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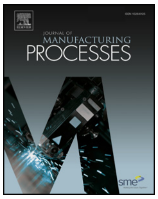

Inhomogeneous interface structure and mechanical properties of rotary friction welded TC4 titanium alloy/316L stainless steel joints

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ABSTRACT

The inhomogeneous interface structure and mechanical properties along the radius direction of rotary friction welded TC4 titanium alloy/316 L stainless steel dissimilar joints were investigated under as-welded and post-weld heat treated conditions. The interface in the joint is convex-shaped on TC4 titanium alloy side and concave-shaped on 316 L stainless steel side. The mechanical properties of joints are highly correlated with the inhomogeneous interface structure and the dimension of tensile samples. The tensile strength of the as-welded entire joint was 117 MPa, while it dramatically increased to 419 MPa after post-weld heat treatment at 600 °C for 2 h due to homogenization of aggregated atoms. However, the sliced samples was relatively weak even after post-weld heat treatment, because the internal defects became surface crack sources after machining, and caused stress concentration and sharply reduced the strength of samples. All tensile samples failed through the interface. The X–ray diffraction patterns of TiC, $Cr_{23}C_6$, Fe_2Ti, FeTi, $FeNi_3$, $AlTi_3$, $CrTi_4$, NiTi and TiCr phases and the river-like features on fracture surfaces indicate a brittle quasi-cleavage fracture mode. C and Cr aggregated around the interface under as-welded condition. Nonetheless, elemental homogenization occurred in the joint after post-weld heat treatment.

Introduction

Titanium and its alloys have some highly attractive properties, such as high specific strength, high temperature strength retention and excellent corrosion resistance, which attract considerable attention for structural manufacturing. However, the high cost limits extensive applications of titanium and its alloys. The hybrid metal combinations of titanium alloy and steel can combine the advantages of the two materials and can be applied in aerospace, chemical and nuclear industries [1–3]. However, joining of titanium to steel is still a great challenge due to (i) the large differences in thermo-mechanical properties, such as linear thermal expansion coefficient, thermal conductivity and melting point, which could lead to high residual stress and excessive distortion, and (ii) the formation of brittle Ti-Fe series intermetallic compounds (IMCs) because of the limited solubility between Ti and Fe [4], which will severely deteriorate the joint strength.

Several methods have been tried to weld titanium and steel, including fusion welding [5–8], brazing [9–11] and solid-state welding [12–27]. Nevertheless, the tensile strength of titanium/steel couple is relatively low made by fusion welding and brazing process. Solid-state welding of titanium to steel such as diffusion bonding [12–17], explosion welding [18–23] and friction welding [24–27], could produce high quality joints by avoiding most problems (e.g. segregation, pore, grain coarsening) that occur during fusion welding or brazing process. The rotary friction welding (RFW) has been proved to be the most effective method to weld titanium and steel due to the lower welding temperature and shorter welding cycle, which are useful to suppress metallurgical reaction and reduce residual stress. Several publications reported RFW of titanium and steel couples [2,3,28–31], and these researches mainly focused on the optimization of process parameters through analyzing the microstructure and tensile strength of the entire joints with arbitrary dimensions. These investigations are necessary but not sufficient.

It is known that the radial gradient heat generation and uneven deformation, which are the intrinsic nature of the RFW process [32–34], will result in inhomogeneous interface structure in joint. Especially for the dissimilar metals joint, asymmetric deformation turns much severer. When bearing external load, the integrity of the joint is easy to be destroyed due to fracture which initiates at the weak part. At a rather early stage, Vill [35] investigated the effect of welding parameters on the interface structure and proposed the “X” and “I” patterns under relatively low and high rotation speeds, respectively. Crossland

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[36] also reached the similar conclusions. Nguyen et al. [37] investigated and defined three type of welding conditions, i.e., hard & fast welding condition, optimal condition and long-time welding condition, under which the corresponding three type of interface structures were obtained. Ellis [38] pointed that the “X” and “I” patterns were formed under relatively large and small friction pressures, respectively. Kimura et al. [39] studied the interface evolution from the beginning to the end of the welding process in detail. Li et al. [40] specially investigated the evolution of the interface structure during the initial stage of welding process. Subsequently, researchers of Ellis [38], Selvamani [41], Kimura [42] and Sahin [43] further researched the mechanical properties of the entire joints using different dimensions of tensile samples, and obtained the optimized welding parameters in their own works. However, they didn’t further analyze the relationship between the inhomogeneous interface structure and joint strength. Fortunately, the problem attracts Chen et al’s attention and they investigated the strength of TC4 titanium alloy rotary friction welded (RFWed) joint along the radius, and found that the strength was of large difference in radius direction [44]. However, no literature has been reported on this issue of dissimilar material joining. Furthermore, the residual stress in the dissimilar joints caused by thermal expansion mismatch often generates deformation and cracks, which deteriorates the mechanical properties of joints. Accordingly, post-weld heat treatment (PWHT), which is an effective approach to reduce or even eliminate the residual stress in the joint, was employed by some researchers. Dong et al. [45] reported that PWHT could enhance comprehensive properties of RFWed joints between TC4 titanium alloys and 40Cr steel bars. Qin et al. [46] found that the PWHT could promote the elemental diffusion and improve the tensile strength to the equivalent strength of base material. Therefore, PWHT was also implemented in this study.

