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Effect Of Tool Tilt Angle On The Mechanical Properties Of Friction Stir Lap Welds Of AZ31B Magnesium Alloy Sheets

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Friction stir lap welding,
AZ31B magnesium alloy,
Tool tilt angle,
Microhardness,
Tensile shear load

Abstract: Friction stir lap welding of AZ31B magnesium alloy sheet pairs was conducted under various welding tool tilt angles (0°, 1°, 2°, 3° and 4°) while keeping other variables constant. Tensile shear load capacity and microhardness of the welds were obtained. Furthermore, the fracture mechanism of the weld was examined. The tilt angle significantly affected the weld cross-sectional area structure and tensile load capacity of the weld. A tunnel defect formed at the tilt angle of 0°. It was determined that the strongest weld with a 5083 N tensile load made at the 1° tilt angle is slightly more than three times as strong as the weakest one with a 1584 N made at 4°. The weld strength considerably decreased with increasing the tilt angle after 1° because the effective top sheet thickness on the advancing side was highly reduced because of more tool shoulder penetration. Hardness in the heat-affected and weld zones of the weld decreased when the tilt angle was improved due to the more heat input. The average hardness in the heat-affected and the weld zones of the welds made at 0° and 4° inclination angles are (62 and 61 HV) and (56.7 and 50.7 HV), respectively. The fact that no breakage occurred from the weld areas during the tensile test is proof of strong joining.

Takım Eğim Açısının AZ31B Magnezyum Alaşımlı Levhaların Sürtünme Karıştırma Bindirme Kaynaklarının Mekanik Özelliklerine Etkisi

Anahtar Kelimeler
Sürtünme karıştırma bindirme kaynağı,
AZ31B magnezyum alaşımı,
Takım eğim açısı,
Mikrosertlik,
Çekme kesme mukavemeti

Öz: AZ31B magnezyum alaşımlı levha çiftlerinin sürtünme karıştırma bindirme kaynağı, diğer değişkenler sabit tutularak çeşitli kaynak takımı eğim açıları (0°, 1°, 2°, 3° ve 4°) altında gerçekleştirildi. Kaynakların çekme kesme yükü taşıma kapasitesi ve mikrosertliği elde edildi. Ayrıca kaynağın kırılma mekanizması da incelenmiştir. Eğim açısı, kaynak kesit alanı yapısını ve kaynağın çekme yükü kapasitesini önemli ölçüde etkilemiştir. 0° eğim açısında tünel kusuru oluştu. 1° eğim açısında üretilen 5083 N çekme yüküne sahip en güçlü kaynağın, 4° eğim açısında üretilen 1584 N çekme yüküne sahip en zayıf kaynaktan üç kattan biraz daha fazla mukavemete sahip olduğu tespit edildi. Kaynak mukavemeti, 1°'den sonra eğim açısının artmasıyla önemli ölçüde azaldı çünkü ilerleyen taraftaki etkin üst plaka kalınlığı, daha fazla takım omuzu nüfuzu nedeniyle oldukça azaldı. Eğim açısı artırıldığında, daha fazla ısı girdisi nedeniyle ısıdan etkilenen ve kaynak bölgelerindeki sertlik azalmıştır. 0° ve 4° eğim açılarında yapılan kaynakların ısıdan etkilenen ve kaynak bölgelerindeki ortalama sertlikleri sırasıyla (62 ve 61 HV) ve (56,7 ve 50,7 HV)'dir. Çekme testi sırasında kaynak bölgelerinden herhangi bir kırılmanın meydana gelmemesi birleştirmenin sağlam olduğunun kanıtıdır.

