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ARTICLE

Preparation of Cu-Fe-Cu Composite Plate with Large Thickness by Explosive Welding

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Abstract: Fe-Cu composite plate has good ductility, electrical and thermal conductivity, the ferromagnetism of Fe, and the diamagnetism of Cu, so it can be widely used in power, electronics and other industries. However, it is hard to weld Fe and Cu using conventional methods due to their low mutual miscibility. In the present study, the explosive welding method was adopted to prepare the Cu-Fe-Cu (with the thickness 17, 5, 17 mm) composite plate. Firstly, the theoretical model was adopted to design explosive welding parameters. The weldability window, the detonation velocity and thickness of the charge, and the gap size were obtained. Then, a new numerical simulation method, in which the SPH (smoothed particle hydrodynamic method), Lagrange and Euler methods are used and no equivalent treatment of the explosive welding components is taken, was used to analyze the explosive welding process. The collision velocity of the flyer plate, temperature and pressure distribution near the bonding interface as well as wavy interface were obtained, and it proved the validity of the theoretical design parameters. Finally, the Cu-Fe-Cu composite plate was successfully prepared by the explosive welding method. The hardness distribution and the shear strength of the bonding interfaces were tested. The results show that parameters of the interface wave obtained experimentally and numerically are basically the same; compared with that of the original ones, the hardness of Fe and Cu near the bonding interface increases by about 34.2% and 49.8%, respectively; the average shear strength of the first and the second interface is 212.7 MPa and 225.3 MPa, respectively.

Key words: explosive welding; Cu-Fe-Cu composite plate; weldability window; wavy interface

Explosive welding is a high-energy-rate solid-phase welding method, which uses the detonation of explosive to drive the flyer plate to collide with the base plate at high speed to achieve welding[1, 2]. After welding, a wave-shape ripple is formed at the bonding interface, which is called an interface wave. Such a wavy interface increases the bonding area between the metals, thereby contributing to an increase in the bonding strength of the composite plate. Explosive welding of metals is known to be capable of producing large area bonding between metal plates, including couples of grossly different mechanical properties. A well-known example is the bonding between large plates of lead and steel, which cannot be achieved by any other methods[3].

Both iron and copper have good ductility, electrical conductivity and thermal conductivity. Iron has strong ferromagnetism and it is a magnetic material. But, copper has good diamagnetic resistance. The Fe-Cu composited plate will be an ideal conductive transition material for industrial sectors such as power, electrolysis and electronics, and even for household cookware[4]. However, iron and copper are two metals with very low mutual miscibility, which makes it difficult to compound by conventional welding methods. Livne and Munitz[5] had proved that thin iron and copper plates can be bonded by explosive welding successfully. However, preparation of thick Fe-Cu composite plate has been seldom reported.

In the present research, the Cu plate with large thickness

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of 17 mm and the Fe plate with thickness of 5 mm are used as flyer plate to manufacture the Cu-Fe-Cu composite plate with large thickness. The Fe plate is welded to a copper plate firstly, and then another copper plate is welded to the Fe-Cu composite plate. The parameters of explosive welding of Cu-Fe-Cu plate are designed by a theoretical model firstly. Then, the effectiveness of the designed explosive welding parameters is verified by a new numerical simulation method. Finally, experimental preparation of Cu-Fe-Cu composite plate is carried out. The microscopic morphology and the shear strength of the two interfaces are studied, and the micro-hardness across the interfaces is tested.

1 Design of Explosive Welding Parameters

In order to determine more suitable explosive welding parameters, the 'v_p-v_c window' is determined herein.

The minimum velocity of the flyer plate (generating metal jet) is determined by[6]

$$v_{p,\min} = K\,(H_v/\rho_f)^{0.5} \tag{1}$$

where K is a constant, and it lies between 0.6 and 1.2. When the surfaces to be bonded are well pretreated, the value of 0.6 can be taken. H_v and ρ_f are the Vickers hardness and the density of the flyer plate, respectively.

