Preparation of Ti/Al composite plates by differential temperature rolling with induction heating

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Abstract
In the current study, we proposed a method of differential temperature rolling with electromagnetic induction heating to prepare Ti/Al composite plates in a protective atmosphere to realize the homogeneous deformation of Ti/Al bonding rolling and improve the interfacial bonding strength of the composite plates. The temperature field required for homogeneous deformation rolling of titanium and aluminum was constructed using finite element simulation by adjusting the parameters of electromagnetic induction heating, which made a temperature difference of about 632 °C between titanium and aluminum, and the temperature of each plate was relatively uniform. The induction heating experiment was designed based on the finite element simulation, and the experiment verified the accuracy of the simulation results. The effects of rolling temperature and reduction rate of homogeneous deformation and bonding strength of Ti/Al composite plates were evaluated by rolling experiments. With the increase of rolling temperature and reduction rate of titanium, when the heating temperature of the Ti plate is 750–850 °C, and the reduction rate is 30%–48%, the reduction rate of Ti plate and Al plate gradually tend to be the same. When the titanium plate and aluminum plate temperature is 850 °C and 188 °C, respectively, with a rolling reduction rate of 48%, the deformation rate of Ti plate and Al plate is 46.8% and 48.6%, respectively. Moreover, the bonding strength of the composite plate reaches 77MPa.

Keywords Ti/Al composite plate · Electromagnetic heating · Differential temperature rolling · Interfacial bonding strength · Homogeneous deformation

1 Introduction
Titanium, "space metal", with excellent properties such as high strength, low density, corrosion resistance, and fatigue resistance, is widely used in aerospace, military, and medical fields [1–3]. Aluminum has a broad application in various industrial fields due to its optimum electrical and thermal conductivity, corrosion resistance, and low price [4–8]. However, the high price of titanium limited its application. The performance of aluminum at high temperature and the corrosive environment is significantly reduced. The Ti/Al composite plate has a "complementary effect", maintaining the characteristics of Ti and Al, realizing excellent comprehensive performance and significantly reduce the operating cost after proper combination [9]. Ti/Al composite has a broader application in aerospace, metallurgical machinery, petrochemical industry, and other fields [10–12].

The main preparation methods of Ti/Al composite plate include explosive welding [13], solid-liquid cast-roll bonding [14], and roll bonding [15]. Fan et al. [16] successfully prepared Ti/Al/Ti composite laminates by explosive welding using rock powder emulsion explosives and studied the interfacial characteristics and bonding properties. However, the explosion produces seismic waves, noise, and toxic gasses during preparation, which goes against the trend of green development of modern industry. Huang et al. [14] prepared Ti/Al composite plates by solid-liquid cast-rolling bonding and analyzed the mechanical properties and interfacial microstructure. There are various challenges, including heat transfer and flow in the solid-liquid cast-rolling bonding process, control casting temperature, and cast-rolling speed still demand prompt solutions. Compared with explosive welding and solid-liquid cast-rolling bonding, roll bonding has many advantages, including high dimensional accuracy of the product,
uniform thickness of each plate of composite material, uniformity, and consistent properties of composite material, high production continuity, which is conducive to the realization of mass production and automation [17, 18]. Based on rolling, Zhao et al. [19] further performed cold spraying and heat treatment before and after rolling, respectively. Through rolling combined with other processes, composite plates with better bonding properties could be obtained, which had good tensile strength, elongation, and shear strength.

