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ARTICLE

Effect of Pre-set Welding Wire on Microstructure and Mechanical Properties of Al/Cu Dissimilar FSW T-Lap Joints

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Abstract: It is difficult to achieve Al/Cu dissimilar welds with good mechanical properties for T-lap joints, due to the low heat input and poor plastic flow of the inner corner of the T-joint in friction stir welding (FSW), which leads to easy occurrence of wormholes, tunnel, bonding line defects, etc, and thus further causes stress concentration. Therefore, pre-set welding wires at the fillet were innovatively applied to 6061-T6 aluminum alloy (4 mm in thickness) and pure copper dissimilar plate FSW T-lap joints, in order to improve the internal plastic flow of T-joints, reduce defects, and obtain joints with good microstructure and properties. The effect of three types of pre-set wires on the microstructure and mechanical properties of Al/Cu dissimilar FSW T-lap joints was analyzed. Results reveal that three types of pre-set wire joints exhibit onion ring-like pattern in the large pin stirring zone at a constant travel speed of 35 mm/min and a rotation speed of 700−800 r/min. The progressive tool at all rotation speeds effectively inhibits migration of large amounts of stringer material to the skin and avoids base materials mixing. Small amounts of Cu particles are mechanically stirred and have a long flow path in the large pin stirring regions, which inhibits the formation of brittle Al/Cu intermetallic compound (IMC) phases during welding. Al/Cu forms effective metallurgical bonding, and the IMC thickness of the Al/Cu interface is less than 1 μm. The Al/Cu T-joints with pre-set Cu are similar to butt joints of the same material in the skin direction, showing a typical ductile fracture. In Al/Cu T-joints with pre-set Al, the direction of the bonding line defects is changed, a certain height of Al/Cu mixing zone is obtained in the direction of the stringer, achieving optimal mechanical interlocking bonding, and break mostly occurs at the intersection, with a tensile strength of 157 MPa, showing hybrid fracture. The pre-set welding wire is proved to be a good method for Al/Cu dissimilar FSW T-lap joints.

Key words: Al/Cu dissimilar welding; friction stir welding; T-lap joints; pre-set welding wire; intermetallic compounds; mechanical properties

To a certain extent, the aluminum/copper (Al/Cu) composite structure and the appropriate intermetallic compound (IMC) distribution influence the welding quality. A good metallurgical combination of Al/Cu joints can combine the advantages of both metals to attain sufficient strength and electrical and thermal conductivity of the component, in addition to lightweighting and economy[1]. Thus, it has broad application in power and electronics fields, new electric vehicles, etc[2]. In contrast, when Al and Cu are joined, IMCs will inevitably be produced, leading to increased joint brittleness. This is due to the difficulty of precisely controlling the heat input in Al/Cu joining and the large differences in plastic flow and physical and chemical properties of the two materials, making it easy to form large internal stresses inside the joint and reducing the reliability of the joint. At present, a large number of research results have been achieved about the dissimilar welding[3–9], such as friction stir welding (FSW) of Al/Cu butt and lap joints[8–9], but there are few reports on FSW of T-joints.

The structure of the T-joint can reduce the mass of the material to a certain extent while not reducing the structural strength. The special configuration of T-joints leads to defects such as wormholes, tunnels and weak connections of the bonding line at the two corner fillets[10–11], resulting in stress concentration, which severely restricts the application of FSW T-lap joints in engineering. This is actually due to the low heat

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input, poor plastic flow and insufficient stirring at the fillet transition of the corner region. Thus, in order to increase the liquidity of the materials and eliminate defects, it is necessary to improve the welding technique of the T-joints. Feistauer[12] used double-pass reverse FSW for AA5083 Al-Mg alloy T-lap joints, and revealed that the size of the bond line defects is reduced and the mechanical properties of the welds are significantly improved after the second pass treatment. Hao[13] used two-pass reverse FSW T-lap joint for AA5083 and AA7075 dissimilar aluminum alloy welding, and revealed that the bonding line defect dimensions are reduced and the joint performance is significantly improved at suitable offsets. Some researchers have used corner stationary-shoulder FSW to obtain defect-free T-joints of the similar or dissimilar aluminum alloys[14–15].

The size of the corner fillet is very important for the good forming of T-joints. Zhao et al[16] showed that smaller fillets are beneficial in reducing T-joint defects. The larger the corners fillets, the more the material is required to fill the rounded corners here. Defect-free T-joints with fillet not only increase the effective load-bearing area, but are also an effective measure to relieve stress concentrations and to smooth the transition at their structural mutations. However, defects arising at the corner fillets of T-joints, which become the origin of cracks, can significantly reduce the load-bearing capacity of the joint. How to achieve sufficient material flow at the corner fillets and eliminate defects with good formation is the focus of current research. The filling of the corner fillets were completed using measures such as increasing the skin plate material by 1 mm[17], using corner stationary-shoulder FSW pre-set welding wire[18] and changing the height of the stringer[19]. Memon et al[20] completed a FSW T-joint of AA6068 aluminum alloy using different down-pressure amounts (tool depth). They found that the depth of penetration of the weld core, the heat production and axial forces increase with the increase in the amount of downward pressure. And increasing the amount of pressure under the pin can fill corner, but the effective thickness of the skin joint will be thinned, resulting in a reduction in the load-bearing capacity of the joint.

In addition to its special structure and corner fillets, designing a matching pin structure should be also considered in T-joint welding. This research designed a progressive pin structure with large and small pins. The “small shoulder” effect of the large pin can reduce the mixing of Al/Cu by preventing a large amount of stringer metal from flowing towards the skin, while the structure matching the small pin with the supporting fillet can promote the flow of material at the fillet weld. In this work, T-lap FSW using self-designed progressive pin was used to join 6061-T6 alloy and C1100-T2 Cu plate with three types of pre-set welding wires. The microstructure and mechanical properties were tested and investigated. It lays a solid foundation for the application of T-lap FSW process in joining Al/Cu dissimilar materials.

1 Experiment

The dissimilar T-joints were produced with 6061-T6 alloy as skin and T2 Cu as stringer. The dimensions of the skin and stringer plates were 400 mm×100 mm×4 mm and 400 mm×50 mm×4 mm, respectively. The inclination of the pin spindle was 2°, and the press amount was 0.2 mm constantly. The pin was made of H13 steel, whose shoulder diameter was 20 mm and concave was 5°. The pin was progressive, in which the large pin was 10 mm in diameter and 3.6 mm in length, and the small pin was conical, with 3 mm in the minimum diameter and 2 mm in pin length. The special fixing device was designed in-house and the fixing support was made of mild steel plate with a bevel angle of 45° (edge length 2.1 mm) to ensure the formation of the corner weld inside the T-joint. Inner fillet weld was pre-set with HS201 copper wire with 1.6 mm in diameter and ER6061 or ER5356 aluminum alloy wire, as shown in Fig.1, to fill the gap among the skin, the stringer and the fixed support fillet. The rotational speeds and travel speeds of pin are shown in Table 1.

