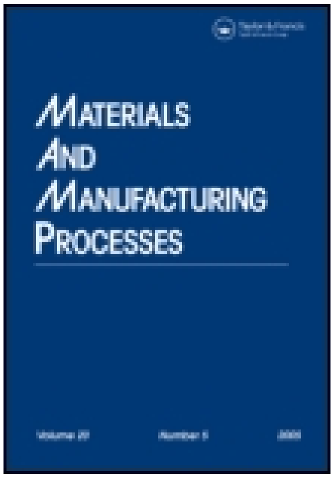

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Experimental Investigation of Material Flow and Welding Defects in Friction Stir Welding of Aluminum to Brass

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Experimental Investigation of Material Flow and Welding Defects in Friction Stir Welding of Aluminum to Brass

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In this research, the formation of a nugget zone in dissimilar friction stir welding (FSW) of brass to aluminum has been investigated. Also, the main parts of a stir zone (SZ) besides their dependency to the welding parameters are probed. The base materials play the role of marker to reveal the material flow pattern. Investigations carried out by optical microscopy and scanning electron microscopy verifies the formation of three different areas including pin affected zone, shoulder affected zone, and swirling zone within the SZ. Moreover, the various types of defects such as tunneling defect, coarse fragment defect created during dissimilar FSW are analyzed. Also, an attempt has been made to remove the defects by adjusting the welding parameters especially the offset value which features in defects formation.

Keywords Aluminum; Composite; Defect; Dissimilar; Flow; Welding.

Introduction

Friction stir welding (FSW) process was developed at The Welding Institute "TWI" for the first time in 1991 [1]. Since then, several attempts have been made to make this process feasible for industrial applications. Generally, these efforts can be classified into three main categories: 1) investigating the mechanism of process by means of studying pattern of material flow during welding [2–7]; 2) probing the effect of various welding parameters on mechanical and metallurgical properties of joint [8–14]; and 3) attempt to extend this process into dissimilar joining of materials [15–19].

Undoubtedly, material flow features in ultimate properties of friction stir welded couples. Consequently, studying the pattern of material flow during welding has engrossed researchers. In order to ease the observation of material flow, several experimental methods have been utilized. Laying a thin dissimilar foil along the interface will lead to a better understanding of material flow [3]. Also, in steel shot tracing technique and stop action technique, putting small balls in different locations along the weld will leave behind projections during radiographic testing where distribution of balls can reveal flow of materials [20]. Moreover, inserting a proper material possessing dissimilar etching characteristic in various locations of welding path in material insert technique (MIT) is helpful to reveal the material flow [2, 21]. In addition, numerical methods are used to visualize the flow of materials during FSW process [22].

In previous studies carried out by the authors, a comprehensive investigation about weldability and mechanical and metallurgical properties of friction stir welded Al/brass joints has been performed [23, 24], where an optimum strength was obtained, and the important role of weld defects besides material flow on the weld behavior was revealed. Both brass and aluminum have high corrosion resistance and high thermal and electrical conductivity, and the joining of these two metals can be used in heat transfer systems, power generation, and electrical applications.

Until now, no significant study has been carried out on material flow of dissimilar FSW where existence of simultaneous dissimilar material flows makes the situation different in comparison with what occurs in similar FSW. Shifting the tool location towards the softer material defining the offset value controls the fragment formation in the stir zone (SZ). Creation of fragments coming from harder material will act as barrier against material flow in the SZ, which cannot be observed in a similar joining of materials by FSW. In this study, the effect of offset value on flow of material in dissimilar FSW of brass to aluminum has been investigated. Furthermore, as an innovation, it has been proved through this study that the base materials (specially the harder material) can be used as marker for observation of material flow instead of using mentioned common techniques.

In other joining methods, the occurrence of defects is inevitable. Tunneling defects, voids, grooves, and cracks are most known defects in similar and dissimilar FSW. Also, the existence of coarse fragments of harder material dispersed within the softer material introduces a new important weld defect in dissimilar FSW, which is not considered in similar joining of materials. Hence, the formation of these defects during FSW is strongly

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TABLE 1.—Welding parameters used to fabricate joints.

Parameter	Value
Welding speed (mm/min)	8
Rotational speed (rpm)	450
Depth of sinking pin (mm)	0.25
Welding tilt angle	1.5
Offset (mm)	0–1.6

related to the material flow and consequently welding parameters, defects creation should be investigated beside studying the flow of materials. In this study, the formation of weld defects and their relation with material flow have been probed.

