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S-N BEHAVIOUR OF FRICTION STIR WELDED AZ31B MAGNESIUM ALLOY JOINTS

***Venkatesan S[1], Rajamani G P[2], Balasubramanian V[3] and Rajakumar S[3]**

[1]Department of Mechanical Engineering, VMKV Engineering College, Vinayaka Missions University, Salem-636 308.Tamilnadu, India.
[2]Rathinam Technical Campus, Madukkarai, Coimbatore-641021.Tamilnadu, India.
[3]Centre for Materials Joining and Research, Department of Manufacturing Engineering,Annamalai University, Annamalai Nagar 608002, India

ABSTRACT

Friction stir welding (FSW) is a relatively new joining technique particularly for magnesium and aluminum alloys that are difficult to fusion weld. In this paper, an excellent friction stir weld of rolled AZ31B magnesium alloy joints were obtained at proper process parameter. The base metal and welded joints of AZ31B were analyzed using on optical microscopy, scanning electron microscopy (SEM), tensile testing, fatigue properties and Vickers microhardness measurements. Fatigue experiment was conducted using computerized servo hydraulic controlled fatigue testing machine (INSTRON-8801). Fatigue strength, fatigue notch factor and notch sensitivity factor were evaluated. Fatigue properties of AZ31B welded joints were evaluated, and it was found that the fatigue strength of AZ31B welded joints is 46Mpa which is approximately 34 % lower than that of the base metal fatigue strength due to friction stir welding process.

Keywords: *Magnesium alloy, Friction stir welding, Fatigue*

1. Introduction

In recent years, most of the researchers are focused on magnesium and its alloys because of their excellent properties such as light weight, high strength-to-weight ratio and high specific stiffness, exceptional dimensional stability, high damping capacity, and high recycle ability[1] and therefore, they have recently been increasing interest as structural materials in many applications, in particular, they are considered to be replacing aluminum alloys with a consequent saving in weight in automotive industries to lower the fuel consumption [2]. Therefore, magnesium and its alloys are considered to be one of the most promising basic materials categories for the 21st century [3]. Conventional fusion welding methods for joining magnesium alloys produce some defects such as porosity and hot crack, which deteriorate their mechanical properties. Magnesium alloys are currently welded using techniques such as gas tungsten arc welding (GTAW) and gas metal arc welding (GMAW) while reasonable welding speeds can be achieved, problems can be experienced such as high welding residual stresses and changes in microstructure resulting from melting and solidification. High purity shielding gases are necessary to prevent weld contamination; magnesium alloys can readily oxidize in the weld zone because of their high-chemical reactivity at high temperatures [4].

Friction stir welding (FSW), a novel solid 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 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 weld joints [5]. Magnesium alloys used as structural components are often subjected to cyclic loading; a deep understanding of their cyclic behaviors is therefore an essential safety requirement. It is necessary to investigate the cyclic loading behavior, especially high cycle fatigue properties.

The majority of the available literature [6-10] are focused on effect of welding processes microstructure, tensile properties of AZ31B and AZ91 magnesium alloys.However there is no literature available on fatigue behavior of friction stir welded AZ31B magnesium alloy joints. Hence, the present investigation was carried out to study the effect of friction stir welding on fatigue properties of AZ31B magnesium alloy joints.

**Corresponding Author - E- mail: thasen_venkat@yahoo.com*

2. Experimental Work

The rolled plates of AZ31B magnesium alloy joints were machined to the required dimensions (300 mm x 150 mm x 6 mm). The chemical composition and mechanical properties of base metal are presented in Table 1a and 1b. Square butt joint configuration was prepared to fabricatethe joints. The surface contamination of the plates to be joined was eliminated chemically cleaned by acetone before welding. The direction of welding was maintained normal to the rolling direction of base plates. A non-consumable, rotating tool made of high carbon steel was used to fabricate FSW joints. The welding conditions and the optimized process parameters used to fabricate the joints are presented inTable 2.