A body microscope and Zeiss EVO LS15 scanning electron microscope (SEM) were used for microstructure observation. The metallographic etching agent was Keller reagent for the aluminum alloy side and acetone:nitric acid:acetic acid=3:2:3 for the copper side. A WDW-200 microcontrolled tensile tester was used for tensile testing with a stretching speed of 4 mm/min in the skin direction and 1 mm/min in the stringer direction. Microhardness was tested with a spacing of 0.5 mm between each point at a test force of 0.98 N and a loading time of 10 s. The XRD characterization plane was selected as the Al/Cu intersection plane.

2 Results and Discussion

2.1 Morphology of welds

As can be seen in Fig.2, good weld surface quality can be obtained on the upper surface of the skin under all parameters. Surface profile of the weld is similar to that of an FSW butt joint of the same material. The intermetallic compound (IMC) produced by the Al/Cu dissimilar material does not flow to the

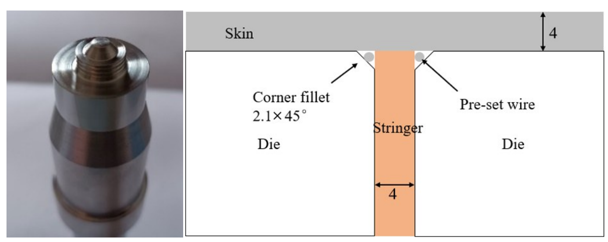

Fig.1 Schematic setup for welding

Table 1 Weld series and weld process parameters

No.	v/mm·min^{-1}	ω/r·min^{-1}	Fillet (1.6 mm)	Name
1	35	700	HS201	700-Cu
2		800	HS201	800-Cu
3		700	ER6061	700-Al6
4		750	ER6061	750-Al6
5		800	ER6061	800-Al6
6		800	ER5356	800-Al5

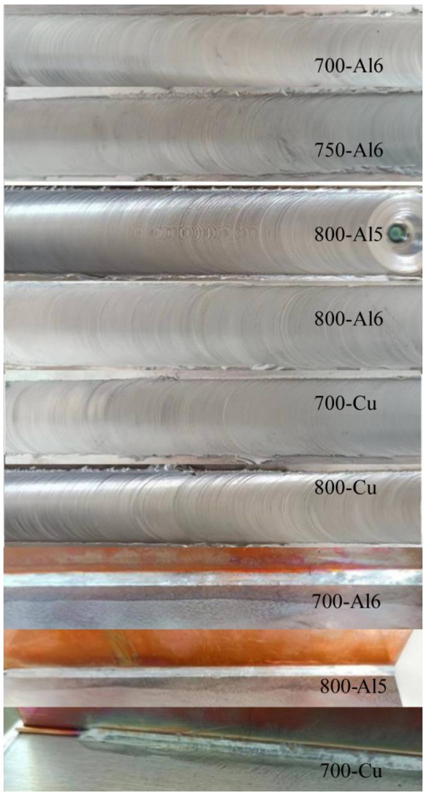

Fig.2 Appearances of the skin and corner of Al/Cu FSW T-joint

surface and deteriorate the formation. The inner corners of T-lap joint are well filled without macro defects.

FSW T-lap joints are shown in Fig. 3, no defects such as wormholes and tunnel appear in the T-lap joints at both speeds, and the inner corners are well filled. Onion rings-like patterns of aluminum alloy are found in the large pin stirring zone (SZ). No large particles of Cu are found in the laminated aluminum matrix composite strip. Progressive pin effectively prevents Cu particles from flowing into the large SZ.

2.2 Cross-sectional morphology of T-lap joints

For T-lap joints, the weld formation requires vertical metal flow. Under sufficient forging action, the aluminum alloys of the skin on the advancing side (AS) are extruded in the direction of the stringer, which is prone to bonding line defects formation, as shown in Fig. 3a. The 700-Cu joint has lower heat input and less heat transferring at the inner corners, resulting in a longer bonding line on the AS than that of the 800-Cu joint. The bonding line defects are formed between the downward extruded skin Al and the pre-set welding wire Cu, and there is no such defect at the interface between the pre-set Cu and the stringer Cu.

In 700-Cu joint, the intersection of skin and stringer exhibits a laminated band structure within the plastically deformed Cu. A large number of bands of Al fill the high and low grain boundaries of plasticized Cu, forming an Al/Cu interlocking bond with a certain height. This is because the pin rotation axis is perpendicular to the Al/Cu surface to be welded. The plastic material flow ring is parallel to the Al/Cu surface to be welded, the large pin has a cylindrical shape and the thermoplastic material moves less in the vertical direction. In addition, the difference in diameter between the large and

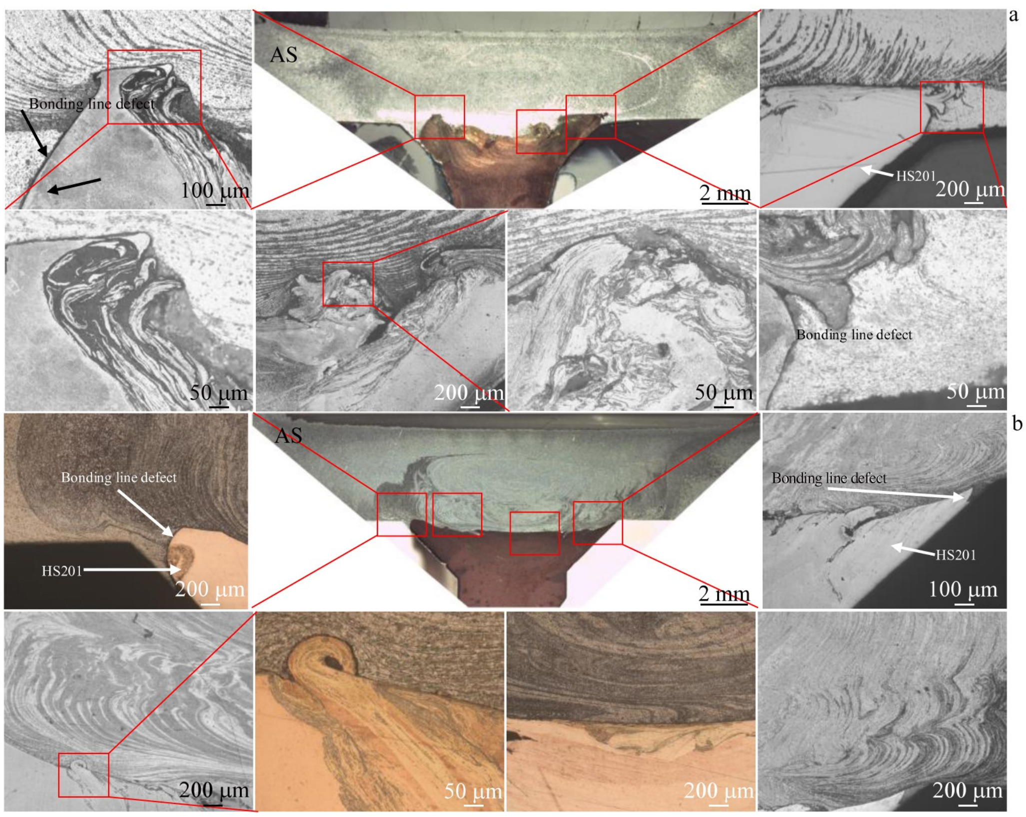

Fig.3 Microstructures of Al/Cu FSW T-lap joints pre-set with Cu: (a) 700-Cu and (b) 800-Cu

