Original Article

Study on explosive welding of Ta2 titanium to Q235 steel using colloid water as a covering for explosives

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Abstract

This paper presents the first extensive research on secondary hazards and welding quality of a novel explosive welding technique, where colloidal water is used to cover the upper surfaces of the explosives. The use of the colloidal water is proposed for improvement of energy efficiency and reduction of pollution of noise and dust. Welding tests were carried out to consider the effects of covering thickness on impact velocity of flyer plate, microstructure of bonding interface, explosion noise and dust. The results show that the colloidal water significantly improves the ability of the explosive to drive the flyer plate, and reduce environmental pollution caused by explosion. The noise and dust decrease exponentially with increasing covering thickness, due to part of the shock energy and dust being absorbed by the colloidal water. Microstructure studies show that all the welds display wavy interfaces, and the wavelength and amplitude first increase and then decrease with increasing covering thickness. Vortices characterized by localized melting zone surrounded by strongly deformed bulk materials are formed for the welds performed with covering, and the EDS results indicate that the distribution of elements in the vortex region is gradually varied.

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1. Introduction

Explosive welding technique is one of the most promising solid-state welding methods for producing laminated composite materials, which are widely applied in both chemical and nuclear industries due to their good corrosion resistances and mechanical properties [1–3]. This technique produces a weld joint by a high-speed oblique collision on the order of several hundred meters per second, aided by detonation energy of an explosive [4,5]. During the oblique collision process, a high-speed jet is first formed between the metal plates, which can sweep away the oxide film that is detrimental to formation of metallurgical bond, and then thevirginially clean surface are bonded together under very high pressure [5]. Due to the fact that the time gap of this process is very short (~10–6 s), a
heat transfer cannot be observed between the metallic plates [6,7]. Thus, explosive welding is capable to directly join wide varieties of dissimilar metals which may not be joined by any other techniques, due to potential technical problems such as existence of brittle intermetallic compounds and metallurgical incompatibility between flyer and base materials [8]. Currently, more than 260 various similar and dissimilar metals and alloy combinations have been successfully cladded using explosive welding technique, and the application of the products is also rising [9,10].

Compared to other welding technologies, explosive welding shows advantages such as high bonding strength, small heat affected zone, and the ability to directly join metal plate with large area [1,11]. Thus, this technique has been playing an irreplaceable role in many industrial fields. However, shortcomings such as low energy utilization and severe environmental damage always exist, which hinder further development of the technique. In the traditional explosive welding technique, the upper surface of the explosive is exposed to air, so amounts of energy are released in the air in the form of shock wave. As a result, not only the energy utilization rate of explosives is low, but also the pollution of noise and dust is serious. Lysak and Kuzmin [6] have proven that energy efficiency factor in explosive welding did not exceed several percent of the total energy of the explosive charge. In order to improve the energy efficiency, Miao et al. [12] presented a double sided explosive cladding setup, which can produce two welded plates through one explosive, however, the high-speed uncontrollable motion of the upper welded plate made the direct application difficult. Yang et al. [13] proposed a self-restrained explosive welding technique, which can increase the energy efficiency of explosives and restrained the motion of welded plates. In addition, some researchers [14–17] employed underwater explosive welding technique to join easily damaged metals, in which the pollution of noise and dust was significantly reduced due to that a lot of energy was absorbed by water. However, this method shows limitations in the welding of large-sized plates. In fact, the noise produced by industrial explosive welding can still reach 80–90 dB at 5 km away from the initial position [12], which seriously affects the safety of civilian houses and the daily life of ordinary people around. Moreover, a great deal of dust and poisonous gas produced in explosion process can not only cause serious environmental pollution, but also directly harm to the health of worker. To our knowledge, however, there have been no studies concerning reducing the pollution of noise and dust caused by explosive welding.

