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ARTICLE

Preparation and Performance of Large-Size Seamless Zirconium-Titanium-Steel Composite Plate

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Abstract: Zirconium-titanium-steel composite plate with the size of 2500 mm×7800 mm×(3+0.7+22) mm was prepared by explosive welding+rolling method, and its properties were analyzed by ultrasonic nondestructive testing, phased array waveform shape, interface structure shape, electronic scanning, and mechanical property testing. Results show that the rolling temperature of zirconium-titanium complex should be controlled at 760 °C, and the rolling reduction of each pass should be controlled at 10%–25%. The explosive velocity to prepare zirconium-titanium-steel composite plates should be controlled at 2450–2500 m/s, the density should be 0.78 g/cm^3, the stand-off height should be 12 mm, and the explosive height of Zone A and Zone B should be 45–50 mm. Explosive welding combined with rolling method reduces the impact of explosive welding and multiple heat treatment on material properties. Meanwhile, the problems of surface wrinkling and cracking, which occur during the preparation process of large-sized zirconium-titanium-steel composite plate, can be solved.

Key words: large-size seamless; zirconium-titanium-steel composite plate; explosive welding+rolling; phased array; interface structure

In order to manufacture materials satisfying the requirements of mechanical parts, special processing techniques are proposed to produce composite materials. Explosive welding method is an important material processing technique, which integrates the characteristics of diffusion welding, fusion welding, and pressure welding[1–3]. Through explosive welding, composite plates can be prepared ignoring the size restriction, and the prepared materials usually have excellent heterosexual characteristics, such as high-strength interface bonding and reprocessing ability. Consequently, the explosive welding technique is widely used in the aerospace, nuclear power, chemistry, and atomic energy fields, presenting great application potential of traditional single metal materials.

With the development of modern industrial equipment, various chemical equipment puts forward higher requirements for the size specifications and quality of composite plates. Meanwhile, in order to save zirconium resources and reduce equipment cost, zirconium composite plate has become a preferred material for the manufacture of core equipment and highly corrosive equipment. R60702 alloy has high oxygen content, so it is necessary to place titanium plate as the interlayer between the steel plates for explosive welding. Besides, additional stress release annealing is required. Such repetitive explosive welding and heat treatment may cause the substrate cracking and reduce the base performance strength[4–9]. Zirconium is an extremely active metal, so it can easily react with gases in the air and most solid substances at high temperatures, which results in high brittleness. Therefore, the welding process of zirconium is full of challenges[10–12].

The formation of ripples at the bonding interface during explosive welding is subject to the mechanism of multiple factors[13–17]. The theoretical formula for explosive blast pressure calculation is $P=\rho_0 V_d^2/(k+1)$ with $k=1+\rho/\rho_0$, where P is the blast pressure, V_d is the explosive velocity, ρ_0 is the initial explosive density, and ρ is the density of explosive product of the blast. Fig. 1 shows the dynamic change of

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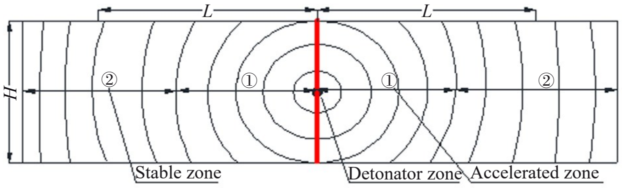

Fig.1 Dynamic change of interface during explosive welding

interface during explosive welding process, blast wave, and superposition of explosive products caused by the increase in blast pressure with the explosion reaction. Plate width increases, and the stability of the blast pressure decreases, indicating that the control and stability of blast pressure are the key to prepare high-quality composite plate. With the increase in the order specifications, in the production process, due to the uniformity of explosion composite process and the stability of explosion wave, the exhaust time required by the explosion speed is prolonged under the same conditions, resulting in the difficulty of exhaust process control. For the preparation of large-size composite plate (length⩾4 m), the composite plates often have cracking and surface wrinkles, as shown in Fig. 2 and Fig. 3, respectively. During the bending experiments of composite plate, the delamination phenomenon may occur, as shown in Fig.4, directly affecting the final product quality[18–20].

