Original Article

Strength improvement and interface characteristic of TC4 Ti alloy and 304 stainless steel joint based on a hybrid connection mechanism

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\textbf{A B S T R A C T}

Laser welding of TC4 Titanium (Ti) alloy to 304 stainless steel (SS) has been applied using Ag73-Cu16-Zn11 alloy as filler metal. A new welding process for SS-Ti alloy joint was introduced on the basis of the controlling the formation of Ti-Fe intermetallics in the joint. One pass welding involving creation of a joint with one fusion weld and one diffusion weld separated by remaining unmelted SS. When laser beam on the SS side was 1.5 mm, SS would not be completely melted in joint. Through heat conduction of unmelted SS, the atomic diffusion occurred at the SS-Ti alloy interface. A diffusion weld was formed at the SS-Ti alloy interface with the main microstructure of $\gamma$-Fe + Fe$_2$Zn$_3$, Ag$_2$Zn$_3$ + Cu$_3$Zn$_8$ and $\alpha$-Ti + Ti$_2$Cu. The joint fractured at the diffusion weld with the maximum tensile strength of 129 MPa.

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1. Introduction

Due to its high strength, good toughness, low density, high temperature resistance and corrosion resistance, titanium (Ti) alloy has been widely used in many industrial fields [1]. However, the application of Ti alloy is limited because of the high cost of titanium alloy, poor weldability and processing properties, and poor creep resistance. Stainless steel (SS) is the most commonly used structural material and has many excellent properties in terms of weldability, wear resistance and mechanical properties [2]. The composite structure of Ti alloy and SS can fully exploit the advantages of these two materials, complementing the superior performance of the two materials [3]. The direct welding of Ti alloy and SS was easy to form a large number of high-brittle Ti-Fe intermetallic compounds, which seriously reduced the strength and plasticity of Ti alloy-SS joints [4,5]. Therefore, the Ti alloy-SS joints formed by direct welding was brittle and easy to crack. In order to reduce the formation of brittle Ti-Fe intermetallic compounds, scholars have proposed several methods and verified them. The results showed that there are two ways to inhibit the formation and growth of Ti-Fe intermetallic compounds: one was solid phase welding, and the other was an intermediate layer that dissolved in Ti or Fe during fusion welding.

Since the base metal remains solid during the joining process, solid state welding can eliminate problems in direct
fused welding. As mentioned above, these two different materials can be joined by diffusion bonding [6], friction [7] and explosive welding [8]. S. Kundu et al. [6] studied the vacuum diffusion bonding of Ti-6Al-4V and micro duplex stainless steel, and explored the effect of bonding temperature and time on the strength properties of room temperature. The shear strength was 397.5 MPa and the elongation was 6.5% when the diffusion couple was treated at 850°C for 90 min. Fazel Najafabadi et al. [7] adjusted the parameters of the friction stir welding process to achieve defect-free dissimilar lap joint of CP-Ti to 304 stainless steel. The shear strength of the joint was tested and the maximum breaking load was 73% of CP-Ti. Mousavi and Sartangi [8] obtained theoretical and experimental parameters windows suitable for explosive welding of CP Ti-SS 304. It was found that the formation of intermetallic compounds under low load was completely avoidable. However, the service conditions may make a particular process inappropriate. The diffusion process generally takes a long time to achieve. For high temperature applications, brazing cannot be used as a candidate. In addition, the required joint geometry may make friction welding and explosive welding difficult to apply.

In fact, the butt welding process of titanium alloy and steel was convenient. Laser welding has made great achievements in the jointing of refractory materials and dissimilar materials as an efficient and flexible non-contact welding technology. Therefore, the laser was used as a welding heat source for Ti alloys and SS. Two welding mechanisms (fusion welding and diffusion welding) are combined to avoid melting and liquid mixing of the base metals during welding, and the advantages of the two welding methods are complementary. In view of the above analysis, Ag73-Cu16-Zn11 alloy was used as an filler metal for joining Ti alloy and SS that the laser can be bias to the SS with the distance of 1.5 mm so that fusion welding occurs on the SS side of the joint, while diffusion welding occurs on the SS-Ti alloy interface of the joint. Two different joining mechanisms were identified for the SS-Ti alloy joint. In this way, a peculiar joint was acquired and Ti-Fe intermetallics can be completely avoided in the joint since the unmelted SS acted as a diffusion barrier.