1. INTRODUCTION

Reducing the weight of ground and air vehicles effectively improves fuel efficiency and mitigates environmental pollutants. Magnesium (Mg) alloys are the lightest and almost most excellent weight-reducing structural metals. Furthermore, they can replace steel and aluminum in many structural applications as they have low density, high specific strength, good sound-damping capacity, castability, machinability, electromagnetic interference shielding capacity, recyclability, and plentiful [1]. For this reason, they are utilized in sectors like automotive, aviation, and transportation [2-4]. According to several reports, Mg alloys are vital for future developments in the automotive and aerospace industries [5-7]. Joining technology plays a critical role in increasing the applications of Mg alloys. Nevertheless, since they have low melting points, low boiling points, high thermal conductivity, and active chemical properties, it is difficult to weld them. For example, imperfections (cracks, pores, and oxide inclusions) that are detrimental to the joint mechanical properties take place in the joint when joined by general fusion welding techniques [8-11]. Friction stir welding (FSW), the solid-state joining method created by TWI, is thought excellent for welding light metals [12]. FSW has demonstrated to offer a number of advantages over traditional arc welding techniques involving a notable decrease in distortion and elimination of solidification cracking [13-15]. Since melting of the materials does not occur in the FSW process, there are no flaws associated with the fusion welding, and thus high-strength joints can be produced. Researchers have shown that this welding technology is successful in combining light metallic materials like Mg alloys, Al alloys and Ti alloys [16-19]. Lap joints are frequently seen in the production of components and structures. For instance, the majority of sheet metal structures used in aerospace and aircraft include lap joints [20, 21]. Therefore, the lap joint appears to be quite important in the assembly of bodies in industries. Normally, rivets have been dominant for lap joining aerospace and aircraft structures at the beginning, however, since rivet holes likely lead to the formation and propagation of cracks and corrosion, and FSW can generate stronger joints and also provides significant weight and cost reductions, FSW has replaced most rivets [22]. FSW has been used mostly for butt joining of especially aluminum alloys, but there are also studies made on lap joining materials by FSW. Based on my research, there are fewer investigations into the lap joining Mg alloys via FSW. FSW process parameters determining the weld quality in terms of microstructure and mechanical properties are the welding tool geometry, tilt angle, plunge depth, rotation and travel speeds [23-25]. Cao and Jahazi [26] investigated the influence of tool rotation rate (500, 750, 1000, 1500 and 2000 rpm) and probe length (2, 2.25, 2.75 and 3.5 mm) on the microstructure, defects, hardness and tensile shear strength of the lap welds of 2 mm thick AZ31B-H24 Mg sheets made at 20 mm/s constant welding speed and 0.5º tool tilt angle by FSW. They found that weld tensile shear load increased when tool rotation speed increased up to 1000 rpm, but then decreased with further increase in tool rotation speed. On the other hand, weld load carrying capacity increased with increasing tool probe length and penetration depth into the lower sheet. Cao and Jahazi [27] researched influence of welding speed (5, 10, 15, 20, 25 and 30 mm/s) on the lap joint tensile shear load of 2 mm AZ31B-H24 Mg alloy sheets produced at constant 2000 rpm tool rotation speed clockwise and 0.5º tool tilt angle through FSW. High quality of lap joints was successfully fabricated. It was found that tensile shear load of lap joint enhanced when welding speed increased up to 15 mm/s and then remained stable with further increase. Yang et al. [28] studied the effect of tool pin geometry on the lap weld load carrying capacity of 2 mm thick AZ31-H24 Mg alloy sheets with FSW. They determined that welds produced by tool with triangular pin had much higher strength compared to the tool having cylindrical threaded pin. Because, triangular pin reduced the hook height growth as a result of providing more material to flow sideways.

Most of the friction stir lap welding investigations were carried out on the influence of welding parameters such as tool geometry, rotation speed, plunge depth, and travel speed on the microstructural and mechanical characteristics of the weld. It is also worth investigating the effect of tool tilt angle parameter on weld properties. Furthermore, No study has been found in the literature on the role of tool inclination angle on the mechanical and microstructural properties of friction stir lap welding (FSLW) of magnesium alloys. Hence, this study focused on tool tilt angle on mechanical properties of the (FSLW) of AZ31B magnesium alloy sheets.