Table 1a.Chemical composition (wt %) of base metal AZ31B magnesiumalloy

Al	Mn	Zn	Mg
3.00	0.18	1.00	Balance

Table 1b. Mechanical properties of base metal AZ31B magnesium alloy

Yield strength (MPa)	Ultimate tensile strength (MPa)	Elongation in a gauge length of 50 mm (%)	Reduction in cross - sectional area (%)	Hardness at 0.05 kg load (Hv)
181	244	14.3	8.43	68

Table 2. Details regarding FSW process parameters and Tools

Rotational speed (rpm)	1600
Welding speed (mm/min)	30
Axial force (kN)	4
Tool shoulder diameter, D (mm)	18
Pin diameter, d (mm)	6
D/d ratio of tool	3
Pin length, L (mm)	5.7
Tool inclined angle in degree	0
Pitch (mm)	1

The welded joints as shown in Fig.2 were sliced using power hacksaw and then machined to the required dimensions as shown in Fig. 3 for preparing fatigue specimens. Hourglass type (smooth) specimens were prepared as shown in Fig.3 (a) from welded joints to evaluate the fatigue life (S-N behaviour). Notched specimens were also prepared as shown in Fig. 3 (b) from welded joints to evaluate the fatigue notch factor and notch sensitivity factor. Procedures prescribed by the ASTM E 466-96 (Reapproved 2002) standard were followed for the preparation of the specimens. Photographs of welded joints of fatigue specimens are displayed in Fig.4a and 4b.

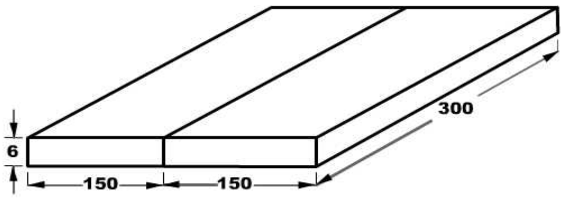
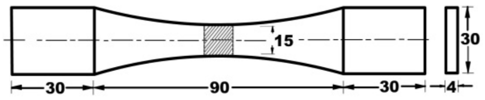
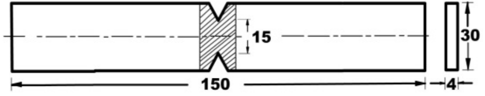


Fig.3 Dimensions of test specimens

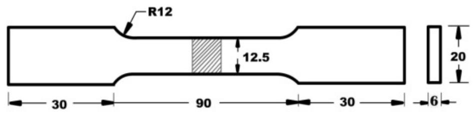
A fully computerized servo hydraulic controlled (make: INSTRON, Model: 8801), 100 kN capacity fatigue testing machine was used to evaluate fatigue life of the welded joints with a frequency of 15 Hz under constant amplitude loading ($R = \sigma_{min}/\sigma_{max} = 0.1$). Fatigue experiment was conducted at five different stress levels (50, 75,100,125 and 150 MPa) for smooth specimen and notched specimen. Tensile specimens were prepared as shown in Fig. 3 (c) to evaluate yield strength, tensile strength and elongation.Tensile test was carried out using a 100 kN, electro-mechanical controlled Universal Testing Machine (Make: FIE-Bluestar, India; Model: UNITEK-94100). The 0.2% offset yield strength was derived from the load-displacement diagram. Vicker'smicrohardness testing machine (Make: Shimadzu, Japan and Model: HMV-2T) was used for measuring the hardness with a 0.05 kg load.