EXPERIMENTAL PROCEDURE

In order to prepare the weld samples, brass and aluminum 1050 sheets with dimensions of 150 mm × 70 mm × 3 mm were fixed in butt position lying on a backing plate. Then, dissimilar plates were welded by various values of offset (shifting of tool center position towards the retreating side). It is important to note that interface is assumed as zero value for offset, and the positive direction for offset is chosen towards aluminum. The parameters used to fabricate welds are listed in Table 1. A schematic view of the tool's geometry is shown in Fig. 1. The material used for the tool was hot working alloy steel (1.234 according to WN standard). Also, the brass played the role of advancing side, whereas the aluminum was retreating side.

Due to observation of material flow and weld defects, the scanning electron microscopy was utilized where the brass phase is bright portion of images. Also, to reveal the primary flow of material just before a complete formation of nugget zone, the center of the key whole was sectioned by means of wire cut machine. In addition, Radiography Test (RT) was carried out to better interpret material flow of joint. Furthermore, optical microscopy was used to obtain a better understanding of weld defects. Moreover, the root of welds was machined to remove a thickness of 0.5 mm which made reaching the substrate defects possible.

RESULTS AND DISCUSSION

Material Flow

Figure 2 shows the nugget zone before completion of welding procedure. As it is seen, the nugget zone can be

FIGURE 1.—Schematic view of the tool's geometry (all dimensions are mm).

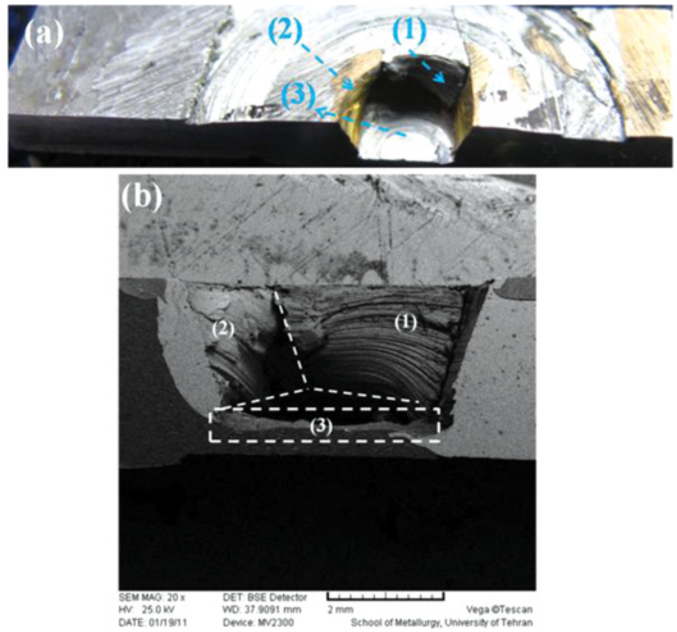

FIGURE 2.—Formation of three distinguished zones before completion of nugget zone: (a) isometric view and (b) front view (color figure available online).

divided into three main areas, as follows: 1) the shoulder affected zone or forged zone, 2) the rotating pin affected zone or shear zone, and 3) the bottom of pin affected zone which is a swirling area. These three distinguished parts will form the SZ in the FSW process where weld is composed of four main areas including Thermo-Mechanically Affected Zone (TMAZ), Heat Affected Zone (HAZ), SZ, and base metals. The majority of formed defects during FSW are arisen from unsuitable material flow within these three zones. This phenomenon will result in a decohesive structure along boundary of mentioned zones. One helpful way to avoid formation of microscopic defects is studying the mechanism of material flow.

During FSW, by penetration of pin into the interface of plates, a continuous flash forms. The formation of this flash is initiated by means of pin penetration, whereas the shoulder contact intensifies flash formation. Due to using leading angle of 1.5 degree, the significant amount of material flow will appear behind the shoulder.