2. MATERIAL AND METHOD

AZ31B magnesium alloy sheets with a 2 mm thickness, 100 mm length, and 100 mm width were purchased. Chemical and mechanical characteristics of the AZ31B alloy are presented in Tables 1 and 2. AZ31B sheet pairs were lap-welded for various welding tool inclination angles clockwise (0°, 1°, 2°, 3° and 4°) by the friction stir welding technique. Welding operations were carried out on a Falco FMH-4 model universal milling machine as shown in Figure 1. The welding tool was produced from H13 steel and its profile is shown in Figure 1. The tool has a conical-shaped pin without thread. Tool rotation speed of 1325 rpm, plunge depth of 3.7 mm, and feed rate of 37 mm.min-1 were kept constant. Welding parameters are also given in Table 3. Welding configuration is given in Figure 2. The photo of the sheets joined at different tool tilt angles is provided in Figure 3. The tensile shear test specimens with 25 mm width were obtained as in Figure 4, cutting the joined sheets with a bandsaw. The tensile shear specimens were tested on an Instron 2736-004 machine using 1 mm.min-1 constant tensile speed at room temperature as in Figure 5. To examine the cross-sectional areas of the welds, cross-sectional area samples were attained by cutting the joined sheets, and then they were sanded and polished with sandpaper up to 1500 grit. Microhardness of the welds was measured from cross-sections of the welds along the line just above the interface of the sheets from the base metal to the weld center via an AOB THV-1D Vickers tester using a 0.3 kg load and 11 seconds dwell time.

Table 1. Chemical composition

Material	Element (wt.%)								
AZ31B Mg alloy	Fe	Ni	Cu	Si	Mn	Zn	Al	Ca	Mg
	0.005	0.005	0.05	0.1	0.2-1	0.6-1.4	2.3-3.5	0.04	Rest

Table 2. Mechanical properties

Material	Yield strength	Tensile strength	Elongation	Vickers hardness
AZ31B Mg alloy	185 $N.mm^{-2}$	270 $N.mm^{-2}$	% 12	68.5 HV

Table 3. Welding parameters

Tool profile	Tool inclination angle	Tool rotation	Tool plunge	Tool feed rate
With conical pin and 8° concave shoulder	0° 1° 2° 3° 4°	1325 rpm	3.7 mm	37 $mm.min^{-1}$

