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Vacuum brazing of TiAl alloy to 40Cr steel with $Ti_{60}Ni_{22}Cu_{10}Zr_8$ alloy foil as filler metal

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ABSTRACT

Dissimilar metal vacuum brazing between TiAl alloy and 40Cr steel at 900 °C for 5 min, 10 min and 15 min was conducted with Ti-based alloy foil as the filler. Five distinct regions were detected in the brazed seam from each joint during microstructure examination. The hardness in the brazed seam was measured much higher than those in the two substrates, and the hardness in the filler metal layer was higher than that in the reaction layer. However, brazing for longer time can reduce the hardness of the brazed seam. The average shear strength of the joint was 26 MPa when the joint was brazed for 5 min, and it increased to 32 MPa when brazed for 10 min and 15 min. The specimen brazed for 5 min fractured through the interface between 40Cr steel base metal and filler metal layer, but the specimen brazed for 10 min and 15 min fractured through the filler metal layer in the brazed seam. It was found that the compositions of the filler material and sufficient interdiffusion between the filler and substrates are important to improve the joint strength, and the mechanical properties of the filler metal also control the strength of the resultant joint.

1. Introduction

TiAl alloys have high specific strength, excellent high-temperature creep strength and good oxidation resistance, especially, their properties in creep and oxidation are far better than traditional titanium alloys. Therefore, TiAl alloys have a promising application prospect in automotive, aerospace and nuclear industries [1]. However, the application of TiAl alloys is restricted by their high cost and complex manufacturing process. Joining TiAl alloy to other materials is an important approach to reduce cost and a necessary way to manufacture complicated structures with TiAl alloy replacing conventional metallic materials such as steels. Actually, dissimilar metal structure between TiAl alloy and 40Cr steel already found application in manufacturing automotive engine [2].

Fusion welding processes with high heat input can hardly be used in welding of TiAl alloys due to the low fracture toughness of TiAl alloy [1] and high residual stress produced upon solidification [3] which can easily cause cracks in the resultant joint. Especially, massive generation of Ti–Fe intermetallic compounds (IMCs) in the interface during fusion welding of TiAl alloy to steel will seriously degrade the joint strength [4]. To solidly join TiAl alloys to steels, brazing [5–9], diffusion welding [10–11] and friction welding [12–13] processes have been reported. And brazing process displays advantages over diffusion welding and friction welding processes in the flexibility of joint design during joining TiAl alloy to steel, and integral heating of the workpieces in the furnace and the filler metal used during brazing can effectively reduce residual stresses and control the generation of brittle Ti–Fe intermetallic compounds.

Brazing of TiAl alloy to steel reported in literatures mainly concentrated on using Ag-based alloy as filler metals [7–9]. However, the tensile strength and creep strength of most Ag-based alloys at temperatures above 400 °C is inferior to that of Ti-based filler metal [14]. Noda et al. [5] conducted induction brazing of TiAl alloy to AISI4340 structural steel with 63Ag–35.2Cu–1.8Ti and 70Ti–15Cu–15Ni (wt%) filler metals and the joint strength was lower with Ti-based filler metal than with Ag-based filler metal due to the generation of carbide layer while using the Ti-based filler. Tetsui [6] investigated the effects of brazing fillers, including Ti–Ni alloy and Ag–Cu alloy, on the properties of brazed joints between TiAl and Incoloy 909 (Fe-38Ni-13Co-2Ti-5(Nb, Ta), wt%), however, all brazing fillers in his experiments reacted with the TiAl base metal to form hard and brittle phases.

Commonly, Ti-based filler metals were used for brazing titanium and its alloys [14–17], and sound joints with tensile strength close to that of Ti-based metal can be obtained due to

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good compatibility between Ti-based filler metal and Ti-based substrates. Developing appropriate compositions of Ti-based filler metal would be helpful to explore the possibility of brazing TiAl alloy to steels with Ti-based filler metals.

Ti-based alloy foil, made by rapid solidification technology, with uniform composition and good flowability in melting state will be used in this paper to braze TiAl alloy to 40Cr steel. The microstructure and mechanical properties of the resultant dissimilar metal joint will be investigated to evaluate the joining effect.

2. Experimental

The base metals used in the experiment were TiAl alloys and 40Cr steel with nominal compositions of Ti-48Al-2Cr-2 Nb (at%) and Fe-0.4C-1.0Cr-0.7Mn-0.3Si-0.2Ni (wt%), respectively. The dimensions of the workpieces were 60 mm × 20 mm × 2 mm. All faying surfaces were ground with SiC papers up to grit 1200 and then ultrasonically cleaned with acetone prior to vacuum brazing. The $Ti_{60}Ni_{22}Cu_{10}Zr_8$ (at%) alloy foil, 50 μm thick and 2 mm wide, was used as the filler material. This filler foil was made with rapid solidification technology to achieve amorphous structure with aforementioned characteristics of uniform composition and good flowability during brazing. The X-ray diffraction (XRD) pattern of the $Ti_{60}Ni_{22}Cu_{10}Zr_8$ (at%) alloy foil is revealed in Fig. 1, and it can be seen that the foil shows essentially amorphous structure. Its melting point was measured in the range of 809–858 °C with differential thermal analysis (DTA). Generally, the brazing temperature is set at 30–90 °C above the liquidus temperature to ensure that the filler material is entirely melted during brazing process [18], so the brazing temperature was fixed at 900 °C in this paper.

