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Influences of Welding Speed on Tensile Properties of Friction Stir Welded AZ61A Magnesium Alloy

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This article reports the influences of welding speed on tensile properties of the friction stir welded AZ61A magnesium alloy. Five different welding speeds ranging from 30 to 150 mm/min were used to fabricate the joints. Tensile properties of the joints were evaluated and correlated with the stir zone microstructure and hardness. From this investigation, it is found that the joint fabricated with a welding speed of 90 mm/min exhibited the acceptable tensile properties compared to other joints. The formation of fine grains in the stir zone is the main reason for the higher hardness and acceptable tensile properties of these joints.

Keywords friction stir welding, magnesium alloy, microhardness, microstructure, tensile properties

1. Introduction

In the automotive and aerospace industries, the need to reduce fuel consumption and associated costs has led to the replacement of heavy components with lighter alloys. One of the potential alloys under consideration is magnesium because it is 35% lighter than aluminum and possesses low density, good machining, and casting characteristics. Furthermore, it has excellent specific strength, high elastic modulus, and good vibration/damping properties (Ref 1). They are also considered as advanced materials in terms of energy conservation and environmental pollution regulations. However, the joining of magnesium alloy parts, which may be crucial for the above applications, is still limited (Ref 2).

Fusion welding of magnesium alloys produces some defects such as porosity and hot crack, which deteriorate their mechanical properties. The production of the defect-free weld requires complete elimination of the surface oxide layer and selection of suitable welding parameters. Although reasonable welding speeds can be achieved, some 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 (Ref 3). Friction stir welding (FSW) is capable of joining magnesium alloys without melting and thus it can eliminate problems related to the solidification. As FSW does not require any filler material, the metallurgical problems associated with it can also be reduced and good quality weld can be obtained (Ref 4).

Even though the process offers many advantages, very limited numbers of investigations were carried out so far on FSW of magnesium alloys. The relationship between material flow and defects formation during friction stir welding of AZ31 magnesium alloy was reported by Zhang et al. (Ref 5). Grain growth and lower hardness in the FSW zone of AZ31B-H24 magnesium alloy were reported by Lee et al. (Ref 6). Wang et al. (Ref 7) observed grain refinement and higher microhardness in FSW zone of AZ31 magnesium alloy. Pareek et al. (Ref 8) investigated the microstructural changes due to friction stir welding of AZ31B-H24 magnesium alloy and analyzed their effect on mechanical properties and corrosion behavior of the joints. They found that the mean grain size across all weld samples was coarser than the mean grain size of the as-received magnesium alloy samples. The influence of different ratios of rotational speed/traverse speed on mechanical properties of different zones of friction stir welded AZ31 magnesium alloy was studied by Abbasi Gharacheh et al. (Ref 9). Esparza et al. (Ref 10) found a recrystallized and equiaxed grain structure in the FSW zone of AZ31B magnesium alloy. The effect of welding speed on the material flow patterns was studied by Hua et al. (Ref 11). They suggested that there are two main material flows in the nugget, one is from the advancing side (flow 1), and the other is from the retreating side; flow 2 decides whether the weld is defect-free or not. Cao et al. (Ref 12) investigated the influence of welding speed on joint quality of friction stir welded AZ31B-H24 magnesium alloy. They concluded that the hardness decreased gradually from the base metal through the heat-affected zone to the thermomechanically affected zone and then to the stir zone where the lowest hardness was obtained. Higher welding speed produced marginally higher hardness in the stir zone.

Kazuhiro et al. (Ref 13) investigated the effect of welding speed and welding speed on the formation of defect in various grades of magnesium alloys. They reported that magnesium alloys with higher aluminum contents are difficult to join without defects and the optimum welding parameters are restricted to narrow region. Park et al. (Ref 14) attempted to

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relate the microstructural and mechanical properties of friction stir welded AZ61 grade magnesium alloy. They found that the tensile properties of AZ61 grade magnesium alloy were sharply influenced by crystallographic orientation distribution as well as by grain size and dislocation density. Du Xing-hao (Ref 15) used friction stir processing technique combined with rapid heat sink to produce ultra-fine grained structure in AZ61 magnesium alloy. He observed that the hardness of FSP region was five times higher than base metal hardness and grain size was reduced to 300 nm. Srinivasan et al. (Ref 16) investigated the stress corrosion cracking behavior of friction stir welded AZ61 grade wrought magnesium alloy. They found that the weld nugget region is quite susceptible to stress corrosion cracking even at a strain rate of 10^{-6} $s^{-1.}$ However, in electrochemical test the weld nugget showed a better corrosion resistance than the base metal.

