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Anisotropic property of material arrangement in friction stir welding of dissimilar Mg alloys

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ABSTRACT

Microstructure and mechanical properties of friction stir weld joints of dissimilar Mg alloys AZ31 and AZ80 were investigated in the present work. Several different welding parameters were adopted in the study, and the effects of rotation speed and welding speed on the joint quality were discussed comprehensively. In addition, material arrangement which means that AZ31 alloy was at advancing side or at retreating side has significant influence on the joint formation, including the joint microstructure and mechanical properties. A few kinds of defects were observed when the improper parameters were taken in the experiment, and the reasons for generating these defects were revealed in this work. Sound joints with good mechanical properties could be easily obtained when AZ31 was at retreating side, but it was difficult to obtain the sound joint with the contrary material arrangement. These results suggest that the material with inferior plastic deformability should be set at the advancing side and the material with superior one should be set at the retreating side in order to get sound FSW joint of dissimilar Mg alloys.

1. Introduction

Friction stir welding (FSW) invented by the TWI in 1991 [1] has been widely used for welding Al alloys [2–4], Mg alloys [5,6], Ti alloys [7–10] and steels [11–13]. The 1050-H24 aluminum alloy was successfully friction stir welded by the optimum parameters, and the maximum tensile strength of the joint is equivalent to 80% of that of base material [2]. In addition, some types of defects formed with different FSW conditions were concretely analyzed as well [3]. In recent years, Ti alloys and steels are also friction stir welded although they are of high activity and high melting point, and investigations on microstructural characteristics [7,9], mechanical properties [13] as well as superplastic forming behavior [8] have been performed. Low cost, high joint quality and capability of welding kinds of hard-to-weld materials make FSW more and more attractive, especially in the joining of dissimilar materials [14–17]. Chen and Nakata [15] made a detailed investigation for AC4C Al alloy and AZ31 Mg alloy friction stir lap joining, and could get no visible welding cracks in the joint and satisfied joint strength. Aluminum and steel [14], as well as magnesium alloy and steel [17], were already successfully joined by friction stir welding. Mg alloys have the advantages of low density, high specific strength and excellent damping characteristic [18], and have become potential structural materials in aerospace and automobile manufacture fields. Problems caused by the conventional fusion welding can be dispelled by FSW, which can significantly widen the applications of Mg alloys. Varieties of Mg alloys have been successfully welded by FSW, including Mg–Al–Zn, Mg–Al–Ca and Mg–Al–RE [5,6,19]. The microstructure and mechanical property of stir zone of FSWed AE42 Mg alloy joint have been comprehensively studied [5], while the material flow and grain structure evolution in the AZ31 Mg alloy during friction stir welding were examined by EBSD technique [6]. AZ31 alloy has the widest commercial application among varieties of Mg alloys, but sometimes its strength is not high enough [18]; while AZ80 alloy is of higher strength but with poor deformation ability [20]. Therefore, joining of AZ31 and AZ80 alloy can further enlarge the application of Mg alloys in the industry, and few relative reports have been found so far. The objective of the present work is to obtain defect free FSW joints of AZ31 alloy and AZ80 alloy, and evaluate the anisotropic effect of material arrangement when AZ31 alloy and AZ80 alloy are taken as advancing side, respectively, from view point of microstructure and mechanical properties of the dissimilar joints. The present research can provide general suggestions for friction stir welding of dissimilar materials with different deformability.

2. Experimental procedure

AZ31 alloy and AZ80 alloy processed by extrusion forming with the thickness of 3 mm were adopted in the experiment. SKD61

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stirring tool (nominal chemical composition: 0.36 wt.% C, 0.91 wt.% Si, 0.42 wt.% Mn, 0.023 wt.% P, 0.002 wt.% S, 0.11 wt.% Co, 0.14 wt.% Ni, 5.28 wt.% Cr, 1.22 wt.% Mo, 0.8 wt.% V, balance Fe) with shoulder diameter of 15 mm was used in the study, and the probe length is 2.9 mm with M6 left-hand thread. FSW was conducted at a rotation rate ranging from 750 rpm to 1500 rpm, and the welding speed was from 200 mm/min to 1000 mm/min, with the tool tilt angle of 3° to make sure the rear of the tool was lower than the front. A constant applied load of 9.8 kN was used during the welding process. The schematic illustrations of the FSW of AZ31 alloy and AZ80 alloy are shown in Fig. 1, with AZ80 alloy as the advancing side (AS) (see Fig. 1a) and retreating side (RS) (see Fig. 1b), respectively, and the stirring tool proceeded along the centerline of the two plates in both cases. All the surfaces to be welded were polished by abrasive paper and cleaned by acetone before welding.

