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ARTICLE

Microstructure and Mechanical Properties of Explosively Welded R60702/TA2 Composite Plate

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Abstract: R60702 plate and TA2 plate were successfully bonded together by explosive welding. The microstructure, element diffusion, microhardness changes near the bonding interface before and after heat treatment were investigated using optical microscopy (OM), scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and microhardness tester. The mechanical properties and fracture morphology in initial and heat treated states were examined as well. The results demonstrate that after explosive welding, the explosively welded bonding interface has a wavy appearance, obvious deformations and slight element diffusion. The microhardness values decrease gradually with increasing the distance to the interface due to the diminishing plastic deformation. After heat treatment, a diffusion layer and recrystallization appear in the microstructure. The overall microhardness values, tensile strength, and shear strength decrease while the plasticity and ductility improve compared with in the initial state. The explosively welded R60702/TA2 composite plate shows a good bending performance after heat treatment.

Key words: Zr-Ti composite plate; explosive welding; microstructure; mechanical property

Chlorination reactor is the crucial production device for chlorinated polyethylene. Materials with high corrosion resistance are essential for the chlorination reactor due to the formation of acid during service[1,2]. At present, the explosively welded Zr/Ti/steel tri-metallic composite plates are the most widely used materials. However, iron contamination, which cannot be avoided during welding on account of abundant iron ions in the Zr/Ti/steel composite plate, provides a stimulative condition for the corrosion cracking of welded joints. Consequently, there are big leakage threats to the chlorination reactor[3,4]. As a solution, Zr/Ti bimetallic plate is put forward to replace the steel-based Zr/Ti/steel tri-metallic plate since it can improve the corrosion resistance significantly.

Explosive welding can realize the welding between similar or dissimilar materials and it has been used to fabricate a wide variety of composite plates successfully[5]. In addition, there is no possibility of forming the brittle intermetallic compounds at the bonding interface of Zr/Ti composite plate during explosive welding, because Zr is a congener element of Ti and they have similar properties[6]. Therefore, explosive welding is a suitable method for producing the Zr/Ti bimetallic plate.

The research on the explosively welded composite plates containing Zr or Ti plates is mainly focused on the explosive welding of Ti and steel. Song [7], Ma [8] and Zu [9] et al studied the microstructure and interfacial bonding mechanism of explosively welded Ti/steel composite plate. Akbari et al[10] investigated the influence of variable explosive welding parameters on the properties of explosive cladding Ti/steel plate. Yan [11], Akbari[12] and Wachowski [13] et al discussed the heat treatment effect on the properties of explosively welded Ti/steel composite plate. However, there are few reports about the Zr/Ti bimetallic plates fabricated by explosive welding.

In this paper, Zr plate was bonded to Ti plate through explosive welding. Then the microstructure, mechanical properties and underlying mechanism of the explosively welded Zr/Ti bimetallic plate were investigated. The effect of heat treatment on interface and mechanical properties of Zr/Ti composite plate was studied as well. The results obtained in this study have certain guiding significance for the practical application of explosively welded Zr/Ti composite plates.

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1 Experiment

The zirconium plate (R60702) was used as the flyer plate and the titanium plate (TA2) was used as the base plate. The dimensions of R60702 plate and TA2 plate were 550 mm×550 mm×3 mm and 500 mm×500 mm×12 mm, respectively. The chemical composition of R60702 and TA2 is listed in Table 1 and Table 2, respectively. Fig.1 shows the parallel layer arrangement adopted in the explosive welding. The expanded ammonium nitrate was chosen as the explosive, with a thickness of 30 mm and a detonation velocity of 2247 m/s. The distance between R60702 plate and TA2 plate was 8 mm.

In order to eliminate the residual stress and to improve the microstructure and mechanical properties of the R60702/TA2 composite plate, heat treatment was carried out after explosive welding. The previous research[14] showed that when annealing at 500~540 °C, the strength and plasticity of Zr plate cooperated very well. And the annealing temperature of 540 °C was found to be appropriate for the Ti/steel composite plate produced by explosive welding[15]. Based on the previous works, the heat treatment temperature of 540 °C for 4 h was selected in this study.

