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Original Article

Improve the quality of 1060Al/Q235 explosive composite plate by friction stir processing

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ABSTRACT

The common aluminum/steel composite plates made by explosive welding often have steel cuttings, holes, cracks and other defects at the interface, which make the component premature failure. Friction stir processing (FSP) can make the microstructures stirred strongly, forming the uniform and fine structure, also repairing the defects. However, how to improve the quality of composite plate by FSP is still in blank and needs to be investigated. Results show that FSP can repair defects of the interface for aluminum/steel composite plate and improve the bonding strength of composite plate by metallurgical connection. Also, the nanocrystals formed by FSP have a significant improvement to the bonding strength of interface. When the overlap (l/d) is 5/25 and the multi-pass is three, the aluminum/steel composite plates after FSP exhibit good mechanical properties. The smaller overlap (l/d) will obtain higher efficiency, which shows attractive application for the repairing of composite plate.

1. Introduction

Explosive welding is well known for its capability to directly join a wide variety of both similar and dissimilar combinations of metal plates and is most often used where conventional fusion welding is unpractical [1]. Explosive welding is one of the common process for preparing the composite plate, which enables very large sections of plate to be clad in a single operation [1]. However, owing to the instantaneous high temperature and pressure of explosion, there are obvious defects such as steel cuttings, holes, cracks at the interface [2–5]. The above defects affect the service life of composite life seriously and therefore, need to be repaired for better mechanical properties. Friction stir processing (FSP), which is developed based on the friction stir welding (FSW), has been used in improving mechanical properties of materials [6–8]. The composite plates have been stirred intensely after FSP, leading to form uniform and fine structures. However, how to improve the quality of composite plate by FSP is still in blank and therefore, it needs to be researched systematically.

The parameters of FSP in repairing composite plate are include the overlap and multi-pass. Single-pass FSP can not achieve effective repairing effects on the materials stirred. Meanwhile, it can also form tunnel and cavity defects in pro-

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Table 1 – Chemical compositions for 1060Al/Q235 explosive composite plate/wt.%.

	Fe	Al	Si	Mn	Ti	Zn	C	S	P
1060Al	0.19	Ral.	0.15	0.03	0.017	0.012	–	–	–
Q235	Ral.	0.029	0.12	0.32	–	–	0.13	0.009	0.022

cessed materials. The appearance of tunnel defects is due to the theory of sucking-extruding. That is, when the plastic material flows along the direction of the pin with the rotation of the stir tool, producing a sucking effect. At another end of the pin, the plastic metal will change its flowing direction and extrude the plastic metal, producing an extruding effect [9]. The softened material is subjected to extrusion by the tool pin rotational and traverse movements leading to formation of FSP zone [10]. Multi-pass FSP broadens the selection of process parameters, because a second or third overlapping pass could be performed to repair these defects [11]. Chen et al. found that multi-pass friction stir processing (M-FSP) can improve the mechanical properties of 7B04-O Al and reduce the tunnel defects [12]. El-Rayes et al. reported that increasing the number of passes leads to an increase in grain size and reduces the tensile strength of the SZ owing to the heat accumulation [13]. However, Chen et al. found that increasing the number of passes is beneficial for inhibiting the expanding of abnormal grain growth [14]. Therefore, the uniform and small grains with no tunnel defects will be obtained by the appropriate multi-pass FSP procedure.

The second parameter of FSP in repairing composite plate is overlap. The overlapping of passes can be used to produce bulk-processed materials. 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. Normally, the l/d is less than 1. The smaller size of overlap l/d it has, the faster repairing rate it obtained. However, the microstructures of overlapping region are complex owing to multi-pass stirring effects. If the pin inserts into or near the position of tunnel defect, the tunnel defect will be eliminated by the strong stirred. Otherwise, the tunnel defect will be retained and a newly tunnel defect will be formed. Therefore, optimizing the overlap (l/d) parameter is important to obtain a satisfied structure for the composite plate.

The intermetallic compounds (IMCs) often exist at the interface after explosive welding. The IMCs are formed at the interface through diffusion and recrystallization due to the effect of temperature and pressure [15,16]. Owing to the materials for composite plates are different in physical and chemical properties, for example, the aluminum and the steel, then Fe_3Al, FeAl, Fe_2Al_5, $FeAl_2$ and $FeAl_3$ (Fe_4Al_{13}) are the main IMCs formed in the process of welding [17,18]. Different intermetallic compounds have different effects on the properties of composite plate [19]. How to control the IMCs in an appropriate amount is a key problem to obtaining a satisfied structure for the composite plate.

In order to decrease the cost of production, the explosive composite plate can be applied by FSP. In this paper the 1060Al/Q235 explosive composite plates are applied for FSP repairing due to its superior plastic flow and widely usage, for example, in automobile, ship, aerospace and pressure vessel fields [20–22]. Also, compared with other alloys, pure aluminum and carbon steel contain fewer elements, which makes it easier to research the failure mechanism of interface. Different passes and overlaps are researched in order to study the relationship between microstructures and properties. Finally, the optimized FSP procedures are determined, which gives a good data basis for the production of aluminum/steel composite plate in the future.