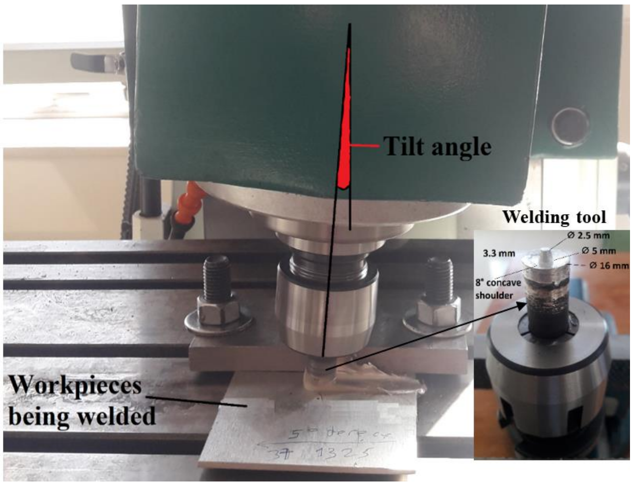

Figure 1. Friction stir lap welding operation and the welding tool

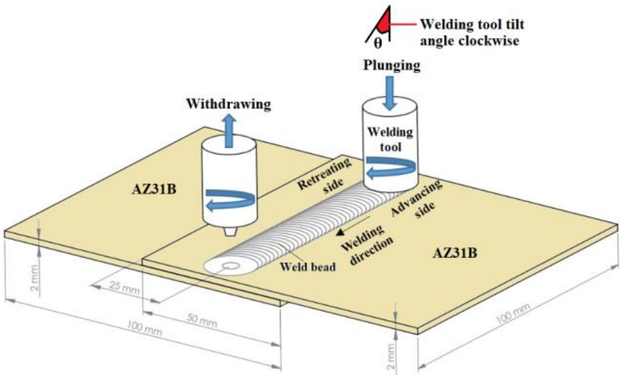

Figure 2. Friction stir lap welding configuration

Figure 3. The Joined sheets

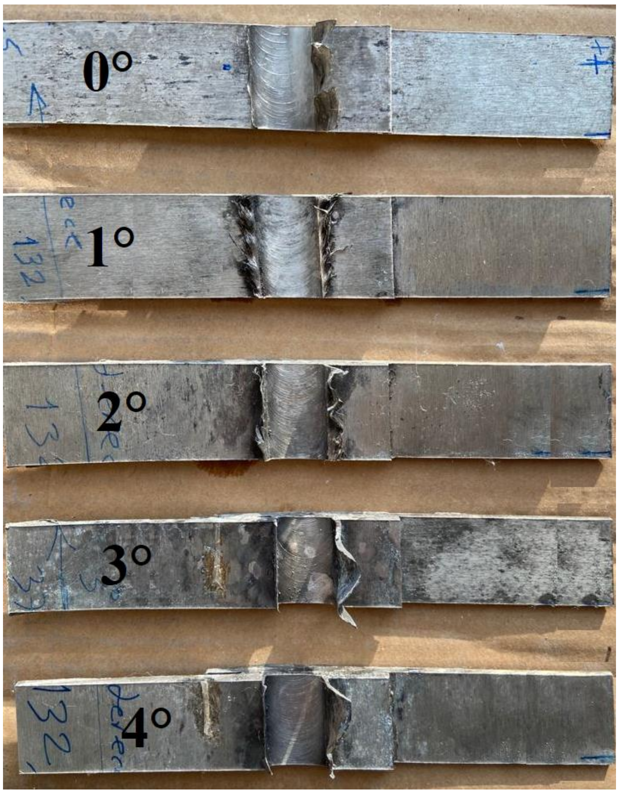

Figure 4. The weld specimens for the tensile shear test

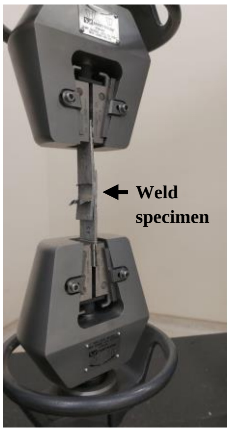

Figure 5. The tensile shear test of the weld specimens

3. RESULTS AND DISCUSSION

Macro cross-sectional areas of the produced welds are shown in Figure 6. It can be seen that a tunnel defect formed in the weld created with the 0° tool inclination angle. This tunnel most likely occurred due to insufficient tool shoulder pressing pressure on the upper sheet because there is no tool tilt and thus insufficient compression of the sheets at the interface. The effective upper sheet thicknesses exposed to tensile force (the lowest distance between the interface of the sheets and the top of the upper sheet) on the advancing sides of the welds were measured. The effective thicknesses on the advancing sides of welds made at 0° and 1° are very close and nearly equal. However, it significantly decreased with an increase in the tilt angle above 1°, reaching the lowest value of 0.45 mm at 4°. Additionally, as the tool inclination angle increases, it is seen that more material is headed upwards from the top part of the upper sheet by flowing. This is because the back side of the tool shoulder immersed more into the top sheet. Moreover, the lowest upper sheet thicknesses on the retreating sides of the welds were obtained. Accordingly, the weld created at 0° tilt angle had the smallest value while the weld created at 1° had the biggest. Furthermore, it became thinner with increasing tilt angle from 1° to 4°. Vickers microhardness values of the welds obtained along the red line just above the interfaces of the sheets on their cross-sections are given in Figure 7. The hardness of the AZ31B base metal (BM) was found to be around 68.5 HV. In general, hardness gradually decreased from base metal (BM) to heat-affected zone (HAZ) and then weld zone (WZ). The average hardness in the HAZs of the welds made at 0°, 1°, 2° and 4° tilt angles is 62, 59.5, 57.7 and 56.7 HV, respectively while it is 61, 55.5, 52.9 and 50.7 HV in their WZ. The smallest hardness values were found in the WZs of the welds. In addition, the hardness of HAZ and WZ of the weld declined when the tool tilt angle was enhanced, therefore it became maximum at the smallest tilt angle of 0° and minimum at the highest tilt angle of 4°. This is due to the greater immersion of the tool shoulder into the upper sheet with a higher inclination angle, resulting in more heat input at the interface of the sheets. Cao and Jahazi [26] also found that the lowest hardness values are in the weld zone in the FSLW of AZ31B-H24 Mg alloy sheets, and higher tool rotation speed led to lower hardness because of higher heat input resulted in larger grains in the weld zone.

