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Experimental and numerical approach to titanium-aluminum explosive welding

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Abstract

The welding parameters of TA2/1060/5083 were calculated accurately through a combination of explosive welding weldability window and numerical simulation, based on which explosion welding experiments were conducted using these parameters obtained. Then, a test was carried out on the mechanical properties of the composite plates obtained from the experiments and microstructure characterization was performed. As suggested by the results, TA2/1060 was a excellent straight bond, and the interface of 1060/5083 was a sine-wave featuring both vortex structure and splashing molten block structure, with an average wavelength of 700 μm and a wave height of 100 μm. The tensile strength and shear strength of the composite materials reached 354 MPa and 110 MPa, respectively, while the material showed the signs of ductile fracture. Moreover, work hardening and fine grain strengthening occurred at the interface, as did the element diffusion of Ti-Al, with a maximum diffusion depth of 32 μm.

1. Introduction

Explosive welding technology relies on the energy generated by explosive explosion to achieve the high-speed oblique collision between base plate and flyer plate, thus leading to tight metallurgical bonding [1, 2]. The explosive welding technology makes full use of the property advantages of different materials and realizes the high strength combination of different metals. As a special processing technology for layered (tubular) composite materials, explosive welding technology has been widely used in aircraft design, lightweight equipment, high-speed vehicle operation and other fields, and has high research value and application significance [3–5].

Both titanium and aluminum are classified as high-quality lightweight metal materials. Industrial pure titanium is advantaged by high specific strength and strong corrosion resistance. For example, 5 series Al-Mg alloy 5083 as a variety of aluminum alloy demonstrates high strength and excellent machinability. The explosive welding technology of TA2/5083 is essential for the study on how to improve the mechanical properties and corrosion resistance of Ti-Al explosive composite plate while maintaining such advantages as lightweight and corrosion resistance. However, it is practically difficult to carry out TA2/5083 explosive welding [6, 7]. The magnesium contained in the alloy can evaporate and burn when the temperature reaches 1000 °C as a result of collision, which leads to the development of micro-defects inside the composite plate [8]. In addition, the thermal conductivity and linear expansion coefficient of 5083 and TA2 can vary significantly. As indicated by Honarpisheh M et al [9], when the above-mentioned properties of the two composites show clear differences, there would be a high residual stress generated due to heating and cooling of the composites, which will affect the usability of the materials in practice. As argued by Saravanan S et al, an increase in the strength of aluminum alloy makes it more difficult to perform welding [10]. In addition, both titanium and aluminum are strongly passive and easily oxidized materials, which makes it easy to produce TiAl2, TiAl3, Ti3Al, TiAl, Ti2Al5 and other brittle intermetallic compounds at high temperatures, thus resulting in the micro-defects inside the materials [6, 7, 11, 12].
In order to determine the most appropriate parameters of explosive welding for dissimilar metals, the theory of explosive weldability window was proposed. When the flyer plate strikes the base plate at high speed, there are three core dynamic parameters involved, including impact velocity \( V_p \), collision angle \( \beta \) and impact point movement velocity \( V_c \), all of which are correlated with each other in the process of parallel explosive welding. Therefore, if two of the three parameters are determined, it means that all these three dynamic parameters of explosive welding can be obtained.

\[
V_p = 2V_c \sin (\beta/2)
\]  

Figure 1 shows the existing weldability of explosive welding, and the weldability window of explosive welding can be determined according to the moving velocity and collision angle of explosive welding impact point [13, 14]. Curve 1 indicates the lower limit of explosion welding as established according to the material hardness curve [15]. In curve 2, the maximum welding energy, excessive melting and solidification time and interface reflection wave are considered, so the upper limit of explosive welding condition is established [16]. In curves 3 and 4, an analysis is conducted of the jet-forming conditions and the interface jet conditions of upper and lower limits are indicated [17]. Curves 5 and 6 show the movement velocity at the impact point where wavy combination occurs. Curve 7 indicates the maximum movement velocity at the material impact point, which is generally 1.2 \( \sim \) 1.5 times the velocity of its volume sound [18]. The closed area constructed according to the above curve can be used to determine the weldability window of explosive metal welding, where the blue closed area (area 1) represents the direct bonding area and the red closed area refers to the wavy bonding area. It is widely believed that wavy bonding is the ideal bonding effect of explosive welding, despite the argument made by some scholars that the dissimilar metals obtained through direct bonding have higher bonding strength [19].

