigation, it is found that the joints fabricated using a tool rotational speed of 1600 rpm, welding speed of 0.5 mm/sec and an axial force of 4 kN yielded superior tensile properties compared to other joints. Formation of finer grains and higher hardness in stir zone are the main reasons for the superior tensile properties of these joints.

Keywords: *magnesium alloy, microstructure, tensile properties.*

1. Introduction

Magnesium and its alloys, as the lightest structural material, are about 40% lighter than aluminium and as much as about 78% lighter than steel, and therefore, they have been increasing interest as structural materials in many applications, in particular, they are used to replace steel/aluminum for automotive, structural applications. Magnesium and its alloys are attractive for aerospace and automotive industries owing to their excellent properties such as light weight, high specific strength, stiffness [1-3]. The components that are made of magnesium alloys have better strength to density ratio, ductility and energy absorbing characteristics. Improvements in magnesium alloying and processing techniques will make it possible for the automotive industry to manufacture lighter, more environmentally friendly, safer and cheaper cars.

Formation of porosity and hot cracking during fusion welding is not preferable, which deteriorates mechanical properties of the joints. However, Friction stir welding (FSW), a solid state joining technology is potentially useful and shows many promising advantages over traditional fusion welding, which is capable of joining magnesium alloys without melting and thus it can eliminate problems related to the solidification such as solidification cracking, liquation cracking and porosity. Good quality weld joints can be obtained by FSW process and the metallurgical problems associated with it can also be eliminated, because, there is no filler materials used in during welding.

Wang Xunhonga & Wang Kuaishe **[4]** analysed the effect of transverse speed on tensile properties of friction stir welded AZ31B magnesium alloy. They found the value of tensile strength increased with the increase in the tool rotation speed. Afrin et al [5] examined the effect of tool rotational speed on tensile properties of AZ31B-H24 magnesium alloy. They found that, the yield strength decreased with increasing rotational speed, whereas the ultimate tensile strength decreased to certain extent, and then increased. Cao et al [6] studied the effect of welding speed on quality of FSW joints of AZ31B-H24 magnesium alloy. They reported that, the yield strength increased with increasing welding speed owing to reduction in grain size in the stir zone. The tensile strength also increased with increasing welding speed. Padmanaban et al [7] investigated the influences of welding processes on microstructure, hardness, and tensile properties of AZ31B magnesium alloy. GTAW process greatly reduces the yield strength and tensile strength of the AZ31B magnesium alloy joints compared to FSW

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joints. Razal Rose et al [8] investigated the influences of welding speed on tensile properties of friction stir welded AZ61A magnesium alloy. They found that the joint fabricated with a welding speed of 90 mm/min exhibited the acceptable tensile properties.

There is a need of systematic investigation to study the effect of welding speed on tensile properties and fatigue behavior of friction stir welded AZ31B magnesium alloy joints. Hence, the present analysis was carried out to study the effect of tool rotational and welding speed on tensile properties of AZ31B magnesium alloy joints.

2. Experimental Works

The rolled plates of AZ31B magnesium alloy joints were cut and machined to the required dimensions (300 mm x 150 mm x 6 mm). The chemical composition and mechanical properties of base metals are presented in Table 1a and 1b. Square butt joint configuration was prepared to fabricate the joints as shown in fig.1a. Before welding, scrupulous cleaning by steel wire brush and then acid pickling were done to eliminate the surface oxide layer on the plates to be joined. The direction of welding was maintained normal to the rolling direction of base plates. FSW joints were fabricated using a rotating tool made of high speed steel (HSS) which is non-consumable. The conditions of welding and the optimized process parameters used to fabricate the joints are presented in Table 2.

Tensile specimens were prepared evaluate yield strength, tensile strength and elongation. A 100 KN, electro-mechanical controlled Universal Testing Machine (Make: FIE-Bluestar, India; Model: UNITEK-94100) was used to carry out tensile test. The 0.2% offset yield strength was derived from the load-displacement diagram. The hardness test was carried out using a Vicker's micro hardness testing machine (Make: Shimadzu, Japan and Model: HMV-2T) with a 0.05 kg load. The specimens were sectioned to the required size from the welded joint including weld metal and base metal regions for metallographic examination. Different grades of emery papers were used to polish the specimens. The specimens were etched with a standard reagent made of 4.2 g picric acid, 10 ml acetic acid, 10 ml diluted water and 70 ml ethanol to reveal the macro and microstructure. Microstructural analysis was carried out using a light optical microscope (Make: MEIJI, Japan; Model: MIL-7100).