Samples with a size of 15 mm×15 mm×10 mm for micro-structure observation were cut parallel to the explosion direction using a wire cut machine. Then these samples were ground and polished. Both Zr and Ti plates were etched in the etchant consisting of 20 mL HNO_3, 10 mL HF and 170 mL H_2O. Subsequently, the metallographic samples were observed through an Olympus DSX510 optical microscope (OM) and a JSM-6360LV scanning electron microscope (SEM). And also, the energy dispersive spectroscope (EDS) analysis was performed to study the distribution and diffusion of elements.

To investigate the changes in mechanical properties of the explosively welded R60702/TA2 composite plate before and after heat treatment, the tensile test, shear test and three-point bending test were conducted. All the mechanical test specimens were prepared by a wire cut machine. The dimensions in detail are shown in Fig.2 according to GB/T 6396-2008[16]. The tensile test was performed at ambient temperature on the MTS-809 testing machine with a loading rate of 1 mm/min. The shear test was conducted using the MTS-809 testing machine at a speed of 0.5 mm/min. In the bending test, the internal and external bending tests were both carried out on the MTS-809 testing machine at a loading rate of 1 mm/min. The diameter of indenter used in the bending test was 60 mm and the roller span was 98 mm. The microhardness distribution across the interface was measured by the HVS-1000Z microhardness tester with a load of 100 g and a measurement interval of 100 um. Fractography studies of the broken specimens after tensile and shear tests were carried out using the JSM-6360LV SEM.

Table 1 Chemical composition of R60702 (wt%)

Zr	Hf	Fe+Cr	C	N	H	O
Bal.	2.2	0.07	0.03	0.018	0.003	0.11

Table 2 Chemical composition of TA2 (wt%)

Ti	Fe	C	N	H	O	Others
Bal.	0.3	0.04	0.01	0.01	0.2	0.5

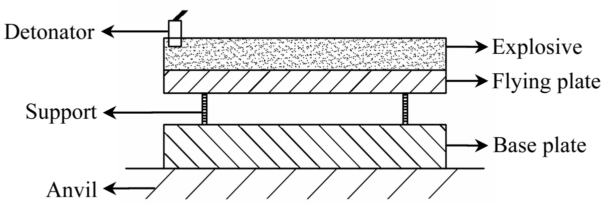


Fig.1 Parallel layer arrangement of explosive welding process

2 Result and Discussion

2.1 Microstructure characterization after explosive welding

The bonding interface of explosively welded composite plates can present three kinds of morphologies: straight, wavy and melting[17]. The wavy interface is expected due to its better mechanical properties[18]. Fig.3a shows the optical micrograph near the bonding interface of the R60702/TA2 composite plate after explosive welding. The Zr and Ti plates are bonded closely without pores, cracks and other defects. A typical wavy bonding interface is formed and severe plastic deformation occurs at the interface. The waves formed along

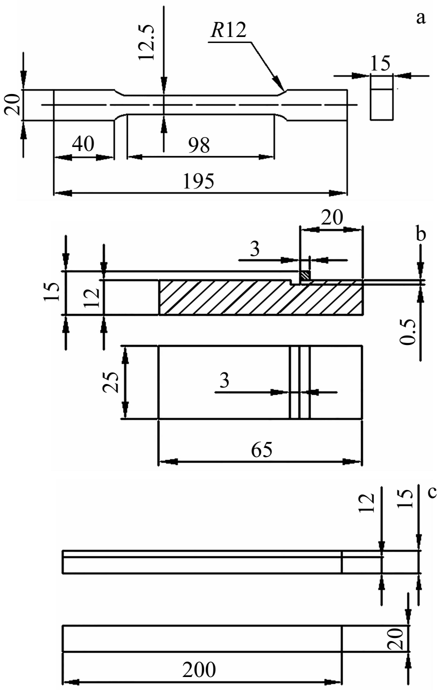


Fig.2 Dimensions of tensile test specimen (a), shear test specimen (b), and bending test specimen (c) (mm)