Although explosive weldability window is capable to solve most of the problems arising from explosive welding of dissimilar metals, it remains difficult to determine the parameters of explosive welding for some dissimilar metals with high strength, high hardness, easy oxidation, or significant variation in physical and chemical properties. As mentioned above, the weldability window of TA2 and 5083 is extremely narrow, so that the reliability of parameters cannot be ensured by the window theory alone.

In order to obtain the titanium-aluminium explosive clad plates free of micro-defects and macro-damage, interlayer technology was also adopted in this paper. In recent years, interlayer technology has been recognized as an effective solution to improving the quality of welding. Xiang, C et al [20] adopted sandwich technology to improve the welding strength between aluminium alloy and high-strength stainless steel effectively, based on which it was suggested that the use of interlayer can enhance the uniform distribution of welding energy. Zhang, Y et al [21] pioneered in making use of TA2/1060 clad plate as the interlayer between TC4 and 304 stainless steel through explosive welding, which proved effective in reducing the generation of Ti-Fe brittle intermetallic compound. Despite the ease to weld the interlayer onto the base plate and flyer plate, it still requires the redistribution of welding energy. For this reason, pure aluminium 1060 was taken as the interlayer in this paper. The parameters of TA2/1060/5083 welding were calculated in line with the explosive weldability window theory. Combined with the numerical simulation, the SPH-FEM coupling algorithm was applied to closely observe the interface morphology. Finally, an explosive welding experiment was carried out using the optimized parameters. The macroscopic mechanical properties of the composite plates as determined during the
experiments were tested and characterized to demonstrate the accuracy of numerical simulation. Besides, the accuracy of parameters was demonstrated using the material bonding strength.

2. Numerical simulation of explosive welding

2.1. Physical model

Since explosive welding experiment is instantaneous and risky, numerical simulation, as an auxiliary means used to study explosive welding problems, has attracted increasing attention from researchers. For example, Wang et al [22] performed numerical simulation of the mG-Al explosive composite, which suggested the existence of local high temperature and severe plastic deformation in the welding process. Mahmood et al [23] conducted numerical simulation of Ti6Al4V-SS304 explosive welding with an added interlayer and demonstrated that the use of the interlayer can be effective in improving the bonding strength. Besides, HLA [24] carried out the underwater numerical simulation of explosive welding using the smooth fluid particle dynamics algorithm. The essence of parallel explosive welding is to make the composite plate tilt at high speed and hit the bottom plate. Therefore, this paper establishes the physical model shown in figure 2(b) to simulate the explosive welding of TA2/1060/5083. As shown in figure 2(a), the inclined angle of flyer plate indicates the bending angle of cladded plate under the action of explosives in the experiment process, while the velocity of flyer plate indicates the impact velocity of flyer plate driven by explosive products in the experimental process. The collision angle and impact velocity can be obtained using equations 2–4 [25]:

\[
V_f = \left( \frac{6ER}{5 + R + 4/R} \right)^{1/2}
\]  
(2)

\[
E = \frac{1}{\gamma^2 - 1} \left( \frac{\gamma}{\gamma + 1} \right)^{\gamma} V_d^2
\]  
(3)

\[
R = \frac{\rho_e \delta_e}{\rho_f \delta_f}
\]  
(4)

where \( E \) represents the Gurney coefficient of the explosive, \( \rho_e \) indicates the density of the explosive, \( \delta_e \) denotes the thickness of the explosive, \( \rho_f \) stands for the density of the cladded plate, \( \delta_f \) means the thickness of the flyer plate, \( \gamma \) refers to the effective multiparty index of the explosive, and \( V_d \) represents the detonation velocity of the explosive. Explosive welding requires high explosive velocity, and there is an error between the existing explosive model and explosive welding. The kinetic energy of the flyer plate was calculated theoretically using the high speed inclined impact model. The dynamite was used indirectly in the numerical calculation system, which led to the results of numerical calculation suggesting high repeatability. In prior studies, it has been found out that SPH algorithm performs better in the accuracy of calculation for significant deformation, damage and shedding, etc., which makes it more suitable for the numerical simulation of explosive welding interface waveform [26, 27]. However, compared with Lagrange algorithm, SPH algorithm is disadvantaged by such drawbacks as long operation cycle and substantial memory consumption. Therefore, the SPH-FEM coupling algorithm was
used in this study. SPH algorithm was used only at the material collision interface, and Lagrange algorithm remained used for flyer plate and base plate, thus improving the speed of calculation without any compromise on its accuracy.