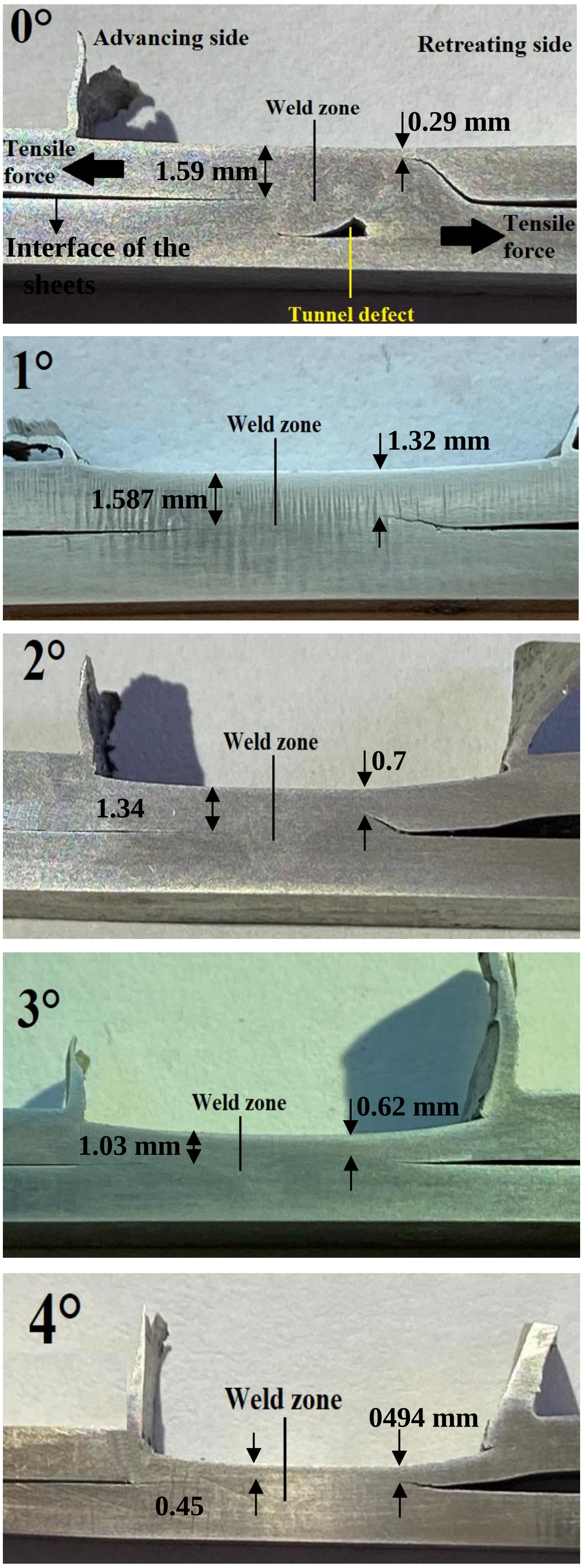

Figure 6. Cross-sections of the welds

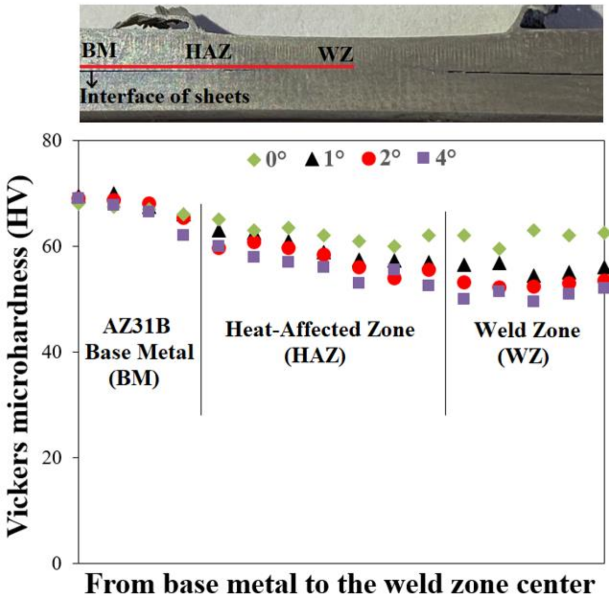

Figure 7. Microhardness of the welds created at various tool tilt angles

The tensile shear load properties of the welds are shown in Figure 8. It is obvious that the tool tilt angle has a significant effect on the tensile shear load of the weld. The tensile shear load increased to the maximum value of 5083 N with an increase in tilt angle from 0° to 1°. However, increasing the inclination angle up to 4° caused a dramatic decrease in the load value. This is because the tool shoulder plunged into the top of the upper sheet more with a higher tilt angle, and resulted in an important reduction in the effective upper sheet load-bearing thickness on the advancing side of the weld as seen in Figure 6. In other words, the effective upper sheet load-bearing thickness considerably got thinner owing to more tool shoulder plunging with increasing tilt angle. The weld formed with the 4° tilt angle has had the lowest tensile shear load of 1584 N. Also, the welds produced at high tilt angles (2°, 3° and 4°) had lower tensile elongation. Rajendran et al. [29] investigated the effect