2. Experimental materials and methods

The 1060Al/Q235 explosive composite plate with 6 mm in thickness was selected in this study and the thickness ratio of aluminum to steel was 1:1. The chemical compositions (wt.%) were measured by ICP direct reading spectrometer, as shown in Table 1. It conformed to 1060Al and Q235 standard specification.

The friction stir processing (FSP) machine was modified by the numerical control machine, with the main axis, workbench and controlling system in it, as shown in Fig. 1(a). The stirring head is made of W-Re alloy with 25 mm in diameter for the shaft shoulder and 7 mm in diameter for the stirring pin, as shown in Fig. 1(c). In order to eliminate the effect of accumulative heating, the plate was cooled down to room temperature after each pass, and then the subsequent pass was performed. The tool rotation speed and forward speed of FSW machine were set at 1000 rpm and 30 mm/min, separately. The stirring head was inserted in the aluminum and the rotational orientation of the tool was counterclockwise.

The microstructures of 1060Al and Q235 were etched with Keller's reagent and 4% nitric acid alcohol, separately. Then, the microstructures were analyzed by optical microscope (OM, Leica DM2700), scanning electron microscope (SEM, Quanta 450) equipped with energy dispersion spectrum (EDS, Oxford) and transmission electron microscope (TEM, FEI Tecnai T12).

The shear specimens were designed on the basis of the national standard GB/T2651-2008. The bending specimens were designed on the basis of the national standard GB/T232-2010. The shear tests and bending tests were carried out using an electronic universal testing machine CSS-44100 with a loading speed of 1 mm/min. The sizes of specimens were shown in Fig. 2.

3. Results and discussion

3.1. *Macro-morphology*

Fig. 3 shows the macro-morphology of composite plate after FSP with different overlap l/d and multi-pass. The four overlapping parameters (l/d) are set as 5/25, 8/25, 10/25 and 15/25, as shown in Fig. 3(a), (b), (c) and (d). Also, the three multi-pass parameters are set as single pass, second passes and third passes, as shown in Fig. 3(b). The composite plates after FSP are in good formation. With the increase of overlap l/d, the flashes for the final weld are becoming more and more seri-

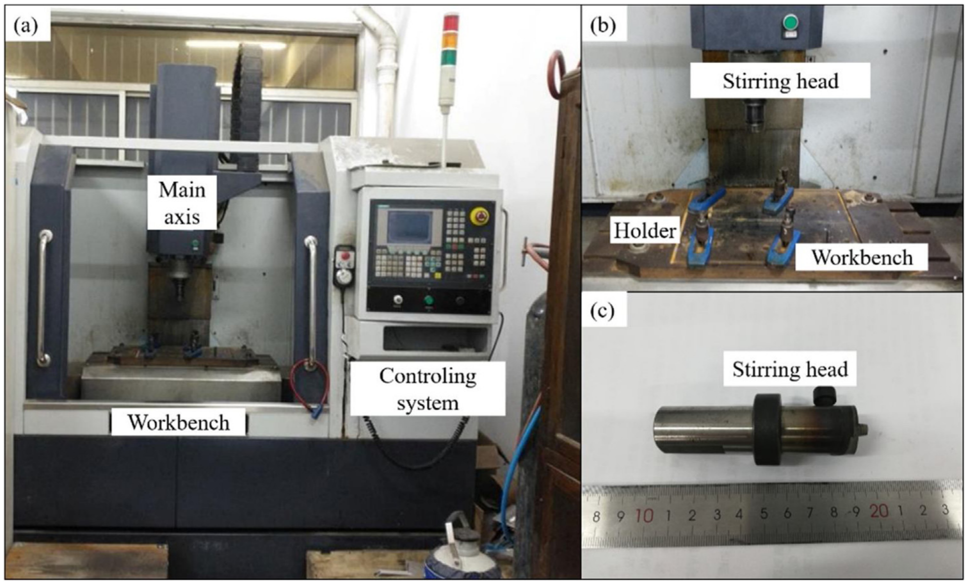

Fig. 1 – Friction stir processing machine: (a) FSP machine; (b) workbench and (c) stirring head.

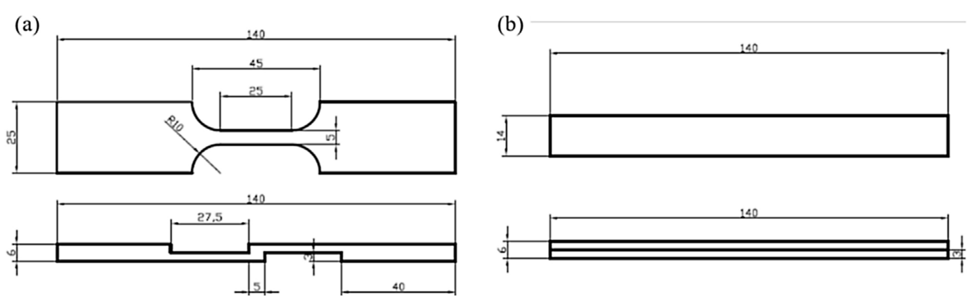

Fig. 2 – Dimensions of shear (a) and bending (b) specimen/mm.

ous, as shown in Fig. 3(a), (c) and (d). There exhibit obvious flashes when the overlap l/d is 15/25, as shown in Fig. 3(d). The formations of flashes are owing to the heat input of FSP and the reduction of shaft shoulder. Too much reduction of shaft shoulder causes the too much plastic deformation of aluminum, which will finally form lots of flashes in the end