After welding, cross section perpendicular to the welding direction was chosen for microstructure observation. The samples were cut, mechanically ground, polished and then etched with a solution consisting of 1 g picric acid, 2.5 mL acetic acid, 2.5 mL H_2O and 17.5 mL ethanol. The microstructure was examined by the optical microscopy (OM) and scanning electron microscope (SEM). In addition, thin foil of stir zone (SZ) for the transmission electron microscopy (TEM) examination was prepared by a focused ion beam (FIB) instrument (JEOL JIB-4500 Multi Beam System).

The tensile testing specimens were machined from the dissimilar joints and then tested using an Instron testing machine at a crosshead speed of 1 mm/min, and the average value of three specimens was taken as the tensile strength of each joint. Microhardness profile was detected on the centerline (see Fig. 2) of cross section by the Vickers hardness tester as well.

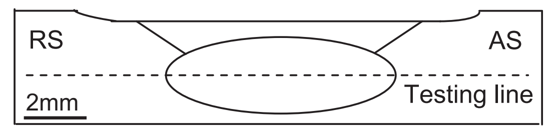

Fig. 2. Schematic illustrations of Vickers hardness testing position on the FSW joints.

3. Results and discussion

3.1. Welding results of AZ80/AZ31 joints and AZ31/AZ80 joints with several different parameters

Welding of AZ80/AZ31 joints (with AZ80 as AS) and AZ31/AZ80 joints (with AZ31 as AS) was performed with several different welding parameters, and the results of X-ray radiography for these joints are shown in Fig. 3a and b, respectively. According to Fig. 3a, sound joints could be obtained with most of welding parameters when AZ80 is at advancing side. When the welding speed was 200 mm/min, welded joints with burr at AZ31 side were formed as the rotation speed increased to 1250 rpm and 1500 rpm. When the rotation speed was kept at 1500 rpm, joint quality turned better with the welding speed increasing from 200 mm/min to 500 mm/min and 1000 mm/min. Therefore, the defect of burr was considered to occur due to the large heat input. Taking AZ31 as advancing side, it was difficult to get high quality joint in most cases as demonstrated in Fig. 3b. Tunnel or rough surface could be observed in most of joints. It suggests that joint qualities differ significantly when different material is set as advancing side with the same welding parameters. This means apparently the anisotropic effect of material arrangement of FSW joint on the joint property. Therefore, the joints welded with three parameters, 200 mm/min, 500 mm/min and 1000 mm/min at the constant rotation speed 1500 rpm as marked by the square in Fig. 3, are focused onto explore the reason for the difference in the following discussions.

3.2. Microstructure and metal flow behavior in the dissimilar joints

The cross sections of the AZ80/AZ31 joints and AZ31/AZ80 joints welded with three different parameters are shown in Fig. 4. For the AZ80/AZ31 joints, as the welding speed decreases from 1000 mm/min to 500 mm/min, distinct onion rings which is considered as good intermixing between two base materials [21] and satisfactory metal flow are observed in the AZ80/AZ31 joint as shown in Fig. 4. The concave surface and burr can be seen when the welding speed is reduced to 200 mm/min, which are caused by excess heat input. Similar defect was found in the FSW joint of ADC12 aluminum alloy as well when higher rotation speed and lower welding speed were used [3]. For the AZ31/AZ80 joints, on the contrary, the metal flow and microstructure become more and more satisfied with the welding speed decreases from 1000 mm/min to 200 mm/min as demonstrated in Fig. 4. Such different degrees of dissimilar mixing were also observed in the FSWed 7075/2024 Al alloys joints corresponding to different welding parameters [21]. Gerlich et al. also indicated that a ribbon of contiguous dissimilar lamellae was produced during each rotation of stirring tool and the tool rotation speed and dwelling time could affect the number of intermingled layer contained in the mixing regions [22]. These results indicate distinctly the welding parameter can influence the pattern of microstructure, and different materials at advancing side result in disparate metal flow behaviors and joining qualities in the stir zone.