In this research, a novel method of explosive welding combined with rolling process was proposed to prepare zirconium-titanium-steel composite plate with dimension of 2500 mm×7800 mm×(3+0.7+22) mm. The rolling process was conducted to prepare zirconium-titanium complex, and the explosive welding technique was used to connect zirconium-titanium complex with the steel plate, finally producing zirconium-titanium-steel composite plate. Different from double explosive welding process, this method improves the performance of the composite plate, shortens the process time of single explosive welding and stress release annealing, and even reduces equipment maintenance cost[21–23]. This research provides new ideas to produce zirconium-titanium-steel composite plates.

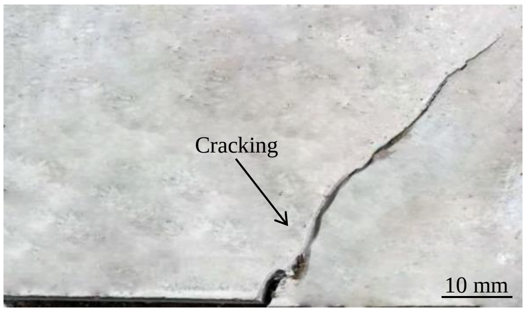

Fig.2 Cracking of zirconium-titanium-steel composite plate

Fig.3 Surface wrinkle of zirconium-titanium-steel composite plate

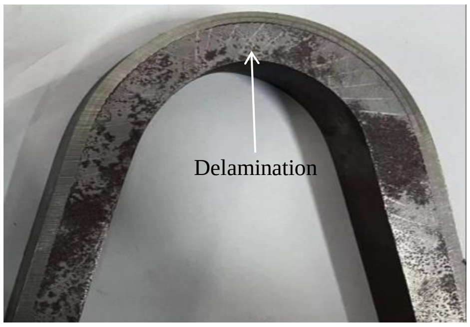

Fig. 4 Interface delamination phenomenon during bending test of zirconium-titanium-steel composite plate

1 Experiment

In this research, R60702 zirconium plate and TA1 titanium plate were used as raw materials, and Q345R steel was used as base metal for explosive welding. R60702 alloy, as a clad material, satisfies ASME SB551/M-2004 standard. The TA1 interlayer satisfies the requirements of GB/T3620-2007 standard. The Q345R base metal satisfies the requirements of GB/T 713-2014 standard. The dimensions of R60702 zirconium plate and TA1 titanium plate were set as 15 mm× 2530 mm×1980 mm and 3 mm×2570 mm×2020 mm, and their chemical composition is shown in Table 1 and Table 2, respectively. The dimension of Q345R steel plate was set as 23 mm×2500 mm×7800 mm, and its chemical composition is shown in Table 3.

Fig.5 presents the rolling process of the zirconium-titanium complex. For the rolling process, a reasonable rolling temperature is particularly important for the hot rolling compound effect. Low rolling temperature may result in low

Table 1 Chemical composition of R60702 zirconium plate (wt%)

Zr+Hf	Hf	Fe	Cr	C	N	H	O
⩾99.2	2.18	0.048	0.004	0.006	0.0062	0.0009	0.059

Table 2 Chemical composition of TA1 titanium plate (wt%)

Fe	C	N	H	O	Ti
0.009	0.011	0.003	0.006	0.0437	Bal.

Table 3 Chemical composition of Q345R steel plate (wt%)

C	Si	Mn	P	S	Cr	Ni	Mo	Fe
0.14	0.30	1.49	0.011	0.001	0.05	0.02	0.01	Bal.

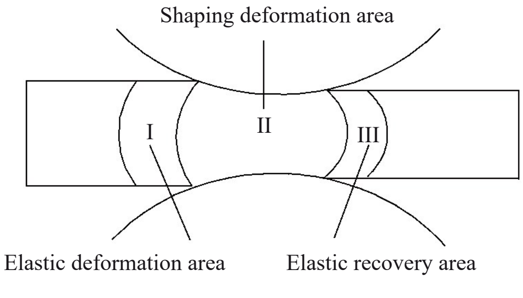

Fig.5 Rolling process of zirconium-titanium complex

metal plastic flow, insufficient diffusion between dissimilar atoms, and insufficient recrystallization temperature. However, over high temperature may lead to rapid thickening of the oxide layer at bonding interface, resulting in insufficient contact between dissimilar metals, blocking the mutual diffusion of atoms, and affecting the rolling composite.

