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Magnetic pulse-assisted semi-solid brazing of Cu/Al tube joints and oxide film removal mechanism

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Abstract. In this paper, the advantages of magnetic pulse welding, brazing and semi-solid forming are combined to propose magnetic pulse-assisted semi-solid brazing (MPASSB) to join copper and aluminum tubes. Based on 3D electromagnetic-structural-fluid finite element simulations, the high-speed impact of the aluminum tube on the filler metal will drive the high-speed shear rheology of the semi-solid filler metal. Based on 2D FEM-SPH finite element analysis, the aluminum tube will have a strong interaction with the filler metal during the high-speed impact on the filler metal, which is conducive to the removal of the oxide film on the surface of the copper-aluminum tube and the promotion of element diffusion. Microscopic characterization of the joints revealed that the interfacial oxide film had been completely removed, achieving interfacial metallurgical bonding, and no brittle copper-aluminum intermetallic compounds were found at the interface, with a shear strength of 40 MPa.

Introduction

Copper-aluminum dissimilar joints save energy, can be lightweight, and are widely used in vehicles, ships and other industries. However, when copper-aluminum joints are made, the dense aluminum oxide film on the aluminum surface prevents the surface wetting of the base material and metallurgical bonding of the joint. In addition, layers of brittle intermetallic compounds (IMCs), such as Cu_9Al_4 and $CuAl_2$, are easily formed at the joint interface, which seriously affect the strength and fatigue performance of the joint [1].

In order to better realize the effective metallurgical bonding at the interface of Cu/Al joints, fusion welding, ultrasonic welding, magnetic pulse welding, and brazing methods have been widely used. The traditional fusion welding technology has a large welding heat input, and it is difficult to control the welding heat input, so the brittle IMCs cannot be effectively suppressed and the mechanical properties are poor [2]. To further reduce the welding heat input, solid-phase welding (ultrasonic welding [3], friction stir welding [4], explosive welding [5], magnetic pulse welding [6], and resistance welding [7]) is widely used for copper-aluminum connections. However, the research and application of the above methods for the connection of small-diameter tubes are rarely reported.

Brazing can avoid the direct contact reaction of heterogeneous base materials through the transition buffer of filler metal, which can inhibit the generation of brittle IMCs to a certain extent. At the same time, it can also effectively alleviate the differences in the physical properties of base materials, and improve the strength of the joints and fatigue load resistance. Flame brazing is mostly used in the industrial production of Cu/Al tubes, but too high brazing temperatures are prone to the dramatic growth of brittle phases, which seriously affect the joint properties.

In order to further reduce the brazing temperature, this paper proposes a new method of MPASSB by combining the composite advantages of electromagnetic forming, semi-solid forming and brazing. This method uses electromagnetic force to promote high-speed plastic deformation of the aluminum tube and, at the same time, the aluminum tube impact and extrusion of semi-solid filler metal to promote high-speed shear rheology of the filler metal. Oxide film will be removed and element diffusion will be promoted. Moreover, the use of semi-solid forming characteristics will reduce the brazing temperature and inhibit the growth of brittle IMCs. In the paper, the effect of the assembly method on the removal of interfacial oxide layer and the joint microstructure will be analyzed in combination with finite element simulation and experimental results.

Experiment

The outer tube was made of 1060-O aluminum tube with an outer diameter of 19 mm and a thickness of 1 mm, and the inner tube was made of T2 copper tube with an outer diameter of 15 mm and a thickness of 1.5 mm. The filler metal is Zn-15Al, with a thickness of 400μm and an axial length of 10mm. Before welding, the outer wall of the copper tube, the inner wall of the aluminum tube, and the surface of the filler metal were polished and cleaned with alcohol to remove the oxide film and oil on the surface of the tubes and filler metal.

When clamping forming, the copper and aluminum tubes, filler metal, coils and field shaper are assembled according to Fig. 1(a), and the height between the top of the aluminum tube and the top of the inner wall of the field shaper is 12 mm. After the assembly is completed, the capacitor is charged and the clamping forming discharged, causing the Cu/Al tubes joint to form a stop, as shown in Fig. 1(a). After the clamping forming is completed, the capacitor is recharged after the area of the tube to be brazed is moved to the working area of the field shaper, and discharged again after the brazing temperature is reached, as shown in Fig. 1(b).