2.2. Explosive welding parameters

Given the advantages in performance, the thickness of flyer plate, interlayer and base plate was set to 1.5 mm, 1 mm and 8 mm in the experiment, respectively. As proposed by Ezra [28] through a large number of experiments, when the thickness of flyer plate ranges between 0 and 5 mm, the clearance should be 1/3 to 2/3 the density of flyer plate. To be exact, the clearance between base plate and flyer plate should vary between 1.5 mm and 3 mm for this study.

According to the explosive weldability window, the detonation velocity of the explosive is supposed to be lower than that of the material to be welded, and the volume sound velocity of the metal can be calculated using equation 5 [29].

\[ V_S = \left( \frac{G}{\rho} \right)^{1/2} \]  

where \( G \) represents the elastic modulus of the material. With the relevant parameters of TA2, 1060 and 5083 inputted into the formula, it can be obtained that the sound velocity of TA2 volume is 4825 m s\(^{-1}\) and the sound velocity of 1060 volume is 5089 m s\(^{-1}\). Since subbase 5083 has the smallest volume sound velocity, the explosive detonation velocity is supposed to be less than 2981 m s\(^{-1}\).

Wylie [18] put forward the theory of heat conduction based on the energy analysis of explosive welding and then determined the calculation formula of the upper limit value of explosive welding collision velocity as follows.

\[ V_{P_{\text{max}}} = \frac{10(t_{\text{mp}} V_f)\gamma^{1/2}}{V_c} \left( \frac{\kappa c V_{ef}}{\rho_e \rho_f} \right)^{1/4} \]  

where, \( V_{P_{\text{max}}} \) represents the upper limit of the impact velocity of the base flyer plate, \( t_{\text{mp}} \) indicates the smaller value of the melting point of the base flyer plate, while \( \kappa \) and \( c \) denote the thermal conductivity and specific heat capacity of the welding metal with a lower melting point, respectively. As the 1060 melting point of pure aluminum in TA2/1060/5083 explosion welding was the lowest, the melting point of 1060 was substituted into the temperature of 660 °C, the thermal conductivity of 217 J/(m·K) and the specific heat capacity of 921 J/(kg·K) to determine the maximum impact velocity as 887 m s\(^{-1}\).

Different from mechanical occlusal, the dissimilar metals at the explosive welding interface are tightly bonded by interatomic gravity. Compared with the flat interface, the wavy interface without continuous melting zone or continuous non-bonding zone has a larger contact area, which results in higher bonding strength. According to literature [30], when the collision angle ranges between 5° and 25°, metal jet can be generated due to interface collision, and the metal jet scours the material surface to form a smooth welding joint, which is conducive to interface welding and wavy morphology.

The parameter ranges as calculated according to the weldability window theory are shown in Table 1.

| Gap (mm) | Collision speed \( V_c \) (m s\(^{-1}\)) | Explosive detonation velocity \( V_d \) (m s\(^{-1}\)) | Collision Angle \( \beta \) (°) |
|---------|---------------------------------|---------------------------------|--------------------------|
| 1.5 ~ 3 | ≤887                            | ≤2981                           | 5 ~ 25                   |

9.

2.3. Material model

In the study on explosive welding of materials with high strength and hardness, it is common to observe the phenomenon of adiabatic shear line that occurs only when the strain rate exceeds 10\(^6\)/s [31, 32], which indicates that an extremely high strain rate plastic deformation occurs at the interface in the process of explosive welding. At present, there are two constitutive models suitable for the severe deformation occurring at high strain rates. The Johnson–Cook constitutive model is ideal for numerical simulation of strain rates below 10\(^3\) s\(^{-1}\), while the Steinberg-Guinan constitutive model is suitable for numerical simulation of strain rates above 10\(^5\) s\(^{-1}\). Shock state equation and Steinberg-Guinan (S–G) strength equation were used to calculate the material state, which is
purposed to accurately calculate the stress and strain, the patterns of change in the temperature and internal energy of materials at high temperature, high pressure and high strain rate during explosive welding. The Shock state equation is shown below:

