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ARTICLE

Explosive Cladding and Hot Pressing of Ti/Al/Ti Laminates

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Abstract: Ti/Al/Ti laminates were prepared by an explosive cladding method. Then hot pressing was employed to further process the laminates. The results indicate that both linear and wavy bonding interfaces coexist and element diffusion occurs in the interfacial zone between the titanium and aluminum layers after explosive cladding. After 25 h heat treatment and 2.5 h hot pressing, the aluminum layer is consumed completely. The reaction layer consists of Al_3Ti and Ti_2Al_5 phase.

Key words: Ti/Al/Ti laminate; explosive cladding; bonding interface; hot pressing

New materials with high strength and excellent high-temperature behavior play an important role in aerospace engineering. Conventional titanium alloys have a higher strength to weight ratio than other metals, but because of their decreased strength at high temperatures (≥ 700 ℃) they can not meet the engineering requirements for aerospace applications. Compared to titanium alloys, nickel-based alloys have excellent high-temperature mechanical properties. However, the density of these alloys is too high to meet the light weight requirements for spacecraft.

Ti/Al intermetallics exhibit high strength at temperatures up to 900 ℃ and their density is half that of nickel-based alloys. Of the possible Ti/Al intermetallics, Al_3Ti has the lowest density at 3.36 g/cm^3, the best high temperature oxidation resistance, and the highest strength to mass ratio. Therefore, Al_3Ti or Al_3Ti/Ti laminated composites have excellent potential for many applications, especially in the field of aerospace [1,2].

Because of their light weight and excellent mechanical properties, $Ti/Al_3Ti/Ti$ laminated composites were considered as the ideal raw materials for high-temperature parts in the aerospace engineering. One problem with these composite materials is that they are difficult to fabricate into complex parts owing to their brittleness. Fortunately, the Ti/Al laminated composites are suitable for plastic forming to fabricate parts with complicated shapes. After a plastic deformation procedure, heat treatment and hot pressing were used to further process laminated parts, resulting in Ti/Al_3Ti laminated parts[3,4]. In addition, Ti/Al/Ti laminated composites have better bonding interfaces and less interfacial cracks, compared with Ti/Al laminated composite. The purpose of this research, therefore, is to investigate the preparation and subsequent hot pressing of Ti/Al/Ti laminated composites[5].

In our investigations, an explosive cladding method was employed to fabricate the Ti/Al/Ti laminated composites using titanium and aluminum plates as blanks[6,7]. Then, the laminated composites were hot pressed by the gas-pressure bulging process. In the hot press experiment, the effects of temperature and time on the microstructure of the interface were investigated and the phases at the interface were characterized. The results about the explosive cladding with subsequent hot press processing have an important significance on the fabrication of practical $Ti/Al_3Ti/Ti$ laminates.

1 Experiment

Aluminum and titanium plates with dimensions of 300 mm × 350 mm × 0.5 mm were the raw materials used to prepare the Ti/Al/Ti laminates. The aluminum sheet was sandwiched

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between the titanium sheets. The gap between the titanium layer and the aluminum layer was 0.5 mm, as shown in Fig.1.

The assembly was fixed on the cement foundation. An iron plate of 5 mm thickness, used as the impact object, was oiled and then placed on the assembly. The distance between the iron plate and the assembly was set at 5 mm. An emulsion explosive was selected as main composition. The detonation velocity ranged from 2000 m/s to 3000 m/s (detonation wave speed through the explosive) [8,9]. Sodium chloride was added to the explosive to lower the detonation velocity. Electrical blasting caps were used to detonate explosives on the iron plate. Detonation wave and kinetic energy of explosion product were transferred to the impact plate. The impact plate forced high-speed movement of flyer pipe towards base pipe. Plastic deformation, local metal melting and atomic mutual diffusion subsequently occurred at the explosive cladding interface, and finally metallurgical bonding was formed.

Metal "sandwich" samples were heat treated at 650 ℃ for 25 h after the explosive cladding process to promote the formation of intermetallic compounds at the metal interfaces. Then the samples were heated in the vacuum furnace at 650 ℃ under 2 MPa gas pressure to eliminate the residual aluminum layer after the heat treatment. Hot pressing time of 1, 1.5, 2, 2.5 and 3 h were selected to study the influence of time on the removal of residual aluminum layers and porosity[10, 11]. Microstructural observations of hot-pressed specimens were performed using scanning electron microscope and energy-dispersive X-ray spectroscopy. The intermetallic phases were characterized using X-ray diffraction.

2 Results and Discussion

2.1 Morphology and element distribution of the bonding interface

Fig.2 shows the micromorphology of Ti/Al/Ti laminate composites prepared by explosive cladding. The results show that the bonding at the Ti/Al interface has a wavy morphology. Because of this wavy interface, the total bonding interface surface area of Ti/Al/Ti laminate composites increases, although the wavy interface is more pronounced near the explosives. This obvious wavy interface is attributed to more detonation energy acting on the first layer of the interface. It is clear that no crack and microholes are formed near the interface, resulting in excellent bonding between titanium layers and aluminum layers [12].

