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Interface repairing for AA5083/T2 copper explosive composite plate by friction stir processing

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Abstract: Multi-pass friction stir processing (M-FSP) was performed to repair the interface defects of AA5083/T2 copper explosive composite plates. The interface morphology and its bonding mechanism were explored. The results show that higher rotation speed and lower transverse speed produce more heat generated during FSP. The defect-free and good mechanical properties of the AA5083/T2 copper composite plate can be obtained under the condition of the rotation speed of 1200 r/min, the transverse speed of 30 mm/min and the overlap of 2/24. Moreover, M-FSP changes the interface bonding mechanism from metallurgical bonding to vortex connection, improving the bonding strength of composite plate, which can guarantee the repairing quality of composite plates.
Key words: friction stir processing; aluminum/copper composite plate; interface repairing; mechanical properties

1 Introduction

The production of aluminum/copper (Al/Cu) hybrid system enables the development of a new generation engineering material by combining the improved mechanical, thermal and electrical properties of copper with low density and cost of aluminum [1]. Cu and Al joints have been widely used in many cases, such as electrical connectors, bus-bars, foil conductor in transformers, capacitor and condenser foil windings, refrigeration tubes, heat-exchanger tubes, and tube-sheets [2]. Explosive welding is one of the ideal processes for preparing a large section of composite plate in a single operation [3]. However, some defects are always formed during explosive welding processes, which influence the mechanical properties. Defects, resulting from the poor surface finishing, large amounts of brittle intermetallic structures, voids and cracks at the interface are main problems for Al/Cu composite plates [4].

Friction stir processing (FSP), which is developed based on the friction stir welding, has been widely used in improving mechanical properties of Al/steel composite plates before [5,6]. The process parameters as well as strategies of friction stir welding both have an impact on the mechanical properties with the differences in microstructure and defect formation [7]. How to obtain the defect-free composite plate with good mechanical properties is a key problem. Researchers point out that the surface quality is affected by the rotation speed and the transverse speed. Sharp weld flashes and coarse surface are observed at low rotation speed (600 r/min) and high transverse speed induced by low heat generated [4]. Meanwhile, extremely high transverse speed will

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produce joints with incompletely welded interfaces owing to lack of enough heat input. Voids are easily formed owing to the differences in flow stress of Al and Cu materials [2]. Lower transverse speed produces higher heat input, and generates more amounts of intermetallic compounds (IMCs) [8]. Hence, appropriate parameters are important to obtain good performance [9]. The formation of a thin, continuous and uniform IMCs layer between Al and Cu enhances the interfacial bonding, improving the mechanical properties of the Al/Cu composite plate. The IMCs are formed at temperatures over 120 °C according to the Cu−Al phase diagram [10]. Al_4Cu_9, AlCu and Al_2Cu are the main IMCs formed in Al/Cu, which directly affect the mechanical properties [4].

Multi-pass FSP (M-FSP) is then put forward in order to achieve the industrial application of FSP for repairing the composite plates. How to improve efficiency and ensure quality at the same time is crucial. M-FSP is an effective method for producing fine-grained 7B04-O aluminum alloy, and its grain size has nothing to do with the moving distance of the pin [11]. The key parameter of M-FSP is the overlap. The overlap can be defined by l/d, where l is the moving distance of the pin between two successive passes and d is the diameter of the pin [5]. With smaller size of overlap l/d, the faster repairing rate can be obtained. Besides this, a pin with larger diameter produces a larger bonding area, enhancing the bonding strength at the interface of the friction stirred Al/Cu lap joint. Good metallurgical bonding is achieved on the Al/Cu interface with the hook-like structure due to the existence of a similar thin IMCs layer [12]. The fractures originate from the brittle IMCs, and the fracture mode in the Al/Cu plates is the ductile type [13]. Tensile−shear strengths of joints are reduced after annealing due to the increment of layer thickness of IMCs and the type evolution of IMCs [14]. Table 1 lists the parameters and tensile shear fracture loads of different dissimilar Al/Cu friction stirred lap joints. Generally, the tensile shear fracture load is high with the high rotation speed and the low transverse speed.

Interface defects are the main problems for the explosive composite plates, while there are few methods to repair them. M-FSP is a completely new technology to repair the defects from the explosion process. However, few researches have been reported and the repairing mechanism is still unknown. In this work, microstructures and mechanical properties for AA5083/T2 copper composite plates by M-FSP are studied. The process parameters, including the transverse speed, the rotation speed and the overlap size, are optimized. The interface morphology and its bonding mechanism are observed and analyzed.

2 Experimental

The initial materials used in this experiment were AA5083/T2 copper explosive composite plates. The chemical compositions measured by ICP are given in Table 2. It is conformed to the standard specification of AA5083 and T2 copper explosive

Table 1 Parameters and tensile shear fracture loads of different dissimilar Al/Cu friction stir lap joints

No.	Material	Thickness/mm	Rotation speed/(r·min^{-1})	Transverse speed/(mm·min^{-1})	Tool tilt angle/(°)	Tensile shear fracture load/N
1	Pure Cu + AA1060 [12]	3+3	600	50	−	2680
2	Pure Cu + AA7070 [15]	2+2	1120	25	2	4000
3	Brass + AA5083 [16]	2.5+2.5	1120	6.5	1.5	3400
4	Pure Cu + AA1060 [17]	4+3	1500	118	3	2709
5	Pure Cu + AA6060 [18]	3+4	1120	25	2	4673
6	Pure Cu + AA1100 [19]	2+2	1998	198	3	238
7	Pure Cu + AA6061 [20]	1.6+1.6	1400	127	3	4000

Table 2 Chemical compositions for AA5083/T2 copper explosive composite plate (wt.%)

Material	Cu	Al	Si	Mn	Ti	Zn	Mg	Fe	S	P
AA5083	0.1	Bal.	0.4	0.4	0.15	0.25	4.0	0.4	−	−
T2	99.9	−	−	−	−	0.005	−	0.005	0.005	0.001

composite plates. The thickness of AA5083/T2 copper explosive composite plate was 4.5 mm, and the thickness ratio of aluminum to copper was 2:1.

The tool was made of hot working steels, with a shoulder of 24 mm in diameter and a threaded pin of M8 mm × 4.3 mm. Experimental tests were conducted with a plunging depth of 0.2 mm and a tilt angle of 2.5°. The rotation speeds were varied from 600 to 1200 r/min and transverse speeds ranged from 30 to 120 mm/min. The experimental parameters are listed in Table 3.

