Investigation of the microstructure of TC1/1060/6061 explosive composites based on experiments and numerical simulations

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Abstract

In this study, the microstructure of TC1/1060/6061 composites manufactured by explosive welding was investigated using experiments and numerical simulations. The results showed that the two interfaces of the TC1/1060/6061 composites exhibited an overall linear bonding interface without defects such as macroscopic cracks or pores. A melting layer caused by the adiabatic compression of air was observed, and the overall welding quality of the composites was good. There were no intermetallic compounds observed at the TC1/1060 interface, and the diffusion area was short, which formed a metallurgical bond. After heat treatment, the grains on the base plate and interlayer side of the composites formed a cubic recrystallized texture, while the grains on the flyer plate side developed a fine-grained structure. The microhardness of the base plate and flyer plate was higher closer to the interface due to the process hardening effect, while the microhardness of the interlayer remained stable. The formation process of these two interfaces was analyzed by numerical simulations, and jetting was observed at the 1060/6061 interface. The TC1/1060 interface in the numerical simulations showed a linear morphology, and the 1060/6061 interface showed a microwave morphology.

1. Introduction

In the field of engineering materials, different material combinations are required for different environments. Composites composed of two or more metals combine the advantages of different materials, including a high load-bearing performance, low cost, and high corrosion resistance [1]. Materials used for bridge decks must have a high strength, high corrosion resistance, and low cost, especially for emergency bridges that are subjected to high vehicle loads and exposed to corrosive environments. Al alloys are widely used in bridge decks because they are lightweight and inexpensive, but they are prone to pitting, intergranular corrosion, and stress corrosion in seawater environments owing to the existence of chloride in sea fog and seawater, which can significantly reduce the structural life. Ti alloys have a high specific strength and strong resistance to pitting, acid corrosion, and stress corrosion in a seawater environment, but their high price limits their wider applications [2, 3]. Therefore, thin Ti alloy plate can be used as a corrosion-resistant layer for Al alloy plates. Such composites take advantage of the corrosion resistance of Ti alloys, while Al alloys are used as the main load-bearing component.

Nevertheless, the performance of Ti alloys and Al alloys are quite different, and it is difficult to combine the two materials via traditional welding techniques. At present, the main preparation method of Ti/Al composite plates is the solid-state cladding method, which includes explosive welding cladding and rolling cladding. However, the rolling cladding process is greatly affected by the preparation technology. Even if a metallurgical bond is formed at the interface, the interface generated by rolling is a linear bond, whose strength is lower than the wavy interface. In addition, intermetallic compounds, warping, and edge cracks must be eliminated. In recent years, foil metallurgy cladding and solid-liquid casting-rolling have become the focus of research. However, their technological processes are still imperfect, and it requires continuous exploration. Explosive welding can be used to join almost any different kind of metal, which is a solid-state welding method that uses...
the energy generated by explosions to combine two identical or different metals [4–8]. Due to the high welding quality and low cost, it is rapidly developing in various fields [9–12].

Ti alloys and Al alloys can be used to develop load-bearing and lightweight composites by explosive welding, which also exerts the corrosion resistance of Ti alloys. Generally, the interfaces obtained by explosive welding present a linear or wavy interface. The wavy interface increases the bonding area of the two materials and has a better binding quality [13–15], while the wavy interface is likely to be accompanied by the formation of intermetallic compounds, which is very unfavorable for the applications of composites. It has been demonstrated that a small wavy interface has the highest bonding quality with almost no defects such as melting, which reduces the likelihood of forming intermetallic compounds [16, 17]. Additionally, the microstructure of the interface can directly reflect the bonding quality of the Ti/Al composites. Therefore, studying the microstructure of Ti/Al composites is of great significance for their practical applications in bridge structures.

The effects of the interlayer on the bonding interface have been investigated. The existence of an interlayer transforms a single interface into two interfaces, which is more conducive to energy distribution. An interlayer can prevent excessive kinetic energy loss, and thus significantly improve the energy efficiency [18, 19]. The quality of the bonding interface with the interlayer is good, with a smaller continuous melting zone and non-welding zone, which prevents the generation of intermetallic compounds [20]. Additionally, the addition of an interlayer can reduce excessive melting, enlarge the weldability window, reduce the vortex region, and reduce the large plastic deformation between interfaces. These help improve the bonding strength of the interface [21]. Therefore, the interlayer technique can be used to improve the bonding quality of Ti/Al composites.

