A dynamic study of effect of multiple parameters on interface characteristic in double-vertical explosive welding

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Abstract

Previous studies focused on the research of single parameters on the bonding quality of explosive welded composite plates. To explore the dynamic influence of multiple parameters on the interface, a VST (velocity, stand-off gap and charge thickness) function was proposed. The three-dimensional diagram clearly and intuitively showed that the collision velocity was comprehensively affected by the explosive thickness and stand-off gap. Four different sets of parameters were chosen and the composite plates were successfully manufactured in the experiment of double vertical explosive welding (DVEW). The interface morphology, element distribution and the mechanical property were discussed respectively. The optical microscope showed that all the samples were wavy interface but the dimensions of the ripples was different. The defects, such as melting layer and island region, appeared less frequently at bonding interface when the collision velocity was lower. The grain refinement, adiabatic shear bands were found at the crest and side of wave respectively. The width of elements diffusion layer of joint increased in line with higher collision velocity. It was indicated the maximum microhardness reached 293HV at the bonding interface due to work hardening. Shear and tensile tests suggested the the mechanical property of large wave was better than that of small wavy interface. The fracture morphology showed obvious stratification and the dimple at the bonding interface was smaller in diameter and less plastic.

1. Introduction

The explosive welding can combine alloy with similar or dissimilar metals to achieve a high-strength interface of bonding with the high-speed impact of flyer plates and high-pressure of explosive [1]. Double-layer or multi-layer dissimilar metal cladding plates welded via explosive welding satisfied the comprehensive requirements regarding the material properties in many areas [2, 3]. However, a considerable amount of energy was dissipated in the air during the forming of the composite plates using the traditional parallel explosive welding (PEW), resulting in energy waste and noise pollution [4]. Shi et al invented the double vertical explosive welding (DVEW), a method of manufacturing two composite plates at one detonation by placing the base plate and flyer plate vertically on the ground and sealing charging between two layers of flyer plate. The DVEW reduced the adverse impact of blast wave on the surrounding environment [5].

Additionally, the welding parameters, charge thickness $\delta_0$ and stand-off gap $S$, play a major role in the bonding quality of the interface which affects the practical application of the composite plate. The defects such as metallic compounds and melting layer appear more frequently in the bonding interface when using too much explosive [6], and it results in unsuccessful welding when $\delta_0$ is too thin [7]; similarly, excessive $S$ will leads to insufficient exhaust and result in bulge, and too small $S$ will lead to insufficient flyer cladding acceleration. Thus, it is important to choose suitable welding parameters for better bonding quality.
In previous studies, the effect of $\delta_0$ and $S$ on the characteristic of the joint was discussed through a large amount of experiments respectively. Different explosive ratio $R$ used in explosive welding changed the wavelength and wave altitude of bonding interface [8–14]. Durgutlu A [11] and Zamani [15] found that the explosive ratio $R$, which was related to $\delta_0$, could contribute to the formation of wavy structure in Cu/Steel composites. Likewise, other researchers considered the relationship between $S$ and the dimension of the wave of the bonding interface and they reported the interface morphology range from straight to wave with the increase of $S$ [1, 11, 16, 17]. It was noted that both of parameters related to the collision velocity $V_p$ in previous studies. When the $\delta_0$ and $S$ increased, the $V_p$ increased. Cowan et al [18] indicated that the altitude of wave increased with the growing $V_p$ in the bonding interface. Generally speaking, the microwave may be more ideal interface morphology than large wave for explosive welding. Shi et al [19] considered the microwave may be better interface in the explosive welding with no melting defects nearly compared with other interface morphology in the explosive welding. Manikandan et al [20] gave a view that the formation of small wave reduced the possibility of intermetallic compounds at the interface.