\[
U = C_0 + S U'_P \\
P = P_H + \Gamma \rho (e - e_H) \\
P_H = \frac{P_0 C_0 \mu (1 + \mu)}{[1 - (S - 1)\mu]^2} \\
e_H = \frac{P_H}{2P_0} \left( \frac{\mu^2}{1 + \mu} \right)
\]

where \( \rho \) represents density, \( S \) indicates Hugoniot slope, \( P \) denotes pressure, \( U'_P \) is referred to as particle velocity, \( U \) stands for impact velocity, material velocity \( C_0 \), Gruneisen parameter \( \Gamma \), \( \mu = (\rho/\rho_0) - 1 \), and \( e \) denotes energy.

The Steinberg Guinan strength model was used to solve the temperature effect and pressure effect-related parameters of cubic crystal structure materials such as metals:

\[
G = G_0 \left( 1 + \frac{G_T'}{G_0} \right) \left( \frac{P}{\eta^{1/3}} + \frac{G_T'}{G_0} \right) (T - 300)^n \\
Y = Y_0 \left( 1 + \frac{Y_T'}{Y_0} \right) \left( \frac{P}{\eta^{1/3}} + \frac{G_T'}{G_0} \right) (T - 300)^n (1 + \beta \varepsilon)^n
\]

where \( G \) represents the shear modulus, \( \varepsilon \) indicates the effective plastic strain, \( Y \) denotes the yield stress, and \( T \) stands for the temperature. Representing the relative volume, \( \eta, Y_0, G_0, G_T, G_T' \) and \( P \) are all constant. The parameters of numerical simulation on the material used are shown in Table 2.

### 3. Experiment

#### 3.1. Experiment materials

According to the requirements on the weldability window of explosive welding, powder emulsion explosive was used in the test, in which 30% quartz sand was mixed to reduce the speed of detonation, with a small amount of sawdust contained. In a large number of tests, it was demonstrated that to introduce a small amount of sawdust was conducive to eliminating the edge effect commonly found in the course of explosive recombination. The detonation velocity of the prepared explosive was set to 2200 m s$$^{-1}$$, the density was set to about 0.8 g cm$$^{-3}$$, and the effective multi-party index was set to 1.8. The powder emulsion explosive with low detonation velocity is advantageous in controlling the total energy input into the system. The thickness of the explosive was calculated as 15 mm according to equations 1–3. In addition, the thickness of TA2 flyer plate was set to 1.5 mm, the thickness of 1060 interlayer was set to 1 mm, and the thickness of base plate was set to 8 mm. The specification was 1000 mm $$\times$$ 1000 mm. The material composition and mechanical properties used in the experiment are detailed in Tables 3 and 4, respectively.

#### 3.2. Explosive welding experiment

Figure 3 shows the site layout of explosive welding experiment. Soft sandy ground was taken as the foundation to prevent the welded composite plate from fracture when it moved on a continued basis. Base plate, flyer plate and interlayer were all mechanically polished on the surface, and then wiped with ethanol or acetone to expose the fresh joints. The V-shaped metal sheet formed by the bending of thin copper sheet was used to control the gap. The detonation and metal jet generated by explosive detonation were taken advantage of to blow away the vast majority of copper plates, with a small number of copper plates remaining at the interface and showing compatibility with the material. As a result, the bonding strength of the material was unaffected. The detonator was placed in the geometric center of the explosive, and a small amount of pure charge was arranged around it to facilitate detonation.

### Table 2. Material numerical simulation parameters.

| Material | \( \rho \) (g cm$$^{-3}$$) | GC | CI (km s$$^{-1}$$) | \( S_1 \) | Specific Heat (J/Kg K) | \( \beta \) | \( n \) | \( G_x \) | \( G_y \) | \( Y_x \) |
|----------|-----------------|----|----------------|--------|-------------------|---------|------|--------|--------|--------|
| TA2      | 4.50            | 1.23| 5.02           | 1.54   | 500               | 210     | 0.10 | 0.50   | 2.70   | 0.010  |
| 5083     | 2.80            | 2.00| 5.33           | 1.34   | 875               | 680     | 0.10 | 1.80   | 1.70   | 0.019  |
| 1060     | 2.70            | 1.97| 5.38           | 1.34   | 884               | 400     | 0.27 | 1.77   | 1.67   | 0.003  |