For the AZ80/AZ31 joint obtained with the parameter of 1500 rpm–500 mm/min–9.8 kN, the microstructure of stir zone near RS (AZ31 side) marked by A in Fig. 4 is magnified in Fig. 5a, while that near AS (AZ80 side) labeled by B in Fig. 4 is shown in Fig. 5b. It can be seen clearly that AZ80 and AZ31 alloy have been staggered sufficiently via the metal plastic flow in the stir zone at both AS and RS, and the grains have been refined. As for the AZ31/AZ80 joint acquired with the parameter of 1500 rpm–200 mm/

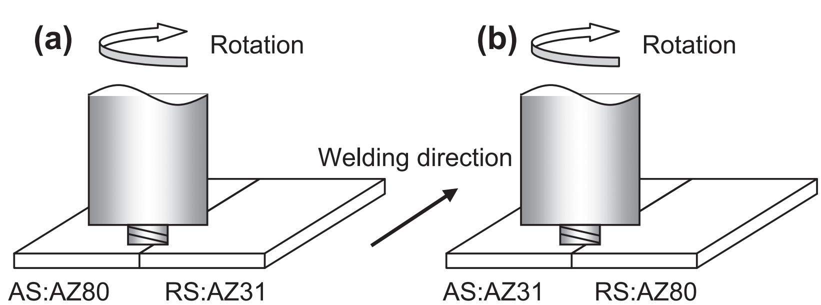

Fig. 1. Schematic illustrations of the FSW of AZ31 alloy and AZ80 alloy: (a) AZ80 is at advancing side (AZ80/AZ31 joint), (b) AZ31 is at advancing side (AZ31/AZ80 joint).

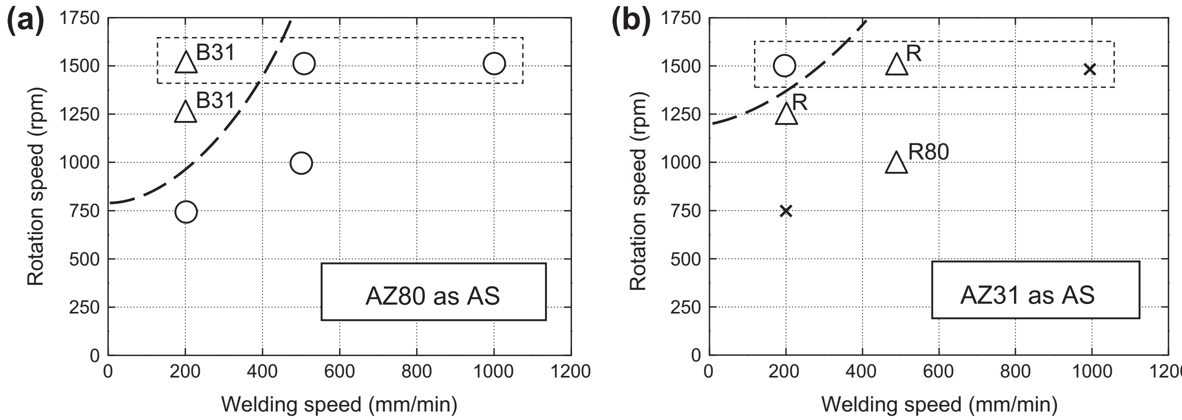

Fig. 3. The results of X-ray radiography for these dissimilar joints: (a) AZ80/AZ31 joint and (b) AZ31/AZ80 joint (○ – Defect-free, △ – joint with external defect, × – joint with internal defect, B-large burr, R-rough surface, T-tunnel, 80-defect occurs at AZ80 side, 31-defect occurs at AZ31 side).