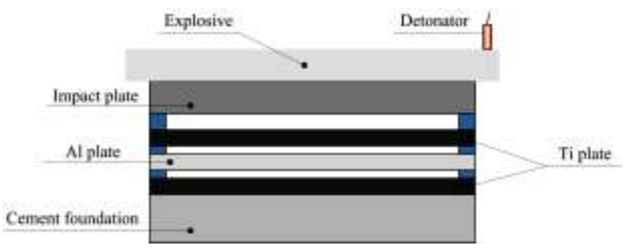

Fig.1 Explosive cladding experiment of Ti/Al/Ti laminate composites

Fig.3 shows the distribution of aluminum and titanium at the bonding interface using EDX method. The curves indicate the content of aluminum and titanium elements along the scanning line. The distribution of titanium element decreases gradually from the titanium layer to one side of the aluminum layer for the first bonding interface. For the second interface, the titanium composition shows the same tendency. Concurrently, the aluminum content increases gradually from 0% to 100%. For this reason, there is a certain width of element mutual diffusion layer. Hence, the metallurgical bonding is observed at the interface of Ti/Al/Ti laminate composites.

2.2 Heat treatment of Ti/Al/Ti laminates

Fig.4 shows SEM micrographs of Ti/Al/Ti laminates after heat treating at 650 ℃ for 25 h. The thickness of the

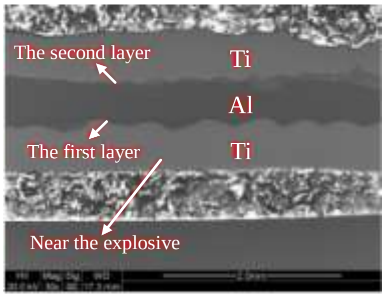

Fig.2 Bonding interface of Ti/Al/Ti laminate composites

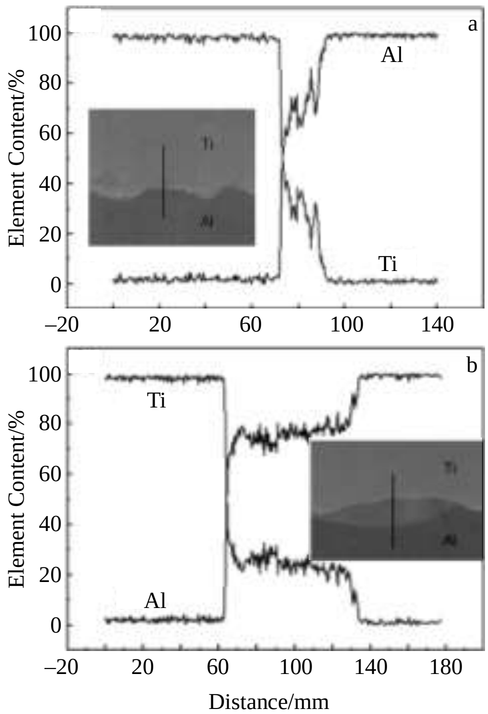

Fig.3 EDX line scanning analysis results of the interface: (a) the first layer and (b) the second layer

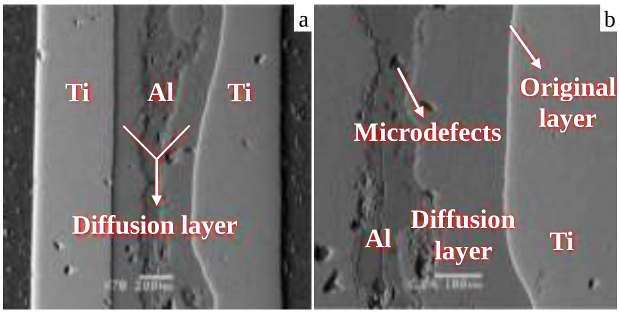

Fig.4 SEM images of Ti/Al/Ti laminates after heat treatment

aluminum layer is reduced obviously, but the mutual diffusion layers are increased.

Moreover, we observed that there are fewer microstructure defects near the original interfacial zone and more microstructure defects close to the aluminum. The occurrence of the microdefects is possibly due to the reactions between aluminum and titanium with atomic diffusion leading to holes in the aluminum layer. With the forward movement of the reaction interface, aluminum is consumed gradually, but these micro-holes are pushed to the middle area of the aluminum layer and finally connect to form obvious cracks. Fig.5 illustrates the element distribution results in the diffusion layer after heat treatment. Diffusion reactions evidently occurs in the transition layer. The sharp decrease in signal intensity of both aluminum and titanium at the position of 270 μm can probably be attributed to the microholes and cracks in this region.