The maximum velocity of the flyer plate (no over-melting) is determined by[7]

$$v_{p,\max} = \frac{2\sqrt{2}}{N^{1/2}v_D}\left[\left(T_m - T_0\right)^2 \frac{\pi\gamma c C_0^4}{c_1\rho_1 h_1}\left(\frac{h_1+h_2}{h_2}\right)^2\right]^{1/4} \tag{2}$$

where N=0.039, v_D is the detonation velocity of the explosive, T_m, γ and c are the lowest melting point, the lowest thermal conductivity and the lowest specific heat of the metal plates, respectively; T_0 is the room temperature, C_0, c_1 and h_1 are the sound velocity, the volume wave velocity and the thickness of the flyer plate, respectively; h_2 is the thickness of the base plate.

Moreover, in order to ensure the formation of re-entrant jet, it is generally considered that the pressure at the collision point is 10~12 times larger than the strength of the metal material (i.e. the flow limit) and the moving speed of the collision point must be less than the sound speed of the material (i.e. the sound speed limit). They are determined by the following formulas

$$v_{c,\max} = C_{0\,\min} \tag{3}$$

and

$$\rho v_{c,\min}^2/2 \geq 10\sigma_b \tag{4}$$

where $v_{c,\max}$ and $v_{c,\min}$ are the maximum and the minimum moving velocities of the collision point, respectively; $C_{0\,\min}$ is the minimum sound velocity among welding materials, ρ and σ_b are the density and the static strength of the material, respectively.

The material parameters of the Fe and Cu plates used in this study are shown in Table 1. Taking parameters given in Table 1 into Eqs. (1)~(4), then the window of acceptable v_p and v_c is determined. Because of the lager thickness of the copper plate (17 mm), it is better to weld the iron plate to a copper plate firstly and then weld another copper plate to the welded Fe-Cu composite plate when preparing the Cu-Fe-Cu composite plate. Following this thought, the corresponding windows of acceptable parameters are given in Fig.1a and 1b.

The next step is to determine the detonation velocity of the explosive (v_D), the charge ratio R (the area density ratio of the explosive to the flyer plate) and the gap size δ between the flyer plate and the base plate. Herein, v_D takes the value of 2100 m/s. And, v_c= v_D for parallel installation. The charge ratio R can be determined by Gurney formula[7]

$$v_p = \sqrt{2E}\,[3R/(5+R+4/R)]^{1/2} \tag{5}$$

where $\sqrt{2E}$ is Gurney energy. When cladding the Fe plate to a Cu plate, if we take the charge thickness as 30 mm, then R = 0.61, and v_p = 407.21 m/s. While cladding the copper plate to the welded Fe-Cu plate, if we take the charge thickness as 80 mm, then R = 0.42, and v_p = 305.82 m/s. As shown in Fig.1, it can be found that the two v_p are inside the windows and are far from the upper limit.

In addition, the gap size δ for thin flyer plate is determined by empirical formula: $\delta = 0.2(h_1+h_2)$. And, the gap size for thick flyer plate is determined by semi-empirical formula: δ =(0.5~1)t_f, where t_f is thickness of the flyer plate.

2 Numerical Simulation

In order to verify the validity of the parameters obtained theoretically, the numerical simulation is carried out, since the thick flyer plates are used.

Besides, features of interface in explosive welding were researched generally by the smoothed particle hydrodynamic method (SPH). Such as the composition of the metal jet[8-10], the temperature distribution[11] and the historical changes of shear stress[12], effective plastic strain of materials[13] were all developed by SPH. Different from the conventional simulation that only use the SPH method and the process of driving flyer plate is equivalent to giving the flyer plate an initial collision velocity and an initial colli-

Table 1 Material parameters of the iron and copper plates

Material	ρ/g·cm^{-3}	C_0/m·s^{-1}	c_1/ m·s^{-1}	T_m/°C	σ_b/MPa	H_v/MPa	h/mm	c/J·kg^{-1}·K^{-1}	γ/W·m^{-1}·K^{-1}
Iron	7.83	4595	5893	1538	166	1660	5	477	80
Copper	8.93	3910	4674	1083	132	833	17	394	401