Although Ti/Al composites have been studied, the most commonly-used Ti/Al composites are industrial pure titanium (α type). The TC1 (α + βtype) used in this work have a higher strength and lower plasticity than industrial pure titanium. Al alloy 6061 used in this work also has a higher strength and lower plasticity than 1060. The explosive welding window of these two materials is narrow, which is difficult to combine. At present, the combination of TC1/1060/6061 materials has not been studied, and analogical studies of the combination of different microstructures are relative shallow. Therefore, the explosive welding in this work provides experience for subsequent studies using the same material combination and high-quality components for bridges.

In this study, the microstructure of a TC1/1060/6061 composites was investigated by experiments and numerical simulations. The interface morphology, element diffusion, and grain development of the TC1/1060/6061 composites were investigated by optical microscopy (OM), scanning electron microscopy (SEM), x-ray diffraction (XRD), energy-dispersive spectroscopy (EDS), and electron back-scattered diffraction (EBSD). The explosive welding process was simulated by using the meshless SPH method, and the dynamic formation process of the two bonding interfaces was obtained. This article studied the bonding of Ti/Al composites, which provides a basis for the preparation of large-size, high-strength Ti/Al composites and their further application in bridge decks.

2. Experiment

Explosive welding used TC1 (620 mm × 300 mm × 3 mm) as the flyer plate and Al alloy 6061 (600 mm × 300 mm × 6 mm) as the base plate. Interlayer technology was used to improve the bonding quality of the interface during explosive welding. Al alloy 1060 (600 mm × 300 mm × 1 mm) was chosen as the interlayer. This was because 1060 and 6061 have better solid solubility and similar properties, which is conducive to the formation of a regular interfacial morphology and higher bonding quality at the second interface. Tables 1 and 2 illustrate the chemical compositions of TC1, 6061, and 1060.

In this work, TC1/1060/6061 composites were manufactured by a single shot explosive welding experiment, which was carried out using the parallel method, as shown in figure 1. To obtain a sufficient impact

| Table 1. Chemical composition (wt%) of TC1. |
|------------------------------------------|
| Al | Mn | Fe | C | N | H | O | Ti |
|-----------------|----|----|---|---|---|---|----|
| TC1             | 1.0–2.5 | 0.7–2.0 | 0.3 | 0.08 | 0.05 | 0.012 | 0.15 | residual |

| Table 2. Chemical composition (wt%) of 6061 and 1060. |
|------------------------------------------|
| Fe | Ti | Si | Mn | Zn | Mg | Cu | Cr | Al |
|-----------------|----|----|----|----|----|----|----|----|
| 1060            | 0.35 | 0.03 | 0.25 | 0.03 | 0.1 | 0.03 | 0.06 | Residual |
| 6061            | 0.7  | 0.15 | 0.4–0.8 | 0.15 | 0.25 | 0.8–1.2 | 0.15–0.4 | 0.04–0.36 | Residual |
velocity and to allow gases to escape smoothly, the distance between the base plate and the interlayer, as well as the distance between the flyer plate and the interlayer, were both set to 2 mm. In the experiment, a low-explosive-velocity powder emulsion explosive [22] was used with an explosive density of about 0.8 g cm\(^{-3}\) and detonation velocity of about 2200–2400 m s\(^{-1}\). A fiberboard was placed between the base plate and ground, which can provide energy absorption and cushioning, thus improving the foundation conditions and ensure the welding quality. The explosive thickness was set to 35 mm, and the end initiation of detonation was adopted.

Figure 2 shows the experimental process of explosive welding. After the preparation of each layer, the distance between the plates was set to 2 mm by placing copper sheets. The explosive was placed evenly on the flyer plate and detonated by detonators at the end. The composites obtained by explosive welding had complex residual stress [23–25]. To apply the Ti/Al composites in a bridge deck, a heat treatment at 400 \(^{\circ}\)C for 1 h was used to relieve the stress. Then, the Ti/Al composites were leveled.