Currently, there are two main problems in the process of rolling Ti/Al composite plates. First, the strength of the composite is on the low side. Second, due to the large difference in deformation resistance between titanium and aluminum metals, the deformation of the composite plate is not homogeneous, thus the plate warps, and the plate thickness ratio after rolling is difficult to control [20]. Chen et al. [21] found that the deformation of Ti/Al laminated composites prepared by hot rolling was not homogeneous. In case of large deformation, the necking and fracture of the Ti layer became the bottleneck of the preparation of Ti/Al composites. Qin et al. [22] showed that the main causes of Ti/Al fracture in tensile tests were inhomogeneous deformation and stress concentration. Peng et al. [23] prepared Ti/Al composite plates by cold rolling and annealed at 515 °C×12 h, and the bonding strength reached the maximum of 40MPa; however, with the increasing annealing time, the interfacial bonding strength decreased. Cao et al. [24] believed that the interfacial bonding strength of composite plates was bound up with failure, and the composite plates exhibited complex mechanical behaviors at high temperatures, which depended on two competitive mechanisms: on the one hand, the deformation between dissimilar metals could be coordinated through stress-strain transfer under strong constraints; On the other hand, the presence of intermetallic compounds at the interface would disrupt this coordination. Ma et al. [25] found that the deformation coordination between titanium and aluminum metal became worse with the increase of heating temperature during the preparation of Al/Ti/Al laminated plates by hot rolling. To solve the inhomogeneous deformation of Ti/Al rolling, Xiao et al. [26] stacked titanium plates heated separately to 800 °C with aluminum plates of room-temperature and rolled them together, which improved the coordination of deformation of titanium and aluminum in the differential temperature state. The titanium plate needs to be placed on the steel plate and heated together because the titanium plate is thin and heat dissipation is fast. The steel plate can transfer heat and thermal insulation on the titanium plate from the furnace to the rolling. The operation of this method is complex, and the surface of the titanium plate is highly oxidized, and the thickness of the oxide layer reaches 5 μm. Therefore, Qi et al. [27] adopted the stacking order of slab of “Al/Ti/separators/pure iron/separators/Ti/Al”, and made the aluminum and titanium to form a temperature difference of 305 °C through heat transfer of pure iron plate. They utilized the characteristic that pure iron can be heated to Curie point 770 °C rapidly in the alternating magnetic field due to the magnetic agglomeration effect, reducing the deformation resistance difference between titanium and aluminum. The rolled plates are separated from the separator, and two Ti/Al composite plates are obtained. However, the complicated assembly pattern will waste the pure iron plate, which is not conducive to industrial production.

The Ti/Al blank was heated by an electromagnetic induction coil in this paper. A large temperature difference of the titanium and aluminum was formed by selecting the suitable electromagnetic induction heating parameters, realizing the coordinative deformation of Ti/Al differential temperature rolling composite. This method is simple and easy to operate, and thus, beneficial to industrial production.

2 Results and discussion

2.1 Induction heating model of the combined slab

The longitudinal magnetic induction heating efficiency is reduced by heating nonferromagnetic metals, and the slab cannot even be heated to the specified temperature. The transverse magnetic induction heating was adopted in this paper. The magnetic force line of the transverse induction heating is perpendicular to the surface of the slab, and the eddy current distribution is approximate to the projection of the coil on the workpiece. The magnetic flux line of the magnetic sheet field could be redistributed using a magnetizer piece [28]. The rectangular induction heating coil is established according to the shape of the slab, and the magnetizer is placed in the middle of the coil to increase the magnetic gathering ability, increasing the heating temperature in the central zone of the slab.

Figure 1a shows the slab combination, in which 1mm thick aluminum shims are placed between the titanium plate and the aluminum plate to reduce the heat transfer from the titanium plate to the aluminum plate. Figure 1b shows the induction heating model, and the induction heating parameters, as shown in Table 1. Considering the influence of the skin effect, the mesh was refined at the edge of the workpiece to ensure the accuracy of the calculation. The temperature-related material parameters of TA1 and 6061 are shown in Table 2. In the finite element model, the Ti plate and Al plate mesh size were 3mm. Considering the skin effect in reality, the edge mesh of the plate was refined to a certain extent, with a size of 0.6mm. The air layer in the middle was similarly treated, and the mesh size of the coil was 5mm. Solid97 unit was used in all models in the electromagnetic physical environment, and with the boundary condition that the electric potential on the boundary of the whole space is 0. In the thermal physical environment,
the model adopted the Solid70 unit. The initial temperature of the boundary condition was set at 20°C, and a convective load was exerted on the surface of the slab.

