



Effect of Post-weld Heat Treatment on Properties of Friction Welded Joint Between TC4 Titanium Alloy and 40Cr Steel Rods



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Dissimilar metal joining of Ti–6Al–4V (TC4) titanium alloy to as-rolled 40Cr steel rods was conducted with friction welding, and the effect of post-weld heat treatment (PWHT) on the microstructure and mechanical properties of the resultant joints was investigated. The average tensile strength of the as-welded joints reached 766 MPa and failure occurred in 40Cr steel base metal. However, after PWHT at 600 °C for 0.5, 1, 2 and 3 h, the tensile strength of the joints decreased and fracture happened through the interface with quasi-cleavage features. The bending angle of specimens was improved from 9.6° in as-welded state to 32.5° after PWHT for 2 h. The tensile strength of the joint was enhanced by martensitic transformation near the interface in as-welded state. Sorbite formed near the interface in PWHT state and improved the bending ductility of the joint. TiC brittle phase formed at the interface after PWHT for 0.5 h and deteriorated the tensile strength and bending ductility of the joint. After PWHT for 2 h, no TiC phase was detected at the interface. The microhardness on the interface in as-welded state was higher than that after PWHT, indicating that the decrease of microhardness around the interface could be accompanied by degradation of tensile strength but improvement of bending ductility of the joints.

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1. Introduction

Titanium and its alloys have been widely applied in aerospace, nuclear, and chemical industries, due to their excellent properties such as high specific strength, high melting point and excellent corrosion resistance. Nevertheless, the extensive applications of titanium and its alloys are limited owing to their high cost. Therefore, great attention has been paid to dissimilar metal joining of titanium or its alloys to steels because joining of dissimilar materials can reduce cost and improve efficiencies^[1,2]. However, welding between titanium or its alloys and steels is still a challenge due to the large differences in their thermo-physical properties, e.g. melting point, thermal expansion coefficient and thermal conductivity, etc.

Different welding methods have been reported in joining titanium alloys to steels, including fusion welding^[3,4], brazing^[5,6] and solid state welding^[7,8]. Since fusion welding involves melting of

the base metals, joining of titanium alloys to steels by conventional fusion welding processes easily causes stress concentration and formation of massive intermetallic compounds in the resultant joint, which restricts the industrial application of fusion welding of titanium alloys to steels^[9,10]. Yue et al.^[11] conducted vacuum brazing of TC4 titanium alloy to stainless steel with AgCuTi foil as filler metal and found that massive intermetallic compounds formed in the brazed seam. He et al.^[12] carried out diffusion bonding of Ti–6Al–4V alloy to 18Cr–10Ni stainless steel with Ni interlayer, and their results revealed that adding pure Ni as the interlayer can restrict the atomic diffusion and migration between Ti and Fe or C. Baek et al.^[13] investigated the microstructure and mechanical properties of friction welding and vacuum brazing of titanium and 321 stainless steel under various welding conditions, and their results showed that the maximum tensile strength of friction welded and brazed joints was about 420 MPa and 275 MPa, respectively. The friction welded joint had much stronger tensile strength probably owing to the thinner intermetallic compound layer in the resultant joint.

Besides tensile strength, the bending ductility is another important consideration for dissimilar metal friction welded joint. Dey et al.^[14] post-weld heat treated the friction welded joint between

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Table 1
Nominal composition of TC4 titanium alloy and 40Cr steel

Materials	Composition (wt%)				
TC4 alloy	Fe ≤ 0.3	Al 5.5–6.8	V 3.5–4.5		Ti Bal.
40Cr steel	C 0.37–0.45	Si 0.17–0.37	Cr 0.8–1.1	Mn 0.5–0.8	Fe Bal.

pure titanium and 304 L stainless steel rods, and increased the bending ductility of the joint to 5°. However, their findings contradicted the bending ductility of 40° reported by Fuji et al.^[15]

This paper reports the microstructure and mechanical properties of the friction welded joints between TC4 titanium alloy and 40Cr steel rods under as-welded and post-weld heat treatment (PWHT) conditions to evaluate the effect of PWHT with different parameters.

2. Experimental Procedures

The nominal composition of TC4 titanium alloy and 40Cr steel are listed in Table 1. The dimensions of TC4 titanium alloy and as-rolled 40Cr steel rods are 16 mm in diameter and 100 mm in length. The friction welding of TC4 titanium alloy to 40Cr steel rods was conducted using a type of HSMZ-20 (200 kN capacities) friction welder with a constant rotating speed of 1500 r/min, which was designed and manufactured by the Harbin Welding Institute, Harbin, China. Before welding, the faying surfaces were polished by SiC papers up to grit 1000 and then cleaned with acetone. During friction welding, the 40Cr steel rod was fixed in the tailstock, which can travel along the axial direction, and the TC4 titanium alloy rod rotated with the spindle of friction welder.

