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ORIGINAL ARTICLE

Microstructural and Mechanical Behaviour Evaluation of Mg-Al-Zn Alloy Friction Stir Welded Joint

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ABSTRACT – The weight reduction concept is most effective to reduce the emissions of greenhouse gases from vehicles, which also improves fuel efficiency. Amongst lightweight materials, magnesium alloys are attractive to the automotive sector as a structural material. Welding feasibility of magnesium alloys acts as an influential role in its usage for lightweight prospects. Friction stir welding (FSW) is an appropriate technique as compared to other welding techniques to join magnesium alloys. Field of friction stir welding is emerging in the current scenario. The friction stir welding technique has been selected to weld AZ91 magnesium alloys in the current research work. The microstructure and mechanical characteristics of the produced FSW butt joints have been investigated. Further, the influence of post welding heat treatment (at 260 °C for 1 h) on these properties has also been examined. Post welding heat treatment (PWHT) resulted in the improvement of the grain structure of weld zones which affected the mechanical performance of the joints. After heat treatment, the tensile strength and elongation of the joint increased by 12.6 % and 31.9 % respectively. It is proven that after PWHT, the microhardness of the stir zone reduced and a comparatively smoothened microhardness profile of the FSW joint obtained. No considerable variation in the location of the tensile fracture was witnessed after PWHT. The results show that the impact toughness of the weld joints further decreases after post welding heat treatment.

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INTRODUCTION

High specific strength, ductility, and low density of magnesium (Mg) alloys enhance its importance as a lightweight material in construction [1], transportation [2] and aerospace industries [3]. But, the scarcity of potential welding techniques is an obstacle in using Mg alloys for the industries [4]. The broad application and subsequent scopes encouraged researchers to explore the welding feasibility of such alloys. Mg alloys can be welded using arc welding [5], resistance spot welding [6], electron beam welding (EBW) [7] and laser welding [8]. However, the joints fabricated by these conventional welding processes were of poor quality and had some defects like-hot cracks, residual stress, partial melting, porosity [9]. Such inferior joints obstructed the applications of these alloys in the industries [10]. To avoid these associated issues, FSW seems the best alternative for welding the lightweight alloys, including Mg alloys [11].

FSW was invented by The Welding Institute, United Kingdom in 1991 as a solid-state welding process, and it has been found more appropriate to weld Mg alloys [12, 13]. Initially, FSW was used to weld aluminium alloys, but nowadays, it is also used to weld Mg alloys, steels, and other lightweight metals [14, 15]. FSW is capable of fabricating Mg alloys joint in solid-state and also eliminates the associated metallurgical problems [16]. FSW has many metallurgical, environmental, energy, safety advantages, along with better mechanical characteristics than the other welding technique [17]. It is used in shipbuilding, construction, aerospace, automobile, railway and many more industries [18–20]. In FSW, the rotating tool having specially designed pin [21] inserted into the abutting edges of workpiece and traversed to produce the joint [22]. During welding, the frictional heat, produced between the rotating tool surface and the surface of the metal sheet, is responsible for the plastic deformation of the workpiece material [22, 23]. This localised heat softens the material around the tool pin. At the earlier stage of this soften material, the combined role of tool rotation and transverse lead made the materials to move toward the back of the tool pin from the front of the tool pin [24]. In this way, the joint is fabricated in solid-state [25]. In FSW, tool rotation speed, tool transverse speed, welding direction, applied axial force, the material of tool, and tool design/geometry are key process parameters that affect the quality of the weld joint [26].

Many researchers have been reported FSW of magnesium alloys and tried to make a good attempt to explore the applications of magnesium alloys in industries. In this work, AZ91 magnesium alloys have chosen due to its better industrial importance. Earlier, Kadigithala and Vanitha [27], Lee et al. [28], and Kouadri-Henni and Barrallier [29] have studied friction stir welded joint of AZ91D magnesium alloy and observed mechanical and microstructural modifications in the various zones of the weld joint whereas, Rouhi et al. [30] and Sevvel and Jaiganesh [23] have reported the FSW joining of AZ91C Mg alloys. Some researchers including Patel et al. [31], Zhang and Wan [32] and Nakata [33] also

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investigated on FSW joint of AZ91 Mg alloys and inferred the influences of various process parameters on quality as well as properties of joints. Though FSW joints are of good quality with low-distortion, Singh et al. [34] reported that during the fabrication of joint, certain residual stresses might be induced in the joint. These residual stress induced in FSW joint due to large deformation of material that affects the properties of the joint [35, 36]. These induced stress and variations in the microstructure of weld reduce the strength of the joint. These losses can be reduced or recovered to some extent by following means: 1) selection of proper welding method, 2) welding process parameters, 3) controlling of the tool penetration ratio and, 4) post welding heat treatment. Post welding heat treatment (PWHT) is more appropriate to restore the strength and enhance the performance of the joints [37]. The critical review of the existing literature revealed that Mg alloys have a broad scope in automotive industries and FSW is comparatively suitable to weld these alloys. Furthermore, PWHT process might be capable to improve the FSW joint performance, and information on PWHT of FSW joints of Mg alloys is still inadequate. Therefore, FSW was selected to weld AZ91 Mg alloy further PWHT of weld joints was carried out. The aim of the investigation was identification of the effects of post welding heat treatment on FSW joints of AZ91 Mg alloy via destructive and nondestructive testing methods and microstructural analysis.

EXPERIMENTAL PROCEDURE

The Mg-Al-Zn alloy (AZ91) sheets of 4 mm thickness were used. The chemical compositions of the substrate metal are listed in Table 1. The plates (150 mm × 50 mm) of base material (BM) AZ91 Mg alloy were cut for butt joint configuration, see Figure 1(a) and 1(b). The workpieces were cleaned with acetone to remove surface contamination. A fixture in Figure 2 was used to fix the workpieces on the machine bed.

Table 1. Chemical composition of AZ91 Mg alloy base metal.

Element	Al	Mn	Zn	Mg
mass fraction, %	8.91	0.42	0.69	Bal.