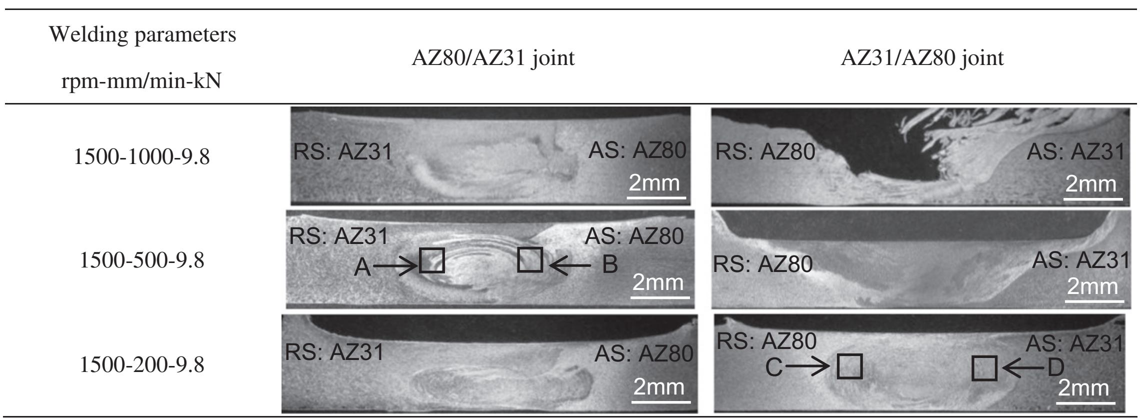

Fig. 4. Microstructure evolution of AZ80/AZ31 joints and AZ31/AZ80 joints with three different welding parameters.

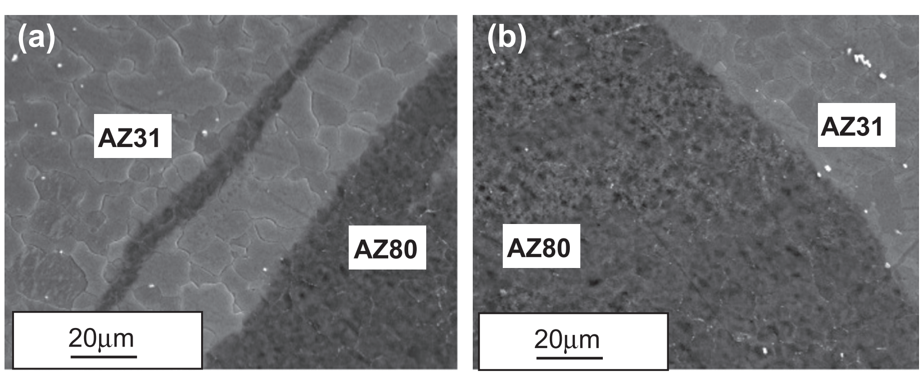

Fig. 5. Microstructures of stir zone of AZ80/AZ31 joint welded at 1500 rpm–500 mm/min–9.8 kN: (a) magnification of site A in Fig. 4, and (b) magnification of site B in Fig. 4.

min–9.8 kN, two sites in the stir zone marked by C and D in Fig. 4 have been magnified in Fig. 6. Fig. 6a indicates that metal flow of stir zone at RS is adequate, which can be confirmed by the interlaced AZ31 alloy and AZ80 alloy. However, according to Fig. 6b, poor metal flow of stir zone at AS is identified because almost all the microstructure of this zone is AZ31. The movements of base materials from AS to RS and from RS to AS under the shoulder were mentioned in dissimilar Al alloys FSW joint from view point of effects of tool rotation and welding parameters, and different degrees of dissimilar mixing of AA7075/AA2024 were achieved in the weld depending on the rotation speed [23], however, the intense onion ring and better weld appearance could not be obtained simultaneously with the same condition.

The feature of microstructure shown in Figs. 5 and 6 can be explained by the following two reasons. The first one is, even for the FSW of the same material, the metal flow from AS to RS is easier than that from RS to AS. The second one is AZ80 alloy contains higher content of element Al than AZ31, and the compounds containing Al (see Fig. 7) attributes to higher strength and hardness but lower plastic distortion ability of AZ80 than that of AZ31. Therefore, when AZ31 is at retreating side, the flow of plastic metal back from RS to AS tends to be more fluent as shown in Fig. 8a and c, while when AZ80 is at retreating side, poorer deformation of AZ80 leads to the hindered flow back to the AS as demonstrated in Fig. 8b and d. That is why the joint with AZ80 as RS needs more heat input to accomplish the sufficient metal flow in order to get

