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Microstructure and mechanical properties of dissimilar pure copper/1350 aluminum alloy butt joints by friction stir welding

LI Xia-wei, ZHANG Da-tong, QIU Cheng, ZHANG Wen

National Engineering Research Center of Near-Net-Shape Forming for Metallic Materials,
School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China

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Abstract: The dissimilar friction stir welding of pure copper/1350 aluminum alloy sheet with a thickness of 3 mm was investigated. Most of the rotating pin was inserted into the aluminum alloy side through a pin-off technique, and sound welds were obtained at a rotation speed of 1000 r/min and a welding speed of 80 mm/min. Complicated microstructure was formed in the nugget, in which vortex-like pattern and lamella structure could be found. No intermetallic compounds were found in the nugget. The hardness distribution indicates that the hardness at the copper side of the nugget is higher than that at the aluminum alloy side, and the hardness at the bottom of the nugget is generally higher than that in other regions. The ultimate tensile strength and elongation of the dissimilar welds are 152 MPa and 6.3%, respectively. The fracture surface observation shows that the dissimilar joints fail with a ductile-brittle mixed fracture mode during tensile test.

Key words: friction stir welding; dissimilar butt joint; microstructure; mechanical properties

1 Introduction

Copper has excellent ductility, corrosion resistance, thermal and electrical conductivity, and has been widely used to produce engineering parts such as electrical component and radiator. Aluminum can be used as a substitute for copper since it is similar to copper in the above-mentioned properties. Replacing copper by aluminum has potential applications since similar electric properties can be achieved at a lower price and a lower density [1]. Aiming at replacing copper with aluminum successfully, the welding of these two metals is a key problem to be solved. However, due to the difference of chemical, physical and mechanical properties between the components to be welded, the welding of dissimilar materials is generally more difficult than that of homogeneous materials. High-quality Cu−Al dissimilar joint is hard to be produced by fusion welding techniques due to the large difference of melting points, brittle intermetallic compounds existence and crack formation [1−3]. Therefore, dissimilar welding of copper and aluminum alloys is a challenging technique to be developed.

As a newly-developed solid-state joining technique, friction stir welding (FSW) has many advantages including low processing temperature, easy work-piece preparation, no need of shielding gases and microstructure refinement in the welds, and has been applied widely to joining metallic materials such as aluminum, magnesium and copper alloys [4,5]. Recently, FSW is considered to be a potential candidate to join dissimilar metals and alloys effectively, and dissimilar FSW of Al/Mg, Al/steel, Al/Ti, etc. has been studied [6−9]. In a recent review paper, MURR [10] pointed out that a host of unweldable systems by fusion welding can be effectively jointed by FSW without melt, including contrasting melting temperature systems. As to joining copper to aluminum alloys, some studies have also been carried out [2,3,11−15]. XUE et al [11] studied the effects of FSW parameters on the microstructures and properties of Cu−1060Al dissimilar joints, and suggested that a thin and continuous layer of intermetallic compounds was necessary to achieve sound Cu−Al joints. OUYANG et al [3] measured the welding temperature profile and investigated the microstructure evolution in the FSW process of Cu−6061Al system. Based on the experimental results, they discussed the mechanism of the intermetallic compounds formation in detail. SAEID et al [12,13] used FSW to produce the lap joints of

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Corresponding author: ZHANG Da-tong; Tel: +86-20-87112272; Fax: +86-20-87112111; E-mail: dtzhang@scut.edu.cn
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Cu−1060Al. Compared with the FSW process of homogeneous alloys, the material flow and microstructure evolution during dissimilar FSW process is much more complicated. MURR et al [15] investigated the microstructures of Cu−6061Al FSW joints, and found that a complex intercalation microstructure consisting of vortex-like and swirl features was formed in the joint. Although many researchers reported that intermetallic compounds existed in the FSW Cu−Al dissimilar joints [3,11−14], LIU et al [2] found that there were no new Al−Cu intermetallics in the Cu−5A06Al joints. As MISHRA and MA [4] pointed out that, the FSW of dissimilar metals, such as aluminum to copper, was still not successful in sound joint production. In particular, the mechanical properties of the FSW Cu−Al joints still need to be improved according to the published data. Until present, the studies on dissimilar FSW of Cu−Al systems are not enough, and there are many problems to be solved including deep understanding of the microstructure evolution and processing parameter optimization.