Occurrence of friction between shoulder and upper surface of materials in addition to cold deformation around the pin produces sufficient heat to soften materials. Consequently, the materials will be able to flow freely under the effect of tool rotation. Results reveal that by forward movement of tool, brass as an advancing material rotates around the pin. As it is shown in Fig. 3, this flow will end after rotating θ degrees around the pin. This angle depends on offset values drastically. According to the obtained results, by changing the offset value, i.e., shifting the tool position towards the aluminum, the θ angle will decrease (Fig. 3a,b). Figure 3a shows 180 degrees rotation of a thin layer of brass,

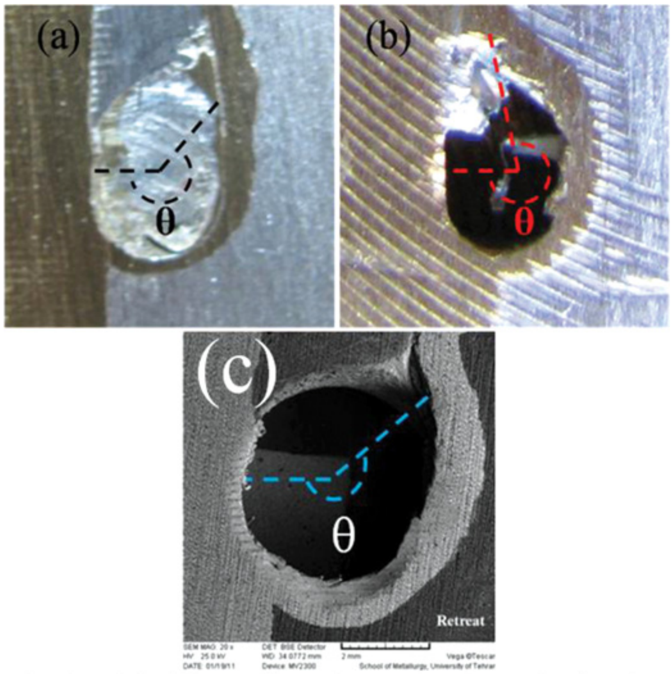

FIGURE 3.—Changing of rotational angle in different offset values: (a) 180 degrees in offset of 1 mm, (b) 300 degrees in offset of 0 mm, and (c) SEM image of rotational angle of thin brass layer in shear zone (color figure available online).

whereas this angle increases to higher degrees about 300° for lower offset values in Fig. 3b. Figure 4 illustrates changes of brass layer during moving from pin affected zone to the end of shoulder affected zone. As you can see in this figure, the height of brass layer gradually diminishes when it passes along the shoulder affected zone (h1 > h2). On the other hand, due to increment of applied force by advancing of shoulder, the thickness of brass layer increases (T1 < T2).

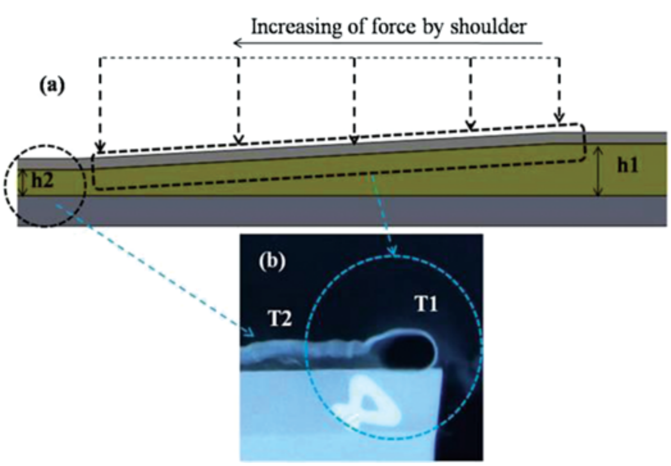

FIGURE 4.—Changing of brass layer in matrix of aluminum through the shoulder affected zone: (a) decreasing of the height of brass layer (h1 > h2) in side view and (b) increment of the thickness of brass layer (T2 > T1) in top view of the weld (color figure available online).

Also, increment of offset value is accompanied by crumbling the continuous layer of advancing material in shear zone which will lead to formation of a composite structure in an optimum offset value of +1.6 mm (Fig. 5a–c).

Furthermore, it is observed that extreme increase of offset makes the advancing material flow within the retreating side disappear in the shear zone. It is seen that pin rotation extrudes the aluminum as retreating material towards back of the pin in a lamellar form. During movement of layers, flow of materials shifts up. This path illustrated by means of red arrow in Fig. 6 can be attributed to the leading angle of pin and resistance against movement of extruded layers imposed by cold part of retreating side. This lamellar extrusion of retreating material besides flow of advancing material all arisen from rotation of pin forms the pin affected area in the SZ. Also, this zone will not exist till end of welding procedure. By passing the shoulder, the imposed forging force affects this temporary area. As a matter of fact, pin affected zone provides the coming forged zone with primary requirements including a chamber behind the pin besides the filling material to be forged within, and will be sacrificed for formation of shoulder affected zone which shall be discussed in detail through following paragraphs.