During heat treatment the reaction of aluminum and titanium to produce the intermetallic Al_3Ti occurs between the titanium and aluminum layers. The diffusion mechanisms between aluminum and titanium layer consist of both solid-solid state and solid-liquid state mechanisms.

For the solid-solid reaction mechanism, Hao et al. proposed a model of the Ti/Al diffusion couple [13]. According to the Ti-Al binary phase diagram, the solubility of the titanium in aluminum is only 0.12 at% between 520 and 650 ℃. In the range of temperature studied in this work (520~650 ℃), the solubility of aluminum in titanium is 11.7 at%. Consequently, the Al(Ti) solid solution saturates much earlier than the Ti(Al). The preferential nucleation of Al_3Ti generated in the interface of the Ti/Al laminate occurs by a solid-liquid reaction mechanism. The formation of Al_3Ti occurs between aluminum and titanium accompanied by the release of heat. Thus, the temperature of local area might be up to 1180 ℃, which is sufficient to melt aluminum at the reaction interface [14].

2.3 Influence of hot pressing time on the microstructure of the Ti/Al/Ti laminates

Fig.6 shows SEM images of the diffusion layer thickness of Ti/Al/Ti laminate samples after hot pressing at 650 ℃ for different time. The thickness of diffusion layer increases with hot pressing time. There are only thin diffusion layers in

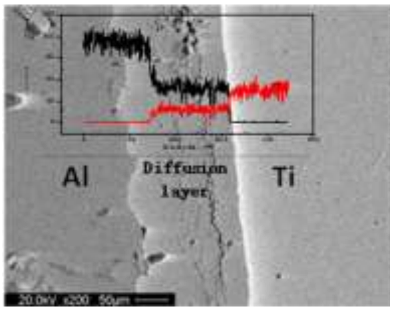

Fig.5 EDX line scanning analysis results of the diffusion layer after the heat treatment

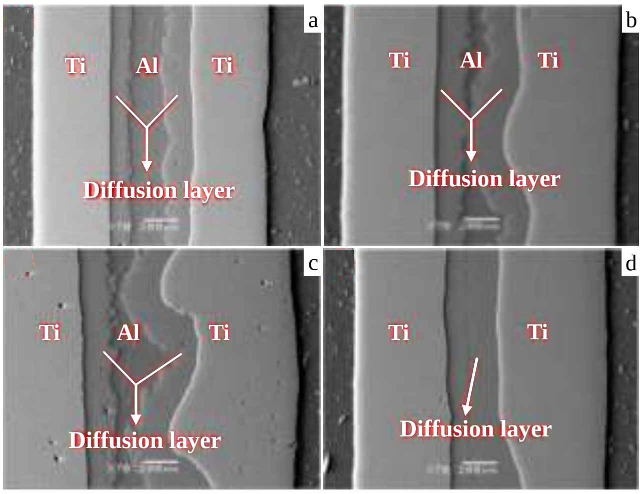

Fig.6 SEM images of Ti/Al/Ti laminates after hot pressing at 650 ℃ for different time: (a) 1 h, (b) 1.5 h, (c) 2 h, and (d) 2.5 h

Fig.6a, but when the time increases to 2.5 h (Fig.6d), the diffusion layers are formed completely and the aluminum layer is almost totally consumed. After the hot pressing at 650 ℃ for 2.5 h, the microstructure of Ti/Al/Ti laminates is improved under the action of high pressure and high temperature. However, there are still local cracks and loosening phenomenon. These defects are probably caused by the solid-liquid reaction, which makes aluminum melt instead of diffusing. In the subsequent cooling process, the melt position does not obtain the supplement of the aluminum.

Fig.7 illustrates the resulting diffusion layer after hot pressing at 650 ℃. It is clear that after the hot pressing for 2.5 h, the aluminum layer has been consumed sufficiently. In the diffusion layer, the proportion of atomic percent aluminum and titanium atomic percent is about three to one, the same as the atomic ratio in Al_3Ti.

XRD was employed to characterize the residual pure aluminum remains in the diffusion layer and to identify the specific phases in the diffusion layer. X-ray diffraction peaks of Al_3Ti and Ti_2Al_5 are evident in Fig.8, but there are no

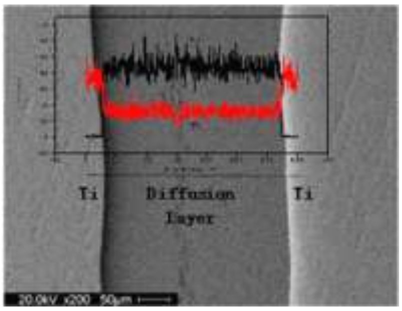

Fig. 7 EDX line scanning analysis results of the diffusion layer after hot pressing for 2.5 h