In dissimilar FSW, some researchers use pin offset technique to activate the faying surface, avoid intermetallic compounds formation and decrease tool wear. Pin offset means the rotating pin is not inserted into the exact centerline of the abutting edge of the two plates, but around a position some distance away from the faying surface [7,11,16]. XUE et al [11] reported that sound Cu−1060Al dissimilar joints could be produced through pin offset technique. Bonding mechanism between the dissimilar components is strongly dependent on the material flow in dissimilar FSW with pin offset, which is not fully understood up to now.

In this work, dissimilar FSW of commercial pure copper and 1350 aluminum alloy sheets was carried out, and the microstructure and mechanical properties of the dissimilar joints were investigated. Based on the experimental results, the formation of the dissimilar joints was discussed.

2 Experimental

Commercially-available pure copper and 1350 aluminum alloy sheets with a thickness of 3 mm were used, and the chemical compositions of the experimental materials are listed in Table 1. Before welding, the sheets were cut into pieces with dimensions of 200 mm×80 mm. The surfaces of the sheets were ground with grit paper to remove the oxide film and then cleaned with ethanol.

A schematic illustration of the dissimilar FSW experiment is shown in Fig. 1. During FSW process, pure copper and 1350 aluminum alloy were placed at the advancing side (AS) and the retreating side (RS) of the tool pin, respectively. The pin was inserted into the 1350 aluminum sheet with about 2 mm offset to the welding line. Dissimilar friction stir welding was carried out on FSW−3LM−003 welding machine made by the China Friction Stir Welding Center at a tool rotation rate of 1000 r/min and a traverse speed of 80 mm/min with the butt joint parallel to the rolling direction of the sheets. A welding tool with a concaved shoulder of 16 mm in diameter, and a cone-threaded pin of 5.2 mm in diameter and 2.75 mm in length was applied. The tilt angle of the tool was 2.5° from the normal surface of the plates. The stir pin was penetrated into the joint with full length in welding experiments.

Table 1 Chemical compositions of pure copper and 1350 Al alloy (mass fraction, %)

Material	Cu	Zn	Fe	Ni	Mn
Pure copper	Bal.	0.025	0.009	0.009	−
1350 aluminum alloy	0.02	0.01	0.36	−	0.01
Material	**Pb**	**Si**	**Ti**	**V**	**Al**
Pure copper	0.017	0.007	−	−	0.027
1350 aluminum alloy	−	0.08	0.01	0.01	Bal.

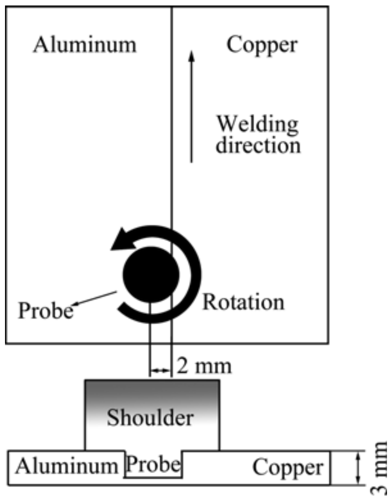

Fig. 1 Schematic illustration showing set-up of dissimilar FSW

Microstructural analysis was performed on the cross section perpendicular to the welding direction. A solution of $FeCl_3$ (10 g)+HCl (6 mL)+C_2H_5OH (20 mL)+H_2O (80 mL) was used to etch the copper side of the joints, while the Al side was electrochemically etched with 2% fluoride boric acid aqueous (BF_4) solution. The microstructures of the weld were observed by optical microscopy (OM, LEICA) and scanning electron microscopy (SEM, Quata200 and Nano430) equipped with an EDX system. Vickers hardness measurements were preformed on a HVS−1000 digital hardness tester at the top, middle and bottom line across the weld zone prior to etching under a 3 N load for a dwelling time of 20 s. Tensile tests were conducted at a crosshead speed of 1 mm/min.