Also, due to incomplete rotation of sheared material including brass and aluminum around the pin besides forward movement of pin which lowers the pressure behind the tool, a cavity occurs locating behind the pin and adjacent to the advancing side. As it is shown in Fig. 7, this cavity is extended from bottom of the SZ into the surface right behind the shoulder. It is seen that by further shifting of the tool position towards the aluminum, the cavity shrinks, and finally disappears at

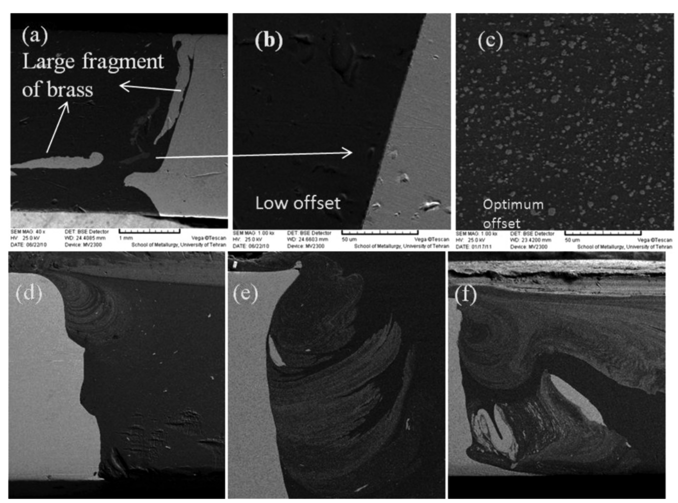

FIGURE 5.—Crumbling of large fragment to fine particles by increasing of offset value toward the optimum value: (a), (b) low offset; (c) optimum offset; (d), (e) various distributions of fine brass particles in aluminum matrix in form of regular onion rings at optimum value of offset; and (f) harsh distribution at lower values of offset.

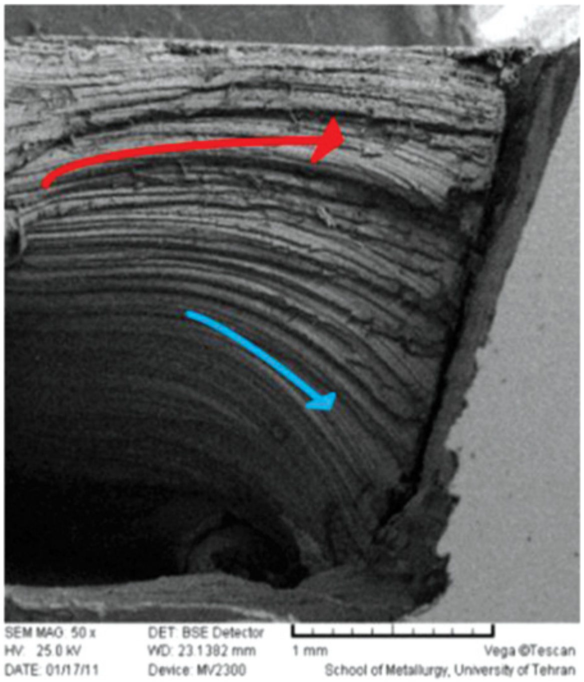

FIGURE 6.—Extruded layers of materials in shoulder affected zone (color figure available online).

an optimum value of offset. Also, the front section of this unfilled cavity formed just back of the pin is shown in Fig. 2.

As it was discussed, upward shifting of materials accumulates the extruded layers under the shoulder surface which is accompanied by a cavity formation behind the pin. Rotation of shoulder produces sufficient heat to soften materials over the cavity. By advancing of shoulder, the pressure imposed by slight penetration of shoulder into the materials surface will jam the soft materials under the shoulder towards the existing cavity behind the pin. Filling of the cavity will not occur once. On the other hand, by advancing the tool, the cavity will be filled gradually. This step-by-step filling process leaves a lamellar pattern within the SZ, known as onion rings, illustrated in Fig. 5d,e. Severe friction occurs under the shoulder crumbles the brass particles in the matrix of aluminum. As a result, the filled cavity by fallen material behaves as a composite structure where size and distribution of brass particles can vary strongly according to the welding parameters. Figure 5 shows several composite structures within the SZ possessing various particle size and particle distribution.