In the finite element model, the model of plates was simplified to a certain extent. The entity model assumed that there is no oxide layer on both Ti and Al plates. Rivets used to fix the relative position of the slab were neglected. It was assumed that the current was uniformly distributed across the coil when a current was exerted. In the unheated stage, the temperature of the slab was considered to be 20°C.

The finite element software ANSYS was used to perform the calculation using the sequential coupling method. The calculation results of the electromagnetic field were taken when the load of the temperature field to realize the electromagnetic-thermal coupling analysis. The flow chart is shown in Fig. 2.

### 2.2 Materials and methods

1. The experimental materials are industrial pure Ti TA1 and AA 6061 aluminum alloy, and their chemical compositions are shown in Tables 3 and 4. The dimensional parameters of the two plates are given in Table 1.

2. In the experiment of electromagnetic heating, heating equipment adopted Dongguan SMARTTRY SMTR-80, the maximum output power of 80 kW. Its high-frequency current produced eddy current on the slab to heat the assembled plates. The actual temperature distribution of the slab was obtained using Flank’s F-8855 thermocouple thermometer and FLIR’s E95 thermal infrared imager.

#### Table 1 Main parameters of induction heating coil

| Parameters               | Values     | Parameters               | Values     |
|--------------------------|------------|--------------------------|------------|
| Size of TA1 /mm          | 100×50×2   | Size of coil /mm         | 92×36×6    |
| Size of 6061/mm          | 100×50×4   | Area of coil /mm         | 6×6        |
| Size of magnetizer/mm    | 80×10×8    | Clearance between coil and titanium plate /mm | 3         |
| Current frequency/Hz     | 76000      | Electric current density / (A/m²) | 2.4×10⁷ |

#### Table 2 Material properties

| Material | Temperature (°C) | Electrical resistivity (×10⁻⁷Ω·m) | Coefficient of heat conduction (W·(m·K)⁻¹) | Specific heat capacity (W·(kg·K)⁻¹) |
|----------|------------------|-----------------------------------|------------------------------------------|----------------------------------|
| TA1      | 600              | 14                                | 19.4                                     | 591                              |
|          | 700              | 14.2                              | 19.55                                    | 633                              |
|          | 800              | 14.4                              | 19.7                                     | 654                              |
|          | 900              | 14.8                              | 20.7                                     | 675                              |
| 6061     | 20               | 0.27                              | 176                                      | 960                              |
|          | 100              | 0.39                              | 180                                      | 963                              |
|          | 200              | 0.45                              | 184                                      | 1005                             |
|          | 300              | 0.6                               | 188                                      | 1047                             |
(3) Parameter of two-high mill used in the rolling experiment: ∅200×200mm; Rolling speed of 100mm/s.

2.3 Design of induction heating experiment

The experimental device was designed according to the parameters of the finite element model. Figures 3 and 4 are, respectively the schematic diagram of the composite process and actual process diagram of Ti/Al induction heating and differential temperature rolling. Induction heating equipment is mainly composed of a transverse magnetic coil, cooling system, and electronic control system. The composite slab from the top of the induction coil was pushed into the mill with a push rod immediately to get rolled in different temperature when the process of heating finished, which realized the whole process of sealing and argon gas protection from heating to rolling, and prevent the oxidation on the surface of the plate while heating.