The outer tube impinges on the semi-solid filler metal at high speed under the action of electromagnetic force, causing it to flow at high speed, and the oxide film on the tube wall is crushed and sheared by the solid phase particles inside the filler metal, thus breaking and removing it, as shown in Fig. 2(c-d).

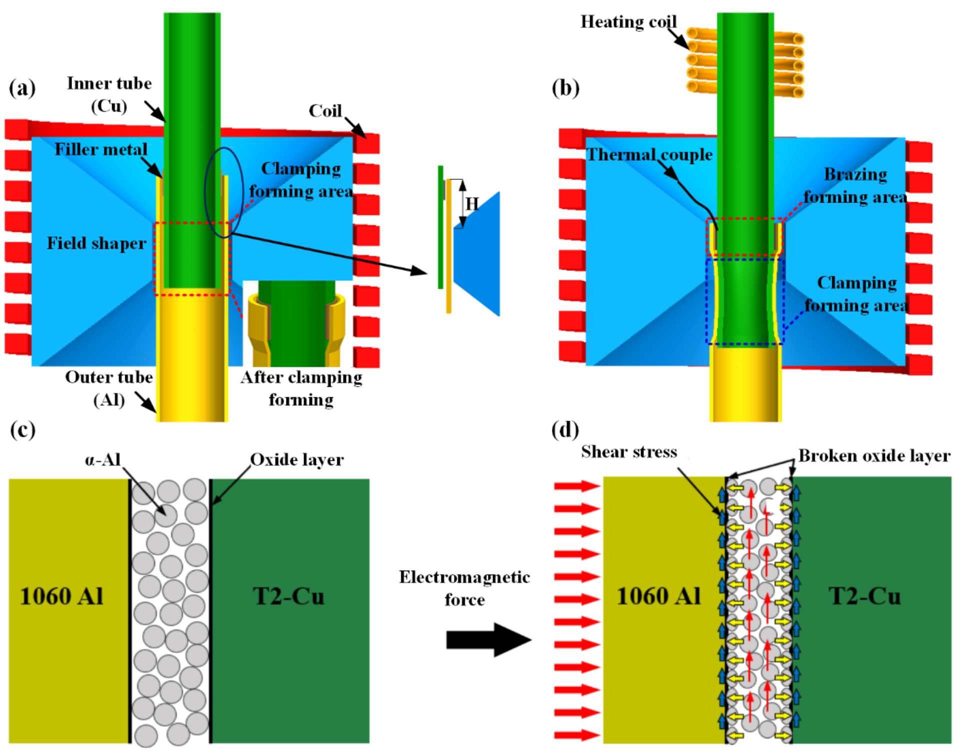

Fig. 1. Principle of MPASSB process: (a) clamping forming; (b) brazing forming; (c) state of tubes and filler metal before brazing forming; (d) oxide film removal and shear rheology of filler metal during brazing forming.

Simulation
For the 3D simulation, the air cell is added during brazing forming to provide a shear rheological region for the filler metal, as shown in Fig. 2(a-b). The finite element analysis region is shown in Fig. 2(b). Meanwhile, the Johnson-Cooker intrinsic model was used to characterize the high strain rate plastic deformation behavior during the forming process [8], and the filler metal shear rheology model was measured to be 1.79 Pa·s. The 2D simulation was performed by loading the electromagnetic force obtained from the 3D simulation into the 2D simulation.

