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ARTICLE

Copper/Steel Explosive Welding with Self-Constrained Structural Explosives

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Abstract: In order to improve the utilization rate of explosive energy and reduce the amount of welding charge, self-constrained structure explosive was proposed to carry out explosive welding. A T2 copper plate and a Q345 steel plate were used as base layer and flyer layer, respectively, and T2/Q345 explosive welding window was obtained through theoretical calculation. An experimental study on explosive welding of T2 copper and Q345 steel was carried out with double-layer honeycomb structure explosive as self-constrained welding energy. The bonding properties of the clad plate were studied by mechanical property testing and microstructure observation. The results show that compared with single-layer explosive with detonation velocity of 2505 and 3512 $m \cdot s^{-1}$, the charge of double-layer honeycomb structure explosive used in T2/Q345 explosive welding can be saved by 54.4% and 31.4%, respectively. The bonding interface of the clad plate transforms from straight to wavy as the propagation distance increases. The tensile shear strength of the clad plate is 237.0 MPa, meeting the requirements of bonding strength of T2/Q345 clad plate. Explosion hardening occurs near the bonding interface. The T2/Q345 clad plate obtained by explosive welding with double-layer honeycomb structure explosive has good bonding property.

Key words: self-constrained structure; double-layer honeycomb explosive; explosive welding; mechanical property; microstructure observation

Explosive welding is a kind of composite process which integrates fusion welding, pressure welding and diffusion welding[1,2]. Explosive energy is converted to kinetic energy of flyer layer, which makes flyer layer collide with base layer at high speed to produce metallurgical bonding. As a special composite process, explosive welding is widely used for the production of clad plates, pipes and bars. So far, hundreds of identical or dissimilar metals have been welded successfully[3,4]. However, most of welding explosive energy is released in the form of shock wave, and dissipated into the environment unrestrictedly, resulting in low utilization efficiency of welding energy.

Somasundaram et al[5] studied the microstructure and mechanical performance of titanium/steel clad plate by changing the mass ratio of explosive to fly layer and collision angle, and concluded that the bonding interface of the clad plate changes from linear bonding to wavy bonding with the increase of mass ratio. Khanzadeh et al[6] varied stand-off distances and mass ratios to conduct explosive welding simulation and experiment, and three wavy morphologies were achieved because of the change of collision velocity and collision angle. Lysak et al[7] proposed a method to evaluate the explosive welding efficiency required for explosive welding, which is determined by the specific energy of an explosive converted to the energy spent on the plastic deformation of metal in the weld joint zone varied from 0.5% to 3%. In Sun's work[8], double vertical explosive welding adopted a closed charge structure, and two clad plates were welded by one explosion experiment. Double vertical explosive welding can improve energy efficiency and save at

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least half of the explosives. According to Gurney theory[9], compared with unrestrained charge, the constraint of superstructure can more effectively convert explosive energy into kinetic energy of flyer layer, thereby saving the amount of explosive. In Miao et al's[10] work, honeycomb structure explosive was used in the explosive welding of double-sided metal plates. The composite of multi-layer plates was realized through double-sided welding technology to improve the energy utilization rate of explosive. However, the upper clad plate was prone to deform and fly apart. In Yang's[11] study, superabsorbent resin was mixed with water to prepare colloidal water material. It was placed on the upper surface of welding explosive to provide covering constraint. The results show that the colloid water as covering layer can improve energy utilization rate of explosive. However, compared with detonation pressure of explosive, the restriction effect of colloidal water was smaller, and the surrounding environment might be polluted by the dispersion of colloidal water.

In order to improve the utilization rate of explosive energy and reduce welding charge, the research on explosive welding with self-constrained structure explosive was conducted. Honeycomb structure emulsion explosives with different detonation velocities were prepared with emulsion matrix as base, hollow glass microspheres as sensitizer and diluent, and aluminum honeycomb plate as charge frame. The two layers of explosives were stacked in a tight state to prepare self-constrained structure explosive. The upper explosive with high detonation velocity was used to restrain detonation direction of the lower explosive with low detonation velocity, which can reduce energy dissipation of the lower explosive and improve the utilization efficiency of welding charge.

T2/Q345 explosive welding window was calculated by formulation, and T2/Q345 explosive welding was carried out by double-layer honeycomb structure explosive which was less than the lower limit of welding charge. Microstructure observation and mechanical property testing were conducted to characterize the bonding property of the T2/Q345 clad plate.