small pins results in a much larger flow path in the mixing zone of the large pin than that of the small pin at the same speed. As the speed increases to 800 r/min, the high and low magnitudes of the Al/Cu interlocking bond at the skin and stringer intersection are reduced. This is the result of lower Cu plastic deformation resistance at higher rotation speeds, reduction in the size of the junction line defects on the AS, and flattening of the Al/Cu intersection under large pin forging, thus avoiding base materials mixing. In addition, the coefficient of linear expansion of thermoplastic Al is greater than that of Cu. The large SZ has a squeezing effect on the small SZ and the high-density Cu tends to flow more in the small SZ, resulting in almost no large Cu particles appearing in the large SZ.

Fig.4 shows the microstructures of the FSW T-lap joints pre-set with Al (700-Al6 and 750-Al6). As can be seen, no defects such as wormholes and tunnel appear in the T-lap joints at both speeds, and the inner corners of T-lap joint are well filled. Onion ring-like patterns of aluminum alloy are found in the large pin SZ. 700-Al6 joints have a flat Al/Cu intersection, less Al/Cu intermixing, and a small degree of mechanical interlocking bonding. When the rotational speed is increased to 750 r/min, there is a small amount of Cu at the retreating side (RS) at the bottom of the large pin mixing zone. In other words, the upward movement of the Cu at the RS of the stringer is caused by the forging action of the "small shoulder" of the large pin, resulting in a part of the Cu moving downwards. The "small shoulder" is not sufficient to inhibit the upward flow of plastic metal from the SZ of all small pins. Due to the FSW weld surface flying edge defect, some of the plastic material wraps around the periphery of the larger SZ. This is further confirmed by the distribution of Cu on the RS in Fig. 4b, suggesting that the "small shoulder" of the progressive pin does not prevent all the Cu atoms from flowing into the skin under the high heat input conditions of the T-joint pre-set with Al welding wire.

The bonding line defects appear at the AS of the fillet weld in the 700-Al6 joint, as shown in Fig. 4a. The length of the junction line defect in Fig. 4 is much smaller than the aluminum, copper and welding wire intersectional interface size of the fillet weld, which means that the small pin has a certain stirring effect on the fillet weld.

The 750-Al6 also shows small onion ring-shaped microstructures (Fig. 4b), which is not produced in the large pin SZ but appears in the microstructure of small pin flowing at high speed. That is, as the heat input increases, more heat production promotes the flow of aluminum alloy from the larger pin zone to the smaller pin zone. The plastic flow strain in the center region of the weld core is greater than that of AS and RS, which is more durable to the full flow of the thermoplastic material. The Cu with poor plastic deformation is driven to the periphery of the pin by the high-speed rotating pin, showing the microstructure and morphological characteristics of a small onion ring mainly composed of aluminum-based composites, which also contains band-like structures within the Cu at the periphery of the pin.

Fig. 5 shows the microstructures of the 800-Al6 and 800-Al5 joints, whose inner corners are both well filled. Onion ring-like patterns of aluminum alloy are found in the large pin

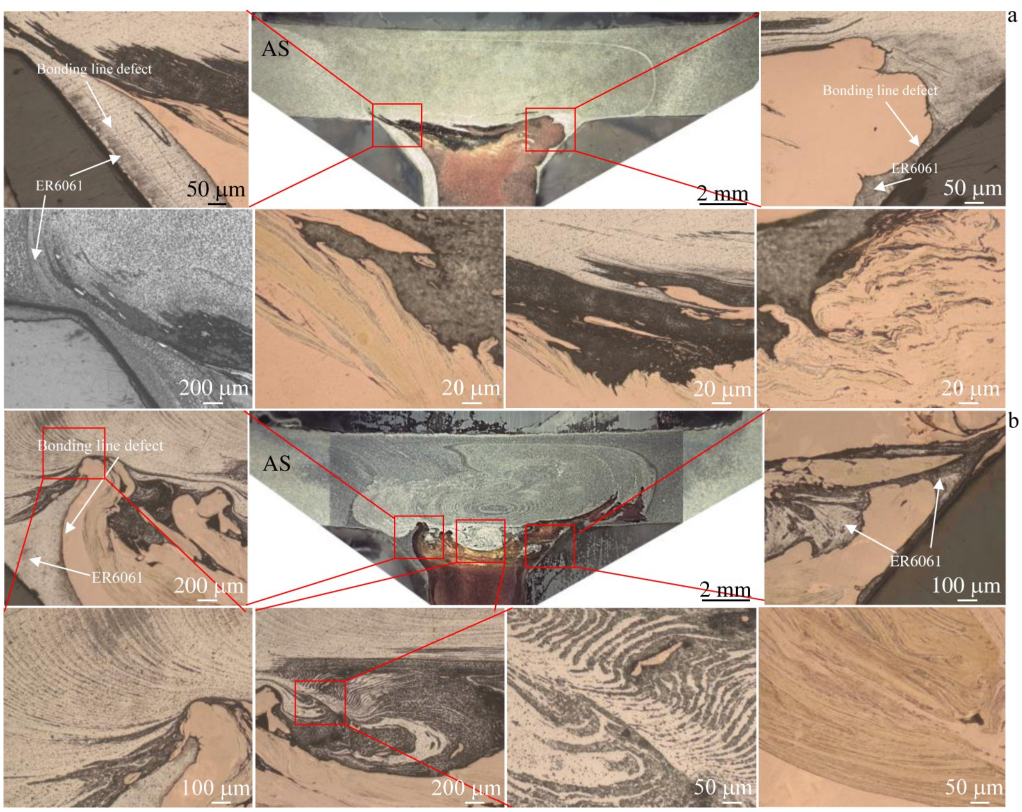

Fig.4 Microstructures of Al/Cu FSW T-lap joints pre-set with Al: (a) 700-Al6 and (b) 750-Al6