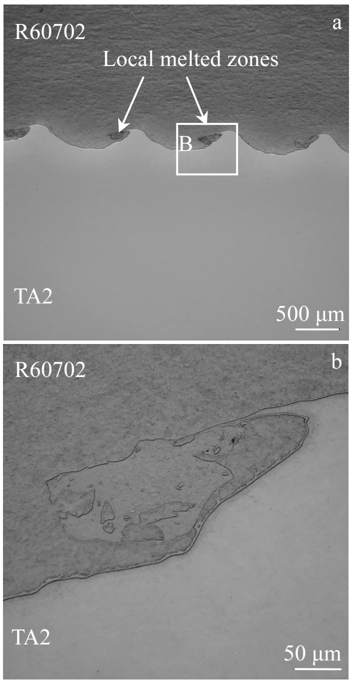


Fig.3 OM microstructures of bonding interface of R60702/TA2 composite plate (a) and enlarged view of position B in Fig.3a (b)

the interface have a period of 1086 μm and a height of 269 μm. It can also be observed from Fig.3a that local melted zones exist at the front of wave crests with a width of about 120 μm and a length of about 210 μm. Its enlarged figure is shown in Fig.3b. During the explosive welding, the high kinetic energy of impacting plates is dissipated in the form of heat, which causes local melting. Under the impact of shock wave, the local melted zones are distributed at the interface along the explosion direction. As shown in Fig.3, there is no intermetallic layer at the interface, which can deteriorate the bonding quality[12]. It indicates that the R60702/TA2 composite plate exhibits a sound joint after explosive welding.

The EDS line scan for Zr and Ti elements was carried out to further investigate the element distribution near the bonding interface after explosive welding. The scanning path and analysis results are shown in Fig.4. Apparently, there is a short diffusion layer of about 2.5 μm across the bonding interface. Although short, the diffusion layer contributes to the metallurgical bonding between Zr and Ti elements.

The microstructure of TA2 near the bonding interface after explosive welding is shown in Fig.5a. Dramatic plastic deformation occurs on the TA2 side. The grains are distorted and elongated into a streamlined morphology along the explosion direction due to the violent collision induced by the explosion. As shown in Fig.5b, the fine equiaxed grain zone is distributed along the wavy interface with a width of approximately 15 μm. Since the microstructure adjacent to the interface is strongly deformed, the initial coarse grains are

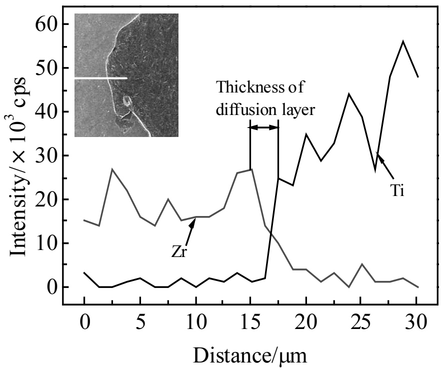


Fig.4 Element line scan results of bonding interface

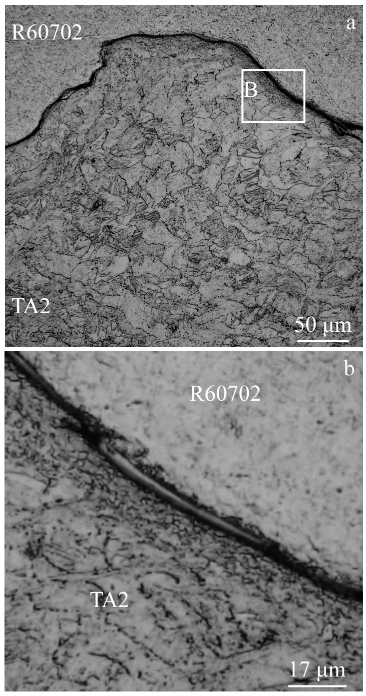


Fig.5 Microstructures of TA2 near the interface (a) and enlarged view of fine equiaxed grain zone of position B in Fig.5a (b)

broken up into small grains. Besides, the temperature of the bonding interface rises fiercely during the collision and will remain for a while[19]. Though the time is short, it creates an annealing effect. Thereby, the fine equiaxed grains are obtained as a result of plastic deformation and recrystallization.

Adiabatic shear bands are observed in the microstructure of TA2 side, as indicated by the arrows in Fig.6. These oblique bands originate from the bonding interface and gradually disappear inside TA2. They are inclined at approximately 45° to the bonding interface. During the explosive welding, local shear deformation along the narrow areas at a high rate results in the formation of adiabatic shear bands. The deformation

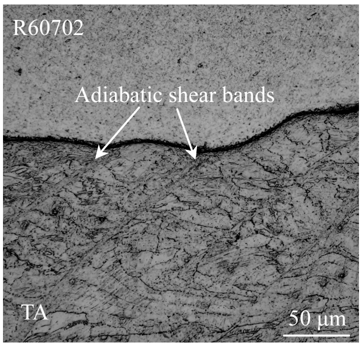


Fig.6 Adiabatic shear bands in TA2 side

process can be considered as adiabatic because the temperature rises sharply and remains in a narrow zone. This phenomenon was also observed in the explosively welded Ti/steel composite plate[20].