1 Explosive Welding Parameters

The quality of explosive welding depends on the selection of welding parameters. Explosive welding parameters include dynamic parameters, static parameters and bonding zone parameters, among which dynamic parameters include collision angle, collision velocity, collision point velocity, etc. The dynamic parameters are independent each other, and any two parameters can form a weldability region in the same plane, namely explosive welding window[12]. In general, good welding quality can be obtained within explosive welding window, and the welding quality is better when the parameters near the lower limit of the explosion window are used.

1.1 Dynamic parameters

1.1.1 Lower limit of collision velocity

The minimum collision velocity $v_{\mathrm{p,min}}$ for dissimilar metallic materials can be presented as[13]:

$$v_{\mathrm{p,\,min}} = \begin{cases} v_{\mathrm{p}_1}\left(\dfrac{C_1\rho_1 + C_2\rho_2}{C_1\rho_1 C_2\rho_2}\right) & p_1 > p_2 \\ v_{\mathrm{p}_2}\left(\dfrac{C_1\rho_1 + C_2\rho_2}{C_1\rho_1 C_2\rho_2}\right) & p_2 > p_1 \end{cases} \tag{1}$$

$$v_{\mathrm{p}_1} = \sqrt{\frac{\sigma_{\mathrm{b}_1}}{\rho_1}};\ v_{\mathrm{p}_2} = \sqrt{\frac{\sigma_{\mathrm{b}_2}}{\rho_2}} \tag{2}$$

$$p_1 = \frac{C_1\rho_1 v_{\mathrm{p}_1}}{2};\ p_2 = \frac{C_2\rho_2 v_{\mathrm{p}_2}}{2} \tag{3}$$

where v_{p_1} and v_{p_2} are the minimum collision velocity between fly plates and between base plates, respectively; p_1 and p_2 are the collision pressure between fly plates and between base plates, respectively; C_1 and C_2 are the sonic speed of fly and base plates, respectively; ρ_1 and ρ_2 are the density of fly and base plates, respectively; σ_{b_1} and σ_{b_2} are the tensile strength of fly and base plates, respectively.

1.1.2 Lower limit of collision point velocity

According to the theory of fluid mechanics, when the collision point velocity exceeds its lower limit, the metal at the interface transforms from laminar flow to turbulent flow, resulting in wavy bonding. The lower limit of collision point velocity $v_{\mathrm{c,min}}$ is calculated using the following expression[14]:

$$v_{\mathrm{c,\,min}} = \sqrt{\frac{2Re(H_1 + H_2)}{\rho_1 + \rho_2}} \tag{4}$$

where Re is the Reynolds number, H_1 and H_2 are the Vickers hardness of fly and base plates, respectively.

1.1.3 Upper limit of collision velocity

The upper limit of collision velocity $v_{\mathrm{p,max}}$ between flyer and base plates can be expressed as[15]:

$$v_{\mathrm{p,\,max}} = \frac{2\sqrt[4]{\dfrac{t_{\min}}{\pi}}}{v_{\mathrm{c,\,min}}}\sqrt{\rho_1 C_{\mathrm{p1}}\sqrt{\alpha_1} + \rho_2 C_{\mathrm{p2}}\sqrt{\alpha_2}}\sqrt{\frac{T_{\mathrm{mp\,min}} C_1^2 C_2^2}{N\left(C_1^2 + C_2^2\right)}}\sqrt{\frac{\rho_1\delta_1 + \rho_2\delta_2}{\rho_1\delta_1\rho_2\delta_2}} \tag{5}$$

where C_{p1} and C_{p2} are the specific heat of fly and base plates, respectively; α_1 and α_2 are the thermal diffusivities of fly and base plates, respectively; δ_1 and δ_2 are the thickness of fly and base plates, respectively; T_{mpmin} is the lower melting point of fly and base plates, $t_{\min}$ is the shortest time for the reflection of sparse wave to bonding interface; N is the coefficient related to the sonic speed of the material.