However, these studies primarily focused on the influence of separate parameter, $\delta_0$ or $S$, and kept another parameter as a constant in the PEW experiments. The selection of welding parameters was usually done based on the weldability window [21], which consisted of the collision angle $\beta$ and detonation velocity $V_d$ and were built by different researchers (lower limit [22], upper limit [23, 24], left limit [18, 25] and right limit [26]). But the parameters obtained through the weldability window had certain non-intuitiveness and uncertainty, requiring workers to determine the parameters through their actual experience. The comprehensive relationship among $V_p$, $S$ and $\delta_0$ has not been reported. The conclusion obtained by controlling a single variable may be insufficient to guide actual industrial production in explosive welding.

After detonation, the explosive produced a strong shock wave and detonation gas. Under the action of shock wave and detonation gas, the flyer plates accelerated continuously and finally impacted with the base plate. In this process, the acceleration of flyer plate was constantly changing because the state parameters of detonation gas were continuously changing. The duration of this process was extremely short. Fortunately, the analytical expression of flyer plate motion can be expressed by mass conservation and C-J detonation model. Gurney [27] and Kennedy [28] put forward with a formula for the velocity of the collision, called ‘Gurney Formula’. However, the $V_p$ calculated from Gurney Formula only related to the mass ratio $R$ and neglected another parameter, $S$. Thus, considering the accuracy of $V_p$, it may be better to propose the binary function expression of $V_p$, including $\delta_0$ and $S$. Fan et al [29] revised the formula on this basis. Unfortunately, the revised formula was based on the model of cylindrical explosive detonation and did not apply to plate type explosive welding. Thus, to find the binary function of collision velocity $V_p$ on $\delta_0$ and $S$ was required to explore their dynamic influence on the bonding characteristic.

Thus, it is hoped that finding the binary function of collision velocity $V_p$ on $\delta_0$ and $S$ so as to explore their dynamic influence on the bonding characteristic. This paper focused on the dynamic effect of $\delta_0$ and $S$ on the interface bonding quality and the VST (velocity, stand-off gap and charge thickness) function was expressed. The experiments of stainless steel (304 l)/steel (Q235B) composites were performed by using different $\delta_0$ and $S$ via DVEW. The microstructure and morphology of bonding interface were studied by Optical Microscope (OM). The element distribution was probed by Scanning Electron microscopy (SEM) and Energy-dispersive x-ray spectroscopy (EDS). The mechanics test and microhardness test were used to assess the mechanical property of materials. The fracture morphology of shear test specimens was characterised by SEM. The binary function of collision velocity reflects the dynamic relationship among $V_p$, $S$ and $\delta_0$. The application of it will better predict the quality of the interface and better guide future industrial production in explosive welding with its stronger applicability.

2. Methods

2.1. The relationship between dimension of wave and collision velocity

Wittman et al illustrated the relationship between $\beta$ and $V_p$ from the equation (1) [30]. At the same time, Deribas [31] gave the empirical formula (equation (2)) for wavelength $\lambda$, which is a function of thickness of flyer $h_1$ and $\beta$. Combining equations (1)), it can be obtained that the $\lambda$ is affected by the $V_p$ when the $h_1$ and explosive detonation velocity $V_d$ is determined as a constants in the process of welding, as shown in equation (3).

Therefore, the $V_p$ was an important parameter to determine the wavelength of wavy interface, which was in compliance with the previous studies [18].

$$V_p = 2V_d \sin \left(\frac{\beta}{2}\right)$$

(1)
2.2. The VST function of flyer plate

The Gurney Formula (equation (4)) mentioned in section 1 is shown below. Here, E was the Gurney Energy.

\[
V_p^2 = \frac{2E}{1 + 5R + 4R^2}
\]  
(4)

The schematic diagram of DVEW is shown in figure 1. The expression for the velocity of the flyer plate changing with time from the initial position to the collision position is given, as the following equation (5) [29].

