

Mechanical Properties and Interfacial Structure of Ti/Al Clad Plates Generated by Differential Temperature Rolling

Zichen Qi¹, Hong Xiao^{1,a}, Na Li², Chao Yu¹ and Zhongkai Ren¹

¹ National Engineering Research Center for Equipment and Technology of Cold Strip Rolling, Yanshan University, Qinhuangdao, Hebei, China

² College of Mechanical Engineering, Yanshan University, Qinhuangdao, Hebei, China.

^a xhh@ysu.edu.cn

Abstract. In this study, a Ti/Al clad plate was prepared by differential temperature rolling, where only the titanium layer is heated. The effects of the rolling reduction and Ti layer heating temperature on the shear strength and interface of Ti/Al clad plates were investigated. The results indicate that when the titanium layer was heated to 800 °C and the rolling reduction was 50%, the shear strength of the titanium/aluminum clad plates interface reached 107.5 MPa, which is close to the shear strength of aluminum matrix, and the fracture surface presented ductile fracture characteristics. During the heating process, an oxide layer was produced on the surface of the titanium plates. However, the oxide layer was completely broken with a large rolling reduction, and then, aluminum metal extruded into the cracks and made contact with fresh titanium metal. Under the action of high pressure and high temperature, Ti and Al atoms mutually diffuse so that the Ti/Al clad plates achieved a strong metallurgical bond.

1. Introduction

Preparation methods of the titanium/aluminum clad plates mainly include explosion compound, explosive welding, diffusion welding, and hot rolling bonding. Boronski [1] prepared the Al/Ti laminated composite plates by the method of explosive welding and studied the fracture toughness of the composite plates under low temperature. Lazurenko [2] prepared multilayer Ti/Al composites by the method of explosive welding and investigated the structure and transformation during heat treatment. The technology of explosive welding for preparing titanium/aluminum composite plates is very mature. However, the explosion welding process will produce seismic waves, noise and toxic gases, which are not conducive to large-scale production of clad plates. Obielodan [3] used the ultrasonic consolidation method to prepare titanium/aluminum clad plates and found that the resulting clad plates had a relatively low bonding strength. Compared to other methods, the method of hot rolling compound has the advantages of stable product quality, simple equipment, easy automation and mass production.

Currently, the preparation of Ti/Al composite plates by hot rolling has become popular. However, the metal properties (deformation resistance, plasticity, thermal conductivity, melting point, etc.) of titanium and aluminum are quite different, and two problems are found in the preparation process; the first is that the deformation of titanium/aluminum after hot rolling is extremely uncoordinated, and the second is that the bonding strength of the prepared composite plate is low. Chen [4] found that the deformation of the titanium and aluminum layers is uncoordinated in the hot rolling process of Ti /Al composite plates. Ma [5] prepared Al/Ti composite laminates by hot rolling and found that the



deformation of titanium and aluminum became increasingly uncoordinated as the rolling temperature increased. When adopting the method of hot rolling directly, due to the low melting point of aluminum, the deformation resistance of titanium is much greater than that of aluminum when the titanium/aluminum composite plates are rolled at a temperature below 600 °C, and the deformation of the titanium layer after rolling is much smaller than that of the aluminum layer, which leads to extremely uncoordinated deformation. Yu [6] who studied the effect of annealing on the microstructural and mechanical properties of Al/Ti/Al laminate sheets found that the interface contained TiAl_3 and other compounds, affecting the bonding properties of composite panels in the processing of hot-rolled Ti/Al clad plates.

To improve the deformation coordination and the bonding strength of titanium/aluminum clad plates, a new method for the preparation of titanium /aluminum composite plates was established in this study. Ti/Al clad plates were prepared by rolling at differential temperatures, where only the titanium layer is heated. The titanium plate was heated to a high temperature to allow for optimal plasticity and to greatly reduce the deformation resistance of titanium, which made the deformation resistance of the titanium plate become close to the deformation resistance of the aluminum plate at room temperature, and then, the effects of the rolling reduction and Ti layer heating temperature on the shear strength and interface of the Ti/Al clad plates were investigated.

The new method used in this study can also provide reference for the composite rolling of two or three kinds of metals, such as Ti/Cu, Ti/Mg and Al/Ti/Mg [7], which have greatly different physical and chemical properties.