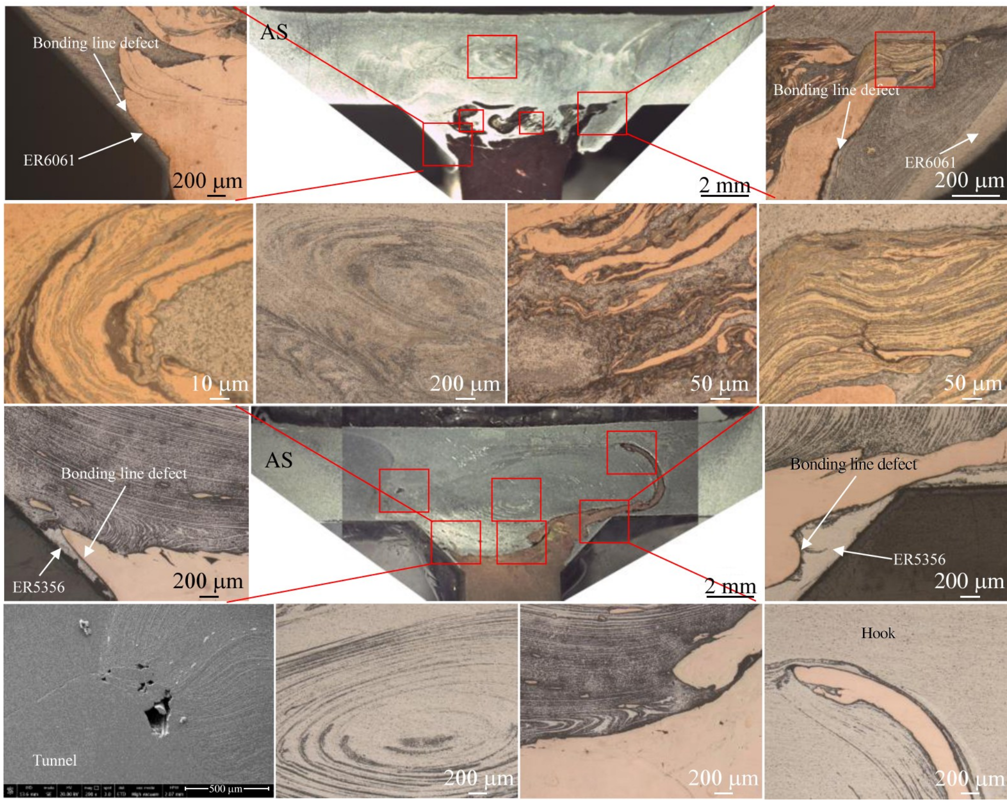

Fig.5 Microstructures of Al/Cu FSW T-lap joints pre-set with Al: (a) 800-Al6 and (b) 800-Al5

SZ, with a small amount of stringer Cu entering the large pin SZ. This indicates that progressive pin effectively prevents a large amount of Al/Cu intermixing.

Fig.5a shows the microstructure of the 800-Al6 joint, where Al/Cu is mechanically intermixed during the FSW process to form a laminar striped aluminum matrix composite. At this speed, the plastic flow of Cu is more adequate and the amount of small granular Cu distributed in the aluminum base-like composite near the Al/Cu intersection increases. This is similar to the improved performance of FSW joints obtained with suitable offsets to the aluminum side in Al/Cu butt joints[21], with a more easily formed ribbon microstructure[22]. A small amount of Cu is brought into the Al matrix by shear rotation, driven by the plastic flow of Al which is stirred up and elongated, in the form of fine particles distributed on the Al matrix composite with laminar characteristics to achieve effective metallurgical bonding. In addition, the banded Cu microstructure in Fig. 5a shows that the Cu plastic flow is more adequate at this process parameter.

Fig.5b shows the microstructures of the 800-Al5 joint. The tunneling defect appears inside the aluminum alloy matrix in the large pin SZ on the AS, and there are a few small Cu particles distributed in the aluminum matrix around this defect. More plasticized Cu enters the large pin SZ from the bottom of the RS of the small pin SZ, showing a microstructure outside the “onion ring” of the large pin SZ and Cu hook junction. The AS and the center of the pin SZ are dominated by Al, and the RS of the pin SZ consists mainly of Cu, showing a pin SZ with Cu surrounding Al. The plastic flowing Cu is properly “forged” by the “small shoulder” and builds up in volume, with some of the Cu winding from the bottom of the large pin SZ to form a huge Cu hook outside the large pin SZ. The bonding line defect is further reduced between the pre-set Al and the stringer Cu, confirming the sufficient mixing effect of the small pin on the corner filled at high speed.

Fig.5b also shows that the center of the “onion ring” in the large pin SZ moves downwards. 5356Al has poorer plastic deformation ability than 6061Al. The pre-set Al welding wire, together with the stringer plate Cu, is rotated and squeezed up from the bottom of the large pin mixing zone to the junction of the shaft shoulder and the large pin mixing zone. Huge Cu hooks are formed, together with plastic flowing of 5356Al outside. High deformation resistance of Cu and 5356Al prevents the rotational flow of RS thermoplastic material to the rear of the forward side filling. The inflow of Cu and 5356Al results in poor plastic flow in the large pin mixing zone, making it more difficult to fill the transient cavities left on the AS and prone to the formation of tunneling defects. In addition, the material flow and temperature gradient are asymmetric in the FSW. The plastic material flow on the AS is better than that on the RS. Under this conditions, the microstructure shows that Al with good plastic flow aggregates on the AS, accompanied by a downward shift of the center “onion ring”, and Cu with poor plastic flow is aggregated on the RS.

Campanella et al[23] simulated the temperature field of FSW T-joints using progressive pins, and found that the AS temperature is higher than the RS temperature, and the stirring effect is more pronounced on the AS. Aluminum alloys on AS with high temperature gradient are more likely to combine with the pre-positioned aluminum wires when extruded downwards, forming an "onion ring" structure. For the low temperature gradient on the RS, Cu is extruded and flows to the periphery of the large pin SZ in the space formed by the fixed support and the stirring pin. Rana et al[24] studied the performance of TC4 titanium alloy/aluminum alloy T-lap joint, and the results show that with increasing the rotational speed, the height of the stringer titanium alloy flow arm increases, which is conducive to the generation of interlocking structures, and the hook-shaped height of RS titanium alloy is significantly higher than that of AS. Under the conditions of this experiment, the huge "copper hook" structure is similar to the geometry of the titanium alloy flow arm, and the Cu flows poorly from the RS of the stringer to the skin, which shows the asymmetry of material flow in the FSW T-joint.

On the one hand, the higher rotational speed leads to sufficient heat input at the filled corner to promote plastic flow of the pre-set welding wire, which in turn makes it easier for the plasticized material to be squeezed out of the small pin SZ to form a large hook microstructure. On the other hand, ER-5356, as gap filler at the fillet weld, has a poorer plastic transformation capacity than ER-6061, which makes it more difficult to adequately intermix ER-5356 with the skin and stringer materials.

