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Interfacial Characterization and Mechanical Property of Ti/Cu Clad Sheet Produced by Explosive Welding and Annealing

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Abstract: It was aim to investigate the interfacial microstructure and shear performance of Ti/Cu clad sheet produced by explosive welding and annealing. The experimental results demonstrate that the alternate distribution of interfacial collision and vortex of flyer layer forms in the interface a few of solidification structure. TEM confirms that the interfacial interlayer contains obvious lattice distortion structure and intermetallic compounds. It interprets the explosive welding as the interfacial deformation and thermal diffusion process between dissimilar metals. The interfacial shear strength is very close to the Cu matrix strength, which is determined by the mixture of the mechanical bonding and metallurgical bonding. Several cracks exist on the shear fracture owing to the intermetallic compound in the interfacial solidification structure and also the probable welding inclusion.

Key words: explosive welding; interface; TEM; intermetallic compound; fracture

1 Introduction

The explosive welding can be utilized in the bonding of different metals because of its enormous explosive pressure and deformation heat. A good metallic bonding can be obtained between different metals through controlling the explosive parameters and thermal diffusion[1-3]. Findik has given a comprehensive review on explosive welding and reported over 260 kinds of similar and dissimilar metals and alloys. Through explosive welding, we can manufacture many large-scale clad plates with high surface areas that are joined by any other techniques difficultly[1]. Many industries adopt Ti/Cu clad sheet with a good interfacial bonding and thickness distribution, which possesses a combination of matrix properties[4]. The joining techniques of Ti and Cu metals include explosive welding, friction welding[5], roll bonding[6] and electron-beam welding[7].

Nowadays, the shear, bending and hardness tests were conducted to perform the interfacial bonding strength of various clad sheets[3,4]. Kahraman *et al*[4] studied the relationship between interfacial bonding and explosive parameters to understand the explosive welding process, and also interpreted the interfacial evolution during the explosive welding process based on the metallographic methods in laboratories[8,9]. Owing to the crucial role of interface, we should clarify the interfacial evolution to completely understand the explosive welding mechanism.

Saravanan *et al* studied the explosive welding mechanism on the aspects of thermal kinetics analysis[10], numerical study[11], molecular dynamics simulations[12] and electron microscopy. Findik investigated various systems of clad sheets, such as Ti/steel, Ti/Al, Ti/Cu, steel/steel and Cu/Al clad sheet[1]. Yang *et al* studied the unique adiabatic shear band on the pure titanium side in the titanium/mild steel explosive cladding interface experimentally[8]. But very few publications have systematically reported the Ti/Cu explosive cladding interface based on the microstructure observation, chemical phases measurement, and the interfacial strength and failure analysis.

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Table 1 Chemical compositions and specifications of T2 and TA2 sheet

Raw material	Chemical composition/wt%	Shear strength/MPa	Thickness/mm	Melting temperature/°C
T2	99.7Cu-0.05O	150	5	1 083
TA2	Ti-0.3Fe-0.2Si-0.2O	265	7	1 668

This paper is aiming to study the interfacial microstructure through the high-resolution electron microscopic observation, and interpret the interfacial influence on the compression shear performance of the Ti/Cu clad sheet produced by the explosive welding and annealing.

2 Experimental

The raw materials were commercially pure copper sheet (T2) and titanium sheet (TA2), and their chemical compositions and specifications are listed in Table 1. We conducted the explosive welding experiments in the Northwestern Institute for Nonferrous Metal Research, with a distance of 12 mm between the metal sheets assembled. We exploded the expanded ammonium nitrate explosives in the center of clad layer TA2, with the density of 0.57 g·cm^{-3} and thickness of 65 mm, and the explosive velocity was 1970 m·s^{-1}. Then the as-explosive clad sheets were annealed at 540 ℃ for 3 h and cooled down to room temperature in the atmosphere. The metallographic observations were performed on the longitudinal section of the clad sheet along the explosive direction.

The interfacial microstructure of clad sheets was observed by an optical microscope (OM) and scanning electron microscope (SEM) SSX-550 equipped with energy dispersive X-ray detector (EDX). The chemical phase in the interfacial zone was measured through the X-ray diffraction (XRD) analysis on X'Pert Pro instrument. Especially, the interfacial crystallographic characteristics of the clad sheet were clarified by a transmission electron microscope (TEM) JEOL COM Orius with a 200 kV accelerating voltage. The observation film of the longitudinal section was thinned by a precision ion milling instrument.