After trial welding, the friction pressure and forged time in the present work were kept at 160 MPa and 5 s, respectively. To optimize the other welding parameters, friction welding experiments with burn-off length of 3, 5 and 7 mm and forged pressure of 266, 293 and 399 MPa were conducted, and then tensile test was conducted on straight specimens, whose flash was machined off up to the final dimensions shown in Fig. 1(a). Consequently, the welding parameters for the strongest joint were determined and used for the rest friction welding experiments and subsequent mechanical tests with standard specimens, whose dimensions are shown in Fig. 1(b). In this work, the burn-off length was set at 5 mm and the forged pressure 293 MPa.

To investigate the effect of post-weld heat treatment on the microstructure and mechanical properties of welded joints, the joints were heat treated at 600 °C for 0.5, 1, 2 and 3 h with heating rate of 15 °C/min, and then cooled down to 400 °C and held for 0.5 h in furnace to avoid additional thermal stress, and finally cooled straight down to room temperature.

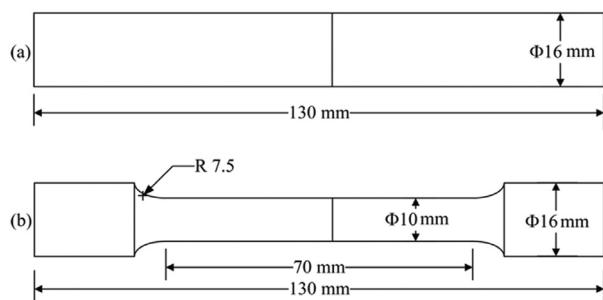


Fig. 1. Dimensions of (a) straight specimen and (b) standard specimen for tensile test.

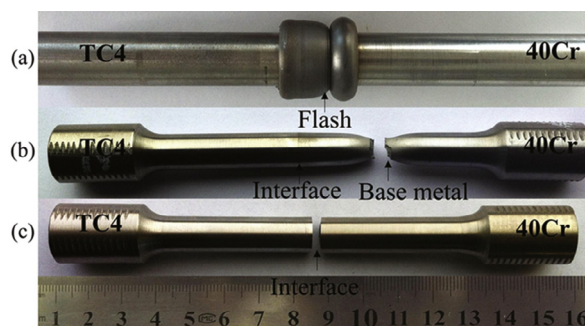


Fig. 2. Friction welded joints between TC4 titanium alloy and 40Cr steel rods: (a) as-welded specimen before tensile test, (b) after tensile test with failure through 40Cr steel base material, and (c) post-weld heat treated specimen No. T2 after tensile test with failure through the interface.

Three specimens were tested in tension for the same welding parameters to obtain the average tensile strength of the resultant joint. Three-point bending test was carried out, according to the standard GB/T 232-1999, to evaluate the bending ductility of the joints. The specimens for bending test, with dimensions of 158 mm × 16 mm × 1.5 mm, were taken from the joints by wire cutting machine. During bending test, the radius of the mandrel was 5 mm, and the distance between two supporting points was 15 mm. Generally, at least three specimens are needed for each PWHT condition for bending test. In our experiments, the friction welding process was automatic and the resultant tensile strength of the joints was consistent, so we measured one specimen for bending test under each condition for convenience. Then microhardness measurement on each specimen was conducted at a load of 300 g for 15 s using an MVC-1000B microhardness tester, and 60 indents with spacing of 500 μm were tested.

The specimens prepared from the as-welded and post-weld heat-treated joints were polished and then etched with mixed solution (HF:HNO₃:H₂O = 2 ml: 4 ml: 90 ml) for microstructure examination with optical microscopy. The distribution of major alloying elements across the interface was measured by scanning electron microscopy (SEM, JSM-5600LV) coupled with EDS (energy dispersive spectroscopy). And the fracture morphology of the specimens after tensile test was also evaluated by SEM-EDS. The phase constitution was detected by EMPYREAN X-ray diffraction (XRD), and the scan speed was 4°/min.

3. Results and Discussion

3.1. Mechanical properties

The photos of friction welded joints between TC4 titanium alloy and 40Cr steel rods before and after tensile test are displayed in Fig. 2, and the corresponding tensile strength and fracture location are listed in Table 2. Fig. 2(a) shows the as-welded joint without machining off the flash. During friction welding, the plastically deformed metal was squeezed out of faying surfaces under the forged pressure to form the flash, which was a typical feature for friction welded joints.

Table 2
Post-weld heat treatment parameters and tensile test results

Sample No.	PWHT	Fracture strength (MPa)	Fracture location
T1	As-welded	766 ± 20	Steel substrate
T2	600 °C, 0.5 h	652 ± 10	Interface
T3	600 °C, 1 h	700 ± 10	Interface
T4	600 °C, 2 h	718 ± 20	Interface
T5	600 °C, 3 h	652 ± 10	Interface

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