From the literature review, it is understood that the published information on friction stir welding of magnesium alloys are less in numbers when compared to aluminum alloys. Further, most of the investigations on magnesium alloys were carried out on AZ31 grade (Ref 4-12) which contains 3% aluminum and 1% zinc. Recently, few studies (Ref 13-16) were carried out to evaluate the weld ability of AZ61 grade magnesium alloys. However, the effect of FSW process parameters on mechanical and metallurgical properties of AZ61A grade magnesium alloy has not yet been understood clearly as AZ31 grade magnesium alloy. Only countable numbers of papers are available in the literature on the effect of welding speed of FSW joint properties of AZ61A magnesium alloy. Hence, in this investigation, an attempt has been made to study the effect of welding speed on tensile properties of FSW joints of AZ61A magnesium alloy.

2. Experimental Work

The extruded plates of 6 mm thick AZ61A grade magnesium alloy were used in this investigation. The nominal chemical composition (wt.%) of experimental alloy AZ61A Mg (as received) was; Al—5.96%, Mn—0.17%, Zn—1.28%, and Mg—balance and it has the following mechanical properties: yield strength—217 MPa, ultimate tensile strength—271 MPa, elongation—8.4%, reduction in cross-sectional area—14.3%, and hardness at 0.05-kg load—70 Hv. The friction stir tool made of HCS composed of a pin with a diameter of 6 mm, pin length of 5.9 mm, and a shoulder with a diameter of 18 mm. The tool has a constant rotational speed of 1200 rpm and the travel speed of the tool was varied from 30 to 150 mm/min with an axial pressure of 5 kN. Square butt joint configuration (300 × 300 mm) was used to fabricate the joints. The initial joint configuration was obtained by securing the plates in position using mechanical clamps. The direction of welding was normal to the extrusion direction. Single pass welding procedure was followed to fabricate the joints. Computer numerical controlled FSW machine (Make: R.V. Machine Tools, India; capacity: 60 kN; 3000 rpm) was used to fabricate the joints. Five joints were fabricated in this investigation using five levels of welding speed, keeping other parameters constant.

From each joint, three tensile specimens were extracted from the mid-length of the joint, ASTM E8M-04 guide lines for sheet type material (gauge length 50 mm, width 12.50 mm, and overall length 200 mm) were followed to prepare the specimen. Figure 1 displays the joints and tensile specimen configuration used in this investigation. Smooth tensile specimen was prepared to evaluate yield strength, tensile strength, elongation, and joint efficiency. Notch tensile specimen was prepared was to evaluate notch tensile strength and notch strength ratio. Tensile test was carried out in 100 kN, electro-mechanical controlled universal testing machine (Make: FIE-Bluestar, India; Model: UNITEK-94100). The 0.2% offset yield strength and the percentage of elongation were recorded. Vicker's microhardness testing machine (Make: SHIMADZU, Japan; Model: HMV-2T) was employed for measuring the hardness across the weld region with 0.05 kg load for 20 s of dwell time. The specimens for metallographic examination were sectioned to the required dimensions and then polished using different grades of emery papers. Polished samples were etched with an acetopicral solution (0.4 g picric acid, 13 mL ethanol, 3 mL glacier acetic acid, and 3 mL boiled water) to reveal the microstructure of the welded joints. Macro- and microstructural analysis was carried out using a light optical microscope (Make: MEIJI, Japan; Model: MIL-7100) incorporated with an image analyzing software (Metal Vision). Fracture surface of the tensile specimens were analyzed by Scanning Electron Microscopy (SEM) (make: JOEL, Japan; model: 5610 LV) to reveal the mode of fracture.

3. Results

3.1 Tensile Properties

The transverse tensile properties such as yield strength, tensile strength, notch tensile strength, notch strength ratio, percentage of elongation, percentage of reduction in cross-sectional area, and joint efficiency of friction stir welded AZ61A magnesium alloy joints were evaluated. In each condition, three specimens were tested and the average of three results is presented in Table 1. From the table, it can be inferred that the welding speed is having appreciable influence on tensile properties of welded joints. The load displacement curve of base metal and welded joints are displayed in Fig. 2. The yield strength and tensile strength of base metal are 217 and 271 MPa, respectively. Of the five joints fabricated, the joint fabricated with welding speed of 90 mm/min, axial force of 5 kN, tool rotational speed of 1200 rpm, and heat input of 302 J/mm^1 exhibited higher yield strength of 178 MPa, tensile strength of 224 MPa, elongation of 7.4% and the joint efficiency of 83%. Notch strength ratio (NSR) is found to be less than unity irrespective of the welded joints. This suggests that the AZ61A magnesium alloy is sensitive to notches, they fall on the "notch brittle materials" category. The NSR is 0.92 for unwelded parent metal and FSW causes reduction in NSR of the weld metal. The joints fabricated using a welding speed of 30 mm/min (heat input of 905 J/mm) have shown lower tensile strength and elongation compared to the joints fabricated at a welding speed of 90 mm/min. Similarly, the joints fabricated using a welding speed of 150 mm/min (heat input of 181 J/mm^1) has also shown lower tensile strength and elongation when compared to the joint fabricated at a welding speed of 90 mm/min. To understand the reason for variation in tensile properties of the joints, macrostructure analysis, microstructure analysis, and microhardness measurements were carried out and the results are presented in the following sections.