The compression shear test was conducted on the materials testing system SANSCMT 5000 with the loading stress rate of 4MPa·s^{-1}. The shear samples with gauge length of 5 mm and width of 25 mm were prepared according to ASTM 264. The external force was loaded on the interface along the explosive direction. After that, the fracture was observed to analyze the interfacial failure.

3 Results and discussion

3.1 Interfacial microstructure and chemical phases of the Ti/Cu clad sheet

The optical micrographs of the interfacial zone in Fig.1 indicate that the explosive bonding interface contains some obvious waves. Along the explosive direction, Cu matrix embeds some Ti metals by forming the interfacial vortex, and Ti streamlines are discontinuous because of the limited explosive energy. The explosive energy significantly influences the interfacial microstructure[2,8]. The higher explosive energy makes the interface much rough with a large number of waves. Among the vortex indicated by the dotted line in Fig.1(b), some black particles exist in some locations, especially in the broken place of the streamline.

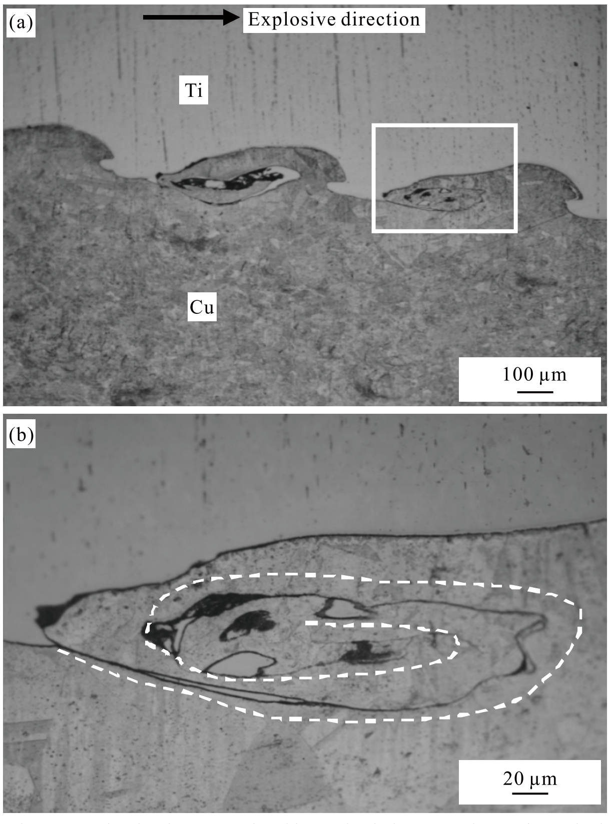

Fig.1 Optical micrograph of interfacial zone of TA2/T2 clad sheet along the explosive direction: (a) low magnification; (b) high magnification of vortex as indicated by the rectangle in (a). A dotted line is drawn in (b) to reveal the streamline of vortex

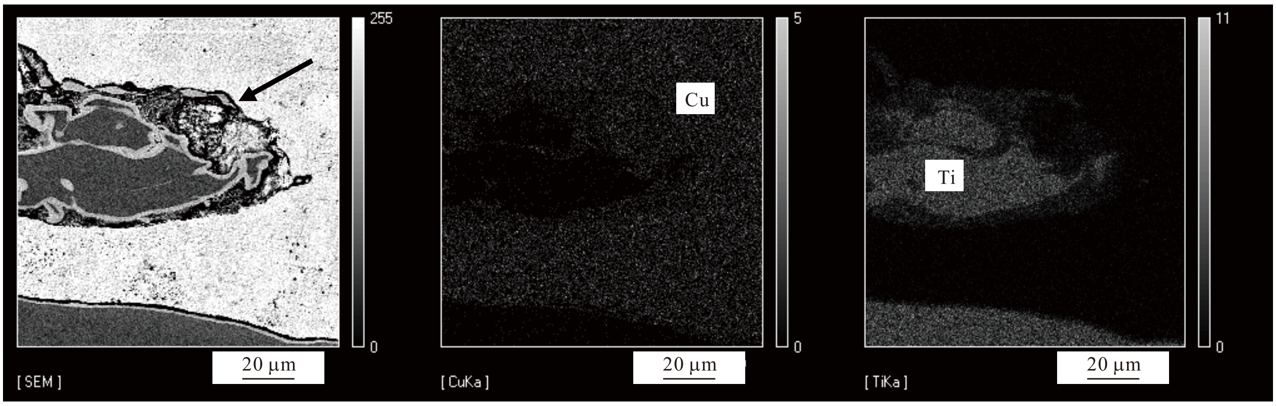

Fig. 2 EDX element distribution maps of Cu and Ti element on the vortex of explosive interface