Table 1a Chemical composition (wt %) of the base metals (as received)

Alloys	Al	Mn	Zn	Mg
AZ31B	3.00	0.2	1.00	Balance

Table 1b Mechanical properties of the base metals (as tested)

0.2 % Yield strength (MPa)	Ultimate Tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Reduction in cross - sectional area (%)	Notch strength (MPa)	Notch strength ratio (NSR)	Hardness (Hv) at 0.05 kg load
181	244	11.25	8.43	198	0.81	68

3. Results And Discussion

3.1 Tensile properties

The process parameters used to fabricate the joints are presented in Table 2. In total, five joints were fabricated using different tool rotational speeds for AZ31B Mg alloy (1400, 1500, 1600, 1700, and 1800rpm) was followed to fabricate joints, prepare specimens, evaluate tensile and hardness properties and microstructure analysis. From each joint, three tensile specimens were prepared and tested. The average of three results is presented in Tables 3 and 4. Of the five joints fabricated, the joint fabricated with a tool rotational speed of 1600 rpm exhibited higher yield strength (168 MPa), tensile strength (209 MPa), elongation (9.26%) and reduction in cross sectional area (6.25%) in AZ31B Mg alloy. The joint fabricated with a tool rotational speed of 1600 rpm exhibited higher notch strength ratio (0.78), which is 3.7 % lower compared to unwelded parent metal of AZ31B Mg alloy. The joint fabricated with a tool rotational speed of 1600 rpm exhibited a maximum joint efficiency of 85.6%. Similarly, three joints were fabricated using different welding speeds for AZ31B Mg alloy (0.4, 0.5, 0.6 mm/sec were followed to fabricate joints, prepare specimens, evaluate tensile and hardness properties and macro and microstructure analysis. From each joint, three tensile specimens were fabricated and tested. The average of three results is presented in Tables 5.7.

Table 2.FSW parameters used for joining AZ31B Mg alloy.

Tool rotational speed (rpm)	1400, 1500, 1600, 1700, 1800
Welding speed (mm/sec)	0.4, 0.5, 0.6
Axial force (kN)	4

Table 3 Effect of tool rotational speed on transverse tensile properties of FSW joints of AZ31B Mg alloy

Tool Rotational speed (rpm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Reduction in cross - sectional area (%)	Notch tensile strength (MPa)	Notch strength Ratio (NSR)	Joint efficiency (%)
1400	157	196	5.65	4.43	141	0.72	80.3
1500	161	201	6.23	5.11	152	0.75	82.3
1600	168	209	9.26	6.25	164	0.78	85.6
1700	165	206	7.31	5.74	149	0.72	84.4
1800	163	204	6.83	4.93	143	0.70	83.6

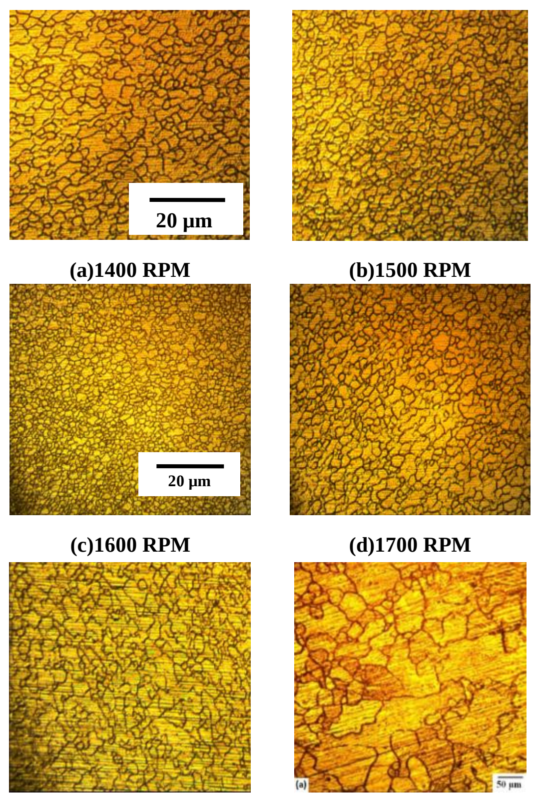
Of the three joints fabricated, the joint fabricated with a welding speed of 0.5 mm/sec exhibited higher yield strength (168 MPa), tensile strength (209 MPa), elongation (9.26%) and reduction in cross sectional area (6.25 %) in AZ31B Mg alloy. The joint fabricated with a welding speed of 0.5 mm/sec exhibited higher notch strength ratio (0.78), which is 3.7 % lower compared to unwelded parent metal. The joint fabricated with a welding speed of 0.5 mm/sec exhibited a maximum joint efficiency of 85.6 %.

