Forming and Properties of Friction Stir Welding Process for Dissimilar Mg Alloy

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Abstract: For hot extrusions of magnesium alloy sheets, Dissimilar AZ80 and AZ31 were used, in which AZ80 was placed on advancing side and AZ31 on retreating side, using friction stir butt welding with different process parameters. Some defect-free welded joints with good weld surfaces could be obtained with some suitable welding conditions. The maximum tensile strength of welded joint which is 225.5 MPa can reach 98% that of the AZ31 base material. Influence of process parameters on defects, weld shaping and mechanical property were discussed systematically. And the microstructure of different zones was compared. The fracture of the welded joints takes place at the junction of mechanical heat affected zone and nugget zone in AZ31 magnesium alloy set retreating side, since existing difference in metallographic structure of alloy diversely suffered by heat, pressure and depositing impurities. Fracture initiation site may be the P line defect which should be eliminated, and the P line defect formation was analyzed.

Keywords: Defect, dissimilar magnesium alloy, fracture location, friction stir welding, mechanical properties, metallographic structure.

1. INTRODUCTION

Due to the demand of lightweight and remanufacturing in various fields, magnesium alloy as the light weight structure material of commercial value, has been adopted [1]. Friction stir welding (FSW) introduce by the British institute of welding in 1991, gives solid joining. Because of avoiding various defects produced by the traditional fusion welding of magnesium alloy [2], FSW application and research in magnesium alloy has been expanded gradually. Process parameters, heat input, plastic deformation and flow of material, organization evolution, mechanical properties of FSW for AZ31 magnesium alloy have been researched comprehensively [3-7]. Microstructure and mechanical properties of FSW for AZ31B magnesium alloy under the environment of air and water were compared already [8, 9]. Microstructure, dislocation density and tensile properties of FSW for AZ61 magnesium alloys were discussed [10]. Rose studied the influence of axial force on defects, grain size, the welding zone hardness and tensile properties for AZ61A magnesium alloy joint friction stir welded [11]. The thread direction of stir tool impacts fatigue strength and tensile strength of magnesium alloy, AZ31B - H24 FSW joint [12, 13]. Influence of welding speed on organization forming of FSW joint of AZ80 magnesium alloy was discussed [14]. The research shows that performance differences of the same magnesium alloy FSW joints were more than that of dissimilar magnesium alloy FSW joints. Wang discussed the impact of the friction stir welding process parameters on the organization and the performance of welded joint for the deformation magnesium alloys, AZ31B and AZ61A, assuming that the joint of the AZ31B placed at retreating side can form a good defect-free joint [15]. Liu investigated microstructure and mechanical properties of FSW joints of dissimilar Mg alloys AZ31 and AZ80. Sound joints could be easily obtained when AZ31 with superior plastic deformability was placed at retreating side [16]. On the basis of literature [16], different FSW process parameters were selected to weld AZ80 placed on AS and AZ31 set on RS. Specific defects and their forming were contrasted; the relationship of process parameters, defects, forming, mechanical properties were analyzed, and fracture location and type were discussed.

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2. EXPERIMENTAL PROCEDURE

Commercially, for the extrusion of AZ80 and AZ31 alloy sheets extruded with the thickness of 3mm, friction stir welding (FSW) experiment was carried out, as shown in Table **1**. The length direction of plate is the extrusion direction, that is also welding direction. The welding experiment for AZ80 and AZ31 alloy was conducted on FSW-RS32-015 welding machine made by China FSW Center with a H13 steel welding tool which has a 10 mm diameter shoulder and a threaded 2.8 length taper probe. AZ80 was placed on advancing side (AS) and AZ31 on retreating side (RS). Two tool rotating speeds of 1500 and 1800 r/min were selected, and for each rotational speed there are three traverse speeds of 80, 160, and 240 mm/min. Moreover, the heel plunge depth was uniformly set at as 0.2 mm and the tilt angle of the welding tools, 2.5°.

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Table 1. Magnesium alloy main components and mechanical properties of magnesium alloy.

