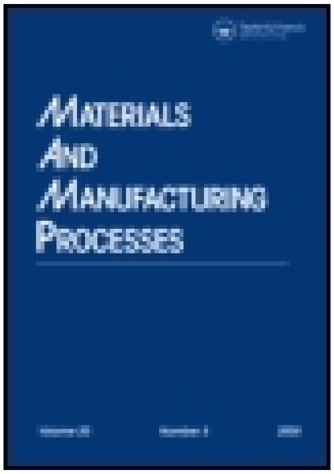

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Direct Friction Welding of TiAl Alloy to 42CrMo Steel Rods

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Abstract

The effect of post-weld heat treatment (PWHT) on the mechanical properties and microstructure of direct friction-welded joint between TiAl alloy and 42CrMo steel rods was investigated in this paper. It was found that solid joint between TiAl alloy and 42CrMo steel could be obtained without adding interlayer. After PWHT at 580 °C for 2 h, the tensile strength of the joint reached 405 MPa, and fracture happened through the TiAl alloy substrate with quasi-cleavage features. The tempered sorbite formed near the interface, improving the joint strength significantly. It was found that $TiFe_2$, TiAl, and small amount of TiC brittle phases formed at the interface, and the interfacial layer was as thin as 2-5 μm. The precipitated phases were 1μm in average size, and distributed discontinuously at the interface.

KEYWORDS: Welding; TiAl; Steel; Heating; Intermetallic

INTRODUCTION

TiAl intermetallic compounds are regarded as ideal high-temperature materials due to their excellent features, such as low density, high specific strength, high stiffness, good high-temperature mechanical properties and oxidation resistance. They are generally applied in aero-engine and automobile engine components which need to reduce weight urgently [1-2]. Especially, turbo technology is used in aerospace and automotive products to improve the engine starting performance. Turbocharger made by TiAl alloy can lighten the turbine rotor by more than 50 % due to lower density of TiAl alloy (3.7-3.9 g/cm^3), compared to that made by nickel-base superalloy. Consequently, the boost time of the engine declines significantly. Therefore, TiAl alloy plays a key role in improving the accelerated transient response of the engine, reducing the tailpipe emission and increasing the thermal efficiency of fuel oil [3-5]. Then, the research on dissimilar metal joining between TiAl alloy and steels seems to be particularly important for the application prospects of TiAl alloy.

The mechanical properties of the welded joint between TiAl alloy and steels are commonly poor using the conventional fusion welding techniques, because of the large differences in physical properties between these two materials. Solidification cracks and hardening tendency can be generated in the welded joint. Especially, Ti-Fe intermetallic compounds will deteriorate the joint strength [6]. Presently, many welding processes were conducted to join TiAl alloy to steels, including brazing [7-8], diffusion bonding

[9-10], and friction welding [11-12]. Nevertheless, the TiAl alloy/steel joint strength is relatively low by brazing, which limits the application of TiAl/steel structure in certain situations. Furthermore, although the satisfactory joint can be obtained by diffusion bonding, the long welding thermal cycle and the complex treatment for the faying surfaces decrease the production efficiency.

Friction welding is a solid-state joining process which can guarantee high quality, efficiency, energy saving and environmental protection. Lee et al. [12-13] explored the mechanical properties of friction welded joints between TiAl alloy and AISI4140 structure steel without interlayer or by adding Cu as interlayer. Their results indicated that brittle phases and martensitic structure formed at the joint interface without interlayer and deteriorated the joint strength. While adding Cu as interlayer, the joint strength reached 375 MPa and fracture occurred through the TiAl alloy substrate.

It is still a challenge to achieve satisfactory joints between TiAl alloy and steels by direct friction welding. This paper conducted direct friction welding of □-TiAl alloy to 42CrMo steel rods, and investigated the mechanical properties and microstructure of the resultant joint after post-weld heat treatment (PWHT).