Moreover, passing the shoulder presses the filled cavity. As it is illustrated in Fig. 6, the blue arrow reveals the deflection of material flow under pressure of advancing shoulder towards cavity, whereas flows located near the pin which have not received sufficient pressure yet are still moving upward (illustrated by red arrow in Fig. 6). As a matter of fact, the leading angle of tool makes existing pressure nonuniform where pressure decreases by approaching the pin. Consequently, the flows located near the pin will not fall until the shoulder advancement provides sufficient pressure. In other words, shoulder will crush the material into the cavity leading to complete removal of hole and creation of the forged zone.

Beside the upward movement of material in front of the pin, a small part of flow will escape under the pin and form the swirling zone. Lack of forging force exerted by the pin in this area increases the probability of decohesion occurrence. As a result, it is important to remove a sufficient layer of the root side by machining to reach the real root. In this way, the swirling zone which can aggravate the mechanical properties severely will be removed.

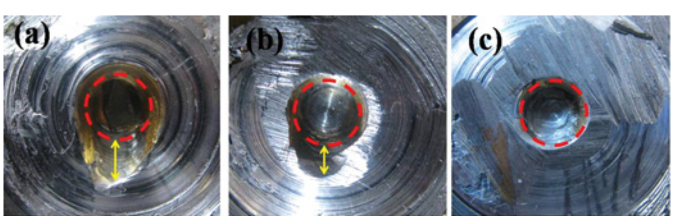

FIGURE 7.—Removal of cavity behind the pin through shifting tool position towards aluminum: (a) offset of 0.5 mm, (b) offset of 1 mm, and (c) offset of 1.6 mm as an optimum offset (color figure available online).

Defects

The major reason developing weld defects during FSW is the occurrence of an improper flow of material which makes the formation of an inhomogeneous weld structure possible. Selecting unsuitable welding parameters plays an important role in inappropriate material flow formation. As it was explained, the hole formed behind the pin during welding is the most potential area not to be filled completely. This area of the boundary of three defined subzones is illustrated in Fig. 2b. Usually, the severe soften material under the shoulder will not allow the upper part of the cavity to remain unfilled.

However, the lower part needs sufficient pressure to be filled completely. Consequently, lack of pressure results in a continuous defect trailing behind the pin called Tunneling defect. Figure 8 shows a tunneling defect occurred in aluminum side as a result of low penetration value. As it is seen, in spite of a sound appearance, the tunneling defect can lay beneath the surface and above the root.

Another major defect seen just in dissimilar FSW is the existence of large advancing material particles distributed within the retreating material. This defect categorized as fragment defects will aggravate the mechanical properties of weld strongly. This effect can be attributed to two main characteristics of these fragments. All above, the existence of harder material particles through a flow of soft material will disturb the stream severely. According to the obtained results, the disturbed flow will not be able to fill sharp edges and contact surfaces of fragments. Consequently, occurrence of these large fragments will be accompanied by some

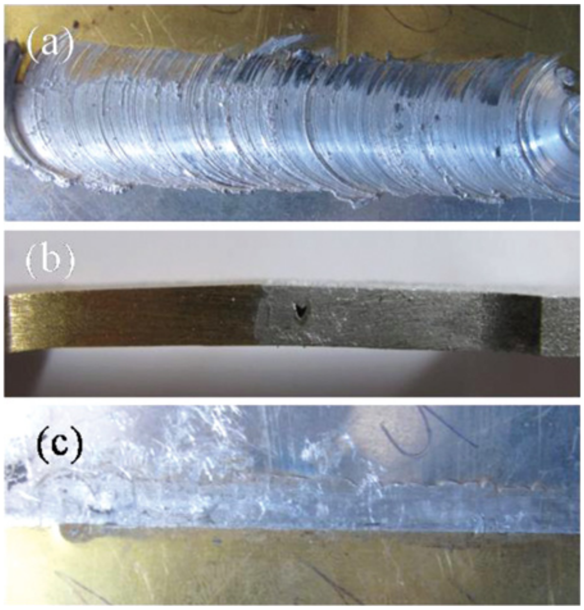

FIGURE 8.—Tunneling defect. Cross-sectional view (b) beside apparently sound upper and root surfaces (a), (c) (color figure available online).