of tool tilt angle (0°-4°) on tensile shear load of the weld for FSSW of 2014-T6 aluminum alloy. They claimed that the weld made at 1° was defect-free, but the strongest one made at 2°, and the weld made at 3° had a low tensile load capacity because of unbalanced material flow.

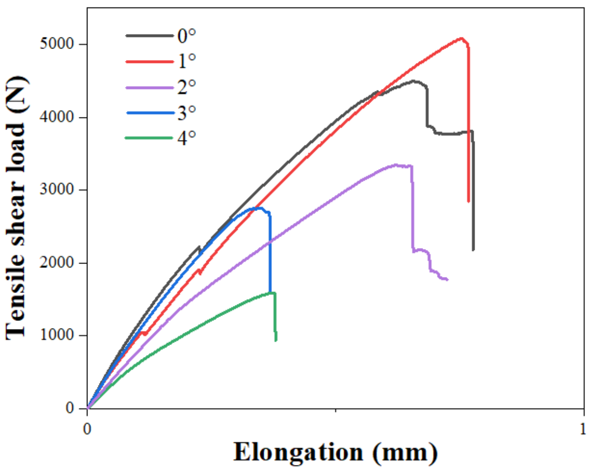

Figure 8. Tensile shear loads of the welds

Photos of the failure of welds during the tensile shear test are shown in Figure 9. It can be seen that all the welds failed away from the weld zones. Since there are no any failures from the weld zones, it can be said that weld zones are stronger than the acquired results. All the welds indicated a tensile mode fracture from the upper sheet material on the advancing side. The welds produced at 0°, 1° and 2° fractured from their upper sheet HAZs, their advancing sides, and almost vertically to the tensile force direction. But, the weld made at 1° broke slightly more away from the weld zone. The welds made with 3° and 4° failed from the top sheets just outside the plunging place of the tool shoulder due to excessive penetration of the tool shoulder into the top side of the upper sheet and the upper sheet becoming very thin.