Alloy	Mass Fraction/%					Ultimate Tensile Strength/MPa	Elongation Rate/%
	Al	Mn	Zn	Si	Mg		
AZ31	2.5~3.5	0.15~0.4	0.6~1.4	≤0.3	Bal	230	20.4
AZ80	7.8~9.2	0.15~0.50	0.2~0.8	≤0.3	Bal	360	10.2

After welding, cross-sectioning samples were taken for carrying out the macro observations. To understanding the microstructure of dissimilar FSW joints, the sample was ground and mechanically polished and then etched for about 10 s. Microscopic observations were then conducted by using OLYMPUS GX51 optical microscopic (OM) and Hatchi-4800 scanning electron microscope (SEM). After OM examination, the experiment for obtaining Vickers hardness values of middle of the weld height, was conducted using 432SVD Vickers hardness tester.

To evaluate the quality of the weld, tensile specimens were sectioned from the finished weldments, as shown in Fig. (**1**). Static load tensile test was then carried out using CSS-44100 universal testing machine with a 100 KN load cell and a crosshead speed of 3 mm/min. For each welding parameter, at least three tensile samples were examined and the average of the test results was adopted. After tensile test, fracture locations of samples were photographed and facture surfaces were inspected by using scanning electron microscope (SEM) to investigate the tensile behaviors.

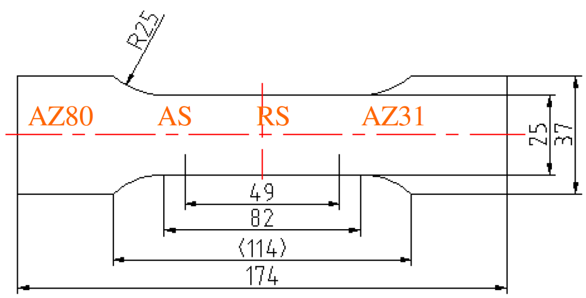


Fig. (1). Drawing of tensile sample.

3. RESULTS AND DISCUSSION

3.1. Macro Morphology

When for workpiece welding all process parameters are selected, the mixing head can smoothly move forward on workpiece surface, and weld surface was smoothed without wrinkling, both sides of weld have the flash, as shown in Fig. (**2**).

Cross section of different processes are as shown in Fig. (**3**), all work pieces have flash on both sides of weld and in a cross section of 1800/160 there is clear hole defects, as shown in Fig. (**3e**). At the back welding joint is contacted by base plate, and when the bottom end of stir pin stirred the parent metal at both sides, weld defects along the entire weld were formed, which is called a P line defect which is on point P at cross section diagram needle contacting with the parent metal on both sides along the entire weld defect called a P line defect. When the mixing head begins to stir parent metal, both sides of the plate are fixed by the clamping fixtures, in middle of the two plate compacted by the mixing head, which turns into a plastic organization, and both sides of the weld are still highly rigid solid organizations. At the same time, the terminal of the mixing head has undergone circular arc chamfering, when the welding speed and rotating speed don't match, the joint can produce such P line defects. To eliminate such defects, the mixing head should avoid the use of arc chamfering of stir head and pressure device is as far as possible close to the seam.

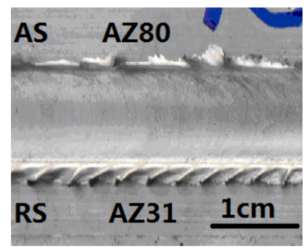


Fig. (2). Macrograph of friction stir welded joint.

3.2. Microstructure Evolution

Each letter of zoning maps in Fig. (**3a**) is respectively corresponding to ones in the Fig. (**4**). A, B, C, D of welded joint separately denote AZ80 mother materials (BM), heat affected zone (HAZ), the thermo-mechanical affected zone (TMAZ) at AS, and nugget zone (NZ) respectively; E is central NZ, and F, G, H, J, respectively are marked as NZ, TMAZ, HAZ, AZ31 BM. HAZ which did not sustain plastic flow, beared heat conduction. TMAZ sustained the impact of plastic flow of NZ grain and extrusion of stirring head and thermal transmission. NZ suffered friction stir heat and rotary motion, thus occured plastic flow and dynamic recrystallization, and the organization of center welding is more uniform and finer. But microstructures of AZ80 and AZ31 have their own characteristics. In AZ80 HAZ of AS, tiny particles will be grown up, is small and uneven, and compared to TMAZ tissue that is deformed and obviously is uneven size, some grains are elongated. In AZ31 HAZ of RS organization is whereas less than that of AZ31 base metal and non-uniform, TMAZ organization by extrusion, some narrow and lengthen. Equiaxed grains of NZ in both AS and RS come from collision of the two parent metal grain, that stagger each other.

