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High strength electron beam welded titanium–stainless steel joint with V/Cu based composite filler metals

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ABSTRACT

Composite V/Cu based filler metals for electron beam welding of titanium–stainless steel joint were designed, based on the element metallurgical compatibility. Powder metallurgy method was used to manufacture the filler metal. To determine the feasibility of these filler metals, microstructures were analyzed by optical microscopy, scanning electron microscopy and X-ray diffraction. Mechanical properties of the joints were evaluated by tensile strength tests. The feasibility of the Cu/V filler metal was poor for the differences in physical properties between copper and vanadium, vanadium and titanium. A non-fusion defect was produced in the joint under low heat input, and cracking occurred in the joint under higher heat input due to the continuously distributed brittle TiCu, TiFe and τ_2 compounds. However, such defects were eliminated using a powder metallurgical V/Cu–V filler metal. A joint with a tensile strength of 395 MPa, 72% of that of the stainless steel was obtained. And almost no intermetallics were detected in Ti/V/Cu–V/Fe joint.

1. Introduction

Titanium alloys are preferred structural materials in the aeronautics and astronautics industries because of their high specific strengths [1]. There is considerable interest in joining titanium–steel to reduce the cost for that stainless steel is an inexpensive material in most industrial fields [2]. It has been acknowledged that fusion welding methods are not feasible for the joining of Titanium–stainless steel because of their metallurgical incompatibility. Ding et al. [3] reported that solid-state cracking appeared in the electron beam welded cast γ-TiAl to low alloy steel joint due to a high thermal stress, as well as the formation of a brittle TiC phase and Ti_3Al intermetallics. Therefore, solid-state joining is a viable solution to overcome this difficulty. Sudha et al. [4] studied the interface microstructures in explosive clad joint of Ti5Ta1.8Nb titanium alloy to 304L stainless steel. The presence of intermetallic phases at the weld interface was not revealed by X-ray diffraction and electron microprobe. However, direct diffusion bonding, as the most frequently used solid-state joining method, was also very difficult because of the low solubility of Fe in α-Ti at room temperature. Qin et al. [5] showed that when titanium was directly diffusion bonded to stainless steel, intermetallics like σ-phase, Fe_2Ti and FeTi were produced at the interfaces by interdiffusion among elements of the base metals, which resulted in the embrittlement of the joints (both the strength and the ductility of the joints were significantly lowered). Kundu et al. [6] studied the diffusion bonding of Ti–6Al–4V to microduplex stainless steel. Such σ phase, λ + FeTi and λ + FeTi + β-Ti phase mixtures were observed at the interface. Failure took place through the λ + FeTi phase and σ phase. Orhan et al. [7] suggested that the formation of Fe–Cr–Ti intermetallics resulted in even worse mechanical properties of the diffusion bonded Ti/Fe joints. Additionally, Dey et al. [8] joined stainless steel and titanium alloy by friction welding. The joints had almost zero bend ductility because of the formation of Ti–Fe intermetallics. Najafabadi et al. [9] obtained a defect-free dissimilar lap joint of CP-Ti onto SS304 by friction stir welding. Fracture occurred at the TiFe intermetallic-based interface and the tensile shear strength decreased with the thickening of the intermetallic interface. On the other hand, Aleman et al. [10] reported another factor responsible for crack formation during the diffusion bonding. They found that large internal stresses formed because of differences in the linear expansion and heat conductivity coefficients between Ti and Fe elements.

Currently, indirect joining was realized by adding an intermediate metal layer to prevent atomic diffusion during diffusion bonding processes. Kundu et al. [11] prepared solid-state diffusion bonded joints between commercially pure Ti and SS304 using nickel as an intermediate material. However, the nickel interlayer

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cannot restrict the diffusion of Ti into SS. $\lambda + \chi + \alpha$-Fe, $\lambda +$ FeTi and $\lambda +$ FeTi $+ \beta$-Ti mixtures were formed at the SS–Ni interface. Failure occurred for the above mixtures during a tensile strength test. Elrefaey and Tillmann [12] investigated the diffusion bonding process of dissimilar Ti/steel metals using a Cu-based interlayer. Atom diffusion and migration between Ti and Fe or C was effectively prevented. Hence, Ti–Fe and Ti–C intermetallics were not formed in the joint. Özdemir and Bilgin [13] studied the joining performance of diffusion bonded Ti–6Al–4V onto AISI SS304 by inserting a Cu interlayer. Similarly, no Ti–Fe(Ni,Cr) intermetallics were found in the joint. Among the interlayer metals mentioned above, copper is used the most frequently. Copper does not produce brittle intermetallics with iron, chromium, nickel or carbon. Moreover, it is a soft metal which can deform and accommodate the stress caused by the thermal expansion coefficient mismatch. However, for Ti and Cu elements, a series of closely spaced, structurally related compounds such as Ti_2Cu, TiCu, Ti_2Cu_3 Ti_3Cu_4 and $TiCu_4$ have been reported by Murray [14], which may make weld chemistry and performance unpredictable. So, a composite interlayer may be the optimized choice. Lee et al. [15] obtained a remarkably high strength diffusion bonded joint of commercially pure Ti and super stainless steel without any detrimental phases using a V–Cr–Ni interlayer. The interface structure was Ti(base)/Ti solid solution/V/Cr/Ni/STS(base).