In FSW, the tool material and design have a vital role in attaining superior microstructure and mechanical properties [38]. The quality and appearance of the joint are highly influenced by the tool material [39]. The porosity can be eliminated by the left-hand threaded tool pin with clockwise turning [40]. For material flow during FSW, a tri-fluted or triangular tool pin is better than a cylindrical pin [41]. Therefore, a tool of H13 steel having a tri-fluted pin with the left-hand threaded was used to produce the joint, see Figure 1(c). H13 is a hot worked chromium tool steel, can be used at higher temperatures. Tool pin with 6 mm diameter and 3.8 mm length was prepared for experimentation, and special design with straight tri-flutes also provided. The shoulder diameter was kept at 18 mm (D/d=3; where D is shoulder diameter, d is pin diameter). In FSW procedure, single-pass welding was performed, and the optimised values of process parameters reported by Ratna Sunil et al. [42] were taken (i.e., tool rotational speed of 1400 rpm and 25 mm/min transverse feed rate). A CNC milling centre was used to perform the FSW process. The fabricated joint is represented in Figure 1(d).

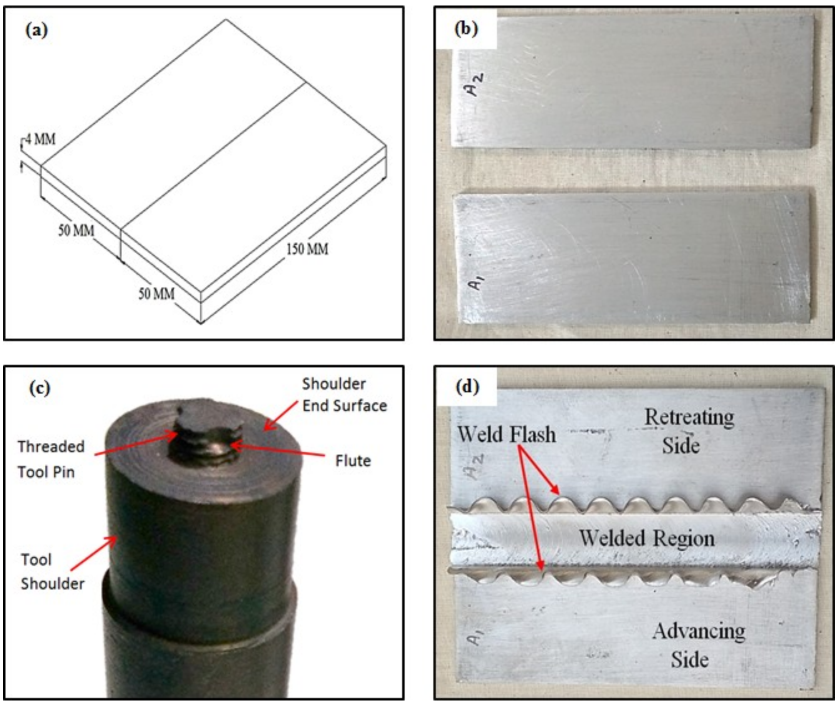


Figure 1. (a) A schematic diagram with plate dimensions used in FSW, (b) Mg alloy plates used for preparing joint, (c) tri-fluted FSW Tool, (d) joint prepared using FSW technique.

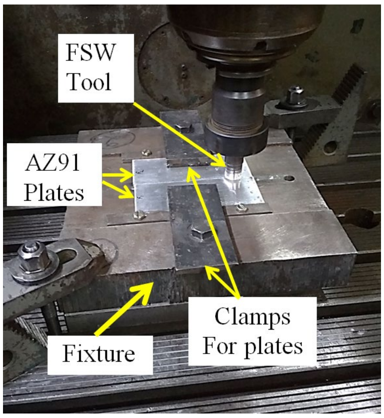


Figure 2. The fixture arrangement of workpieces on machine.

Post Welding Heat Treatment

Post welding heat treatment is a controlled practice in which a welded joint is reheated to a temperature (i.e., below its lower critical transformation temperature) and then kept at the same temperature for the specified holding time and followed by a specific cooling process [43]. The welded plates of AZ91 Mg alloys were reheated in an electric oven to a temperature of 260 ºC for a soaking time of 60 minutes. After that, the plates were remained in the oven to cool down to room temperature. The temperature range and span for PWHT were taken from the ASM handbook [44]. No heat treatment was applied to as-welded samples, and characterisations were evaluated directly.

Microstructural Evaluation

The metallurgical specimens were prepared using a specific process. The specimens were prepared on a rotating disc machine using various grades of SiC papers in the sequence of 400, 600, 1000, 1500 and 2000 and followed by the diamond paste polishing with ethanol as a lubricant. The etching was conducted by immersing the polished specimens in Acetic-picral solution (50 ml ethanol, 5 ml water, 2.5 ml acetic acid, 3 g picric acid) for 15–20 s. Microstructural characterisation of specimens has been performed using optical microscope.

Mechanical Property Evaluation

Tensile test samples were cut with a gauge length of 25 mm and a width of 6 mm as per ASTM E-8M specifications. The tensile specimen with standard dimensions is shown in Figure 3. An electro-mechanical controlled universal testing machine (UTM) was used to carry out the tensile testing. The crosshead speed was set at 1.5 mm/min to carry out the tensile tests. Three specimens in each condition of base metal, heat-treated base metal, as-welded joint and PWHT joint were used for tensile tests; the average results were taken for discussion.

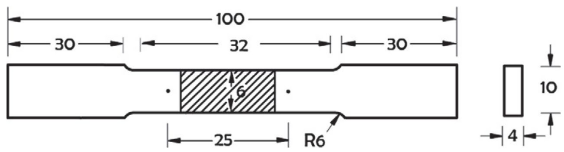


Figure 3. ASTM E-8M specifications of the tensile specimen.

Microhardness test was carried out by Vickers indentation method on Wilson Instruments Minuteman microhardness tester by applying 100 g load for 10 seconds as per ASTM E-384 along the mid-thickness line of the cross-section of the weld. Charpy toughness test was performed on a pendulum-type impact testing machine at room temperature. The Charpy specimen, prepared as per the ASTM E23-06 specification, is shown in Figure 4. The impact toughness of the weld joint was evaluated at the stir zone (the centre of the joint).