In recent years, more and more attention has been paid to energy and environmental protection. Therefore, many explosive welding factories have been compulsively shut down in China due to the serious secondary hazards such as noise and dust. Thus, the goal of this work is to explore a new explosive welding method with promising industrial applications to improve the energy utilization ratio and reduce the secondary hazards. For this, colloid water was used as an upper covering of explosives. Titanium and steel were chosen as a model system due to the broad application prospects, and that they are hot materials which attract much attention of researchers [8,10,18–21]. Several experiments were carried out to investigate the effects of the covering thickness on the impact velocity, noise, and dust produced by this explosive welding technique. The microstructure evolution of the bonding interface has also been conducted by optical microscopy (OM) and scanning electron microscope (SEM).

2. Experiment

2.1. Experiment materials

Due to the poor mechanical properties of the conventional explosives used in explosive welding, they may collapse under the gravity of covering. Thus, honeycomb structure explosives were employed as the explosive materials in this work, as shown in Fig. 1. The honeycomb structure explosives were consisted of aluminium honeycomb filled with emulsion explosives in regular hexagon cells, which can effectively improve mechanical strength of the explosives and guarantee their uniformity. The emulsion explosives are composed of 75% emulsion matrix and 25% hollow glass microspheres, and the components of the emulsion matrix are presented in Table 1. The thickness of aluminium foil for making aluminium honeycomb is 60 μm and the side length of the regular hexagon cell is 6 mm. The height of aluminium honeycomb is equal to that of the emulsion explosives. The density and detonation velocity of the honeycomb structure explosives are about 0.85 g/cm³ and 2500 m/s respectively.

Colloidal water was employed as the covering materials for explosives, which was composed of 1% Super Absorbent Polymer (SAP) and 99% water, and the density of it was 0.97 g/cm³. SAP is a crosslinked acrylic acid/sodium acrylate copolymer, which can absorb water hundreds of times more than its own weight and has excellent water retention performance. As shown in Fig. 2, the colloidal water is granular and behaves as a solid, it is easy to precisely control the covering thickness, and there is no potential risk such as flying stone during the

![Fig. 1 - Honeycomb structure explosives.](image-url)
explosion process. In addition, the colloidal water is a green high-tech chemical product, because it is nontoxic, odorless, nonirritating to the skin, and can completely degrade into water under certain conditions.

The flyer plate and base plate were made from Ta2 titanium and Q235 steel. The dimensions of titanium and steel plates used in this work were 150 mm × 100 mm × 2 mm and 150 mm × 100 mm × 20 mm, respectively. The surfaces of the base and flyer plates were ground with emery papers up to No. 400, and then they were cleaned by absolute ethyl alcohol. Their chemical compositions are given in Tables 2 and 3.

### 2.2. Experiment methods

Fig. 3 shows the schematic diagram of explosive welding setup used in this work. The parallel set-up geometry located on a steel anvil was employed, and all experiments were carried out in a cylindrical explosion vessel with 2.5 m in diameter and 5 m in length. Unlike the ordinary explosive welding setup, colloidal water was used to cover the upper surfaces of the explosives. The thickness of the colloidal water is an important factor that affects the experimental results. Thus, five groups of tests were carried out with different covering thicknesses, and the initial parameters of the five tests are listed in Table 4.

In order to investigate the effects of the covering thickness on the secondary hazards of explosion, noise and dust tests were carried out. The explosion noise was measured by a decibel meter (AR814 with a resolution of 0.1 dB), which can record the maximum value of noise during the explosion process. Due to the fact that the value of the explosion noise is large and may be out of range of the decibel meter (30–130 dB), the meter was placed 10 m away from the initial position of explosion. To investigate the dust concentration, the explosion vessel was cleaned to meet the condition that the initial dust concentration in the explosion vessel was consistent before each explosion test, and then a dust meter (CCHZ-1000 with a sampling flow of 2 L/min) was used to record the dust concentration in three minutes after the explosion.

In order to reveal the interface morphology, specimens were cut parallel to the detonation direction, and the cross-section of the specimens were ground with emery papers up to No. 5000 and polished to 0.5 μm by diamond paste. Then the specimens were etched by etchant consisting of hydrofluoric acid and nitric acid. A scanning electron microscope (GeminiSEM 500) and an optical microscope (Leica DM4M) were employed for microstructure observation of the bonding interfaces. Energy-dispersive X-ray spectrometry (EDS) analysis was also done to characterize the distribution of the alloy elements across the bonding interface.