3 Results and discussion

3.1 Macrostructure and microstructure of dissimilar joint

Since the melting point, density and hardness of copper are higher than those of aluminum, aluminum should have better plastic flowability at the same processing temperature. By plunging the stir pin into the aluminum side, Al−Cu dissimilar joint can be formed with abundant material supply during FSW. However, groove defect would form if the stir pin is totally inserted into the aluminum side with an offset of 2.6 mm in this study. Therefore, the pin offset to the welding line is set at 2 mm during FSW. Figure 2 shows the surface morphology of the dissimilar FSWed specimen. The surface of the joint is covered by a layer of aluminum alloy and some small flash can be found at the edge of the joint. Figure 3 shows the cross sectional macrostructure of the dissimilar weld. The nugget zone is composed of aluminum and copper, and its structure is complicated due to the dissimilar materials flow. No pore or other defect can be found in Figs. 2 and 3, indicating that sound joint could be produced with the designated experimental parameters.

Fig. 2 Surface appearance of dissimilar joint prepared by FSW

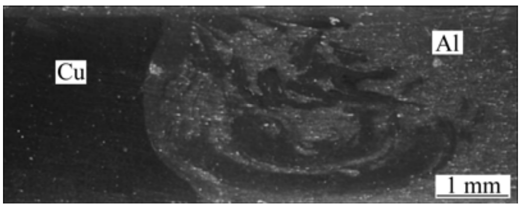

Fig. 3 Optical macrograph showing cross-section structure of dissimilar joint prepared by FSW (Cu lies in AS and Al in RS)

Figure 4 shows the optical microstructures of the dissimilar joint. There are four different regions in the dissimilar joints including base material (BM), heat affected zone (HAZ), thermo-mechanically affected zone (TMAZ) and stir zone (SZ). As shown in Fig. 4(a), the microstructure of 1350Al BM is a typical as-rolled structure which is mainly composed of elongated aluminum grains. Figure 4(b) shows the microstructure of copper BM, which is a mixture of coarse and fine copper grains. Figures 4(c) and (d) show the microstructures of HAZ and TMAZ in the Al side and the copper side, respectively. No plastic deformation occurred in HAZ, but the grains in HAZ were heated to grow during FSW. Compared with the microstructures of BM, it could be seen that the grain shape in HAZ does not change, but the size becomes coarse due to the thermal cycle in the welding process. Meanwhile, the grains in TMAZ show a curved shape, indicating that these grains undergo notable plastic deformation caused by the welding tool. Figures 4(e) and (f) show the microstructure of 1350Al alloy and copper in SZ, and the grains of both materials are greatly refined due to dynamic recrystallization. The average grain sizes of Al and Cu in SZ are 11.4 and 3.7 μm, respectively. This is consistent with the finding of MURR et al [15], in which they reported that in dissimilar FSW of 6061 Al/Cu, the recrystallized Cu grains were finer than Al grains since the grain growth of 6061 Al was faster than that of Cu at a processing temperature of 430 °C.

3.2 Material flow during dissimilar FSW

The microstructures of the nugget zone were examined in detail by SEM and the results are shown in Fig. 5. Figure 5(a) shows the cross-sectional macrograph of the dissimilar weld. As shown in Fig. 5(a), there is no obvious welding defect in the joint and a complex material flow is observed in the SZ. Since most of the rotating pin is inserted into the aluminum side, the majority of the nugget is 1350 aluminum alloy, and copper is distributed in this zone with different shapes. In the upper part of the joint, large bulk of copper with irregular shapes can be observed, while in the bottom part of joint copper, continuous strips with elongated shapes exist. Moreover, the intermixing of copper and aluminum is complicated and different microstructures are formed in different regions of the nugget.

The FSW of dissimilar-materials is distinguished from those of similar materials by the formation of complex, intercalated vortex and related flow pattern [10]. In Fig. 5, vortex-like and swirl patterns can be seen clearly in the dissimilar joint with large magnification. Figures 5(b)−(f) show BEI micrographs of different regions marked in Fig. 5(a). The light area is copper, and the dark area is aluminum. The nugget boundaries in the copper side and aluminum side are shown in Figs. 5(b) and (c), respectively. A sharp boundary between the parent material and the nugget can be observed in the copper side, while the boundary in the aluminum side is not as distinct as that of the copper side. Figures 5(d) and (e) show the microstructures inside the nugget, small copper particles and large copper bulks with length of