1.1.4 Upper limit of collision point velocity

A large enough collision angle is required to drive the interface to produce metal jet. The formulation of the maximum collision point velocity $v_{\mathrm{c,max}}$ expressed by the collision angle β is proposed in Ref.[16]:

$$v_{\mathrm{c,\,max}} = \frac{\beta}{10} + 5.5 \tag{6}$$

1.2 Static parameters

1.2.1 Mass ratio

When the explosive welding between fly plate and base plate is simplified to one-dimensional motion, the collision velocity v_p between the two plates can be expressed as[17,18]:

$$v_p = 1.2v_d \frac{\left(1+\frac{32}{27}R\right)^{\frac{1}{2}}-1}{\left(1+\frac{32}{27}R\right)^{\frac{1}{2}}+1} \quad (7)$$

where v_d is the detonation velocity of explosive, and R is the mass ratio of explosive to fly plate.

1.2.2 Stand-off distance

The empirical formulation for the stand-off distance h_0 can be presented as[19]:

$$h_0=0.2(\delta_0+\delta_1) \quad (8)$$

where h_0 is the stand-off distance between flyer plate and base plate, and δ_0 is the thickness of explosive.

2 Experimental Materials

Fly and base plates were T2 copper and Q345 steel with dimensions of 3 mm×150 mm×300 mm and 15 mm×150 mm×300 mm, respectively. The physical and mechanical properties of fly and base plates are shown in Table 1.

Two kinds of emulsion explosives (Table 2) with 15% and 25% microspheres were prepared using hollow glass microsphere with average particle size of 60 μm as sensitizer and emulsion matrix as base. An aluminum honeycomb panel with a hexagonal unit side length of 8 mm was used as explosive frame, and the single-layer honeycomb structure explosive was prepared by filling the pores of aluminum honeycomb with emulsion explosive, as shown in Fig.1.

The aluminum honeycomb panel can ensure uniform thickness and good compression resistance of the explosive. When hollow glass microspheres were used as diluent, the detonation velocity of emulsion explosive decreases as the content of the microspheres increases[20]. The detonation velocity of emulsion explosive A with 15% hollow microsphere and emulsion explosive B with 25% hollow microsphere was 3512 and 2505 m·s^{-1}, respectively. Emulsion explosive A with higher detonation velocity was placed on the upper layer of emulsion explosive B and compressed together to prepare double-layer honeycomb structure emulsion explosive C.

The inner surface of T2 copper and Q345 steel plates was polished and cleaned for rust removal. The assembled explosive welding set-up was placed on the foundation of the explosion tank, and butter was applied to the surface of flyer plate to prevent heat burns. Explosive welding set-up was equipped with a parallel installment structure, as shown in Fig. 2. The interfacial bonding properties of T2/Q345 clad plate were investigated by microscopic morphology observation and mechanical property testing after explosive welding. An A1m type optical microscope and a Flex SEM 1000 type scanning electron microscope were used for the microstructure observation at the interfaces of T2/Q345 clad plate. The specimens for the tensile shear testing were prepared according to GB/T6396-2008. The tensile testing was carried out with a MTS-810 type universal testing machine at a constant rate of 0.2 mm/min.

Table 1 Physical and mechanical properties of flyer and base plates

Material	T_{mp}/°C	HV/×9.8 MPa	σ_s/MPa	σ_b/MPa	C/m·s^{-1}
T2	1083	65	185	295	4700
Q345	1523	135	345	515	5900

Table 2 Emulsion matrix component

Component	NH_4NO_3	$NaNO_3$	H_2O	$C_{18}H_{38}$	$C_{24}H_{44}O_6$
Content/%	71	11.5	11	3.7	2.8

Fig.1 Schematic of honeycomb structure explosive

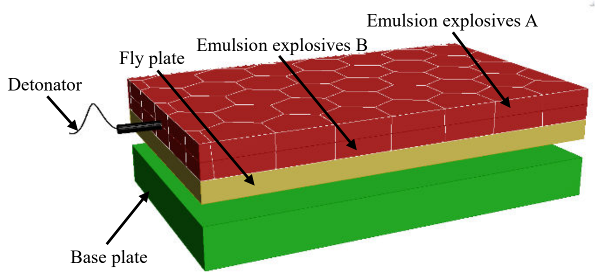

Fig.2 Schematic diagram of explosive welding set-up with double-layer honeycomb emulsion explosive

3 Results and Discussion

3.1 Result of calculation

According to Eq.(1~6) and the parameters of fly and base plates in Table 1, the upper and lower limit parameters of T2/Q345 explosive welding window were calculated, as shown in Table 3.