The Ti/Al composites were cut by a wire-cutting machine (DK7750, China), and a sample with dimensions of 10 mm \(\times\) 30 mm \(\times\) 10 mm was obtained. The sample was ground and polished and then etched with a corrosive agent (10% HF + 10% HNO\(_3\) + 5% HCl). Then, the microstructure of the interface was observed by OM (DM4000M, Leica, Germany) and SEM (Merlin Compact, Zeiss, Germany). The distribution and composition of elements near the interfacial bonding region were obtained by EDS (NordlysMax3, Oxford, England) and XRD (ULTIMA IV, Rigaku, Japan).

EBSD was performed by field emission scanning electron microscopy (NordlysMax3, Oxford, England), and the data were analyzed using Channel 5 software. To obtain a suitable surface quality, the specimens were subjected to vibration polishing for 96 h continuously, with silicon oxide as the main component of the polishing solution. The EBSD parameters were a tilt angle of 70\(^{\circ}\), voltage of 20 kV, working distance of 17 cm, mapping step of 2 \(\mu\)m, and acquisition speed of 19.87 Hz.

To obtain the hardness variation near the interface, a microhardness test was performed on the area near the sample interface using a DHV-1000Z tester. A load of 100 g was applied near the bonding interface with a loading time of 15 s and a spacing of 0.2 mm between measurement points.

### 3. Numerical simulation

The explosive welding simulation of the TC1/1060/6061 composites was carried out in ANSYS/AUTODYN-2D, which has a variety of solvers and many material models for solving highly nonlinear dynamics problems. Figure 3 shows the proposed geometric model of the TC1/1060/6061 composites. The material and its related parameters were consistent with those in the explosive welding experiment. The detonation point was at the edge position of the flyer plate (TC1). SPH and Lagrange algorithms were used to simulate the different parts of the composites during the explosive welding process. To reproduce the waviness of the bonding interface, the generation of vortexes, and jetting, SPH was used to simulate the TC1 flying plate, 1060 interlayer, and 6061 base
plate. The Lagrange algorithm was used to simulate foundation and emulsion explosive. Generally, the smaller the particle size of SPH, the higher the accuracy of the simulation, but this reduces the computational efficiency.

Considering the accuracy and computational costs of numerical simulations, the particle size of SPH was set to 0.1 mm, and the total number of particles was set to 306,000.

To accurately describe the dynamic mechanical behavior, a reasonable equation of state and constitutive model must be selected. When simulating the emulsion explosive, the Jones-Wilkins-Lee (JWL) state equation was selected, whose pressure and energy were calculated by:

\[
P = A \left( 1 - \frac{\omega}{R_1 V} \right) e^{-R_1 V} + B \left( 1 - \frac{\omega}{R_2 V} \right) e^{-R_2 V} + \frac{\omega E_0}{V}\]

(1)

where \(P\) is the pressure; \(V\) is the relative volume, \(E_0\) is the initial specific internal energy of the detonation products, and \(\omega, R_1, R_2, A,\) and \(B\) are material constants. Table 3 shows these parameters [26].

The Shock equation of state was used to describe the basic relationship between the particle velocity and impact velocity for simulating both the interlayer and foundation (equations (2)–(6)):
Plastic strain, and indicated that there were no macroscopic cracks, holes, or major delamination at the TC1 interface. Figure 4 shows OM images of the bonding interface of the TC1

4. Results and discussion

4.1. Bonding interface microstructure

Table 4. Numerical simulation parameters.

| Material     | ρ (g/cm³) | C_p (m/s) | S | Γ₀ | G'p | G'p(Pu/K) | Y'p | G (GPa) | Y (GPa) |
|--------------|-----------|-----------|---|----|-----|------------|-----|---------|---------|
| Al-6061      | 2.703     | 5.24      | 1.40 | 1.97 | 1.80 | −1.70       | 0.0189 | 2.76   | 0.29    |
| Al-1060      | 2.705     | 5.05      | 1.35 | 1.97 | 1.766 | −1.669      | 0.0029 | 2.653  | 0.12    |
| TC1          | 4.55      | 5.24      | 1.03 | 1.23 | 0.482 | −2.698      | 0.0153 | 4.807  | 0.46    |