Table 3 Friction stir processing parameters for AA5083/T2 copper explosive composite plates

Plate	Rotation speed/($r\cdot min^{-1}$)	Transverse speed/($mm\cdot min^{-1}$)
A	900	30
B	900	60
C	900	120
D	600	30
E	1200	30
F	1200	60

The metallographic samples were cut perpendicular to the welding direction and polished until the surface was smooth and scratch-free. The microstructures of AA5083 were first obtained by etching in Fuss's reagent (1 mL sulphuric acid + 1 mL hydrochloric + 0.5 mL hydrofluoric acid + 100 mL distilled water) for 30 s, and then the samples were immersed in Klemm's reagent (100 mL saturated sodium thiosulfate in distilled water + 2 g potassium disulfate) for 120 s to show the microstructures of T2 copper. The micro-structures and the interface morphologies were observed by an optical microscope (OM, Keyence VHX-6000) and a scanning electron microscope (SEM, FEI Quanta650) equipped with EDS. The IMCs at the interface were identified by means of μ-XRD (Rigaku D/Max−2500PC), and the cover high definition scans were performed at a rate of 0.02 (°)/s in the 2θ interval ranging from 20° to 100°.

Since the interface performance was the most critical, the shear strength of the AA5083/T2 copper explosive composite plate was measured. The shear specimens were designed with the National Standard of GB/T 2651 — 2008. The bending specimens were designed on the basis of the National Standard of GB/T 232—2010. The size of specimens is shown in Fig. 1.

The test was carried out using an electronic universal testing machine MTS311.32, conducting constant strain rate load with a loading speed of 1 mm/min. The micro-hardness tests were carried out on a Zwick Roell Indentec ZHV 2 system using $HV_{0.1}$ with the distance of 0.3 mm between indentations.

3 Results and discussion

3.1 Process optimization for single FSP

Figure 2 shows macrographs and appearances for the repair zone of the AA5083/T2 copper composite plate after FSP with different transverse speeds. The rotation speeds are fixed at 900 r/min while the transverse speed varies from 30 to 120 mm/min. The surface shows a series of part-circular ripples, and the spacing of the arc corrugation increases with the increasing of transverse speed, as shown in Figs. 2(b, d, f). When the transverse speed increases to 120 mm/min, some voids appear on the surface of the weld, as shown in Fig. 2(f). By observing the cross section of the repair zone in detail, there is one large void at the interface, as shown in Fig. 2(b) with the yellow arrow. The voids are located at the bottom of the pin, which means that the materials cannot flow adequately under the high transverse speed. The reason is that copper has high thermal conductivity. The high transverse speed applied to copper does not generate enough heat to soften the aluminum and therefore, the voids are formed after FSP. When the transverse speed decreases to 60 mm/min, there are also some small voids formed in the stirring zone of AA5083, as shown in Fig. 2(c) with the yellow arrow. Besides this, the weld surface has a

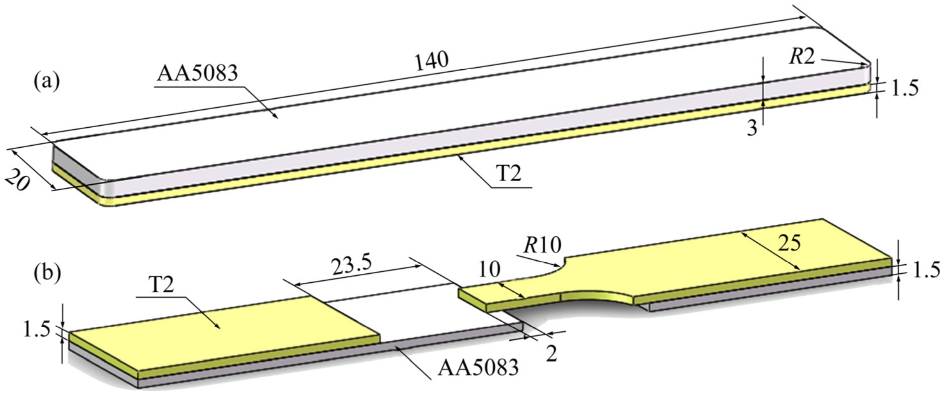

Fig. 1 Dimensions of bending (a) and shear (b) specimens (mm)

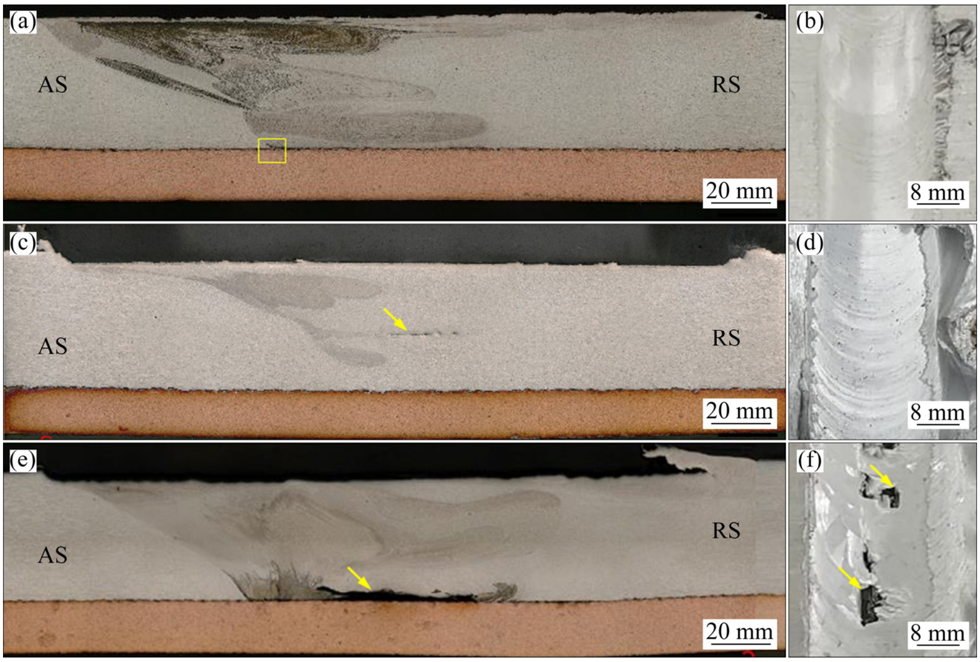

Fig. 2 Macrographs (a, c, e) and appearances (b, d, f) of repair zone for AA5083/T2 copper composite plate after FSP with rotation speed of 900 r/min and different transverse speeds: (a, b) 30 mm/min; (c, d) 60 mm/min; (e, f) 120 mm/min

certain degree of depression, as shown in Fig. 2(c). When the transverse speed decreases to 30 mm/min further, good weld appearance is shown with no defects. The typical onion ring features are located at the advancing side in the stirring zone, as shown in Fig. 2(a). To sum up, the defect-free repair zone can be obtained with the low transverse speed.

Figure 3 shows typical microstructures of different areas in Plate A. The grains in the base metal for AA5083 are obviously elongated (Fig. 3(a)), indicating that the aluminum plate is in the rolled condition. Equiaxial grains with grain size about 30 μm appear in the base metal of T2 copper, as shown in Fig. 3(b). In Fig. 3(c), the enlarged view of square area in Fig. 2(a) is presented, as well as the thermo-mechanical affected zone in the advancing side. Figure 3(c) confirms a vortex-like connection at the interface and some of the aluminum fragments are stirred into the copper matrix. The stirring zone of AA5083 near the advancing side exhibits the streamline feature as a result of the severe plastic deformation. Fig. 3(d) exhibits the stirring zone of AA5083 in the middle position. The grains are fine and uniform, with the size of about 30 μm. The dynamic recrystallization process produces the equiaxed grains in the stirring zone.