2.3 IMCs

In order to gain a deeper understanding of the thickness of the IMCs at the interface, a high-resolution SEM equipped with energy disperse spectroscope (EDS) was used. Fig. 6 demonstrates the morphology of the Al/Cu interface of three pre-set wires, and the thickness of the IMC layers is found to be less than 1 μm. EDS point scanning is performed on IMC layers, and results show that the possible phases are Al_2Cu and AlCu, as shown in Table 2. Xue[25] reported the property deterioration of joint with IMCs more than 2.5 μm in thickness, and it is found that excellent metallurgical bonding is obtained for joints with IMC thickness of about 1 μm. The regional surface scan results of Cu particles in the 750-Al6 joint are shown in Fig.6e–6f. From the EDS results, it can be seen that Al and Cu elements mutually diffuse at the interface, there is a clear transition zone along the interface, which is continuously distributed, and the transition layer widths are different.

XRD patterns of the Al/Cu intersection surface in the SZ of progressive pin in FSW joints are shown in Fig.7. The results show that the joints contain matrix Al and Cu, as well as the generated IMCs AlCu and Al_2Cu. Due to the effective suppression of a large amount of Al/Cu mixed by the "small shoulder" and the long flow path of the large pin diameter, the material flow is effectively promoted, forming a layered composite material structure without providing favorable conditions for the mass generation of IMC. Therefore, it is easier to obtain joints with excellent performance.

2.4 Mechanical properties of joints

Fig. 8 shows the ultimate tensile strength of the joint along the skin and stringer directions at the welding speed of 30 mm/min. There is a large difference between the ultimate tensile strength of joints pre-set with Cu and Al. The ultimate tensile strength of the welds pre-set with Cu is similiar to that of butt joint of the same material along the skin direction, with an ultimate tensile strength of 187 MPa, while the ultimate tensile strength along the stringer is low (97 MPa). This is because the pre-set Cu is more readily bonded to the Cu metallurgy of the stringer, the mixed thickness of Al/Cu in the

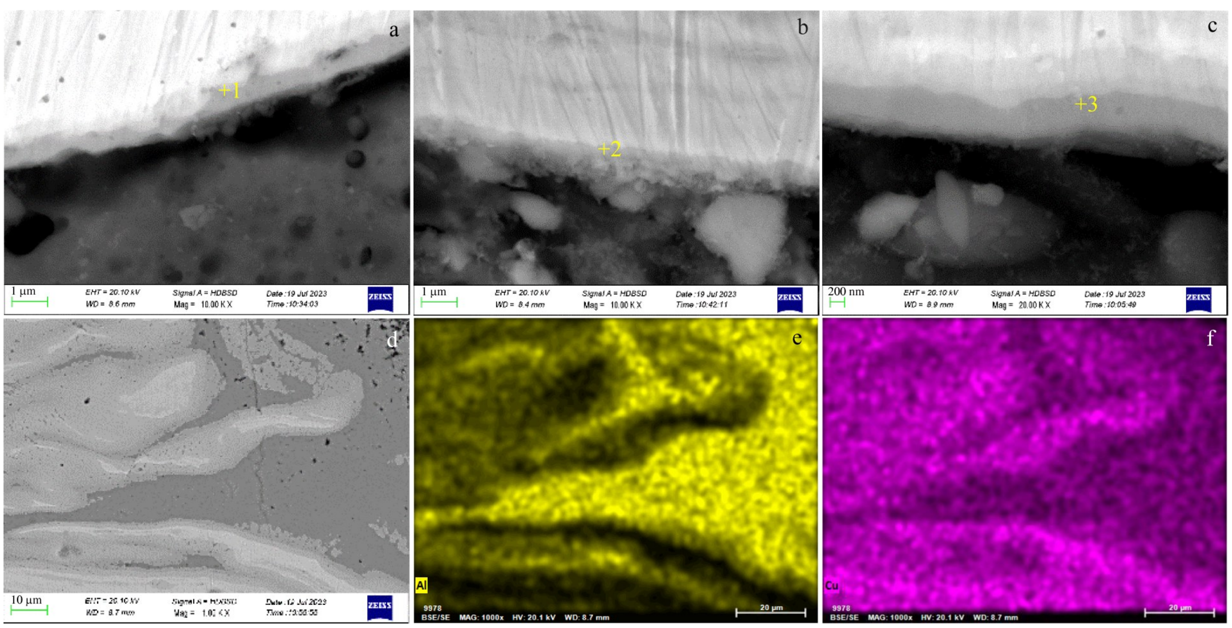

Fig.6 High-magnification SEM images of the bonding interface (a–d) and corresponding EDS mappings (e–f): (a) 800-Al5, (b) 700-Al6, (c) 700-Cu, and (d–f) 750-Al6

Table 2 EDS analysis results of points in Fig.6

Point	Al/at%	Cu/at%	Possible phase
1	67.74	32.26	Al_2Cu
2	48.90	51.10	AlCu
3	67.57	32.28	Al_2Cu

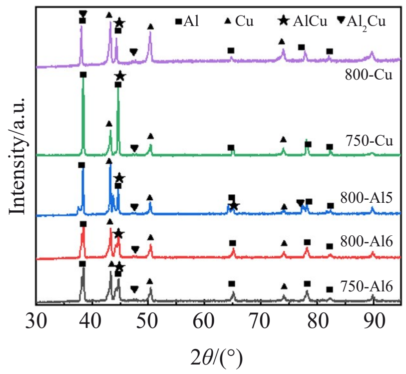

Fig.7 XRD patterns of the cross section in Al/Cu T-lap FSW joints

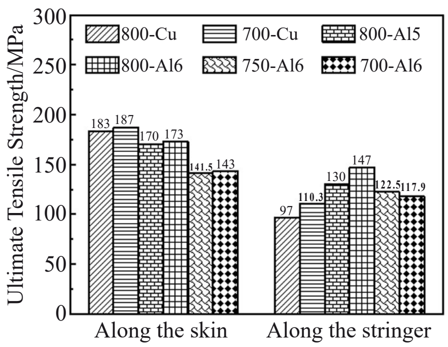

Fig.8 Ultimate tensile strength along the skin and stringer directions

vertical direction is reduced, and the mechanical interlocking effect is greatly diminished. In addition, the bonding line defects of Al/Cu are perpendicular to the direction of the stringer, and fracture tends to occur firstly at this defect, which is not conducive to the improvement of mechanical properties.

As seen in Fig. 8, the ultimate tensile strength of the joint pre-set with Al decreases with decreasing rotational speed along the skin direction, reaching 170 MPa at 800 r/min. The ultimate tensile strength of the joint pre-set with ER6061 decreases with decreasing the rotational speed in the direction of the stringer. This is due to the higher heat input at high speed, which makes it easier for the stringer material to achieve full flow and for the skin Al to metallurgically bond with the pre-set Al under extrusion, facilitating vertical Al/Cu mixing and maximizing mechanical interlocking bonding to 157 MPa. At low speed, both heat input and stirring action are reduced, resulting in insufficient flow of material in the vertical direction, and thus leading to a reduction in ultimate tensile strength along the stringer.