MATERIALS AND METHODS

Friction welding of TiAl alloy to 42CrMo steel rods was carried out using HSMZ-20 friction welder with a constant rotating speed (1500 rev/min) and maximum upset pressure (200 kN) which was designed and manufactured by Harbin Welding Institute, Harbin, P. R. China. The chemical composition of □-TiAl alloy is Ti-43Al-2Cr-Zr-Fe (at. %), and that of 42CrMo steel is Fe-0.43C-1.09Cr-0.67Mn-0.31Si-0.2Mo (wt. %), and the tensile strength of TiAl alloy and 42CrMo steel base metals is 515 MPa and 898 MPa, respectively. The length of TiAl alloy and 42CrMo steel rods was 110 mm, the diameter of TiAl alloy rod was 12 mm, but the diameter of 42CrMo steel rod was 16 mm. Prior to welding, faying surfaces are polished by SiC paper up to grit 1000, and then cleaned by acetone. During friction welding, the TiAl alloy rod rotated with the spindle at 1500 rev/min, but the 42CrMo steel rod was fixed at the tailstock moving along the axial direction. After trial welding, the optimized welding parameters were determined. The friction pressure and forged pressure were set at 186 MPa and 346 MPa, respectively, the burn-off length and upsetting displacement remained at 8 mm and 8.2 mm, the forged time were 5 s, and the time from start to end of the welding process was 33 s. After welding, the workpieces were heat treated at 580 ^{o}C for 2 h with a heat rate of 15 K/min, and then cooled down to the ambient temperature in furnace.

The welded joints were machined to the final size according to standard GB/T228.1-2010 for tensile test with DNS-100 universal tensile machine at ambient temperature. The cross section of the heat-treated joint between TiAl alloy and 42CrMo steel was polished and then etched for microstructure examination using Olympus optical microscope. A mixed solution (HF: HNO_3: H_2O = 2 ml: 4 ml: 100 ml) was used to etch TiAl alloy, and 4 % natal solution was used to etch 42CrMo steel. The phase constitution was analyzed by EMPYREAN X-ray diffraction (XRD) with a scan speed of 0.08 ^{o}/s. The distribution of precipitated phases near the interface and the fracture morphology after tensile test were detected by JSM-5600LV scanning electron microscope (SEM) with an accelerating voltage of 15 kV.

RESULTS AND DISCUSSION

Mechanical Property

Figure 1 presents the friction welded joint between TiAl alloy and 42CrMo steel rods after PWHT at 580 ^{o}C for 2 h. As shown in Figure 1(a), flashes were formed by the squeezed hot metal and deformed layers under forged pressure during welding. It also can be seen that the flashes mainly consisted of steel, and TiAl alloy deformed slightly because TiAl alloy has stronger high-temperature strength, compared to 42CrMo steel [14-15]. The tensile strength of the joint reached 405 MPa, and fracture happened through the TiAl alloy base metal, as shown in Figure 1(b), which is higher than the reported tensile strength of 375 MPa by Lee et al. [13]. However, the as-welded joint (i.e. without PWHT) failed while it was machined to the final size for tensile test, due to the low ductility of TiAl alloy at ambient temperature and the formation of brittle phases and martensitic structure, which deteriorated the joint strength [12]. This phenomenon implied that PWHT is necessary to improve the joint strength.

Microstructure

Figure 2 shows the macrograph of a typical joint between TiAl alloy and 42CrMo steel rods. It can be seen that the friction welded joint has a convex shape in the central region on TiAl alloy side, due to inhomogeneous deformation ability of TiAl alloy and 42CrMo steel at elevated temperatures during friction welding. The flow lines on steel side are axially curved from the central region to peripheral region.

The microstructure in the central, half radius and peripheral regions of the joint in PWHT state are shown in Figure 3. It is obvious that the deformation layers in the half radius region and peripheral region are thicker than that in the central region. During friction welding, the linear velocity is higher in the periphery than in the center, resulting in uneven distribution of temperature along the faying surface. The heavier plastic deformation and heat were generated in half radius and peripheral regions of the joint, which coarsened the dynamic recrystallised (DRX) grains and increased the thickness of deformation layer to 15-20 μm [12,16], as shown in Figure 3(c)-(f). Also, the outside metal softened rapidly, but inside metal was forged by larger upset pressure at low temperatures leading to thin deformation layer of 8 μm and fine DRX grains which could enhance the tensile strength of the resultant joint [17], as displayed in Figure 3(a)-(b).

Additionally, fine tempered sorbitic structure distributed uniformly near the interface on steel side, without forming martensite. Normally, the workpiece cooled down to ambient temperature rapidly after welding, and martensitic structures which have adverse effect on the joint strength could generate near the joint interface [13]. However, as the tempering temperature increased to 250^{o}C-400^{o}C, cementite formed directly in the region where C agglomerated. Subsequently, the cementite dissolved, and then the tempered sorbite formed, consisting of finely dispersed alloy carbide particles and ferrite when the tempering temperature reached 500^{o}C-600^{o}C [18]. Therefore, after PWHT at 580 ^{o}C for 2 h, the martensites disappeared, the tempered sorbitic transformation occurred instead near the interface, which significantly improved the tensile strength of the joint.