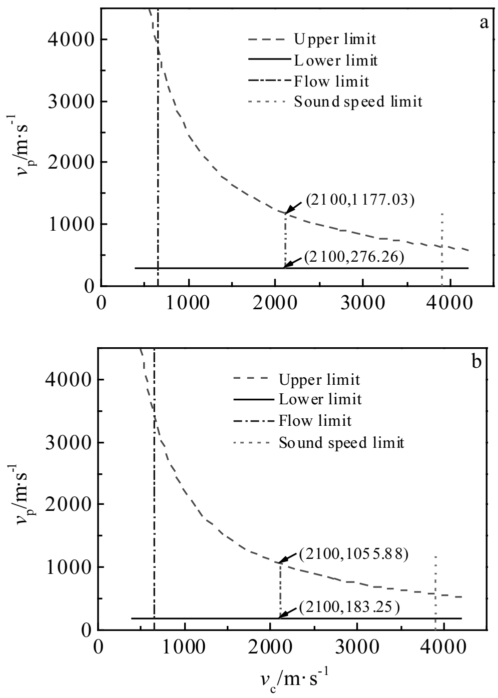

Fig.1 Window of acceptable parameters: (a) explosive welding a 5 mm Fe plate to a 17 mm Cu plate, and (b) welding a 17 mm Cu plate to the welded Fe-Cu composite plate

sion angle[8-13], SPH, Lagrange and Euler methods are all used and no equivalent treatment is taken in this study. For explosive, the Euler method is employed. For part of the flyer plate and part of the base plate that chose to the bonding interface, the SPH method is used. And, for the rest of the flyer plate and the base plate, the Lagrange method is used. The finite element software AUTODYN is adopted and the corresponding 2D planar model is shown in Fig.2.

To describe the deformation near the bonding interface in detail and reduce computation requirements, the SPH particles are divided into partitions with a minimum size of 15 μm and a maximum size of 200 μm. Both Lagrange and Euler elements have a size of 200 μm. Only the process of welding the Fe plate to the Cu plate is simulated, and the length of the plates is 200 mm. The thickness of the explosive, the Fe plate, and the Cu plate is 30 mm, 5 mm, and 17 mm, respectively. The gap size is 5 mm. The IRON, COPPER, ANFO and AIR materials in the AUTODYN material library are used directly. But, the density, the C-J detonation velocity, and the C-J pressure of the ANFO explosive are changed to 0.8 g/cm^3, 2100 m/s, and 923.4 MPa, respectively.

The numerical simulation result shows that both straight and wavy interfaces are formed. The typical wavy interface is given in Fig.3. The average values of the wavelength and the amplitude of the interface wave measured from Fig.3 are about 505 μm and 140 μm, respectively.

The observation of a single wave formation is shown in-Fig.4a~4d). As shown in Fig. 4a~4d, the re-entrant jet par-

Fig.2 Numerical simulation model of explosive welding

ticles come from both plates, i.e. the flyer plate and the base plate, which is not accordance with the assumption given by Bahrani et al.[14] that the base plate is perfectly rigid and the re-entrant jet is all come from the flyer plate.

As shown in Fig.4, the interface wave formation mechanism can be explained as follows. When the lifted upward re-entrant jet is completely choked, the stagnation point moves from the trough to the crest of the wave as shown in Fig.4a. The high pressure at the stagnation point will depress and elongate the hump so that a forward trunk is formed. As the hump continues to move downstream, the stagnation point descends the forward slope of the hump as shown in Fig.4b. As the re-entrant jet descends the forward slope of the hump, a second stagnation point is formed and part of the jet enters the cavity under the trunk, causing a vortex, as shown in Fig.4c. As shown in Fig.4d, the new stagnation point moves forward, a new hump forms and the re-entrant jet is lifted upwards. The lifted upward re-entrant jet will be trapped again and formed a vortex at the back of the hump as shown in Fig.4a, and then a loop will go. And, the front vortex and behind vortex have formed in Fig.4d.

The melted temperature of iron and copper are 1535 °C and 1082 °C, respectively, as shown in Table 1. The temperature shown in Fig.5a varies from 0 to 2500 K, and thus it is clear that the re-entrant jet particles that escaped are almost all melted. Meanwhile, some melted particles are stored in the bonding interface and the wavy interface was formed. And, most particles in the front and behind vortex of the wavy interface are melted. The pressure distribution shown in Fig.5b indicates that the pressure in the collision area is much higher than that in other areas.

