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Microstructure and mechanical properties of titanium/steel bimetallic joints

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ABSTRACT

In this paper, we report the investigation of Ti/Fe bimetallic plates welded with Cu-V filler. The microstructures and mechanical properties of individual phase were examined using combined microstructural analysis and nanoindentation test. Bending test was conducted to understand the overall mechanical behavior of the joint. The metallurgical reactions and evolution of phase composition during the welding process were discussed. It is interesting to note that the crack nucleation and propagation in different phases depend not only on the size and distribution of brittle intermetallics but the morphology of ductile phases.

1. Introduction

Titanium-steel bimetallic plates are increasingly used due to their excellent corrosion resistance [1]. However, joining these dissimilar materials remains as a challenge because the metallurgical incompatibility in a dissimilar joint often leads to the formation of brittle phases [2–4]. To solve this problem, one approach is to introduce intermediate alloys that can modify the final phase compositions [5–9]. The most widely used intermediates are Cu alloys [6–11] because of their high ductility and relatively low cost. A series of compounds such as $CuTi_2$, CuTi, Cu_3Ti_2, Cu_4Ti_3 and Cu_4Ti observed in Cu-Ti system can reduce or change the distribution of brittle Fe-Ti intermetallics [12]. Tomashchuk et al. [8] confirmed that a Cu interlayer could reduce the Fe-Ti intermetallics in titanium-AISI 316 steel dissimilar joints. Lee et al. [13] employed composite filler containing more than two metals for joining titanium-steel. Due to high compatibility with titanium, vanadium can be used for joining titanium to steel, confirmed by the work of Wang et al. [14] on joining high strength titanium-stainless steel.

In our previous studies [15–16], crack free joints were obtained when joining Ti/Fe bimetallic plate with Cu-V based fillers. However, these joints showed very low ductility in bending. It was reported that the type, amount and distribution of the intermetallic phases (M_yTi_x) affect the mechanical behavior [7,17]. However, the underpinning mechanisms have not been well understood. One of the technical difficulties is how to accurately evaluate the intrinsic properties of individual intermetallics at micro or even nano scale. Compared to conventional mechanical tests, nanoindentation has demonstrated to be a powerful tool for mechanical characterization at small scales [18–19].

In this work, with extensive microanalysis and nanoindentation, the properties and distribution of intermetallics were investigated in the Ti/Fe dissimilar joints. A simplified model was proposed to build the link between local phase composition and overall mechanical behavior.

2. Experiment

The base materials to be joined were explosion-bonded Ti/Fe bimetallic plates with the size of 350 mm × 250 mm × 16 mm (Ti + Fe ~ 16 mm). ERTi-1, ER50-6 and Cu-V were used as filler materials. The chemical compositions are listed in Table 1.

The groove dimensions of the Ti/Fe bimetallic plates were similar to our previous study [15]. The joints were prepared using Tungsten inert gas (TIG) welding method with the welding parameters listed in Table 2.

The welding sequence is schematically shown in Fig. 1a. Cu-V intermediate layer was introduced between Fe and Ti weld metals. The cross-sections were prepared to observe the microstructures along three interfaces, i.e., Fe/Cu-V, Ti/Cu-V/Fe and Cu-V/Ti WM, Fig. 1b. SEM (JEOL-7001F) and TEM (JEOL-2100) were used to further examine the microstructures at Ti/Cu-V/Fe and Cu-V/Ti WM interfaces, as shown in Fig. 1c.

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Table 1
Chemical compositions of materials applied (wt%).

Elements	C	Si	Mn	Ti	Cu	Fe	V	O	N	H
CP-Ti	0.10	–	–	Bal.	–	0.25	–	0.20	0.03	0.015
Q345	0.20	0.50	1.20	–	0.35	Bal.	–	–	–	–
ERTi-1 (φ1.2 mm)	0.03	–	–	Bal.	–	0.10	–	0.10	0.012	0.008
ER50-6	0.08	0.89	1.51	–	0.18	Bal.	–			
Cu-V (φ1.2 mm)	–	–	–	–	Bal.	–	30	–	–	–

The TEM samples were prepared using focused ion beam (FIB, FEI Quanta 200 3D dual beam). Nanoindentation was conducted using Berkovich indenter (Hysitron Triboindenter TL-950). Load control mode was adopted with a constant loading rate of 300 μN s^{-1} up to maximum load of 3 mN. The measured hardness was the average from at least five indentations. X-ray diffraction (XRD) patterns were collected on the cross sections using a Rigaku-binary diffractometer (Rigaku SmartLab) with Cu Kα incident X-rays. Patterns were collected from 30 to 110° (2θ) at a step size of 0.05° (2θ). The specimens for standard three point bending tests were prepared and the testing parameters were set as that in our previous study [16].