Table 3. EOS parameters of the emulsion explosive.

| ρ (g/cm³) | ν (m/s) | E_c (GJ) | A (GJ) | B (GJ) | R₁      | R₂      | ω       |
|-----------|---------|-----------|--------|--------|---------|---------|----------|
| 0.8       | 2100    | 1.8       | 8.615  | 0.818  | 3.754   | 0.807   | 0.001    |

U = C₀ + SU_p

where U is the node impact velocity, C₀ is the bulk sound speed, S is the linear Hugoniot slope coefficient, and U_p is the particle velocity.

P = P_H + Γ₀ρ₀(ε − ε_H)

P_H = \frac{P_0C₀μ(1 + μ)}{[1 − (S − 1)μ]}

ε_H = \frac{P_H}{2P_0}\left(\frac{μ}{1 + μ}\right)

μ = \frac{ρ}{ρ₀} − 1

where Γ₀ is the Gruneisen coefficient, P_H is the pressure of solid material after deformation, ε_H is the energy of the material after deformation, ρ is the density, ρ₀ is the initial density, and μ is the compression ratio.

The Steinberg-Guinan constitutive model was used to describe the mechanical behavior of the flyer plate, base plate, and interlayer in the simulation. This model was suitable for the case of a high strain rate and could describe the plastic deformation of the material under large deformation. The expressions for the shear modulus and yield strength as functions of effective plastic strain, pressure, and internal energy (temperature) were as follows:

\[ G = G₀\left\{1 + \left(\frac{G'p}{G₀}\right)^\frac{P}{η'} + \left(\frac{G'Y}{G₀}\right)(T − 300)\right\} \]

\[ Y = Y₀\left\{1 + \left(\frac{Y'p}{Y₀}\right)^\frac{P}{η'} + \left(\frac{G'Y}{G₀}\right)(T − 300)\right\}(1 + βε)^α \]

where G is the shear modulus, Y is the yield stress, η is the relative volume, T is the temperature, ε is the effective plastic strain, and G₀, G'p, G'Y, p, Y₀, Y'p, and β are material parameters, which were extracted from AUTODYN [27] (table 4).

4. Results and discussion

4.1. Bonding interface microstructure

Figure 4 shows OM images of the bonding interface of the TC1/1060/6061 composites. Metallographic studies indicated that there were no macroscopic cracks, holes, or major delamination at the TC1/1060 interface or the 1060/6061 interface. Due to adiabatic compression of the undischarged air between the flyer plate and interlayer during collision, a continuous melting layer of about 130 μm was observed at the TC1/1060 interface (figure 4(b)). Melting layers are believed to decrease the bonding strength of the interface; therefore, the formation of melting layers should be avoided. Defects caused by corrosion were observed in the 1060 interlayer due to corrosive agents (figure 4(b)).

Both TC1/1060 and 1060/6061 interfaces exhibited a linear bonding interface, no intermetallic compounds were produced, and the overall welding quality was good. The use of an interlayer redistributes the interfacial energy. The advantage of an interlayer is that the original excess energy of a single interface is changed into the energy of two different interfaces, which can avoid the formation of defects caused by the excess energy of a single interface. In the explosive welding process, the continuous effect of detonation cannot be ignored. The TC1/1060 interface lost less energy but also gained less energy, while the 1060/6061 interface lost more energy.
but gained more energy. Thus, the TC1/1060 interface presented straight bonding, while the 1060/6061 interface presented a straight bonding and microwave bonding [18, 20].

Figures 5(a)–(c) shows SEM images of the bonding interfaces. In agreement with the metallographic results, there were no intermetallic compounds at the interface, and no obvious cracks or holes were produced. In figure 5(e), the trunk structure is shown in area A. When the flyer plate collided with the interlayer, the flyer plate underwent violent plastic deformation, and the interlayer formed a depression when the two were combined. Then, jetting was captured when the interlayer rose, thereby forming this structure [28]. Due to the density difference or adiabatic heating of the compressed gas between the plates, the jetting was captured within the vortex at the forward or backward slope of the wave [29], which formed the vortex area (Region B in figure 5(e) and Region C in figure 5(f)). Defects such as shrinkage and pores often occurred near larger-vortex areas. There were fewer and smaller vortex areas around the TC1/1060 interface, and no defects were observed, which had less impact on the bonding strength.