The experimental materials were commercial-purified titanium TA1 and AA 6061 aluminum alloy, and the sizes of the sheet are shown in Table 1. In the experiment, dirt and oxides on the surfaces of plates were cleared by a grinding machine equipped with 180 grit SiC paper; then, the surfaces were cleaned with acetone and alcohol repeatedly to remove the grease stains on them and blown dry with a hairdryer. The

| Table 3 Chemical composition of TA1 (mass fraction, %) |
|----------------|----------|----------|----------|----------|----------|----------|----------|
| Fe  | Si   | C      | N      | H       | O       | Ti      |
| 0.15 | 0.1  | 0.05   | 0.03   | 0.015   | 0.15    | Bal.    |

| Table 4 Chemical composition of AA6061 (mass fraction, %) |
|----------------|----------|----------|----------|----------|----------|----------|----------|
| Cu   | Si    | Mg      | Zn       | Mn       | Cr       | Fe       | Ti       | Al        |
| 0.15 | 0.6   | 1.2     | 0.25     | 0.15     | 0.2      | 0.7      | 0.15     | Bal.      |
slab was assembled as shown in Fig. 1a. Shims with a thickness of 1mm were placed between the titanium plates and aluminum plates. Finally, four ends of the slabs were fixed with aluminum rivets. A thermocouple thermometer and thermal infrared camera were used to record the temperature variation of the slab in the induction heating experiment. A hole with a diameter of 1mm and a depth of 10mm was drilled on both sides of the TA1 and AA 6061. Then, one end of the thermocouple (K-type) was inserted into the hole, and the other end was connected to the thermometer to record the changes in temperature of the slab. The surface of the titanium plate was photographed with the thermal infrared camera to record its temperature distribution.

2.4 Results of simulation and experiment

Figure 5 shows the comparison between the slab temperature recorded by the thermocouple and simulation. During the heating time of 25s from the beginning, the simulated and experimental slab temperatures are consistent. The heat loss of the titanium plate increases with the increase in titanium plate temperature; therefore, the warming trend of the titanium plate gradually slows down. The heat transfer from titanium plate to aluminum plate increases gradually, leading to a faster temperature rise of aluminum plate. The temperature difference between titanium and aluminum is first increases and then decreases. When induction heating lasted for 24s, the temperature of the titanium plate was 850 °C, and that of the aluminum plate was 188 °C, and the deformation resistance difference between the two metals was significantly reduced. Meanwhile, the required temperature field of the Ti/Al differential temperature rolling was successfully constructed.

Setting the heating time as 24s, Fig. 6a and b) show the cloud picture of the simulated slab temperature distribution and the diagram of the slab temperature distribution observed by the experimental thermal camera. Comparing Fig. 6a with Fig. 6b, it can be seen that the surface temperature distribution of simulated and experimental titanium plates is consistent. The temperature distribution of titanium plates ranges from 700 to 911 °C, and that of aluminum plates ranges from 171 to 177 °C, meeting the requirements Ti/Al differential temperature rolling.

To study the temperature inhomogeneity in the transverse direction of the heated slab, the cross-sections at the front and middle positions of the slab were taken as the research objects, as shown in Fig. 7. The temperature distribution of the cross-sections, as well as the temperature distribution and changes on the paths AB and MN were analyzed.

Figure 8 shows the temperature distribution of the cross-section of aluminum plate and titanium plate under heating induction for 24s. As can be seen from Fig. 8a and b, on the two sections, the temperature distribution along the thickness and width directions of the aluminum plate is homogeneous, and the temperature difference is less than 6 °C. However, the temperature distribution of the titanium plate is homogeneous only along the thickness direction. In the width direction, the fringe temperature of the titanium plate is 182 °C, higher than the central temperature at the interface of ABCD. At the MNPQ section, the fringe temperature of the plate is about 131 °C, which is lower than the central part. Where the fringe temperature of titanium plate is high, the magnetic field and current effect are the strongest. In the middle part, the magnetic field is weak, and the efficiency of heating is low.
Moreover, the slow heat transfer rate of titanium leads to the inhomogeneous temperature distribution of titanium plates. The heat transfer rate of the aluminum plate is more than five times that of titanium, so the temperature distribution of the aluminum plate is homogeneous. In production, the billet is long, and mobile induction heating is generally adopted. When the billet passes through different coil positions, the heating effect of the fringe and the middle position is complementary. Consequently, the billet can be heated more evenly along the width direction.