2.2 Microstructure characterization after heat treatment

It can be clearly seen from Fig.7 that a diffusion layer exists at the bonding interface after heat treatment. Although it is impossible to form intermetallic compounds at the interface according to the Zr-Ti binary phase diagram, the heat treatment can promote the element diffusion to form the infinite Zr-Ti solid solution. It was also demonstrated that there is no distinct difference in the crystalline structure between Zr-Ti alloy and pure Ti according to the X-ray diffraction[21]. So the diffusion layer may consist of the Zr-Ti solid solution.

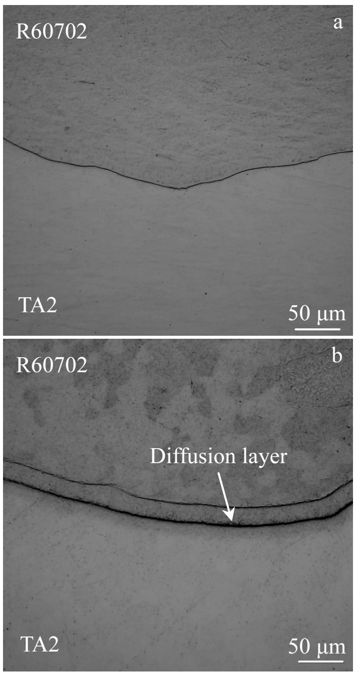


Fig.7 OM images of bonding interface before (a) and after (b) heat treatment

In order to identify the diffusion layer, EDS line scan and point analysis were conducted across the interface. The specified path and the results of line scan are shown in Fig.8. The intensity-distance curves of Zr and Ti elements both present a stepwise change and the thickness of diffusion layer increases to 23 μm. Table 3 gives the point analysis results. It can be concluded that the diffusion layer consists of the Zr-Ti solid solution.

Fig.9 shows the microstructure on the TA2 side near the bonding interface after heat treatment. Obviously, the heat treatment has a significant effect on the microstructure near the interface. The uneven and extended grains grow into the equiaxed hexagon grains and the adiabatic shear bands disappear completely. The microstructure becomes more homogeneous through annealing. Therefore, the recovery and recrystallization must occur during the heat treatment.

2.3 Microhardness test

The microhardness profile near the bonding interface before and after heat treatment is shown in Fig.10. Whether heat treat is performed or not, the maximum microhardness value is obtained at the position closest to the bonding interface on both Zr and Ti sides. Before heat treatment, the peak value

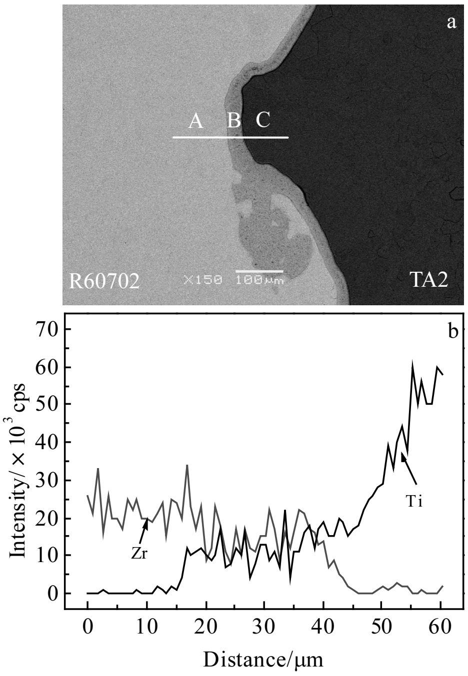


Fig.8 EDS analysis path (a) and line scan results across the bonding interface (b) after heat treatment

Table 3 EDS analysis results of points in Fig.8a (at%)