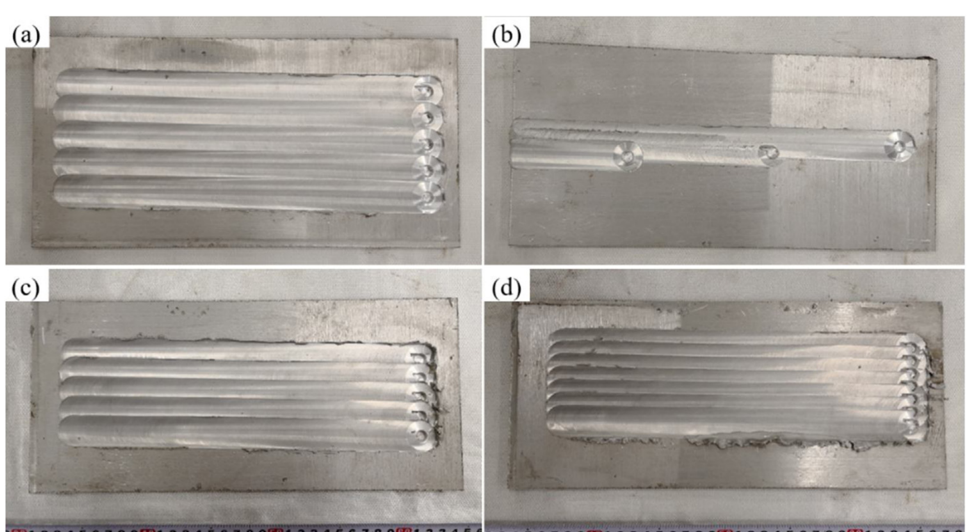

Fig. 3 – Macro-morphology of composite plate after FSP with different overlap l/d and multi-pass: (a) 5/25; (b) 8/25; (c) 10/25 and (d) 15/25.

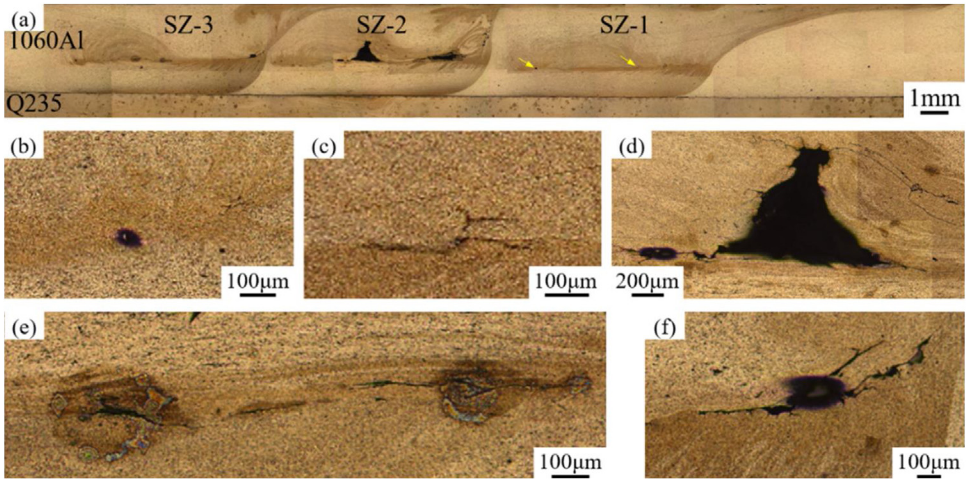

Fig. 4 – Microstructures of 1060Al/Q235 explosive composite plate after M-FSP with overlap (l/d) 8/25: (a) repairing zone; (b) and (c) defects in SZ-1; (d) defects in SZ-2; (e) and (f) defects in SZ-3.

and make the plate thin. Therefore, controlling the amount of flashes is necessary. In this study, the microstructures and mechanical properties for the composite plate (shown in Fig. 3(b)) with three multi-pass parameters are studied first, then four overlapping parameters are studied to find the optimized overlap l/d. Finally, the optimized overlap l/d and multi-pass parameters are put forward to repairing the composite plate.

3.2. *Effect of multi-pass*

Fig. 4 shows the microstructure of 1060Al/Q235 explosive composite plate after M-FSP with overlap (l/d) 8/25. The three multi-pass areas are marked as SZ-1, SZ-2 and SZ-3 for convenience. There exhibit obvious tunnel defects in the repairing zone, which is in the stirring zone of aluminum, about one millimeter away from the interface, as shown in Fig. 4(a).