From the above discussion, diffusion bonding with single or composite interlayers can be a preferred process to join titanium–stainless steel. However, it is particularly true for components with complex geometric shapes that diffusion bonding (as well as other solid-state bonding methods) is not applicable. In addition, diffusion bonding requires that the whole component be heated, which is not recommended for some components. Consequently, further development of a feasible fusion welding process is still necessary for further development. Electron beam welding is the most frequently used fusion welding technique for joining dissimilar metals because of its certain advantages such as high energy density, vacuum atmosphere and precise control of heating position and area [16–18]. Therefore, it is reasonable to consider electron beam welding as a preferred candidate process for the fusion welding of titanium alloys to stainless steels.

As with diffusion bonding, a filler metal is also required for electron beam welding and laser beam welding. Gao et al. [19] joined Ti6Al4V titanium alloy and 304L stainless steel by laser beam welding using a Mg interlayer. A joint with a tensile strength of 221 MPa was obtained. The intermetallic compound of $Mg_{17}Al_{12}$ was observed in the Ti/weld interface, while no intermetallic compound was found in the SS/weld interface. Wang et al. [20] reported that a crack free electron beam welded Ti6Al2Mor2V2Zr alloy to 304 stainless steel joint was produced using Cu filler metal, which had a tensile strength of 310 MPa. Fracture occurred in the Cu–Ti intermetallics in the Ti/weld interface during the tensile strength test. Thus, in this paper, composite V/Cu and V/Cu–V filler metal were used to prevent the formation of Ti–Cu intermetallics previously in the electron beam welded Ti/Cu/Fe joint. Microstructures and tensile strengths were examined to analyze the usefulness of the resultant joint. In addition, another experiment using a V/Cu composite layer was conducted. Comparing the two experiments allows us to demonstrate the necessity of the powder metallurgical V/Cu–V alloy layer.

2. Experimental

2.1. Materials and preparation

Materials used in these experiments were a near α-type titanium alloy (Ti6Al2Zr2Mo2V) and austenitic 304 stainless steel (18Cr9Ni). Physical properties at room temperature of the base metals and the filler metals are given in Table 1. In Table 1, large differences in thermal conductivity and linear expansion coefficient exist between the two base metals. These will lead to large temperature gradients and thermal stresses in the joint during the welding process.

Table 1
Physical properties of the base metals and filler metals at room temperature.

Alloy type	Melting point (°C)	Specific heat (J kg^{-1} K^{-1})	Thermal conductivity (W m^{-1} K^{-1})	Linear expansion coefficient (10^{-6} K^{-1})
Ti-6-2-2-2	1677	495	7.4	8.6
304	1450	461	14.6	16.0
Cu	1085	385	388	16.9
V	1902	498	30.7	8.3
V–Cu alloy[a]	–	–	72	13.6

[a] Note: Data for the V–Cu alloy were measured by the authors.

The metals were machined into 50 × 25 × 2.5 mm plates. Before welding, the specimens were mechanically and chemically cleaned. Two types of composite filler metal were prepared. One is an assembly of a 0.7 mm thick commercially pure Cu sheet and a 0.7 mm thick commercially pure V sheet. The other is a V/Cu–V compositionally graded alloy sheet made by a powder metallurgical process. The powder metallurgy process is shown in Fig. 1. Firstly, a given amount of V powder was placed in the female die and pressed under a low pressure of 120 MPa. Then a given amount of powder blend with 67 wt.% V and 33 wt.% Cu was overlaid on the V layer in the die. The quantities of the V powder and the V–Cu powder blend were calculated according to the ultimate thickness of the filler metal plate. In the end, all powders were pressed into a rectangular plate under a pressure of 540 MPa. After cold pressing, the plate was sintered in vacuum furnace at 930 °C for 120 min. The microstructure of the composite filler metal is given in Fig. 2. The thicknesses of the V layer and Cu–V alloy layer are both about 0.7 mm and the density of the plate was around 97% of the theoretical maximum.

2.2. Welding process and test work

Before welding, the filler metal sheets were embedded in the contact face as previously done in the experiments of Barreda et al. [21] and Irisarri et al. [22]. In this experiment, V layer was close to Ti alloy and Cu or Cu–V alloy layer was close to stainless steel. Dual-pass electron beam welding was employed. For the first pass, an electron beam was focused on the Cu or Cu–V alloy layer, 0.2 mm from the stainless steel, and electron beam was focused on the central line of V layer for the second pass. A schematic diagram of the welding procedure is shown in Fig. 3. The welding parameters are listed in Table 2.

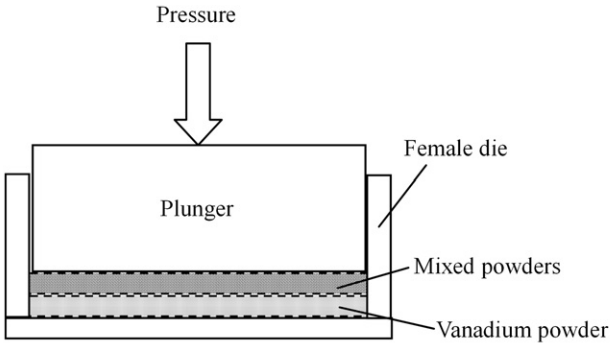

Fig. 1. Schematic diagram of the powder metallurgical process.