Different rotation speeds are adopted for further investigation based on the above results. The macrographs and appearances are shown in Fig. 4.

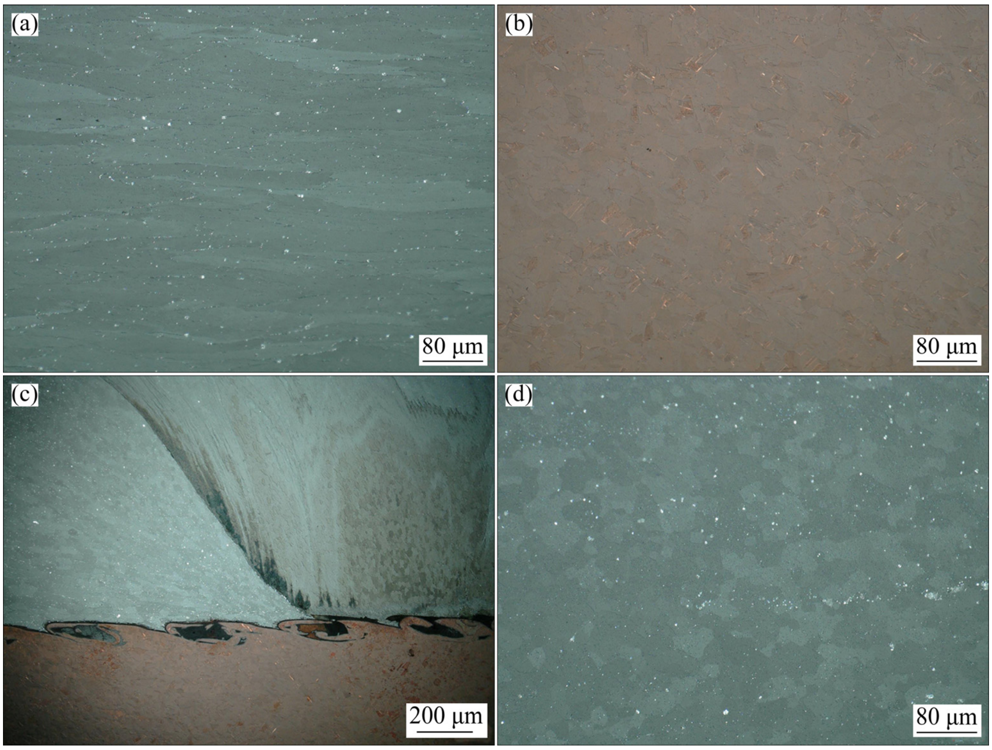

Fig. 3 Microstructures of different areas in Plate A: (a) Base metal of AA5083; (b) Base metal of T2 copper; (c) Enlarged view of square area in Fig. 2(a); (d) Stirring zone of AA5083

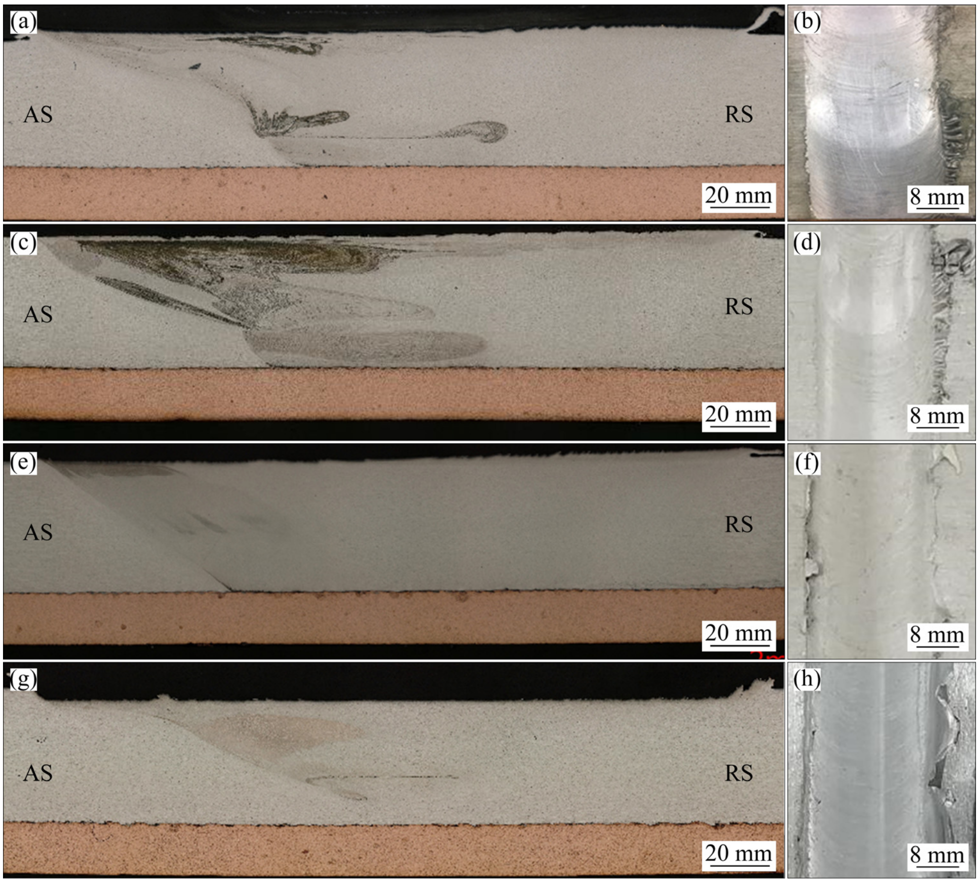

Fig. 4 Macrographs (a, c, e, g) and appearances (b, d, f, h) of repair zone for AA5083/T2 copper composite plate after FSP: (a, b) 600 r/min, 30 mm/min; (c, d) 900 r/min; 30 mm/min; (e, f) 1200 r/min, 30 mm/min; (g, h) 1200 r/min, 60 mm/min

The advancing side (AS) presents an abrupt "zigzag line" boundary distinctly, while that in the retreating side (RS) is not obvious. The reason is that the temperature and the flow fields on the AS are different from those on the RS. It is noted that no obvious defects appear in the repair zone after FSP. The onion ring structures are located at the AS in the stirring zone of AA5083. The weld surfaces are smooth with little flashes on them, as shown in Figs. 4(b, d, f).

