Study on microstructure and properties of TA1-304 stainless steel explosive welding cladding plate

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Abstract
Bonding TA1 and 304 stainless steel by explosive welding to obtain cladding plate. the microstructure of the bonded interface of the cladding plate was analyzed and its properties were tested. It was observed that the bonding interface of the cladding plate was periodically wavy. There is a large melting zone at the end of the interface waveform, and a vortex exists near the melting zone. The EDS surface scanning of the interface shows that there is element diffusion at the interface, and it is speculated that the bonding at the interface of the cladding plate belongs to metallurgical bonding. The microhardness measurement results show that the Vickers hardness (HV) at the interface is up to 413.10, and then the microhardness is lower with the distance from the interface junction, and gradually decreases to the same raw material. The tensile strength of 304 material after explosive welding reached 865MPa; the longitudinal shear strength of titanium-stainless steel cladding plate was 325MPa, and the transverse shear strength was 309MPa; The tested cladding plate has excellent corrosion resistance, and its corrosion resistance is between TA1 and 304. The self-corrosion current of the cladding plate is 233 μA.

1. Introduction
Titanium alloy has excellent comprehensive mechanical properties such as high strength, low density and good corrosion resistance, and plays an indispensable role in aerospace and nuclear energy. However, titanium alloy still has shortcomings, its process performance is very poor, and cutting is relatively difficult. Compared with titanium alloys, stainless steel materials also have good corrosion resistance and are relatively inexpensive in terms of price. Conventional welding or rolling does not achieve a good combination of the two, but the use of explosive welding can achieve effective recombination between the two [1–6]. At present, many researchers have studied the explosive welding of titanium-steel cladding plates. Michal Gloc [7] studied the bonding and bonding properties of explosively welded TA1-low alloy steel ST52-3N. Xuan Yang [8] studied the effects of different explosive cladding processes on the properties of titanium-steel cladding plates. Marcin Wachowski [9] studied the effect of heat treatment on titanium-steel cladding plates. At present, researchers in the industry have studied the explosion welding of titanium-steel cladding plates, mainly focusing on low alloy steel in the selection of base plate. Low alloy steel has poor corrosion resistance, heat resistance, low temperature strength, and is not safe enough to work in high temperature or strong corrosive environments. Using 304 stainless steel as the base plate can improve the mechanical properties of the cladding plate under extreme conditions, and it is very helpful to improve the overall corrosion resistance of the cladding plate. In this paper, explosive welding experiments of TA1 and 304 stainless steel were carried out, and then the properties and microstructures of cladding plates were studied, in order to provide reference for practical production and application.
2. Experimental procedure

The experimental material used a 520 mm $\times$ 520 mm $\times$ 3 mm TA1 plate as a base plate, and a 500 mm $\times$ 500 mm $\times$ 10 mm 304 plate as a flying plate. The size of the flying plate used is larger than the size of the base plate, and the purpose is to ensure an effective bonding area of the connection interface. The TA1-304 cladding plate was composited by means of explosive welding. The size of the sample is 500 mm $\times$ 500 mm $\times$ 13 mm. The chemical composition and mechanical properties of the experimental raw materials are shown in tables 1 and 2, respectively. Reasonable process parameters were determined by theoretical calculations and actual tests. See table 3. Explosives using powdered emulsion explosives. The explosives need to be diluted according to the requirements of the process. In this experiment, perlite is used to dilute the explosives. The post-explosion cladding plate is heat treated to eliminate residual stress in the cladding plate. Firstly, the cladding plate is uniformly heated from room temperature to about 540°C, and the heating rate is $100^\circ$C$^{-1}$. It was then incubated at 540°C for two hours. The final cooling can be divided into two phases. The first stage composite plate is cooled with the furnace, and the cooling rate is $100^\circ$C$^{-1}$. In the second stage, when the temperature is cooled to about 300°C, the composite sheet material is cooled to room temperature in air. The treated cladding plate were cut by the wire cutting method to the desired size for analysis. When preparing the metallographic observation sample, the sample is pre-ground with sandpaper. After pre-grinding, the sample is polished with a polishing machine, and then the sides of the sample are etched with different etching solutions. Stainless steel is etched with $\text{HCl}:\text{HNO}_3:\text{H}_2\text{O} = 3:1:96$. Titanium alloy is etched with $\text{HF}:\text{HNO}_3:\text{H}_2\text{O} = 3:2:95$. Then observe the sample on the metallographic microscope MIT500. The SU8020 scanning electron microscope and the attached energy spectrometer were used to observe and analyze the bonding interface and interface element distribution of the cladding plate. The samples were subjected to tensile and shear tests using a WEW-600 microcomputer screen display hydraulic universal testing machine. The HVS-1000A Vickers hardness tester was used to test the microhardness at the interface of the cladding plate. The load of the hardness tester was 10 N for 10 s, and the interval between each test point was 0.5 mm. CHI660D electrochemical workstation was used to measure the polarization curve of the cladding plate.