(a) Unnotched fatigue specimen



(b) Notched fatigue specimen



(c) Smooth tensile specimen

Fig.3 Dimensions of test specimens

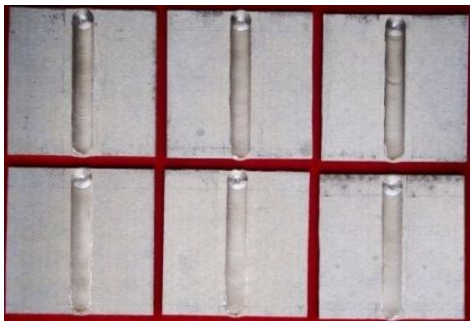
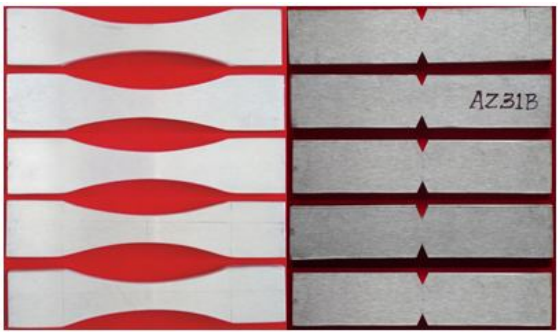
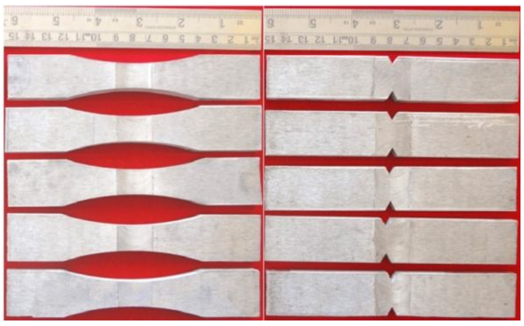


Fig.2 Photograph of fabricated joints using FSW



(a)Unnotched specimen (b)Notched specimen

Fig.4a Photographs of fatigue specimens of base metal



(a)Unnotched specimen (b)Notched specimen

Fig.4b Photographs of fatigue specimens of base metal

The specimens for metallographic examination were sectioned to the required size from the joint comprising weld metal, HAZ and base metal regions and polished using different grades of emery papers. 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 micro and macrostructure. Microstructural analysis was carried out using a light optical microscope (Make: MEIJI, Japan; Model: MIL-7100) incorporated with an image analyzing software (Metal Vision) and scanning electron microscope (JEOL, Japan; Model: 5610LV).

3. Results

3.1 Fatigue Properties

The fatigue test results are used to plot S-N curves as shown in Figs.4 and 5. The S-N curve in the high cycle fatigue region is represented by the Basquin equation [11]

$$S^n N = A \qquad (1)$$

Where 'S' is the stress amplitude, 'N' is the number of cycles to failure and 'n' and 'A' are empirical constants. Each S-N curves shown in Figs.6 and 7 can be represented by the above equation. From those equations, the empirical constants 'n' (slope of the curve) and 'A' (intercept of the curve) were evaluated and they are presented in Table 3.When comparing the fatigue strengths of different welded joints subjected to similar loading, it is convenient to express fatigue strength in terms of the stresses corresponding to particular lives, for example 10^5, 10^6 and 10^7 cycles on the mean S-N curve. The choice of reference life is quite arbitrary. Usually, 2×10^6 cycles has been used, and indeed some design codes refer to their S-N curves in terms of the corresponding stress range [12]. The stress corresponding to 2×10^6 cycles was taken as an indication of the endurance limit and it was evaluated for all the joints and is presented in Table 3.

The effect of notches on fatigue strength is determined by comparing the S-N curves of notched (Fig.7) and unnotched specimens (Fig.6). The data for notched specimens are usually plotted in terms of nominal stress based on the net section of the specimen. The effectiveness of the notch in decreasing the fatigue limit is expressed by the fatigue strength reduction factor or fatigue notch factor, K_f. The fatigue notch factor for all the joints was evaluated using the following expression [13] and they are given in Table 3.

K_f = Fatigue limit of unnotched specimen / Fatigue limit of notched specimen (2)

The notch sensitivity of a material in fatigue is expressed by a notch sensitivity factor 'q' and it was evaluated using the following expression [14]

$$q = (K_f-1) / (K_t -1) \qquad (3)$$

Where K_t is the theoretical stress concentration factor and is the ratio of maximum stress to nominal stress. Using the above expression fatigue notch sensitivity factor 'q' has been evaluated for all the joints and they are presented in Table 3.