defects such as voids which are shown by dashed circles in Fig. 9. Secondly, the coarse fragments usually contain microcracks spoiling weld strength. These cracks are illustrated in Fig. 9 by white arrows. It is important to note that fine brass particles seen in onion rings play reinforcing role within the aluminum, despite aggravating role of large brass particles. The results show that selecting optimum offset value besides rotation speed can decrease fragment defects strongly. Shifting the tool position towards aluminum and reduction of the rotation speed decreases the fragment defects. However, according to the obtained results, severe lowering the rotation speed or increment of offset value will be accompanied by fabrication of a weak joint. As a result, an optimum value should be selected for offset value and rotation speed. The offset value of +1.6 mm and rotation speed of 450 rpm resulted in a sound joint during FSW of brass to aluminum.

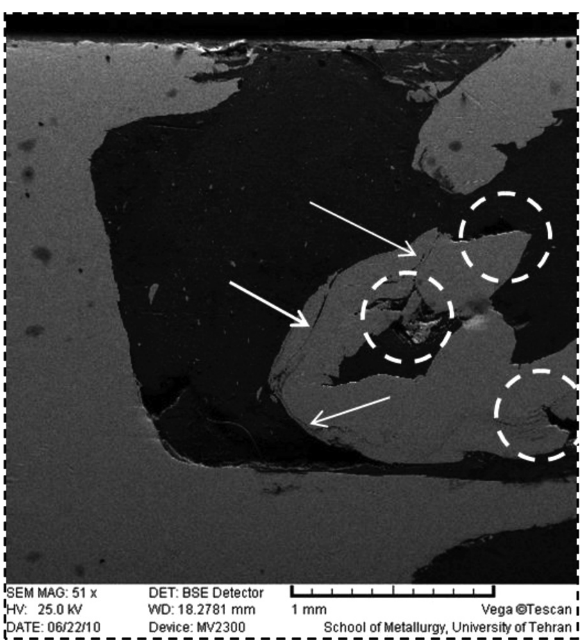

FIGURE 9.—Fragment defects accompanied by cracks and voids.

Totally, the role of offset in creating fragment defect is more important than rotation speed. However, a coarse fragment can be seen in high rotation speed (Fig. 10b). High and low rotation speed will intensify weld defects. Weld defects such as tunneling defect, and macroscopic cracks are usually arisen from an improper material flow in the SZ [25]. Due to lack of heat production, slow rotation (200 rpm) will not achieve a suitable temperature. Therefore, the SZ cannot be plasticized appropriately, and an improper flow will result in defects especially macrocrack along upper surface of the weld (Fig. 10a).

Moreover, when rotation speed is high (900 rpm), the excessive heat will plasticize the SZ severely besides decreasing yield strength of brass in vicinity of interface. So, low viscosity in SZ will create more turbulence resulting in weld defects especially tunnel defects, and brass softening in vicinity of interface leads to appearance of large brass fragments in the SZ. Formation of these large fragments will be accompanied by sharp edges which cannot be filled by plasticized aluminum perfectly. Consequently, weld defects will be observed in vicinity of fragments (Fig. 10b).

Another defect resulted by low rotation speed is appearance of spongy structure in cross section of the joint. Lack of heat production during welding will reduce the plasticity of material flow. Results reveal that this phenomenon leads to formation of a spongy structure locating near the interface. Figures 11a–c shows a spongy structure within the aluminum in vicinity of interface. Moreover, using slow rotation such as 200 rpm forms a decohesive interface which is illustrated in

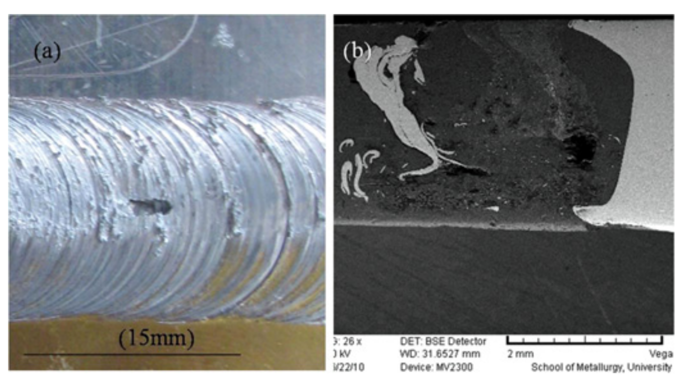

FIGURE 10.—The effect of rotation speed on the formation of defects: (a) macrocrack in low rotation, (b) fragment defect in high rotation low rotation, and (c) fragment defect in high rotation (color figure available online).