On watching 1000 times with OM, joints found without defect were 1500/80, 1500/160, 1500/240, 1500/240, 1800/240. 1800/160 joint has a hole whose width is 158 μ *and* height 206 μm, as shown in Fig. (**4k**). Fig. (**4l**, **m**) shows nugget transition of AS and RS respectively [16]. Literature considered that for NZ content organization of both sides of two alloy metals, plastic flow is sufficient and recrystallization takes place [16].

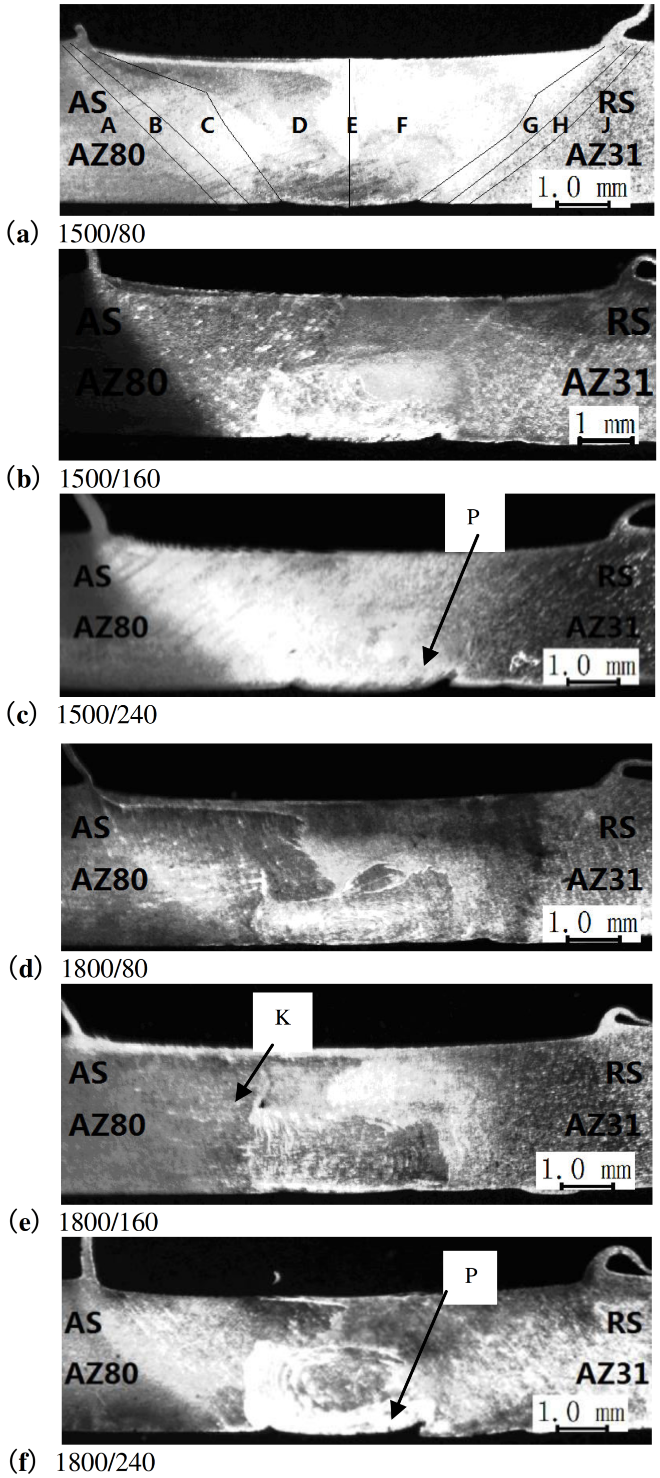


Fig. (3). Overviews of transverse sections.