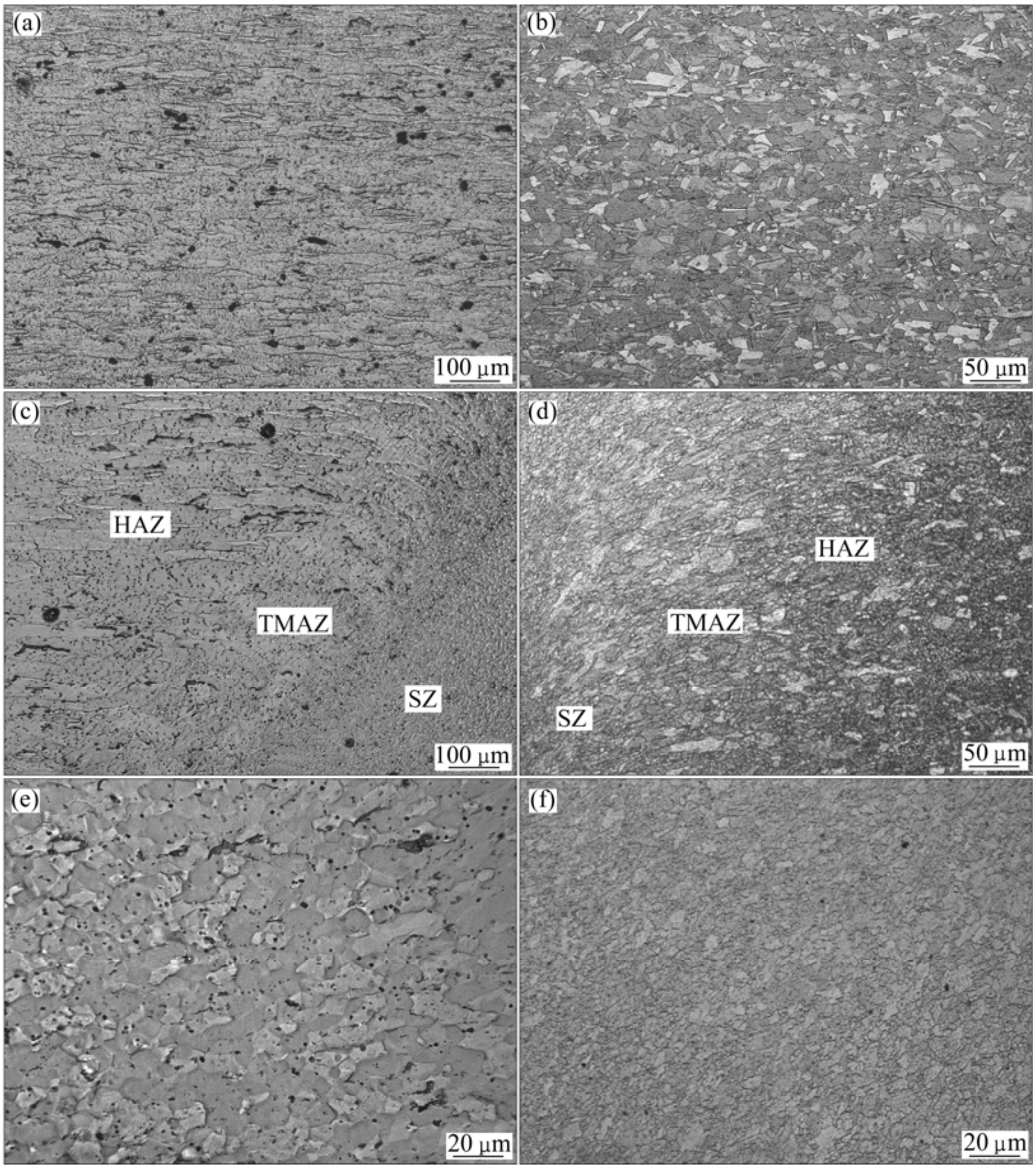

Fig. 4 Optical microstructures of dissimilar joint in different regions: (a) BM in Al side; (b) BM in Cu side; (c) HAZ and TMAZ in Al side; (d) HAZ and TMAZ in Cu side; (e) SZ in Al side; (f) SZ in Cu side

150 to 300 μm are heterogeneously distributed in these regions. Furthermore, the copper bulks with an elongated shape indicate that severe plastic deformation has taken place during FSW. At the bottom of the nugget, a lamellae structure composed of copper particles with a streamline shape and continuous aluminum strips can be observed, as shown in Fig. 5(f). This interlaced structure formed by aluminum and copper indicates that the dissimilar sheets are bonded together firmly in this region. Figure 5(g) illustrates the magnified view of Fig. 5(f), and copper particles with size ranging from 2 to 40 μm can be seen clearly. The intercalated vortex structure is a manifestation of the solid-state flow in dissimilar FSW, in which complex interdiffusion and interaction of the two materials take place [3,15]. Due to the complex material flow, the size, shape and distribution of copper phases are not homogeneous in the dissimilar nugget.