Table 4. Effect of welding speed on transverse tensile properties of FSW joints of AZ31B Mg alloy

Welding speed (mm/sec)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in 50 mm gauge length (%)	Reduction in cross - sectional area (%)	Notch tensile strength (MPa)	Notch Strength Ratio (NSR)	Joint efficiency (%)
0.4	160	200	6.31	5.23	151	0.75	82.0
0.5	168	209	9.26	6.25	164	0.78	85.6
0.6	162	204	6.81	4.89	143	0.70	83.6

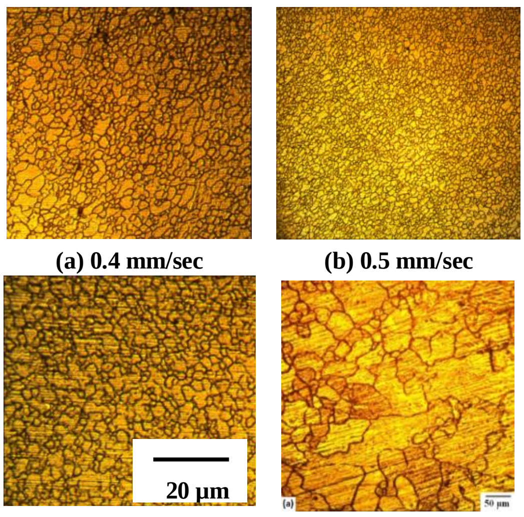
3.2 Microstructure

The optical micrographs taken at FSW zone of all the joints are displayed in Fig. 1 and 2. From the micrographs, it is understood that there is an appreciable variation in average grain diameter of weld region in AZ31B magnesium alloys. Due to FSW, the coarse grains of base metal are changed in to fine grains in the weld region. The joints fabricated using AZ31B Mg alloys with a rotational speed of 1600 rpm and welding speed of 0.5 mm/sec contain finer grains in the weld region compared to other joints. This is also one of the reasons for higher tensile properties of these joints compared to other joints.



(e)1800 RPM (f) Base metal

Fig. 1 Effect of tool rotational speed on stir zone microstructure of AZ31B Mg alloy



(a) 0.4 mm/sec (b) 0.5 mm/sec

(c) 0.6 mm/sec (d) Base metal

Fig. 2 Effect of welding speed on stir zone microstructure of AZ31B Mg alloy

3.3 Microhardness

The hardness was measured across the joint along the mid thickness using Vicker's microhardness testing machine and the values are presented in Fig. 3 and 4. The hardness of base metal (unwelded parent metal) of AZ31B Mg alloy is 69 Hv. The joints fabricated with the rotational speed of 1600 rpm and welding speed of 0.5 mm/sec recorded higher hardness (72 Hv) in the stir zone of AZ31B Mg alloy joint, and this is also one of the reasons for superior tensile properties of these joints compared to other joints. There are two main reasons for the improved hardness of stir zone. Firstly, since the grain size of stir zone is much finer than that of base metal, grain refinement plays an important role in material strengthening. Secondly, the small particles of intermetallic compound also benefit to hardness improvement (Wang & Wang 2006) [4]. All the joints were nondestructively inspected using ultrasonic testing and no defect was detected in the joint, indicating that the sound joint was achieved. The location of failure in all the tensile specimen was invariably at the TMAZ region on the advancing side, which is consistent with the lowest hardness distribution in the TMAZ of advancing side.

4. Discussion

4.1 Effect of tool rotational speed

The ultimate requirement for a FSW process is to create a certain amount of friction heat, which can keep the welding material in a well plasticized state with a suitable temperature and to generate a high hydrostatic pressure along with the joint line so that a sound weld can be generated. The heat generation in FSW is in direct proportion to deformation and frictional energy created during the stirring process. The latter depends on the friction factor and friction area between the tool shoulder and work piece surface, as well on the rotation speed of the welding head pin and the pressure applied to the welding tool head shoulder [9]. Intense plastic deformation and frictional heating during FSW resulted in the generation of fine recrystallized grains. During dynamic recrystallization, either decreasing the temperature or raising the strain rate will produce a finer grain structure [4]. In this investigation, relatively finer magnesium grain structure is produced by FSW.

The tensile properties of the joints made with different welding conditions resulted in lowest tensile strength and ductility at lowest spindle speed for a given welding speed. As the spindle speed increased, the strength and ductility improved, reaching maximum before falling again at high rotational speeds. Higher tool rotational speed usually results in higher temperature and slower cooling rate in the FSW zone. A higher rotational speed also causes excessive release of stirred materials to the upper surface, which results in micro voids in the FSP zone and this is one of the reasons for lower tensile properties of the joints. Lower heat input condition due to lower rotational speed results in lack of stirring and this is one of the reasons for lower tensile properties of the joints [14]. Of the five joints fabricated using five different tool rotational speeds, the joint fabricated at a rotational speed of 1600 rpm for AZ31B exhibited superior tensile properties.