After explosive welding, clad sheet must be annealed to remove the work-hardening[13]. Thermal annealing improves the bonding interface strength in clad sheets primarily. In general, the annealing temperature should be higher than the recrystallization temperature of the two metals in order to eliminate the residual explosive stress completely. Moreover, the appropriate diffusion induces a strong atomic force to enhance the interfacial bonding. The high temperature provides a high thermal energy to the clad sheet, making the activation of the metallic atoms and inter-diffusion. Controlling the inter-reaction on the interface plays crucial role to avoid forming destructive compositions between dissimilar components of the active metals. Therefore, the annealing temperature should be in the range of 0.4T_m (Cu) to eutectic temperature of Ti-Cu binary system[8,14]. According to the previous investigations, 2 μm diffusion interlayer in the bonding interface at 600 ℃ anneal for 10 min[15]. And the annealing temperature chosen as 540 ℃ in this work for 3 h ensures the complete recovery of clad sheets.

Fig.2 shows the EDX result of the element distribution in the interfacial vortex, and some broken Ti particles are embedded into the Cu matrix, demonstrating the explosive impact making the superficial titanium sputter into the molten Cu matrix. The solidification structure exists in the interface of metal matrix and flyer layer, as the arrow shown in Fig.2.

The pulsed pressure pushes the clad layer to the matrix layer during exploding. The collision with remarkable energy causes a few of surface metal into the flyer layer. Meanwhile, the matrix yields heavy plastic deformation under the explosive impact. In general, a remarkable metal flow of the matrix layer is formed along the explosive direction and causes the elongated grains[3]. The flyer layer and Cu matrix collide when they meet a new explosion pulse, and form the vortex. Thus, the alternate collisions and vortexes appear in the interface[9].

Meanwhile, the collision with enormous explosive-induced heat would result in the flyer layer melting in the interface. The melting layer provides an approach to the atomic diffusion between dissimilar matrixes and improves the interfacial bonding strength. After cooling, the solidification structure of the Ti flyer layer retains in Cu matrix. It is in good agreement with the numerical simulation result of the explosive welding process[16,17].

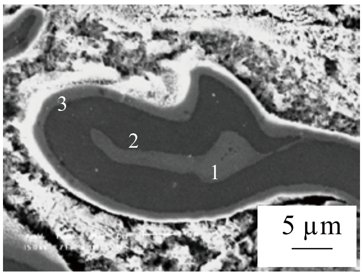

Fig. 3 SEM image of vortex on the explosive welded interface

Table 2 Chemical compositions of the interfacial vortex in Fig. 4

Point	Cu/at%	Ti/at%	Possible chemical phase
1	49.81	50.19	TiCu
2	0.00	100.00	Ti
3	48.43	51.57	TiCu

For clarifying the microstructure and composition of vortex, we observed a part of the vortex through SEM with EDX analysis. As shown in Fig.3, a diffusion layer with the thickness of 3 μm forms in the interface between the component metals. And we observe a few solidification structures existing in the boundary of the flyer streamline. We measured the chemical compositions of typical points 1, 2 and 3 in Fig.3 through EDX point analysis which are listed in Table 2. Some possible phases, with a fixed ratio of Cu and Ti element, exist in the interfacial zone. In general, Cu occurs melting easily comparing with Ti matrix under the severe explosive impact. A few Ti flyer layers impact into the molten Cu matrix and form the surrounding region.