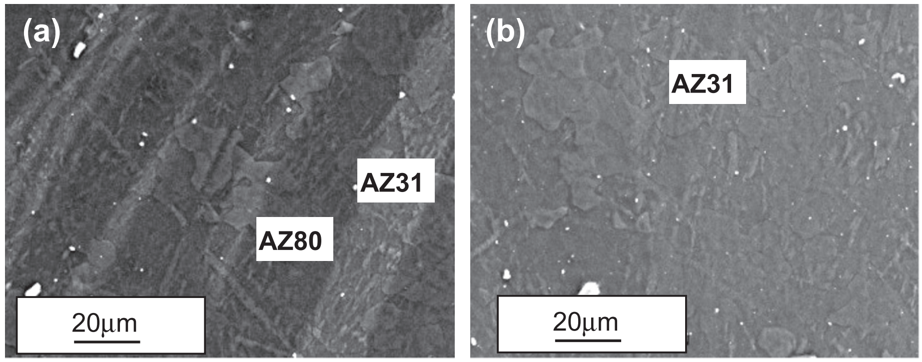

Fig. 6. Microstructures of stir zone of AZ31/AZ80 joint welded at 1500 rpm–200 mm/min–9.8 kN: (a) magnification of site C in Fig. 4 and (b) magnification of site D in Fig. 4.

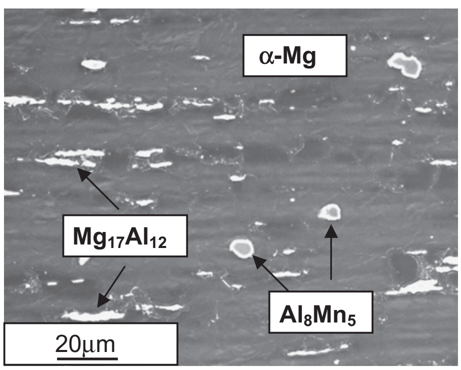

Fig. 7. Microstructure of AZ80 base material.

satisfied joint quality. The Ti alloy was also positioned as AS while Mg alloy as RS during FSW of Mg–Al alloy/Ti alloy in Ref. [19], but the difference was that the probe was inserted in Mg alloy side and touched Ti alloy slightly, resulting in the thin reaction layer at the joint interface between two base materials.

Further magnification for the staggered AZ31 and AZ80 alloy in the stir zone of AZ80/AZ31 joint welded with the parameter of 1500 rpm–500 mm/min–9.8 kN is shown in Fig. 9a, and grains containing both grey microstructure and black microstructure are observed at the interface of the two alloys as marked by the white dotted line in Fig. 9a. Element distributions of Mg and Al shown in Fig. 9b and c indicate that content of Mg decreases and content of Al increases from the left to the right side along the white solid line, which suggests that AZ31 and AZ80 are probably contained in one grain, and there seems to be an interface dividing this grain into two parts. To further prove this, TEM observation and map scanning have been performed at this interface as shown in Fig. 10a and b. According to Fig. 10b, the grains below the black dotted line contain more Al than those above the line in Fig. 10a. Then the zone circled by the square in Fig. 10a is further magnified and map scanned, as demonstrated in Fig. 10c and d. It can be seen distinctly that content of Al at the left part is more than that at the right part of the grain. This indicates that metal plastic flow is

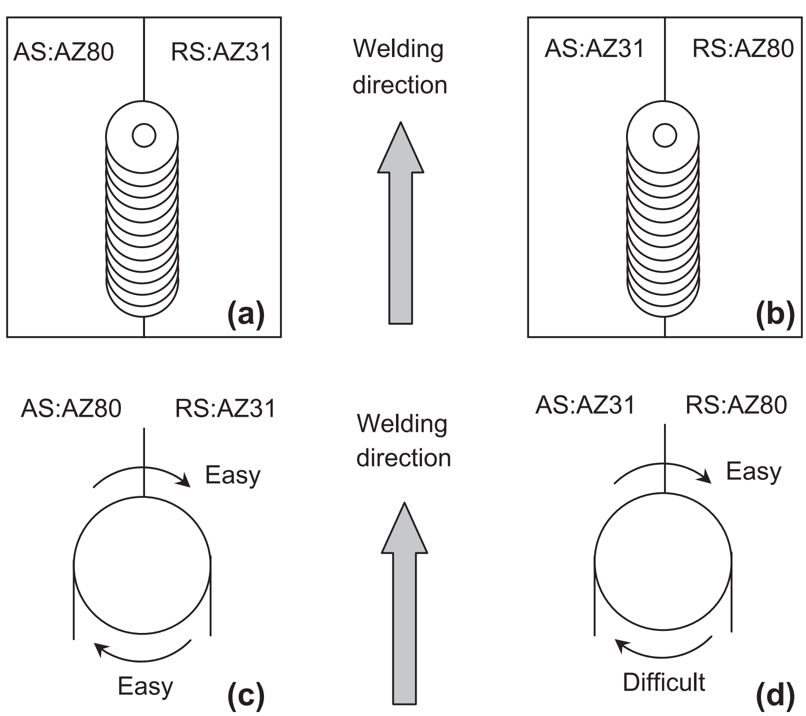

Fig. 8. Schematics of metal flow behavior in dissimilar welding of AZ31 and AZ80 alloys: (a) AZ80/AZ31 joint, (b) AZ31/AZ80 joint, (c) metal flow behavior during one rotation of tool in AZ80/AZ31 joint, and (d) metal flow behavior during one rotation of tool in AZ31/AZ80 joint.