Point	Zr	Ti
A	99.30	0.70
B	46.71	53.29
C	0.40	99.60

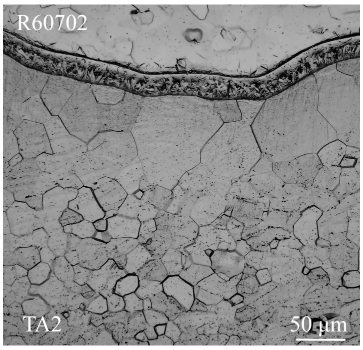


Fig.9 OM microstructure of TA2 near the interface after heat treatment

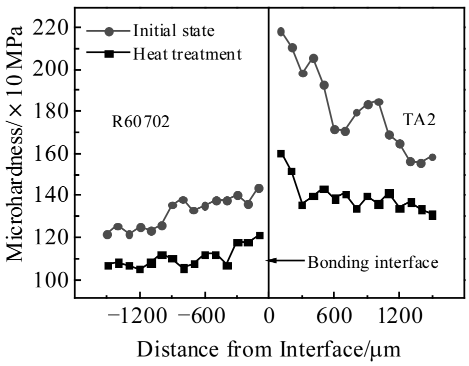


Fig.10 Microhardness profile near the bonding interface before and after heat treatment

reaches 1440.8 MPa on the Zr side and 2185.9 MPa on the TA2 side. This can be attributed to the high-density dislocation and work hardening effect resulted from the severe plastic deformation near the interface. The microhardness values of both sides decrease gradually with increasing the distance from the bonding interface and begin to stabilize far from the interface as a result of the diminishing plastic deformation. After heat treatment, the overall microhardness values on Zr and Ti sides both decline. It is due to the recovery and recrystallization of grains which can result in the elimination of residual stress and a more homogeneous microstructure. The microhardness value on the Zr-Ti solid solution in the diffusion layer is apparently higher than that of the pure Zr and Ti owing to the solution strengthening effect. In this test, the microhardness value of point B in Fig.8a is 2289 MPa, which is much higher than that on the pure Zr and Ti sides after heat treatment.

2.4 Tensile test

Fig.11 shows the stress-strain curves of the explosively welded R60702/TA2 composite plate before and after heat treatment. It can be observed that the tensile strength in the initial state is 486 MPa, and then it decreases to 451 MPa after heat treatment. Since recovery and recrystallization occur during heat treatment, the degree of work hardening and

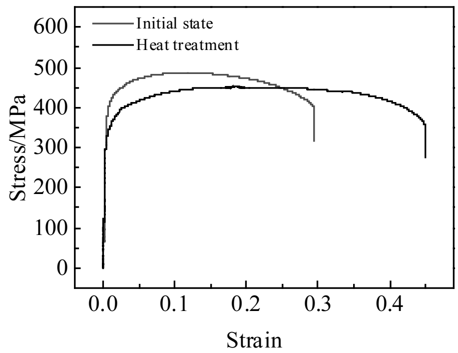


Fig.11 Stress-strain curves of the explosively welded R60702/TA2 composite plate before and after heat treatment

residual stress is both lowered considerably, which in turn leads to the reduction of tensile strength. But the elongation after heat treatment has a sharp increase, which is closely related to the formation of the diffusion layer at the bonding interface. The diffusion layer can transfer part of the loads and bear additional plastic deformation during the tensile test[22], thereby raising the elongation of the explosively welded R60702/TA2 composite plate.

To investigate the influence of heat treatment on the tensile fractography, SEM observation was conducted. The fracture morphologies of the broken tensile specimens before and after heat treatment are illustrated in Fig.12. The tensile specimens present typical characteristics of ductile fracture since a large number of dimples are observed on the fracture surfaces of both Zr and Ti sides under different conditions. After heat treatment, there is a significant increase in the size and depth of ductile dimples on the two sides. It illustrates that the specimen after heat treatment undergoes more sufficient plastic deformation before fracture and exhibits better plastic and ductile properties than the initial one.

2.5 Shear test

The stress-displacement curves of the explosively welded R60702/TA2 composite plate before and after heat treatment are displayed in Fig.13a. The shear strength of Zr-Ti bonding interface is 285 MPa in the initial state and then it drops to 257 MPa after heat treatment. This phenomenon can be explained by the elimination of work hardening effect and residual stress as a result of the recovery and recrystallization in the microstructure. But the shear strength does not decline dramatically after heat treatment, because the heat treatment promotes the element diffusion. Thus the bonding forces between Zr and Ti atoms near the interface are enhanced, which conduces to increasing the shear strength. The shear strength of the Zr-Ti bonding interface acquired in this study is higher than that of the explosively welded Zr/Ti/steel tri-metallic composite plate (170 MPa)[23]. The fractography of the broken shear test specimens and the EDS point analysis