Here, \( M_e \) and \( m_e \) are the weight of flyer plate and explosive charge respectively, \( M_e = S_f \times h_1 \times \rho_0 \) \( m_e = S_f \times h_1 \times \rho_f \); \( k \) is the shape coefficient, take value of 1/6 for plate; \( S_f \) is the contact area of the explosive and flyer plate; \( P \) is the pressure exerted by the explosive on the flyer plate.

\[
(M_e + km_e) \frac{dv_p}{dt} = S_f P
\]  
(5)

It is assumed that the detonation process is C-J detonation model and the velocity of the flyer plate is the same everywhere in the process of explosive welding. In addition, It is considered that the motion of detonation products is isentropic adiabatic motion. The \( P \) after collision can be obtained by mass conservation and C-J detonation condition, as shown in the following equation (6). Where, \( \gamma \) is the effective polytropic index; \( P_0 \) is the pressure at detonation front, \( P_0 = \rho_0 V_{d0}^2/(\gamma + 1) \) in C-J detonation model; \( \rho_e \) is the density of explosive; \( \rho \) is the density of detonation products at impact; \( a_0 \) is the radius of detonation products in initiation detonation (state 1); \( a \) is the collision radius (state 2).

\[
P = P_0 \left( \frac{\rho}{\rho_0} \right)^\gamma = P_0 \left( \frac{a_0}{a} \right)^{3\gamma} = \frac{\rho_0 V_{d0}^2}{2(\gamma + 1)} \left( \frac{\delta_0}{\delta_0 + S} \right)^{3\gamma}
\]  
(6)

Since equation (5) gives the derivative of velocity \( V_p \) with respect to time \( t \), it is convert it to the derivative of V with respect to distance \( r \), \( dV/dr = 1/2dv^2/dr \). The VST function was obtained from equations (3), (6), as shown in equation (7).
Taking 304 L/Q235B as an example, the three-dimensional diagram among $V_p$, $\delta_0$ and $S$ can be obtained, as showed in figure 2. The parameters of equation (7) used in figure 2 are shown in table 1. The intersecting line of the same collision velocity and the three-dimensional diagram is a binary function of thickness charge $\delta_0$ and stand-off gap $S$, that is, the collision velocity is dynamically determined by the charge thickness $\delta_0$ and stand-off gap $S$ together.

3. Experiments

In this study, four 304 L/Q235B composite plates were manufactured with different parameters by DVEW. The chemical compositions of the parent materials are shown in table 2. Parameters of four samples are listed in table 3 and marked in figure 2. The powdery emulsion explosive of explosive welding, which mixed with 38% perlite, $\rho \approx 0.85 \text{ g cm}^{-3}$, $V_d \approx 2,000 \text{ m s}^{-1}$ and $\gamma = 1.8$. The dimension of flyer plate (304 l) was $1.01 \text{ m} \times 1.01 \text{ m} \times 6 \text{ mm}$. The that of base plate (Q235B) was $1 \text{ m} \times 1 \text{ m} \times 23 \text{ mm}$.

Before welding, the surface of materials was firstly polished to clear away the oxide layer and then was cleaned with industrial alcohol for easier welding before the detonation; next, stand-off pieces was placed and

\[ V_p = f(\delta_0, S) = \sqrt{\frac{6V_d^2}{(\gamma + 1)(3\gamma - 1)}} \left[ \frac{0.5\delta_0 \rho_e}{6h_2 \rho_f + \delta_0 \rho_e} \right] \left( 1 - \left( \frac{0.5\delta_0}{0.5\delta_0 + S} \right)^{\gamma - 1} \right) \]  

(7)
the flyer plates covered the flyer plate subsequently. Finally, the flyer plate was greased and the explosives and electronic detonations were placed, the explosives were detonated after the crowd kept at a safe distance.

After welding, the test-pieces were cut from the same position of the four composites by line-cutting. To obtain proper surface quality, these smaller samples were sanded, polished and etched (4% HNO$_3$, 96%C$_2$H$_5$OH). The microstructure and morphology of the bonding interface were investigated by using an optical microscopy (OM) (Axiophot2, ZESS, Shanghai, China) and a JSM-6360LV scanning electron microscope (SEM) (JEOL, Tokyo, Japan). Energy-dispersive x-ray spectroscopy (EDS) (GENESIS200XMS60, EDAX Inc., UT, USA) was employed to study the element distribution and composition of the bonding interface. The value of microhardness was recorded by a FMX2000 microhardness tester (SIMCO, Dongguan, China). The mechanics performance tests, including tensile strength, tensile shear strength were carried out by a CMT5305 universal testing machine (XINSANSI, Shenzhen, China) according to GB/T 228.1-2010, GB/T 6396-2008, and GB/T 232-2010, respectively. The fracture morphology of the tensile samples was observed by a SEM. Figure 3. 304 L/Q235B composite clads produced by DVEW.