3.3 XRD analysis

Figure 6 shows the XRD pattern measured in the 1350Al−Cu dissimilar FSW nugget. As shown in Fig. 6, only aluminum and copper exist in the joint, and no Al−Cu intermetallic compounds are found. This indicates that neither chemical reaction between aluminum and copper nor phase transformation has occurred during the dissimilar FSW process, which is in consistence with the results by LIU et al [2]. OUYANG et al [3] reported that intermetallic compounds formed through liquid-state reactions in Cu−6061Al alloy dissimilar FSW process, and considered that these phases were harmful due to

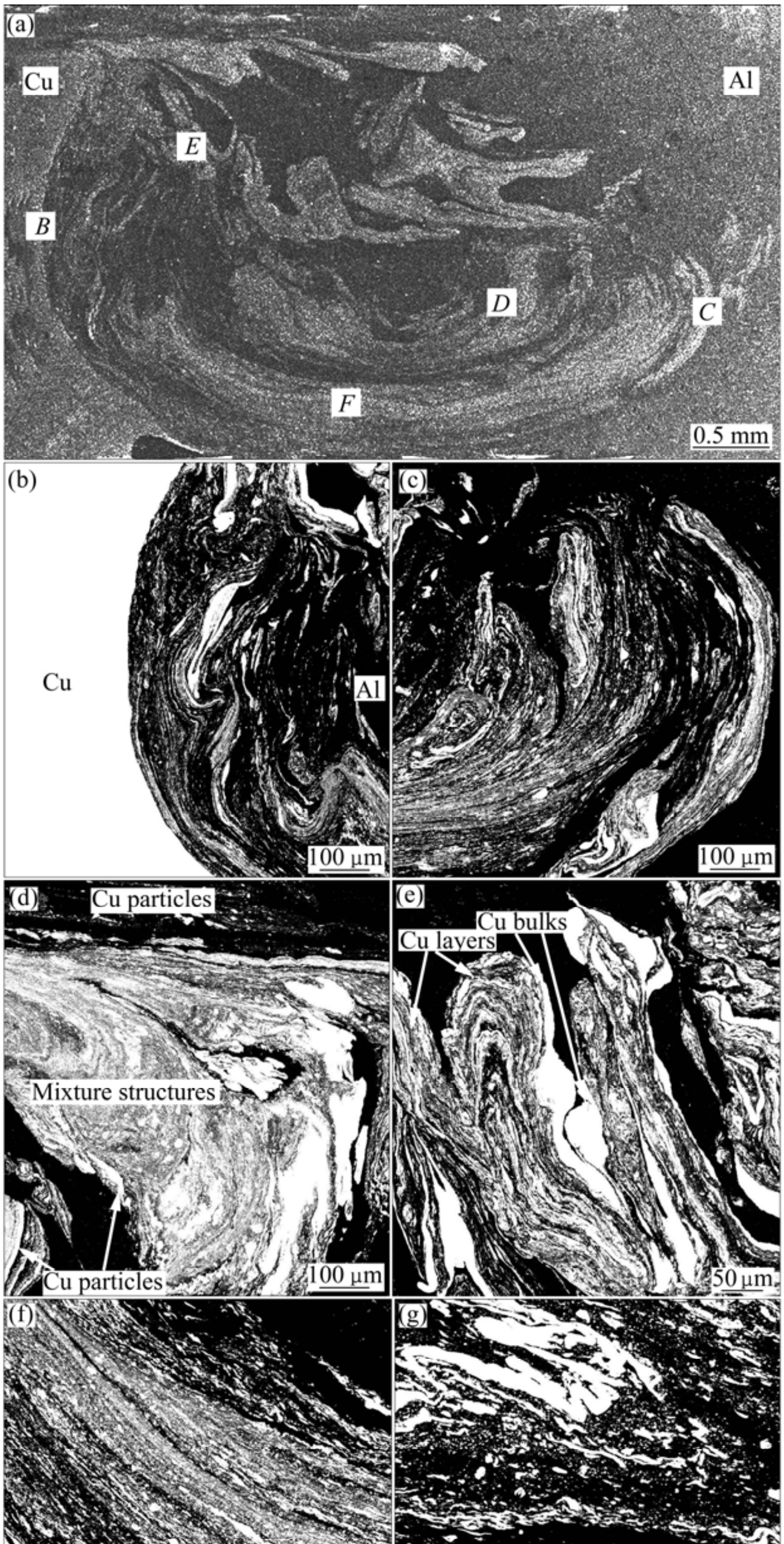

Fig. 5 SEM images of dissimilar FSW Al−Cu joint: (a) Macrostructure of joint; (b)−(f) BEI images of different regions marked *B*−*F* in Fig. 5(a); (g) Magnified view of layer structure as shown in Fig. 5(f)

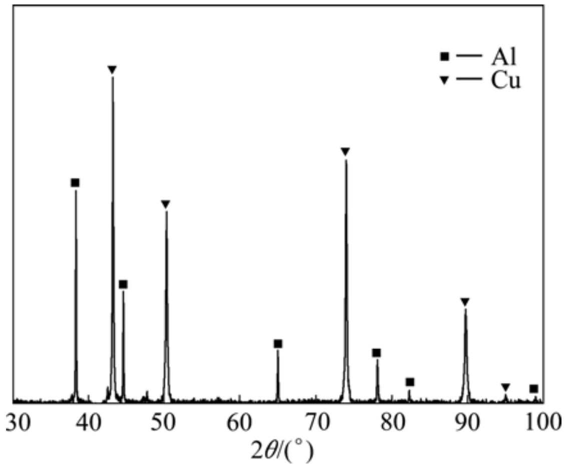

Fig. 6 X-ray diffraction pattern of dissimilar 1350Al−Cu joint

their brittle nature. On the other hand, MURR et al [15] reported that there were no evidence for melting in the Cu−6061Al alloy FSW nugget, and no intermetallic compounds phases were found according to their TEM examination. XUE et al [11] found a thin, continuous and uniform intermetallic compounds layer formed at the boundary between copper and 1060Al alloy, and thought that these phases were beneficial to the dissimilar components bonding. The formation of intermetallic compounds depends on many factors, including the chemical composition of BM, processing parameters, welding temperature, etc. One of the reasons for the variance on intermetallic compounds in the above studies may lie on the different dynamic conditions in FSW experiments. The thickness of the sheet is 3 mm