The zirconium-titanium complex was prepared by traditional hot rolling composite. The detailed rolling process was as follows: pretreatment of surfaces of titanium plate and zirconium plate→warm charging (760 °C/1 h)→oxide layer removal for quick metal combination by angle grinder→hot rolling of first pass (reduction ratio of 10%–25%)→warm charging (600 °C/1 h)→hot rolling of secondary pass (reduction ratio of 10%–25%)→cold straightening.

The surfaces of Q345R substrate and R60702/TA1 zirconium-titanium complex were polished until they were flat, smooth, and clean, and the average surface roughness of the zirconium-titanium complex and steel plate was $R_a \leqslant 3.2$ μm. During explosive welding, the surface of zirconium-titanium complex was evenly coated by butter to prevent burning caused by high pressure and high temperature, which were generated by explosives.

Due to the propagation characteristics of detonation waves in explosive welding of large-size plates, the operation site was designed, as shown in Fig. 6. Zone A and Zone B were determined. This combined process not only solves the low interface bonding strength problem of the composite plate caused by low process parameters, insufficient detonation energy, and difficult exhaust, but also avoids the edge tearing and interface over-melting phenomena caused by high energy. Table 4 shows the explosive process parameters at the explosive welding site.

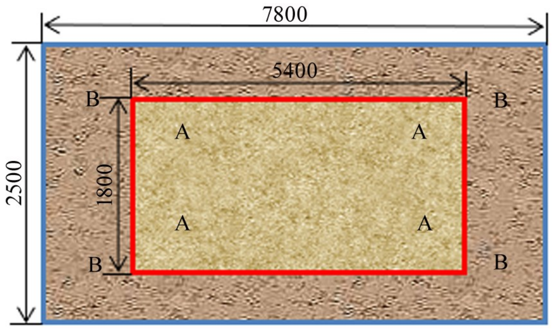

Fig.6 Schematic diagram of explosive welding site

The explosive velocity is a key parameter in theoretical calculation. The calculated explosive velocity is V_m=2373 m/s[24]. In this research, the explosive velocity is the same as the moving speed of the interface collision point of the composite plate. To ensure the lower limit of the explosive velocity of weldability window requirements, the velocity should be controlled at 2450 – 2500 m/s. Five types of explosives[25] (A – E) were selected, and the on-site process used explosive C and E. The experiment results of different explosives are shown in Table 5.

Ultrasonic nondestructive testing, phased array interface imaging, interface ripple metallography, and shear strength tests were conducted. Three annealing processes were selected and corresponding samples were used to characterize the mechanical properties. The explosive state and annealed state were compared, and the standard interfacial structures were analyzed by scanning electron microscope (SEM). The acceptance criteria for composite panels were implemented in accordance with ASTM B898-2020: Class A[26]. Anyscan-31 ultrasonic flaw detector was used for nondestructive testing. OmnicCan X3 phased array instrument was used for interface imaging; CMT5105 electronic universal test machine was

Table 4 Explosive process parameters at explosive welding site

Explosive velocity/m·s^{-1}	Density/g·cm^{-3}	Height of distributed explosive in Zone A/mm	Height of distributed explosive in Zone B/mm	Height of stand-off/mm
2450–2500	0.78	45–50	45–50	Zone A: 12 Zone B: 12

Table 5 Test data results of five types of explosives

Explosive	Bulk density/ g·cm^{-3}	Deviation of bulk density/g·cm^{-3}	Explosive velocity/m·s^{-1}	Deviation of explosive velocity/m·s^{-1}	Brisance, H/mm	Stabilized bursting distance/m
A	0.75	0.02	2182–2389	207	8.1	2.9
B	0.76	0.04	1965–2176	211	7.2	2.3
C	0.78	0.01	2463–2497	34	10.0	4.7
D	0.77	0.02	2438–2495	57	9.5	3.8
E	0.78	0.02	2458–2476	18	8.6	3.5

used for tensile equipment, and they were tested according to GB/T 228.1-2021; the impact test was conducted using RIE-F1432 750 J Charpy impact test machine in accordance with ASTM E23-2017 standard; the shear strength test was processed according to ASTM B898-2020; the microstructure was analyzed by MIRIE-F2573 equipment. Vickers hardness test was performed according to GB/T 232-2010 standard, and the interfacial structures were analyzed by tungsten SEM in VEGA 3 XMU large sample chamber.