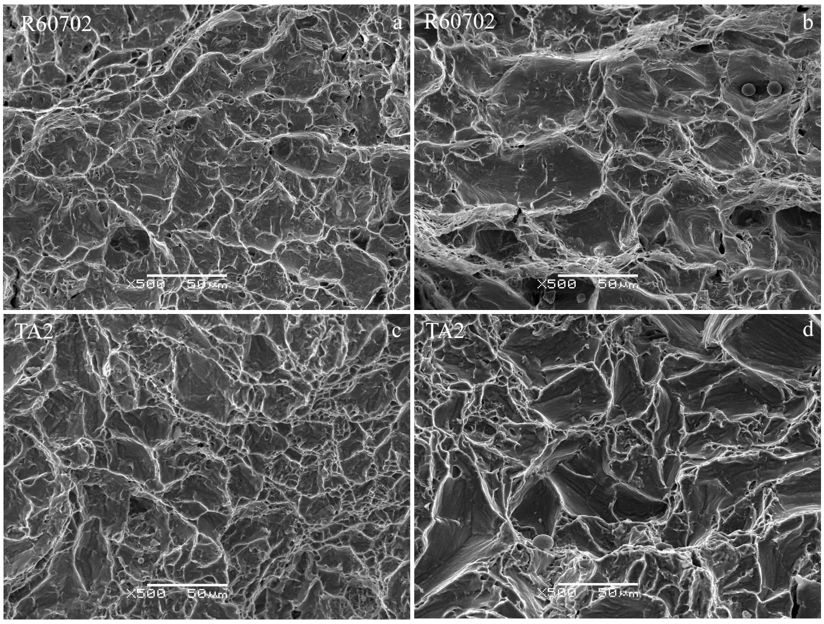
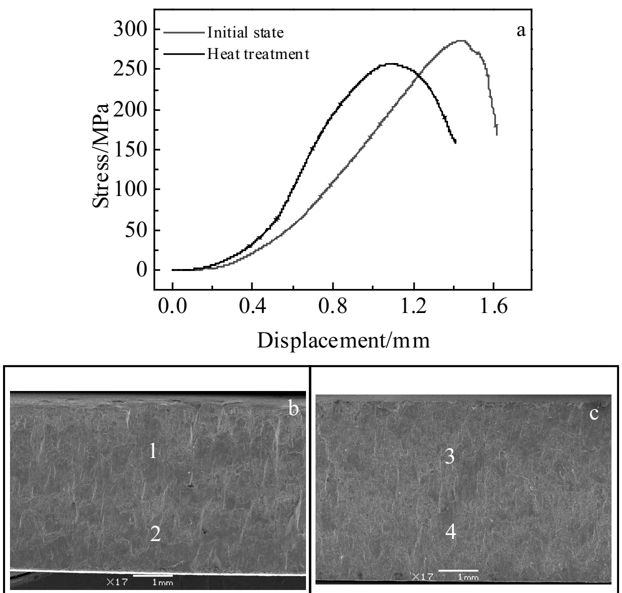


Fig.12 Tensile fractographs of R60702 before (a) and after (b) heat treatment; TA2 before (c) and after (d) heat treatment



Point	Zr/at%	Ti/at%
1	99.44	0.56
2	99.78	0.22

Point	Zr/at%	Ti/at%
3	99.25	0.75
4	99.54	0.46

Fig.13 Shear test results of the Zr-Ti bonding interface: stress-displacement curve (a); fractography and EDS results before (b) and after (c) heat treatment

results before and after heat treatment are shown in Fig.13b and Fig.13c, respectively. The EDS results indicate that the fracture mainly occurs on the Zr side no matter the specimen is heat treated or not. In the initial state, the microhardness close to the interface and the overall microhardness on the Ti side are higher than that on the Zr side. After heat treatment, the Zr-Ti solid solution formed at the interface has good ductility as its crystalline structure is similar to that of pure Zr and Ti. And its microhardness value is much greater than that on the Zr side on account of the solution strengthening effect. Therefore, it tends to crack from the Zr side rather than from the bonding interface or the Ti side during shear test. On the basis of the obtained results, it can be concluded that the interface of explosively welded R60702/TA2 composite plate has good bonding strength.