2. Experimental

The materials used in the experiments were commercial-purity titanium TA1 sheets and aluminum alloy AA6061 sheets, both with a thickness of 2 mm. The as-received materials were cut in the transverse direction to produce 100 mm×60 mm pieces. To eliminate the internal stress and work-hardening in sheet metal, the TA1 and AA6061 were annealed. AA6061 aluminum alloy sheets were annealed at 350°C for 2 h and then air-cooled. TA1 sheets were annealed at 780°C for 2 h and then air-cooled.

The surfaces of the annealed TA1 plates and AA6061 plates were treated to remove grease, dirt and oxide to facilitate the combination of dissimilar metals. In this experiment, grease, dirt and oxides on the surfaces of the metals were removed by use of a grinding machine, and then, the surfaces were repeatedly cleaned with acetone and alcohol and then immediately dried. To be rolled into the rolling mill at the same time, the heated titanium plates needed to be combined with the aluminum plate, which was at room temperature. However, due to the thinness of the titanium plates, a delay of a few seconds would lead to a large temperature drop, which affects the objectivity of the experimental results. Therefore, in the rolling process, a piece of iron was first put into the resistance furnace and heated to the rolling temperature of the titanium plates, and then, the titanium plate was put into the resistance furnace on the iron plate for 5 minutes. Five minutes later, the iron and titanium plates were removed to the entrance of the rolling mill. Then, the iron plate played a role in the heat preservation of the titanium plates. Finally, the heated titanium plate and the aluminum plate were pushed at room temperature into the rolling mill with the guide plate. The schematic diagram for rolling Ti/Al clad plates at differential temperature is shown in Figure 1. The AA6061 plates were at room temperature. The TA1 plates were heated in a furnace for 5 min at temperatures of 500°C, 600°C, 700°C, 800°C and 900°C. The reductions were 20%, 25%, 29%, 34% and 50%. The parameters for the two-rolling mills in the experiment were the following: the roll size was $\phi 200 \text{ mm} \times 200 \text{ mm}$ and rolling speed was 50mm / s.

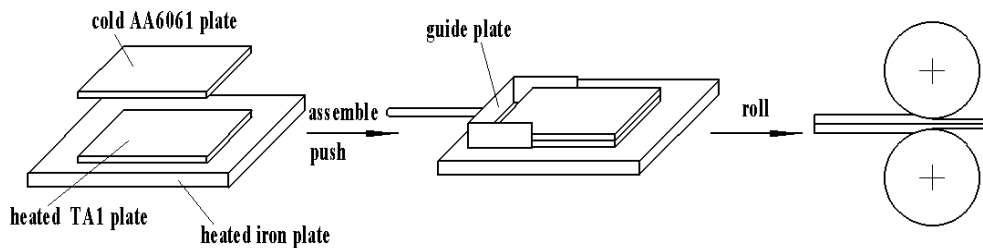


Figure 1. Schematic diagram for rolling Ti/Al clad plates.

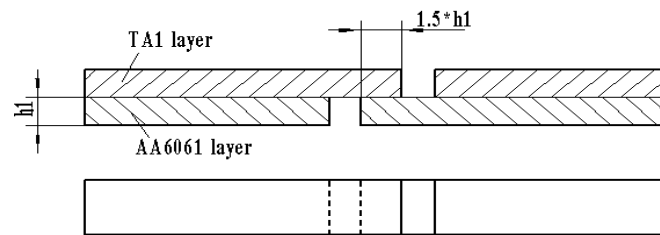


Figure 2. Schematic for the shear test.

The shear strength and the bonding rate of the two metals are the two basic parameters for measuring the properties of the clad plates as described by Gou [8]. Three samples for each plate were cut parallel to the rolling direction and were tested to obtain an average shear strength. The tension-shear test was carried out using an INSPEKT Table 100kN instrument. The stretching speed was 0.5 mm/min. Figure 2 shows the tension-shear test sample.

Specimens for microstructure examination were extracted along the rolling direction. The surfaces of the specimens were ground with emery papers up to No. 4000 and polished with an SiO_2 suspension with a particle size of $0.04 \mu\text{m}$, and then, the morphology of the fracture surface along the interface was observed using an optical microscope (OM, ZEISS Scope A1) and scanning electron microscope (SEM, ZEISS Sigma 700). The distribution of elements across the interface was examined by an SEM equipped with an energy dispersive spectrometer (EDS).