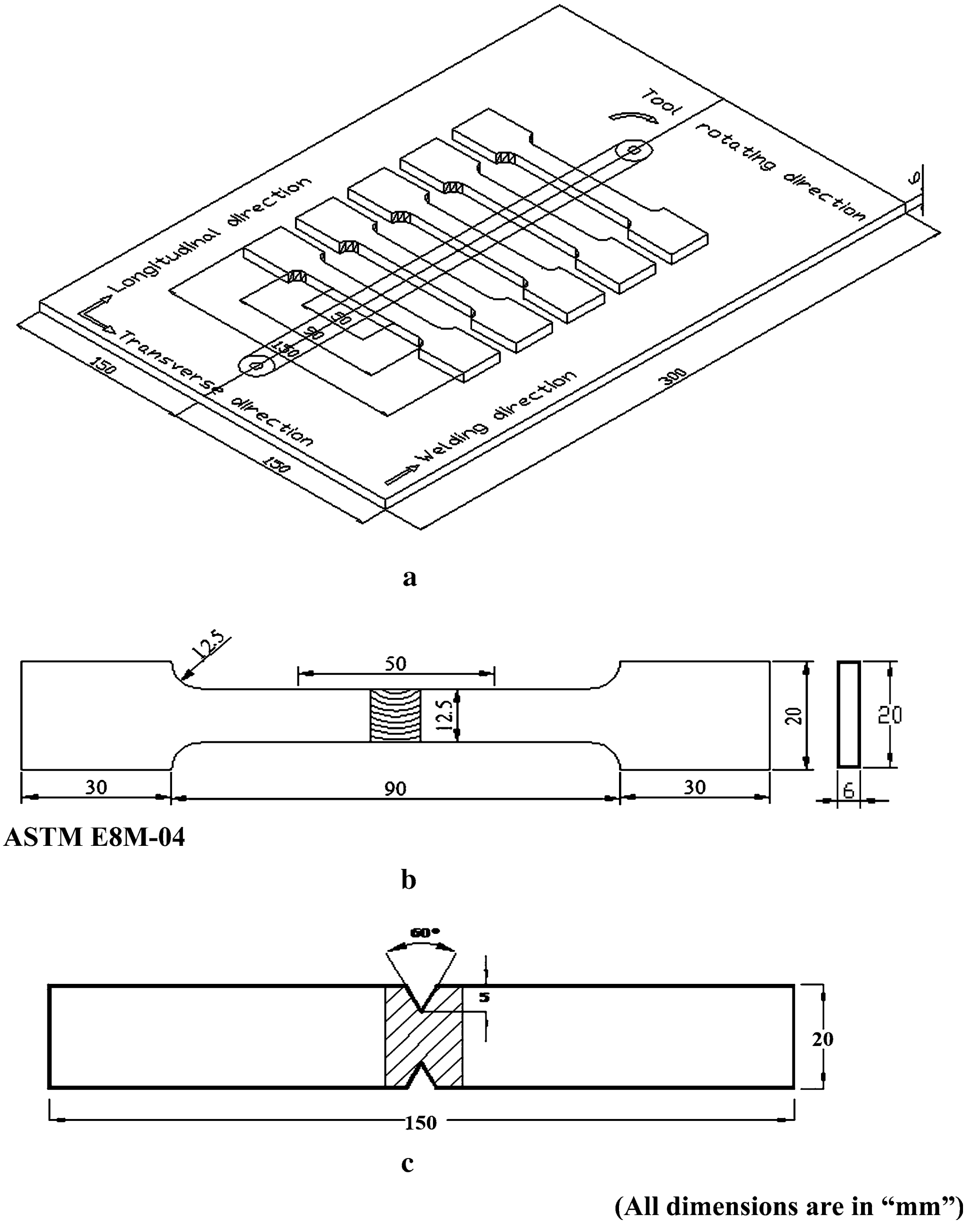


Fig. 1 Joint and tensile specimen configuration. (a) Scheme of extraction of tensile specimen, (b) dimensions of flat tensile specimen, and (c) dimensions of notched tensile specimen (all dimensions are in mm)