The Al/Cu intermixing is facilitated by pre-set Al joints compared with pre-set Cu joints. The smaller size of the bonding line defects in pre-set Al joints facilitates mechanical property improvement along the stringer.

The microhardness reflects to some extent the degree of Al/Cu mixing in the joint and the degree of metallurgical bonding. Fig. 9 shows the microhardness distribution of SZ at different rotational speeds. The microhardness varies slightly in the skin direction, similar to the microhardness of butt joint under the same material. The "small shoulder" of the progressive pin effectively inhibits Al/Cu intermixing and the distribution of small amounts of Cu particles in the "onion ring" region of the aluminum alloy, while the large pin mixing volume results in a longer plastic flow path, reducing IMC generation.

Fig. 9b shows the microhardness of the T-lap joint in the stringer direction. The microhardness in the middle and upper parts of the large pin SZ does not vary much under all process parameters, and it shows a large variation near the intersection of stepped pins. A peak in microhardness in the center of the small pin SZ of the pre-set Al joint indicates that a metallurgical reaction has taken place in Al/Cu joints to produce a certain amount of IMC.

In contrast, only the upper part of the progressive pin shows a change in microhardness in the pre-set Cu joints, with little change in microhardness in the small pin SZ. This is consistent with the histomorphology of Fig. 3, where the pre-set Cu is more readily metallurgically bonded to the stringer Cu, the vertical intermixing height of Al/Cu is greatly reduced, and the "small shoulder" of the forging dominates, effectively preventing the flow of stringer Cu to the skin.

In the tensile test along the skin direction, the 700-Cu joint

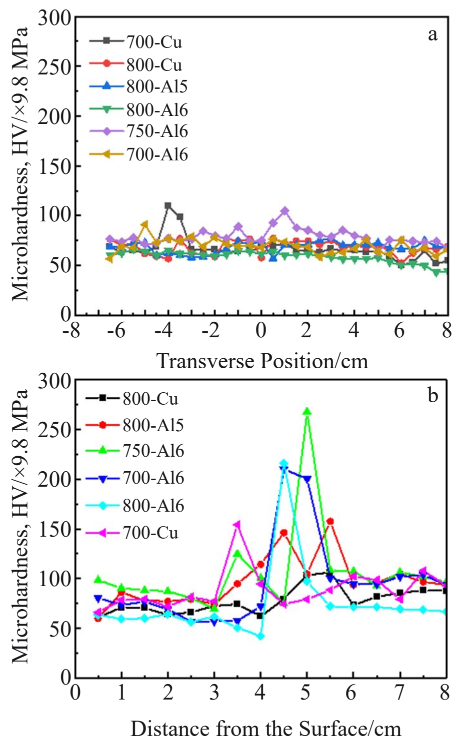

Fig.9 Microhardness distributions along the skin (a) and stringer (b) directions at a travel speed of 35 mm/min

is broken in the heat affected zone and its fracture morphology is shown in Fig. 10a. This indicates that the strength of the weld along the skin direction is optimal under this process parameter, which is consistent with the highest ultimate tensile strength values obtained. Tensile fracture along the skin direction is located on the AS and RS of the SZ under all process parameters except 700-Cu, which shows typical ductile fracture.

In tensile tests along the stringer direction, the fractures occur all at the Al/Cu junction, dominated by brittle fractures as well as a few mixed fractures. According to the microstructure morphological description, the SZ has defects such as tunneling and bonding lines. The inner corner bonding line defect in the T-lap joint pre-set with Cu is perpendicular to the stringer tensile direction, and this defect becomes a stress concentration area, which is the first point of initiation of tensile fracture in the stringer direction. This is consistent with the result that the tensile strength of pre-set Cu joint in stringer direction is much lower than that of pre-set Al joint. Under tension in the stringer direction, the Al/Cu intersection becomes the starting point of fracture instead of the SZ, indicating that the IMC at the intersection is more likely to be the path of crack expansion. EDS line scanning of Al/Cu content is shown in Fig. 10d, indicating that the Al/Cu intersection forms an IMC layer and the joint achieves a metallurgical bond. Partial area of the fractures of 800-Al6 and 800-Al5 joints has dimples, indicating ductile fracture characteristics, as shown by the red circle in Fig.10e. This is due to part of the Al remaining on the Cu side of the fracture, and the mechanical interlocking forms an interface which is more conducive to its strength. The circular shape left by the pin in Fig.10f shows that the 800-Cu joint has a small height of the Al/Cu intermixing zone along the stringer direction, which is consistent with the microstructural characteristics in Fig.3.

2.5 Discussion

For T-lap joints, there is only one lapped surface to be welded between the skin and the stringer. With conventional pins, 70% – 80% of the generated heat comes from the shoulder during the FSW process, and the temperature difference between the upper surface of the skin and the Al/Cu lap reception weld is relatively large. The use of progressive pins enables the transfer of the "small shoulder" from the upper surface of the skin to the Al/Cu lap reception surface. The red line in Fig.11 illustrates the main heat source. This is an effective measure to increase the heat input at the fillet weld.

In addition, the use of progressive pin for welding SZ is dominated by skin Al. Large pins produce SZ over 2/3 of the entire weld core area. On the one hand, it has the advantage that the heat produced by the large pin can be transferred more effectively to the fillet weld, which promotes the flow of material in the fillet. On the other hand, the large width of the SZ of the large pin is fully used. The long flow route of the plastic material makes it easy to form long ribbons of aluminum-based composite microstructure, which facilitates a fine distribution for a small amount of Cu particles on the Al-rich ribbon under the effect of high-speed rotational stirring. This is like the formation of joint bonding under a suitable offset to the Al side in Al/Cu butt joints. Such a mixing mechanism facilitates plastic flow, greatly reducing the IMC formation and improving joint reliability. The large pin is conducive to heat transfer to the fillet weld, and the progressive pin effectively inhibits the stringer Cu from entering the skin and reduces Al/Cu intermixing. T-lap joints along the skin direction at low rotational speeds resemble butt joints of the same material, which is consistent with the research results of Memon[20].