Prior to brazing, the workpieces and filler material were assembled as shown in Fig. 2, and put in a furnace with a vacuum atmosphere of 4×10^{-3} Pa. Then the workpieces were preheated at 800 °C for 5 min in the furnace for the consideration of thermal equilibrium, and subsequently heated up to 900 °C and maintained at 900 °C for 5 min, 10 min and 15 min. Consequently, the joint was cooled in the furnace to room temperature. The heating rate was 30 °C/min throughout the experiment.

After brazing, the joints were longitudinally cut with a wire-cutting machine for microstructure examination. The cross-sections of the joints were examined with an optical microscope. The elemental distribution in the brazed seam was detected with electron probe microanalysis (EPMA). Microhardness along the interface was measured with the load of 0.98 N and loading duration of 15 s. The room temperature shear strength of the resultant joints was evaluated, and fracture locations were checked.

3. Results and discussion

The microstructure of the joints brazed at 900 °C for 5 min, 10 min and 15 min is shown in Fig. 3. It can be clearly seen that the TiAl alloy and 40Cr steel substrates were tightly bonded through the filler metal foil. No pores and cracks existed in the brazed seams. A reaction layer formed between the TiAl alloy substrate and filler metal layer, and the thickness of the reaction layer slightly increased with the increase of brazing time. However, the interface between the 40Cr steel and filler metal is very thin and flat, as seen in Fig. 3, which indicates stronger reaction between the filler metal and TiAl alloy than that between the filler metal and 40Cr steel. The filler metal layer in the joint brazed for 5 min consists of white matrix and black blocks distributing in the matrix. With the increase of brazing time, the amount of gray phases increased, and the size and color of phases apparently changed in the joint. This phenomenon suggests that the reaction and interdiffusion between the filler metal and TiAl alloy was enhanced with the increase of brazing time.

The backscattered electron images and EPMA map scanning results of the joints brazed for 5 min, 10 min and 15 min are displayed in Fig. 4, Fig. 5 and Fig. 6, respectively. In each joint, five regions (A, B, C, D and E) can be observed between the two substrates, as shown in the backscattered electron images. The reaction layer and black blocks distributing in the filler metal layer, which were already displayed in Fig. 3, were labeled as A and D, respectively. An off-white phase B and gray phase C also distribute in the filler metal layer. A thin diffusion layer between the 40Cr steel substrate and filler metal layer, which was not clearly seen in Fig. 3 but apparently shown in the backscattered electron images, was labeled as E. EPMA quantitative analysis results at typical spots 1–6 in five regions of each joint (in the backscattered electron image) are listed in Table 1, Table 2 and Table 3.

It can be seen from Fig. 4(a), Fig. 5(a) and Fig. 6(a) that, the thickness of brazed seam between TiAl alloy and 40Cr steel substrates was 33 μm, 36 μm and 39 μm. And the thickness of the interface (layer E) between the 40Cr steel substrate and filler metal also apparently increased with the increase of brazing time. The layer A brazed for 15 min in Fig. 6(a) is thicker and flatter than that brazed for 5 min. Obviously, the increase of brazing time can enhance the diffusion of elements between the filler metal and base materials. It can be seen from Figs. 4(b), 5(b) and 6(b) that, Fe from the steel substrate did not diffuse into the brazed seam. Although 21.8 at% Fe was detected at spot 6 in layer

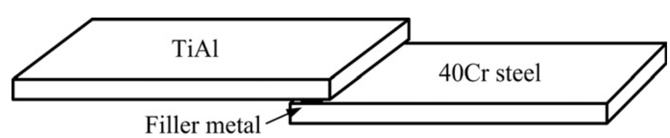

Fig. 2. The schematic diagram of assembling the workpieces and filler material.

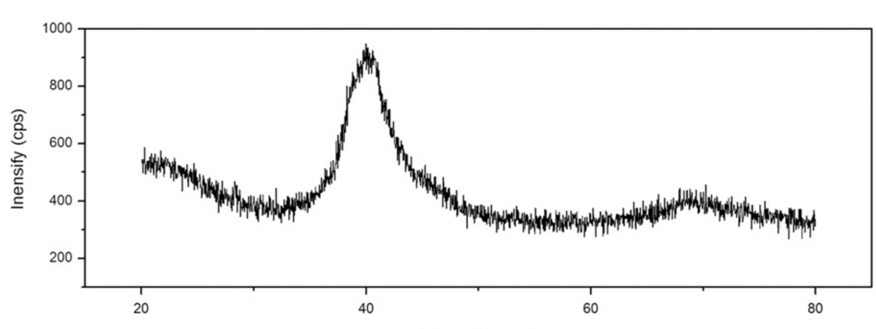

Fig. 1. XRD pattern of the $Ti_{60}Ni_{22}Cu_{10}Zr_8$ alloy foil.