in previous study [2] and this experiment, which is thinner than that in the research by OUYANG et al (12.7 mm) [3] and XUE et al (5 mm) [11]. Compared with thick plates, the holding time at elevated temperature is shorter in the FSW of thin sheets due to the higher cooling rate. Therefore, the diffusion time is not long enough for the Al−Cu intermetallic compounds formation. Further study, especially the thermal history measurement, is necessary to elucidate this issue.

3.4 Mechanical properties

The representative transverse cross-section of Vickers hardness profiles of dissimilar weld were measured along the dashed lines marked in Fig. 7, which were 0.75 (top), 1.50 (middle) and 2.25 mm (bottom) from the top surface, respectively. It is obvious that the hardness at the copper side is higher than that at the aluminum side. The highest hardness exists at the bottom of SZ near the copper side, which is even higher than that of Cu BM. The reason may lie in the solid solution strengthening and grain refinement strengthening. The hardness at the bottom of the nugget is generally higher than that of top or middle region, as shown in Fig. 7. In a 1060Al−Cu dissimilar FSW joint, XUE et al [14] also found that the hardness in the bottom area was higher than that in the upper nugget zone, and they attributed this to the higher fraction of intermetallic compounds in the bottom. Since no intermetallic compounds are found in the specimen, it is believed that the high hardness in the bottom area is due to the following reasons: 1) the fraction of copper in the bottom region is higher than that of other areas, as shown in Fig. 5(a); 2) the lamella structure is more homogeneous and finer than that in other areas, as shown in Fig. 5(f).