The pressure in the collision area is about 7.5 GPa, which is much larger than $10\sigma_b$=1.66 GPa. The collision velocity of the flyer plate obtained by numerical simulation is about 427 m/s, which is in good accordance with the theoretical result (407.21 m/s). And, the wavy interface is formed. It

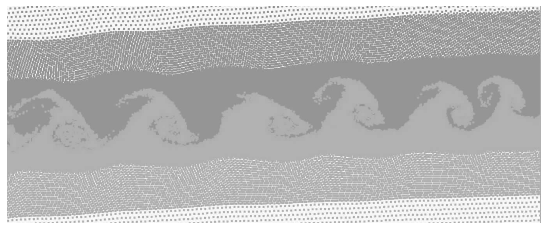

Fig.3 Enlarged view of wavy interface

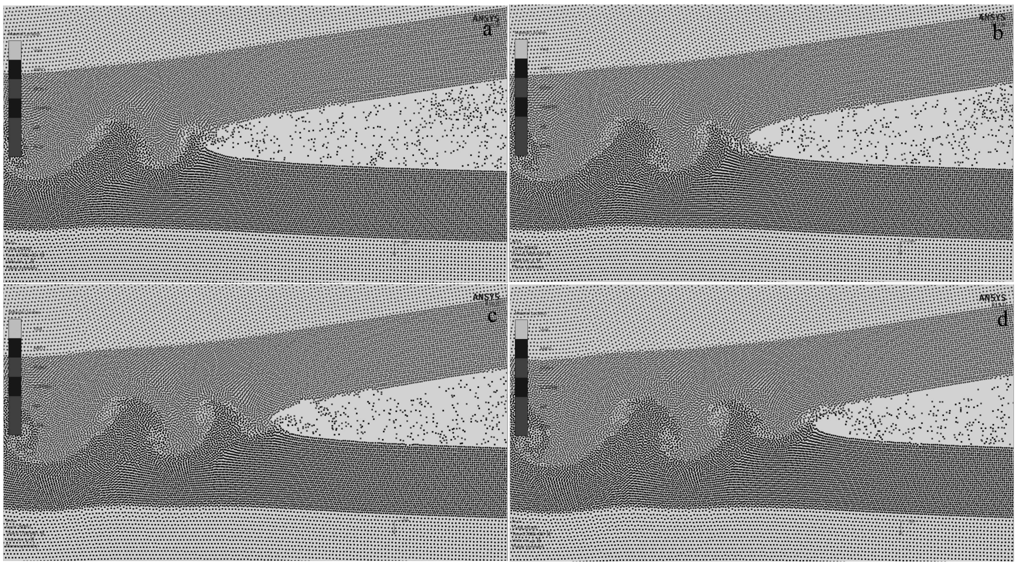

Fig.4 A single wave formation process: (a) 87.5 μs, (b) 87.6 μs, (c) 87.7 μs, and (d) 87.8 μs

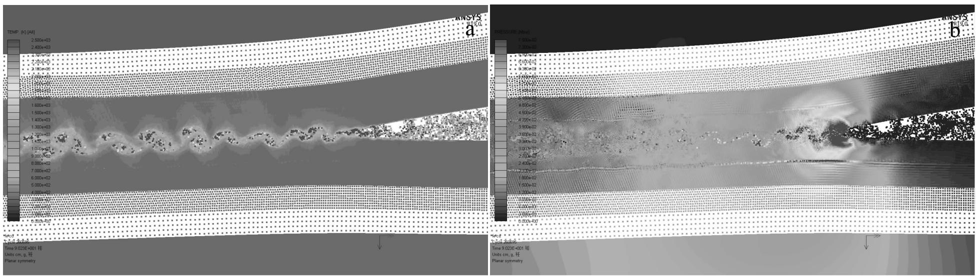

Fig.5 Distribution of temperature (a) and pressure (b)

can be concluded from the above discussion that using the welding parameters determined by theoretical model can obtain a continuous wavy bonding interface.

3 Experiment

Cu plate with dimensions of 400 mm×200 mm×17 mm and Fe plate with dimensions of 400 mm×200 mm×5 mm are the raw materials used to prepare the Cu-Fe-Cu composite plate. The Fe plate is sandwiched between the Cu plates. As mentioned above, the Fe plate is clad to a Cu plate firstly, and then another Cu plate is welded to the Fe-Cu composite plate. The schematic of explosive welding device is shown in Fig.6.

The modified ANFO explosive with low detonation speed is used. The detonation velocity and the density of the modified ANFO explosive are measured to be 2148.671 m/s and 0.8 g/cm^3, respectively. When welding the Fe plate to a Cu plate, the gap size and the thickness of the explosive are set to 5 mm and 35 mm (a little larger than that used in numerical simulation), respectively. While cladding the Cu plate to the composited Fe-Cu plate, the gap size and the thickness of the explosive are set to 15 mm and 80 mm, respectively.