![Fig. 5 Temperature variation of the slab (a) Temperature of Ti plate (b) Temperature of Al plate](image)

![Fig. 6 Cloud picture of slab temperature distribution (a) cloud picture of the simulated Ti plate temperature (b) cloud picture of the simulated Al plate temperature (c) cloud picture of the experimental Ti plate temperature distribution](image)
To compare the influence of rolling temperature on the composite plate property, we selected heating times as 18s, 21s, and 24s. At these times, the central temperature of the titanium plate was about 750 °C, 800 °C, and 850 °C. The differential temperature composite rolling experiment was conducted under different reduction rates with a roll diameter of 200 mm and a rolling speed of 50 mm/s.

In this experiment, six shear specimens were cut from each composite plate parallel to the rolling direction, and the tensile-shear test was performed using an INSPEKT Table 100kN instrument with the test speed of 1mm/min. Then, the average of the six results was obtained as the shear strength of the composite plate. The diagram of tensile-shear specimens is shown in Fig. 9. Metallographic specimens for observation were extracted along the rolling direction. The specimens were gradually burnished to No.3000 using emery papers from small particle size to high particle size, and then polished with SiO2 suspensions. Ti/Al composite plates morphology of the nearby bonding interface and the tensile-shear fracture microstructure were observed using a scanning electron microscope (SEM), and the adjacent combining interface and element distribution of the shear fracture were analyzed using an energy dispersive spectrometer (EDS).
The thickness of each plate of Ti/Al composite plate was measured via an optical microscope, and the metal deformation ratio of each plate is shown in Fig. 10. We found that with the increase of rolling temperature, the deformation ratio of titanium and aluminum and the rolling reduction ratio of composite plates tend to be close. It shows that with the increase of the titanium plate temperature, the difference of deformation resistance between titanium and aluminum metal becomes smaller. The deformation of the Ti/Al composite plate tends to be homogeneous. Therefore, appropriately increasing the rolling temperature of the titanium plate is conducive to the homogeneous deformation of the composite plate.

As can be seen from Fig. 11, when the rolling temperature of the titanium plate is 850 °C, with the increase of the overall reduction of laminated composite, the deformation amount of both metals tends to be consistent, and the homogeneity of deformation is improved to a certain extent. When the reduction is 48%, the deformation of the titanium plate is 46.8%, and that of the aluminum plate is 48.6%. Therefore, appropriately increasing the rolling reduction is conducive to the homogeneous deformation of titanium and aluminum.

Figure 12 shows the interfacial bonding strength of Ti/Al laminated composites under the conditions of different rolling temperatures and different reductions. As can be seen from Fig. 12a, the interfacial bonding strength of the laminated composites obtained at a rolling temperature of 800 °C was higher than the composite plates prepared at 750 °C, while the interfacial bonding strength of the laminated composites decreased slightly to 800 °C. Comparing the bonding strength of titanium plates made at the rolling temperature of 800 °C with that of 850 °C, the variation of interfacial bonding strength of composite plate with the reduction is shown in Fig. 12b. The interfacial bonding strength of the laminated composites was consistent at the rolling temperature of 800 °C and 850 °C. When the reduction was less than 40%, the bonding strength increased approximately linearly with the reduction. When the reduction was greater than 40%, the increasing trend of the interfacial bonding strength slows down. The bonding strength of the Ti/Al composite plate reached the peak value of 77MPa at 48% reduction and the rolling temperature of the titanium plate of 850 °C.