3. Results and discussion

3.1. Microscopic analysis at the interface

The macroscopic topography of the titanium-stainless steel cladding plate after the 25-fold magnification of the bonding interface is shown in figure 1(a). It is apparent from figure 1(a) that the two sheet materials are wavy bonded and the waveform exhibits periodicity along the direction of the explosion. Figure 1(b) shows a microscopic topography that is magnified 100 times in combination with the interface. No delamination was found at the interface, and a good combination was formed between the two. The presence of the vortex zone

| Table 1. 304 and TA1 chemical composition. |
|-------------------------------------------|
| Sample | C  | Si  | Mn | S  | P  | Ni | Cr  | N  | Ti  | O   | Fe   | H   |
|--------|----|-----|----|----|----|----|-----|----|-----|-----|------|-----|
| 304    | 0.022 | 0.41 | 1.50 | 0.001 | 0.026 | 0.03 | 18.0 | 0.066 | -  | -  | Balance | -  |
| TA1    | 0.0154 | -  | -  | -  | -  | -  | 0.0113 | Balance | 0.0678 | 0.778 | 0.0013 |

| Table 2. 304 and TA1 mechanical properties. |
|---------------------------------------------|
| Sample | $R_m$/MPa | $R_{p0.2}$/MPa | hardness/HV |
|--------|------------|---------------|-------------|
| 304    | 623        | 272           | 160         |
| TA1    | 401        | 300           | /           |

$R_m$-tensile strength; $R_{p0.2}$-Yield Strength.

| Table 3. Explosion process parameters. |
|----------------------------------------|
| placement method | Explosive type | Detonation method | spacing/mm | Explosive thickness/mm | Detonation speed |
|-----------------|----------------|-------------------|-------------|------------------------|-----------------|
| Parallel placement | Powder emulsion explosive | Edge detonation | 6           | 37                     | 2000 m s$^{-1}$ |
and the melt zone can be observed at the end of the wave at the bonding interface. Further observation in figure 1(b) shows that the molten layer and the vortex are mixed together and do not form a complete vortex. The lower left side presents a ‘hook-like’ fusion zone and penetrates into the metal structure on the stainless steel side [12].

The EDS scan is further performed on the bonding interface, as shown in figure 2. By observing the distribution views of Ti, Fe and Cr on both sides of the bonding interface, it is found that element diffusion occurs during the explosion welding. The diffusion of elements occurs at the atomic scale where atomic bonding occurs at the interface. At the same time, the research of Akbari Mousavi [13] also confirmed the presence of Fe2Ti, Fe2Ti4O and Cr2Ti intermetallic compounds at the bonding interface of TA1-304.

Exploring the reasons for the diffusion of elements at the interface, the main reasons for this phenomenon are as follows:
2. At high temperatures, the irregular movement of atoms is more intense. The higher the temperature, the greater the probability that the atom will leave the equilibrium position and the greater the probability of diffusion. In the explosion welding of titanium-stainless steel, the metal at the interface is exposed to high temperature and high pressure, which tends to bring the bonding interface to a very high temperature, thereby accelerating the diffusion of elements at the bonding interface.

3.2. Melting zone at the interface

As shown in figure 3, the melting zone at the interface. In the figure, the melting zone is well transitioned to the base and the flying, and the two materials form a metal ‘bonding’ interface at the interface.

The formation mechanism of the melting zone is as follows: It can be seen from figure 1(a) that the bonding interface of the titanium-stainless steel cladding plate is wavy, so that when the base plate is combined with the flying plate, the gas in the wave is blocked by the bonding zone and cannot be discharged in time. The bulge is formed, but the explosion load generated by the explosion compresses the bulge, the internal gas is compressed to increase the air pressure, and the temperature inside the bulge rises as the air pressure rises, thereby exacerbating the thin metal near the interface [15]. Further melting, eventually forming a melting zone (As shown in figure 3).