Table 2 lists the tensile properties of the Al−Cu FSW joints. As shown in Table 2, the strength of the

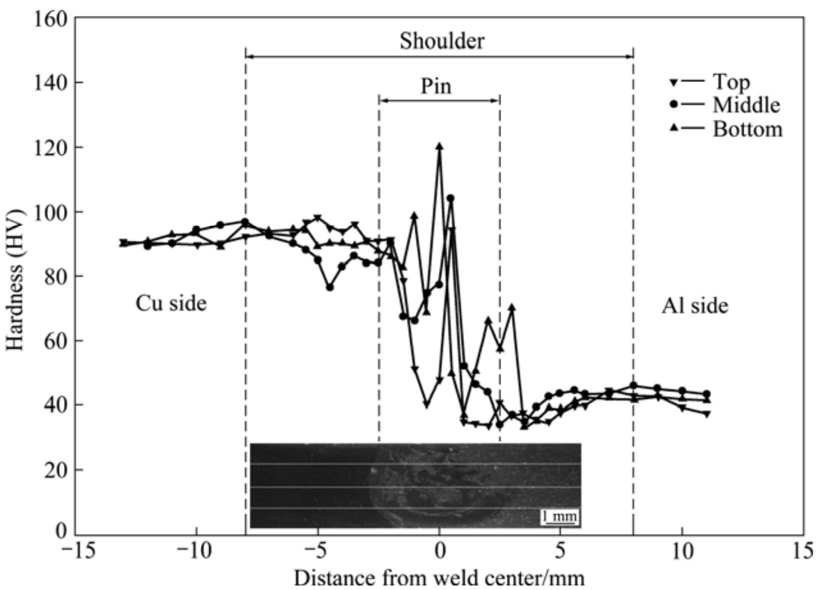

Fig. 7 Hardness profiles measured on cross-section of Cu−1350Al dissimilar weld along top, middle and bottom lines

Table 2 Tensile properties of Al−Cu FSW joints

Material	UTS/MPa	Elongation/%
1350 Al alloy	205	12.8
Copper	301	27.4
Al−Cu joints	152	6.3

dissimilar joints is relatively good, with an ultimate tensile strength (UTS) of 152 MPa, which is 74% that of the 1350Al BM. The elongation of the dissimilar joints is 6.3%. Due to the inhomogeneous microstructure, the strength of the dissimilar FSW joint is generally lower than that of the base materials. As a comparison, the UTS of Al−Cu FSW joints produced by XUE et al [14] was 110 MPa. Figure 8 shows the macrograph of fractured joints, and the location of the fracture can be seen clearly in this picture. All the samples fractured in the Al side of the nugget, and the similar fracture location in Al−Cu dissimilar FSW joints were also reported by XUE et al [14]. Necking can be observed in the fractured samples, indicating that strong bonding is formed between 1350Al and copper through FSW.

Figure 9 illustrates the SEM images of the tensile fracture surface. Figure 9(a) shows the appearance of tensile fracture, and the fracture features vary