Table 1 Effect of welding speed on tensile properties

Welding speed, mm/min	Heat input (a), J/mm	Yield strength, MPa	Ultimate tensile strength, MPa	Notch tensile strength, MPa	Notch strength ratio, NSR	Elongation in 50 mm gauge length, %	Reduction in cross-sectional area, %	Grain size, μm	Joint efficiency, %
30	905	116	146	108	0.73	3.4	2.7	18.0	54.0
60	452	127	157	119	0.75	5.2	3.2	13.5	58.0
90	302	178	224	188	0.84	7.4	5.2	9.0	83.0
120	226	156	191	152	0.79	5.8	4.4	12.0	71.0
150	181	141	174	129	0.74	4.6	3.8	14.2	64.0

(a) The heat input for friction stir welding process was calculated using the following expression (Ref 21): $q = 2\pi/3S \times \mu \times P \times \omega \times R_s \times \eta$, where μ is the coefficient of friction, P is the normal force in kN, ω is the rotational speed in rev/s, R_s is the shoulder radius in m, S is the welding speed in mm/min, η is the efficiency of the process (assumed as 0.8)

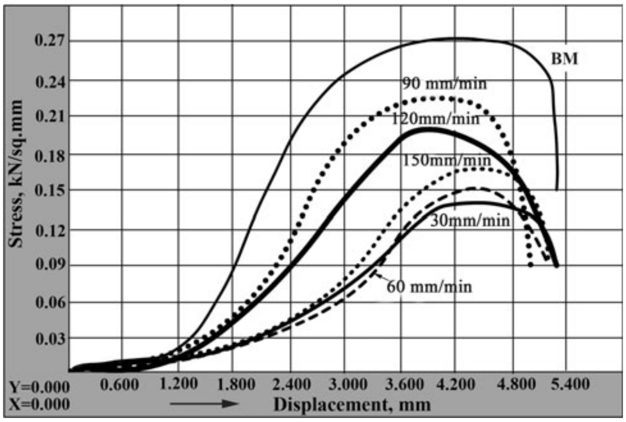


Fig. 2 Load-displacement curve

3.2 Macrostructure

In fusion welding of magnesium alloys, the defects like porosity, slag inclusion, solidification cracks, etc., deteriorate the weld quality and joint properties. Usually, friction stir welded joints are free from these defects since there is no melting takes place during welding and the metals are joined in the solid state itself due to the heat generated by the friction and flow of metal by the stirring action. However, FSW joints are prone to other defects like pinhole, tunnel defect, piping defect, kissing bond, cracks, etc., due to improper flow of metal and insufficient consolidation of metal in the stir zone (sz). The weld cross section of the joints was analyzed at low magnification (5×) using stereo zoom optical microscope and the macrographs are displayed in Table 2. From the macrographs, features like, SZ shape, SZ dimension (height and width), presence of defects was analyzed and they are reported in Table 2. From the macrostructure analysis, it can be inferred that the formation of defect-free FSW welds is a function of optimum welding speed (heat input). From the macrostructure analysis, it is found that the joint fabricated at a welding speed of 90 mm/min yielded spherical-shaped, defect-free stir zone, and this may be one of the reasons for superior tensile properties of these joints.

3.3 Microhardness

Microhardness was measured at mid-thickness region across the weld and the values are presented in Fig. 3. The base metal recorded a hardness of 70 Hv, which is lower than stir zone but higher than TMAZ region. The hardness of the stir zone is considerably higher than that of the base metal irrespective of the welding speed used. There are two main reasons for the improved hardness of stir zone. (i) The grain size of stir zone is much finer than that of base metal, grain refinement plays an important role in material strengthening. According to the Hall-Petch equation, hardness increases as the grain size decreases. (ii) The small particles of intermetallic compounds are also a benefit to hardness improvement, according to the Orowan hardening mechanism (Ref 7). The difference in hardness between the heat affected zone and stir zone is attributed to the grain refinement in the stir zone. The lowest hardness was recorded in the joint fabricated with a welding speed of 30 mm/min at the TMAZ region of advancing side. The joint fabricated with a welding speed of 90 mm/min recorded the highest hardness value of 83 Hv in the stir zone region and this may be one of the reasons for superior tensile properties of this joint.

3.4 Microstructure

The optical micrographs taken at stir zones of all the joints are displayed in Fig. 4. From the micrographs, it is understood that there is an appreciable variation in average grain diameter of the stir zone microstructure. The coarse grains of base metal are changed into fine grains in the stir zone. Hence, an attempt was made to measure the average grain diameter of the stir zone of all the joints by applying Heyn's line intercept method (Ref 17). The joint fabricated with a welding speed of 90 mm/min contains finer grains (9.0 μm) in the stir zone compared to other joints. This may be one of the reasons for acceptable tensile properties of these joints.

Optical micrographs were taken at different regions across the weld but for the comparison purpose, the micrographs of SZ-TMAZ interface regions (AS and RS) are displayed in Fig. 4. There is an appreciable variation in grain size of TMAZ of advancing side and retreating side. The metal pulled (extruded) from advancing side undergoes dynamic recrystallisation (characteristic feature of FSW process) and redeposited on the retreating side and hence the grains are relatively finer in RSTMAZ when compared to ASTMAZ.