Compared with the EDS surface scan of the general interface (figure 2), it can be seen that the interdiffusion of the elements in the melt zone of the combined interface is greater than that at the normal interface (figure 4). The reason is analyzed mainly because the metal in the melting zone melts and forms an intermetallic compound [16]. According to Fick’s law, when the metal reaches the melting point, the diffusion coefficient will be maximized, and the diffusion of the elements at the bonding interface will be faster. The formation of intermetallic compounds at the interface also exhibits diffusion of interfacial elements, while the intermetallic compounds at the interface increase the microhardness at the bonding interface.

3.3. Mechanical performance analysis

3.3.1. Stretching test

The tensile strength was observed and recorded by performing a tensile test on a set of three samples. Further, the cross-sectional area after stretching and the length of the sample were measured, and the elongation at break δ was calculated to obtain the results shown in table 4. The stretching curve of group 1 was shown in figure 5.

It can be seen from the data obtained in table 4 that the tensile strength and the elongation after break δ of the three tests are small, and the average tensile strength of the cladding plate is 865 MPa, and the average area shrinkage is 50.1%. By observing the figure 5, we can clearly find that there is no yield platform for the stress-strain curve of stainless steel.

Comparing the tensile strength of the stainless steel raw material in table 2 is 623 MPa, the tensile strength of the stainless steel material after the explosion welding is greater than the tensile strength before the explosion welding. Therefore, the tensile properties of the stainless steel side after the explosion welding can meet the needs of production practice.
3.3.2. Shear test

The experimental samples were divided into two groups, one set parallel to the direction of the explosion and the other set perpendicular to the direction of the explosion. Each group was measured three times and averaged as the actual shear strength of the cladding plate. The experimental data records are shown in tables 5 and 6.

Comparing tables 5 with 6, the average shear strength of the longitudinal corrugation is 325 MPa, and the average shear strength of the transverse corrugation is 309 MPa. Both shear strengths are greater than the theoretical lower limit shear value. Combined with the analysis of the bonding mechanism of the explosive welding interface. Since the titanium-stainless steel bonding interface is wavy, the contact area at the interface is increased and the shear strength is also increased. Therefore, the combined interface shear strength of the explosive welded cladding plate is greater than the theoretical lower limit shear strength. From the GBT 8546-2017 titanium-stainless steel cladding plate \[17\], the theoretical lower limit shear strength is 196 MPa, and the experimental data in tables 5 and 6 are larger than the theoretical values. It can be seen that the mechanical properties of the titanium-stainless steel composite used in the experiment meet the requirements and can meet the shear strength requirements of practical applications. It can be seen that the mechanical properties of the titanium-stainless steel cladding plate used in the experiment meet the requirements and can meet the shear strength requirements of practical applications.

3.3.3. Microhardness

The hardness distribution curve shown in figure 6 can be obtained by testing the microhardness of the titanium-stainless steel cladding plate. It can be seen from the figure that the Vickers hardness at the joint interface of the cladding plate reaches 413.10, which is higher than the original hardness of the original titanium alloy and stainless steel, and gradually decreases with the distance from the interface. The microhardness is lower to the distance. When the interface is about 2 mm, the microhardness value is gradually stable. According to the

![Figure 4. EDS surface scan of the melting zone at the interface. (a) Melting zone microstructure at the interface; (b) Ti element scan distribution at the interface; (c) Fe element scan distribution at the interface; (d) Cr element scan distribution at the interface.](image)

| Test number | \(R_m/\text{MPa}\) | \(\delta/\%\) |
|-------------|------------------|--------------|
| 1           | 852              | 48.0         |
| 2           | 880              | 52.5         |
| 3           | 864              | 49.7         |
| average     | 865              | 50.1         |

\(R_m\)-tensile strength; \(\delta\)-Elongation after break.
forming mechanism of the cladding plate and the microscopic observation and analysis, there are three reasons for the increase in microhardness [18, 19]:

1. During the explosion welding process, the interface is plastically deformed, and a large number of dislocations accumulate at the interface to form high-density dislocations, resulting in work hardening, which increases the microhardness at the interface.