4.2. Element diffusion at the interface
The Ti and Al contents at the TC1/1060 interface suddenly changed, which might have led to the formation of intermetallic compounds. Intermetallic compounds are often formed at interfaces, but their presence might lead to brittle damage, so their formation should be avoided. Figure 6 shows the XRD pattern of the TC1/1060 bonding interface. As observed, there were no intermetallic compounds in the pattern. Due to the large thermal diffusion coefficient of the interlayer, non-equilibrium solidification occurred, and elements existed in the interlayer as solid solutions [15]. This indicated the advantage of using an interlayer, which prevented Ti from
diffusing into the base plate, thus avoiding the production of intermetallic compounds. From another perspective, it also fundamentally enhanced the bonding strength.

To analyze the elemental diffusion on both sides of the TC1/1060 and 1060/6061 interfaces, EDS analysis was performed for the TC1/1060 interface according to Routes 1 and 2, and for the 1060/6061 interface according to Routes 3 and 4. As shown in figure 7(c), the width of the diffusion layer of both elements was only about 1.9 μm due to the low solid solubility of Ti and Al, which led to a narrow diffusion layer of both elements. When the concentration of elements exceeded the solubility between Ti and Al, intermetallic compounds were easily formed. Therefore, a narrower diffusion layer formed a metallurgical bond and avoided the formation of intermetallic compounds to some extent. As shown in figure 7(d), the distribution of Al increased in two gradients, while the distribution of Ti decreased in two gradients due to partial fracture at the TC1/1060 interface caused by the unstable explosive kinetic energy during explosive welding.

Figure 8 shows the EDS results of the 1060/6061 bonding interface. There was a crevice about 5.5 μm in length and 0.6 μm in width at the 1060/6061 interface (figure 8(a)). Due to the high velocity of the 1060 interlayer hitting the 6061 base plate, overmelting may have occurred in some areas, which led to the generation of a crevice. At this crevice, the Al content decreased sharply and then rose rapidly to its original level, while the O content increased first and then decreased (figure 8(c)). Figure 8(d) shows the EDS results of Route 4. At a distance of 5 μm, the Al content significantly decreased, followed by a rise to its original level. According to the high-resolution image of Route 4 (figure 8(b)), there was also a small crevice at this location, and the Al was much lower. However, this crevice was small and did not affect the bonding strength of the 1060/6061 interface.

Figures 9(b)–(c) illustrates the element distribution on both sides of the TC1/1060 interface. In Route 1, the Al content at the interface increased sharply, while the Ti content at the interface decreased sharply, and the diffusion layer was narrower. The color was more uniform around the interface as shown in figures 9(b) and (c). In Route 2, due to partial fracture at the interface, both Ti and Al showed two increasing/decreasing gradients, as verified by the black area in figure 9(b) and the red area in figure 9(c). Additionally, in Route 2, the elements on both sides of the interface in figure 9(b) and (c) were unevenly distributed, and then more uniformly distributed after a distance, and the width of the uneven part was the width of the diffusion layer of the two elements. Figure 9(e) shows the element distribution on both sides of the 1060/6061 interface. There was a clear black crevice at the interface, and the color distribution was uniform on both sides of the interface. The Al content was much lower at the crevice, which was consistent with the results in figure 8.