The grains in the stir zone are finer than TMAZ. The average grain diameter of TMAZ region is influenced significantly by the welding speed. The grains are relatively finer at TMAZ of the joint fabricated with the welding speed of 90 mm/min (Fig. 4d, f). From the micrographs, it is confirmed that the metal is extruded (pulled) from advancing side during stirring action of rotating tool. Due to this extrusion action grains become elongated in TMAZ when compared to base metal. Of the five joints, the joint fabricated with a welding speed of 90 mm/min contains finer grains in RSTMAZ (Fig. 4c, e) compared to other joints

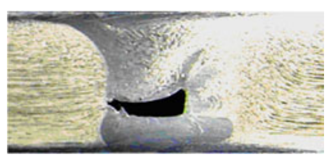
3.5 Fracture Surface Analysis

Figure 4 displays the SEM fractographs of unnotched tensile specimens. All the fractographs invariably contains dimples and hence it is confirmed that all the joints are failed in ductile mode, irrespective of the welding speed (heat input) used to fabricate the joints. However, minor variation in the shape and size of the dimples are observed and this is mainly due to the difference existed in the stir zone microstructure. The fractograph of the joint fabricated at a welding speed of 90 mm/min (Fig. 4g) contains a depression, which is an indication of cup- and cone-type fracture. This type of failure pattern will occur only when the material undergoes uniform deformation. The uniform deformation in FSW joint is possible only when the stir zone is free from macrolevel defects. These may be the reason that the joint fabricated at a welding speed 90 mm/min exhibited required tensile properties.

4. Discussion

The yield strength and tensile strength of all the joints are lower than that of the base material, irrespective of the welding speeds used to fabricate the joints. Of the five welding speeds used to fabricate AZ61A magnesium alloy joints, the joint fabricated at a welding speed of 90 mm/min yielded good

Table 2 Macrostructure analysis

Welding speed, mm/min	Heat input, J/mm	Macrostructure (AS … RS)	Size of FSP zone, mm W	Size of FSP zone, mm H	Shape of FSP zone	Name of the defect and location	Quality of weld metal consolidation	Probable reasons
30	905		12.4 6.7 5.2	5.9	Inverted Trapezoidal	Tunnel at the lower portion of the FSP in advancing side	Hardness: 73 poor	Excess heat input per unit length of the weld and no vertical movement of the metal
60	452		10.0 6.3 5.1	5.9	Elliptical	Tunnel at the middle portion of the FSZ in advancing side	Hardness: 76 poor	Excess heat input per unit length of the weld but lesser than 30 mm/min resulted in tunnel defect at the advancing side.
90	302		8.0 4.6 5.2	5.9	Spherical	No defect	Hardness: 84 good	Adequate heat input due to optimum welding speed
120	226		7.8 4.2 4.6	5.8	Cylindrical	Tunnel at the lower portion of the FSP in advancing side	Hardness: 80 poor	Insufficient heat input due to increased welding speed causes inadequate flow of material
150	181		5.2 4.0 4.3	5.8	Partially spherical	Tunnel at the middle portion of the FSP in advancing side	Hardness: 78 poor	Further increases in welding speed resulted in poor plasticization of metal and associated defect

RS, retreating side; AS, advancing side; W, width of the FSP at top, middle, and bottom, respectively; H, height of FSP tensile properties. The above joints showed a maximum joint efficiency of 83% when compared to other joints. The joints fabricated using the welding speeds lower and higher than these values, exhibited comparatively inferior tensile properties and the reason are explained in the following paragraphs.

When the welding speed is slower than a certain critical value, the FSW can produce defect-free joints. When the welding speed is faster than the critical value, welding defects can be produced in the joints. The defects act as a crack initiation site during tensile test. Therefore, the tensile properties and fracture locations of the joints are determined by the welding speed (Ref 18).

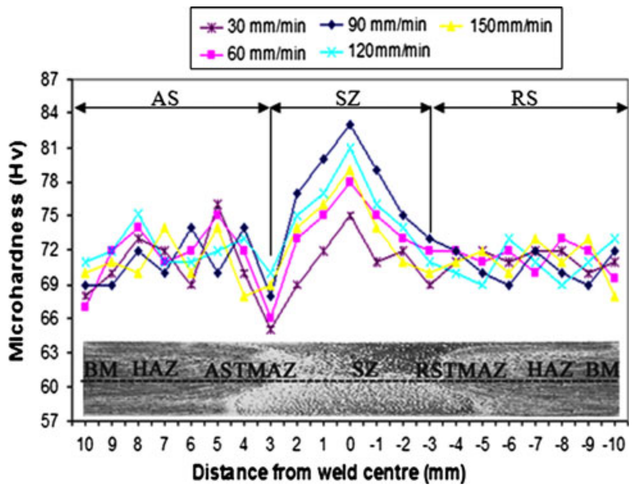


Fig. 3 Effect of welding speed on microhardness

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-plasticised state with a suitable temperature, and to generate a high hydrostatic pressure along 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 welding speed of the tool pin and the pressure applied to the welding tool head shoulder (Ref 19).