3. Results and Discussion

3.1. Solidification Process

The microstructure of the Ti/Fe joints depends on the phase composition and welding process. As shown in Fig. 2, a model is proposed to predict the possible phases during fusion with the Cu-V and Ti fillers. As shown in Fig. 2a, Cu-V weld metal is composed of Cu-V and Fe. Since Cu has very limited solubility with Fe and V, possible reaction in the molten pool is Fe-V binary system. Fe and V have large solubility and tend to form solid solution [20–21]. Therefore, the undercooled Fe-Cu-V liquid is then separated into two phases $L_{Fe,V}$ and L_{Cu}. In fact, liquid-phase separation is a common feature in rapid solidification of Fe and Cu system [22–23]. The solidification in Fe-V starts at around 1600 °C. At a high cooling rate, it is also possible to form Fe solid solution. Liquid Cu can exist around these solid phases ((Fe,V)ss, Fe) and then solidifies at about 1084 °C, Fig. 2b. Once a Fe rich solid phase forms, a small amount of Cu solid phase can also form via a peritectic reaction: $Fe + L_{Cu} \rightarrow Cu$ (~1096 °C). Additionally, the heat input resulted from the Cu-V fusion leads to melting of Ti/Fe base metal. Compared to Fe, the lower thermal conductivity of Ti results in significant heat accumulation [24] and melting of Ti base metal. From the Fe-Ti binary phase diagram, the possible reaction is $L \rightarrow FeTi + \beta\text{-}Ti$ at 1085 °C. It should be noted that C in the Fe base metal may form brittle TiC with Ti alloy [25]. Due to its relative lower content compared with Cu and V, this reaction can be neglected.

Table 2
Welding parameters with different filler materials.

Welding sequences	Current (A)	Voltage (V)	Welding speed (mm/min)	Wire rate (mm/min)	Shielding gas
Ti filler (ERTi-1)	90	8	100	800	Ar (99.999%)
Fe filler (ER50-6)	160	13.7	150	1200	Ar (99.999%)
Cu-V	140	8	60	500	Ar (99.999%)

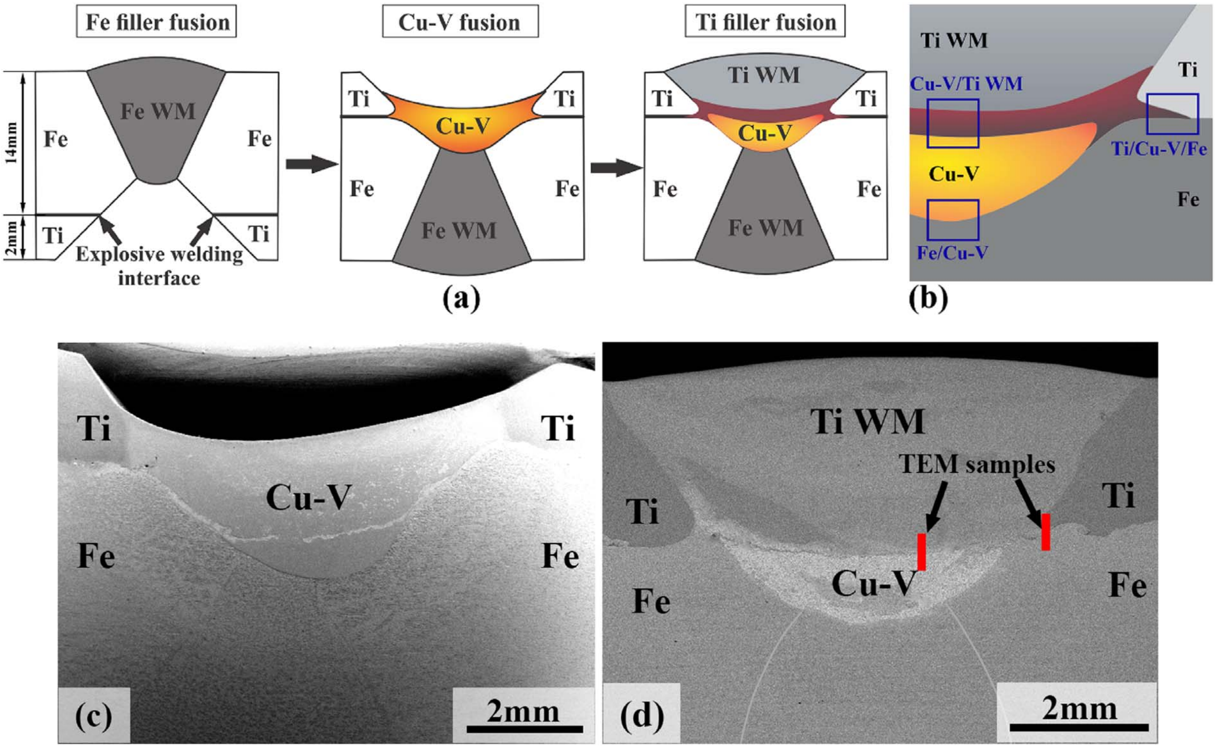

Fig. 1. (a) Schematic of welding sequence; (b) possible phase interfaces; (c) cross section before depositing Ti filler and (d) cross section after depositing Ti filler. The locations indicated by the red bars are where the TEM samples are extracted. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)