### 3. Results and discussion

#### 3.1. Impact velocity

For the explosive welding setup with a covering for explosive, as shown in Fig. 3, the impact velocity $v_{pg}$ is estimated from the Gurney Theory [22] adapted for asymmetric sandwich configurations.

$$v_{pg} = \sqrt{\frac{2E}{2\pi}} \left[ \frac{1 + A^3}{3(1 + A)} + \frac{N}{C} \frac{A^2}{C} + \frac{M}{C} \right]^{1/2}$$  

(1)

A is given by the following equation:

$$A = \frac{1 + 2\frac{M}{E}}{1 + 2\frac{E}{C}}$$

(2)

And $E$ is determined by the formula below [23].

$$E = \frac{1}{\gamma - 1} \left( \frac{\gamma}{\gamma + 1} \right)^\gamma v_{pg}^2$$

(3)
Table 4 – Selected parameters for explosive cladding.

<table>
<thead>
<tr>
<th>Test no.</th>
<th>Covering thickness (mm)</th>
<th>stand-off distance (mm)</th>
<th>explosive thickness (mm)</th>
<th>Load ratio (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>8</td>
<td>8</td>
<td>0.76</td>
</tr>
<tr>
<td>2</td>
<td>30</td>
<td>8</td>
<td>8</td>
<td>0.76</td>
</tr>
<tr>
<td>3</td>
<td>60</td>
<td>8</td>
<td>8</td>
<td>0.76</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
<td>8</td>
<td>8</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>150</td>
<td>8</td>
<td>8</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Table 5 – Calculated results of impact velocity for different covering thickness.

<table>
<thead>
<tr>
<th>Covering thickness (mm)</th>
<th>Impact velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>441</td>
</tr>
<tr>
<td>30</td>
<td>583</td>
</tr>
<tr>
<td>60</td>
<td>604</td>
</tr>
<tr>
<td>100</td>
<td>615</td>
</tr>
<tr>
<td>150</td>
<td>621</td>
</tr>
</tbody>
</table>

Fig. 4 – The effect of covering thickness on impact velocity of the flyer plate.

where E is the Gurney energy, N, C and M are the mass per unit of area of the covering, the explosive and the flyer plate, respectively. γ is the polytropic exponent of detonation products, the value for emulsion explosive is equal to 2.5.

Because the value of the impact velocity \( v_{pE} \) given by Eq. (1) corresponds to the terminal velocity, the following equation was proposed to describe the acceleration history for asymmetric sandwich configurations [24].

\[
    u_p = u_{pE} \left[ 1 - \left( \frac{t}{t + (1 + A)S} \right)^{\gamma - 1} \right]^{1/2}
\]

(4)

where \( t \) is the initial thickness of explosives, \( S \) is the stand-off distance between the flyer plate and base plate.

According to the aforementioned procedure, the impact velocity for different covering thicknesses can be calculated and the results are listed in Table 5 and plotted in Fig. 4. It can be seen from Fig. 4 that the impact velocity of flyer plate increases continuously until it reached a maximum with increasing covering thickness. Compared to the explosive with no covering, the impact velocity is increased by 32.2%, 37.0%, 39.5%, and 40.8% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively. This indicates that the covering can significantly improve the ability of the explosive to drive the flyer plate, and this improvement is more pronounced at low covering thickness. It is generally recognized that the movement of the flyer plate is driven by shock wave and detonation products. During the detonation process, the covering of the explosive can not only reduce the influence of the air rarefaction wave on the detonation, but also restrain the motion of the detonation products, so more detonation energy is used to accelerate the flyer plate. As a result, the energy utilization of the explosive improves. This improvement also means that the explosive consumption can be reduced by using a covering for explosive, when obtaining the same impact velocity with the traditional method.