### Table 3. The welding parameters used in samples.

| Samples | $\beta$(deg) | $\delta_0$(mm) | $S$(mm) | $V_p$(m s$^{-1}$) |
|---------|--------------|---------------|---------|------------------|
| Sample 1|  8.22        |    40         |   10    |     315          |
| Sample 2|  8.83        |    50         |   10    |     338          |
| Sample 3|  8.75        |    40         |   20    |     335          |
| Sample 4|  8.21        |    35         |   18    |     315          |

4. Results and discussion

4.1. Morphology of bonding interface

Figure 4 shows the morphology of the bonding interface for different parameters under a 50X OM. All the samples were wavy bonding. This phenomenon can be summarized as the pressure on the flyer plate after the detonation of the explosive fluctuates periodically. At the same time, the jetting generated when the collision took place between the flyer plate and base plate with a high-speed [32]. Cowan and Holtzman [18] believed that the periodic separation and confluence of metal around the jet obstacle will result in a wavy interface. However, the dimensions of the wave are changed with variable parameters. The theoretical (in equation (3)) and actual dimensions of the ripples in welding joint were listed in table 4. It can be seen from table 4 that the actual wavelength $\lambda_a$ was larger than the theoretical wavelength $\lambda_t$, which may be because the influence of material factors was not considered in equation (3). In sample 1 and 4, the small wave, with the actual wavelength and waveAltitude of about 1 000 $\mu$m and 400 $\mu$m respectively, was observed in the bonding interface of 304 L/Q235B. There was a gap existing in wavelength of a wave between sample 1,4 and sample 2,3. As shown in figures 4(b), (c), the large waves were found in samples using thicker explosives or bigger stand-off gap, which was in line with the previous researches [16–18]. Thicker explosive or larger stand-off gap resulted in the flyer plate achieving higher $V_p$ when it collided with the base plate, which leads to the generation of large wave in
Althought the welding parameters including $\delta_0$ and $S$ used in sample 1 and sample 4 were different, the size of interface wave was almost the same due to the same collision velocity. The small wave of bonding interface had the better bonding quality for two reasons: firstly, the wave interface had a larger contact area due to its mechanical mesh than straight interface; secondly, the small wave prevented the formation of intermetallic compound (IMC) \[19, 20\].

Additionally, defects such as melting layer, island region and vortex region appeared more frequently in sample 2 and 3 than sample 1 and 4. Figures 5(a) and (b) show the morphology of melting layer and island region from sample 2 under an OM with 50X and 200X respectively. The island region was essentially another form of melting layer. It can be contributed that the higher collision velocity caused more heat, complying with the previous researches \[33, 34\]. In the explosive welding process, due to the violent impact of the flyer plate in a very short time, the whole process can be regarded as an adiabatic process, and a large amount of heat was generated, resulting in the generation of melting layer. In general, the existence of melting layer is detrimental to quality of bonding interface \[35\].

Moreover, the shape and size of the grains had changed in the joint of all the samples, and the refinement region can be roughly divided into three regions from peak to trough: fine-grained zone, fibrous zone and torsional zone, as shown in figure 5(d). The fine-grained region was a mixture zone consisting of crushed cementite particles and ferrites grains. This region underwent the most intense deformation owing to its proximity to the bonding surface. There were broken pearlite and...
elongated ferrite with a length-width ratio of 10 to 1 in the fibrous region, where the adiabatic shear bands (ASB) were located. An interesting phenomenon to be noted that ASBs were noted on the wave side and the direction of the ASBs was 45° from the direction of the bonding interface. As shown below, the ‘fibrous zone’ was the ‘torsional region’, where the cementite in the pearlite did not break and existed in long strips. The grains in these areas were deformed to different degrees and changed compared with the original structure shape of the matrix, indicating that the metals at the joint in the explosive welding process suffered strong plastic pressure and the closer to the bonding surface, the greater the deformation degree was. It can be concluded that the small wave is possibly the better interface morphology with fewer defects and lower plastic deformation.