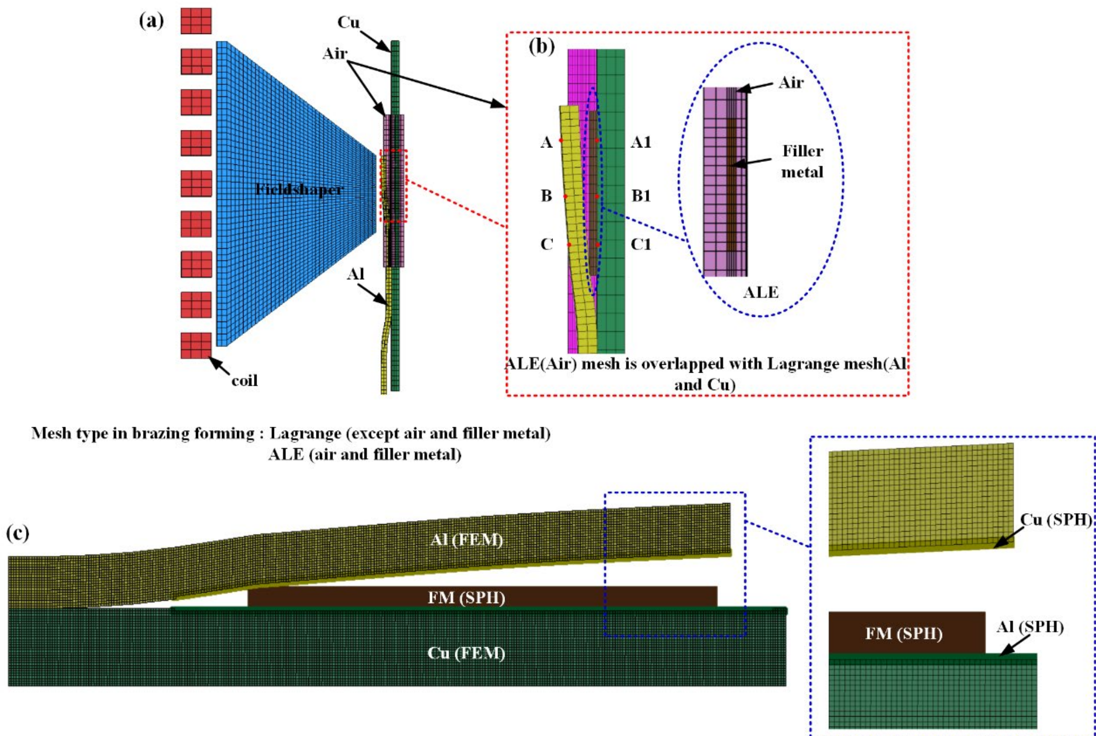

Fig. 2. Schematic of MPASSB simulation: (a) cross section of brazing forming model; (b) enlarged view of brazing forming area; (c) FEM-SPH model.

Results
Fig. 3 shows the compressive stress on the filler metal at different moments of brazing forming. Since the bottom of the aluminum tube is already in contact with the filler metal at the end of the clamping forming, the bottom of the filler metal is the first to be extruded by the aluminum tube during brazing forming, as shown in Fig.3(a). As time progresses, the aluminum tube continues to deform under the action of the electromagnetic force, and the contact area with the filler metal gradually increases, so that the top of the aluminum tube contacts the top of the filler metal at 0.027ms, and continues to extrude the top of the filler metal, as shown in Fig. 3(b). The middle area of the braze material is finally squeezed as shown in Fig. 3 (c). It can also be seen that the filler metal is ejected outwardly by the continuous squeezing of the aluminum tube. At the same time, the pressure on the filler metal decreases as the deformation time progresses, as shown in Fig. 3(d-f).

Fig. 4 shows the distribution of compressive and shear stresses in different areas of the interface between the Cu/Al tubes and the filler metal. As can be seen from the figure, the compressive stress at the interface between the Cu/Al tubes and the filler metal decreases from the top downward. Among them, the compressive stress in the top region of the interface is the largest, respectively 551.5 MPa and 494.1 MPa; the compressive stress in the middle region of the interface is the second largest, respectively 364.8 MPa and 410.6 MPa; and the compressive stress at the bottom of the interface is the smallest, respectively 113.4 MPa and 73.3 MPa. The shear stress at the interface between the Cu/Al tubes and the filler metal are slightly different compared to the compressive stress. Among them, the top region of the interface is the largest, respectively 56.2 MPa and 39.5 MPa. However, the values of shear stress in the middle and bottom regions of the interface between the aluminum/filler metal (Al/FM) or the copper/filler metal (Cu/FM) are essentially the same separately. The values in the middle and bottom region of the Al/FM interface are 33.1 MPa and 31.5 MPa, respectively, while the middle and bottom region of the Cu/FM interface are 14.9 MPa and 15.2 MPa.