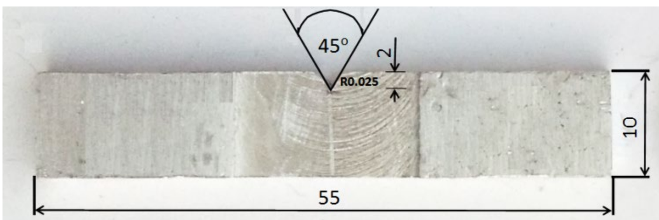
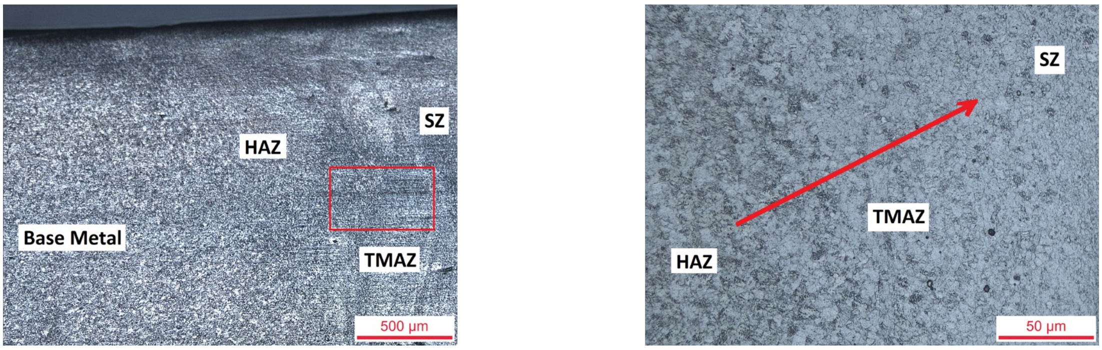


Figure 4. Charpy test specimen prepared as per the ASTM E23-06.

RESULTS AND DISCUSSION

Microstructure

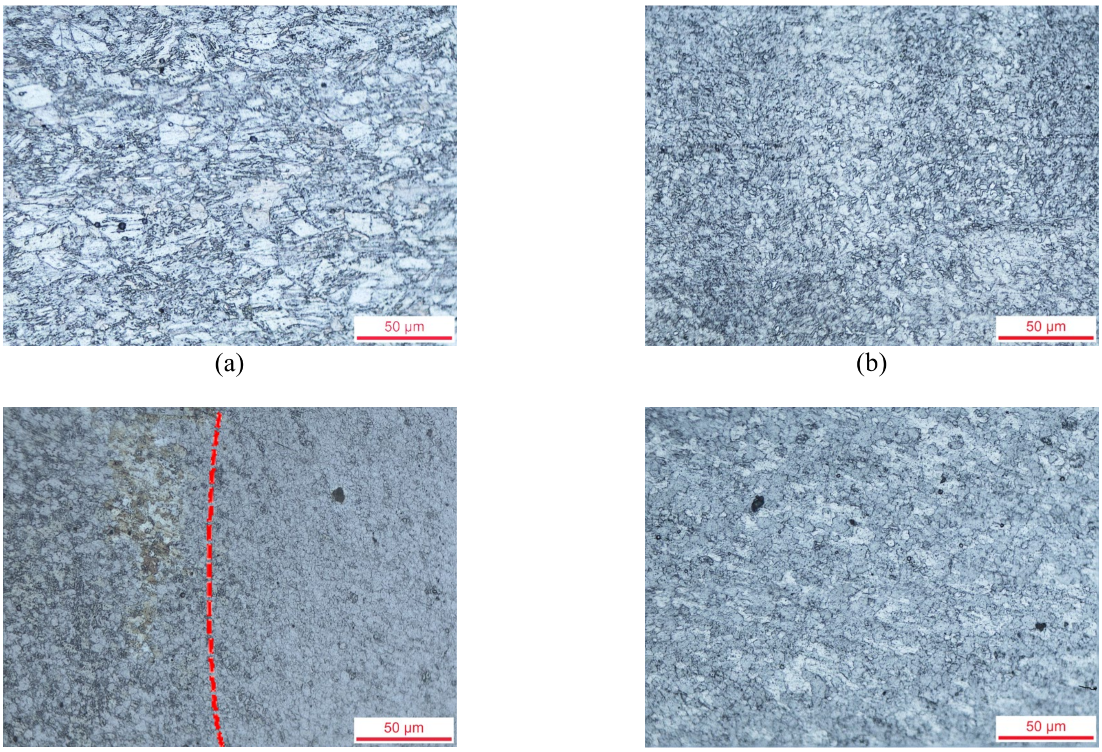
Welds joint of good quality and free from any defect were obtained. The weld joints prepared by FSW consist of stir zone (SZ), thermo-mechanically affected zone (TMAZ), and heat-affected zone (HAZ), see Figure 5 and 6. In the weld zone, abrupt and relatively smooth transitions were found towards the advancing side (AS) and retreating side (RS) of the joint, respectively. The upper surface of welds was little wider than the lower surface. The upper surface faced severe deformation and frictional heat during the welding process, due to the direct contact of FSW tool shoulder and workpiece [45, 46]. The microstructure of BM consisted of elongated shaped grains with little varying in sizes. The deformation of the metal sheet and partial dynamic recrystallisation caused heterogeneity in BM grain structure [47]. A complex mixture of microstructure observed because each zone experienced a difference of thermal cycles during the welding process and SZ, as well as TMAZ, experienced the deformation as reported by Sullivan and Robson [48]. The variation in grains' shape and size were observed. The change in grains is illustrated in Figure 6(c) by the red dotted line where the grains in the base metal were not affected by the welding. The grains in SZ were observed to be fine equiaxed.