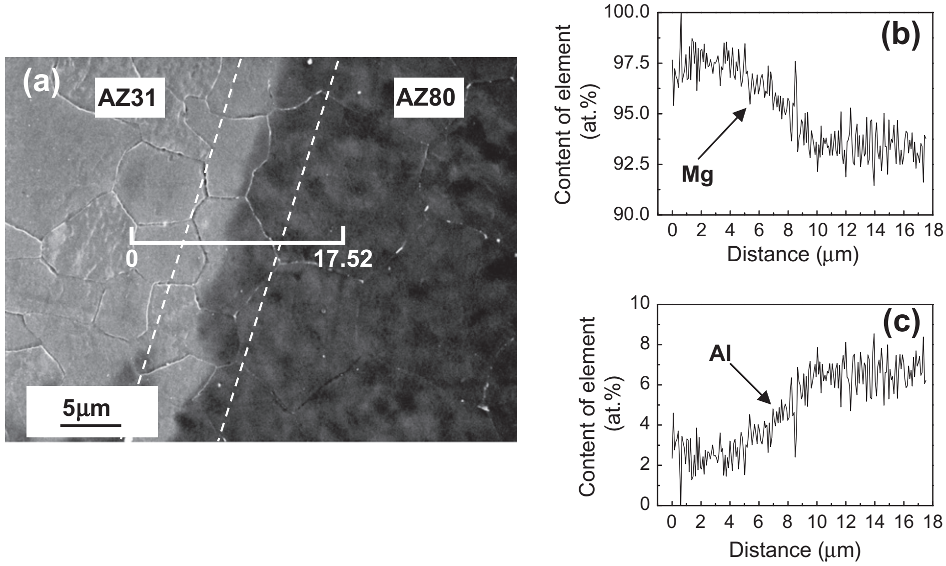

Fig. 9. Microstructure and element distribution of stir zone for the AZ80/AZ31 joint welded at 1500 rpm–500 mm/min–9.8 kN.