Higher tool rotational speed resulted in a higher temperature and slower cooling rate in the stir zone after welding. A higher rotational speed causes excessive release of stirred materials to the upper surface, which resultantly creates voids in the stir zone. Lower heat input condition due to lower rotational speed resulted in lack of stirring. The area of the stir zone decreases with decrease in the tool rotational speed and affects the temperature distribution in the stir zone [11]. As the rotation speed increases, the strained region widens, and the location of the maximum strain finally moves to the advancing side from the original retreating side of the joint. This implies that the fracture location of the joint is also affected by the rotation speed [12]. Rotational speed appears to be the most significant process variable since it also tends to influence the translational velocity. Hence, in this investigation an attempt was made to study the effect of tool rotational speed on tensile properties of AZ31B.

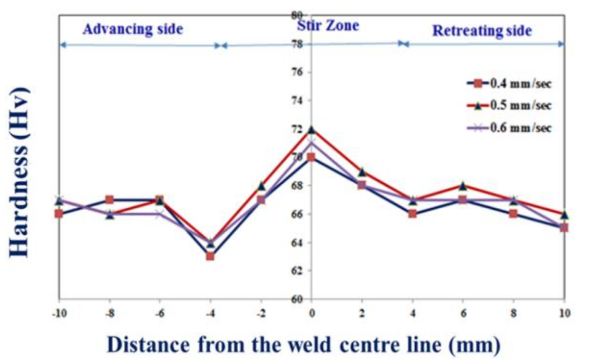


Fig. 3 Effect of welding speed on hardness of AZ31B Mg alloy joints

4.2 Effect of welding speed

A significant increase in welding speed resulted in high weld quality and excellent joint properties. The softened area was narrower for the higher welding speed than that for the lower welding speed. Higher welding speeds are associated with low heat inputs, which result in faster cooling rates of the welded joint. This can significantly reduce the extent of metallurgical transformations taking place during welding (reprecipitation and coarsening of precipitates) [13]. The welding speed has a strong impact on productivity in streamlined production of friction stir welded joints.

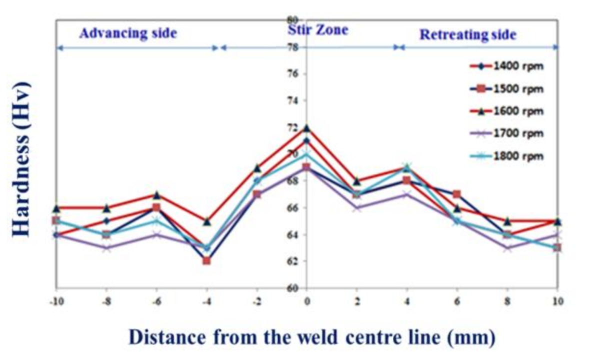


Fig. 4 Effect of tool rotational speed on hardness of AZ31B Mg alloy joints

Generally, more frictional heat input is generated at a lower welding speed. The inadequate stirring and mixing can be caused by higher welding speed or inadequate combination of welding speed and pin tool rotational rate. At low heat input (i.e. low temperature) material mixing is difficult. Higher welding speed which results in lower heat input per unit length of the weld, causes lack of stirring in the friction stir processing zone, which leads to lower tensile properties of the joints. Lower welding speed results in higher temperature and slower cooling rate in the weld zone causes grain growth, which subsequently leads to lower tensile properties of the joints [14]. Of the three joints fabricated using three welding speeds, the joint fabricated at a welding speed of 0.5 mm/sec for AZ31B exhibited superior tensile properties.

5. Conclusions

The tensile and microstructural behaviour of friction stir welded AZ31B magnesium alloy joints were investigated and the following conclusions were derived:

- AZ31B magnesium alloys were successfully joined without any macro level defects under the range of tool rotational speed between 1400 rpm and 1800 rpm and welding speed between 0.4 mm/sec and 0.6 mm/sec.
- Moreover, the joint fabricated with the welding speed of 0. 5 mm/sec, tool rotational speed of 1600 rpm and axial force of 4 kN showed higher tensile properties, compared to their counterparts of AZ31B Mg alloy.
- The absence of defects in nugget region, presence of very fine equiaxed grains in the nugget region and the formation of more number of subgrains in nugget region are the main reasons for higher hardness and subsequently for the superior tensile properties of the above joints of AZ31B magnesium alloy.

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