The typical XRD pattern for the interface between TiAl alloy and 42CrMo steel in PWHT state was shown in Figure 4. It can be seen that a small amount of TiC phases formed at the interface, due to the strong affinity between Ti and C and its lower free energy of formation compared to other carbides. According to the investigation reported by Lee et al. [12], the formation of large amount of TiC brittle phases was the main factor to deteriorate the strength of TiAl alloy/AISI4140 joint. However, the content of TiC phase in this experiment was low according to the low peak displayed in Figure 4, which was insufficient to deteriorate the joint strength. Meanwhile, $TiFe_2$ and TiAl phases formed at the interface, as also shown in Figure 4.

To investigate the effect of interfacial intermetallic compounds (IMCs) on the joint strength, the distribution of IMCs at the interface was detected by SEM in high magnification, as shown in Figure 5. It can be seen that the precipitated phases evenly dispersed at the interface in the central and peripheral regions, and the average size of precipitated phases was 1 μm. Also, the interface in the central region was 2 μm thick in Figure 5(a), but that in the peripheral region was 5 μm thick in Figure 5(b). Although IMCs such as $TiFe_2$ and TiAl existed at the interface, they did not degrade the joint strength because the interface was thin and the fine precipitated phases and IMCs discontinuously distributed around the interface. It is agreed that if the interface in dissimilar materials weld is thinner than 10 μm, the resultant joint strength could be reasonably high [19]. Especially, the compressive residual stress in the friction welded joint also benefits the joint strength [20].

Fracture Morphology

Figure 6 reveals the fracture morphology of the specimen after PWHT. As shown in Figure 6(a), small cleavage steps appeared in the peripheral region of the fractured surfaces. However, quasi-cleavage fractures with tearing ridges were observed in the central region of the fractured surfaces, in Figure 6(b), revealing the low ductility of TiAl alloy at ambient temperature.

CONCLUSIONS

TiAl alloy was solidly joined to 42CrMo steel rods by friction welding process. The tensile strength of the joint after PWHT 580 ^{o}C for 2 h reached 405 MPa, and the fracture happened through the TiAl alloy substrate with quasi-cleavage features. The heavy plastic deformation appeared near the joint interface, and the deformation layers in the half radius and peripheral regions were thicker than that in the central region. The fine tempered sorbite formed near the interface, improving the joint strength significantly. $TiFe_2$, TiAl and TiC phases formed at the interface which was only 2-5 μm thick. The precipitated phases were 1 μm in average, dispersively distributed at the interface.

ACKNOWLEDGEMENTS

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Figure 1. Friction welded joint between TiAl alloy and 42CrMo steel rods after post-weld heat treatment at 580 ^{o}C for 2 h, (a) before tensile test, and (b) after tensile test.

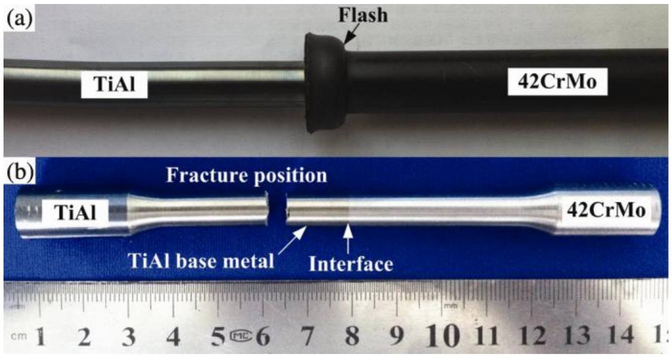

Figure 2. Macrograph of the joint between TiAl alloy and 42CrMo steel rods.

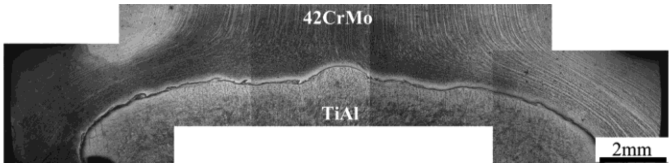

Figure 3. Microstructure around the interface of the joint between TiAl alloy and 42CrMo steel rods in as-welded state: (a)-(b) in the central region, (c)-(d) in the half radius region, and (e)-(f) in the peripheral region.