In order to detect the interface morphology for the AA5083/T2 copper composite plate before and after FSP, the samples are observed in the polished condition in order to avoid the influence of corrosion products. Figure 5(a) shows the overall interface morphology for the composite plate before FSP with some cracks distributing at the interface. When the rotation speed is set at a relatively low value, for example, 600 and 900 r/min, a certain number of voids will be formed after FSP, as shown in Figs. 5(b, c) with yellow arrows, in comparison with Fig. 5(a) for the sample before FSP. When the rotation speed increases to 1200 r/min, the interface is complete and waved, as shown in Fig. 5(d). In comparison with the sample before FSP (Fig. 5(a)), less number of cracks are formed in the IMCs, which means that FSP can repair defects to some extent.

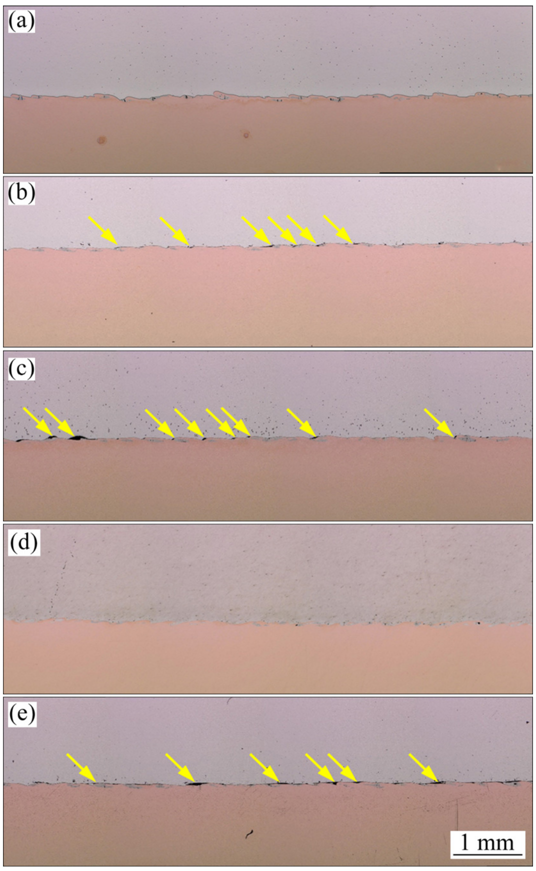

Fig. 5 Overall interface morphologies for AA5083/T2 copper composite plates before (a) and after (b−e) FSP: (b) 600 r/min, 30 mm/min; (c) 900 r/min, 30 mm/min; (d) 1200 r/min, 30 mm/min; (e) 1200 r/min, 60 mm/min

The transverse speed increases from 30 to 60 mm/min in order to increase the repair efficiency. Figure 5(e) shows the overall interface morphology for the plate. The voids are formed again at the interface with the transverse speed of 60 mm/min. Therefore, with higher rotation speed and lower transverse speed, better repair zone with free defect can be obtained.

Figures 6(a, b) show local interface characteristic for the AA5083/T2 copper composite plate before FSP. The cracks only exist in the aluminum fragments and they do not propagate into the copper matrix. In addition, only a few voids exist at the bottom of the vortex. When the samples are processed by FSP with low rotation speed (600 and 900 r/min), the voids distribute along the interface, as shown in Figs. 6(d, f). Also, the voids exist in long strips at the high transverse speed (60 mm/min), as shown in Figs. 6(i, j). Only the defect-free repair zone can be obtained with the high rotation speed and the low transverse speed, which corresponds to the high welding heat input. The vortex connection is the main connection mode for the samples after FSP, as shown in Figs. 6(g, h). The vortex is functioned as the hook, which makes the interface stronger under the tensile shear process. Therefore, the defect-free AA5083/T2 copper composite plate after FSP can be obtained with the rotation speed of 1200 r/min and the transverse speed of 30 mm/min.

3.2 Process optimization for M-FSP

3.2.1 Microstructure

Figure 7 shows macro-morphologies of the AA5083/T2 copper composite plate after M-FSP with different overlaps. The rotation speed is set to be 1200 r/min and the transverse speed is set to be 30 mm/min based on the previous parameters optimization. The overlaps (*l/d*) are set to be 2/24, 3/24, 4/24, 8/24 and 10/25. There exhibit obvious defects in the repair zone when the overlaps (*l/d*) are 3/24 and 4/24, as shown in Figs. 7(c, e) with red arrows. These voids are formed in the 4th FSP owing to the heat accumulation. Besides this, there