The tensile properties and fracture locations of the joints are to a large extent, dependent on the welding speed and other parameters. When the joints are associated with defects like pinhole, tunnel, and cracks in the stir zone, the joints failed at the defective area and if the joints are defect-free, the failure locations shifted to lowest hardness zone. Macrostructure observations (Table 2) showed that the joints fabricated at lower rotational speeds (30, 60 mm/min) contained defects like tunnel or piping defect in stir zone and resulted in lower tensile properties. On the other hand, joints fabricated at welding speeds (120, 150 mm/min) contained smaller size tunnel or pin hole in the stir zone and resulted in inferior tensile properties.

As welding speed increased, the heat input per unit length of the joint decreased, resulting inferior tensile properties due to

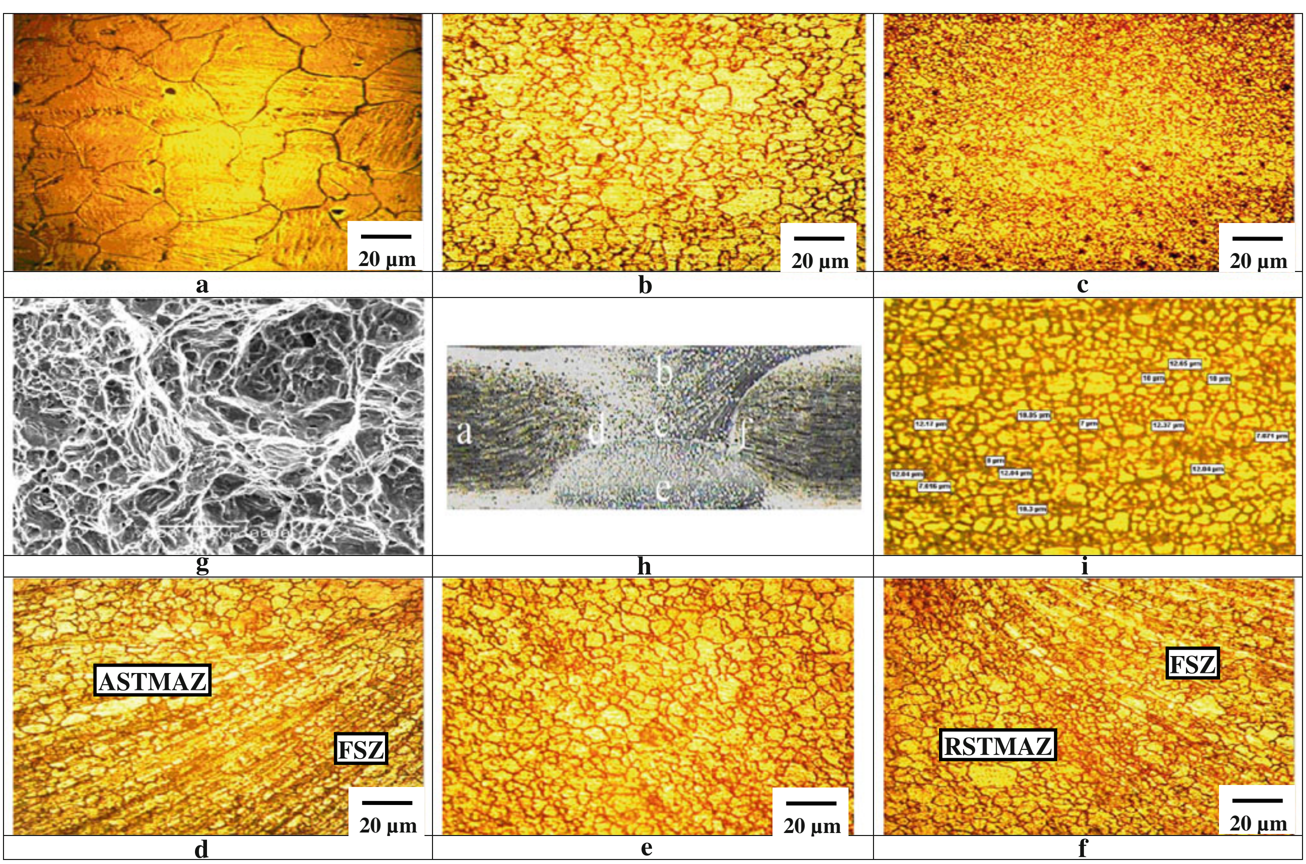


Fig. 4 Micrographs of defect free joint fabricated at a welding speed of 90 mm/min. (a) Base metal, (b) stir zone—top side, (c) stir zone—centre, (d) interface—advancing side of 90 mm/min, (e) stir zone—bottom side, (f) interface—retreating side of 90 mm/min