3.3. Mechanical Property

3.3.1. Tensile Strength

The crystal structure of AZ31 consisting of low amounts of aluminium is the same as magnesium, belongs to close-packed hexagonal structure. But in addition to being it, AZ 80 separates out $Mg_{17}Al_{12}$ strengthening phase, therefore AZ 80 has high tensile strength, and poor plastic deformation

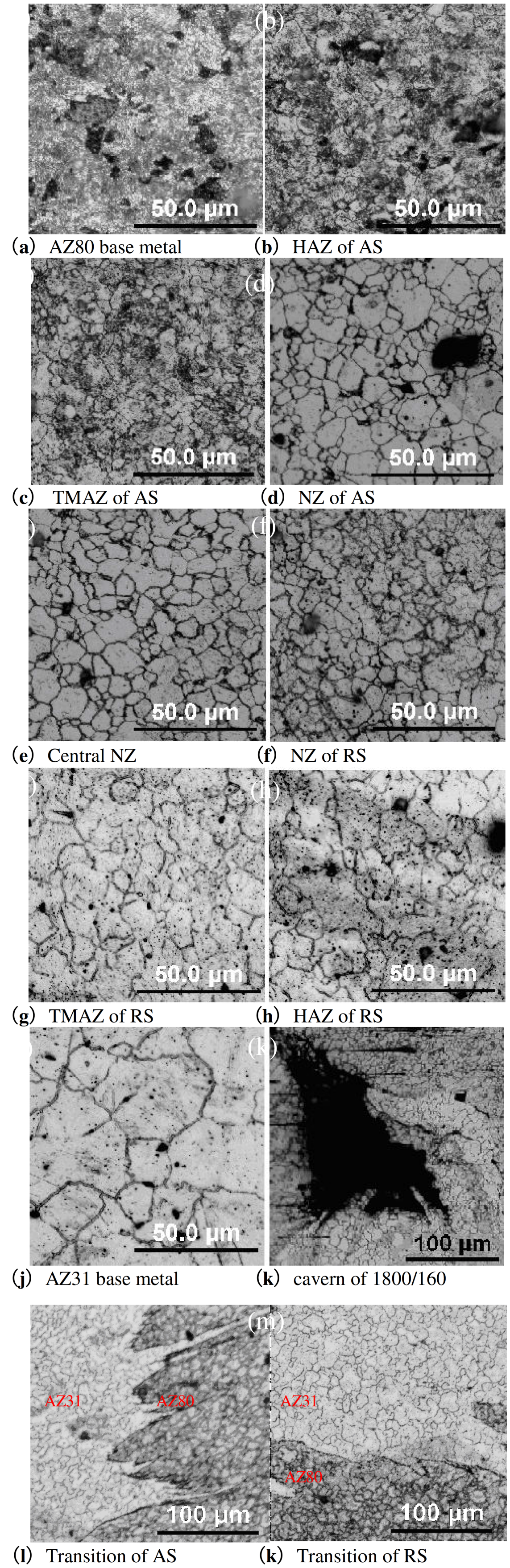


Fig. **(4)**. Metallographs of each point in Fig. (**3**).

ability. The tensile strength of welding joint of different processes is less than that of the parent metal and the longation of joint is far less than the parent metal, the result is shown in Fig. (**5**). The tensile strength of 1500/160 sample is up to 225.5 MPa, 62.6% of AZ80's, 98% of the AZ31's, and its longation is 4.9%.

Inside each weld, there are three kinds of welding speed corresponding to with 1500 r/min rotating speed and there are no defects of holes and tunnel. Among them, the strength of 1500/160 is maximum. In I500/80, AZ80 may be failed to move to the side of AZ31. And 1500/240 is less heat absorbent, also can meet the requirements of plastic deformation and recrystallization. The most insufficient is the P line defect reducing the effective area suffering tensile load, as shown in Fig. (**3**).

In weld of 1800/160, there appeared the tunnel, therefore its tensile strength is the minimum. 1800/80 of the 1800r/min rotating speed has the biggest strength, even though internally it is defect-free, but due to the back of joint there is the P line defects resulting in a decline in strength.

1500/160 joint of all samples has the highest strength, while 1800/160 with internal tunnel has the lowest strength. This shows that due to excessive heat input resulted in a higher rotating speed, AZ31 being higher deformation ability may be excessively moved with high-speed mixing head making cavity of AZ80 side not fill in time, forming holes affecting the mechanical properties. Also suggests that grain group of the rotation speed of 1500/160 can fill up in time the rear cavity left the mixing tool moving forward, proper and sufficient frictional heat can make the perfect recrystallization organization complete, at the same time, the junction of NZ and TMAZ on both sides can be fully staggered fusion joints. Without defect both inside and outside joints, strength of 1800/80 is higher than 1500/80, as can be seen from the Fig. (**3**), In 1800/80, AZ31 colored with white light and AZ80 with ash black can be fully mixed together, and AZ80 flowing to AZ31 side makes the Al content of AZ31 side increase, and so that stiffness and strength performance of the AZ31 is laterally enhance. 1 The strength of 500/240 is higher than 1800/240's, because of the small P line defect being large in the effective load bearing area.