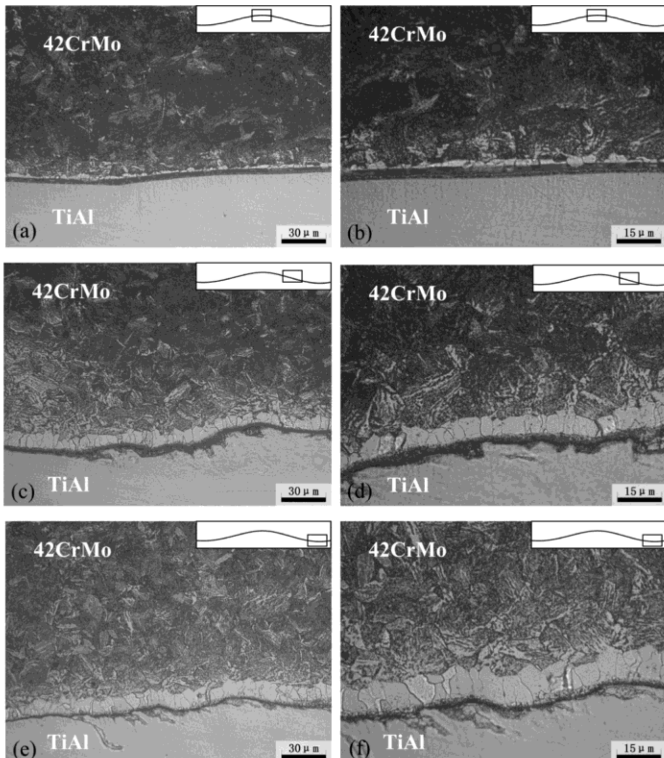

Figure 4. XRD pattern for the interface between TiAl alloy and steel in PWHT state.

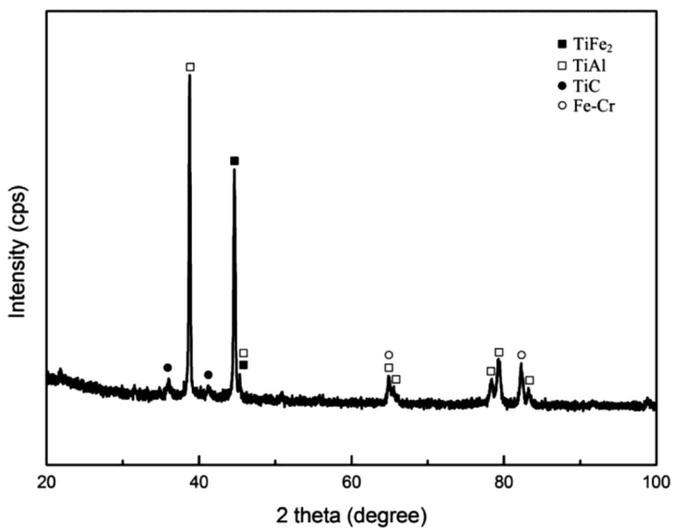

Figure 5 Distribution of IMCs at the interface between TiAl alloy and 42CrMo steel, (a) in central region, (b) in peripheral region.

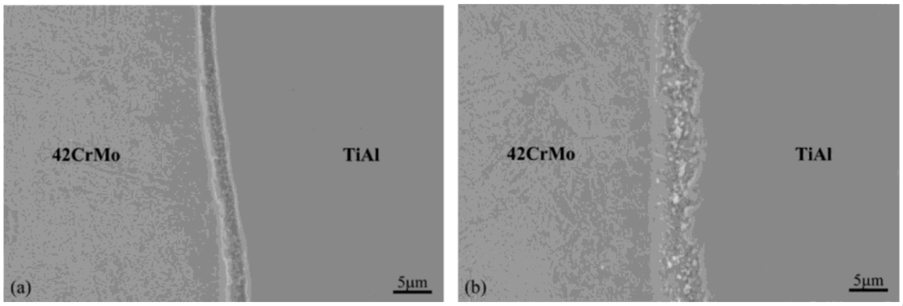

Figure 6. Fracture morphology of the heat treated sample after tensile test: (a) in the peripheral region, and (b) in the central region.