3.2 Tensile properties

The transverse tensile properties such as yield strength, tensile strength and percentage of elongation of AZ31B magnesium alloy joints were evaluated to identify the reasons for variation in fatigue performance. In each condition, three specimens were tested and the average of three results is presented in Table 4. The yield strength and tensile strength of AZ31B base meal are 181 MPa and 244 MPa respectively. But the yield strength and tensile strength of AZ31B FSW joints are 168 MPa and 209 MPa respectively, which are 14.3 % reduction instrength values due to FSW process compared to unwelded parent metal.

Elongation and reduction in cross-sectional area of unwelded parent metal are 12.68% and 14.7 %, respectively. The elongation and reduction in cross-sectional area of FSW joints are 10.48 % and 9.36%, respectively, which are 17.4 % lower compared to the parent metal as the joints fabricated by FSW exhibited lower ductility values. Notch strength ratio is the ratio between the tensile strength of notched specimen at maximum load to ultimate tensile strength of unnotched specimen. Notch strength ratio (NSR) is found to be less than unity for all the joints. This suggests that the AZ31B magnesium alloy is sensitive to notches, and they fall in to the “notch brittle materials” category. The NSR is 0.81 for unwelded parent metal, and FSW causes reduction in NSR of the weld metal [15] is 0.78 which is 4% lower compared to unwelded parent metal.

3.3 Hardness and Microstructure

The hardness was measured across the weld using Vicker’smicrohardness testing machine, and the values are presented in Table 4. During fatigue test and tensile test, the failure occurred in the weld region. Hence, the hardness measurement and microstructure analysis were limited to weld region aloneThe hardness of base metal (unwelded parent metal) is 68 Hv. Vicker’smicrohardness is measured along the mid thickness line of cross section of the joint. The joints fabricated by the FSW with optimum process parameter recorded higher hardness (72Hv) in the stir zone as shown in Fig.8 which is 5.55% higher than the base metaldue to grain refinement in FSW zone [16] and this is also one of the reasons for better tensile properties of these 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 compounds are also a benefit to hardness improvement. 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 thermomechanically affected zone (TMAZ) region on the advancing side (Fig. 5),

Table3. Fatigue properties of welded AZ31B magnesium alloy joints

Joint Type	Slope of the S-N curve (n)	Intercept of the S-N curve (A)	Fatigue strength of unnotched specimens at $1x10^6$ cycles (MPa)	Fatigue strength of notched specimens at $1x10^6$ cycles (MPa)	Fatigue ratio (K_f)	Fatigue notch factor (K_f)	Notch sensitivity factor (q)
Base Metal	-0.32	7306	70	30	0.28	2.33	0.054
FSW	-0.37	9948	46	18	0.21	2.55	0.063

Table 4. Transverse tensile properties of AZ31B magnesium welded joints

Joint Type	Yield strength (MPa)	Ultimate Tensile strength (MPa)	Reduction in cross - sectional area (%)	Reduction in cross - sectional area (%)	Notch strength strength (Mpa)	Notch strength ratio (NSR)	Joint Efficiency (%)	Weld region Hardness (Hv)
Base Metal	181	244	14.3	8.43	198	0.81	-	68
FSW	168	209	9.26	6.96	164	0.78	85.6	72

which is consistent with the lowest hardness distribution in the TMAZ of advancing side.