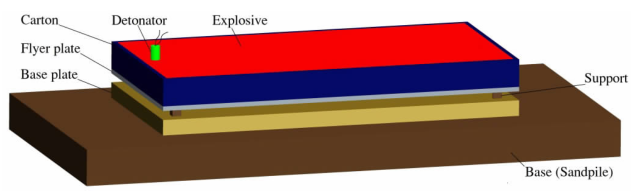

Fig.6 Schematic of explosive welding set-up

The Cu-Fe-Cu composite plate obtained after two times of explosive welding has two bonding interfaces. To find out the individual characteristics of the two bonding interfaces conveniently, the Fe-Cu interface formed after the first explosive welding is called as the first bonding interface and the Cu-Fe interface formed after the second explosive welding is called as the second bonding interface.

3.1 Morphology of the first bonding interface

Micromorphology of the first bonding interface for different distances from the detonation end is illustrated in Fig.7. As shown in Fig.7, the Fe-Cu interface formed by the first explosive welding has a good bonding, and there is no cracking and void. The cladding of Fe plate to Cu plate is achieved successfully by the explosive welding process. The interface morphology is mainly composed of wavy interface, accompanied with few straight interface and un-welded area. About 85% of the interface is wavy. There is an un-welded area 0~40 mm close to the detonation end. In the range of 40 mm to 120 mm, the interface changes from straight to wavy. While, within the range of 160~280 mm from the detonation end, size of the interface wave is basically the same. Then, the wavelength of the interface wave is gradually increased, the amplitude is gradually decreased, and the interface wave disappears finally.

The wave parameters of the interface wave at different distances from the detonation end measured from Fig.7 are shown in Table 2. For distance in the range of 160~280 mm, wavelength and amplitude of the interface wave remain at about 520 and 147 μm, respectively. It indicates that the numerical result is in good agreement with the experimental result.

3.2 Morphology of the second bonding interface

Micromorphology of the second bonding interface for different distances from the detonation end is illustrated in Fig.8. Clearly, the interface morphology is mainly composed of wavy interface and straight interface. About 95% of the interface is wavy. Size of the interface wave within the range of 120~280 mm from the detonation end is basically the same. However, the experimental results of the Fe/Cu plate explosive welding conducted by Livne and Munitz[5] indicated that both wavelength and amplitude are increasing functions of the distance from the detonation point under the same charge ratios *R*. Therefore, it is not in accordance with the result obtained herein.

The parameters of the interface wave at different distances from the detonation end measured from Fig. 8 are shown in Table 3. As shown in Table 3, wavelength increases monotonically as distance increases from 40 mm to 120 mm, and it remains at about 305 μm for the distance varies from 160 mm to 280 mm. While the wavelength decreases with increasing distance for it is larger than 280 mm. However, the amplitude of the interface wave is gradually increased first and then decreased sharply with the increasing distance.

