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Transient liquid phase (TLP) bonding of Ti-6Al-4V/UNS 32750 super duplex stainless steel

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ABSTRACT

Dissimilar metal joining between Ti-6Al-4 V and UNS 32750 super duplex stainless steel (SDSS) alloys was carried out by TLP bonding with a Cu interlayer at 890, 920, 950 and 980 °C for a bonding time of 60 min. In addition to microstructural survey, the microhardness and shear strength of different bonded specimens were also investigated. The results confirmed that the isothermal solidification zone (ISZ) was extended with the rising temperature up to 980 °C. Moreover, the formation of intermetallic compounds (IMCs) like TiCu, Ti_2Cu, Cr_2Ti, Fe_2Ti and FeTi was demonstrated in TLP joints by SEM/EDS examinations. It was found that increasing the bonding temperature promoted the formation of IMCs by increasing the diffusion of Ti, Cu and Fe, which resulted in degradation of shear strength of the joints. Mechanical characterizations indicated that the joint made at 890 °C had the highest shear strength (271 MPa), which was equal to 0.49 strength of Ti-6Al-4 V, as well as 0.47 of UNS 32750. Furthermore, the average hardness of the bonded zone was superior than that of the base metals. Also, the SDSS side exhibited high hardness values in the range of 420–460 HV, while the Ti-6Al-4 V side revealed lower hardness values (330–370 HV).

1. Introduction

Ti-6Al-4 V is one of the most promising materials; it covers about 60% of the total production of titanium [1]. Due to its excellent mechanical behavior and good resistance to corrosion, it is very often required to join Ti-6Al-4 V to stainless steels in various engineering applications such as aerospace and chemical industries [2–4]. On the other hand, duplex stainless steel (DSS) is one type of stainless steel that contains approximately equal ratios of ferrite and austenite in its microstructure [5]. This type of stainless steels has higher strength, better corrosion resistance, and lighter weight in comparison to austenitic stainless steels [6,7]. Therefore, DSSs can be used as a replacement for austenitic SSs to fabricate lighter components with higher strength. Recently, joining of Ti-6Al-4 V to DSS is strongly stimulated in the space, nuclear and chemical industries. However, fabrication of a defect free joining between Ti-6Al-4 V and DSS is not easy by using conventional welding processes. Hence, research on new methods of joining for this dissimilar joint is strongly recommended for further development.

The main challenge associated with dissimilar welding of Ti-6Al-4 V to SSs is the formation of intermetallic compounds (IMC) such as FeTi and Fe_2Ti during the welding of these materials, which is due to the metallurgical incompatibility of the metals [8,9]. The formation of these compounds leads to the brittleness of the joint. On the other hand, the thermal conductivity of Ti-6Al-4 V is 6.6 W m^{-1} K^{-1} [10], while UNS 32750 SDSS has a thermal conductivity of 14 W m^{-1} K^{-1}[11]. This big difference in thermal conductivity of Ti and Fe alloys can lead to cracking, corrosion and fatigue failure during service [12].

Different methods used to join Ti alloys and SSs include fusion welding [8], friction welding [12], diffusion bonding [2,13,14], and transient liquid phase bonding [15,16,9]. However, diffusion bonding method has attracted considerable attention in the literature reports for joining Ti-6Al-4 V to DSS alloy. For example, Kundu et al. [17] investigated the influence of temperature and time on the mechanical behavior of Ti-6Al-4 V - micro-DSS diffusion bonded specimens, concluding that the utmost tensile strength of 510.1 MPa was recorded at 850 °C for bonding time of 90 min. Decreasing the bonding time was also found an effective way to decrease the volume fraction of IMCs and improves the strength. However, the high compressive force between bonded parts as well as time-consuming and expensive surface preparation are considered as the main disadvantages of diffusion bonding [18].

The process of transition liquid phase (TLP) has been proven to be efficient in joining Ti-6Al-4 V [19,18] and DSS [20]. In TLP, the base metals to be joined are placed together with an interlayer inside a fixture. At a suitable bonding temperature, the interlayer melts and the

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subsequent interdiffusion of alloying elements leads to an isothermal solidification. Therefore, the formation of brittle IMC is significantly decreased during TLP [21,5].

The selection of proper interlayer is one of the important steps in TLP process. Soltani Tashi et al. [16] used a silver-based interlayer to join Ti-6Al-4 V to 316 L austenitic stainless steel. They reported that the wettability of the interlayer with base metals was not high at low temperatures, which could be improved with increasing temperature. However, the formation of IMC can be accelerated with increasing the bonding temperature and this potentially reduces the strength of the joint. In another study, Atapour et al. [15] applied a copper interlayer for joining Ti-6Al-4 V to 304 stainless steel. According to their results, in the best conditions, the joint strength reached to 374 MPa, which was much higher than that obtained in the previous study.

Recently, the use of SDSSs is becoming increasingly popular in oil and gas, petrochemical, pulp and paper, power generation, and pollution control industries [5]. In many of these applications, joining of SDSSs to Ti-6Al-4 V is necessary for superior corrosion resistance and reduce the cost. Traditional fusion welding processes cannot be used for joining SDSSs to Ti-6Al-4 V due to their metallurgical incompatibilities. Therefore, the use of solid state joining techniques such as TLP can be a viable solution to solve problems related to this dissimilar joint. According to our survey, no literature was found on the TLP bonding of Ti-6Al-4 V and UNS 32750 (SDSS) materials. Thus, this paper aims at investigating the feasibility of TLP bonding of Ti-6Al-4 V to a SDSS using a pure copper foil interlayer. Also, considering that temperature is one of the important variables in TLP process, the effect of the bonding temperature on the microstructure and mechanical properties of the dissimilar joint between Ti-6Al-4 V and UNS 32750 SDSS has been investigated. Based on the our experience and according to the previous works published in this field [19,18,15,9], the copper is accepted as a useful interlayer for joining titanium based alloys. Copper is a temporary melting-point depressant and diffuses readily in titanium [22]. Furthermore, copper foils have high flexibility, good quality and low cost.