(a) (b)

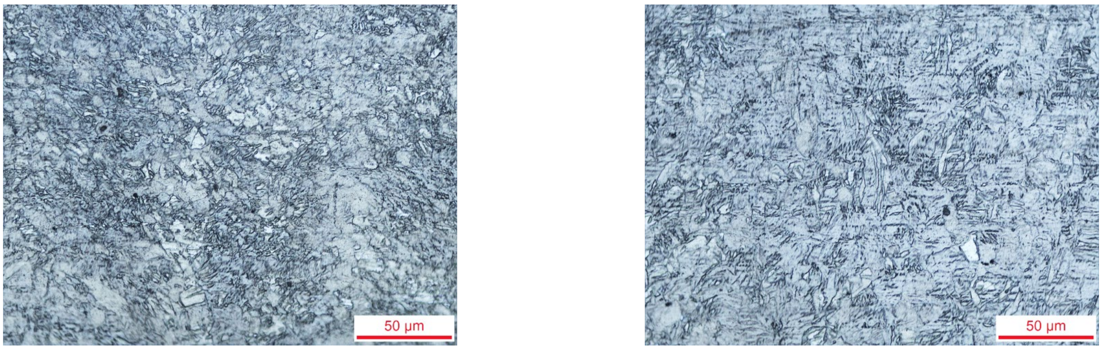
Figure 5. (a) The weld joint showing interfaces of BM, HAZ and SZ; (b) zoom-in views of the red box marked in (a).

The dynamic recrystallisation during the welding process is responsible for the refinement of grains in this zone. Mg alloys experienced dynamic recrystallisation more easily compared to aluminium alloys because of the lower recrystallisation temperature of Mg alloys (about 523 K) as reported by Xunhong and Kuaishe [49]. The TMAZ was mostly composed of equiaxed grains which indicate that complete recrystallisation occurred in this zone during FSW. In the heat-affected zone, equiaxed as well as elongated grains were observed. The existence of the equiaxed grains in this zone indicated that partial recrystallisation of grains had taken place in the zone during the welding process. This was in agreement with the previous results reported by Kulekci [47] and Afrin et al. [50].



(a) (b)

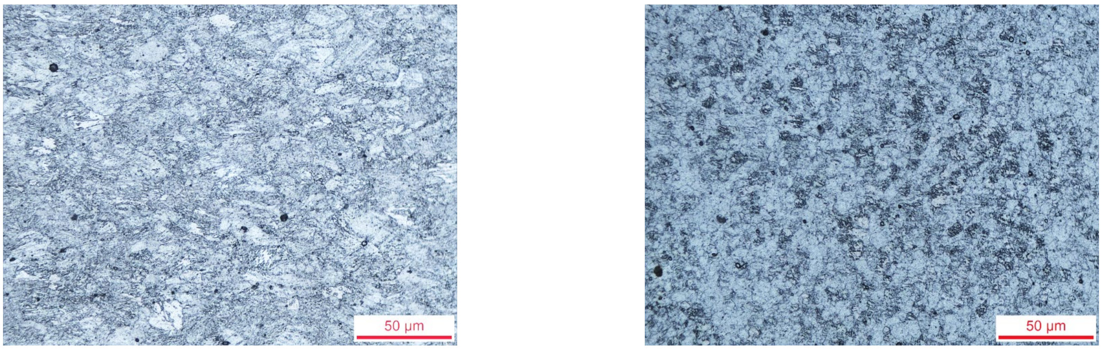
(c) (d)



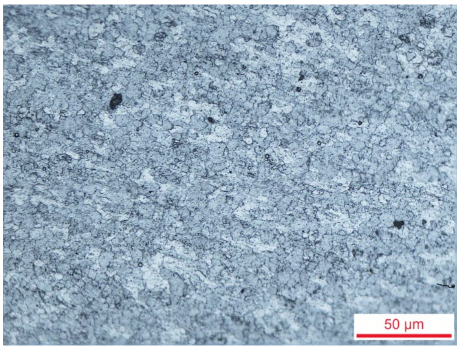
(e) (f)

Figure 6. Different zones of as-welded joint microstructure: (a) BM, (b) SZ, (c) transition zone (AS), (d) transition zone (RS), (e) HAZ (AS) and (f) HAZ (RS).

Figure 7 shows the microstructure of BM, HAZ and SZ of post-weld heat treatment samples of AZ91 Mg alloy. PWHT have influences on the weld joint performance. Mainly, HAZ of the advancing side was taken into consideration for microstructural variation. This zone was the tensile fracture location of the joint. During the PWHT process, static recrystallisation has been accomplished, and the grain size became more homogeneous after PWHT, as reported by Wang et al. [51]. But it has been observed that after post-weld heat treatment, the grain structure in HAZ changed and new grains developed, see Figure 7(b). The variation in grain structure influences the strength of the joint. The formation of new grain in weld zones soften the joint material, which improves the ductility of the joint. This means that the ductile behaviour of the joint increased after PWHT. Similar results of material behaviour after PWHT have been reported for AA2195-T8 Al-Li alloy by Zhang et al. [52].



(a) (b)



(c)

Figure 7. Optical micrographs of (a) BM, (b) HAZ and (c) SZ of PWHT joint.

Tensile Properties

The tensile properties of base metal, heat-treated base metal, as-welded joint and PWHT joint of AZ91 Mg alloys were examined. The tensile samples failed at HAZ of the advancing side in case of the weld and BM specimens failed almost at the centre, see Figures 8(c) and 8(a). Similar observations for the FSW joint were reported by Oztoprak et al. [53] that the as-welded FSW joint was fractured near or at the interface HAZ (AS).

Figure 9 represents the strain-stress curves of BM, as-welded, and PWHT weld joints. Average tensile strength of as-received base metal was 220.2 MPa, and joint fabricated showed a tensile strength of 127.27 MPa. Elongation of the joint was about 6.76 % whereas base material exhibited elongation about 15.76 %. Tensile strength of the joint was 57.79 % of the tensile strength of the base metal. Tensile strength of the as-welded joint was improved by 12.59 % (127.27 MPa to 143.3 MPa) after PWHT, see Figure 10(a). Elongation of the joint was also improved by 31.95 % (6.76% to 8.92%) after heat treatment; Figure 10(b). The heat-treated base metal has a tensile strength of 220.8 MPa which was almost the same as the tensile strength of as-received base metal, but the elongation of base metal was improved about 10% after heat treatment. These results revealed that the heat treatment process enhanced tensile strength and elongation percentage (ductility) of the weld joint as well as the base metal. This improvement in tensile behaviour could be credited to enhancement in the microstructure of joint during PWHT. Similar results have been reported by Singh et al. [34]. For the PWHT specimens, the failure of a tensile specimen of the joints also occurred in the weld zone towards the advancing side; Figure 8(d).