3.3 Mechanical properties

3.3.1 Micro-hardness test

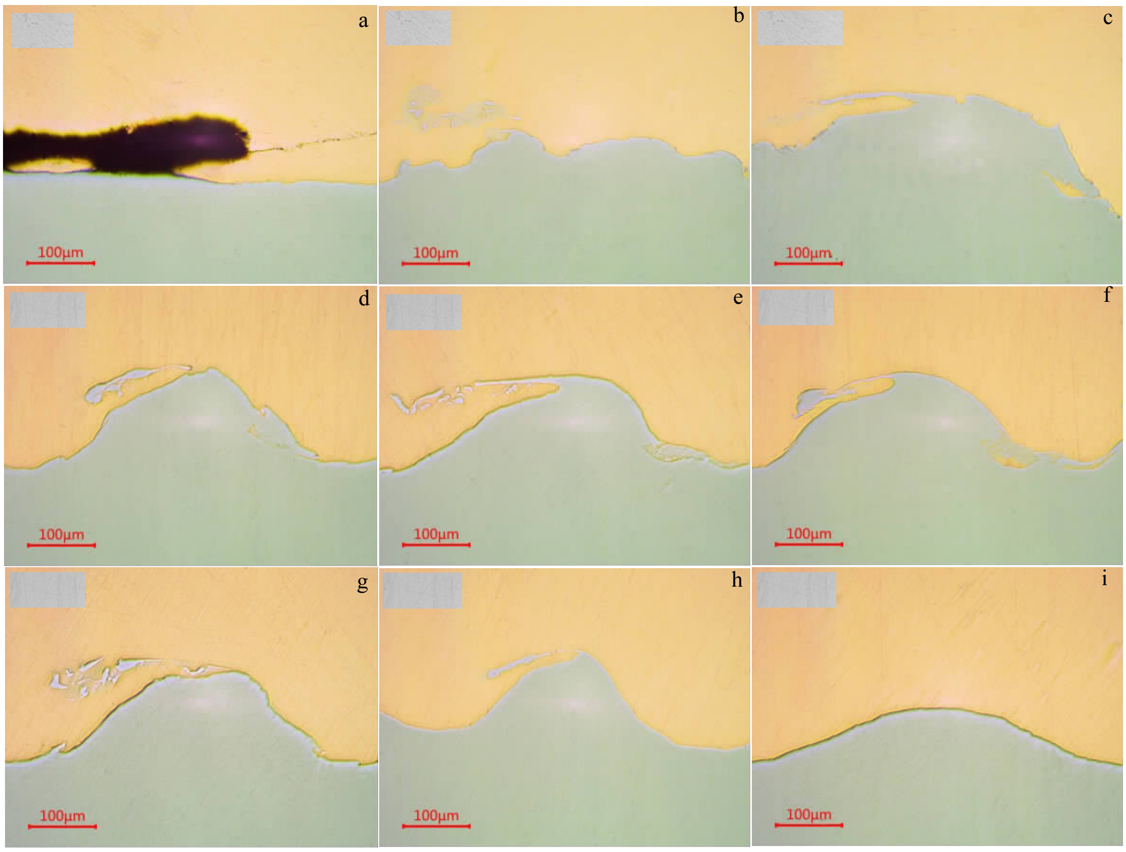

Fig.7 A series of optical microscopy photographs demonstrating the first bonding interface for different distances from the detonation end: (a) 40 mm, (b) 80 mm, (c) 120 mm, (d) 160 mm, (e) 200 mm, (f) 240 mm, (g) 280 mm, (h) 320 mm, and (i) 360 mm

Table 2 Parameters of the first bonding interface wave

Distance/mm	40	80	120	160	200	240	280	320	360
Wavelength/μm	-	-	528.9	518.6	529.1	519.9	512.7	437.5	554.2
Amplitude/μm	-	-	144.8	157.7	149.4	146.8	147.3	146.4	84.5