In the T-joint FSW process, although the large taper of the

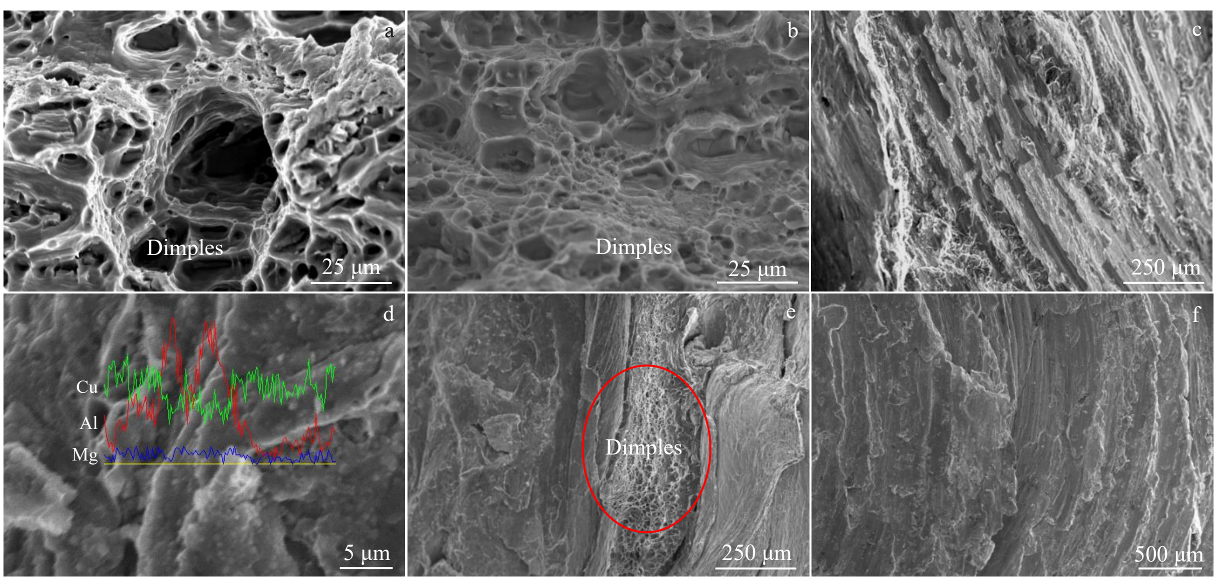

Fig.10 Tensile fracture profiles along the skin (a – b) and stringer (c – f) directions: (a) 700-Cu, (b, d) 750-Al6, (c) 700-Al6, (e) 800-Al6, and (f) 800-Cu

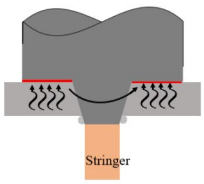

Fig.11 T-Lap diagrams using conventional and progressive pins for heat production

small pin promotes the vertical movement of the material, the poor plastic flow of the material in the small pin mixing zone at low speed is mainly influenced by the forging of the "small shoulder", which greatly reduces Al/Cu intermixing. And the small pin SZ has good plastic flow at high speed, so some Cu atoms bypass the bottom of the large pin, gradually entering the periphery of the large pin SZ. As the speed increases, the small pin produces more heat and the large pin transfers more heat to the small pin mixing area, resulting in increased flow of plastic material in the small pin mixing area. At the same speed, Al generates more frictional heat than Cu, with poor thermal conductivity and low plastic stress, which is more conducive to the full intermixing of Al/Cu in the small pin SZ, increasing the flow volume of Al/Cu intermixing, and thus forming a certain height of Al/Cu intermixing microstructure in the stringer direction.

Under the action of the stirring thermal field, the welding wire placed at the 45° chamfer is subjected to the stirring action in addition to the squeezing action between the small pin and the corner die. Pre-set Al passes more preferentially than stringer Cu through the bottom of the large pin and enters into the periphery of the large pin mixing zone. The microstructure of the pre-set Al thermoplastic deformation is hook-like at different speeds, as shown by the arrows in Fig.12. The height of the aluminum "hook" is smaller on the AS, while the "hook" formed by the extruded aluminum wire is longer on the RS. This indicates an asymmetric material flow at the inner corners of the T-joint. Small pins produce much less heat than large pins, and pre-set Al tends to move towards the skin where the temperature is higher and the flow is better. Without accounting for composition changes, pre-set Al is more likely to undergo plastic transformation, changing the orientation of the bonding line defect, so it no longer becomes the location of fracture initiation. In contrast, the high deformation resistance of pre-set Cu makes it easier to metallurgically bond to the stringer Cu, so it is difficult to promote Al/Cu intermixing, and the higher density of Cu requires greater heat input to compensate for the poor deformation resistance. This indicates that the composition of pre-set wire needs to be identical to that of the base metal side, where the resistance to deformation is the lowest. Well-formed T-lap joints are obtained because the pre-set wires reverse the direction of the bonding line defects.

There are different percentages of Al/Cu with different pre-set welding wire composition in the weld. A large proportion of Al in a pre-set Al weld makes it easier to generate sufficient heat for plastic flow. In contrast, pre-set Cu weld with increased proportion of Cu requires more heat input to be transferred to the corner. Even though the progressive pin can transfer a large amount of heat to the stringer, there is a risk of unaltered bonding line defects due to the unreasonable composition of the pre-set welding wire. This means that the heat transfer behavior of the inner corner is more sensitive and requires not only a "small shoulder" of progressive pin but also a low resistance to deformation of the pre-set welding

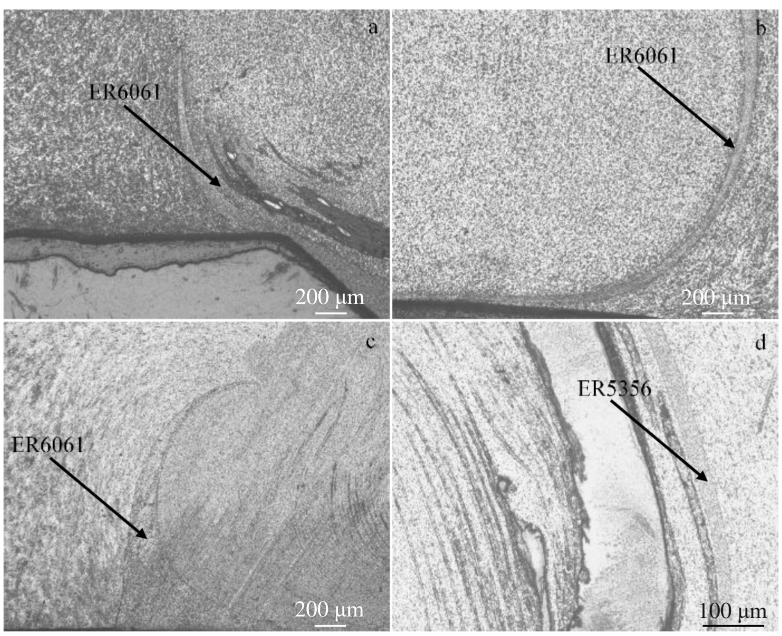

Fig.12 Pre-set aluminum alloy wire for plastic flow in the skin direction: (a) 700-Al6 on the AS, (b) 700-Al6 on the RS, (c) 750-Al6 on the AS, and (d) 800-Al5 on the RS

wire.

Few Cu particulates enter the skin in the pre-set Cu joints, similar to a lap joint of dissimilar metals. The pre-set Cu is more easily metallurgically bonded to the stringer Cu. Large pin down extrusion of Al and Cu under proper flow forms bonding line defects. Even at the same speed, Cu conducts heat well and Cu requires more heat to flow fully, both of which are not conducive to Al/Cu intermixing. The pin morphology changes abruptly and the corner is filled with a rapid cooling at the Al/Cu junction. The rotational speed of 800 r/min is not enough to generate heat for the pre-set Cu to bypass the bottom of the large pin and to enter the skin.