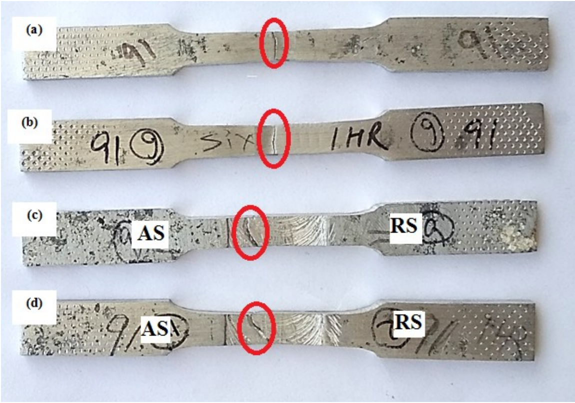


Figure 8. Tensile specimen after testing (a) base metal, (b) base metal heat treated, (c) as-welded joint and (d) PWHT joint.

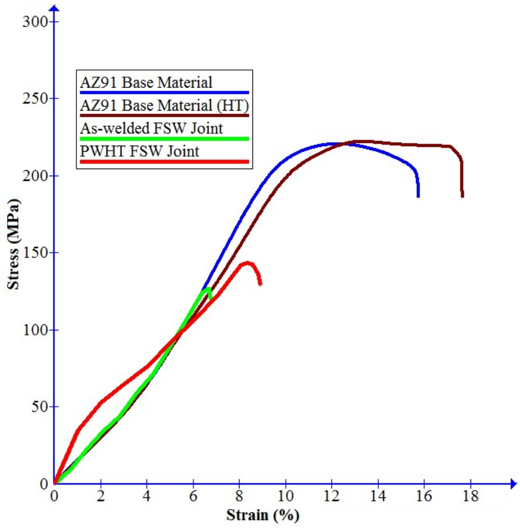
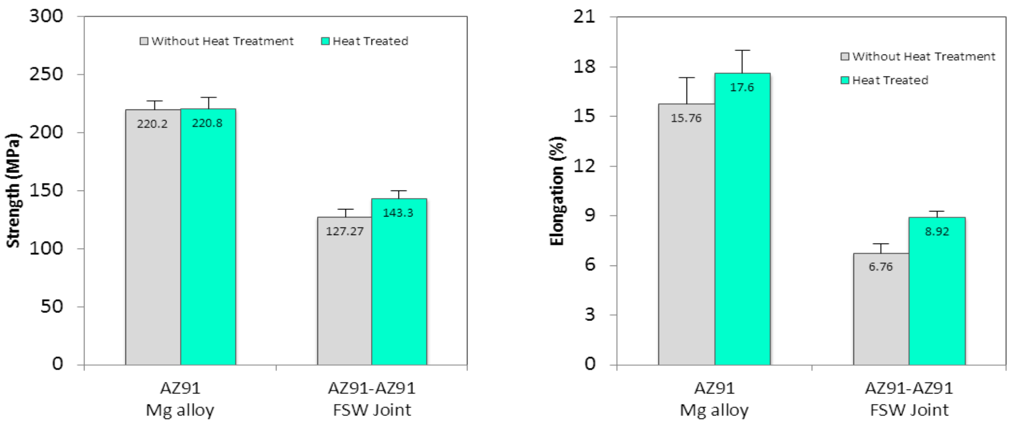


Figure 9. The strain-stress curves of the AZ91 Mg alloy, as-welded and PWHT joint specimens. HT- heat treated.



(a) (b)

Figure 10. (a) Tensile strength and (b) elongation of base metal and FSW joint of AZ91 Mg alloy (before and after heat treatment).

The SEM images of tensile fracture surfaces were represented in Figure 11. The fractured surfaces of BM, FSW joint, and PWHT joint exhibited with dimples. The dimple containing surfaces confirms that the failure mode was ductile. As reported by Wang et al. [51] that the interface HAZ has a lower strength, so, the joint was failed at this HAZ interface of advancing side during tensile testing. The failure of PWHT tensile specimen in HAZ zone confirmed that PWHT had not any influence related to the location of the joint fracture.