4.3. Grain development at the interfaces

EBSD can provide more grain information for the microstructure obtained from metallographic tests and SEM images. Figure 10 shows the EBSD results of the microstructure of the TC1/1060/6061 composites samples obtained from the explosive welding experiment. EBSD images were obtained for the Al and Ti grains without heat treatment in refs.,[30, 31], respectively. The Al grains had an elongated morphology, with grain size reaching 200–300 μm in length and 5–10 μm in width and elongated in the RD direction. The Ti grains consisted of equiaxed grains with crystal twins, and the base electrode (0002) was tilted 20°–30° from the normal direction (ND) to the transverse direction (TD). After explosive welding, the grains on the aluminum and titanium sides had a similar grain morphology as those in the above studies.
After the heat treatment, the shape and size of the grains on the aluminum side changed significantly, and the grains on both sides of the 1060/6061 interface grew abnormally to some extent, forming a cubic recrystallization texture. The grain morphology of both the base plate and interlayer exhibited different morphologies due to the influence of explosive welding (figure 10(a)). On the side of the base plate (6061), the grain size 50–100 μm from the interface was larger and elongated along the RD direction. The grain size significantly decreased farther than 100 μm from the interface. On the side of the interlayer (1060), the grain size was smaller 50–100 μm away from the interface and became significantly larger beyond 100 μm.

As shown in figure 10(b), on the side of the interlayer (1060), the grain on the aluminum side was larger 150 μm from the TC1/1060 interface, and the grain size was smaller farther away, which was different from 1060 side of the 1060/6061 interface. On the side of the flyer plate (TC1), there were no crystal twins on the titanium-side grains after heat treatment, and a fine crystal structure was obtained. The grains were slightly deflected along the ND direction. Due to the process hardening effect, there were two discontinuous areas of grains about 100 μm from the interface, and the crystal grains in the upper and lower parts of this area were incomplete.

4.4. Microhardness testing

Figure 11 shows microhardness distribution near the TC1/1060 and 1060/6061 interfaces. For the TC1 side, the microhardness gradually increased, reaching a maximum value of 253 HV near the TC1/1060 interface. The microhardness at the interlayer remained stable, with an average value of 27 HV. On the 6061 side, the maximum hardness of 54 HV was also reached near the 1060/6061 interface. Additionally, the microhardness at the TC1/1060 and 1060/6061 interfaces was between the microhardness of the base material on both sides. The same trend as the microhardness of the interface in this paper was observed for AISI 410 S A 283Gr −1D −1 [32], multilayer 316 L AA060 composites [33], and Ag/316L steel tube [34]. The microhardness was highest near the interface due to the violent plastic deformation of the metallic plate during explosive welding. The plastic
Figure 8. EDS results for both sides of the 1060/6061 interface: (a), (b) EDS line scanning profile, (c) element diffusion results for Route 3, and (d) element diffusion results for Route 4.

Figure 9. Distribution of elements on both sides of the interfaces: (a)–(c) TC1/1060 interface (d)–(e) and 1060/6061 interface.
deformation and microhardness decreased farther from the interface. Since TC1 had a higher softening temperature, it had a wider hardening zone than 1060 and 6061.

4.5. Numerical simulation results

Figure 12 shows the simulated explosive welding of the TC1/1060/6061 composites. Explosive welding was divided into six processes: explosion-driven flyer plate hitting the interlayer, the welding of the flyer plate and interlayer, the stabilization of the bonding area between the flyer plate and interlayer, explosion-driven interlayer hitting the base plate, the welding of the interlayer and base plate, and the stabilization of the bonding area between the interlayer and base plate.

After explosive detonation, the explosive gas generated rapidly expanded in the surrounding area and caused the flyer plate to hit the interlayer. A circular pressure zone was formed at the collision point, where the pressure rapidly increased to about 14 GPa and then entered the stabilization phase after declining. Reid et al. [35] demonstrated that the pressure gradually increased near the collision zone and then decreased in the elliptical direction, which was consistent with the results of this paper. After reaching the stabilization stage,
Figure 11. Microhardness distribution near the TC1/1060 and 1060/6061 interfaces.

Figure 12. Explosive welding of the TC1/1060/6061 composites in numerical simulation.
the TC1/1060 interface was formed, and the pressure at the junction of the two remained stable. Then, the composites of TC1 combined with 1060 hit the base plate, forming a second circular pressure zone where they collided. The pressure at the collision points rapidly increased to about 20 GPa and then gradually decreased and entered the stabilization phase. As the explosive welding process progressed, jetting occurred at the 1060/6061 interface. In this case, the pressure zone of the two interfaces remained stable, and the maximum pressures at the TC1/1060 and 1060/6061 interfaces were 5 GPa and 9.5 GPa, respectively.