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**Table 5. TA1-304 cladding plate along the wave longitudinal shear test data record.**

| Test number | $a_1$/mm | $a_2$/mm | $S$/mm$^2$ | $F$/kN | $\tau_{b1}$/MPa |
|-------------|-----------|-----------|------------|--------|-----------------|
| 1           | 8         | 3         | 98.57      | 35.62  | 361             |
| 2           | 8         | 3         | 99.71      | 28.84  | 289             |
| 3           | 8         | 3         | 99.02      | 32.08  | 324             |
| average     | 8         | 3         | 99.10      | 32.18  | 325             |

$a_1$-base plate thickness; $a_2$-flying plate thickness; $S$-Joint area; $F$-Maximum pulling force; $\tau_{b1}$-Shear strength.

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**Table 6. TA1-304 cladding plate along the transverse shear test data record.**

| Test number | $a_3$/mm | $a_4$/mm | $S_2$/mm$^2$ | $F_2$/kN | $\tau_{b2}$/MPa |
|-------------|-----------|-----------|--------------|----------|-----------------|
| 1           | 8         | 3         | 98.74        | 31.99    | 324             |
| 2           | 8         | 3         | 99.14        | 29.54    | 298             |
| 3           | 8         | 3         | 98.89        | 30.26    | 306             |
| average     | 8         | 3         | 98.92        | 30.59    | 309             |

$a_3$-base plate thickness; $a_4$-flying plate thickness; $S_2$-Joint area; $F_2$-Maximum pulling force; $\tau_{b2}$-Shear strength.

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**Figure 5.** Stress strain curve of the tensile samples 1.
2. At the time of explosion, the interface is in a high temperature and high pressure state, causing the crystal grains at the interface to recrystallize, so that the original coarse grains become fine, so that the hardness at the bonding interface is increased.

3. During the explosion, the brittle metal phase is generated at the interface, which increases the microhardness of the bonding interface.

3.4. Corrosion resistance analysis

Through the dynamic potential polarization curve test, the characteristics of the electrode polarization process can be judged, so as to determine the possible electrode reactions, factors affecting corrosion, and corrosion mechanisms. The measured polarization curves of TA1, 304 and cladding plate in artificial seawater are shown in figure 7. Table 7 shows the calculated self-corrosion currents and self-corrosion potentials.

It can be seen from figure 4 that before self-corrosion occurs in each sample, the hydrogen evolution reaction of the cathode first proceeds, and the corrosion products generated have a certain protective effect on the sample surface. Since the cathode process is mainly controlled by the diffusion process of dissolved oxygen, the formation of corrosion products hinders the diffusion of dissolved oxygen into the interior of the metal, limiting
the cathode process, which is manifested in the gradual decrease in its current density \[20\]. Due to the small radius of Cl\(^-\) in artificial seawater and its strong penetrability, the corrosion products are destroyed. When the sample self-corrodes, the current density rises sharply. Once new corrosion products are formed and the sample is protected, the corrosion current will level off. Generally, the smaller the corrosion current of a material, the higher the corrosion potential, and the stronger its corrosion resistance. According to the data in table 3, TA1 has the best corrosion resistance, and 304 has the worst corrosion resistance. The corrosion resistance of the cladding plate is between the first two.

4. Conclusions

1. Explosive recombination between TA1-304 stainless steels was successfully achieved by using explosive welding technology. The titanium-stainless steel cladding plate bonding interface exhibits a periodic wave-like bond. There are also melting zones at the interface. The line scan analysis of the bonding interface revealed that the elements at the interface were interdiffused, and it was found that the element diffusion in the melting zone was more severe than that at the ordinary interface, which was beneficial to improve the interfacial bonding strength of the cladding plate.

2. The Vickers hardness value at the interface reached a maximum of 413.10, and gradually decreased as the distance from the interface increased gradually, eventually returning to the same. The tensile strength of stainless steel after explosion welding is 865 MPa. The shear test data showed that the cladding plate had a transverse shear strength of 309 MPa and a longitudinal shear strength of 325 MPa. Through the mechanical property test, it can be concluded that the cladding plate material after the explosion welding can meet the needs of the actual production.

3. The dynamic potential polarization curve measured the corrosion currents of TA1, 304 and cladding plates as 51.24, 257.90 and 233.07 μA. The test results show that the cladding plate has excellent corrosion resistance which is between two different raw materials. The corrosion resistance of titanium-steel cladding plate is lower than TA1, but the reduction is not large. Under the test conditions, it still shows high corrosion resistance, which can meet the requirements of practical engineering applications for the corrosion resistance of cladding plates.

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