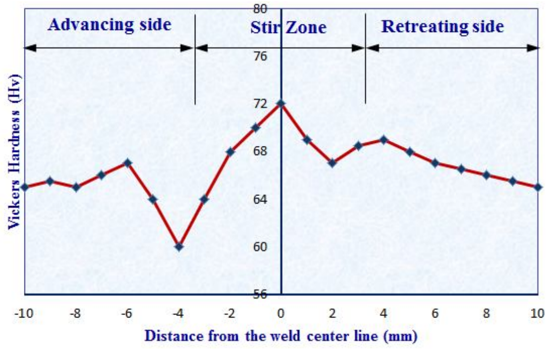
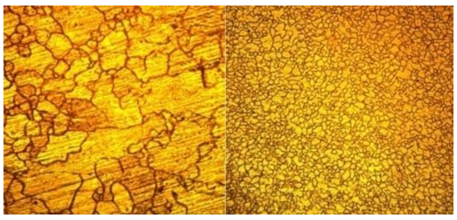


Fig.8 Hardness profile of welded joints

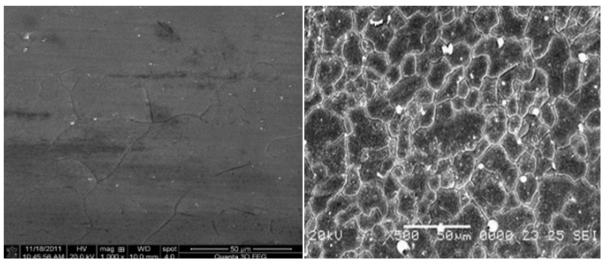
Fig.9 Macrograph of welded joint

Macrostructure of the cross-section of joints are displayed in Fig.9. There is no evidence of macro level defects in all the joints. The optical micrographs of base metal and weld region of FSW joints are shown in Fig.10. From the micrographs, it is evident that fusion zone grains are finer than the base metal due to FSW processes. FSW joint (Fig.10) contains very fine, equiaxed grains in the weld region as compared to base metal due to the dynamic recrystallization that occurred during FSW process[17]. SEM fractographs of fractured smooth fatigue specimens are shown in Fig.12.The base metal and all the joints are fractured in the ductile mode and it is evident from the presence of dimples. The fracture surface of AZ31B welded joint has very fine dimples as compared to the base metal fracture surface. But the shape and size of the dimples are different in all the joints and it is controlled by grain size and precipitates distribution.



(a)base metal **(b)Stir zone**

Fig.10 Optical micrographs



(a)base metal **(b)Stir zone**

Fig.11 SEM micrographs

4. Discussion

The fatigue strength of unwelded AZ31B magnesium alloy is 70 MPa. The fatigue of friction stir welded (FSW) joints is 46 MPa, which is approximately 34 % lower than that of the base metal. Similar tendency has been observed in notched specimens also. Slope of the S-N curve is another measure to understand the fatigue performance of welded joints. If the slope of the S-N curve is larger, then the fatigue life will be higher and vice versa [18]. The unwelded parent metal shows highest slope and the FSW joint shows lowest slope and it is clearly understood from Fig.6.