4.2. Element distribution

4.2.1. Line scanning

Line scanning was used to detect the distribution of elements at the wave crests of bonding interfaces of the four samples. The lines, about 25 μm, were marked and the results were entered in figure 6. These samples shared a common trend: the content of Cr and Ni decreases gradually from flyer plate (304 l) to base plate (Q235B). The diffusion of Cr and Ni elements made up two ‘slopes shapes’ on the bonding interface, indicating the element diffusion took place. The element diffusion may be resulting from the high temperature and grain refinement, which increasing the chances that atoms will gain sufficient energy to diffuse beyond the energy barrier. It could be seen that the thickness of the diffusion layer was diverse. Figures 6(a) and (d), with the width of diffusion layers about 1.5 μm and 1.6 μm respectively, adopted minimum $V_p$. Compared with sample 2 and 3, the layers were thinner. It could be explained that the lower the velocity, the lower the pressure and temperature were produced during the impact, thus reducing the diffusion coefficient. Chen et al got the same point by combining molecular dynamics simulation and classical diffusion theory [37]. Sample 3 with a 20 mm $S$ was adopted, which had the maximum width of the diffusion layer. Although its theoretical $V_p$ was not the highest, it showed that the gap had the greatest influence on the width of the diffusion layer. On one hand, the possibility of intermetallic compound will increased with the width of diffusion layer rising in dissimilar materials welding; On the other hand, the diffusion of the interface metal atoms enhanced the attraction between the base plates and flyer plates, which significantly improved the bonding strength of the cladding plates [38].
4.2.2. Analysis of EDS

Three regions were chosen to detect the element content in different regions of the bonding interface, as shown in figure 7(a). Figures 7(b), (c) and (d) showed the contents of element of these regions including flyer plate region 'A', interface bonding vortex region 'B' and base plate region 'C' near the bonding interface with EDS. It could be seen that the content of Cr and Ni at region 'A' was the largest, and the distribution of elements was close to that of 304 L. The element at region 'C' contained a small amount of Cr and Ni, its element content was closer to Q235B. The element of Cr and Ni in region 'B' was between those in region 'A' and 'C', indicating that 'B' may be the region of 'slopes shapes' in the line scan test. At the same time, there was a small migration of Si from Q235B to 304 L. The test results were in line with the line scan results and the previous studies [39].

4.3. Mechanical tests

4.3.1. Microhardness test

The microhardness of bonding interface was tested and the hardness profiles were presented in figure 8. The length of test was 1400 μm and the direction was perpendicular to the interface. It could be observed that the maximum microhardness was found at the interface joint and the value of hardness decrease from the middle to the sides. Explosive welding had a fine grain strengthening effect on the interface; thus, the grain structure near the interface was relatively fine, and its microhardness was the largest, which was in line with the analysis of section 4.1. The microhardness of the metal far from the interface was a little higher than that of the substrate. This was due to the plastic deformation of the entire base and flyer plates under the brilliant explosion load, which resulted in work hardening. It could be concluded that the large wave interface had higher microhardness than sample 1 and 4 with a slight wave from figure 8. The sample 2 had the highest microhardness at the interface, reaching 290 HV, which was 75% higher than the hardness value of the base plate and 45% of the flyer plate. And the lowest value appeared on the side of the flyer plate far from the interface, reaching 198 HV, which was also higher than the hardness value of the raw material. It could be concluded that the bonding strength of all the composites via explosive welding could meet the need of the industrial project.
4.3.2. Tensile shear strength test