2 Results and Discussion

2.1 Ultrasonic nondestructive test

Fig.7 shows the appearance of zirconium-titanium complex after rolling treatment. Fig. 8 shows the appearance of zirconium-titanium-steel composite plate after explosive welding. It can be observed that the surface of zirconium-titanium-steel composite plate is flat and smooth, and explosive welding combined with rolling method can avoid the problem of wrinkle occurrence on the surface of large-sized composite plates.

The single probe (2.5 MHz, *Φ*20 mm) and water were used for ultrasonic nondestructive testing of zirconium-titanium-steel composite plate. Direct contact process was conducted for ultrasonic testing of the entire plate through diffraction time difference method. Apart from the detonator area in the geometric center of plate within the range of *Φ*25 mm, the bonding rate of the effective detection area reaches 100%, satisfying the requirements of ASTM B898-2020: Class A.

Fig.7 Appearance of zirconium-titanium complex after rolling treatment

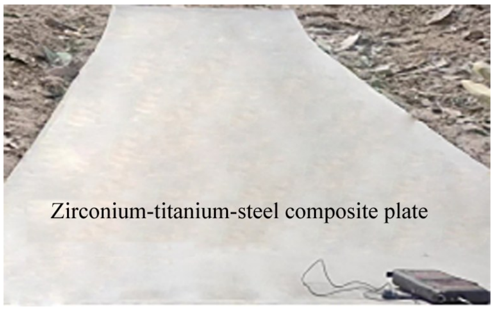

Fig.8 Appearance of zirconium-titanium-steel composite plate after explosive welding

2.2 Morphology characteristics of interface

Phased array imaging adopted a linear phased array probe, and the probe frequency was set as 10 MHz. The number of chips was 128. The array element spacing was 0.5 mm, and the thickness of plexiglass wedge was 20 mm. The probes and encoders were fixed on the handheld scanning frame to form a complete phased array C-scan rapid imaging detection system. With water as the coupling agent, the probe was pressed for well connection with the plate surface, and the scanning mode was linear scanning. The focusing position was located at the combined interface of the composite plate, and the scanning surface was the cladding surface of composite plate.

Fig. 9 shows the phased array imaging morphology of zirconium-titanium/steel interface. The bonding interface of the composite plate shows a typical wave-like combination with uniform corrugations. Phased array imaging reflects the characteristics of the interface without material waste.

2.3 Mechanical properties

2.3.1 Shear strength of composite plate

Shear strength is an important index to evaluate the quality of combined interface of the composite board, and the interface strength at the joint plays a key role in the processing, safe operation, and service life of the equipment. Thus, a certain strength is required for the interface of composite plate. The samples of the composite plate for shear tests were taken from the corner of the composite plate, which is far from the detonation point. The transverse and longitudinal shear strength tests of the zirconium-titanium complex were also conducted, and the results are 252 and 268 MPa, respectively. The shear strength of zirconium-titanium-steel composite plate at initial state and after treatments of 540 °C/4 h, 605 °C/3 h, and 650 °C/2 h was measured, and the results are shown in Table 6.

The shear strengths of zirconium/titanium interface and zirconium-titanium/steel interface are higher than 137.9 MPa, demonstrating that the interfaces have satisfying strength.

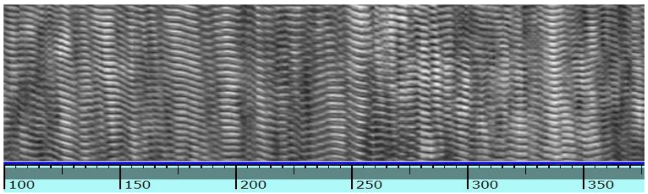

Fig.9 Phasing array imaging morphology of zirconium-titanium/steel interface

Table 6 Shear strength of zirconium/titanium interface and zirconium-titanium/steel interface at different states (MPa)

Interface	Initial state	540 °C/ 4 h	605 °C/ 3 h	650 °C/ 2 h
Zirconium/titanium	265	248	252	253
Zirconium-titanium/steel	210	230	268	212

Obviously, the shear strength of composite plate after the 605 °C/3 h treatment is better than that after other treatments.