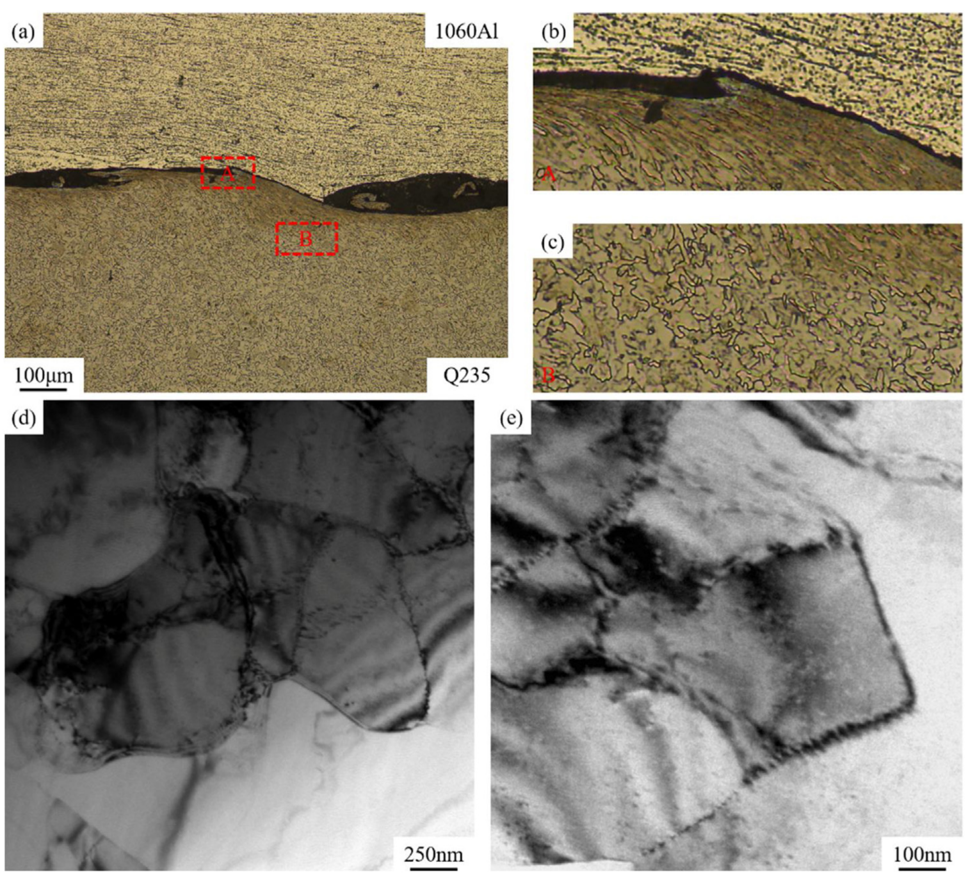

Fig. 5 – Microstructure of interface for the composite plate after FSP: (a) interface; (b) zone A; (c) zone B; (d) and (e) TEM image.

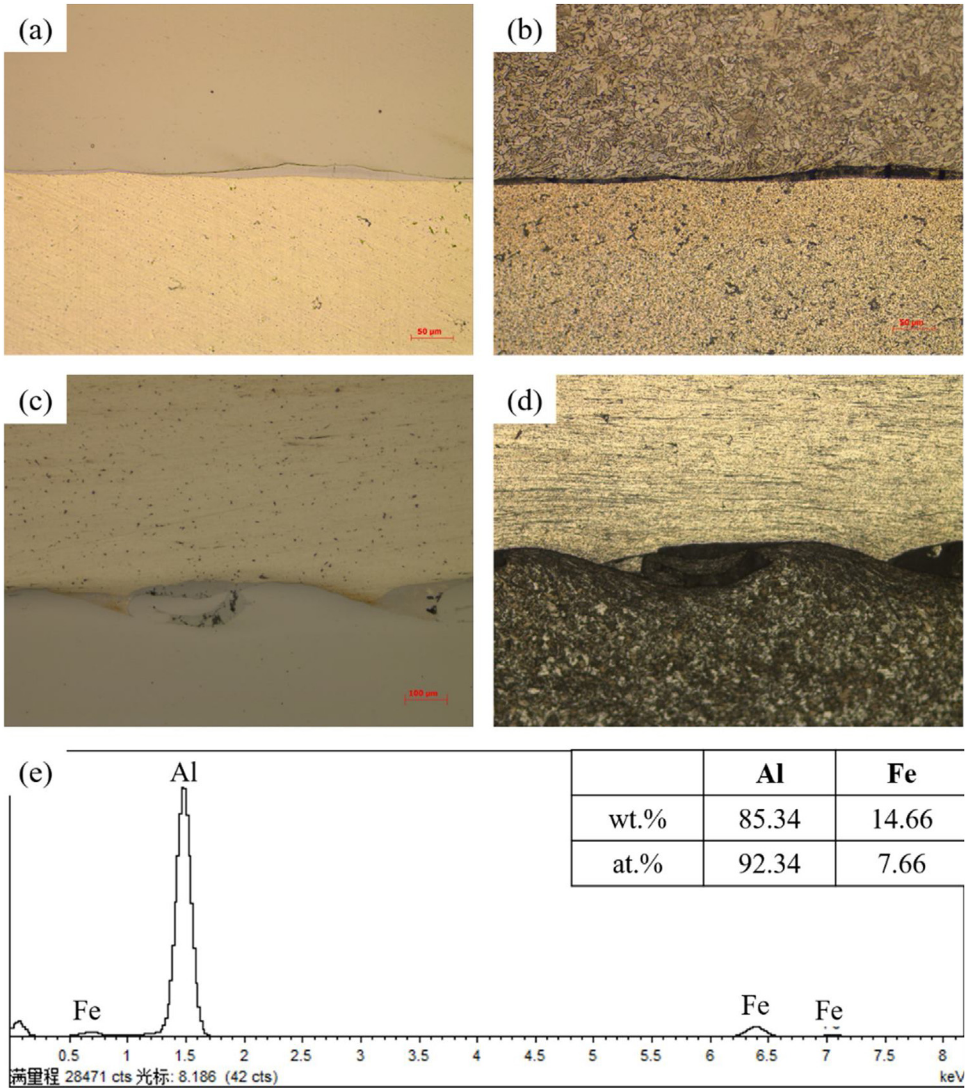

Fig. 6 – Interface connection mechanism of composite plate before ((a) and (c)) and after ((b) and (d)) etched: (a) and (b) metallurgical connections; (c) and (d) mechanical connections; (e) EDS spectrum for the interface in Fig. 6(c).