3.2 Noise results

It is generally recognized that the explosion noise is caused by attenuation of shock wave into sound wave, and the energy of the sound wave is converted from explosive energy with a conversion coefficient in the range of \( 10^{-8} - 10^{-6} \) [25]. Table 6 and Fig. 5 show the noise test results of this work. According to Fig. 5, the noise decreases significantly with increasing covering thickness. Compared to the explosive with no covering, the explosion noise is reduced by 4.0%, 6.3%, 7.4%, and 8.2% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively. Due to the fact that the background noise is 75.0 dB in this work, the noise caused by explosive welding is 31.6 dB for the condition of no covering. Thus, this decrease, as listed in Table 6, is considerable. The energy of the noise is converted from part of the energy released by shock wave of detonation and kinetic energy of flyer plate. The kinetic energy is changed into sound energy mainly in the form of adiabatic compression of air and impact between the flyer and base plate. The conversion coefficients related to impact velocity, stand-off distance, materials and dimensions of the base plate and flyer plate, which is difficult to reduce from
the processing technology. The shock wave energy, however, can be significantly reduced by using a covering for explosive. When a covering is used in explosive welding, part of the shock energy is converted into kinetic energy of the covering, thus the energy coming into the air decreases so as to reduce the noise. It is also noted that the impact velocity increased continuously with increasing covering thickness, which may result in higher noise due to the increasing kinetic energy of flyer plate. Thus, explosion noise may be further reduced by using a covering in case of obtaining the same collision velocity with the traditional method.

3.3. Dust results

According to the components of the emulsion matrix (Table 1), it can be inferred that the main gas products of the explosion is N2, CO, CO2, H2, CH4, and NOx, in which CO, H2 and NOx are poisonous gas. Except for the gaseous products, particle products are also produced by explosion, including dust and unreacted explosive particles and droplets. The concentration of toxic and harmful products after explosion are positively related to the total mass of the explosive. In this work, the initial dust concentration in the explosion vessel is 0.3 mg/m³, while the dust concentration values after detonation of explosives with a mass of 100 g reach to 159.5 mg/m³ using the traditional explosive welding technology. For industrial explosive welding, it usually consumes several tons of explosive by one shot. Thus, it will produce large amounts of dust in industrial production, resulting in serious environmental damage.

Fig. 6 shows the relationship between dust concentration and colloidal water thickness, indicating that the dust decreases significantly with increasing covering thickness. Compared to the explosive with no covering, the explosion dust is reduced by 30.1%, 46.1%, 62.0%, and 70.9% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively. The reason for this decrease is that some colloidal water is vaporized in the explosion process and thrown into the air, which can absorb a lot of dust. Moreover, it should be noted that some of the explosives at the upper surface are thrown into the air without detonation when using the traditional explosive welding technology, due to the influence of the air rarefaction wave. These unreacted explosive particles act as dust. However, the covering of the explosive can reduce the unreacted explosives by reducing the influence of the air rarefaction wave on the detonation. Therefore, the working environment of explosive welding can be improved by using colloidal water. It can be also seen from Fig. 6 that the dust concentration decreases exponentially with the increasing covering thickness. The changed trend is similar to the results of noise tests, and the dust concentration may be further lowered by increasing the covering thickness.

3.4. Microscopic observations

Fig. 7 shows the optical microscope images of Ta2/Q235 bimetallic sheet. Fig. 7a reveals the Q235 steel microstructure, which is mainly composed of equiaxed pearlite with ferrite. Fig. 7b shows fully equiaxed a-Ti grains, which is the typical characteristic of titanium. Fig. 7c-g shows that all the welds display wavy interfaces, with small melted regions for some specimens. For explosive welding, two types of bond are generally observed at the bonding interface, namely straight and wavy bonding. The wavy bonding interface is usually preferred due to the better mechanical properties and more bonding area [26,27]. Thus, the microstructures given in Fig. 7 indicate that high quality wavy welds were achieved for the new welding technology. It was also reported that the bonding interface transformed from straight to wavy interface with increasing explosive loading [28]. Namely, the impact velocity \( v_p \) of flyer plates must be larger than the lower limit of impact velocity \( v_{\text{pmin}} \) to promote plastic deformation. For welding of dissimilar metallic materials, the lower limit of impact velocity can be calculated by the following formula [29].