2.3.2 Tensile strength of composite plate

According to GB/T 228.1-2021 standard and GB/T 6396-2008 standard, the transverse and longitudinal samples were cut from the edge of composite plate and then analyzed. Table 7 shows the tensile strength results of zirconium-titanium complex at initial state and after 650 °C/2 h treatment. It can be found that the material elongation after 650 °C/2 h treatment is favorable to explosive welding. *R*, *D*, and *T* represent the radius of pressure head of S type, the radius of pressure head, and the sample thickness, respectively.

According to Table 8, the measured tensile strengths of zirconium-titanium-steel composite plates at different states are all higher than their theoretical calculated values. When the heat treatment is 540 °C/4 h, good strength and elongation can be achieved, satisfying the strength requirements of actual engineering structures.

2.3.3 Bending test of composite plate

Bending test results are shown in Table 7 – Table 8 and Fig. 10 – Fig. 12. There is no delamination or local separation between the base metal and cladding of the inner and outer bending test samples of the zirconium-titanium-steel composite plate. The bending test results of the composite plate can meet the supplementary requirements of S2 standard in ASTM B898-2020. This method solves the problem of delamination and ensures the sound plastic toughness and cold-working bending property of zirconium-titanium-steel composite plate.

2.4 Interface hardness of composite plate

Fig. 13 shows the Vickers microhardness results of zirconium-titanium-steel composite plate at initial state and after treatments of 540 °C/4 h, 605 °C/3 h, and 650 °C/2 h, exhibiting the plastic deformation after explosive welding. The closer the distance between the zirconium-titanium plate or steel plate and the bonding interface, the greater the material deformation, and the more obvious the work hardening effect caused by the explosion, resulting in greater hardness value of the region. In the process of explosive welding, the cooling rate is very high, which results in localized high temperature and high pressure, so the carbon element on both sides of zirconium-titanium plate and steel plate can hardly diffuse, forming supersaturated solid solution of carbon in iron or hard brittle intermetallic compounds, leading to high microhardness of the interface.

After treatments of annealing at 540 °C/4 h, 605 °C/3 h, and 650 °C/2 h, the explosive work hardening effect of the material can be released. The microhardness of annealed zirconium layer, zirconium/titanium interface, titanium layer, zirconium-titanium/steel interface, and steel layer is significantly smaller than that at explosive states. The changes near the zirconium/titanium interface and the deformation area of the titanium interface are particularly obvious. The further the distance from the interface, the more stable the hardness variation. Besides, the plastic deformation of the composite plate is enhanced, and the machinability is improved.

2.5 Interface

As shown in Fig. 14, the interface of the zirconium-titanium complex is relatively straight. Zirconium and titanium are mutually soluble metals. In the hot rolling process, the interface is easy to form infinite solid solution, as shown in Fig. 15. According to the line scanning results at the interface (Fig. 16), it can be found that the distance between zirconium and titanium of the interface mixture is about 15 μm, indicating that the metal compound between zirconium and

Table 7 Tensile strength of zirconium-titanium complex at different states

State	Location	Strength of extension/MPa	Yield strength/ MPa	Elongation/%	Characteristic after bending (S type) with *R*=5*T* and 105°
Initial	Landscape	383	302	30.0	Flawless
	Lengthways	380	299	30.0	
650 °C/2 h	Landscape	368	263	33.5	Flawless
	Lengthways	365	260	31.0	

Table 8 Tensile strength of zirconium-titanium-steel composite plate at different states

State	Location	Strength of extension/MPa	Yield strength/ MPa	Elongation/%	Incurve characteristic with *D*=3*T* and 180°	Excurvature characteristic with *D*=5*T* and 180°
Initial state	Landscape	577	498	22.0	Flawless	Flawless
	Lengthways	583	505	20.5		
540 °C/4 h	Landscape	565	412	27.0	Flawless	Flawless
	Lengthways	569	415	26.0		
605 °C/3 h	Landscape	538	378	27.5	Flawless	Flawless
	Lengthways	543	394	25.5		
650 °C/2 h	Landscape	533	381	28.0	Flawless	Flawless
	Lengthways	532	367	28.5		