2. Experimental

The base materials used are 1 mm plates of 304 stainless steel (68 wt.% Fe, 19.5 wt.% Cr and 9.25 wt.% Ni), TC4 Ti alloy (88 wt.% Ti, 6.06 wt.% Al and 4.03 wt.% V). The specimens for direct welding experiments were machined into 100 mm × 80 mm × 1 mm plates. The filler metal used was 0.2 mm plate of (melting point 680°C) Ag-base filler metal (73 wt.% Ag, 16.5 wt.% Cu and 10.5 wt.% Zn). Before welding, the specimens were mechanically and chemically cleaned. The gap between the edges of the Ti alloy and SS was very important to adequate heat transfer and prevent porosity formation. The specimens are clamped each other tightly in order to get the minimum gap formation between the edges. CW laser was used with average power of 1.20 kW, wavelength of 1080 nm and beam spot diameter of 0.1 mm. A schematic diagram of the welding procedure is shown in Fig. 1a. In order to ensure that SS was not completely melted, the laser beam was focused on the SS plate 1.5 mm away from the SS interface. The welding parameters were: laser beam power of 500 W, defocusing distance of +5 mm, welding speed of 612 mm/min. Argon gas with the purity of 99.99% was applied as a shielding gas with total flow of 20 L/min at the top of the joint.

3. Results and discussion

The optical microscopy image of the cross section of the joint is shown in Fig. 1b. The joint can fall into three parts: the fusion weld formed at the SS side, unmelted SS and the diffusion weld formed at the SS-Ti alloy interface. The fusion weld did not form Ti-Fe intermetallics due to the presence of unmelted SS. The average width of fusion weld, unmelted SS and diffusion weld was 1.9 mm, 0.34 mm and 0.17 mm, respectively. Because the microstructure of the fusion weld is quite different from that of the diffusion weld, the diffusion weld becomes black after corrosion. Fig. 1c presents the optical image before corrosion of the diffusion weld. It does not present such defects as pores and macro-cracks. The unmelted part of SS acted as a heat sink due to its high thermal conductivity absorbing a significant amount of energy from the welding pool and transferring it to the Ti alloy side [9]. Hence, the SS-Ti alloy interface had a high temperature during welding although it was not subjected to laser radiation. The thermal cycle curve obtained from SS-Ti alloy interface during welding is shown in Fig. 1d. It is suggested that the peak temperature of diffusion welding interface was 678°C, which was below the melting point of filler metal but the entire filler metal was at a relatively high temperature. The temperature was high enough to promote atomic interdiffusion. This meets the temperature requirement for diffusion welding. Moreover, the local heating of the SS side caused uneven volume expansion and thermal stress was produced, which helped to obtain an intimate contact between the SS, Ag-based fillers and Ti alloy surface. The high temperature and the intimate contact at the SS-Ti alloy interface provided favorable conditions for atomic (Ag, Cu, Ti, Fe) interdiffusion. Therefore, a diffusion weld was formed originated from atomic (Ag, Cu, Ti, Fe) interdiffusion at the SS-Ti alloy interface. The unmelted SS acted as a barrier to mixing of the two base materials, which eliminated the formation of brittle Ti-Fe intermetallics in the joint. Additionally, the unmelted SS was beneficial to relieve and accommodate the thermal stress in the SS-Ti alloy joint, which could help to improve the mechanical properties of the joints.

It should be noted that precise control of the laser spot position is crucial to obtain a sound joint. If the laser spot is far away from the SS interface, diffusion process at the SS-Ti alloy interface cannot take place. If the laser spot is far away from the SS interface, the SS is beginning to melt in the joint, thereby amount of brittle Ti-Fe intermetallics is greatly increased in the joint and cannot be realized the effective combination between dissimilar materials of SS and Ti alloy.