\[
v_{\text{pmin}} = \frac{1}{C_1 \rho_1} + \frac{1}{C_2 \rho_2}
\]

(5)

where \( C_1 \) and \( C_2 \) are the sonic speed of the flyer plate and base plate, respectively, \( \rho_1 \) and \( \rho_2 \) are the density of the flyer...
plate and base plate. $p_{\text{min}}$ is minimum collision pressure determined by the formula below [5].

$$p_{\text{min}} = \frac{1}{2}c^2(\rho \sigma)^{1/2} \tag{6}$$

where $c$, $\rho$, and $\sigma$ are the sonic speed, density and tensile strength. The minimum collision pressure $p_{\text{min}1}$ of the flyer plate and $p_{\text{min}2}$ of the base plate can be calculated respectively through Eq. (6), and the $p_{\text{min}}$ is the bigger value of $p_{\text{min}1}$ and $p_{\text{min}2}$.

However, the lower limit of impact velocity is not enough to meet the condition that wavelike welding interfaces occur. The lower limit of collision point velocity is also required to predict the laminar–turbulent flow transition of the metal materials to be welded. Wavy interfaces can be obtained when the collision point velocity is larger than the lower limit. Cowan et al. [30] defined lower limit of collision point velocity with hydrodynamic analogy.

$$v_{\text{c, min}} = \left[\frac{2Re(H_1 + H_2)}{\rho_1 + \rho_2}\right]^{1/2} \tag{7}$$

where $Re$ is a critical Reynolds Number taking values of 10.6 [31], $H_1$ and $H_2$ are the Vickers hardness numbers of the flyer and base plates, respectively.

The material parameters used for calculating the lower limit for wavelike welding are listed in Table 7, and the calculated results are: $v_{\text{c, min}} = 356$ m/s, and $v_{\text{c, min}} = 2153$ m/s. As shown in Table 5, the all values of impact velocity in this work are larger than the lower limit of impact velocity $v_{\text{c, min}}$. Due to the fact that the parallel set-up geometry was employed, the collision point velocity $v_c$ is equal to the detonation velocity $v_d$, namely $v_c = 2500$ m/s, so the values of collision point velocity are also larger than the lower limit. Thus, wavelike welding interface are obtained in this work.

The formation of the wave can be related to oscillatory nature of the propagation of the detonation wave, which triggered the instabilities of the flyer plate [32]. Fig. 8 shows the wave length and wave amplitude in welds performed with different covering thicknesses, which indicates that the wave length and wave amplitude first increase and then decrease with increasing covering thickness. The first increase in wavelength and amplitude with the covering thickness can be related to the increase of impact velocity. Higher impact velocity is expected to result in conditions at the collision interface being closer to the hydrodynamic state, and thus more suitable for the “actuation” of the instabilities, and the formation of bigger waves [11]. Similar results have been reported by many researchers [4,11,28,33]. However, the wavelength and

**Fig. 7** — Optical microscope images of Ta2/Q235 bimetallic sheet. (a) Q235 at away from the interface, (b) Ta2 at away from the interface, (c–g) bonding interface from the Ta2/Q235 interface for different covering thickness: (a) $T = 0$ mm, (b) $T = 30$ mm, (c) $T = 60$ mm, (d) $T = 100$ mm, (e) $T = 150$ mm, (h) high-resolution image of position h in panel e, (i) high-resolution image of position i in panel g.