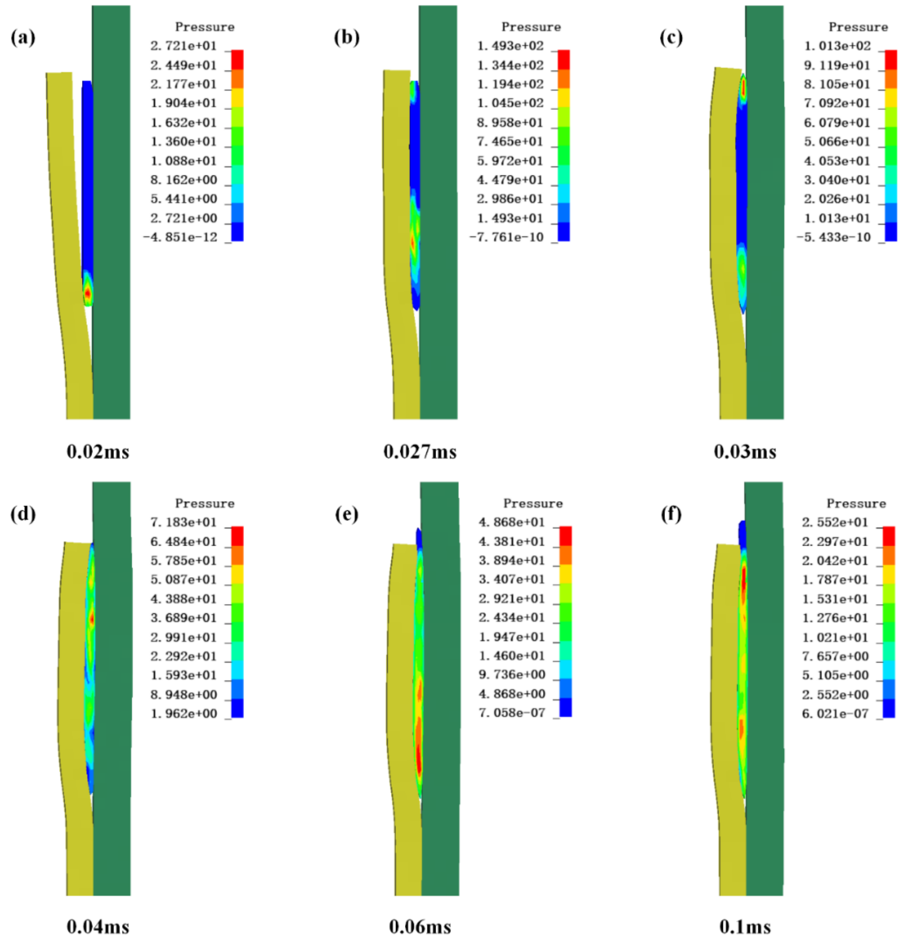

Fig. 3. Compressive stress of filler metal at different moments of MPASSB.