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Table 3. Chemical composition of experiment materials.

| Material | Chemical composition (wt%) |
|----------|---------------------------|
| 5083     | Fe 0.4 Ti 0.03 Residual 0.4 Al 0.4 ~ 1.0 Si 0.25 Mn 0.4 ~ 4.9 Zn 0.05 Mg 0.1 Gr Cu |
| 1060     | Fe 0.35 Ti 0.03 Al 0.25 Si Mn 0.03 Zn 0.03 Mg Cu |
| TA2      | Fe 0.3 C N Residual 0.1 O H Ti |

Table 4. Mechanical properties of materials.

| Materials | Tensile strength (MPa) | Yield strength (MPa) | Elongation (%) | Hardness (HV) | Elastic modulus (GPa) |
|-----------|------------------------|----------------------|----------------|---------------|-----------------------|
| TA2       | 410                    | 375                  | 25             | 140           | 105                   |
| 1060      | 135                    | 78                   | 23             | 25            | 70                    |
| 5082      | 270                    | 110                  | 20             | 67            | 70                    |

Figure 3. Explosive welding experiment: (a) the polished base plate, (b) the gap setting, (c) the powder emulsion explosive placed, and (d) the composite plate obtained after the explosion.

Table 5. Experiment conditions.

| The thickness of the flyer plate (mm) | The thickness of the base plate (mm) | The thickness of the explosive (mm) | Detonation location | Gap size (mm) |
|--------------------------------------|--------------------------------------|-------------------------------------|---------------------|---------------|
| 1.5                                  | 8                                    | 15                                  | Geometric center    | 2             |

All set conditions of the experiment are shown in Table 5.

3.3. Testing of mechanical properties and microscopic characterization

The tensile and shear mechanical properties of the composite plate were tested using the samples collected from the vicinity of the initial point, 2500 mm away from the initial point, and the edge of the composite. The tensile strength test and shear strength test were carried out according to the national standards GB/T228.1–2010 and GB/T6396–2008, respectively. The size of the prepared sample is shown in figure 4. When the mechanical properties of the material were tested, the bonding strength of the material was also verified. SEM scanning e-sports was used to observe the micro morphology of the interface morphology, so as to judge the form taken by the interface bonding of the composite plate, to observe the experimental fracture after tensile fracture, and to analyze the initial position of fracture and fracture properties. In order to determine the microstructure of the interface accurately, metallographic observation was made on the boundary. The corrosion of the metallographic samples was observed using etchant at the ratio of 5%HNO₃ + 10%HF + 85%H₂O. The
appropriate sample was used for microhardness test, so as to determine the hardness of materials at the interface and establish whether the materials at the interface were damaged. Finally, the EDS line scanning was performed to analyze the composition of interface elements, the diffusion of interface elements, and whether intermetallic compounds were generated.

4. Results and discussion

4.1. Calculation results of interface topography

Figure 5 shows the results of numerical simulation. (a), (b) and (c) indicate the interface topography of the initial position at which collision occurred, the middle section of the composite plate, and the position distant from the initiation point, respectively. It can be seen from the figure that TA2/1060/5083 explosive welding had three typical interface morphology of explosive welding. At the beginning of collision, the base cladded plate collision barely produced any jet flow. At this time, the interface of TA2/1069, 1060/5083 was flat. As the collision continued, the metal jet was increasingly generated at the interface. In the meantime, the jet reciprocating between base plate and flyer plate penetrated base plate and the surface material of flyer plate, thus generating the wavelet-like bonding morphology. In this stage, the wavelength and wave height increased progressively. When the waveform grew to a certain size, the wavelength and wave height value became relatively stable. At this time, periodic sinusoidal waveforms can be observed at the interface of 1060 and 5083, with an average wavelength of 700 and an average wave height of 100 μm. Figure 5(d) clearly shows the waveform of interfaces 1060 and 5083.
In the 1060 interlayer, there was the splashing molten block morphology dominated by base plate material; while in the 5083 base plate, there was the whirlpool structure formed by the interlayer material. At all positions of the composite plate, the flyer plate and the base plate maintained a straight bonding morphology, which is in sharp contrast with the waveform morphology formed in 1060/5083. When dissimilar metals with more distinctive physical and chemical properties were welded in explosive welding, the two types of metal showed variation in thermal expansion coefficient and yield strength due to the difference in their properties. Therefore, given the interaction of temperature and pressure with exactly the same numerical value, they tend to show different signs of deformation, which is adverse to the growth of waveform. In another study [33], it was indicated that, there is a certain difference in the interface energy obtained by the two interfaces in the process of explosive welding via interlayer, which is another contributor to the significant difference in the appearance of the two interfaces.