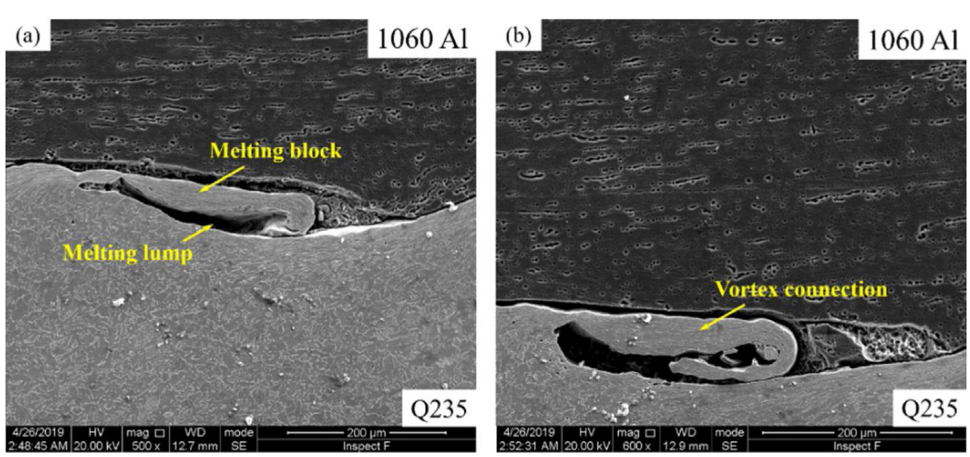

Fig. 7 – Interface mechanical connection mechanism of composite plate: (a) hook connection and (b) vortex connection.

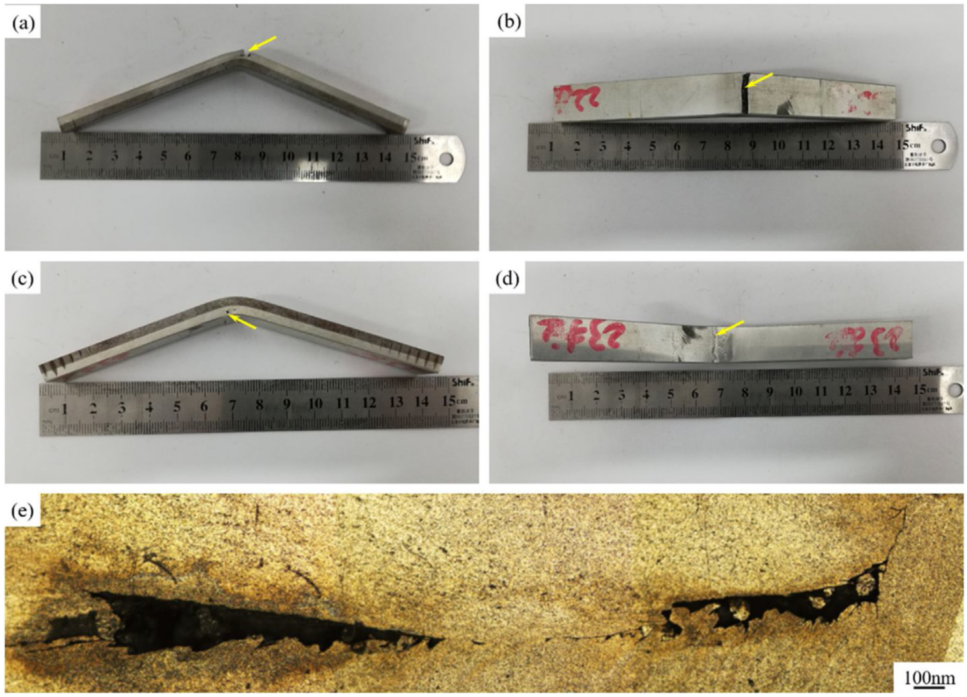

Fig. 8 – Bending specimens of composite plate after FSP with two passes: (a) aluminum under tensile in side view; (b) aluminum under tensile in top view; (c) aluminum under compression in side view; (d) aluminum under compression in top view; (e) longitudinal section of the bending sample for cracks propagation under bending load.