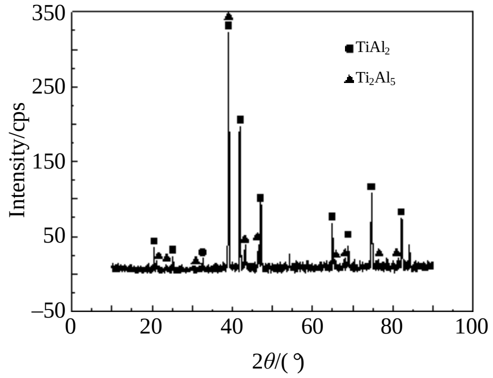

Fig. 8 XRD pattern of Ti/Al/Ti laminates after hot pressing for 2.5 h

diffraction peaks for pure aluminum. One possible reason for the formation of Ti_2Al_5 is that during the hot pressing process, when the aluminum layer is consumed totally, the aluminum in the $TiAl_3$ continues to diffuse to titanium particles, leading to the reduction of Al_3Ti and generation of Ti_2Al_5 at the interface. The diffusion-reaction equation is: $Al_3Ti+Ti \rightarrow TiAl+Ti_3Al+TiAl_2+Ti_2Al_5$. The normal diffusion reaction temperature ranges from 800 ℃ to 980 ℃, which is higher than the practical hot pressing temperature. But in the diffusion reaction process, the latent heat released by the diffusion process of aluminum layer may cause the localized heating (up to 1100 ℃), which leads to the diffusion of aluminum and the generation of Ti_2Al_5 in surrounding areas. In Fig.8, TiAl, Ti_3Al and $TiAl_2$ are not observed.

2.4 Fracture analysis of the Ti/Al/Ti laminates after the hot pressing

Ti/Al/Ti laminate samples are delaminated by shear force after the hot pressing process to observe the fracture morphology. The SEM micrograph (Fig.9a) shows that the fracture of the central diffusion layer is the transgranular cleavage without the dimples. Therefore, the results show that the fracture pattern is mainly caused by the distinct brittle characteristics of Ti-Al intermetallics at the interface of the laminates[15,16]. Furthermore, Fig.9b shows the fracture morphologies of samples after the hot pressing for 3 h. It is

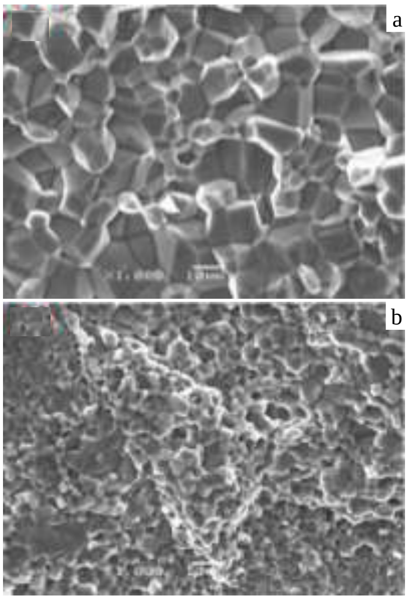

Fig. 9 Fracture morphologies of diffusion layer after hot pressing for 2.5 h (a) and 3 h (b)

obvious that, the grain size of the intermetallics at the interface of the laminates is significantly smaller than that of samples after hot pressing for 2.5 h. The generation of the small grain size is probably because of the existence of the new phase of Ti_2Al_5 at the interface of the laminates.

3 Conclusions

1) Ti/Al/Ti laminates are prepared by explosive cladding. The laminate has wavy and linear bonding interface.

2) The main reaction of titanium and aluminum to produce Al_3Ti occurs in the Ti/Al/Ti laminates. The reactive diffusion between aluminum and titanium layer consists of both solid-solid and solid-liquid reactions.

3) After hot pressing, the aluminum layer is consumed totally, leading to the generation of Ti_2Al_5 at the interface. The fracture morphology indicates that fracture pattern is mainly caused by the distinct brittle characteristics of Ti-Al intermetallics at the interface of the laminates.

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钛/铝/钛层状复合材料的爆炸复合制备及后续热压处理研究

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摘　要：以纯钛板与纯铝板为原料，通过爆炸复合法制备钛/铝/钛层状复合材料，之后采用热处理以及热压工艺对钛/铝/钛层状复合材料进行进一步处理。结果表明：复合板界面主要由波状界面和平直状界面构成，铝元素与钛元素在界面上发生了互扩散，界面结合性能优良，可以承受后续较大的二次塑性变形；热处理后的复合板界面发生明显扩散，在热处理 25 h 后热压 2.5 h 的铝层完全反应，扩散反应层主要由 $TiAl_3$ 相以及 Ti_2Al_5 相构成。

关键词：钛/铝/钛层状复合材料；爆炸复合；界面；热压处理

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