The aim of this study is to solidly join TC4 titanium alloy and 316 L stainless steel by rotary friction welding. Then the research target was focused on revealing the relationship between the inhomogeneous interface structure and mechanical properties of the resultant joints under as-welded and post-weld heat treated (PWHTed) conditions respectively.

Experimental procedure

Commercially available TC4 titanium alloy and 316 L stainless steel rods in diameter of 25 mm were used as base materials, of which the chemical compositions are listed in Table 1. The microstructure of each material is shown in Fig. 1. Before welding, the faying surfaces were polished with SiC papers up to grit 1000, ultrasonically cleaned in ethanol and then dried in air.

Friction welding was conducted using a friction welding machine (HSMZ-20, Harbin Welding Institute, China) with a constant rotation speed of 1500 rpm. Combining trial welding and data of the literatures [47,48], the friction welding parameters used in this study were determined as follows: friction pressure of 150 MPa, upset pressure of 300 MPa, friction burn-off length of 3 mm (the corresponding friction time is 6 s) and forging time of 15 s. After welding, the metallographic specimen was cut from the joint by electric spark machining. The TC4 titanium alloy and 316 L stainless steel were etched in an acid solution (10 m L HF + 10 m L HNO_3 + 100mL H_2O) and electrolytically eroded with a 10% oxalic acid solution respectively. To investigate the effect of PWHT on microstructure and mechanical properties of the joints, a part of the as-welded joints were picked out and heat treated at 600 °C for 2 h and then cooling in a furnace (KSL–1200X, China). The PWHT parameter was selected based on the literatures [31,45]. The microstructural features were obtained by using optical microscope (OM, Leica–MEF4A, German) and scanning electron microscope (SEM, Zeiss–Supra55, German) equipped with an energy dispersive spectroscope (EDS). The quantitative chemical analyses of the joints were performed by using electron probe microanalyzer (EPMA, EPMA–1600, Japan). Microhardness measurement was conducted on a Vickers microhardness test machine (MVC–1000B, China) using a load of 100 g and dwell time of 15 s. The joint strength was evaluated on a tensile test machine (DNS100, China) with crosshead speed of 0.5 mm/min at room temperature. And the tensile test was conducted according to China National Standard GB/T2651-2008. Two type of tensile samples, i.e., the entire sample with cutting off the external materials to diameter of 23 mm, and sliced samples cut from different locations along the radius of joints, were prepared to measure the entire strength and local strength along the radius, respectively. The detailed dimensions and configuration were drew in Fig. 2, and the resultant tensile strength was an average of at least three samples. After tensile test, the fracture surfaces were further examined by using SEM, EDS and X–Ray Diffraction (XRD, PANalytical–Empyrean, Netherlands). The XRD test was performed using Co-Kα radiation. The scanning rate was 1°/min and the range of scanning angle was from 30° to 110°.

Table 1
Chemical composition of the base materials (wt. %).

Materials	Compositions									
	C	Al	V	Ni	Cr	Mo	Mn	Si	Ti	Fe
TC4	-	6.35	3.83	-	-	-	-	0.15	Bal.	0.14
316L	≤0.03	-	-	10.32	16.4	1.98	0.9	0.47	-	Bal.

Results and discussion

Macrostructure and microstructure

Fig. 3 shows the macrostructures of the joints under as-welded and PWHTed conditions. It can be clearly seen that the joint geometry is unsymmetrical and the flash mainly forms on TC4 titanium alloy side, which means a sufficient deformation of TC4 titanium alloy base. Besides, it is interesting that the interface structure on TC4 titanium alloy side is convex-shaped and that on 316 L stainless steel side is concave-shaped. Reasons contributed to this phenomenon are listed as follows. One reason could be that the tensile yield strength of TC4 titanium alloy decreases faster than that of 316 L stainless steel with the increase of temperature. The temperature dependent yield strength of TC4 titanium alloy and 316 L stainless steel are shown in Fig. 4. It can be seen that although the yield strength of TC4 titanium alloy is much higher than that of 316 L stainless steel at room temperature, when the temperature becomes higher than 630 °C, the TC4 titanium alloy turns to be softer than 316 L stainless steel. Moreover, the friction heat will lead to an unsymmetrical distribution of temperature field along the axial direction because the thermal conductivity of 316 L stainless steel ($15\,W\,m^{-1}\,K^{-1}$) is much larger than that of TC4 titanium alloy ($6.7\,W\,m^{-1}\,K^{-1}$). Additionally, the softening effect resulted from the severe dynamic recrystallization is more obvious in TC4 titanium alloy side than that in 316 L stainless steel side during the welding process. As a result, the plastic deformation mainly occurs in TC4 titanium alloy side, resulting in an unsymmetrical appearance with larger flash on TC4 titanium alloy side. Moreover, the convex-shaped interface indicates that the TC4 titanium alloy at the center location has lower temperature and plasticity, while that at the edge location has higher temperature and has been fully plasticized so the material was extruded out of the interface to form flash. Detailed observation at the interfacial region shows that the original streamline structure becomes bent because of the thermal-mechanical coupled effect during welding process. Moreover, the microstructure along the radius direction is of different feature and it changes accordingly after PWHT at 600 °C for 2 h. A further analysis on the evolution of microstructure was conducted on the dashed line box areas along the radius direction.

Fig. 5 displays the evolution of the interfacial microstructure at center position under as-welded and PWHTed conditions. It can be seen