The repairing zone presents an appearance of a 'bowl', with the advancing side (AS) on the right. AS presents a distinctly abrupt 'zigzag line' boundary. When the plate experiences the single pass FSP, the holes are in small size with the area of about $1.9 \times 10^3\ \mu m^2$, as shown in Fig. 4(b). A distinct dividing line is shown in the area of SZ-1 and in the dividing line, there shows lots of fine defects, as shown in Fig. 4(c). When the plate experiences the second pass FSP, there exhibits two large holes in the SZ-2, with the morphology of triangular, as shown in Fig. 4(d). The size is about $400 \times 10^3\ \mu m^2$, which is much larger than that in the SZ-1. By observing the defect in detail, there shows lots of micro-cracks at the vertex positions of triangles. The cracks distribute like 'dead branches' and streamlined. The interface of streamlined structures is the weakest point and often accumulate impurity elements. Therefore, the cracks often initiate at the above position. In addition to this, the triangular defect will cause stress concentration under load, which lead the plate premature failure. When the plate experiences the third pass FSP, the holes are much smaller than those in the second pass FSP. The larger size of the hole is about $25 \times 10^3\ \mu m^2$ (Fig. 4(f)) while the smaller one is about $1.5 \times 10^3\ \mu m^2$ (Fig. 4(e)). Moreover, only one larger hole exists and most part of the holes are ultrafine. Therefore, the defects can be alleviated by the M-FSP when the pass exceeds three.

Fig. 5 shows the microstructure of interface for the composite plate after FSP. The microstructures exhibit streamlined organization after FSP, as shown in Fig. 5(b). Also, the grains near the interface are much smaller than those away from the interface, as compared by Fig. 5(b) and (c). Although just aluminum was stirred, the grains of interface have been refined through the effects of temperature and plastic flows of aluminum. The grains near the interface are about 400–600 nm in size, which are much smaller than those for the normal micron scale structures. The microstructures of nanocrystals have a significant improvement to the bonding and properties of interface.

Fig. 6 shows the interface connections mechanism of composite plate. The connection mechanisms consist of metallurgical connections and mechanical connections. The interface for the metallurgical connections are straight and tiny, as shown in Fig. 6(a) and (b). Also, the color of the interface before etched are close to the color of base metal, which means the elements of metallurgical connection interface are the mixture of two base metals. For the 1060Al/Q235 composite plate, there are two kinds of intermetallic compound, which include Al-rich phase and Fe-rich phase. Normally, the interface with a kind of Al-rich phases are strong [23] while Fe-rich phases are rigid. With the increase of multi-pass, the percentage of metallurgical connections increases, which is beneficial to the performance optimization for the composite plate. Another kind of connections mechanism is mechanical connection. The interface for the mechanical connection are not straight, as shown in Fig. 6(c) and (d). Also, the color of the interface before etched are inhomogenous, with a certain amount of dark spots in the interface, as shown in Fig. 6(c). These dark spots are void, which will lead the performance bad.

The mechanical connection mechanism can be further divided into two parts, including hook connection and vortex connection, as shown in Fig. 7. The hook connections include the melting block and the melting lump, as shown in Fig. 7(a).

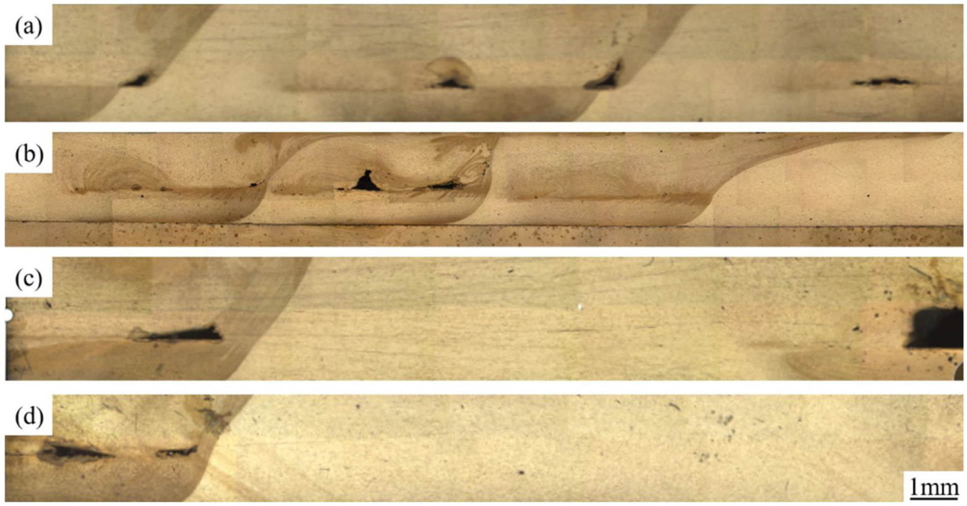

Fig. 9 – Microstructures of 1060Al/Q235 explosive composite plate after FSP with overlap (l/d): (a) 5/25; (b) 8/25; (c) 10/25 and (d) 15/25.

Table 2 – Shear strength of samples after FSP with different passes.

Pass	S (mm^2)	Force (N)	τ (MPa)
1	24.65	732.8	29.73
2	24.75	Break on the aluminum side with yield	
3	25.15	838.6	33.35

When the stirring effect is much stronger, the melting block will gradually transform to the vortex, and the hook connection will transform to the vortex connection, as shown in Fig. 7(b). The vortex looks like the hook, which make the interface stronger. In summary, the interface connection strength is hook connection, vortex connection and metallurgical connection from small to large.