In explosive welding, the pressure at the collision point must be large enough to ensure jetting on the metal surface, which was necessary for the formation of the interface waveform [36]. The maximum pressures of the TC1/1060 and 1060/6061 interfaces were 14 GPa and 20 GPa, respectively. Both of these values were greater than the dynamic strength of the material, at which point the material on the collision surface exhibited a transient fluid state, and jetting occurred at the interface. Figure 13 shows the jetting and velocity distribution obtained in the numerical simulation. As observed, jetting originated from the interlayer and base plate. According to the principle of self-cleaning, one part of the jet with a higher velocity washed the surface of both metals to remove impurities and oxides from the metal surface, which also enhanced the weld quality. The other part of the jet with a lower velocity formed a wave peak and a small molten lump at the collision point. The velocity distribution in figure 13 clearly shows that the jetting direction with the highest velocity was along the direction of the metallic plate, while the slower jetting direction was at an angle along the direction of the metallic plate.

In the explosive welding experiment, the flyer plate was 20 mm long at the end of the detonation point, which prevented non-welding zone caused by the boundary effect. At the detonation point, due to the instability of the initial energy, the bonding pressure on the initial welding side of the interface was low, and it was likely to be less than the dynamic strength of the two materials, resulting in a boundary interface that was not welded. Figure 14 shows the experimental and simulated morphology of the bonding interfaces. As mentioned above, the wavelength and amplitude of the TC1/1060 interface were slightly smaller than those of the 1060/6061 interface, which was verified by the numerical simulation. The numerical simulation results show that the TC1/1060 and 1060/6061 interfaces both showed linear bonding and microwave bonding, and the wavelengths and amplitudes of 1060/6061 interface were slightly larger than those of the TC1/1060 interface. The main reason for the difference between the experimental results and the simulation results is that the explosive parameters used in the simulation are not completely consistent with those in the test. The explosive parameters we obtained may have errors in the manufacturer’s test, and the explosive parameters may also have errors in the subsequent explosive configuration due to artificial reasons. Due to parameter errors, the difference in the interfaces between the experiment and simulation are explained. Overall, numerical simulations can be used to reflect the interface state in experiments. The numerical simulation reproduced the explosive welding process to a certain extent, where the pressures and jetting distributions could be used as a reference for subsequent production practices.

5. Conclusions

In this study, the microstructure of TC1/1060/6061 composites was investigated based on experiments and numerical simulation. The composites can be applied as a deck plate for bridge structures. This study focused on the interface morphology, chemical composition, grain changes, and microhardness of the composites. The
explosive welding process was reproduced by SPH numerical simulation. The following conclusions can be drawn:

1. TC1/1060 and 6060/1060 showed generally linear interfaces, and some areas of 1060/6061 exhibited microwave interfaces. No defects such as macroscopic cracks or holes were observed at the TC1/1060 interface, and a melting layer was observed at the TC1/1060 interface with a high welding rate at both interfaces. No intermetallic compounds were formed at the TC1/1060 interface, and the diffusion layer was narrow, forming a metallurgical bond.

2. After heat treatment, the shape and size of the grains on the aluminum side changed significantly, and the grains on both sides of the 1060/6061 interface grew abnormally and formed a cubic recrystallization texture. On the flyer plate (TC1) side, there were no crystal twins after heat treatment, and a fine crystal structure was obtained. The grains were slightly deflected along the ND direction.

3. The microhardness of the flyer plate (TC1) and base plate (6061) increased closer to the interface due to severe plastic deformation at the interface. The microhardness of the interlayer (1060) remained stable, and TC1 had a wider hardening zone than 1060 and 6061.

4. The numerical simulation results demonstrated that the TC1/1060 and 1060/6061 interfaces formed high-pressure zones at the collision points, at which the pressure increased rapidly and then stabilized after decreasing. Jetting was observed at the 1060/6061 interface, and the final obtained TC1/1060 and 1060/6061 interfaces both showed straight and microwave morphologies.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Disclosure statement

The authors report there are no competing interests to declare.
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