The collision velocity of T2/Q345 explosive welding using emulsion explosives A and B with the same thickness of 8 mm is calculated by Eq. (7), and the positions of welding parameters in the T2/Q345 explosive welding window are

Table 3 T2/Q345 explosive welding window parameters (m·s^{-1})

$v_{p,min}$	$v_{p,max}$	$v_{c,min}$	$v_{c,max}$
345	722	1882	6195

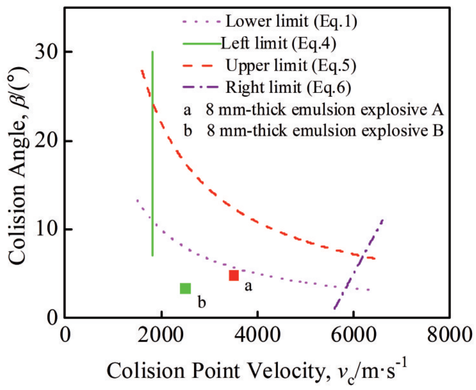

Fig.3 T2/Q345 explosive welding window

displayed, as shown in Fig.3.

Emulsion explosives A and B with the same thickness of 8 mm were used. According to Eq.(7), the collision velocity of the clad plate was calculated to be 293 and 145 m·s^{-1}, which are represented by points a and b in Fig. 3, respectively. Although the detonation velocity of the two explosives is in the range of collision point velocity of T2/Q345 explosive welding window, the collision velocity is less than the critical collision velocity 345 m·s^{-1} of T2/Q345 explosive welding. Therefore, good welding effect cannot be achieved because point a and b are outside explosive welding window.

According to explosive welding formulation and T2/Q345 weldability window, the lower limit parameters of T2/Q345 explosive welding with emulsion explosives A and B were obtained. The mass ratio R satisfying the lower limit of collision velocity can be calculated through Eq.(7), and the minimum charge for explosive welding can be obtained, as shown in Table 4.

It can be seen from Table 4 that the minimum charges of emulsion explosives A and B for T2/Q345 explosive welding are 395.3 and 595.4 g, and the corresponding thicknesses are 9.6 and 22.0 mm, respectively. T2/Q345 explosive welding was carried out by double-layer honeycomb structure emulsion explosive C, the charge is only 271.3 g, and the charge thickness is 8 mm. Compared with emulsion explosive A and B, emulsion explosive C for T2/Q345 explosive welding can save 31.4% and 54.4% charge, respectively.

When emulsion explosives A and B with the same thickness of 8 mm were used for T2/Q345 explosive welding, metallurgical bonding cannot be realized. The parameters for explosive welding of the two explosives are located outside the T2/Q345 explosive welding window, as shown in Fig. 3. Since the welding energy of the two explosives with this thickness is relatively small, most of the energy is dissipated from the upper part of explosive, and the utilization efficiency of welding energy is low. The interface between copper and steel plates is failed to produce strong plastic flow, which leads to unsuccessful weld. In this case, it is necessary to increase the explosive thickness to improve the welding energy and collision velocity of flyer plate, so that metallurgical bonding can be realized at the interface of the clad plate.

Table 4 T2/Q345 explosive welding parameters

Explosive	v_c/m·s^{-1}	ρ/kg·m^{-3}	M/g	δ/mm
A	3512	906	395.3	9.6
B	2505	601	595.4	22.0
C	2832	upper 906/lower 601	271.3	8.0

The detonation velocity of the upper explosive of double-layer honeycomb structure emulsion explosive C is slightly faster than that of the lower explosive. The explosion of the upper explosive can constrain the direction of the explosive energy release of the lower explosive, which can reduce the energy dissipation of the lower explosive, and increase the efficiency of the transformation of the explosion energy of the lower explosive into the kinetic energy of layer plate. It is shown that the double-layer honeycomb structure explosive with self-constrained effect can reduce welding charge and improve the energy utilization efficiency of explosive to convert into kinetic energy of flyer plate.

3.2 Metallographic observation

After explosive welding, the T2/Q345 clad plate is cut along the detonation direction to prepare metallographic specimens. The cut specimens are 5 and 15 cm away from the initiation end, and their metallographic structures are shown in Fig.4.