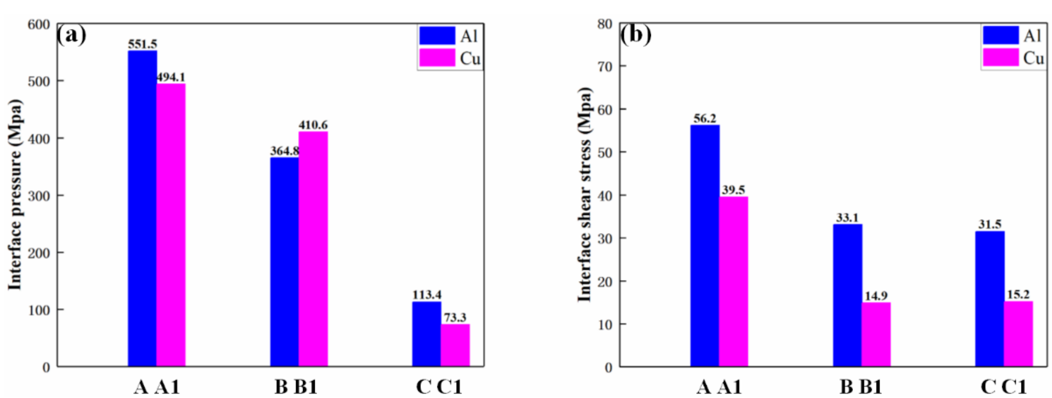

Fig. 4. Interface stress in MPASSB simulation: (a) compressive stress; (b) shear stress.

Fig. 5 shows the results of the Cu/Al tubes interface interaction obtained from the 2D FEM-SPH simulation. From Fig. 5(a-d), it can be seen that the aluminum tube will have certain interactions with the filler metal when it hits the filler metal at a high speed under the action of electromagnetic force, but there will be no waveform interface. After the aluminum tube and the filler metal are completely in contact, the surface of the aluminum tube will be peeled off by the filler metal to a certain extent under the combined effect of interfacial compressive and shear stresses, as shown in Fig. 5(e-f).