Figure 13 shows SEM images and EDS line-scanning for Ti/Al composite interface under different conditions. The results of line-scanning showed that the diffusion depth of two metal elements at the interface of Ti/Al composite plate were 1.286 μm, 1.400 μm, and 1.880 μm at 30%, 40%, and 48% reduction, respectively, deepening the diffusion of metal elements and improved the bonding strength of the interface. It can be seen from Fig. 13 that oxygen exists at the bonding interface, and its distribution at the interface decreased with the increase of the reduction. This is because oxidation was inevitable in rolling, and the presence of a metal oxide layer prevents the bonding of fresh metal. However, the increasing
reduction can promote the tearing of the oxide layer on the metal surface, which formed solid metallurgical bonding of the fresh internal metal, thus improving the bonding strength. Figure 14 shows the SEM images and EDS surface-scanning of shear fracture on the titanium side. As shown in Fig. 14a, b, and c, small cracks appeared on the fracture surface of the titanium plate, and the deformation resistance of the titanium side decreased with the increase of the rolling temperature of
The larger the deformation of the titanium plate relative to the aluminum plate, the wider and more cracks. With the increase of the reduction, the morphology of fracture surface on the titanium side changed, as shown in Fig. 14c, d, and e. At 30% reduction, cracks appeared on the fracture surface, but the Al content was low, forming a small area of metallurgical bonding, which is called a brittle fracture. At 40% reduction, dimples appeared on the fracture surface of the titanium side due to tensile-shear fracture. Compared with the 30% reduction condition, more Al was bonded on the fracture surface of the titanium side, and thus the dimples had higher strength. Meanwhile, ductile fracture formed in the dimple area. At 48% reduction, a large area of Al remained on the fracture surface of the titanium side due to tensile-shear tests, as shown in Fig. 14(f). EDS surface-scanning showed that the fracture surface of the titanium side was covered with Al by 83.1%. It is proved that Ti and Al formed a firm metallurgical bonding at this time, leading to the generation of fracture on the side of the aluminum substrate in the tension-shear test and formed plastic fracture.

The results show that because of cracks on the surface of the Ti side in rolling and good fluidity of aluminum, aluminum was squeezed into the cracks, leading to the metallurgical bonding of two fresh metals under the action of pressure and
high temperature. When the reduction amount increased, the larger the crack on the titanium side surface, the more metals were squeezed into the crack, and the higher the interfacial bonding strength. When sufficient metallurgical bonding of the two-metal formed at the bonding interface, due to the low tensile strength of Al, a large area of Al was bonded on the fracture surface on the titanium side in the tensile-shear process, and the bonding strength was almost equal to the shear strength of the Al substrate. The experimental results show that the Ti/Al differential temperature composite rolling could make the composite plates achieved high bonding strength, improving the coordination of deformation during preparation. Ti/Al differential temperature composite rolling, consequently, can be regarded as an innovative method to fabricate Ti/Al composite plates using electromagnetic heating in Ti/Al differential temperature composite rolling. Figure 13(d) shows the microhardness results near the interface at bonding temperatures of 850 °C, hardness value at the interface was higher than the matrix on both sides of the interface for the reason of elements diffusion. The work hardening phenomenon is more obvious at the Ti side with the increase of the reduction, while the hardness value at the Al side has little change with the increase of the reduction.

4 Conclusion

(1) Using electromagnetic heating, the temperature difference of about 630 °C was observed between the Ti plate and Al plate, and the temperature distribution of the two metal plates was relatively uniform, constructing the temperature field required by the Ti/Al homogeneous deformation bonding rolling.

(2) In the process of rolling, there would be an oxide layer at the bonding interface of the composite plate. The surface cracks became larger as the deformation on the titanium side grew greater, which was more conducive to the squeezing of aluminum into the cracks, forming firm metallurgical bonding with fresh titanium under the action of pressure and high temperature.

(3) When the heating temperature of the titanium plate was 750–850 °C, and the reduction was 30%–48%, the deformation of the titanium plate and aluminum plate was more homogeneous with the increase of temperature of the titanium plate and reduction. The bonding strength of the Ti/Al composite plate reached 77MPa at the rolling temperature of titanium plate of 850 °C and the reduction of 48%.

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Declarations

Ethics approval (include appropriate approvals or waivers) The manuscript has only communicated to one journal only and has not submitted to more than one journal for simultaneous consideration.

Consent to participate The authors have given their consent to participate.

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