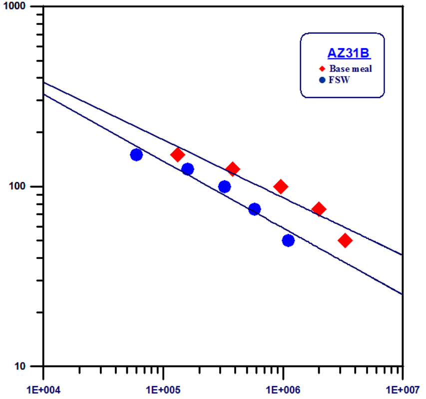


Fig.6 S-N curves for unnotched (smooth) specimen

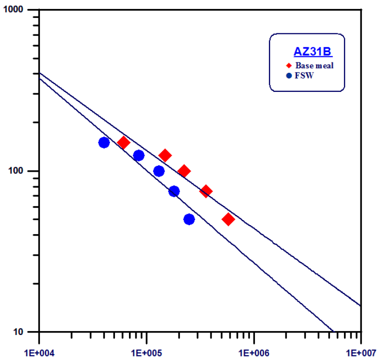


Fig.6 S-N curves for notched specimen

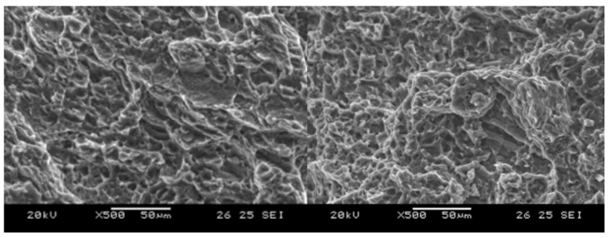


Fig.12 SEM Fractographs of base metal and weld regions

The introduction of notch will alter the stress distribution at the vicinity of notch, the stress value will be magnified nearer to the tip of the notch, and this will have a definite effect on fatigue life of the components [19]. The fatigue notch factor of unwelded AZ31B magnesium alloy is 2.33. But the fatigue notch factor of FSW joint is 2.55. This indicates that there is a8.6% increase in fatigue notch factor value due to friction stir welding. Generally, if the fatigue notch factor is lower, then the fatigue life of the joints will be higher and vice versa [20]. Similar trend has been observed in notch sensitivity factor values also since it is derived using fatigue notch factor values. Slope of the S–N curve is another measure to understand the fatigue performance of welded joints. If the slope of the S–N curve is larger, then the fatigue life will be higher and vice versa.

The unwelded parent metal shows highest slope, the FSW joint shows lowest slope, and it is clearly understood from Fig.6. From the fatigue test results, it is found that the fatigue strength FSW joints have nearly 66% of the base metal fatigue strength.The reasons for the favorable fatigue performance of the FSW joints are: (i) improvedtensile properties of the welded joints, (ii) very fine grains in stir zone, (iii) higher stir zone hardness and (iv) uniformly distributed finer precipitates in the stir zone.

The tensile properties (yield strength, tensile strength and elongation) of AZ31B FSW joints are superior compared to base metal (Table 4). Higher yield strength and tensile strength of the AZ31B FSW joint is greatly used to improve the endurance limit of the joints and hence the fatigue crack initiation is delayed [21]. Larger elongation (higher ductility) of the FSW joints also imparts greater resistance to fatigue crack propagation and hence fatigue failure is delayed. The combined effect of higher yield strength and higher ductility of the FSW joint offers improved resistance to crack initiation and crack propagation and hence the fatigue performance of the joints is superior as compared to the base metal.

The microstructure of fusion zone of FSW joint consists of fine equiaxed grains compared to base metal. Due to fast recrystallization the stir zone is characterized by very fine grains that resulted in increase of hardness.

The stir zone of FSW joint shows traces of fine precipitates, which is not observed in the base alloy. The peak temperature reached in FSW is just sufficient to dissolve the precipitates. Fine grained microstructures relatively contain higher amount of grain boundary areas than coarse grained microstructure and in turn offer more resistance to fatigue crack propagation and this may be one of the reasons for improved fatigue performance of FSW joints. [22].

5. Conclusions

The fatigue behavior of friction stir welded AZ31B Magnesium alloy in comparison with the base metal was investigated and the following conclusions were derived:

The fatigue strength of FSW joint is 70 MPa at 2 × 106 cycles and the reduction in fatigue strength value is approximately 34% compared to the base metal.

The fatigue ratio of the AZ31B magnesium alloy joint was increased by FSW. The FSW joint exhibited slightly lower fatigue ratio value of 0.21 and the reduction in fatigue ratio value is approximately 25% compared to base metal.

The fatigue notch factor and notch sensitivity factor of the AZ31B magnesium alloy joint were increased by FSW. The FSW joint exhibited slightly higher fatigue notch factor value of 2.55 and the increased in fatigue notch factor value is approximately 8.6% compared to base metal.

The improved tensile properties, formation of very fine grains in weld region, higher stir zone hardness and uniformly distributed finer precipitates are the main reasons forthe fatigue strength of FSW jointsreaches66% of that of the base metal fatigue strength.

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