lower in temperature, which causes the regular flow behavior available at higher speed, is also observed. Higher welding speed results in lower heat input per unit length of the weld, causes lack of stirring in the friction stir processing zone, which may lead to lower tensile properties of the joints. In general friction stir welding at higher welding speeds results in short exposure time in the weld area with insufficient heat and poor plastic flow of the metal and causes some microvoids in the joints. It seems that these microvoids formed due to poor consolidation (due to lack of stirring) of the metal interface when the tool travels at higher welding speeds.

Lower welding speed (30 mm/min) results in higher temperature and slower cooling rate in the weld zone causes excessive grain growth, which subsequently may lead to lower tensile properties of the joints (Ref 20). The joint fabricated at a welding speed of 90 mm/min exhibited higher tensile strength and this may be due to adequate heat generation that is exactly sufficient to cause the material to flow plastically with appropriate mechanical working under this condition.

The temperature during FSW is recorded by inserting K-type thermocouple at the back side of the plate (at the weld center line) for five different welding speed conditions. The heat input during friction stir welding process was calculated and correlated using the equation mentioned in Ref 21. The recorded temperature profile is presented in Fig. 5(a). From the temperature profiles, the peak temperature (maximum temperature) attained was noted down and it is related with welding speed as shown in Fig. 5(b) The measured values of average grain diameter of the friction stir processed region of each joints is related with the welding speed as shown in Fig. 5(c). The resulting grain size is in accordance with the operation temperature as mentioned in Chang et al. (Ref 22) and Gerlich et al. (Ref 23). The relationship between the resulting grain size and the applied working strain rate and temperature for the friction stir welded AZ61A Mg alloy joints is systematically examined and an integrated constitutional equation was developed. The Zener-Holloman parameter is utilized in rationalizing the relationship and it was found that the relationship is followed the equation $\ln d = 9.0 - 0.27 \ln Z$ as shown in Fig. 5(d). The peak temperature rise during FSW is traced at the beginning, middle and at the end of the welded joints at the back end of the plate. The peak temperature can be varied between 350 and 475 °C depending on the welding speed. Moreover, the resulting grain size should be in accordance with the operation temperature and strain rate for this Mg alloy AZ61A. We have plotted a graph between the grain size and the peak temperature of the welding thermal cycle as shown in the Fig. 5.