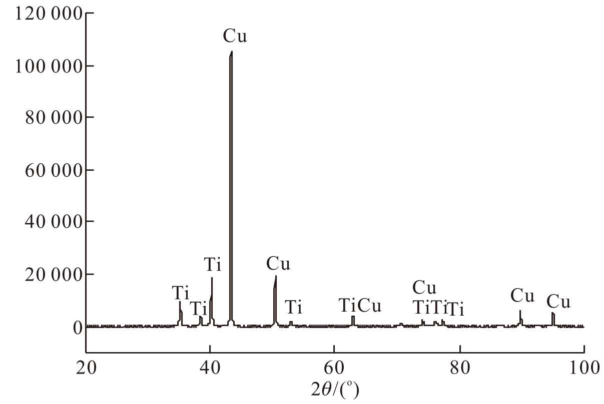

Fig.4 XRD results for the chemical phase analysis of interfacial zone

As the result shown in Fig.4, the XRD analysis on the cross section of clad sheet clarifies the chemical phase of interfacial vortex. We find a few clear intermetallic compounds TiCu forming in the clad sheet. The result consists with the prediction in Table 1. In general, the solid solutions of Ti and Al form firstly, owing to the atomic diffusion in the Cu interface and Ti matrix. With the long annealing time, the massive diffusions occur in the interfacial metals and induce the supersaturated solid solution of Ti and Al metals. Once the thermodynamic condition is satisfied, the solid solution would transit into the new phase of intermetallic compounds[8]. According to the binary alloy phase diagram, several intermetallic compounds can be formed in the interface of Ti-Cu couple. In the present work, the accumulated deformation energy is enormous in the interface, therefore the required activation energy for the formation of new phase is small[18]. During the annealing process, a few of the intermetallic compounds generate in the interface.

Fig.5 indicates the interfacial TEM microstructure of the clad sheet. Three different layers, which are labeled as 1, 2 and 3, are obvious in the interface. Layer 3 demonstrates the normal morphology of Ti matrix, confirmed to be α-Ti by the selected-area diffraction pattern (SADP) in Fig.5(d). The SADP in Fig.5(c) is the typical amorphous diffraction pattern with the visible crystalline spot around the halo. It reveals that the layer 2 is likely to be a mixture of intermetallic compounds and amorphous structure. Owing to the atomic diffusion in the interface, a region with the remarkable lattice distortion forms between the dissimilar metals, causing the diffraction pattern in Fig.5(c) similar to the amorphous structure pattern[8,19]. The high-resolution micrograph in Fig.5(b) shows a clear interface with about 5 nm thickness.

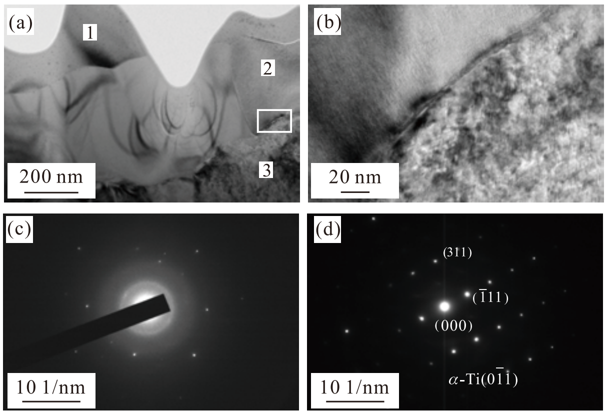

Fig.5 TEM images of interfacial zone of Ti/Cu clad sheet. Labels 1, 2 and 3 respectively represent the different sublayers. The magnification of the selected zone shown in (b). (c) and (d) respectively reveals the diffraction pattern of the sublayers 2 and 3

Table 3 Chemical compositions of the interfacial interlayer in Fig. 6

Point	Cu/at%	Ti/at%
1	49.79	50.21
2	40.09	59.91
3	5.93	94.07

Table 3 lists the chemical compositions of the typical points in Tabels 1, 2 and 3. The EDX results approve the significantly different chemical compositions across the interface. Based on the crystallographic characteristics and remarkable composition difference, the interface in Fig.5(b) can be clarified as the division of Ti matrix and diffusion interlayer[20]. The element content in point 1 is very close to the chemical composition of intermetallic compound TiCu, proving the existence of TiCu phase.

3.2 Compression shear performance of Ti/Cu clad sheets

We conducted the shear tests of the Ti/Cu clad sheet under external compression force along the explosive direction on the interface, to study the effect of interfacial microstructure on the bonding strength. Based on the duplicates tests, the average interfacial shear strength is 140 MPa, nearly reaching the Cu matrix.

Fig.6 indicates the interfacial fracture of Cu side after shear tests. The fracture contains the smooth areas and the ductile areas with obvious plastic deformation, and EDX reveals that they are rich-Cu layer (91.5Cu, wt%) and rich-Ti layer (89.0Ti, wt%), respectively. The magnification in Fig.6(b) indicates that some dimples exist on the interfacial rich-Ti layer. Comparing with the interfacial microstructure in Fig.1, the rich-Cu layer displays brittle fracture mode corresponding to the interfacial collision area, while the rich-Ti layer displays ductile fracture mode corresponding to the interfacial area with the vortex.