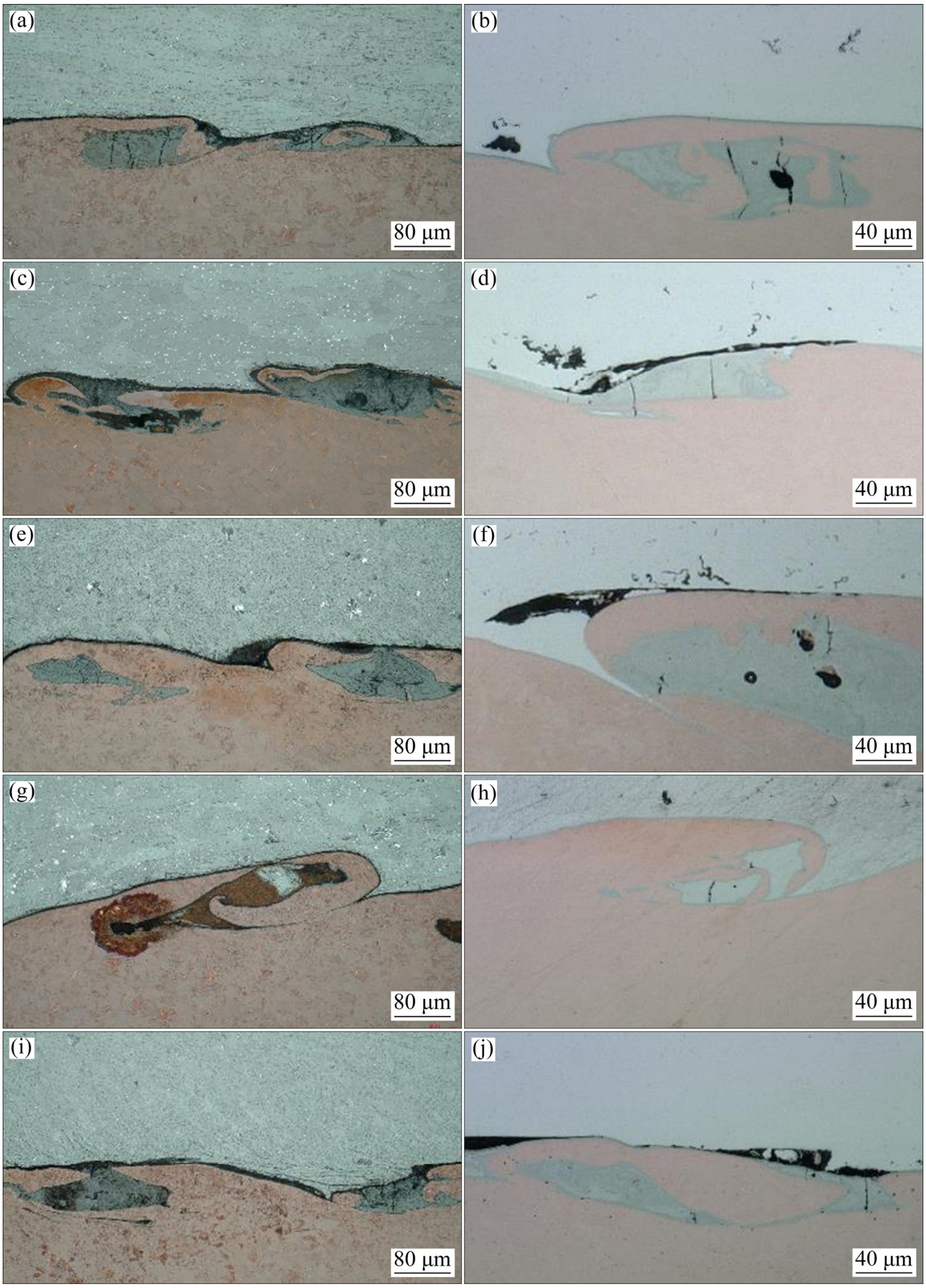

Fig. 6 Local interface morphologies for AA5083/T2 copper composite plate in etching condition and polishing condition: (a, b) Before FSP; (c, d) 600 r/min, 30 mm/min; (e, f) 900 r/min, 30 mm/min; (g, h) 1200 r/min, 30 mm/min; (i, j) 1200 r/min, 60 mm/min

are obvious toe flashes after FSP when the overlaps (*l/d*) are 3/24 and 4/24. The toe flashes become serious after M-FSP owing to continuous axial force. Therefore, the number of passes for M-FSP should be no more than three. The well-formed repair zone with no defects for AA5083/T2 copper composite plates after M-FSP are presented, as shown in Figs. 7(a, g, i).

Figure 8(a) shows macrographs of the repair zone for the plate after M-FSP with overlap of 2/24. The repair zone appears as a shape of basins. The Zone A does not experience the heat of M-FSP and

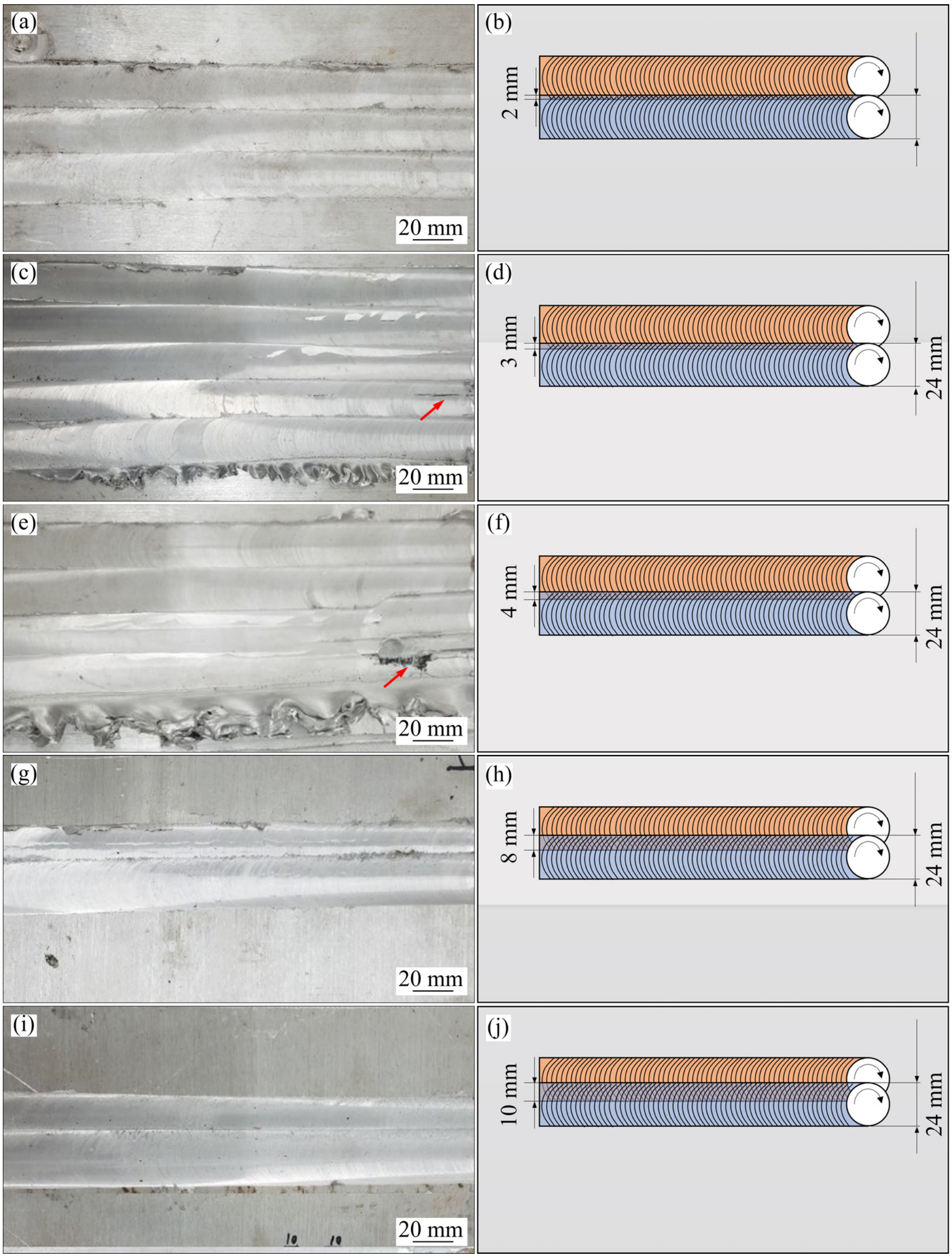

Fig. 7 Macro-morphologies (a, c, e, g, i) and schematic diagrams (b, d, f, h, i) of AA5083/T2 copper composite plate after M-FSP with different overlaps (*l*/*d*): (a, b) 2/24; (c, d) 3/24; (e, f) 4/24; (g, h) 8/24; (i, j) 10/24

therefore, it shows the characteristics of the base metal. The AA5083 exhibits streamline structures in Zone A with obvious rolling characteristics, as shown in Fig. 8(c). Besides, the interface of Zone A is almost flat and straight, with little IMCs at the interface, as shown in Fig. 8(d). The Zone B locates at the overlap region, which receives twice the heat of FSP. Therefore, the grains of AA5083 are fine and equiaxial, as shown in Fig. 8(e). In addition, the interface exhibits the zigzag characteristic and the bonding mechanism changes from the metallurgical bonding to the vortex connection. The mechanical connections consist of vortex connections formed by multiple hooks, with IMCs in them, as shown in Fig. 8(f). Figs. 8(g−j) show microstructures of the repair zone for the AA5083/T2 copper composite plate after two FSP passes. The grains of AA5083 in the stirring zone are much finer than those of AA5083 in Zone B, which is due to the severe plastic deformation, as shown in Fig. 8(i). In