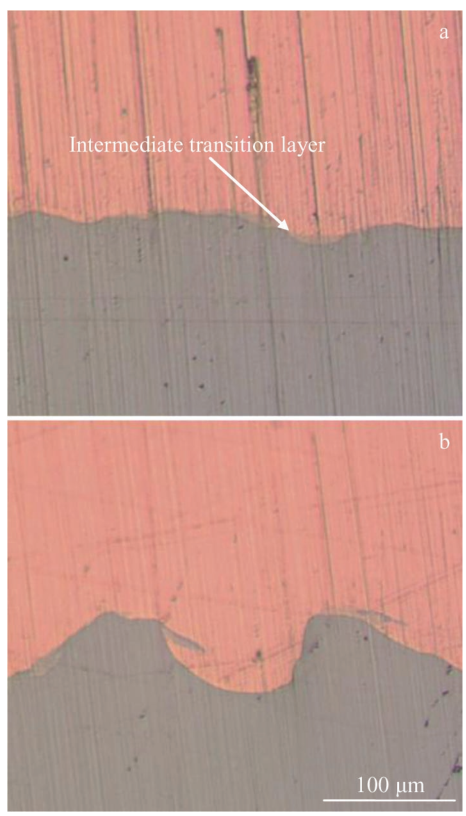

Fig.4 Microstructures of the interface of T2/Q345 clad plate: (a) close to initiation end and (b) away from initiation end

Fig. 4a shows the metallographic structure at the bonding interface of T2/Q345 clad plate at a distance of 5 cm from initiation end. It can be seen that the bonding interface is linear, and no obvious metallic melting layer is observed. Melting blocks appear in local areas, as shown in the white dotted line area of Fig. 4a. The metal close to bonding interface produces strong thermal effect under the action of plastic deformation heat and adiabatic compression heat, which leads to metallic melting at the interface. Thicker melting layer will worsen the bonding quality of clad plate, but thinner melting layer is beneficial to metal diffusion and increases the interfacial bonding strength. The results are coherent with the previous study results[21-23].

Fig. 4b shows the metallographic structure at the bonding interface of T2/Q345 clad plate at a distance of 15 cm from initiation end. It can be seen that the interface of the T2/Q345 clad plate is wavy bonding with an average wave length of 250 μm and wave height of 100 μm. Flat and wavy shapes are two common forms of bonding interface of explosive welding, in which the wavy interface has higher bonding strength because of the larger bonding area[24]. Explosive transformes from initiation to stable explosion as propagation distance increases. Kinetic energy of the flyer plate converted by explosive energy increases correspondingly, and the bonding interface changes from flat to wavy[25].

3.3 Scanning electron microscope observation

Scanning electron microscopy was used to characterize the interfacial property of clad plate. Fig.5 shows the microstructure of the interface of T2/Q345 clad plate. According to the SEM image in Fig. 5, it can be observed that there is an intermediate transition layer which is different from copper and steel microstructures at the waist of the interfacial wave of the clad plate. This is caused by melting and diffusion of metals, consistent with the results of metallographic analysis.

Sound interface bonding and non-excessive intermetallic compounds at the interface should be guaranteed so as to obtain a qualified clad plate. EDS line scanning and point scanning were performed to further analyze the composition of the intermediate transition layer, as shown in Fig. 6 and Table 5.

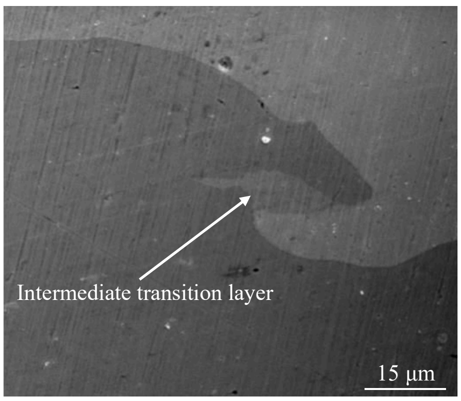

Fig.5 SEM image of the interface of T2/Q345 clad plate

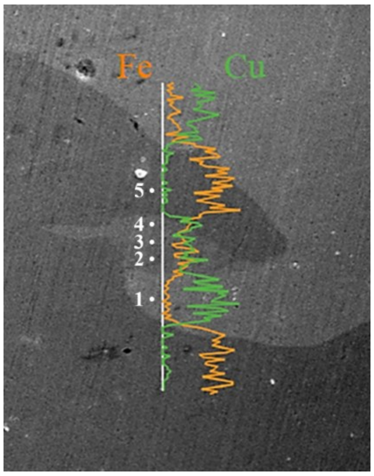

Fig.6 EDS line scanning across the interface of T2/Q345 clad plate

Table 5 EDS results of the points marked in Fig.6 (at%)