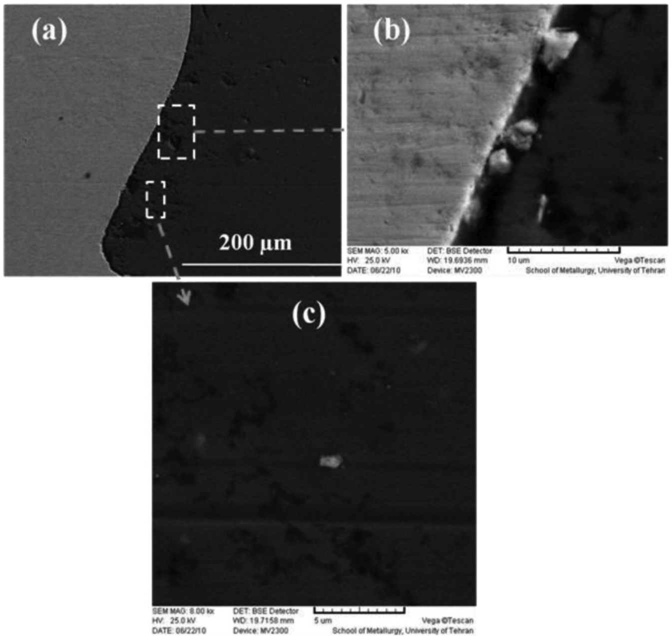

Figure 11.—Spongy structure created in low rotation speed (200 rpm): (a) macroscopic view, (b) microscopic view of interface showing lack of diffusion at interface, and (c) microscopic view in vicinity of interface showing spongy structure.

Fig. 11b. As a matter of fact, lower temperature cannot provide the interface with a good diffusion condition and a consequent metallurgical bonding.

Utilizing extreme or low penetration can leave surface defects in form of groove. The shoulder must penetrate into the base metals sufficiently to make a proper contact between the trailing side of the shoulder and materials. The minimum critical contact is achieved when the friction surface makes a fully semicircle pattern. So, the appearance of friction surface can be used for an appropriate penetration assessment. Results indicate that lack of pressure will form visually detectable surface groove defects on the friction surface which are shown in Fig. 12a,b. As it was discussed previously, utilizing low penetration can initiate the tunneling defect beneath the surface besides the surface groove defects.

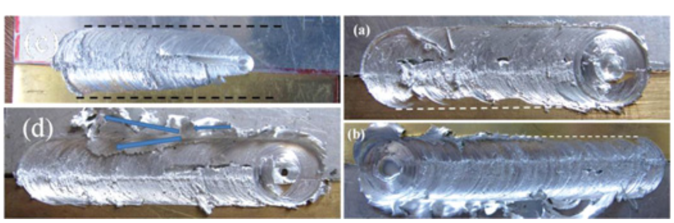

Figure 12.—(a), (b) Surface groove defect at upper surface of the weld formed in low pressure. (c) Gradual appearance of flat surface groove defect by decreasing of penetration depth. (d) Effect of extreme penetration depth on the formation of groove defect (color figure available online).

In order to obtain a better observation of pressure effect on the surface groove defect formation, the penetration depth was reduced during advancement of stirring tool. The results are shown in Fig. 12c where the removal of surface groove by increment of penetration depth can be observed clearly.

Also, it is observed that extreme pressure creates surface groove defects too. In this situation, intensified penetration will produce excessive flash which moves the material away from the friction surface. So, the consequent lack of material in the surface of weld eases the surface groove defect formation. Figure 12d shows the effect of extreme penetration depth on the appearance of weld.

Conclusion

In summary, three distinct zones form the final nugget zone in FSW: a zone affected by the shoulder or forged zone, a zone influenced by the pin or shear zone, and an area affected by bottom of the pin called swirl zone. Also using low values of offset is accompanied by a cavity formation behind the pin. This hole will be eliminated at optimum value of offset (+1.6 mm). It is observed that at an optimum offsetting the type of material in the shear zone changes from brass to brass-aluminum composite gradually. This composite structure consisting of fine brass particles in aluminum matrix was observed, particularly in upper zone of the weld. Finally, results reveal that an improper flow of material arisen from unsuitable welding parameters selection leads to formation of various defects including tunneling defects, crack, spongy structure, surface groove, and a new defect called fragment defect seen just in dissimilar FSW.

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