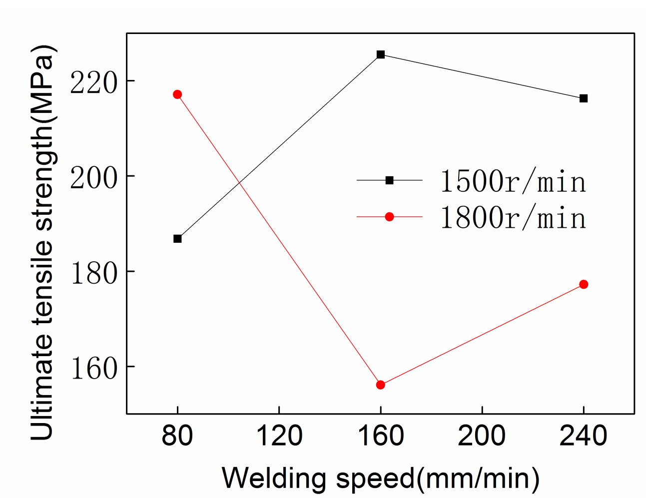


Fig. (5). Effects of FSW parameter on tensile strength.

3.3.2. Microhardness

Microhardness of joints without defects in the cross-section weld is as shown in Fig. (**6**). The hardness values curve and zigzag upward curve, show that all the hardness values were greater than AZ31, and smaller than that of AZ80 magnesium alloy. Hardness value spanning from NZ to HAZ is big, and the NZ hardness as wavy lines is distributed as zigzag.

For 1500/160, hardness value curve locating at the top of all curves, is the largest basically. 1500/80, hardness in AZ31 large floating side showed that due to excessive heat input, the tissues have become hypertrophy giving uneven result in the weak connection and have small strength. And 1500/240 hardness of junction of TMAZ and NZ in AZ31 side is relatively balanced, which explains smooth organization transition forming a strong connection with larger strength. For 1500/240 hardness of the whole joint is less than that of 1800/240 which shows that the strength of 1500/240 may be less and1500/240 and is with smaller P line defects compared to 1800/240's that has greater strength. These results show that the P line defect has great influence on strength. Hardness and strength of the junction of TMAZ and NZ in AZ31 side of 1800/80 are higher than those of 1500/80's, due to the increase of Al content that could easily form the strengthening phase.

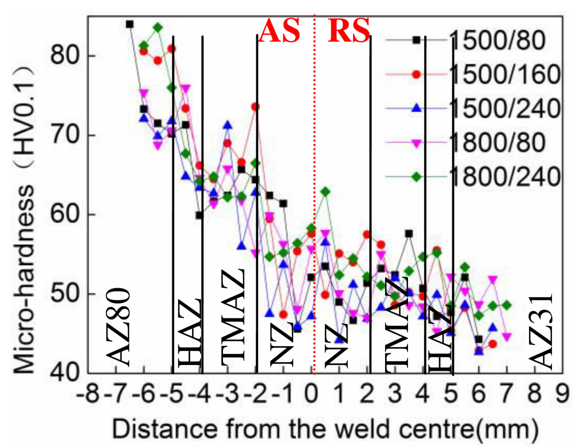


Fig. (**6**). Micro-hardness of different FSW parameter joints.

3.4. Fracture Mechanisms

As shown in Fig. (**7**), weld joints in tensile test fracture at the junction of TMAZ and NZ of AZ31 magnesium alloy set on RS, show that the strength of junction in the welding joint is the weakest. And its hardness value fluctuate greatly. This is because of the large difference between junction organizations suffering different levels of heat and pressure, impurities and other heavy metals deposited at the junction of TMAZ and NZ, as shown in Fig. (**8**) .P line defects of initial fracture easily form stress concentration.