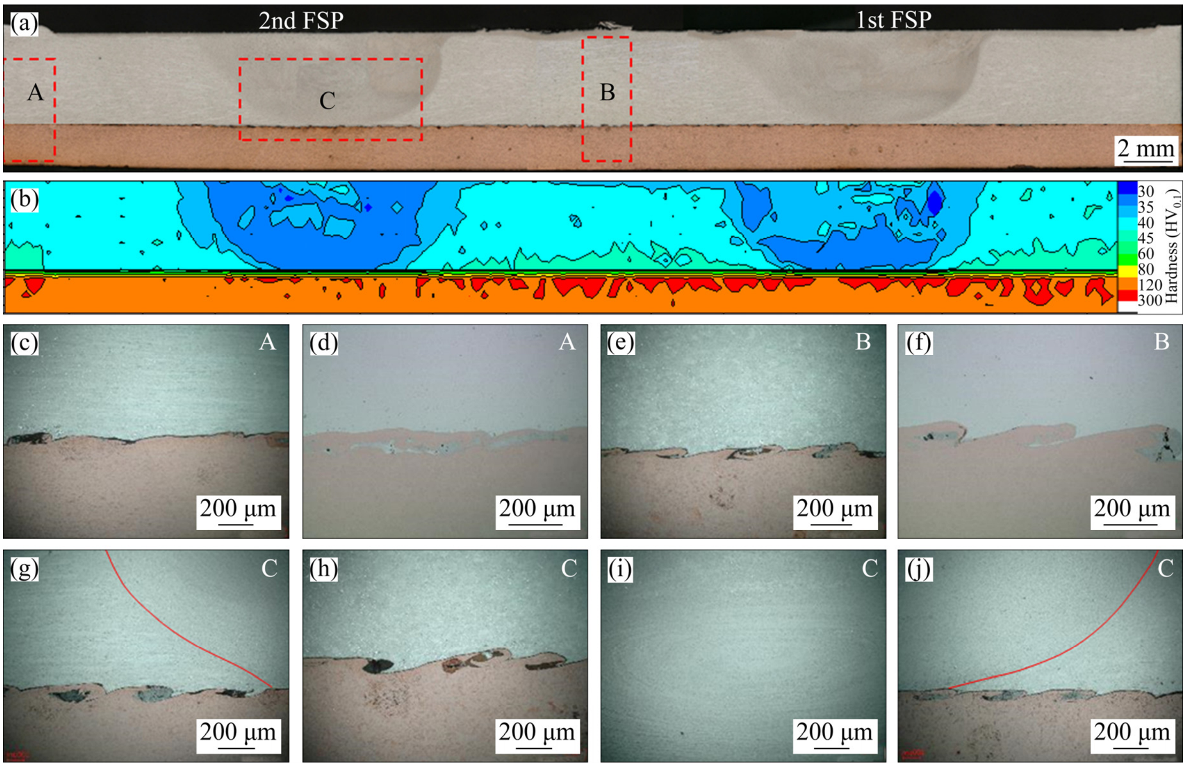

Fig. 8 Macrograph (a), hardness mapping (b) and microstructures of repair zone for M-FSP plate with overlap of 2/24: (c) Interface of Zone A after etching; (d) Interface of Zone A before etching; (e) Interface of Zone B after etching; (f) Interface of Zone B before etching; (g) Repair zone after two FSP passes; (h) Interface of stirring zone after two FSP passes; (i) Stirring zone of Zone C; (j) Repair zone after two FSP passes

addition, the whole interface bonding mechanism of the repair zone after two FSP passes is vortex connection, which is the same with the interface in Zone B, as shown in Figs. 8(g, h, j). There are some discontinuous IMCs at the interface, which are located at interior of the hook.

The hardness mapping of the repair zone for the AA5083/T2 copper composite plate after M-FSP is shown in Fig. 8(b). The global hardness for the repair zone is a little bit lower than that of the base metal. The hardness for the interface is much higher than that for other places. Besides, the peak hardness values do not distribute continuously, which are consistent with the distribution of IMCs. Therefore, the IMCs are the hard phases and the hardness value can reach as high as $HV_{0.1}$ 300.

Figure 9 shows SEM images and EDS spectra for the IMCs in the base metal, after single FSP and M-FSP. The interface bonding mechanism for the base metal is the metallurgical bonding and the interface is flat and straight. There are almost no IMCs at the interface in the base metal, as shown in Figs. 9(d, g). Similar results can also be verified by the result of μ-XRD, as shown in Fig. 10.

Figures 9(b, c) show SEM images for the IMCs after single FSP and M-FSP, respectively. The interface bonding mechanism for the repair zone is the vortex connection and there exhibits the tortuous interface. The IMCs distribute in the hook uniformly, and Al_2Cu and Al_4Cu_9 are the two dominating IMCs in the repair zone, as shown in Fig. 10.

3.2.2 Mechanical properties

In order to compare the mechanical properties for AA5083/T2 copper composite plates after M-FSP with different overlaps, the shear strengths and bending properties have been tested. The over-lapping areas are placed in the test area in order to investigate the influence of overlap on its mechanical properties. The shear strength for the base metal is only 38.4 MPa, as listed in Table 4. However, the shear strength increases remarkably after M-FSP. The maximum shear strength reaches 86.8 MPa when the overlap is 2/24, which is one times higher than that of base metal. Therefore, M-FSP can increase the shear strength remarkably