Fig.10 S-type bending results of zirconium-titanium complex at different states

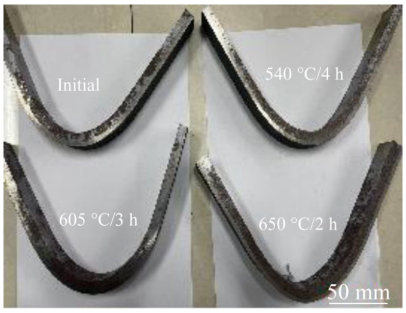

Fig.11 Internal bending results of zirconium-titanium-steel composite plate at different states

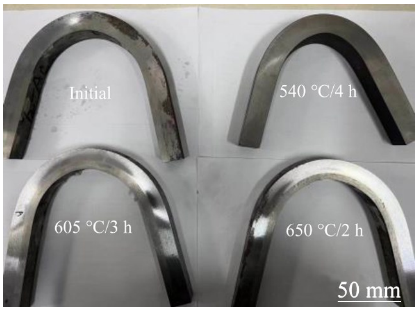

Fig.12 External bending results of zirconium-titanium-steel composite plate at different states

titanium is formed during the rolling process.

Table 9 shows the measurement results of grain grades of zirconium and titanium layers. It can be seen that the grain grade of the zirconium layer is 7.5 – 9.0, and that of the titanium layer is 7.0–7.5. There is no regular deformation near the interface on the titanium layer, and a large number of adiabatic shear lines are generated. Under high-speed impact, local plastic deformation begins, and the generated heat has no time to propagate, reducing the local yield strength of the material. When the dynamic yield strength is lower than the shear stress caused by the impact load, the site will produce instantaneous shear deformation. On the carbon steel side, the closer the distance to the interface, the larger the shape variable of the grain. The original equiaxed crystals gradually extend along the deformation direction, presenting significant

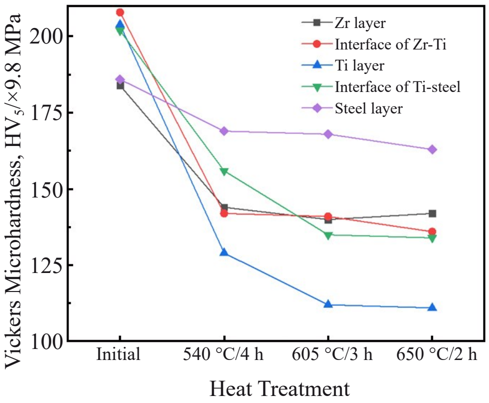

Fig.13 Vickers microhardness results of different regions of zirconium-titanium-steel composite plate at different states