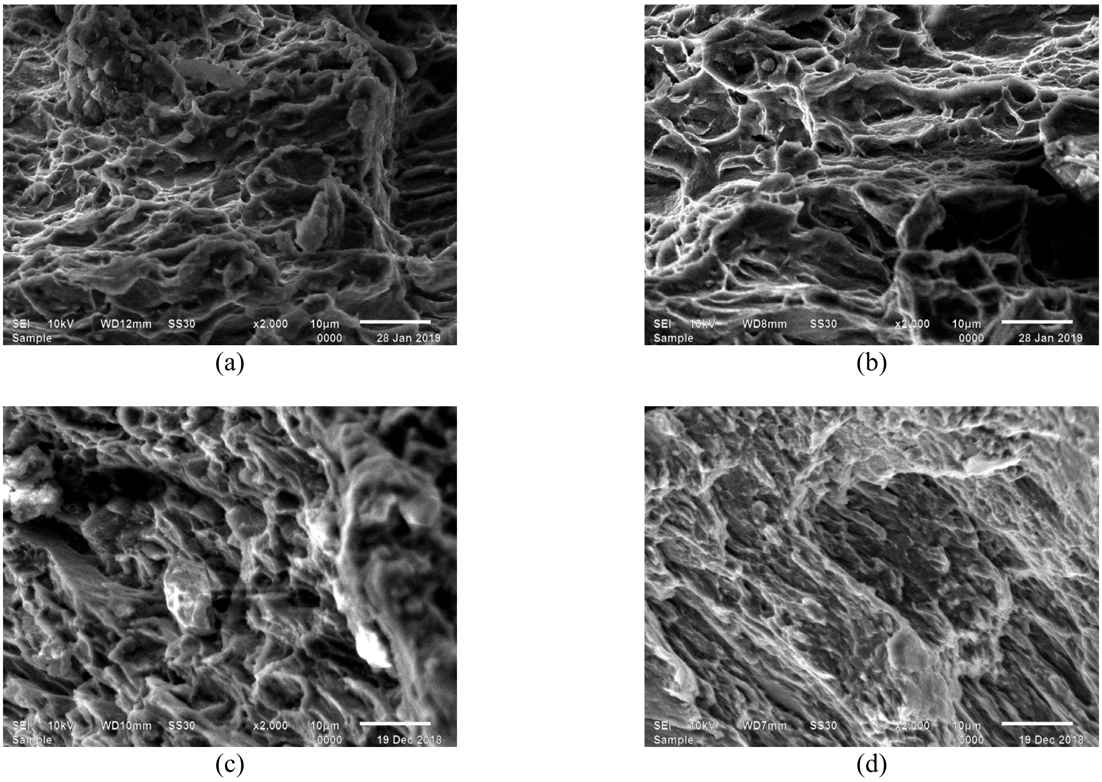


Figure 11. Fractographs of the tensile fracture surface of (a) BM AZ91 Mg alloy, (b) heat-treated BM AZ91 Mg alloy, (c) as-welded joint and (d) PWHT joint.

Microhardness

The as-received BM AZ91 Mg alloy was 66 Hv. SZ exhibited the highest microhardness of about 78 Hv. Advancing side of joint exhibited the lowest microhardness about 60 Hv in HAZ. HAZs have microhardness lower as compared to stir zone and base material. SZ has undergone mechanical deformation and grains were refined and recrystallised during the welding process. Refinement of grains increases the microhardness of joint in SZ [54]. In HAZ, grains became soft due to the influence of heat and microhardness in this zone was reduced. In the advancing side, the spot in HAZ having lowest microhardness was failure location during the tensile test. Similar results have been reported by Han et al. [55]. SZ of PWHT joint has the highest microhardness of about 70 Hv. Advancing side of weld joint exhibited the lowest microhardness about 61 Hv in HAZ. Microhardness of SZ decreased by about 11.11 % (78 Hv to 70 Hv) after heat treatment. Microhardness profile of as-welded and PWHT joint of AZ91 Mg alloy is shown in Figure 12.

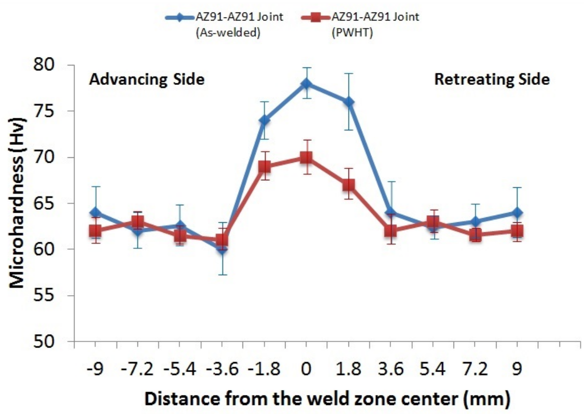


Figure 12. Microhardness profile of FSW joint of AZ91 Mg alloy (as-welded and PWHT).

Impact Toughness

Average impact toughness of FSW joint of AZ91 magnesium alloy was 4.5 J which was 75 % of average toughness of BM. Impact toughness of PWHT joint was 4.2 J. PWHT reduced toughness of FSW joint by 6.6 % (4.5 J to 4.2 J).

Impact toughness of base material AZ91 magnesium alloy was 6 J, which was declined by about 8.3 % after heat treatment. Charpy impact toughness of base metal and FSW joint is presented in Figure 13.

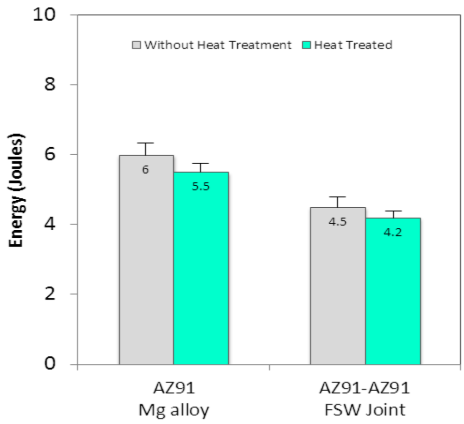


Figure 13. Impact toughness of base metal and FSW joint of AZ91 Mg alloy (as-welded and PWHT).

These results revealed that impact toughness of base metals and friction stir welded joints was reduced after heat treatment. According to Singh et al. [34], ductility (% elongation) of base metal and weld joint was improved after heat treatment, which may be the key reason for the reduction of impact toughness. These results are in contrast with results (for steel) reported by Lu et al. [56] and Wu et al. [57].

CONCLUSION

Based on findings of present work, it can be concluded that friction stir welding can be effectively used to join AZ91 Mg alloys, and further performance of joint can be enhanced by choosing appropriate post welding heat-treatment process. The conclusions are:

i. Mg alloy (AZ91) was welded with FSW, and a quality joint was produced. In a transversal cross-sectional view, the upper surface of the weld appeared wider than the lower surface.
ii. The produced FSW joint has average tensile strength and elongation about 127.27 MPa and 6.76 %, respectively, and the efficiency of the weld joint was 57.7 %.
iii. Post welding heat treatment influenced the microstructure along with the tensile strength of the joint. The tensile strength and elongation improved by about 12.6 % and 31.9 %, respectively after PWHT. PWHT has no effect on the location of the tensile fracture.
iv. Microhardness of SZ was decreased about 11.11 % after PWHT, and relatively smoothened microhardness profile of the FSW joint was obtained.
v. PWHT reduced toughness of FSW joint by 6.6 % whereas toughness of BM was reduced by about 8.3 % after heat treatment.