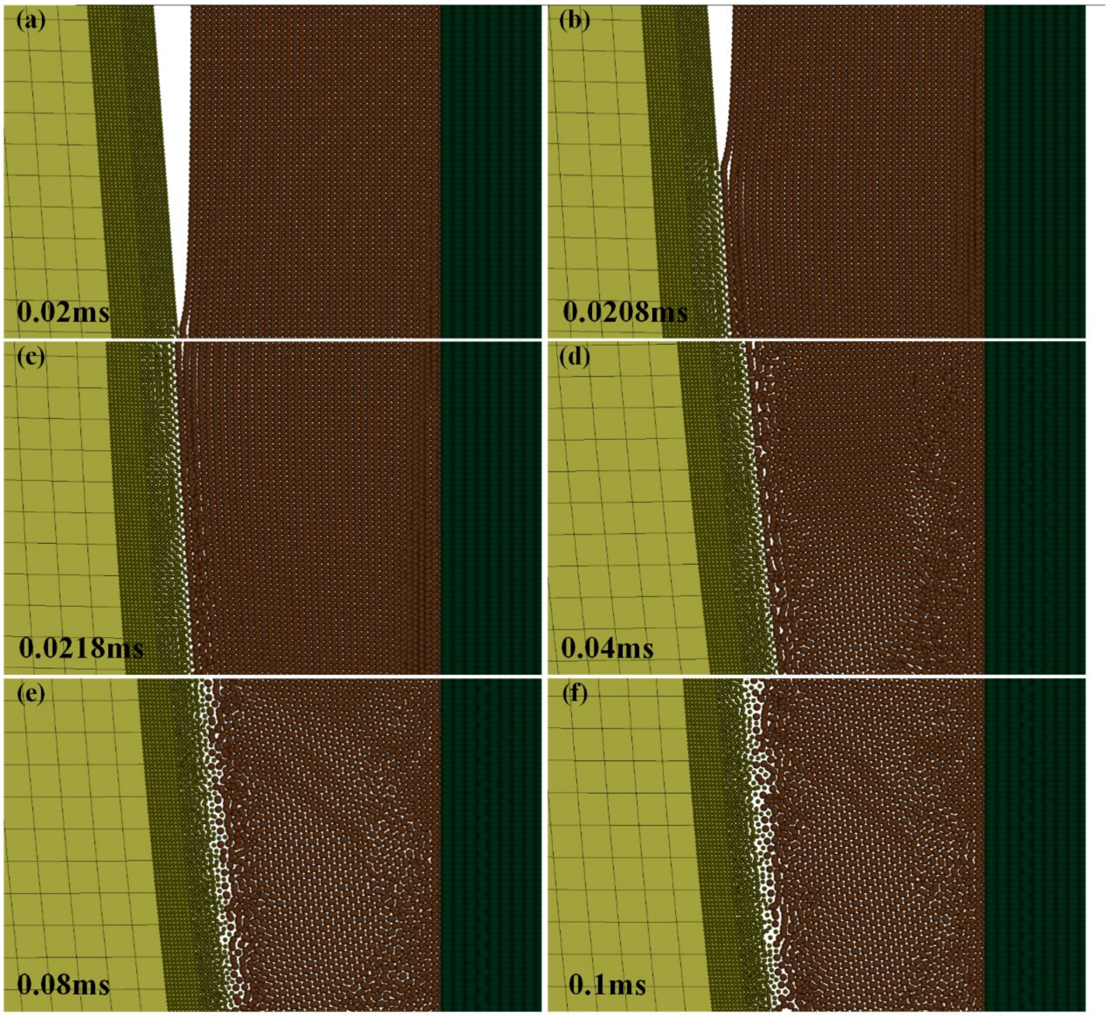

Fig. 5. Cu/Al tubes interface interactions of MPASSB.

The following Fig. 6 shows the organization and morphology of the top, middle and bottom regions of the specimen, and the analyzed area is shown in Fig. 2(b). As can be seen from the figure, the oxides at the interface of the Al/FM are completely removed, and α-Al solid solution perpendicular to the aluminum matrix is formed, which is conducive to improving the mechanical properties of the joint. Less α-Al and a large number of Cu/Zn phases were formed at the brazing joints. At the Cu/FM interface, effective element diffusion was happened in the top, middle and bottom regions, with the organization distribution of $Al_{4.2}Cu_{3.2}Zn_{0.7}$ and Cu/Zn phases, and no Cu/Al brittle IMCs were found at the interface.