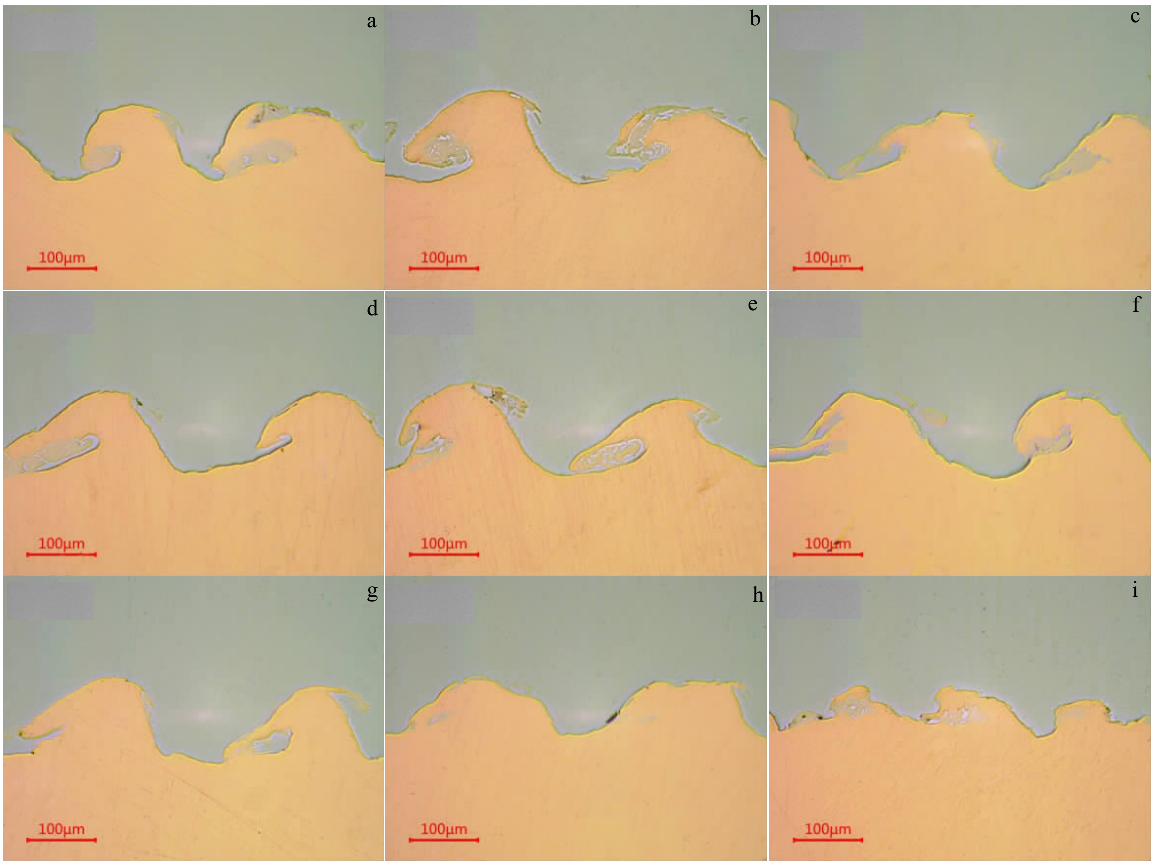

Fig.8 A series of optical microscopy photographs demonstrating the second bonding interface for different distances from the detonation end: (a) 40 mm, (b) 80 mm, (c) 120 mm, (d) 160 mm, (e) 200 mm, (f) 240 mm, (g) 280 mm, (h) 320 mm, and (i) 360 mm

Table 3 Parameters of the second bonding interface wave

Distance/mm	40	80	120	160	200	240	280	320	360
Wavelength/μm	235.3	273.2	281.6	308.4	305.1	302.1	305.7	293.7	188.9
Amplitude/μm	114.6	117.0	115.9	122.6	127.1	133.2	116.3	84.9	71.7

Micro-hardness measurements are made across the bonding interfaces using a load of 9.8 N. The micro-hardness profile across the first and the second bonding interfaces after explosive welding is shown in Fig.9. The maximum hardness was obtained near the welding interface for both sides. It indicates that the micro-hardness of the materials on both sides of the interfaces increases significantly in comparison to the original ones, which implies that the microstructure near the interface is modified by the high degree of plastic deformation resulting from the collision of plates[15]. Deformation during the crash of bonding plates is limited within a very narrow thickness close to the interface. So the hardness of the materials at 1.5 mm (Fe) and 2 mm (Cu) away from the interfaces remain almost unchanged. Besides, the hardness of Fe near the first and the second interfaces is 1561 and 1650 MPa, about 26.9% and 34.2% larger than that of the original one (1230 MPa), respectively. And, the hardness of Cu near the first and the second interfaces is 1402 and 1498 MPa, about 40.2% and 49.8% larger than that of the original one (1000 MPa), respectively.

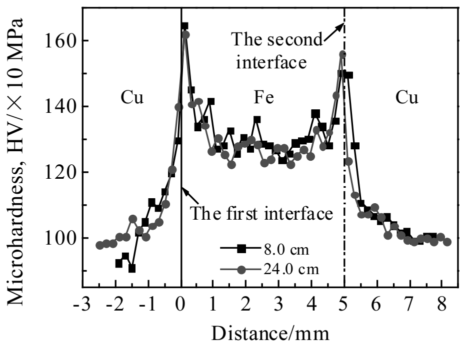

Fig.9 Micro-hardness profile across the first and the second bonding interfaces after explosive welding

3.3.2 Shear test

The shear test is conducted on the explosive welding samples to obtain the bond strength. The images and geometries of samples before and after shear test are shown in Fig.10. The crack firstly occurs on one side of the bonding interface under the shear force. With the load increasing, the crack propagates along the bonding interface and results in the separation of composite plate at the bonding interface finally. The typical load-displacement curve of shear test for Cu/Fe bonding interface is shown in Fig.11. Clearly, there is an obvious yield stage in the process of fracture. It means that the fracture process presents the characteristic of ductile fracture. And, shear strength test results show that the average shear strength of the first and the second bonding interface are 212.7 MPa and 225.3 MPa, respectively.