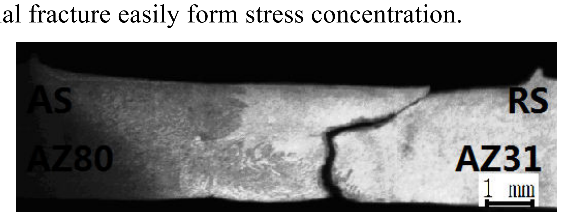
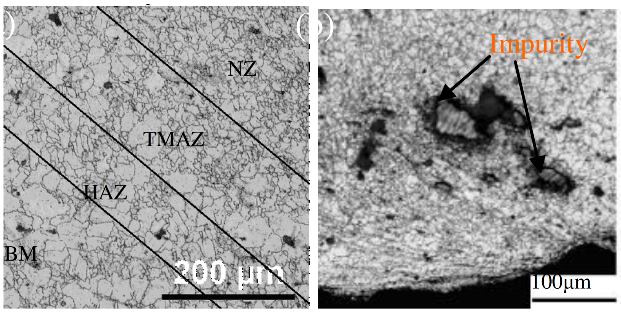


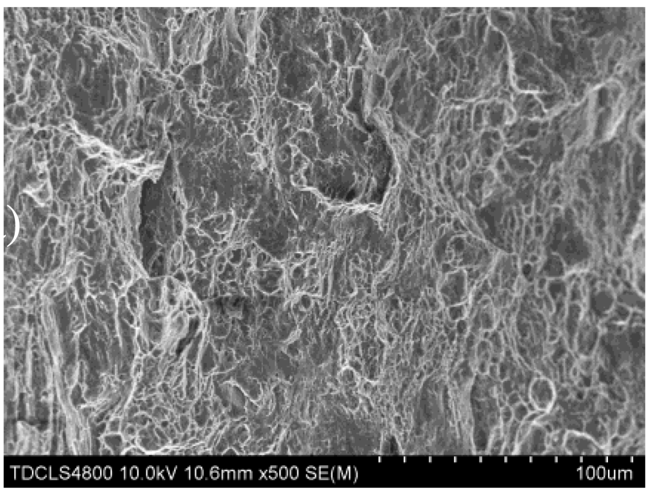
Fig. (**7**). Fracture photo of cross section of 1500/160.



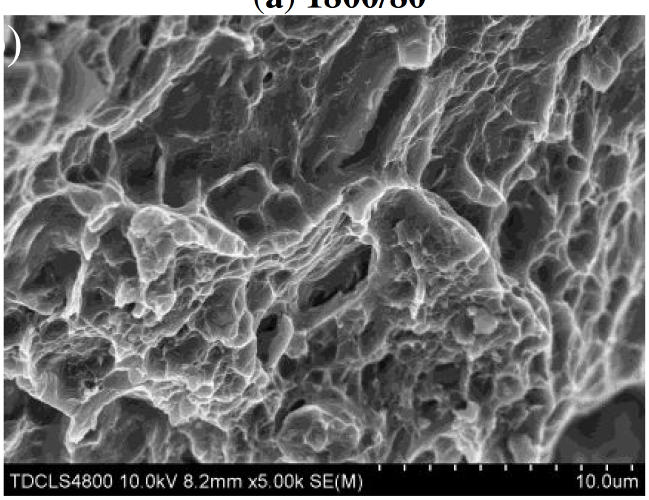
(a) Difference of orgnization (b) The impurity sediment figure

Fig. (8). Metallographs.

As shown in Fig. (**9a**), 1800/80 fracture presents obviously tearing arris and the large number of 10 μm diameter equiaxial dimples. Fig. (**9b**) shows that 1500/160 fracture has many big dimples containing several smaller dimples being even of 1 μm diameter, namely ovate dimple. Large tensile strength of welded joint is in a good toughness, belonging to the ductile fracture.



(a) 1800/80



(b) 1500/160

Fig. (9). SEM morphology of tensile fracture of welds.

CONCLUSION

(1) The FSW joints of welding in which AZ80 is placed on AS, and AZ31, set on RS, will be smooth surfaces of the weld without holes and the tunnel defects.

(2) For the hardness curve and the zig-zag upward curve, the hardness values were greater than AZ31, and smaller than that of AZ80 magnesium alloys, whereas hardness value of 1500/160 is the largest.

(3) The joint sample having 1500 r/min rotation speed corresponding to the welding speed had the maximum tensile strength, compared to that of 1800 r/min which is minimum.

(4) The Strength of joint sample of 1500/160 is the highest because the grain rotation can fill the rear cavity in time when stirring tool moves forward, and sufficient friction heat makes organization perfect recrystallization. At the same time the magnesium alloy of both sides can stagger and blend in NZ.