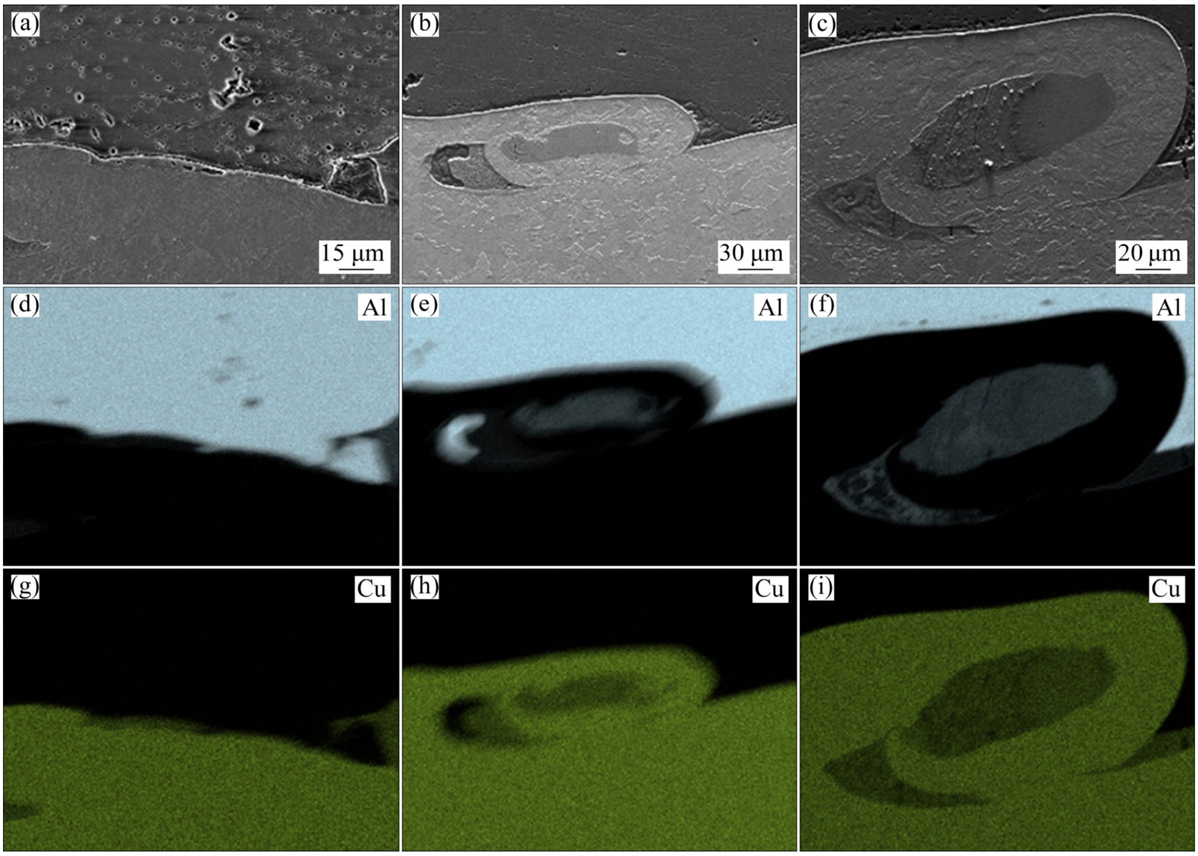

Fig. 9 SEM images and EDS spectra for IMCs: (a, d, g) Metallurgical bonding in base metal; (b, e, h) Vortex connection in plate after single FSP; (c, f, i) Vortex connection in plate after M-FSP with overlap of 2/24

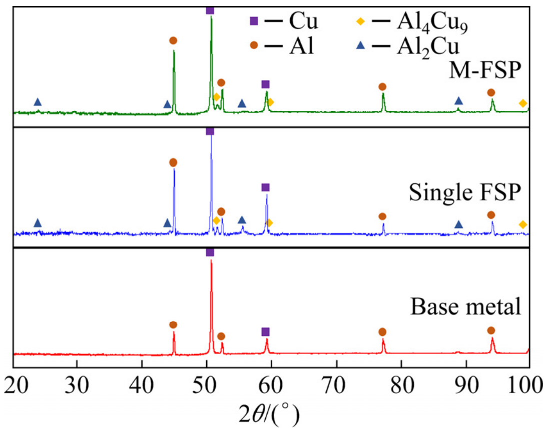

Fig. 10 μ-XRD patterns for IMCs in base metal after single FSP and M-FSP

for the AA5083/T2 copper composite plate, which is benefitted from the transformation of interface bonding mechanism. The vortex connections can bear more loads than the metallurgical bonding during the tensile shear process and therefore, the shear strength is enhanced.

The fracture mode of shear specimens exhibits typical brittle fracture, as shown in Figs. 11(b, c). Strippings are obviously found on the fracture surfaces, as shown in Fig. 11(d) with yellow arrows. It is deduced that these strippings are formed by the failure of the original mechanical connections at the interface under the load. The second phase particles are also obviously shown in Fig. 11(d) with red arrows. The shear strength decreases gradually with the increase of the overlap, and the maximum shear strength for the plate with overlap of 2/24 is 25% higher than the minimum shear strength for the plate with overlap of 10/24. The less overlap means higher efficiency during the manufacturing process, and M-FSP has an important application prospect in repairing explosive composite plate. In summary, the optimized overlap for the AA5083/T2 copper composite plate after M-FSP is 2/24.

The results of bending tests are shown in Fig. 12. The bending strengths are satisfied. And there are no cracks during the process of bending, as shown in Figs. 12(b, d). The excellent bending properties are mainly due to the excellent plasticity of T2 cooper and AA5083.

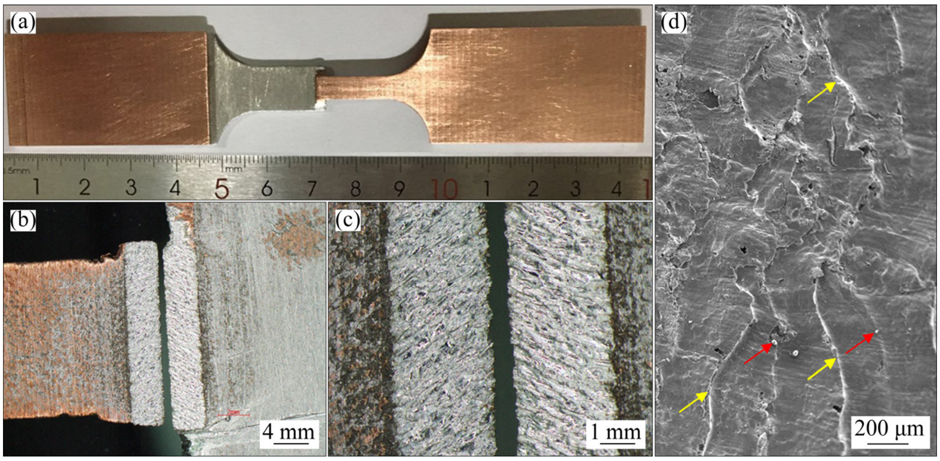

Fig. 11 Fracture morphologies of shear specimens: (a) Shear samples; (b−d) Fracture morphologies

Table 4 Shear strength of samples after M-FSP with different overlaps

Overlap	S/mm^2	Force/N	τ/MPa
Base metal	20.05	770	38.4
2/24	20.1	1744	86.8
3/24	20.05	1552	77.4
4/24	19.95	1423	71.3
8/24	20	1356	67.8
10/24	20.05	1397	69.7

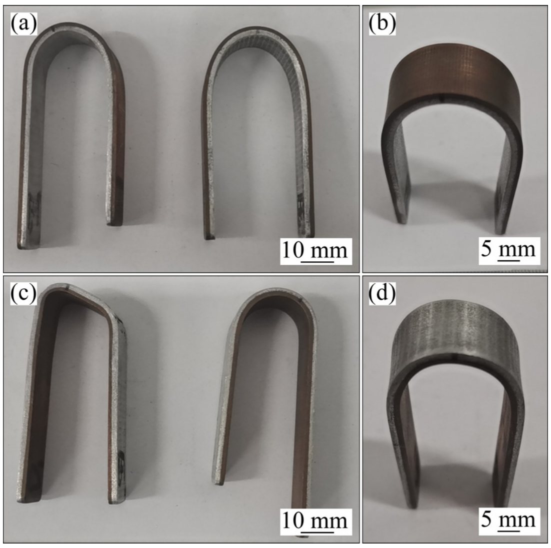

Fig. 12 Bending samples of M-FSP plate with overlap of 2/24: (a) Side view of T2 copper in tensile force; (b) Tensile face of T2 copper; (c) Side view of AA5083 in tensile force; (d) Tensile face of AA5083

4 Conclusions

(1) Higher rotation speed and lower transverse speed produce more heat during FSP. When the rotation speed and the transverse speed are set to be 1200 r/min and 30 mm/min, respectively, the defect-free AA5083/T2 copper composite plate can be obtained.