Point	Cu	Fe
1	98.73	1.27
2	60.02	39.98
3	52.11	47.89
4	47.16	52.84
5	1.06	98.94

Line scan analysis reveals a platform at the interface of copper and steel layers. Fig.6 shows that the component of the intermediate transition layer is different from that of copper and steel layers. High temperature and high pressure produced by explosive welding melt interfacial metal, resulting in the mutual diffusion between base and flyer layers. Compared with the single element on the copper or steel sides, both Fe and Cu elements exist in the molten block. Intermetallic compounds such as FeCu and $FeCu_2$ may appear at the interface between copper and steel layers during explosive welding[26-29]. According to atomic fraction of copper and steel in Table 5, intermetallic compound FeCu may appear at the interface of the clad plate.

3.4 Tensile shear testing

The bonding strength at the interface is one of the important indicators to measure welding quality. In order to characterize mechanical property of the T2/Q345 clad plate, tensile shear testing at room temperature was carried out. The schematic diagram of tensile shear specimen is shown in Fig. 7. The stress-displacement curve and testing results of the T2/Q345

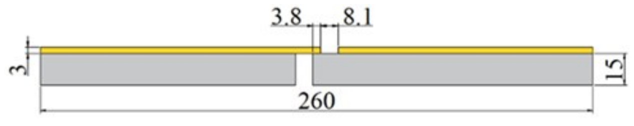

Fig.7 Schematic diagram of tensile shear specimen

clad plate are shown in Fig.8 and Table 6, respectively.

It can be seen from Fig.8 that the average tensile force and shear strength of the T2/Q345 clad plate are 22.5 kN and 237.0 MPa, respectively. According to the physical diagram of tensile shear failure specimen in Fig. 9, the tensile shear fracture occurs on the copper side, indicating that the bonding strength at the interface of the T2/Q345 clad plate is greater than the shear strength of copper plate, and that the interface has a good bonding performance. It is consistent with the previous report that the shear strength of clad plate is higher than that of the weaker metallic plate[30-33].

3.5 Microhardness testing

Microhardness testing was carried out on both sides of the T2/Q345 explosive welding interface, as shown in Fig.10.

Fig. 10 demonstrates that the micro-hardness of Q345 steel and T2 copper generally decreases as the distance from the bonding interfaces increases. The maximum micro-hardness of Q345 steel is approximately 22.2% higher than that of Q345 steel far away from the welding zone; while the maximum micro-hardness of T2 copper is approximately 4.7% higher than that of T2 copper far away from the welding zone. The high temperature and high pressure in the explosive welding process causes strong plastic deformation of interfacial metal, and the microhardness of the two metallic materials close to the bonding interface is also significantly improved. As the distance between the testing point and the welding interface increases, the collision pressure decreases gradually, leading to the decrease in microhardness[34,35].