3. Results and discussion

3.1. Macroscopic bonding property test of the clad plates

Figure 3 and Figure 4 show the shear strength of Ti / Al clad plates for different Ti layer temperatures and different reductions, respectively. It can be seen from Figure 3 that the shear strength increases with an increase in the titanium layer temperature when the reduction is 29% and the temperature is between 500°C and 800°C . The shear strength of the composites interface decreases with an increase in temperature above 800°C . The bonding strength of the composite plates is low at temperatures below 700°C . When the temperature is higher than 700°C , the bonding strength is obviously improved, and the shear strength of the composite plates is the largest at 800°C . Therefore, the titanium layer is chosen to be heated to 800°C , and rolling is carried out with different reductions, as shown in Figure 4. The shear strength increases gradually with the increase in total reduction. The growth rate of shear strength is fast initially and then slows. When the reduction is less than 34%, the growth rate of the shear strength is relatively high. The growth rate is relatively low with a reduction above 34%. The shear strength of the titanium/aluminum clad plates interface reaches 107.5 MPa for a 50% reduction at 800°C , which is close to the shear strength of aluminum matrix. The shear strength obtained in this experiment is even higher than that of titanium/aluminum composite plates prepared by explosive compound; for example, Xia [9] prepared Ti/Al clad plates through the explosive compound, and the shear strength was approximately 73.2 MPa.

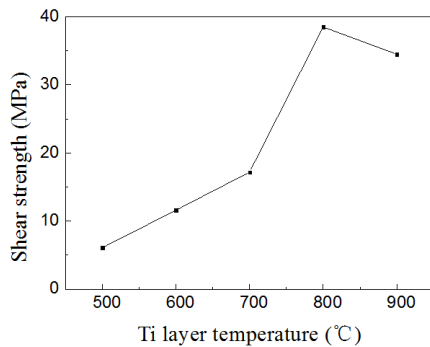


Figure 3. Effect of temperature on the shear strength of the composite plates with a 29% reduction.

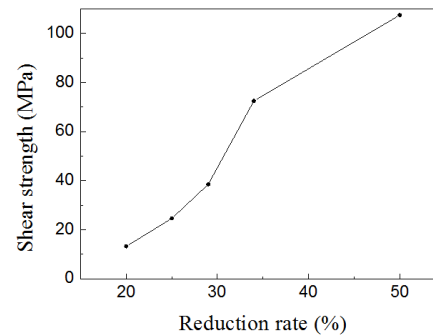


Figure 4. Effect of reduction on the shear strength of the composite plates at 800 °C.

3.2. Interfacial structure of Ti/Al clad plates

It can be seen from Figure 5a and 5c that some strip-shaped cracks are formed on the titanium side, corresponding to some strip-shaped protrusions formed on the aluminum side (Figure 5b and 5d). Table 1 displays the results for the elemental contents of Ti, Al and O at each point in Figure 5. According to the element point scanning analysis of the fracture surface, the elemental contents at point1 and point5 indicate that there is more than 90% Ti and approximately 5% O inside the strip-shaped cracks on the titanium side. The elemental contents at point2 and point6 shows that O and Ti compose approximately 35% and 60% of the fracture plane, respectively. Based on the above analysis, it can be determined that the fracture surface of the titanium side has a layer of titanium oxide. Fresh titanium metal is also exposed, and a small amount of aluminum metal adheres inside the strip-shaped cracks.

In addition to some strip-shaped protrusions formed on the aluminum side, the surface also contains many lumps (Figure 5b and 5d). The elemental contents at point3 and point8 indicate that the strip-shaped protrusions formed on the aluminum side are more than 90% Al and approximately 3% O. The elemental contents at point4 and point7 shows that in the lumps, Al, O and Ti account for approximately 45%, 25% and 25%, respectively. Based on the above analysis, it can be determined that the strip-shaped protrusions are formed by the extrusion of metal aluminum into the titanium cracks and the lumps are the oxide from the surface of the titanium layer adhered to the aluminum plate. From the comparison of Figure 5a and 5c, it can be seen that at a higher temperature for the titanium layer, more and wider cracks formed on the titanium after rolling. As a result, aluminum metal can come into contact with larger amounts of fresh titanium. Therefore, the increase in the temperature of the titanium plate can increase the area of the cracks and increase the bonding area of aluminum and fresh titanium metal, which is beneficial for the combination of the composite plates.