According to the (a1), (b1), and (c1) temperature cloud diagram, it can be seen that, there is a high temperature region at the interface in the welding process, and that the depth of high-temperature diffusion along the thickness direction of the substrate and cladding plate is limited. In general, the interface welding temperature varies between 1000 °C and 1500 °C, which is higher than the melting point of aluminum (600 °C) but slightly lower than the melting point of TA2 (1642 °C). This temperature increases the diffusion energy of interface atoms while promoting the diffusion of interface elements, which is conducive to interface bonding. However, the temperature at the splashing molten block and vortex is significantly higher than at other positions (the area marked by a black circle in the figure 5). This is because the structure of these two locations is comprised mainly of high-temperature jet stacking at the interface. In figures 5(a1)∼(c1), the ultra-high temperatures ranging between 3500 °C and 5000 °C were observed. Such high temperature contributed to the formation of brittle intermetallic compound and ingot structure at this site, while the Ti-Al brittle intermetallic compound and ingot structure were present in the form of microscopic defects, which has an immediate impact on the strength of the material.

4.2. Experiment results and analysis

Interface morphology is the most intuitive indicator of bonding quality. Figure 6 shows the SEM and OM test results obtained for the interface of Ti-Al composite plate. According to the observation made under scanning electron microscope, there were no obvious defects found at the interface of the composite plates, while the interface of 1060 and 5083 showed an ideal morphology of wavy bonding. The interface of TA2 and 1060 was flat.
and straight. According to further observation of the samples after corrosion, in addition to the consistent interface results obtained through scanning electron microscopy, there were obvious swirls and splashing molten block structures developed at the interface of 1060 and 5058, which is attributed to the mutual erosion of the surface materials by the jet generated as a result of collision. A further observation of the vortex structure revealed that ingot structure was prevailing in the vortex, which resulted from the capture of the molten metal at high temperature and high pressure by the vortex. A small amount of ingot construction hindered the formation of a continuous melting zone, which is deemed acceptable. The experimental results are highly consistent with the results of numerical simulation, thus evidencing the effectiveness of the numerical simulation algorithm.

The TA2/1060/5083 composite plate free of surface crack and damage was successfully prepared by means of explosive welding experiment. The tensile and shear mechanical properties of the composite materials were tested respectively. Figure 7 shows the tensile strength curve of the material. The average shear strength of the composite plate was 110 MPa. As a mechanical property indicative of the bond strength of the laminated composite material, the shear strength was obtained through test to suggest that TA2/1060/5083 composite plate had a superior bond quality. The tensile strength curve of the composite plate is shown in Figure 7. The tensile strength of the completely unbonded laminated composite plate was calculated using equation 13:

$$
\sigma_{TA2/1060/5083} = \frac{\sigma_{TA2} \delta_{TA2} + \sigma_{1060} \delta_{1060} + \sigma_{5083} \delta_{5083}}{\delta_{TA2} + \delta_{1060} + \delta_{5083}}
$$

The calculation result was obtained as 330.48 MPa by substituting the tensile strength of flyer plate TA2 of 410 MPa, interlayer tensile strength of 135 MPa, base plate tensile strength of 340 MPa and the thickness of each part into the above equation. The measured tensile strength of the composite plate was 354 MPa (figure 8). To sum up, the experimental results are higher than the minimum value of theoretical calculation.

The actual tensile strength was higher than the theoretical value due to the widespread dislocation occurring during the plastic deformation of explosive welding interface. As a result, the lateral deformation resistance of the material increased. While maintaining lightweight, TA2/1060/5083 explosive composite plate demonstrated advantageous mechanical properties over pure aluminum, which endows it with a massive potential of practical application. To explore the fracture mechanism of composite panels, SEM observation was made of sample fracture through scanning electron microscopy (SEM). The sound was heard twice at the time of tensile fracture. Figures 9(a) and (b) show 1060/5083 interface and TA2/1060 interface, respectively. Due to the different elastic moduli, the dissimilar metals showed variation in the tendency of deformation under almost the same tensile stress, with evident stratification observed at the interface of TA2/1060 and 1060/5083. Figure 9(c) shows the orthogonal dimple morphology, indicating that micropores developed as a result of plastic deformation when the material was subjected to tensile force. At this time, ductile fracture occurred to the composite plate.