**Table 7** — Selected material parameters used for calculating the lower limit for wavelike welding.

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ [kg m$^{-3}$]</th>
<th>$H_1$ [Mpa]</th>
<th>$c$ [m s$^{-1}$]</th>
<th>$\sigma_2$ [Mpa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q235</td>
<td>7850</td>
<td>1300</td>
<td>6000</td>
<td>405</td>
</tr>
<tr>
<td>Ta2</td>
<td>4500</td>
<td>1400</td>
<td>4900</td>
<td>441</td>
</tr>
</tbody>
</table>
amplitude begin to decrease as the covering thickness further increases. The reason for this is that the impact velocity remains roughly unchanged as the covering thickness further increases, as shown in Fig. 4. In addition, the increase in the thickness of covering may increase the duration of pressure at the bonding interface, because more explosive energy is concentrated on the flyer plate, and the impact velocity is not accelerated to the maximum during the collision process. This causes severe deformation of the waves and leads to the separation and drifting of wave crests, as shown in Fig. 7i. Thus, the waviness in this case become irregularity, and wavelength and amplitude become small. In addition, it can be found from Fig. 7h that drastic grain refinement occurs at the interface and grains are elongated in the direction of the explosion. This can be attributed to the tangential component of impact velocity and the shearing stresses produced between the impacting metals, which induce excessive plastic deformation at the interface during explosion [34,35].

It is also noted from Fig. 7c–g that vortices are formed for the welds performed with covering, while they are not found in the weld performed with no covering. The reason for this is that impact velocity of the flyer plate performed with covering is higher, which triggers stronger plastic flow. Localized melting zones can be found in the vortices, which can be attributed to adiabatic heating of trapped jet inside vortices at the front slope of waves as a result of density difference or the adiabatic heating of gases compressed between the plates [4]. However, the melting zones were surrounded by relatively cold metal and subjected to a very high cooling rate that was estimated to be of the order of 10^5–10^7 K/s [4,36]. Thus, these melted zones suffer from the problems normally associated with castings, such as the formation of cooling cavities and the formation of intermetallics, as shown in Fig. 7d–h, which can deteriorate the properties of the bonding interface [37]. In order to further study the property of the localized melting zones, EDS was carried out to characterize the distribution of the alloy elements across the bonding interface. Fig. 5a, b and c show the EDS mapping near a vortex, where the alternating colour contrast being an evidence for strong chemical composition changes inside the zone. This result is in agreement with the previous study [20] about element diffusion on the Ti/Fe interface after explosive welding. According to Ti/Fe phase diagram [38], it is easy to form intermetallic compounds such as TiFe and Ti₂Fe at high temperature. During the welding process, the high temperature conditions were meet by adiabatic compression at the bonding interface [31], so multiple intermetallic compounds might be formed in the localized melting zones [4,18]. Fig. 9d shows the results of element spot scans near the bonding interface. It is found that the distribution of elements in the vortex region is gradually varied. Element Fe decreases gradually from inside to outside of the vortex, in turn, element Ti increases gradually. The formation of vortices containing both Ti and Fe is related to circular movement and intense stirring of the vortexes, which eventually lead to strong intermixing of participant metals. Meanwhile, the melted zone also is affected.
by atomic diffusion, which results in the changing element distribution.

4. Conclusions

In this work, colloid water was used as a covering for explosives for improving energy efficiency and reducing secondary hazards of explosive welding. Several tests were carried out to consider the effects of covering thickness on impact velocity of flyer plate, microstructure evolution of bonding interface, explosion noise, and dust. The following conclusions can be drawn from this study:

(1) The covering can significantly improve the ability of the explosive to drive the flyer plate. Compared to the explosive with no covering, the impact velocity is increased by 32.2%, 37.0%, 39.5%, and 40.8% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively.

(2) The noise decreases significantly with increasing covering thickness, because part of the shock energy is absorbed by the colloidal water. Compared to the explosives with no covering, the explosion noise is reduced by 4.0%, 6.3%, 7.4%, and 8.2% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively.

(3) The working environment of explosive welding is improved by using colloidal water as a covering. Compared to explosive with no covering, the explosion dust is reduced by 30.1%, 46.1%, 62.0%, and 70.9% when the covering thickness is 30 mm, 60 mm, 100 mm, and 150 mm, respectively.

(4) All the welds display wavy interfaces, and the wavelength and wave amplitude first increase and then decrease with increasing covering thickness.

(5) Vortices with localized melting zone are formed for the welds performed with covering, and the EDS results indicated that the distribution of elements in the vortex region is gradually varied.

Conflicts of interest

The authors declare no conflicts of interest.

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