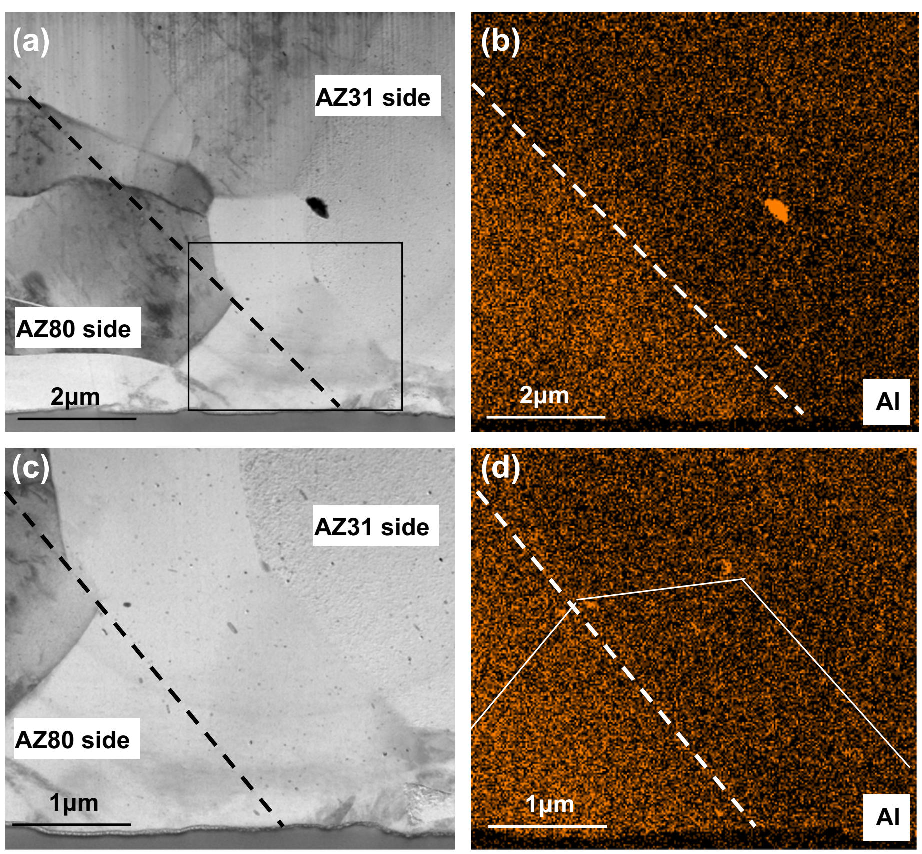

Fig. 10. TEM observation and map scanning of the selected microstructure: (a) microstructure at the interface, (b) map scanning of (a), (c) magnification of the microstructure circled by the square in (a), and (d) map scanning of (c).

sufficient and dynamic recrystallization behavior has occurred in both AZ80 alloy and AZ31 alloy in the SZ with the adequate and proper heat input during the FSW process.

3.3. Mechanical properties of the dissimilar joints

Fig. 11 displays the tensile strength of the dissimilar joints described in Fig. 4. The grey bars represent the tensile strength of AZ80/AZ31 joints, while the white bars express that of AZ31/AZ80 joints. When AZ80 is at advancing side (AZ80/AZ31 joints), the tensile strength of joints welded with parameter of 1500 rpm–1000 mm/min–9.8 kN and 1500 rpm–500 mm/min–9.8 kN is 235 MPa and 240 MPa, respectively, and the strength decreases to 61 MPa as the welding speed reduces to 200 mm/min. That is because excessive heat input was generated with the parameter of 1500 rpm–200 mm/min–9.8 kN, resulting in large

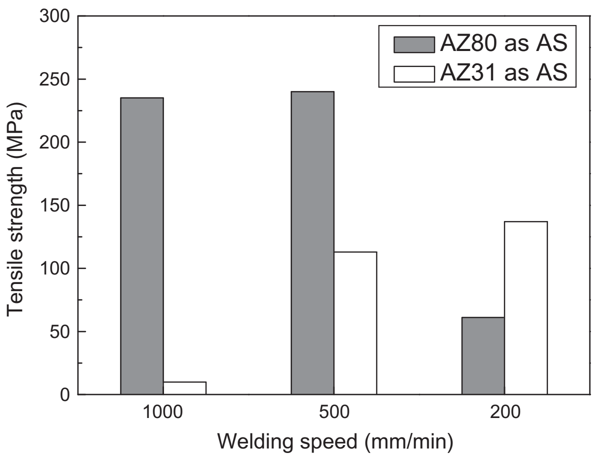

Fig. 11. Tensile strength of AZ80/AZ31 joints (AZ80 is at AS) and AZ31/AZ80 joints (AZ31 is at AS) welded with three different welding parameters shown in Fig. 4.