The mechanical properties for the 1060Al/Q235 explosive composite plate after M-FSP with overlap (l/d) 8/25 are studied afterwards. Table 2 shows shear strength of samples after FSP with different passes. The maximum shear strength is 33.35 MPa when the FSP passes are three. With the increase of FSP passes, the shear strength increases, which means the bonding strength of interface is higher. However, there exhibits no experiment data for the sample after FSP with two passes. The aluminum yields during the loading process and the sample finally breaks on the aluminum side, not on the interface. The reasons can be summed up in the following two points. The first reason is that 1060Al is only pure aluminum with almost no impurity elements, as listed in Table 1. Therefore, the strength for the 1060Al is very low. Relevant data reports the yield strength of 1060Al is only 35 MPa, which is close to the shear strength for the sample after FSP with three passes. The second reason is there shows large and irregular tunnel defects when the passes are two, as shown in Fig. 4(d). The large size tunnel defects reduce the effective loading area, which finally make the sample break on the aluminum side.

The bending tests include two parts, one is steel in tensile, which means aluminum in compression. The other one is steel in compression, with aluminum in tensile. Each type of sample tests only one. Results show that the bending samples after FSP with one pass and three passes are undamaged when they bend to 180°. However, the bending samples after FSP with two passes are break, as shown in Fig. 8. Fig. 8(a) and (b) shows the bending sample with aluminum under tensile. The crack angle is about 45°, also, there exhibit obvious through-wall cracks in the tensile face, as shown in Fig. 8(b). Fig. 8(c) and (d) shows the bending sample with aluminum under compression. The crack angle is about 37°. The cracks are shown in the aluminum side, which are also the stirring areas. However, the aluminum side is under compression in this case. The cracks can easily open under the tensile stress while close under the compression stress. Comparing the microstructure of stirring area in Fig. 4(b), there exhibits large cracks in the test surface. Therefore, the longitudinal section of the bending sample is observed in order to find the crack propagation, as shown in Fig. 8(e). The two large cracks propagate to each other, with lots

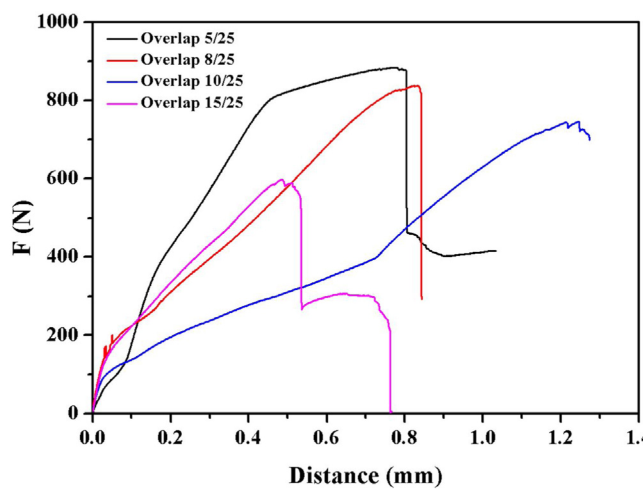

Fig. 10 – Shear curves of 1060Al/Q235 explosive composite plate after FSP with different overlap (l/d).