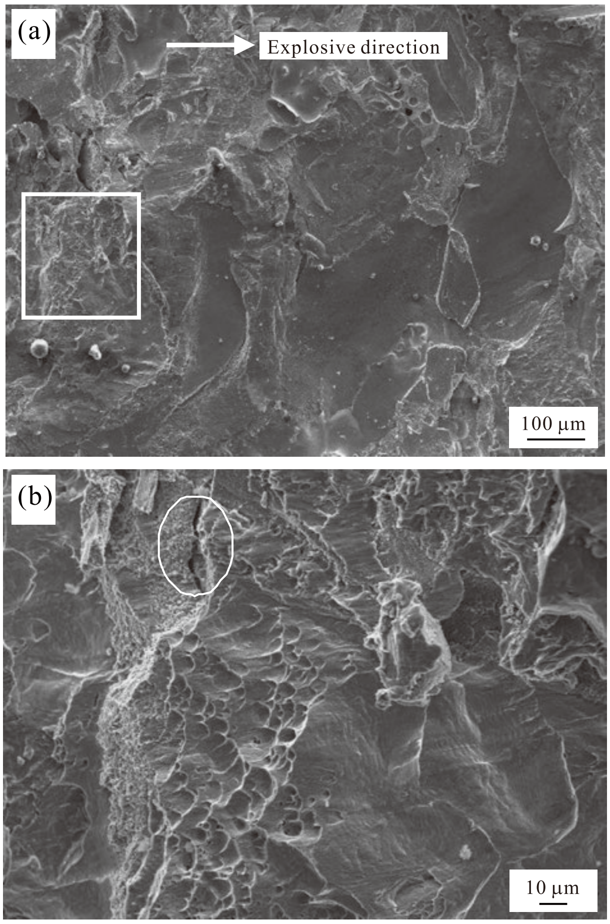

Fig.6 Fracture on the Cu side of explosive welded interface (a) and selected zone magnification (b). The shear force is loaded along the explosive direction

During the explosive welding process of dissimilar metals, the plastic deformation mainly exists on the interfacial collisions zone. The collision points exclude the black solidification structure in Fig.1, so we can ignore the atomic diffusion on these interfacial areas where the interfacial bonding is ascribed to the mechanical bonding. The vortex of flyer layer causes a molten interface between dissimilar matrixes. In general, atomic diffusion involves the reconfiguration of crystallographic structure. The numerical simulation indicates the promotion of interfacial strength because of the remarkable atomic diffusion in the interface of different metals[21]. Thus, a metallurgical bonding with the good bonding strength achieves through the interfacial atomic diffusion in Ti/Cu clad sheets[22].

Consequently, the bonding interface in clad sheets consists of the mechanical bonding and metallurgical bonding. The shear deformation is much sensitive to the microstructural defects. Comparing with the bulk metal matrixes, the interfacial shear strength is weak and easy to fracture[23]. However, the interfacial strength is very close to the Cu shear strength and ensures the mechanical performance in engineering application of the Ti/Cu clad sheets.

The magnified micrograph in Fig.6(b) indicates several dimples on the tearing areas which correspond to the interfacial highest points in Fig. 1. The tearing track suggests the interfacial shear deformation along the loading direction. Usually, the metallurgically bonded interface provides a good resistance to the external load. A remarkable plastic deformation occurs in these interfacial zones until the bonded interface fractures. Finally, the interface delaminates under the shear stress and obtains the visible shear dimples.

Some tiny particles exist near the rich-Ti area in Fig.6, which can be ascribed to the solidification structure of the flyer layer. With the huge deformation heat, the interfacial metal atoms, especially in the molten interfacial zone, significantly diffuse into each metal matrix[24]. After analyzing Fig.4, some intermetallic compounds form in the interface after explosive and annealing process. The brittle intermetallic compounds in the interfacial layer would fracture initially when the shear force is loaded on the interface of the Ti/Cu clad sheet. Therefore, the interfacial fracture displays some micro-cracks in Fig.6(b). The initial contaminations on the metal surface could be involved in the welding interface through the collision and the interfacial vortex[25]. These defects also contribute to the brittle failure of interfacial bonding.

4 Conclusions

a) The interfacial collision and flyer layer vortex in the Cu matrix result from the strong impact during the pulsed explosion. Some solidification structure retained in the interface can be ascribed to the explosion-induced thermal energy.

b) The TEM reveals that the interface consists of the obvious lattice distortion structure caused by the massive atomic diffusion and the intermetallic compounds. It confirms the explosive welding as the interfacial deformation and thermal diffusion process.

c) Compression shear fracture possesses two different failure modes. Brittle fracture occurs on the smooth interfacial zone, which presents the collision point with a mechanical bonding. The fracture also indicates a tearing structure with many dimples, revealing the shear deformation of the metallurgical bonding on the interfacial zone with vortex. The interfacial bonding modes determine the interfacial shear strength to be 140 MPa.

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