The fracture surface presents ductile fracture features with many dimples, see Figure 5e and 5f. The elemental contents at point9, point10 and point11 shows that the dimple is composed of more than 93% aluminum, and the O and Ti contents are very small. No strip-shaped cracks were found on the titanium side and no striped protrusions on the aluminum side, but there was still a small number of lumps, indicating that the oxide layer of titanium was completely broken with a large 50% rolling reduction at 800 °C. The metal aluminum is extruded into the cracks at a large pressure and forms a strong metallurgical bond with a large amount of fresh titanium. In this case, the bonding strength reached 107.5 MPa, basically close to the shear strength of aluminum matrix, and the titanium/aluminum clad plates have very good bonding properties.

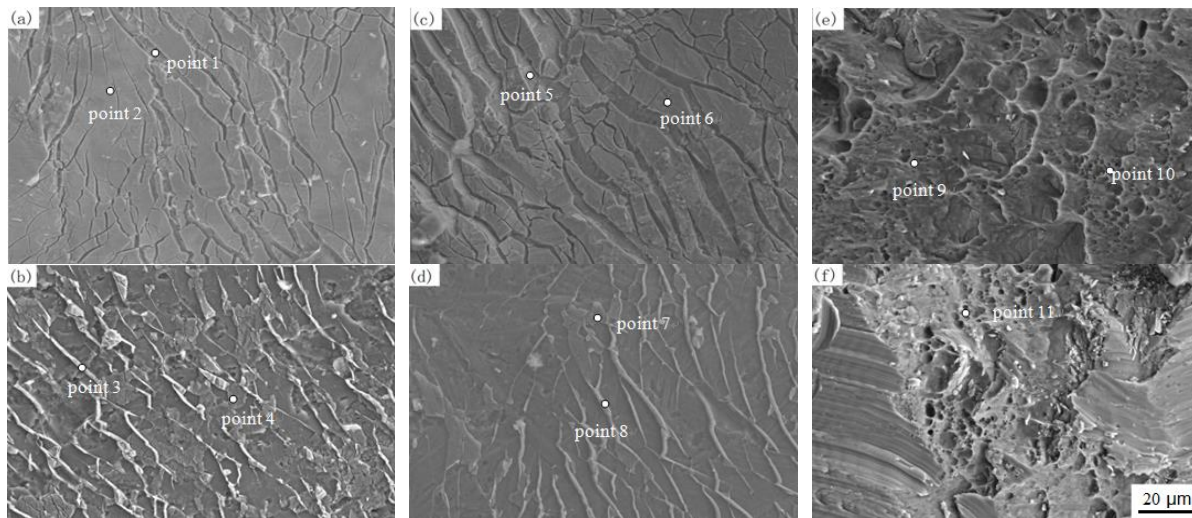


Figure 5. SEM images of the fracture surface and element point scanning under different processes (a) 500°C/29% reduction/Ti side, (b) 500°C/29% reduction/Al side, (c) 800°C/20% reduction/ Ti side, (d) 800°C/20% reduction/ Al side, (e) 800°C/50% reduction/ Ti side, (f) 800°C/50% reduction/ Al side.

Table 1. The elemental contents of Ti, Al and O from element point scanning (wt%).

	point1	point2	point3	point4	point5	point6	point7	point8	point9	point10	point11
Ti	94.06	66.20	0.54	22.61	91.19	60.24	29.10	1.37	0.76	0.87	0.14
Al	0.38	0.44	93.95	47.31	0.42	0.31	39.37	92.18	94.71	93.56	94.60
O	4.54	32.14	3.38	24.35	6.53	37.79	28.15	2.37	0.15	0.42	0.49

Figure 6 shows the SEM image and element line scan of the bonding interface for a 50% reduction at 800°C. It can be seen from Figure 6a that there is a gray stripe in the upper half of the bonding interface and a crack is present, but the lower part does not contain a crack. The upper and lower parts are subjected to element line scanning, and the results are shown in Figure. 6b and 6c. Both the Ti and O distributions exhibit a platform with a width of approximately 2 μm , indicating that the gray stripe is a layer of titanium oxide. There is no O elemental distribution at the bonding interface of line 2, and the platform of Ti element is not present. It can be determined that there is no titanium oxide in the lower half of the interface. Figure 7c shows that the mutual diffusion depth of Ti and Al is approximately 2 μm . Based on the above analysis, the oxide layer of titanium at the interface of Ti/Al clad plates is broken with a large 50% rolling reduction at 800°C, and then, metal aluminum is extruded into the cracks and comes into contact with fresh titanium metal. Finally, the Ti/Al clad plates achieve a solid metallurgical bonding with Ti and Al atom mutual diffusion under high pressure and high temperature.