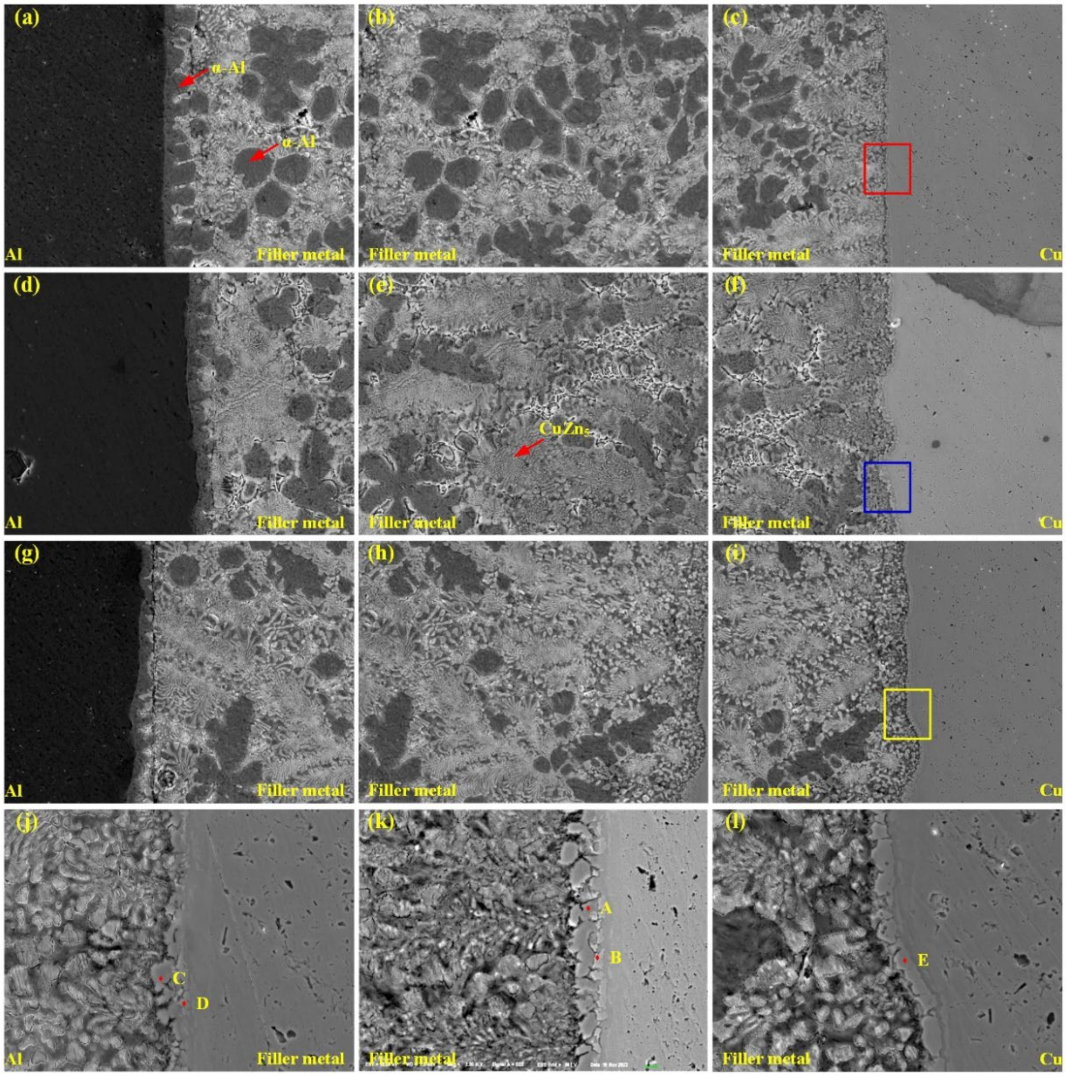

Fig. 6. Microstructure of the MPASSB joints: (a) top interface of Al/FM (b) top of filler metal; (c) top interface of Cu/FM; (d) middle interface of Al/FM; (e) middle of filler metal; (f) middle interface of Cu/FM; (g) bottom interface of Al/FM (h) bottom of filler metal; (i) bottom interface of Cu/FM; (j) enlargement of red box area in Fig. 6(c); (k) enlargement of blue box area in Fig. 6(f); (j) enlargement of yellow box area in Fig. 6(i).

Table 1. EDS analysis results of the points marked in Fig. 6.

Position	O	Al	Cu	Zn	Possible phase
A	1.5	38.1	47.8	12.7	$Al_{4.2}Cu_{3.2}Zn_{0.7}$
B	0.7	3.3	27.4	68.5	$CnZn_5$
C	0.8	32.6	49.7	17.0	$Al_{4.2}Cu_{3.2}Zn_{0.7}$
D	0.6	4.5	32.4	62.5	Cn_5Zn_8
E	0.6	3.6	28.4	67.4	$CnZn_5$

Fig. 7 shows the surface analysis and line analysis of the interface elements on the Al/FM and Cu/FM. As can be seen from the Fig. (a-f) and Fig. (a1-f1), at 440°C, Cu, Al and Zn atoms diffuse to a certain extent, but the ability of Cu atoms to diffuse to the Al/FM interface is weaker, which is mainly limited by the shorter brazing time and brazing temperature. Al atoms are relatively more on the Cu/FM interface, and the Al atoms in the filler metal diffuse to the interface to a greater degree, forming a ternary Al-Cu-Zn alloy phase. Finally, the mechanical properties were also tested in this paper with a shear strength of 40 MPa.