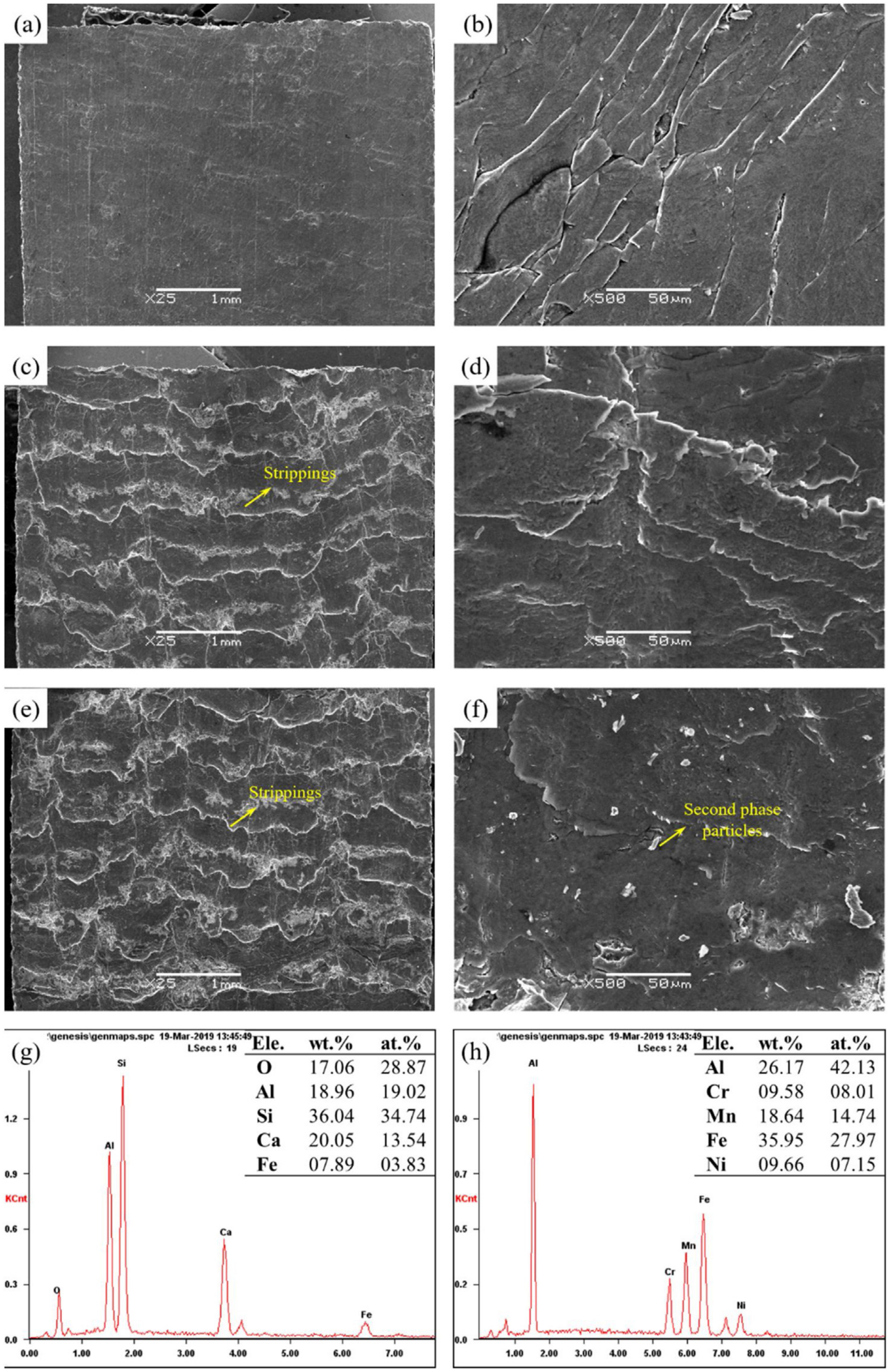

Fig. 11 – The SEM and EDS analysis of shear fracture morphologies with overlap (l/d): (a) and (b) 5/25; (c) and (d) 10/25; (e) and (f) 15/25; (g) and (f) EDS analysis of second phase particles.

of micro-cracks around the vertex. The cracks aggregate gradually under the bending load and finally lead to failure in the end. Hence, it is necessary to control the defects in the composite plate, especially for the larger ones. The 1060Al/Q235 composite plate after M-FSP with more than three passes show good microstructures and mechanical properties (Fig. 9).

3.3. *Effect of overlap*

3.3.1. *Mechanical properties*

As mentioned before, the 1060Al/Q235 explosive composite plate after FSP with different passes should be no less than three. Therefore, four different overlap (l/d) 1060Al/Q235

Table 3 – Shear strength of 1060Al/Q235 explosive composite plate after FSP with different overlap (l/d).

Overlap (l/d)	S (mm^2)	Force (N)	τ (MPa)
5/25	25.15	884.6	35.11
8/25	25.15	732.8	29.73
10/25	24.30	746.0	30.69
15/25	25.20	598.2	23.74

explosive composite plate after FSP have been conducted, as shown in Fig. 3. The four different overlaps (l/d) are 5/25, 8/25, 10/25 and 15/25. Owing to the samples (overlaps (l/d): 5/25, 8/25, 10/25 and 15/25) are too large, the optical microscope samples are just extracted between the last two welds. Results show that there exhibit plenty of defects after FSP with different overlap (l/d). The defects are almost in the position of advancing side. With the increases of overlap (l/d), the tunnel defects grow gradually with the horizontal elongation. Therefore, the smaller overlap (l/d) will obtain the better microstructures and higher efficiency.

The mechanical properties for the 1060Al/Q235 explosive composite plate after FSP with different overlap (l/d) are test. Bending tests show that all of the samples are in good conditions, with no cracks on the surface. Fig. 10 and Table 3 show the shear strength and shear curves of 1060Al/Q235 explosive composite plate after FSP with different overlap (l/d). The fracture mode of shear specimens exhibits typical brittle fracture (Fig. 10). The shear curve of overlap (l/d) 5/25 shows the phenomenon of yielding. The tunnel defects remaining in the aluminum undergoes certain plastic deformation during the process of shear load. With the increase of overlap, the shear strength decreases gradually, as listed in Table 3. The yield strength of 1060Al is about 35 MPa according to the standard requirement. While the shear strength for the sample with overlap (l/d) 5/25 is 35.11 MPa. The shear properties of composite plate after FSP satisfy the application requirements. In summary, the optimized overlap (l/d) should be set at 5/25.

Fig. 11 shows the fracture morphologies of shear samples with different overlap (l/d). There are some obvious strippings in the fracture surface (Fig. 11(a), (c) and (e)). It is analyzed that these strippings are formed by the failure of the original mechanical connections at the interface under load. The second phase particles are also obviously seen in the SEM. The EDS result shows that Si element is contained in these particles, which indicates that these second phase particles are Al-Si compounds (Fig. 11(g) and (h)). A small amount of dispersed Al-Si compounds can improve mechanical properties of composite plate.

4. Conclusion

In this paper, microstructures and properties of interface for 1060Al/Q235 composite plate are studied. The internal relationships between microstructures and mechanical properties of the interface have been investigated. The main conclusions are concluded as follows:

1 When the overlap (l/d) is set at 5/25, the multi-pass is set at three, the aluminum/steel composite plates after FSP exhibit good mechanical properties.
2 FSP can repair defects of the interface for aluminum/steel composite plate and improve the bonding strength of composite plate by metallurgical interconnection.
3 The nanocrystals formed by FSP have a significant improvement to the bonding strength of interface.

Conflicts of interest

The authors declare no conflicts of interest.

Acknowledgments

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