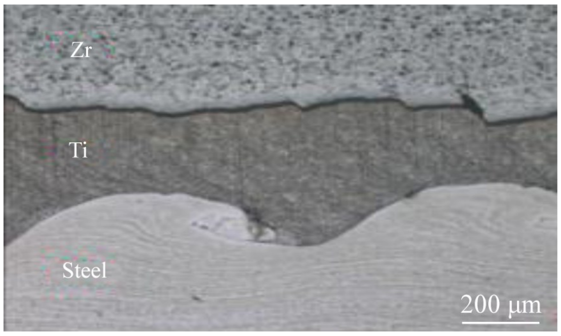

Fig.14 Interface microstructure of zirconium-titanium-steel composite plate

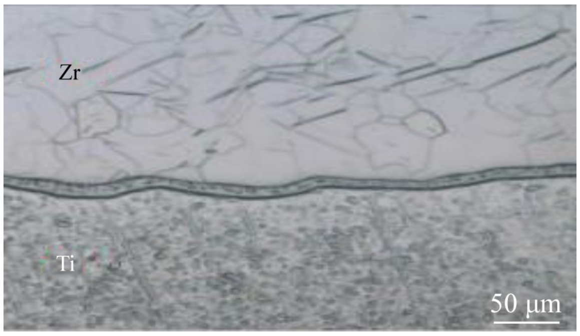

Fig.15 Interface microstructure of zirconium-titanium complex

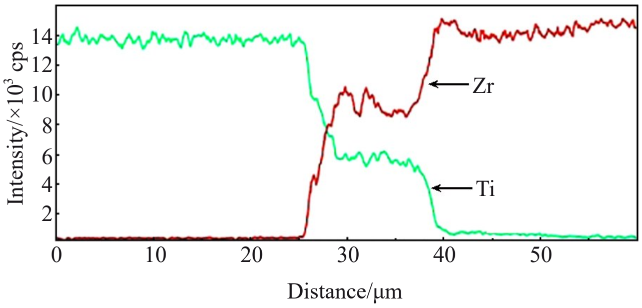

Fig.16 Line scanning results of Zr and Ti elements at interface

Table 9 Grain grades of zirconium and titanium layers at different states

Layer	Initial state	540 °C/4 h	605 °C/3 h	650 °C/2 h
Zirconium	9.0	8.5	8.0	7.5
Titanium	7.5	7.0	7.0	7.5

grain elongation. When the deformation is obvious, grains are difficult to distinguish and appear as a fibrous stripe. The further the distance from the interface, the more the formation of the steel matrix with original structure.

Apart from the non-combination region of the detonator area within *Φ*25 mm, the effective area is well combined. The test results show that these prepared plates (preparation parameters are listed in Table 4) satisfy the Class A requirements of ASTM B898-2020 standard[26], Class 2 requirements of NBT 47011-2010 zirconium-steel composite plate standard[27], and YS/T 777-2011 zirconium-steel composite plate standard[28]. The designed process parameters of explosive welding+rolling method are reasonable.

3 Conclusions

1) The appropriate processing parameters for the large-size (2500 mm×7800mm× (3+0.7+22) mm) seamless zirconium-titanium-steel composite plate are as follows: the rolling temperature of zirconium-titanium complex is 760 ° C; the downward pressure of each pass should be controlled at 10%–25%; the explosive velocity to prepare zirconium-titanium-steel composite plate should be controlled at 2450–2500 m/s; the density should be 0.78 g/cm^3; the height of stand-off is 12 mm; the distribution height of Zone A and Zone B should be 45 – 50 mm. Under these conditions, the prepared zirconium-titanium-steel composite plate can satisfy the Class A requirements of ASTM B898-2020 standard, Class 2 requirements of NBT 47011-2010 zirconium-steel composite plate standard, and the YS/T 777-2011 zirconium-steel composite plate standard.

2) After heat treatment of 650 °C/2 h, the high elongation of the zirconium-titanium complex is conducive to the explosive welding. When the zirconium-titanium-steel composite plate is heat-treated at 540 ° C/4 h, the composite plate not only ensures the strength but also has the optimal elongation, which is conducive to the processing of composite plates.

3) The shear strength of the zirconium/titanium interface is over 250 MPa, and that of the zirconium-titanium/steel interface is more than 200 MPa. The inner and outer bending performance of prepared composite plate is better than that after traditional explosive welding process, and the combination strength is also higher.

4) The grain grade of zirconium and titanium layers remains relatively stable. The grain grade of the zirconium layer is 7.5 – 9.0, and that of the titanium layer is 7.0 – 7.5, which is equivalent to the grain grade of the traditional composite plate.

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大尺寸无缝锆钛钢复合板的制备及性能

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摘　要：采用爆炸焊接+轧制法制备尺寸为2500 mm×7800 mm×(3+0.7+22) mm的锆钛钢复合板，并通过超声波无损检测、相控阵波形形貌、界面结构形状、电子扫描和力学性能测试对其性能进行了分析。结果表明：锆钛复合体的轧制温度应该控制在760 ℃，道次的压下量应控制在10%~25%。制备锆钛钢复合板的爆炸速度应控制在2450~2500 m/s，密度应为0.78 g/cm^3，间隙高度应为12 mm，A区和B区的炸药高度为45~50 mm。爆炸焊接+轧制技术减少了爆炸焊接的冲击和多次热处理对材料性能的影响，同时解决了大尺寸锆钛钢复合板制备过程中出现的表面褶皱和开裂问题。

关键词：大型无缝；锆钛钢复合板；爆炸焊接+轧制；相控阵；界面结构

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