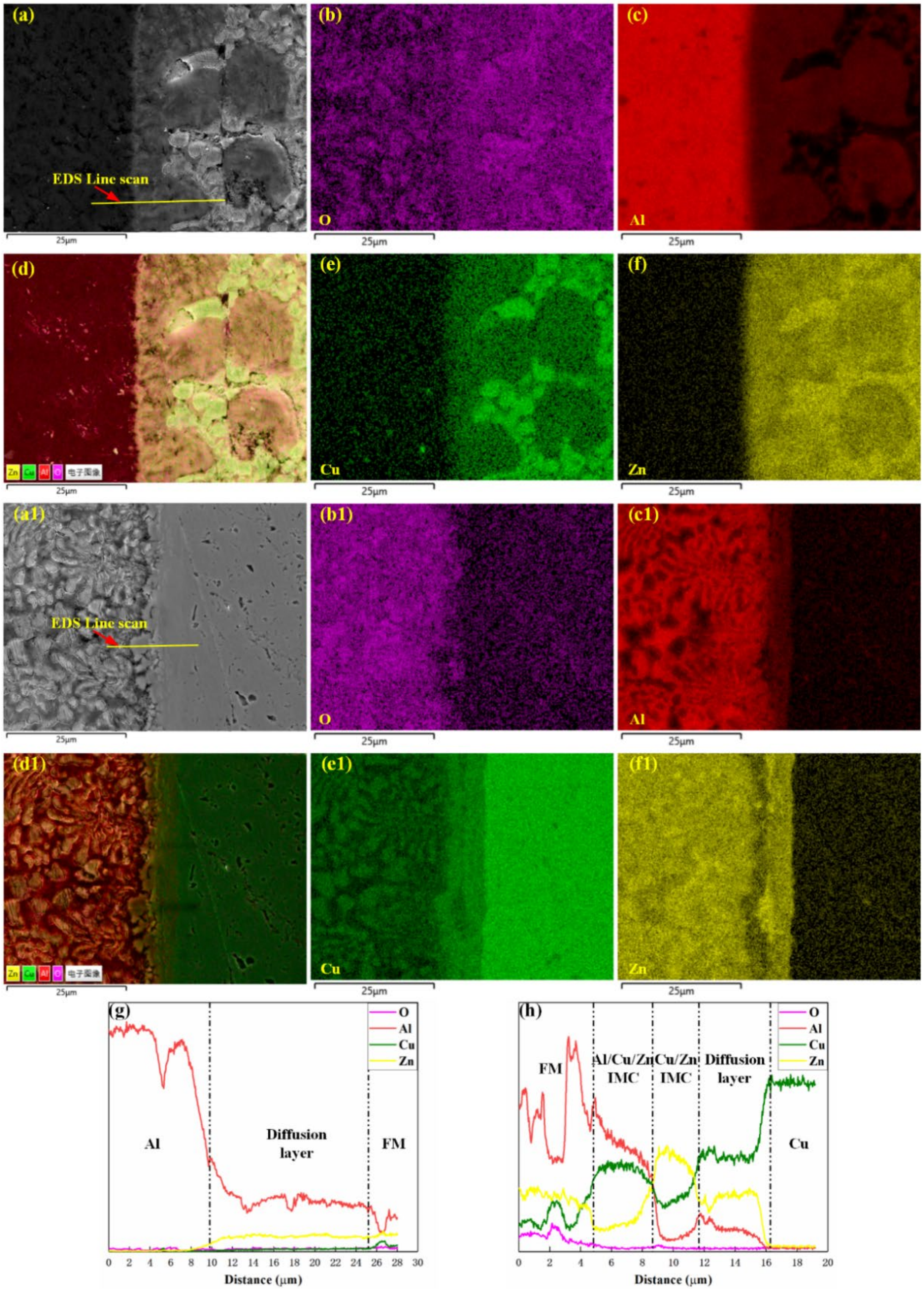

Fig. 7. EDS analysis at the top analysis area of the MPASSB sample: (a) enlargement of red green area in Fig. 6(a); (b) O; (c) Al; (d) combined EDS elemental mapping of Fig. 7(a); (e) Cu; (f) Zn; (a1) enlargement of red green area in Fig. 6(j); (b1) O; (c1) Al; (d1) combined EDS elemental mapping of Fig. 7(a); (e1) Cu; (f1) Zn; (g) elemental line scan analysis at the Cu/FM interface shown in Fig. 7(a); (h) elemental line scan analysis at the Cu/FM interface shown in Fig. 7(a1).

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Conclusion

(1) MPASSB can be used for Cu/Al tubes joining;

(2) The interfacial compressive and shear stresses generated when the aluminum tube impacts the filler metal at high speed are the key to remove the oxide film and achieve interfacial metallurgical bonding;

(3) No visible Cu/Al brittle IMCs was found in the joints, proving that MPASSB can largely inhibit the growth of brittle IMCs.

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