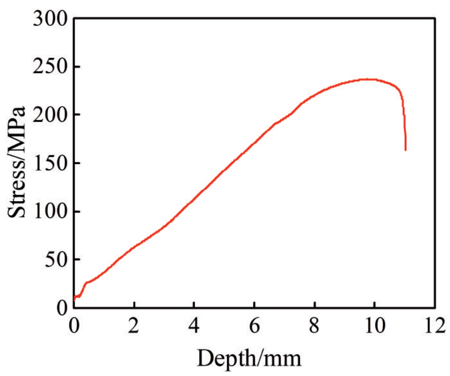

Fig.8 Stress-displacement curve of tensile shear specimen

Table 6 Tensile shear results of T2/Q345 clad plates

S/mm	F/kN	τ/MPa
25×3.8	22.5	237.0

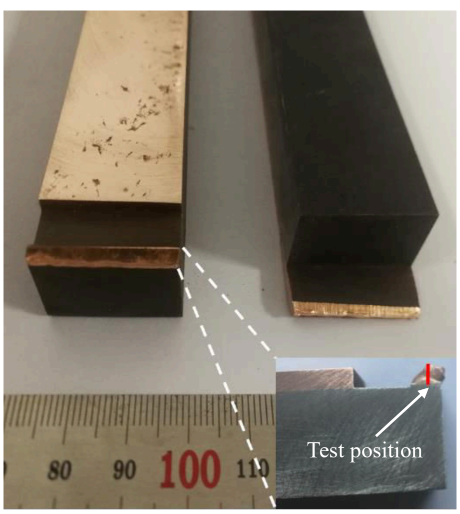

Fig.9 Physical diagram of tensile shear failure specimen

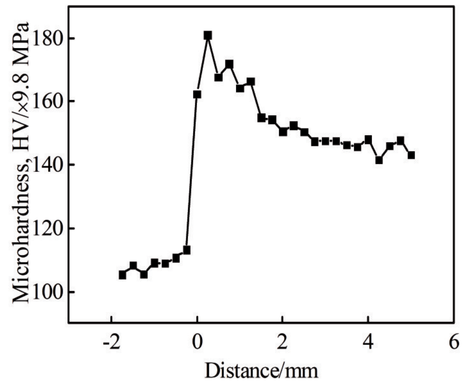

Fig.10 Microhardness of T2/Q345 explosive welding interface

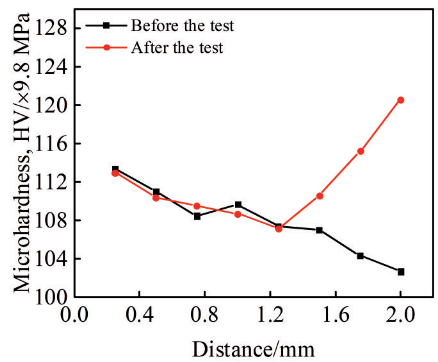

Fig.11 Microhardness changes of tensile shear specimens

In order to analyze the changes of metal hardness of tensile shear specimen after failure, the microhardness of tensile failure specimens was tested. Microhardness testing location is indicated by the white arrow in Fig.9, and the testing result is shown in Fig.11.

Fig.11 shows the microhardness changes on the copper side of tensile shear specimens before and after failure. It can be seen that the microhardness of the copper side farther away from bonding interface increases sharply after tensile shear failure, which is different from the gradual decline of the microhardness of the tensile shear specimen before failure. Because plastic deformation occurs in the tensile shear process of the specimen, the deformation produces work hardening, which leads to the increase in the microhardness of copper layer.

4 Conclusions

1) Due to the restriction of the upper explosive to the lower explosive, the double-layer honeycomb structure explosive can improve the energy utilization rate of welding explosive and reduce welding charge.

2) Compared with two kinds of single-layer explosive with detonation velocity of 3512 and 2505 m/s^{-1}, the double-layer honeycomb structure explosive with self-constrained effect can save 31.4% and 54.4% charges, respectively.

3) The bonding property of the T2/Q345 clad plate is good. As the propagation distance increases, the interface changes from straight bonding to wavy bonding.

4) The average tensile shear strength of the clad plate is 237.0 MPa, indicating that the bonding interface of T2/Q345 clad plate exhibits reliable shear strength.

5) The micro-hardness of Q345 steel and T2 copper generally decreases as the distance to the bonding interfaces of the clad plate increases.

6) The microhardness of the copper side increases sharply after tensile shear failure with increasing the distance away from the bonding interface.

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采用自约束结构炸药的铜/钢爆炸焊接

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摘　要：为了提高爆炸能量的利用率，减少焊接药量，提出采用自约束结构炸药进行爆炸焊接。采用T2铜板和Q345钢板分别作为复板和基板，通过理论计算得到T2/Q345爆炸焊接窗口。采用双层蜂窝结构炸药作为自约束结构焊接炸药，对T2铜与Q345钢的爆炸焊接进行了试验研究。通过力学性能测试和显微组织观察，研究了T2/Q345复合板的结合性能。结果表明：与爆速为2505和3512 $m\cdot s^{-1}$的单层炸药相比，T2/Q345复合板爆炸焊接采用的双层蜂窝结构炸药量分别减少了54.4%和31.4%；随着传播距离的增加，复合板的结合界面由直线结合向波状结合转变。复合板的抗拉剪切强度为237.0 MPa，满足T2/Q345复合板的结合强度要求。爆炸产生的硬化发生在结合界面附近，采用双层蜂窝结构炸药爆炸焊接得到的T2/Q345复合板具有良好的结合性能。

关键词：自约束结构；双层蜂窝结构炸药；爆炸焊接；力学性能；显微观察

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