The fracture morphologies of broken shear test specimens before and after heat treatment are shown in Fig.14. It can be found that there are lots of parabolic shearing dimples and tearing edges on the fracture surfaces, indicating the ductile fracture of specimens. The size and depth of dimples in the initial state are lower than those after heat treatment. It can be ascribed to the limited deformation capacity of grains because the grains near the interface have been strongly deformed during the explosive welding. Thus the specimen without heat treatment tends to fracture easily when the grains have small deformations, which results in the formation of small and shallow dimples. After heat treatment, the increase in the size and depth of dimples implies that the plasticity and ductility of R60702/TA2 composite plate are improved through annealing.

2.6 Bending test

Fig.15 shows the macrographs of bending test results. The internal bending and external bending samples after heat treatment are both bent to the angle of 180° without cracks

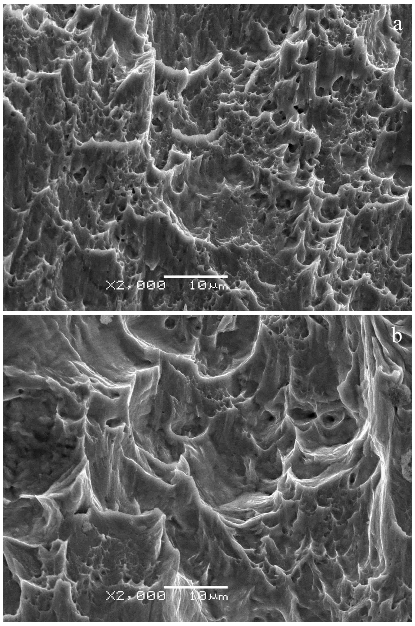


Fig.14 Fractographs of shear test specimen before (a) and after (b) heat treatment

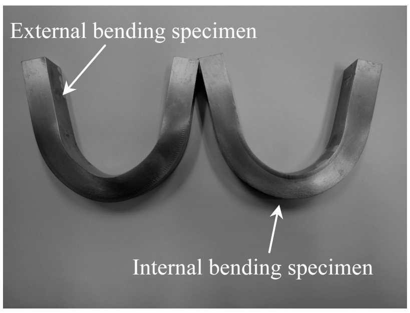


Fig.15 Specimens after bending test

and delaminations at the bonding interface. It reveals that the explosively welded R60702/TA2 composite plate has good bending performance after heat treatment.

3 Conclusions

1) The R60702 plate and TA2 plate are successfully bonded together through explosive welding. The bonding interface presents a wavy morphology with no defects. Severe plastic deformation occurs in the microstructure close to the interface. Local melted zones, fine equiaxed grain area and adiabatic shear bands are observed at the bonding interface.

2) There is slight element diffusion at the interface after explosive welding. Through heat treatment, a thick diffusion layer of 23 um is formed at the interface. The diffusion layer consists of the Zr-Ti solid solution. The recovery and recrystallization occurring in the heat treatment process improve the microstructure.

3) Before heat treatment, the maximum microhardness is obtained at the region closest to the bonding interface due to the high density of dislocation and work hardening effect. The values decrease with increasing the distance to the interface due to the diminishing deformation. After heat treatment, the overall microhardness values decline due to the improved microstructure and the elimination of residual stress.

4) After heat treatment, the tensile strength and shear strength both have a decrease compared with in the initial state since the degree of work hardening and residual stress decrease considerably. But the plasticity and ductility of R60702/TA2 composite plate are improved through heat treatment. And the R60702/TA2 composite plate after annealing shows good bending performance.

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R60702/TA2 爆炸焊接复合板的微观组织及力学性能

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摘　要：通过爆炸焊接的方法实现了 R60702 板与 TA2 板的结合。利用光学显微镜、扫描电镜、能谱仪、显微硬度计对热处理前后锆-钛结合界面的微观组织、元素扩散、显微硬度进行了分析；研究了热处理前后复合板的力学性能和断口形貌。结果表明：爆炸焊接后，锆-钛结合界面呈波状，界面附近产生塑性变形和轻微的元素扩散，随着塑性变形的减弱，界面两侧显微硬度也逐渐减小。热处理后，界面元素扩散明显，组织发生再结晶，显微硬度、抗拉强度、抗剪切强度较热处理前降低，而复合板的塑韧性得到提高。热处理后的复合板弯曲性能良好。

关键词：锆-钛复合板；热处理；微观组织；力学性能

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