(5) The fracture site takes place the junction of TMHZ and NZ in AZ31 magnesium alloy side, due to the large difference of junction organization, impurities and other heavy metals deposited, as well as P line defect of initial fracture.

(6) Using non-circular chamfering stirring needle, can avoid to produce P line defects which should be processed to eliminate if it exiting.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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REFERENCES

[1] H. Xu, J. A. Liu, and S. S. Xie, "*Magnesium Alloy Fabrication and Processing Technology*," Beijing, Metallurgical Industry Press, 2007, pp. 22-93.

[2] W. M. Thomas, J. C. Needlham, and C. J. Dawes, "*Friction Stir Butt Welding*," Great Briton, Patent Application, 9125978.8, 1991.

[3] L. Commin, M. Dumont, and J. E. Masse, "Friction stir welding of AZ31 magnesium alloy rolled sheets: Influence of processing parameters" *Acta Materialia*, vol. 57, no. 2, pp. 326-334, 2009.

[4] U. F. H. R. Suhuddin, S. Mironov, and Y. S. Sato, "Grain structure evolution during friction-stir welding of AZ31 magnesium alloy" *Acta Materialia*, vol. 57, no.18, pp. 5406-5418, 2009.

[5] H. Zhang, L. J. Guo, and S. B. Lin, "Material flow pattern in friction stir welding of AZ31 magnesiumalloy," *Transactions of the China Welding Institution*, vol. 25, no.4, pp. 67-72, 2004.

[6] H. Zhang, S. B. Lin, and L. W. Lin, "Microstructure of friction stir welds in AZ31 magnesium alloy" *The Chinese Journal of Nonferrous Metals*, vol. 13, no. 6, pp.1510-1513, 2003.

[7] S. Y. Yang, and B. L. Zhang, "Microstructures and mechanical properties of thick AZ31 magnesium alloy welded joint by friction stir welding" *Transaction of the China Welding Institution*, vol. 30, no. 5, pp. 1-5, 2009.

[8] K. S. Wang, L. H. Zhou, and J. L. Wu, “Research of submerged friction stir welded AZ31B magnesium alloy” *Rare Metal Materials and Engineering*, vol. 41, no. 6, pp.1111-1115, 2012.

[9] J. A. Esparza, W. C. Davis, and E. A. Trillo, “Friction-stir welding of magnesium alloy AZ31B” *Journal of Materials Science Letters*, vol. 21, no. 12, pp. 917-920, 2002.

[10] S. H. C. Park, Y. S. Sato, and H. Kokawa, “Effect of micro-texture on fracture location in friction stir weld of Mg alloy AZ61 during tensile test” *Scripta Materialia*, vol. 49, no.2, pp. 161-166, 2003.

[11] A. Rose, K. Manisekar, and V. Balasubramanian, “Effect of axial force on microstructure and tensile properties of friction stir welded AZ 61 A magnesium alloy” *Transactions of the Nonferrous Metals Society of China*, vol. 21, no.5, pp. 974-984, 2011.

[12] S. M. Chowdhury, D. L. Chen, and S. D. Bhole, “Effect of pin tool thread orientation on fatigue strength of friction stir welded AZ31B-H24 Mg butt joints” *Procedia Engineering*, vol. 2, no.1, pp. 825-833, 2010.

[13] S. M. Chowdhury, D. L. Chen, and S. D. Bhole, “Tensile properties of a friction stir welded magnesium alloy: Effect of pin tool thread orientation and weld pitch” *Materials Science and Engineering: A,* vol. 527, no. 21, pp. 6064-6075, 2010.

[14] T. L. Li, X. Q. Yang, and Z. S. Wang, “Effect of welding rates on friction stir welded joint shaping and microstructue of AZ80 magnesium alloy”, *Materials for Mechanical Engineering*, vol. 37, no. 5, pp. 26-29, 2013.

[15] X. J. Wang, Y. H. Zhang, and Z. K. Zhang, “Friction stir welding process of AZ31B and AZ61A magnesium alloy” *The Chinese Journal of Nonferrous Metals*, vol. 18, no.7, pp. 1199-1204, 2008.

[16] D. Liu, H. Nisho, and K. Nakata, “Anisotropic property of material arrangement in friction stir welding of dissimilar Mg alloys,” *Materials & Design,* vol. 32, no. 10, pp. 4818-4824, 2011.

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