FUTURE SCOPE

The need in the automotive industries for sophisticated materials tailored to accommodate demands for lightweight structures is an effective driver for further development in the field of FSW and Mg alloys. Some future recommendations are as follows:

i. The material flow, wear of welding tool and microstructural stability are key aspects to commercialise the FSW technology which can be explored for more understanding.
ii. It may also be worthwhile to examine elastic modulus, fatigue strength, corrosion and residual stress in future researches.
iii. Lastly, other post welding heat treatment method could be beneficial attempts. It may be another area of future investigation in order to improve or eliminate the losses of strength and performance of weld joints.

REFERENCES

[1] Pietrzyk M, Kuziak R, Bzowski K, et al. Material characterisation for numerical simulation of manufacturing of automotive part made of magnesium alloy. Archives of Civil and Mechanical Engineering 2020; 20: 6.
[2] Heakal FE-T, Elkholy AE. Smart coatings on magnesium alloys in transportation industries. In: Advances in Smart Coatings and Thin Films for Future Industrial and Biomedical Engineering Applications. Elsevier, 2020, pp. 263–287.
[3] Sahu PK, Pal S. Influence of metallic foil alloying by FSW process on mechanical properties and metallurgical characterisation of AM20 Mg alloy. Materials Science and Engineering: A 2017; 684: 442–455.
[4] He X, Gu F, Ball A. A review of numerical analysis of friction stir welding. Progress in Materials Science 2014; 65: 1–66.
[5] Dong HG, Liao CQ, Yang LQ. Microstructure and mechanical properties of AZ31B magnesium alloy gas metal arc weld. Transactions of Nonferrous Metals Society of China (English Edition) 2012; 22: 1336–1341.

[6] Xiao L, Liu L, Chen DLL, et al. Resistance spot weld fatigue behavior and dislocation substructures in two different heats of AZ31 magnesium alloy. Materials Science and Engineering A 2011; 529: 81–87.
[7] Chi CT, Chao CG, Liu TF, et al. Relational analysis between parameters and defects for electron beam welding of AZ-series magnesium alloys. Vacuum 2008; 82: 1177–1182.
[8] Wang A. A, Xu HGH, Yang P, et al. Nd:YAG laser butt welding of a 12 vol.% SiC particulate-reinforced magnesium alloy composite. Materials Letters 2007; 61: 4023–4026.
[9] Kah P, Rajan R, Martikainen J, et al. Investigation of weld defects in friction-stir welding and fusion welding of aluminium alloys. International Journal of Mechanical and Materials Engineering 2015; 10: 26.
[10] Cizek L, Greger M, Pawlica L, et al. Study of selected properties of magnesium alloy AZ91 after heat treatment and forming. Journal of Materials Processing Technology 2004; 157–158: 466–471.
[11] Mohamed NS, Alias J. The influence of friction stir welding of dissimilar AZ31 and AZ91 magnesium alloys on the microstructure and tensile properties. International Journal of Automotive and Mechanical Engineering 2019; 16: 6675–6683.
[12] Mishra RS, De PS, Kumar N. Friction stir welding and processing: Science and engineering. Cham: Springer International Publishing, 2014. Epub ahead of print 2014.
[13] Singh K, Singh G, Singh H. Investigation of microstructure and mechanical properties of friction stir welded AZ61 magnesium alloy joint. Journal of Magnesium and Alloys 2018; 6: 292–298.
[14] Chen T. Process parameters study on FSW joint of dissimilar metals for aluminum–steel. Journal of Materials Science 2009; 44: 2573–2580.
[15] Kallee SW, Thomas WM, Dave Nicholas E. Friction stir welding of lightweight materials. In: Magnesium Alloys and their Applications. Weinheim, FRG: Wiley-VCH Verlag GmbH & Co. KGaA, 2006, pp. 173–190.
[16] Li Y, Qin F, Liu C, et al. A review: Effect of friction stir welding on microstructure and mechanical properties of magnesium alloys. Metals 2017; 7: 524.
[17] Singh K, Singh G, Singh H. Review on friction stir welding of magnesium alloys. Journal of Magnesium and Alloys 2018; 6: 399–416.
[18] Grimm A, Schulze S, Silva A, et al. Friction stir welding of light metals for industrial applications. Materials Today: Proceedings 2015; 2: S169–S178.
[19] Micari F, Buffa G, Pellegrino S, et al. Friction stir welding as an effective alternative technique for light structural alloys mixed joints. Procedia Engineering 2014; 81: 74–83.
[20] Shtrikman MM. Trends in the development of the friction stir welding process. Welding International 2015; 29: 230–239.
[21] Zhang YN, Cao X, Larose S, et al. Review of tools for friction stir welding and processing. Canadian Metallurgical Quarterly 2012; 51: 250–261.
[22] Ramesh Babu S, Pavithran S, Nithin M, et al. Effect of tool shoulder diameter during friction stir processing of AZ31B alloy sheets of various thicknesses. In: Procedia Engineering. 2014. Epub ahead of print 2014.
[23] Sevvel P, Jaiganesh V. Influence of the arrangement of materials and microstructural analysis during FSW of AZ80A & amp; AZ91C Mg Alloys. Archives of Metallurgy and Materials 2017; 62: 1795–1801.
[24] Lorrain O, Favier V, Zahrouni H, et al. Understanding the material flow path of friction stir welding process using unthreaded tools. Journal of Materials Processing Technology 2010; 210: 603–609.
[25] Sunil BR, Reddy GPK, Patle H, et al. Magnesium based surface metal matrix composites by friction stir processing. Journal of Magnesium and Alloys 2016; 4: 52–61.
[26] Sevvel P, Jaiganesh V. Characterization of mechanical properties and microstructural analysis of friction stir welded AZ31B Mg alloy thorough optimised process parameters. Procedia Engineering 2014; 97: 741–751.
[27] Kadigithala NK, Vanitha C. Investigation on the microstructure and mechanical properties of AZ91D magnesium alloy plates joined by friction stir welding. In: Lecture Notes in Mechanical Engineering. Springer, 2020, pp. 1021–1030.
[28] Lee W-B, Kim J-W, Yeon Y-M, et al. The joint characteristics of friction stir welded AZ91D magnesium alloy. Materials Transactions 2003; 44: 917–923.
[29] Kouadri-Henni A, Barrallier L. Mechanical properties, microstructure and crystallographic texture of magnesium AZ91-D alloy welded by friction stir welding (FSW). Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science 2014; 45: 4983–4996.
[30] Rouhi S, Mostafapour A, Ashjari M. Effects of welding environment on microstructure and mechanical properties of friction stir welded AZ91C magnesium alloy joints. Science and Technology of Welding and Joining 2016; 21: 25–31.
[31] Patel N, Bhatt KD, Mehta V. Influence of tool pin profile and welding parameter on tensile strength of magnesium alloy AZ91 during FSW. Procedia Technology 2016; 23: 558–565.
[32] Zhang Z, Wan ZY. Predictions of tool forces in friction stir welding of AZ91 magnesium alloy. Science and Technology of Welding and Joining 2012; 17: 495–500.
[33] Nakata K. Friction stir welding of AZ91D thixomolded sheet. In: Proceedings of the 3rd international conference on Friction Stir Welding. Japan, 2001.
[34] Singh K, Singh G, Singh H. Microstructure and mechanical behaviour of friction-stir-welded magnesium alloys: As-welded and post weld heat treated. Materials Today Communications 2019; 20: 100600.
[35] Commin L, Dumont M, Rotinat R, et al. influence of the microstructural changes and induced residual stresses on tensile properties of wrought magnesium alloy friction stir welds. Materials Science and Engineering A 2012; 551: 288–292.
[36] Sivaraj P, Kanagarajan D, Balasubramanian V. Effect of post weld heat treatment on tensile properties and microstructure characteristics of friction stir welded armour grade AA7075-T651 aluminium alloy. Defence Technology. Epub ahead of print 2014. DOI: 10.1016/j.dt.2014.01.004.
[37] Lobanov LM, Pashchin NA, Mikhodui OL, et al. Investigation of residual stresses in welded joints of heat-resistant magnesium alloy ML10 after electrodynamic treatment. Journal of Magnesium and Alloys 2016; 4: 77–82.
[38] Padmanaban G, Balasubramanian V. Selection of FSW tool pin profile, shoulder diameter and material for joining AZ31B magnesium alloy - An experimental approach. Materials and Design 2009; 30: 2647–2656.
[39] Singh G, Singh K, Singh J. Effect of process parameters on microstructure and mechanical properties in friction stir welding of aluminum alloy. Transactions of the Indian Institute of Metals 2011; 64: 325–330.
[40] Chowdhury SM, Chen DL, Bhole SD, et al. Tensile properties of a friction stir welded magnesium alloy: Effect of pin tool