Microhardness indicates the capability of the material to withstand plastic deformation caused by external force. For laminated metal composite materials, it is easy for the interface to crack during the hardness test due to the insufficient strength of interface bonding, and the results of hardness test are lower than at other positions. Figure 10 and figures 11 show the results of hardness test for the initiation end and the edge of the composite plate.
Figure 8. Tensile test results.

Figure 9. SEM images of fracture: (a) the TA2/1060 interface, (b) the 1060/5083 interface, and (c) the local amplification effect.

Figure 10. Microhardness test at detonation point.
plate, respectively. The maximum hardness of the two samples measured was 218 HV and 223 HV, respectively, which are significantly higher than that of matrix TA2 (200 HV). In addition, the closer to the TA2/1060 interface or the 1060/5083 interface, the greater the hardness of the material. The hardness test position of No.5 sample in figures 11 falls on the side of pure aluminum. Although the hardness test result is not taken as the maximum hardness, its value is much higher than that of pure aluminum. The findings made in the microhardness test are detailed as follows. Firstly, the interface had extremely high bonding strength and the setting of explosive welding parameters was reasonable. Secondly, due to the collision of the composite plate at the interface, the material at the interface suffered severe plastic deformation, which led to work hardening. Lastly, the interface material underwent fine grain strengthening due to the load applied at high temperature and high pressure.

Given high temperature and high pressure, the energy activity of atoms at the interface was increased, which makes it easy for element diffusion to occur [34, 35]. The study of interfacial element diffusion is conducive to the analysis of interfacial composition and essential for the study of intermetallic compounds. Figure 12 shows the scanning results of elements at three random positions on the TA2/1060 interface. The Ti/Al element had mutation at the interface, and the significant change in element gradient drove element diffusion. However, the test results suggested that the maximum diffusion distance of Ti-Al was only 32 μm. To some extent, low diffusion hindered the formation of brittle intermetallic compounds in large amounts at the interface and improved the bonding strength, which evidences the correctness of the parameters used.

![Figure 11. Microhardness test of edge of composite plate.](image11)

![Figure 12. EDS scanning results of interface.](image12)
5. Conclusion

In this paper, the parameters of TA2/1060/5083 explosive welding were calculated as a preliminary using window theory. SPH-FEM coupling algorithm was applied to perform experimental simulation with specific parameters. According to the exhibited mechanical properties and the characterization results obtained, the interface bonding quality was satisfactory, as was the tensile strength and shear strength of the composites.

When the thickness of explosive was set to 15 mm and the gap was set to 2 mm, the quality of TA2/1060/5083 explosive composite bonding was excellent. Besides, TA2 – 1060 interface conformed to flat bonding, and 1060–5083 conformed to wave-like bonding. Meanwhile, the average wavelength of stable wavelength interval was 700 μm, while wave height was 100 μm.

According to the mechanical properties of the composite plate, the tensile strength and shear strength of the composite plate were 354 MPa and 110 MPa, respectively, which are clearly higher than those of the base plate. The microstructure characterization of the fracture revealed that there were a lot of orthogonal dimples at the fracture, and the material suffered ductile fracture. As suggeted by the SEM and OM results of the interface, the material produced ideal wavy bonding, and there were some typical morphology developing at the interface, such as vortex and splashing melt block. Machining-hardening and fine-grain strengthening occurred at the composite interface, with the hardness of the material at the interface showing a significant improvement. The element diffusion of Ti-Al occurred at the interface, but the maximum diffusion depth reached merely 32 μm.

An extremely high computational accuracy was achieved in the numerical simulation of explosive welding as performed using high speed tilt collision physical model, Shock and Steinberg-Guinan material model and SPH-FEM coupling algorithm, which is an effective solution to calculating the parameters of explosive welding for dissimilar metal.

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Data availability statement

No new data were created or analysed in this study.

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