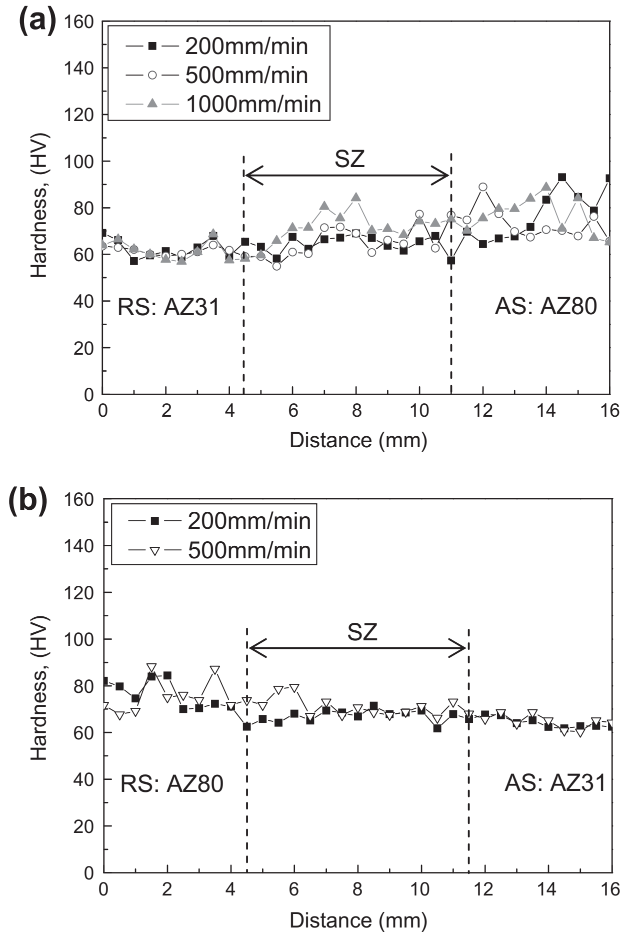

Fig. 12. Microhardness of AZ80/AZ31 joints and AZ31/AZ80 joints welded with different parameters shown in Fig. 4: (a) AZ80/AZ31 joints and (b) AZ31/AZ80 joints.

burr and concave surface on the joint, and the thickness of stir zone of the joint is decreased significantly, which cause the joint to fracture more easily during tensile testing. Similar result was reported in Ref. [2] during tensile strength testing of Al alloy FSW joint when the welding speed was lower than 400 mm/min. When AZ31 is at advancing side (AZ31/AZ80 joints), the tensile strength of joints improves with the welding speed decreased from 1000 mm/min to 200 mm/min, but it remains less than 150 MPa. This result proves again that AZ31/AZ80 joints need more heat input to obtain high quality joining than AZ80/AZ31 joints. Furthermore, taking AZ80 as AS tends to get more satisfied FSW joints than setting AZ31 as AS.

According to the microhardness testing results demonstrated in Fig. 12, the hardness increases gradually from AZ31 side to AZ80 side for both AZ80/AZ31 joints and AZ31/AZ80 joints, even though, SZ hardness of AZ80/AZ31 joints (see Fig. 12a) is a little larger than that of AZ31/AZ80 joints (see Fig. 12b). There are two reasons for this phenomenon, one is that microhardness of AZ80 is larger than that of AZ31 alloy, and as for the microhardness of AZ80 alloy, the fluctuation of value is caused by the rigid compounds which strengthen the base material effectively; the other is more sufficient plastic deformation and metal flow occur in the SZ when AZ80 is taken as AS rather than AZ31. Such heterogeneous micro-hardness distribution was also noted on the dissimilar AA7075/AA2024 joint, especially at the stir zone, and it was indicated that this distribution had been attributed to the absence of adequate material mixing between both Al alloys [21].

As can be seen in Fig. 12a, the value of hardness increases step by step from RS to AS for the AZ80/AZ31 joints although there is some fluctuation caused by AZ80 alloy, while a decrease of microhardness value is displayed around the interface of SZ and RS followed by a nearly flat curve until AS in Fig. 12b. This is in accordance with the microstructural feature observed in the SZ of both AZ80/AZ31 joints and AZ31/AZ80 joints, that is, AZ80 and AZ31 are mixed sufficiently in the SZ of AZ80/AZ31 joints as shown in Fig. 5, while less AZ80 alloy is observed in the SZ near AZ31 side in AZ31/AZ80 joints (see Fig. 6).

4. Conclusions

When AZ80 is taken as advancing side (AZ80/AZ31 joint), satisfied joints can be formed with most of welding parameters, while when AZ31 is at advancing side (AZ31/AZ80 joint), it is difficult to obtain high quality joint in most cases.

Compared with AZ80/AZ31 joints, AZ31/AZ80 joints need more heat input to generate high quality FSW joint. The reason is, on the one hand, even for the FSW of the same material, the metal flow from AS to RS is easier than that from RS to AS, on the other hand, AZ80 alloy presents higher strength and hardness but lower plastic distortion ability than AZ31 due to the higher Al content as well as the rigid compounds within it. Therefore, dissatisfactory deformation of AZ80 in the SZ leads to the impeded flow back to the advancing side when AZ80 is at retreating side.

With the welding speed reduces from 500 mm/min to 200 mm/min, the tensile strength of AZ80/AZ31 joint decreases from 240 MPa to 61 MPa, while that of AZ31/AZ80 joints increases from 113 MPa to 137 MPa. This also identifies AZ31/AZ80 joints need more heat input than AZ80/AZ31 joints to get sound joining. Microhardness testing results for the dissimilar joints show the transition of curve from RS to AS is smoother for AZ80/AZ31 joints, since different materials at advancing side would generate different metal flows, resulting in different microstructures and joint properties.

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