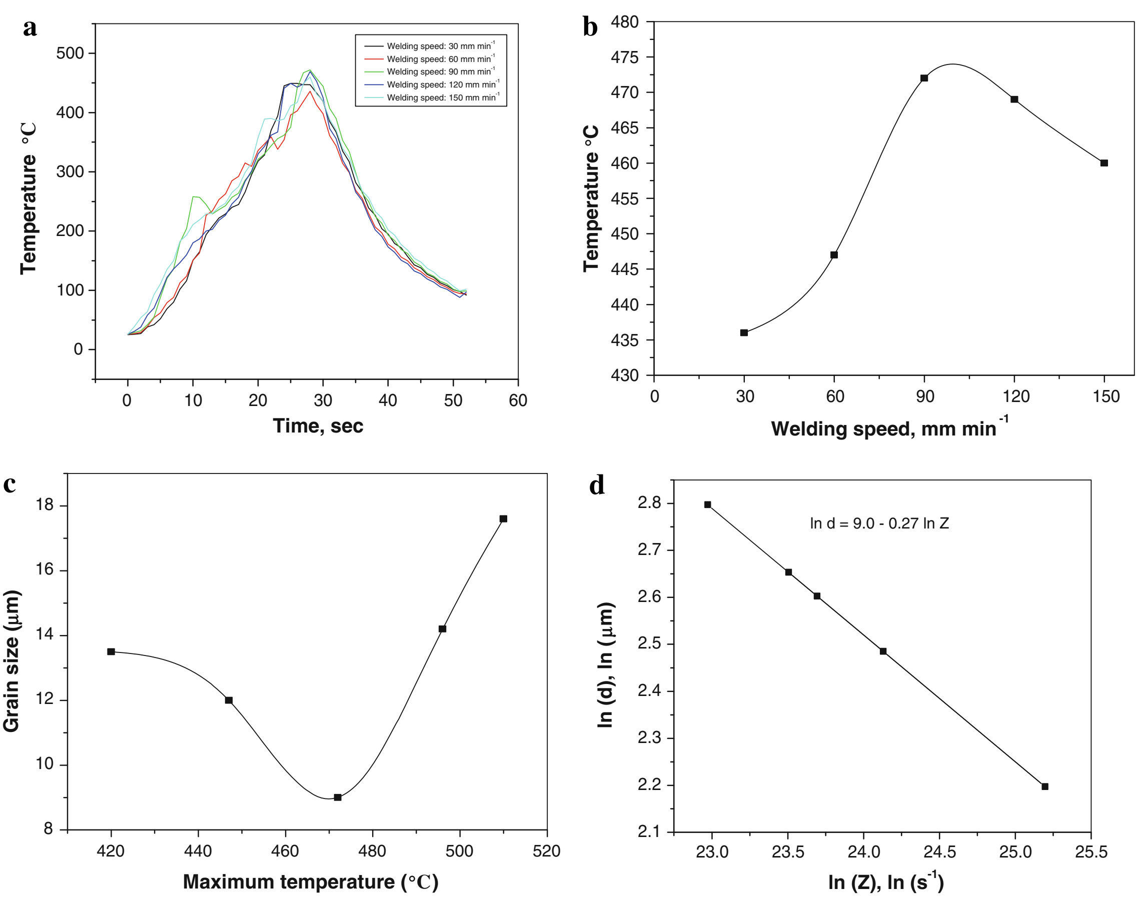


Fig. 5 Relationship between peak temperature, grain size vs. welding speed. (a) Temperature vs. time for different welding speeds, (b) peak temperature vs. welding speed, (c) grain size vs. peak temperature for different welding speeds, (d) resulting grain size vs. Zener-Holloman parameter

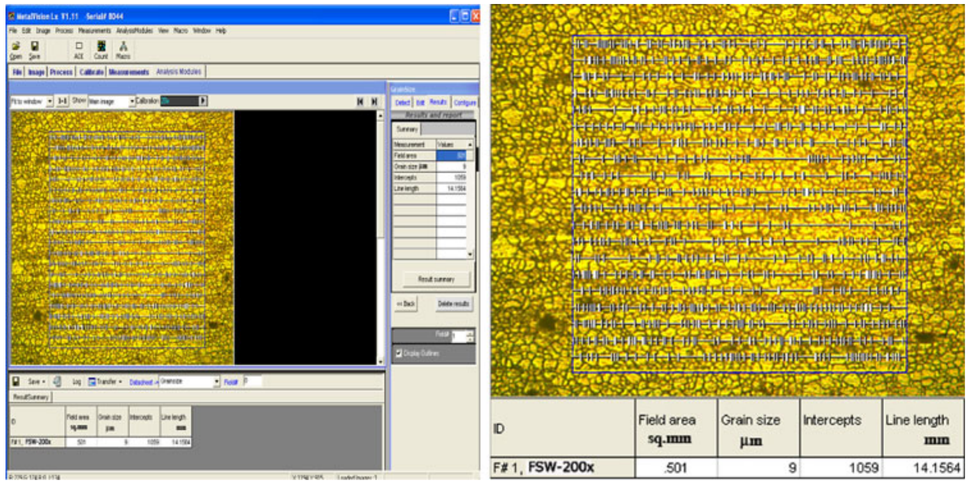


Fig. 6 Measure the overall grain size using line intercept method for welding speed 90 mm/min using computer image analyzing software

The overall grain size was measured using line intercept method in the as received base metal and friction stir welded region of the joints using image analyzing software available in the optical microscope. It was explained in Fig. 6.

The extruded 6 mm AZ61A Mg alloy parent material plate is used in, "as-received" condition and the initial grain size was in an unrecrystallized state without annealing but it may be naturally aged. The 17% reduction of weld efficiency in the 90 mm/min sample is due to microdefects and inhomogeneous material property because the base material is an extruded alloy. During the friction stir welding, no defect is observed either in the beginning or at the final part of the weld, while in the middle there is a microdefect at the cross section (transverse section) due to uneven material flow and volume deficiency, since the base material is an extruded plate with inhomogeneous or heterogeneous microstructure. In order to eliminate this defect, to attain the 100% weld efficiency, the base material AZ61A Mg alloy may be cold rolled after extrusion or annealed to remove the uneven hardness and residual stresses in the parent material.

5. Conclusions

In this investigation, influences of welding speed on tensile properties of friction stir welded AZ61A magnesium alloy joints have been analyzed. From this investigation, following important conclusions are derived:

(i) Welding speed has significance influences on the formation of defects in stir zone, grain size of stir zone, hardness of stir zone, and subsequently tensile properties of friction stir welded AZ61A magnesium alloy joints.

(ii) The joints fabricated with a welding speed of 90 mm/min, rotational speed of 1200 rpm and axial force of 5 kN exhibited a maximum tensile strength of 224 MPa (83% of base metal) compared to other joints. The formation of defect-free stir zone and finer grains at the stir zone under these welding conditions are responsible for higher hardness and higher tensile strength.

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