The pre-set wire size is perfectly matched to the pin inserted into the Al/Cu to be welded and die support, which improves the material flow behavior at the filled corner, greatly increases the bonding area of the T-lap joint without thinning, and provides theoretical guidance and reference for T-lap FSW of other materials.

3 Conclusions

1) Well-formed T-lap joints can be obtained through the combination of progressive tool, pre-set welding wires and fixed supporting fillets.

2) In the pre-set wire joints, the "onion ring" pattern is generated in the large pin mixing zone in all conditions.

3) The progressive pin acts as a "small shoulder" at the T-lap intersection, effectively inhibiting the mixing of large amounts of Al/Cu.

4) The thickness of IMCs layer at the Al/Cu interface is less than 1 μm, forming an effective metallurgical bond.

5) The T-joint pre-set with Cu welding wire has very little Al/Cu intermixing in the stringer direction, and it is fractured at the intersection, with ultimate tensile strength of only 97 MPa. It is similar to butt joint of the same material along the skin direction, with ultimate tensile strength of 187 MPa and a typical ductile fracture.

6) The T-joint pre-set with Al welding wire forms a mixed Al/Cu zone with a certain height in the stringer direction, changing the direction of the bonding line defects, and achieving both metallurgical bonding and mechanical interlocking bonding mechanisms. It is fractured at the intersection, with ultimate tensile strength of 157 MPa, showing mixed fracture characteristics.

References

1 Lakshminarayanan A K, Suresh M, Varshan M Sibi. *JOM*[J], 2015, 67(5): 1032

2 Sejani Devang, Li Wenya, Patel Vivek. *Critical Reviews in Solid State and Materials Sciences*[J], 2021, 47(6): 865

3 Zhao Xiao, Gao Enzhi, Xu Rongzheng. *Rare Metal Materials and Engineering*[J], 2022, 51(5): 1752 (in Chinese)

4 Zhao Fei, Wang Kang. *Rare Metal Materials and Engineering*[J], 2022, 51(3): 1047 (in Chinese)

5 Li Huan, Zhang Changxin, Ao Sansan. *Rare Metal Materials and Engineering*[J], 2022, 51(12): 4624 (in Chinese)

6 Wang Xiangjie, Yang Lingfei, Tan Hongjuan *et al*. *Rare Metal Materials and Engineering*[J], 2022, 51(6): 2033

7 Wu Xiaoyan, Luo Wei, Jiang Haitao. *Rare Metal Materials and Engineering*[J], 2022, 51(9): 3197

8 Zhang Huijie, Sun Shulei, Liu Xu *et al*. *Journal of Materials Engineering and Performance*[J], 2022, 31: 2457

9 Guan Qilong, Zhang Huijie, Liu Huijie *et al*. *Journal of Manufacturing Processes*[J], 2020, 57: 363

10 Cui Lei, Yang Xinqi, Zhou Guang *et al*. *Materials Science and Engineering A*[J], 2012, 543: 58

11 Isa Mohammad Syahid Mohd, Moghadasi Kaveh, Ariffin Mohammad *et al*. *Journal of Materials Research and Technology*[J], 2006, 200: 3713

12 Feistauer E E, Bergmann L A, dos Santos J F. *Materials Science and Engineering A*[J], 2018, 731: 454

13 Hao Dinh Duong, Tra Hung Tran, Okazaki Masakazu Dac *et al*. *International Journal of Advanced Manufacturing Technology*[J], 2022, 121(7–8): 4677

14 Mertinger V, Varbai B, Adonyi Y *et al*. *Welding in the World*[J], 2022, 66(8): 1623

15 Zeng Shenbo, Chen Gaoqiang, Dinaharan *et al*. *Journal of Materials Engineering and Performance*[J], 2020, 29(11): 7094

16 Zhao Yong, Zhou Lilong, Wang Qingzhao *et al*. *Materials & Design*[J], 2014, 57: 146

17 Manuel N, Costa J M, Loureiro A. *Journal of Materials Engineering and Performance*[J], 2019, 28(8): 5233

18 Li D, Yang X, Cui L *et al*. *Science and Technology of Welding and Joining*[J], 2015, 20(8): 650

19 Donati L, Tomesani L, Morri A. *International Journal of Material Forming*[J], 2009, 2(1): 295

20 Memon Shabbir, Fydrych Dariusz, Fernandez Aintzane *et al*. *Materials*[J], 2021, 14(16): 4754

21 Mukesh Kumar, Ashish Das, Raj Ballav. *Materials Today: Proceedings*[J], 2020, 33: 4951

22 Karrar Gihad, Galloway Alexander, Toumpis Athanasios *et al*. *Journal of Materials Research and Technology*[J], 2020, 9(5): 11968

23 Campanella Davide, Fratini Livan. *Production Engineering-Research and Development* [J], 2022, 16(6): 785

24 Rana Harikrishna, Campanella Davide, Buffa Gianluca *et al*. *Materials and Manufacturing Processes*[J], 2023, 38(4): 471

25 Xue P, Xiao B L, Ma Z Y. *Metallurgical and Materials Transactions A*[J], 2015, 46A(7): 3091

预置焊丝对Al/Cu异种FSW T-搭接接头组织和性能影响

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摘　要：在FSW过程中，T型接头的内角热输入低、塑性流动差导致其易出现虫洞、隧道、交界线等缺陷，造成应力集中，很难实现具有良好力学性能的Al/Cu异种焊缝。创新性地将圆角处预置焊丝应用于4 mm厚的6061-T6铝合金和纯铜异种FSW T-搭接接头的连接，以期改善T型接头的内角材料塑性流动，获得具有良好力学性能的接头。分析了3种预置焊丝对Al/Cu异种 FSW T-搭接接头显微组织和力学性能的影响。结果表明，保持焊接速度35 mm/min不变，旋转速度在700~800 r/min条件下，3种预置焊丝接头大针搅拌区都表现出"洋葱环"。阶梯状搅拌头有效抑制了大量筋板材料向壁板的迁移，减少了Al/Cu互混。大针搅拌区由于少量Cu颗粒被搅拌，流动路径长，不易形成金属间化合物。Al/Cu形成了有效的冶金结合，其交界面处金属间化合物厚度小于1 μm。预置Cu的Al/Cu T-接头沿壁板方向像同种材料对接接头，呈韧性断裂；预置Al的Al/Cu T-接头改变交界线缺陷走向，筋板方向获得一定高度的Al/Cu混合区，机械互锁结合效果达到最优，断裂多在交界面处，抗拉伸强度达157 MPa，呈混合断裂。预置焊丝是一种适用于Al/Cu异种FSW T-搭接接头焊接的良好方法。

关键词：Al/Cu异种焊接；搅拌摩擦焊；T-搭接；预置焊丝；金属间化合物；力学性能

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