Fig. 8 Macrographs of fractured Cu−1350Al dissimilar joints

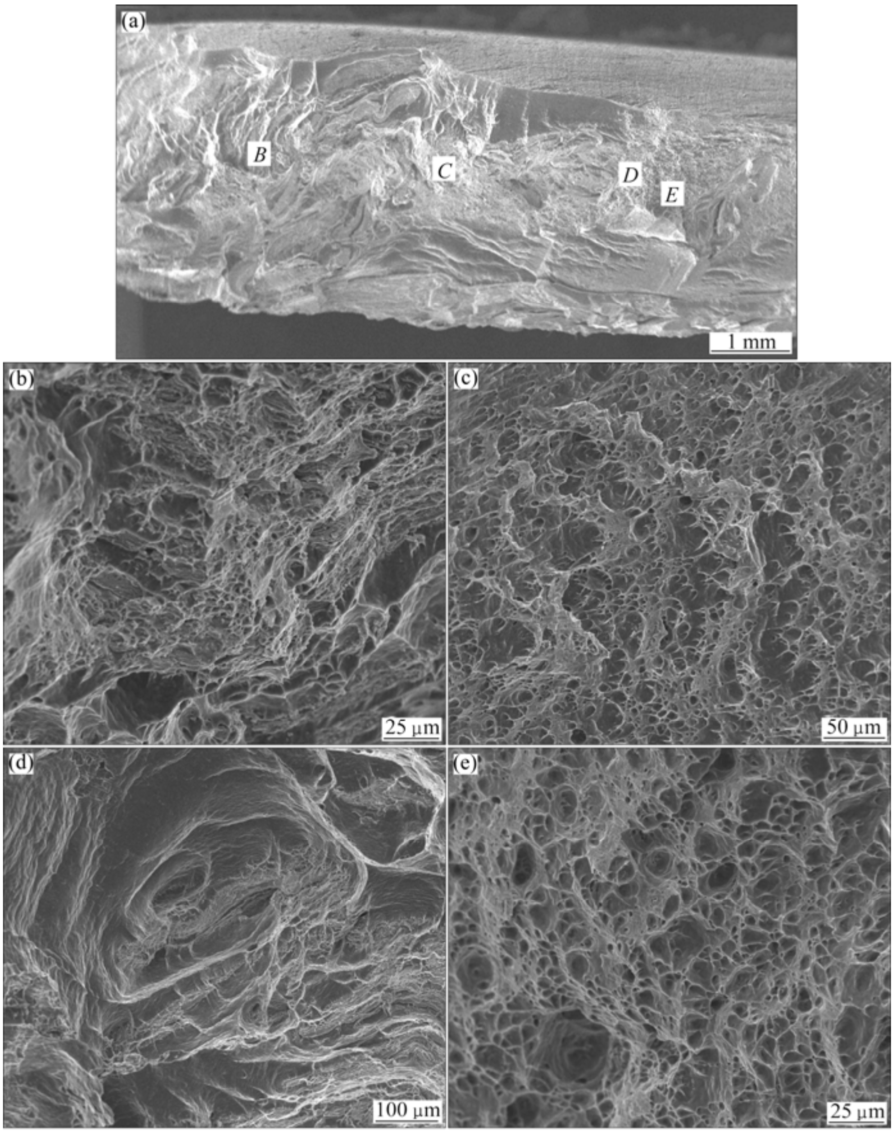

Fig. 9 SEM images showing tensile fracture surface of Cu−1350Al dissimilar joints:(a) Macrograph of tensile fracture surface; (b)−(e) Magnified microstructures of different regions marked *B*−*E* in Fig. 9(a)

appreciably with the locations across the weld due to the complex microstructures of the nugget. Figures 9(b)−(e) show the magnified micrographs of the fracture surfaces observed in different regions marked in Fig. 9(a). As shown in Fig. 9(b), flat surface and small dimples can be observed in this region. Intergranular fracture patterns exist in some regions, as shown in Fig. 9(d), and some cleavage planes can be seen clearly in the region. A large number of dimples with different depth are observed in Figs. 9(c) and (e), indicating that a ductile fracture has taken place in these regions. Therefore, the fracture mode of the dissimilar joints can be defined as a ductile-brittle mixed fracture.

4 Conclusions

1) Pure copper and 1350 aluminum alloy are jointed successfully through FSW with pin offset technique under a tool rotation rate of 1000 r/min and a traverse speed of 80 mm/min.

2) Compared with the base materials, both copper and aluminum are greatly refined after FSW. No intermetallic compound is found according to the XRD results.

3) Complex vortex-like and swirl patterns are formed in the dissimilar FSW joint. The lamella structure in the bottom of the nugget is more homogeneous and finer than other regions.

4) The hardness at the copper side of the nugget is higher than that at the aluminum side. The hardness at the bottom of the nugget is generally higher than other regions. The UTS and elongation of the dissimilar joints are 152 MPa and 6.3%, respectively, and the dissimilar joints fail in a ductile-brittle mixed fracture mode.

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纯铜/1350 铝合金异种板材搅拌摩擦焊接头的组织与性能

李夏威，张大童，邱 诚，张 文

华南理工大学 机械与汽车工程学院，国家金属材料近净成形工程技术研究中心，广州 510640

摘 要：研究 3 mm 厚的纯铜/1350 铝合金异种合金板材的搅拌摩擦焊工艺。通过搅拌头偏置技术，将搅拌头的大部分插入铝合金一侧，在旋转速度和焊接速度分别为 1000 r/min 和 80 mm/min 的条件下，获得无缺陷的接头。在焊核区形成复杂的微观组织中，可以观察到旋涡状花样和层状组织。焊核区没有金属间化合物生成。硬度分布曲线表明，焊核区纯铜一侧的硬度高于 1350 铝合金一侧的硬度，且焊核区底部的硬度高于其它部分的。接头的抗拉强度和伸长率分别为 152 MPa 和 6.3%。断口观察表明，接头断口既存在韧性断裂区域，也存在脆性断裂区域，为混合型断裂。

关键词：搅拌摩擦焊；异种接头；显微组织；力学性能

(Edited by FANG Jing-hua)