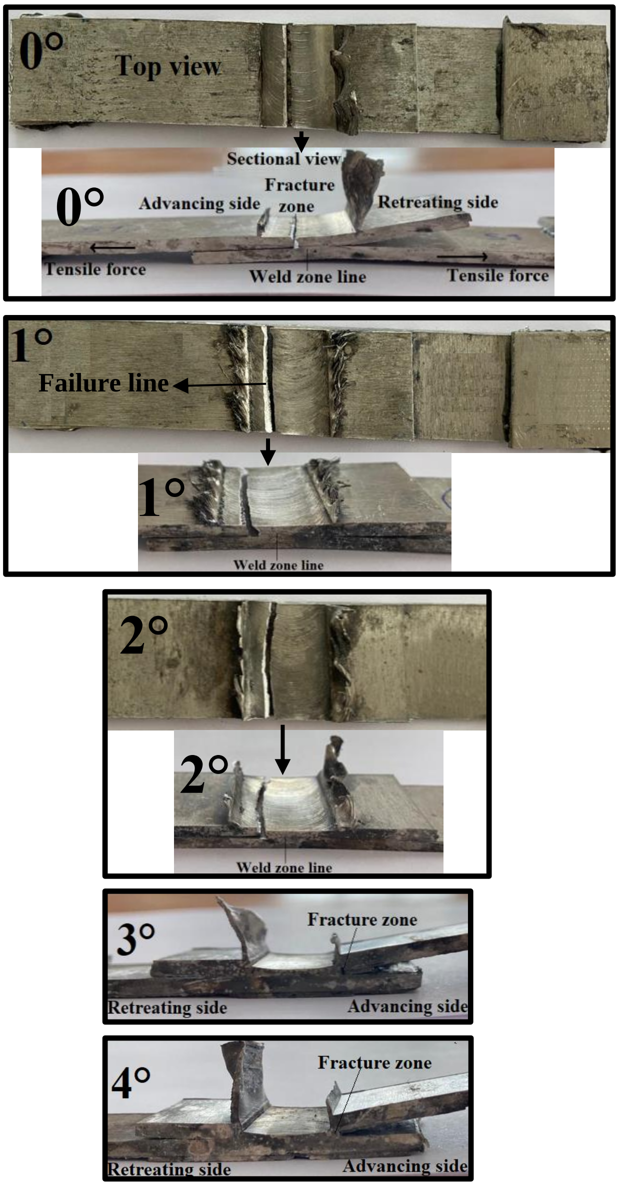

Figure 9. Fracture views of the welds after tensile test operation

4. CONCLUSIONS

Friction stir lap welding of AZ31B magnesium alloy sheets was successfully carried out. Outcomes from evaluating cross-sections and mechanical tests of the welds are as below.

Increasing the tool tilt angle led to the thinning of the upper sheet as the tool shoulder penetrated more. The weld produced at 1° appeared to be the strongest with a tensile shear load of 5083 N because it had no visible defects and an effective high upper sheet load-bearing thickness on the advancing side. The weakest weld with a tensile shear load of 1584 N was made at 4° because, at this angle, the load carrier thickness of the upper sheet became extremely thin. On the other hand, the welds made at 0°, 2° and 3° inclination angles had a tensile shear load of 4497, 3342 and 2751 N, respectively. Weld tensile shear load increased with rising inclination angle from 0° to 1°. However, a further increase in the inclination angle resulted in a significant decrease in weld tensile shear load. The hardness of AZ31B alloy was determined to be around 68.5 HV. As the inclination angle was increased, the hardness in the heat-affected and weld zones of the weld decreased slightly and the lowest hardness values measured in the weld zones. The reason for this is probably more tool shoulder penetration into the upper sheet and generating more friction heat input. The average hardness in HAZ and the WZ is 62 and 61 HV, and 56.7 and 50.7 HV for the welds obtained at 0° and 4° inclination angles, respectively. All the welds failed from the top sheet on the advancing side and in tensile mode during the tensile test. Since no welds failed from their weld areas, we can say that the load carrying capacity of the weld areas is greater than the tensile loads obtained. Mg alloys, which are very difficult to weld with fusion welding, can be welded by friction stir welding method for use in applications such as aerospace and automotive, on condition that appropriate welding parameters are selected, for example, by choosing the tool inclination angle of 1 degree or slightly larger like between 1 and 2 degrees.

REFERENCES

[1] Cao X, Jahazi M, Immarigeon JP, Wallace W. A review of laser welding techniques for magnesium alloys. J Mater Process. Technol. 2006;171:188-204.

[2] Liu FJ, Li YP, Sun ZY, Ji Y. Corrosion resistance and tribological behavior of particles reinforced AZ31 magnesium matrix composites developed by friction stir processing. J Mater Res Technol. 2021;11:1019-30.

[3] Eivani AR, Mehdizade M, Chabok S, Zhou J. Applying multipass friction stir processing to refine the microstructure and enhance the strength, ductility and corrosion resistance of WE43 magnesium alloy. J Mater Res Technol. 2021;12:1946-57.

[4] Wang W, Han P, Peng P, Guo H, Huang L, Qiao K, et al. Superplastic deformation behavior of fine-grained AZ80 magnesium alloy prepared by friction stir processing. J Mater Res Technol. 2020;9(3):5252-63.

[5] Zhang X, Chen Y, Hu J. Recent advances in the development of aerospace materials. Pro Aerosp Sci. 2018;97:22-34.

[6] Vedernikov A, Safonov A, Tucci F, Carlone P, Akhatov I. Pultruded materials and structures: a review. J Compos Mater. 2020;54:4081-4117.

[7] Imran M, Khan R.A. Characterization of Al-7075 metal matrix composites: a review. J Mate Res. Technol. 2019;8:3347-3356.

[8] Qin B, Yin F-c, Zeng C-z, Xie J-c, Shen J. Microstructure and mechanical properties of TIG/A-TIG welded AZ61/ZK60 magnesium alloy joints. Trans Nonferrous Met Soc. China. 2019;29(9):1864-1872.

[9] Gao M, Wang H, Hao K, Mu H, Zeng X. Evolutions in microstructure and mechanical properties of laser lap welded AZ31 magnesium alloy via beam oscillation. J Manu Process. 2019;45:92-99.