thread orientation and weld pitch. Materials Science and Engineering: A 2010; 527: 6064–6075.
[41] Hirasawa S, Badarinarayan H, Okamoto K, et al. Analysis of effect of tool geometry on plastic flow during friction stir spot welding using particle method. Journal of Materials Processing Technology 2010; 210: 1455–1463.
[42] Sunil BR, Kumar GP, Mounika ASN, et al. Joining of AZ31 and AZ91 Mg alloys by friction stir welding. Journal of Magnesium and Alloys 2015; 3: 330–334.
[43] WTIA. Guidance Note 6: Post weld heat treatment of welded structures. 2003.
[44] Avedesian MM, Baker H. ASM specialty handbook: magnesium and magnesium alloys. 1999.
[45] Huang YX, Han B, Tian Y, et al. New technique of filling friction stir welding. Science and Technology of Welding and Joining 2011; 16: 497–501.
[46] Meshram S, Reddy M. Influence of tool tilt angle on material flow and defect generation in friction stir welding of AA2219. Defence Science Journal 2018; 68: 512–518.
[47] Kulekci MK. Magnesium and its alloys applications in automotive industry. The International Journal of Advanced Manufacturing Technology 2008; 39: 851–865.
[48] Sullivan A, Robson JD. Microstructural properties of friction stir welded and post-weld heat-treated 7449 aluminium alloy thick plate. Materials Science and Engineering: A 2008; 478: 351–360.
[49] Xunhong W, Kuaishe W. Microstructure and properties of friction stir butt-welded AZ31 magnesium alloy. Materials Science and Engineering: A 2006; 431: 114–117.
[50] Afrin N, Chen DL, Cao X, et al. Microstructure and tensile properties of friction stir welded AZ31B magnesium alloy. Materials Science and Engineering: A 2008; 472: 179–186.
[51] Wang G, Yan Z, Zhang H, et al. Improved properties of friction stir-welded AZ31 magnesium alloy by post-weld heat treatment. Materials Science and Technology 2017; 33: 854–863.
[52] Zhang J, Feng XS, Gao JS, et al. Effects of welding parameters and post-heat treatment on mechanical properties of friction stir welded AA2195-T8 Al-Li alloy. Journal of Materials Science and Technology 2018; 34: 219–227.
[53] Oztoprak N, Yeni CE, Kiral BG. Effects of post-weld heat treatment on the microstructural evolution and mechanical properties of dissimilar friction stir welded AA6061+SiCp/AA6061-O joint. Latin American Journal of Solids and Structures; 15. Epub ahead of print July 2018. DOI: 10.1590/1679-78254553.
[54] Razal Rose A, Manisekar K, Balasubramanian V. Effect of axial force on microstructure and tensile properties of friction stir welded AZ61A magnesium alloy. Transactions of Nonferrous Metals Society of China 2011; 21: 974–984.
[55] Han Y, Jiang X, Chen S, et al. Microstructure and mechanical properties of electrically assisted friction stir welded AZ31B alloy joints. Journal of Manufacturing Processes 2019; 43: 26–34.
[56] Lu F, Liu P, Ji H, et al. Dramatically enhanced impact toughness in welded 10%Cr rotor steel by high temperature post-weld heat treatment. Materials Characterization 2014; 92: 149–158.
[57] Wu S, Wang D, Zhang Z, et al. Mechanical properties of low-transformation-temperature weld metals after low-temperature postweld heat treatment. Science and Technology of Welding and Joining 2019; 24: 112–120.