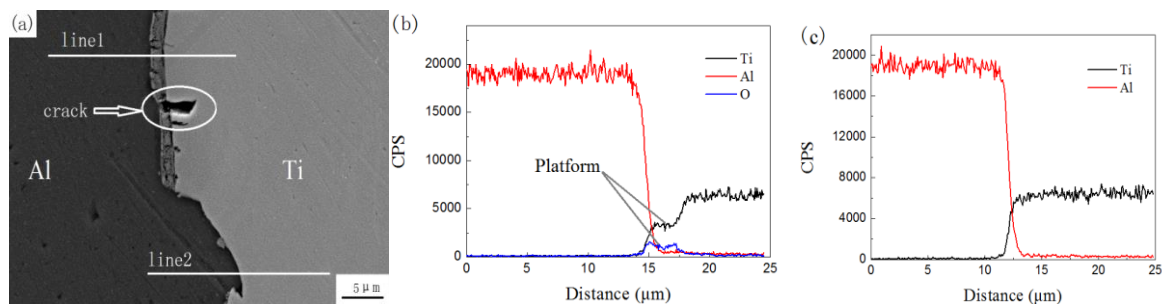


Figure 6. SEM image and element line scan of the bonding interface for a 50% reduction at 800°C (a) SEM image of the bonding interface, (b) (c) Elemental diffusion on line 1 and line 2, respectively.

4. Conclusions

- (1) When the titanium layer was heated to 800°C and the rolling reduction was 50%, the shear strength of the titanium/aluminum clad plates reached 107.5 MPa, which was close to the shear strength of aluminum matrix, and the fracture surface presented ductile fracture characteristics.
- (2) During the heating process, the oxide layer was produced on the surface of the titanium plates. However, in a large rolling reduction, the oxide layer was broken in large area, and then, the metal aluminum extruded into the cracks and came into contact with fresh titanium metal. Finally, the Ti/Al clad plates achieved a solid metallurgical bond with Ti and Al atoms mutually diffusing under high pressure and high temperature.

Acknowledgments

The project was supported by the Natural Science Foundation of HeBei Province (E2015203311) and the National Natural Science Foundation of China (No. 51474190).

References

- [1] Boroński D, Kotyk M and Maćkowiak P 2016 Fracture Toughness of Explosively Welded Al/Ti Layered Material in Cryogenic Conditions *Procedia Structural Integrity* **2** 3764-71.
- [2] Lazurenko DV, Bataev IA, Mali VI, Bataev AA, Maliutina IN, Lozhkin VS, Esikov MA and Jorge AMJ 2016 Explosively welded multilayer Ti-Al composites: Structure and transformation during heat treatment *Materials & Design* **102** 122-30.
- [3] Obielodan JO, Stucker BE, Martinez E, Martinez JL, Hernandez DH, Ramirez DA and Murr LE 2011 Optimization of the shear strengths of ultrasonically consolidated Ti/Al 3003 dual-material structures *Journal of Materials Processing Technology* **211** 988–95.
- [4] Chen ZJ, Chen QZ, Huang GJ and Liu XF 2012 Research on Roll Bonding Technology and Microstructure of Al/Ti/Al Three-layer Clad Sheet Fabricated by Hot Rolling *Materials Review* **26** 106-9.
- [5] Ma M, Huo P, Liu WC, Wang GJ and Wang DM 2015 Microstructure and mechanical properties of Al/Ti/Al laminated composites prepared by roll bonding *Materials Science & Engineering A* **636** 301-10.
- [6] Yu HL, Lu C, Tieu AK, Li HJ, Godbole A and Kong C 2016 Annealing effect on microstructure and mechanical properties of Al/Ti/Al laminate sheets *Materials Science & Engineering A* **660** 195-204.
- [7] Parisa DM and Beitllah E 2015 Microstructure and mechanical properties of Tri-metal Al/Ti/Mg laminated composite processed by accumulative roll bonding *Materials Science & Engineering A* **628** 135-42.
- [8] Gou JF 1995 Property analysis and application of the clad plate *Petro-Chemical Equipment Technology* **16** 49–52.
- [9] Xia HB, Wang SG and Ben HF 2013 Microstructure and Mechanical Properties of Composite Plate between Pure Titanium and Aluminum Alloy with Explosive Welding *Pressure Vessel Technology* **30** 15-20.