The optical image of the fusion weld is shown in Fig. 2a, and no defects were observed in it. SEM image of the fusion weld is shown in Fig. 2b. The fusion weld mainly consists of columnar crystal. The SEM image of the diffusion weld is shown in Fig. 2c. It can be seen that the diffusion weld consisted of a lamellar structure. It can be seen from Fig. 2c that the diffu-
Fig. 1 – (a) schematic diagram of the welding process; (b) optical image of the cross section of the joint; (c) optical image before corrosion of the Ti alloy-SS interface; (d) thermal cycle curve of the SS-Ti alloy interface.

Table 1 – The chemical composition of each phase (wt.%).

<table>
<thead>
<tr>
<th>Region</th>
<th>Composition%</th>
<th>Potential phases</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ti</td>
<td>Fe</td>
</tr>
<tr>
<td>A</td>
<td></td>
<td>7.0</td>
</tr>
<tr>
<td>B</td>
<td>84.3</td>
<td>2.7</td>
</tr>
<tr>
<td>C</td>
<td>69.7</td>
<td>19.4</td>
</tr>
</tbody>
</table>

The fusion weld contained four zones marked as I, II and III sorted by their morphologies and colors. Fig. 2d, Fig. 2e and Fig. 2f correspond to the four zones in Fig. 2c, respectively. The compositions of each zone (denoted by letter A-C in Fig. 2) were studied using SEM-EDS. EDS analysis was applied to these zones to measure the compositions of the reaction products and the results are listed in Table 1. Based on the previous analysis, the microstructure of the diffusion weld was mainly composed of Ag-based fillers. Therefore, the chemical composition of zone I was consistent with the Ag-based fillers. Based on the EDS analyses results and Ag-Cu-Zn phase diagram, the main microstructure of zone I was defined as AgZn$_3$ + CuZn$_8$ phase. When the laser beam was focused near the SS-Ti alloy interface, the element diffusion occurs immediately between the base materials and filler metal, and causes its component to deviate from the original component. The interdiffusion of Ag, Cu, Ti and Fe elements occurred at diffusion welding interface (SS-filler metal and filler metal-Ti alloy). At this moment, the dissolution of Ti and Fe into the filler metal occurred under the high concentration gradient, which formed solid-phase reaction layer, and this reaction layer exists only in the smaller region of the SS-Ti alloy interface. As shown in Fig. 2e and 2f, zone II and zone III were reaction layers formed by element diffusion. Based on Cu-Fe-Zn phase diagram, the microstructure of zone II was defined as γ-Fe + Fe$_3$Zn$_2$. Based on Cu-Ti
phase diagram, the microstructure of zone III was defined as \( \alpha - Ti + Ti_2Cu \). Therefore, the main microstructures of diffusion weld were \( \gamma - Fe + Fe_3Zn_2 \), \( AgZn_3+Cu_2Zn_8 \) and \( \alpha - Ti + Ti_2Cu \).

The maximum tensile strength of the joint was about 129 MPa (Fig. 3a). The joint fractured in Ti alloy side of the diffusion weld during tensile tests (Fig. 3b). Fig. 3c shows fracture surface of the joint exhibiting typical brittle characteristics. Moreover, as shown in Fig. 3d, XRD analyses of fracture surface detected the existence of \( \alpha - Ti \) and \( Ti_2Cu \) phases. This confirmed the presence of Cu-Ti intermetallics at fracture surfaces. It should be noted that there was no Ti-Fe intermetallics in the diffusion weld. Reaction layer at Ti alloy side in diffusion weld became the weak zone of the joint, which led to the failure in the tensile test.

4. Conclusions

With a laser beam offset of 1.5 mm for SS side of the joint, the unmelted SS was selected as an barrier to avoid mixing of the SS and Ti alloy. A diffusion weld was formed at the SS-Ti alloy interface with the main microstructure of \( \gamma - Fe + Fe_3Zn_2 \), \( AgZn_3+Cu_2Zn_8 \) and \( \alpha - Ti + Ti_2Cu \). A great amount of atomic diffusion occurs at the SS-Ti alloy interface during welding, and the thickness of diffusion weld can reach hundreds of micrometres. The tensile resistance of the joint was determined by diffusion weld. The maximum tensile strength of joint was 129 MPa.

Conflict of interest

We declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted

REFERENCES