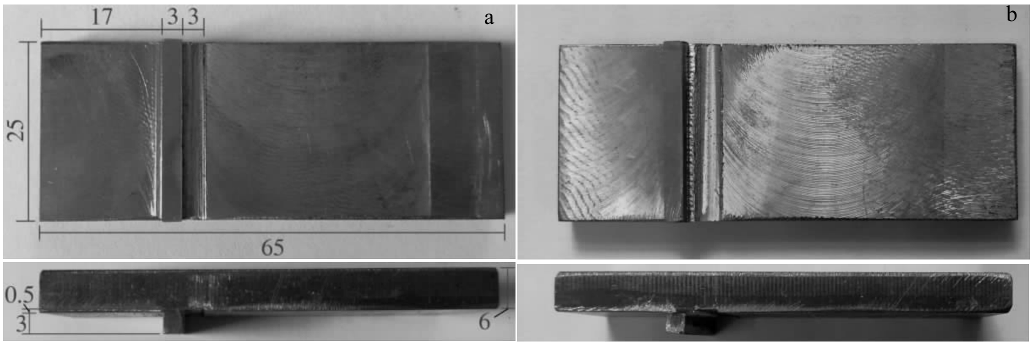

Fig.10 Shear test specimen and its geometric dimensions: (a) before shear test and (b) after shear test

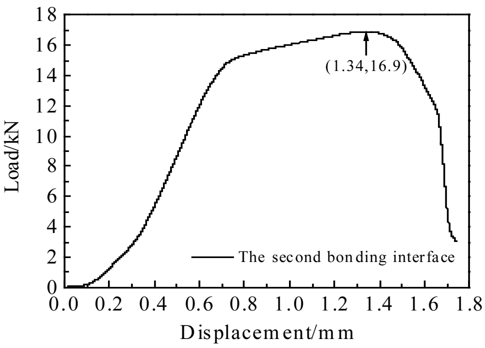

Fig.11 Load-displacement curve of the second bonding interface

4 Conclusions

1) In this study, the explosive welding parameters of Cu-Fe-Cu plate with large thickness are designed by theoretical model firstly. Then, the validity of the designed explosive welding parameters is verified by a new numerical simulation method, in which the SPH, Lagrange and Euler methods are used and no equivalent treatment of the explosive welding process is taken. The result indicates that the theoretical design parameters are valid. Finally, experimental preparation of Cu-Fe-Cu composite plate is carried out.

2) The Cu-Fe-Cu composite plate with large thickness is successfully prepared by explosive welding. And, parameters of the Fe-Cu interface obtained experimentally and numerically are in good accordance. Micro-hardness test show that the hardness near the interfaces is greatly higher than other parts, about 34.2% and 49.8% for Fe and Cu, respectively. And, shear strength test results show that average shear strength of the first and the second bonding interface is 212.7 MPa and 225.3 MPa, respectively.

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爆炸焊接制备大厚度 Cu-Fe-Cu 复合板

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摘 要：铜-铁复合板既有良好的延展性、导电和导热性，又有铁的铁磁性和铜的抗磁性，因此可广泛应用于电力、电子等行业。但铜和铁较差的相容性又使得两种金属难以用常规方法进行焊接。本研究采用爆炸焊接方法进行了大厚度 Cu-Fe-Cu 复合板的制备。首先，采用爆炸焊接理论获得了可焊性窗口，确定了炸药爆速、装药厚度和间隙高度；随后，在数值模拟中同时使用 SPH、Lagrange 和 Euler 方法完整模拟了整个爆炸焊接过程，获得了复板的碰撞速度、结合界面温度和压力，验证了理论设计参数的有效性；最后，开展了爆炸焊接试验，成功制备了大厚度 Cu-Fe-Cu 复合板，分析了结合界面近区的硬度分布和界面结合强度，借助于试验和数值模拟结果讨论了界面波的形成过程。结果表明：数值模拟和试验得到的 Fe-Cu 结合界面的波形参数基本一致；铁和铜在结合面附近的硬度较母材分别增加了约 34.2%和 49.8%；第一和第二结合界面的剪切强度分别为 212.7 MPa 和 225.3 MPa。

关键词：爆炸焊接；Cu-Fe-Cu复合板；可焊性窗口；界面波

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