Figure 9 showed the tensile specimens and shear specimens used in the experiment. The fracture of the four specimens occurred at the bonding interface and the results of mechanical test are presented in table 5. The tensile and shear strength of the composites was greater than 600 MPa and 430 MPa respectively. The tensile strength of the composite was higher than that of the metal matrix and the shear strength was between the flyer plate and base plate, which is agreement with previous research results [10, 13]. Sample 3, the highest collision velocity adopted, also had the highest tensile and shear strength among all samples. This was due to the larger contact areas and stronger work hardening effect, consistent with the above interface morphology analysis [40].
It was indicated that explosive welding was a kind of welding technology which can combine dissimilar metals in a high quality interface.

4.4. Fracture morphology analysis

As shown in figure 10, the tensile fracture morphology was investigated by a SEM. It could be seen that the morphology of fracture showed obvious stratification from figure 10(a). In order to observe the interface morphology of different layers more clearly, four regions were selected and observed under the SEM with 3000X, as shown in figures 10(b), (c), (d) and (e). Equiaxial dimples, with a diameter of 8 μm, were discovered in region b and marked in figure 10(b). Fang et al claimed [6] that good ductile fracture occurred in this region. The same type of fracture was found in region c and marked in figure 10(c), but the size of dimples in this area, about 4 μm, was significantly smaller than that in region b, which indicating that the material here has a weaker toughness. Figure 10(d) presented that the fracture type of region d was quasi-cleavage fracture with the...
existence of tearing edges. The material here exhibited a certain brittleness, which corresponded to the increased hardness of the bonding interface mentioned in the previous microhardness analysis. Shear dimples, marked in figure 10(c), exhibited a characteristic of slip along the bonding interface. Zhang et al [41] described this fracture morphology as a parabolic dimple. Due to the highest strength at the bonding interface, the final fracture occurred at the base plate in the tensile fracture experiment. As a result, the shear dimples were discovered in the region 4 under the action of a shear force. In general, fracture morphology analysis results showed that most areas of tensile fracture show dimple fracture, and a small part of the bonding zone showed quasi-cleavage fracture. The bonding strength of the interface was the highest, and the results were consistent with the previous microhardness tests.

5. Conclusions

A dynamic study of the effect of parameters on the characteristic of the bonding interface was carried out. A VST function was given and the three-dimensional diagram was plotted. Explosive welding of 304 L/Q235B under different parameters was carried out via DVEW and micro-structural features and mechanical property of the interface were investigated. The following conclusions can be drawn:

1. The wave interface was found in all the samples and the dimensions of the wave increased with thicker charge thickness or bigger stand-off gap. The small wave morphology was found in the bonding interface of sample 1 and 4 due to the almost same collision velocity, which indicating that the bonding quality was determined by charge thickness and stand-off gap together.

2. Small wave bonding is the better interface morphology with fewer defects such as melting layer and island region compared with large wave. At the same time, the grain refinement was found in crest, and the degree of plastic deformation increased with the distance to the bonding interface. The fine-grain region, fibrous region and torsional region were found and characterized. The line scan and EDS results showed that the element diffusion took place with a 'slope shape'; The width of 'slope shape' increased with the higher collision velocity.

3. The microhardness test showed that the hardness value decreased gradually from the bonding interface to both sides and the hardness values at the large wave bonding interface were the highest among all the samples. Tensile shear strength indicated that the mechanical property of 304 L/Q235B composites was bigger than raw materials and can satisfy the requirement of engineering.

4. Sample 1 and 4 had close collision velocity and bonding quality, but the sample 1 used more explosive in the experiment. Sample 4 was undoubtedly of higher economic benefits from the perspective of cost saving and environmental protection. The binary function of collision velocity was of great significance to improve the accuracy of interface and guide practical production.

5. The fracture morphology analysis showed that the quasi-cleavage fracture occurred at the interface and the plastic fracture occurred at the flyer plate and base plate. Owing to the work hardening effect at the interface, the brittleness increased in the bonding interface.

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