2. Experimental procedure

In this work, SDSS and Ti-6Al-4 V sheets with the thickness of 4 mm were employed as the base metals, and 20 μm thick pure copper foil with purity of 99.99% was applied as the interlayer. The base metals and the interlayer were cut with the dimensions of 40 x10 mm, using computer-controlled traveling wire electro-discharge machining (EDM). Chemical compositions of the base metals are listed in Table 1. Both Ti-6Al-4 V and SDSS were ground and polished down to 1200 grit surface finish. Before TLP joining, both base metals and the copper foil were ultrasonically degreased with acetone for 30 min with a frequency of 35 kHz and 0.5 A current. The bonding assembly is schematically illustrated in Fig. 1.

TLP bonding process was accomplished under a vacuum of 2×10^{-5} Pa. A bonding pressure of 1 MPa was applied to hold the specimens together. In order to evaluate the influence of temperature, the bonding time was fixed in 60 min and four bonding temperatures of 890, 920, 950 and 980 °C were used. These temperatures were selected according to the Ti-Cu binary phase diagram (Fig. 2). According to Fig. 2, the eutectic temperature is about 870 °C. In this work, the minimum bonding temperature of 890 °C (20 °C higher than the eutectic temperature) was selected to ensure melting. The highest bonding

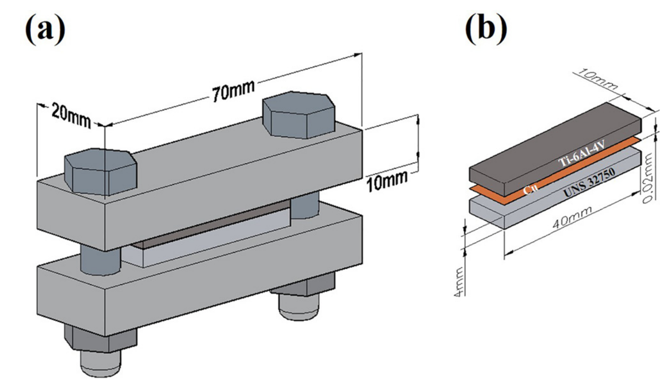

Fig. 1. Schematic image of (a) bonding assembly and (b) base metals and interlayer.

temperature was selected based on the beta-transus temperature of Ti-6Al-4 V (about 980 °C). Also, TLP bonding was carried out in two temperatures of 920 °C and 950 °C to examine the effect of temperature on the mechanical behavior of bonded zones. The heating rate was 10 °C/min. After heating, the specimens were allowed to cool at the same rate to room temperature. The variables used in this study are presented in Table 2. TLP-bonded specimens were sectioned and mounted for optical and SEM microstructural characterization. The mounted samples were ground up to 1200 # SiC paper and then polished with the diamond paste. For metallographic examination, the samples were etched in a chemical solution. At first, the duplex stainless steel side was etched by a solution with the chemical composition of 30 ml HCL + 70 ml water + 1 g $K_2S_2O_5$. After that, the Ti-6Al-4 V side and the joint were etched with kroll solution (5 ml HF + 5 ml HNO_3 + 90 ml water).

Microhardness measurements of the polished surface of the TLP bonds were performed according to ASTM E92 standard and with a load of 100 g. The bond strength of the specimens was determined using shear strength tests with crosshead speed of 1 mm/min. For each of the bonding conditions, at least 3 samples were subjected to tensile-shear test and the mean strength was reported. For this purpose, a shear test fixture was used (Fig. 3). Finally, the fracture surface of the bonded specimens was studied by SEM.

3. Results and discussion

3.1. Microstructural evaluation

Optical micrographs of base metals, Ti-6Al-4 V and UNS 32750 SDSS, are given in Fig. 4. Ti-6Al-4 V consists of two phases of body centered cubic (BCC) β phase and hexagonal closed packed (HCP) α phase. Also, UNS 32750 has a structure consisting of approximately equal amounts of austenite (FCC) and ferrite (BCC).

Fig. 5 shows the microstructure of the TLP joints obtained at different temperatures and the constant time of 60 min. As can be seen, the bonding zone at all temperatures was free of any cracks and discontinuities, indicating the good bonding between these two alloys. Due to the diffusion of elements, the width of the bonded zone was much larger than the initial thickness of the interlayer. In the bonding of polycrystalline specimens by diffusion dependent methods, grain boundary diffusion is much rapid than bulk diffusion, so the grain

Table 1
Chemical composition of the base metals.

Alloy	Ti	Fe	Al	V	Cr	Ni	Mo	Mn	Si	C	N	S	P
Ti-6Al-4 V	Bal.	0.10	6.1	4.5	0.01	0.04	–	1.2	0.4	0.01	–	–	
UNS32750	–	Bal.	–	–	26.85	6.98	4.76	0.56	1	0.029	0.3	0.011	0.023