(2) M-FSP changes the interface bonding mechanism from metallurgical bonding to vortex connection and therefore, improves the bonding strength of composite plate.

(3) The shear strength for the AA5083/T2 copper composite plate after M-FSP reaches the highest with the overlap (l/d) of 2/24. The less overlap makes higher efficiency during the manufacturing process, which has an important application prospect in repairing explosive composite plate.

Acknowledgments

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References

[1] GALVÃO I, VERDERA D, GESTO D, LOUREIRO A, RODRIGUES D M. Analysing the challenge of aluminum to copper FSW [C]//Proc International Symposium on Friction Stir Welding. Huntsville, AL, 2012: 891−907.

[2] MEHTA K P, BADHEKA V J. A review on dissimilar friction stir welding of copper to aluminum: process,

properties, and variants [J]. Materials and Manufacturing Processes, 2016, 31(3): 233−254.
[3] YAN Y B, ZHANG Z W, SHEN W, WANG J H, ZHANG L K, CHIN B A. Microstructure and properties of magnesium AZ31B−aluminum 7075 explosively welded composite plate [J]. Materials Science and Engineering A, 2010, 527(9): 2241−2245.
[4] RASAEE S, MIRZAEI A H, ALMASI D, HAYATI S. A comprehensive study of parameters effect on mechanical properties of butt friction stir welding in aluminum 5083 and copper [J]. Transactions of the Indian Institute of Metals, 2018, 71(6): 1553−1561.
[5] WANG Jian, LU Xiao-feng, CHENG Chen, LI Bo, MA Zong-yi. Improve the quality of 1060Al/Q235 explosive composite plate by friction stir processing [J]. Journal of Materials Research and Technology, 2020, 9(1): 42−51.
[6] WANG Jian, CHENG Yun, LI Bo, CHEN Cheng. Effects of multi-pass friction stir processing on microstructures and mechanical properties of the 1060Al/Q235 composite plate [J]. Metals, 2020, 10(3): 298.
[7] CHEN Yu, DING Hua, MALOPHEYEV S, KAIBYSHEV R, CAI Zhi-hui, YANG Wei-jing. Influence of multi-pass friction stir processing on microstructure and mechanical properties of 7B04-O Al alloy [J]. Transactions of Nonferrous Metals Society of China, 2017, 27(4): 789−796.
[8] MUTHU M F X, JAYABALAN V. Tool travel speed effects on the microstructure of friction stir welded aluminum−copper joints [J]. Journal of Materials Processing Technology, 2015, 217: 105−113.
[9] HAN M S, LEE S J, PARK J C, KO S C, WOO Y B, KIM S J. Optimum condition by mechanical characteristic evaluation in friction stir welding for 5083-O Al alloy [J]. Transactions of Nonferrous Metals Society of China, 2009, 19(S1): 17−22.
[10] OUYANG Jia-hu, YARRAPAREDDY E, KOVACEVIC E. Microstructural evolution in the friction stir welded 6061 aluminum alloy (T6-temper condition) to copper [J]. Journal of Materials Processing Technology, 2006, 172(1): 110−122.
[11] SHARMA N, KHAN Z A, SIDDIQUEE A N. Friction stir welding of aluminum to copper−An overview [J]. Transactions of Nonferrous Metals Society of China, 2017, 27(10): 2113−2136.
[12] XUE P, XIAO B L, WANG D, MA Z Y. Achieving high property friction stir welded aluminium/copper lap joint at low heat input [J]. Science and Technology of Welding and Joining, 2011, 16(8): 657−661.
[13] ASEMABADI M, SEDIGHI M, HONARPISHEH M. Investigation of cold rolling influence on the mechanical properties of explosive-welded Al/Cu bimetal [J]. Materials Science and Engineering A, 2012, 558: 144−149.
[14] SHIRAN M K G, KHALAJ G, POURALIAKBAR H, JANDAGHI M R, DEHNAVI A S, BAKHTIARI H. Multilayer Cu/Al/Cu explosive welded joints: Characterizing heat treatment effect on the interface microstructure and mechanical properties [J]. Journal of Manufacturing Processes, 2018, 35: 657−663.
[15] AKBARI M, BEHNAGH R A, DADVAND A. Effect of materials position on friction stir lap welding of Al to Cu [J]. Science and Technology of Welding and Joining, 2012, 17(7): 581−588.
[16] SHOJAEEFARD M H, KHALKHALI A, AKBARI M, TAHANI M. Application of Taguchi optimization technique in determining aluminum to brass friction stir welding parameters [J]. Materials & Design, 2013, 52: 587−592.
[17] SAEID T, ABDOLLAH-ZADEH A, SAZGARI B. Weldability and mechanical properties of dissimilar aluminum−copper lap joints made by friction stir welding [J]. Journal of Alloys and Compounds, 2010, 490(1−2): 652−655.
[18] AKBARI M, BAHEMMAT P, HAGHPANAHI M, BESHARATI G M K. Enhancing metallurgical and mechanical properties of friction stir lap welding of Al−Cu using intermediate layer [J]. Science and Technology of Welding and Joining, 2013, 18(6): 518−524.
[19] ELREFAEY A, TAKAHASHI M, IKEUCHI K. Preliminary investigation of friction stir welding aluminium/copper lap joints [J]. Welding in the World, 2005, 49(3−4): 93−101.
[20] FIROUZDOR V, KOU S. Al-to-Cu friction stir lap welding [J]. Metallurgical and Materials Transactions A, 2012, 43(1): 303−315.

搅拌摩擦加工修复 AA5083/T2 紫铜爆炸复合板界面

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摘 要：基于多道次搅拌摩擦加工(M-FSP)修复 AA5083/T2 紫铜爆炸复合板的界面缺陷，探讨界面形貌和界面结合机制。结果表明，搅拌摩擦加工过程中的高旋转速度和低前进速度会产生更多的热量。当旋转速度设定在 1200 r/min，前进速度设定在 30 mm/min，搭边量设定在 2/24 时，AA5083/T2 紫铜复合板经多道次搅拌摩擦加工修复后无缺陷，且力学性能优良。多道次搅拌摩擦加工提高复合板的结合强度，其界面结合机制由冶金结合转变为旋涡状连接，为复合板的修复质量提供保障。

关键词：搅拌摩擦加工；铝/铜复合板；界面修复；力学性能

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