[10] Hao K, Wang H, Gao M, Wu R, Zeng X. Laser welding of AZ31B magnesium alloy with beam oscillation. J Mater Res Technol. 2019;8(3):3044-3053.

[11] Song G, Diao Z, Lv X, Liu L. TIG and laser–TIG hybrid filler wire welding of casting and wrought dissimilar magnesium alloy. J Manuf Process. 2018;34:204-214.

[12] Thomas WM, Nicholas ED, NeedHam JC, Murch MG, Templesmith P, Dawes CJ. Friction Stir Welding. In Pat. App. 1991;8 PCT/GB92102203 and Great Britain patent application no. 9125978.

[13] Golbabaei P, Besharati Givi MK, Molaiekiya. Investigating effects of process parameters on microstructural and mechanical properties of Al5052/SiC metal matrix composite fabricated via friction stir processing. Mater Des. 2012;37:458-464.

[14] Barmouz M,Givi MKB. Fabrication of in situ Cu/SiC composites using multi-pass friction stir processing: Evaluation of microstructural, porosity, mechanical and electrical behavior. Comp Part A: App Sci Manuf. 2011;50(10):1445-1453.

[15] Zohoor M, Besharati Givi MK, Salami P. Effect of processing parameters on fabrication of Al–Mg/Cu composites via friction stir processing. Mater Des. 2012;39:5004-5014.

[16] Liu HJ, Fujii H, Maeda M, Nogi K. Tensile properties and fracture locations of friction-stir-welded joints of 2017-T351 aluminum alloy. J Mater Process Technol. 2003;142(3):692-696.

[17] Zhou M, Morisada Y, Fujii H, Ishikawa T. Mechanical properties optimization of AZX612-Mg alloy joint by double-sided friction stir welding. J Mater Process Technol. 2018;254:91-99.

[18] Fujii H, Sun Y, Kato H, Nakata K. Investigation of welding parameter dependent microstructure and mechanical properties in friction stir welded pure Ti joints. Mater Sci Eng A. 2010;527(15):3386-3391.

[19] Tsujikawa M, Abe Y, C. SW, Oki S, Higashi K, Hiraki I, M. Kamita. Cold-rolled Mg-14 mass% Li-1 mass% Al alloy and its friction stir welding. Mater Trans. 2006;47(4):1077-1081.

[20] Salari E, Jahazi M, Khodabandeh A, Ghasemi-Nanesa H. Influence of tool geometry and rotational speed on mechanical properties and

defect formation in friction stir lap welded 5456 aluminum alloy sheets. Mater Des. 2014;58:381-389.
[21] Galvão I, Verdera D, Gesto D, Loureiro A, Rodrigues DM. Influence of aluminium alloy type on dissimilar friction stir lap welding of aluminium to copper. J Mater Process Technol. 2013;213(11):1920-1928.
[22] Thornton PH, Krause AR, Davies RG. Aluminum Spot Weld. Weld J. 1996;75:101.
[23] Mishra RS, M ZY. Friction stir welding and processing. Mater Sci Eng R. 2005;50:1-78.
[24] Cam G, Mistikoglu S. Recent developments in friction stir welding of Al-alloys. J Mater Eng Perform. 2014;23:1936-53.
[25] Singh K, Singh G, Singh H. Review on friction stir welding of magnesium alloys. J Magnes All. 2018;6:399-416.
[26] Cao X, Jahazi M. Effect of tool rotational speed and probe length on lap joint quality of a frictionstir welded magnesium alloy. Mater Des. 2011;32(1):1-11.
[27] Cao X, Jahazi M. Effect of welding speed on lap joint quality of friction stir welded AZ31 magnesium alloy. Trends in Welding Research, Proceedings of the 8th International Conference, 2008;72-80.
[28] Yang Q, Li X, Chen1 K, Shi YJ. Effect of tool geometry and process condition on static strength of a magnesium friction stir lap linear weld. Mater Sci Eng A. 2011;528:2463-2478.
[29] Rajendran C, Srinivasan K, Balasubramanian V, Balaji H, Selvaraj P. Effect of tool tilt angle on strength and microstructural characteristics of friction stir welded lap joints of AA2014-T6 aluminum alloy. Tran Nonferrous Met. Soc China. 2019;29:1824-1835.