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An investigation on bonding mechanism and mechanical properties of Al/Ti compound materials prepared by insert moulding

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ABSTRACT

Al/Ti metallic composites prepared by insert moulding are attracting more attention now because of their low production costs, low energy consumption, simple production procedure and high interface bonding strength. However, the insert moulding of pure Al and pure Ti has not been reported so far though it can be considered as a fundamental in studying Ti-alloy/Al-alloy interface bonding. Therefore, the insert moulding of pure Al and pure Ti is intended in this paper and the corresponding microstructure, elements distribution and mechanical properties of the interface are also analyzed. As a result, a good metallurgical bonding can be achieved at the interface of Al and Ti, which is mainly comprised of intermetallic compounds $TiAl_2$ and $TiAl_3$ formed in the transition zone around Ti insert and Al matrix, respectively, depending on different heat treatment parameters and cooling conditions. It is shown that the hardness of the interface layer varies with the types of interface sublayers. For the compact sublayer, the hardness is higher than those of both base metals (Al and Ti) with the maximum value reaching HV520. However, the hardness of the granular interface sublayer depends on the proportion of the intermetallic compounds and aluminum matrix. The average shear strength of the interface layer could reach about 60 MPa, which is higher than that of the aluminum matrix (43 MPa) tested in this experiment. The result also shows that shear crack initiates at bottom face of the specimen (adjacent to locator) in the aluminum matrix nearby the interface.

1. Introduction

Titanium alloys have been widely used due to their high specific strength, excellent corrosion resistance, notable impact toughness and significant thermal stability. However, high production cost constrains their widespread applications [1]. Aluminum alloys, another kind of important engineering metallic materials, exhibit low density, good formability, high thermal conductivity and low cost, but are short of impact toughness and corrosion resistance at high temperature [2]. Bonding aluminums (Al) alloys and titanium (Ti) alloys would achieve a combination of their excellent properties including low density, strong acid/alkali corrosion resistance, good oxidation resistance at elevated temperatures, high specific strength and high specific stiffness [3]. Consequently, the Al-alloy/Ti-alloy compound materials are promising to be applied in aeronautics, astronautics, as well as petrochemical and defense industries [4]. In the past several years, it has been reported that Al/Ti compound materials have already been fabricated by accumulative roll-bonding [5–7], laser welding–brazing [8,9], friction stir welding [10,11], powder metallurgy [12,13], explosive cladding process [14] and so forth. However, these methods still have much room for improvement as their processing procedures are very complex and the products usually have lower interface bonding strength, limited dimension, and little opportunity for mass production. Recently the insert moulding method has been utilized by Olivier et al. to produce Ti/Al–7Si–0.3 Mg compound ingots, which exhibits excellent industrial application prospects for the preparation of Ti alloys/Al alloys compound materials due to low production costs, low energy consumption, simple production procedure and high interface bonding strength of the products [15,16]. The process of bonding pure Ti and pure Al is fundamental in studies of Ti-alloy/Al-alloy interface bonding, but so far the insert moulding of pure Al and pure Ti has not been reported yet. Based on this condition, insert moulding of pure Al and pure Ti were studied in this paper to produce good metallurgical bonding between the two dissimilar metals. The microstructure, elements distribution and mechanical behaviors at the interface of Al/Ti

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compound materials were also discussed by fabricating the samples using different heat treatments and different cooling methods. Emphasis is placed on the formation mechanism of Al/Ti dissimilar metals bonding.

2. Experimental details

2.1. Specimen preparation

Commercial pure aluminum casting ingots and titanium rods with dimensions of ∅6 mm × 65 mm were used as matrix materials and inserts, respectively, whose compositions are given in Table 1. The surface of titanium rods was mechanically polished with 2000-grit SiC papers before application and then treated by alkaline cleaning, acid pickling and ultrasonically degreasing with acetone. Similarly, aluminum ingots were cut into pieces and pre-treated followed by the same procedure, except mechanical polishing. Then the pre-treated aluminum pieces were then put in a baked corundum crucible (shown in Fig. 1) which was heated in a resistance furnace to obtain the aluminum melts. During the melting, aluminum melt was regularly stirred and the dross floating on the surface was removed. The temperature of aluminum melts was measured with K-type (Ni/Cr) thermoelectric couple plunged in with an accuracy of 0.2 °C. It should be noted that a customized graphitic cover was set on the top of the crucible when the insert moulding experiment is being carried out so that the titanium insert was kept vertical and centered (shown in Fig. 1).

2.2. Heat treatment

In order to achieve good metallurgical bonding between Ti insert and Al matrix, different heat treatment conditions and cooling methods were tested. When the temperature of aluminum melts were stabilized at 740 °C, the titanium rods were immersed and kept at 740 °C for 5 min, 10 min, 20 min, 30 min and 60 min, respectively. After that, two different cooling methods, i.e. air cooling (AC) or furnace cooling (FC) were utilized to cool the samples to room temperature. Hereafter the as-prepared Ti/Al metallic composites were denoted as TIAL-mn, where m represented the heat treatment time (*m* = 5, 10, 20, 30, 60) and n indicated the undergone cooling style (*n* = AC or FC).

2.3. Interface analysis

After solidification, the bimetallic samples were sawn into slices with a thickness of 5 mm by wire cut electrical discharge machining in the way that cross-sections of these slices were all perpendicular to the rod axis. Surfaces of each specimen were then polished with 0.5 μm diamond paste and utilized for the interface structure characterization, chemical composition analysis by scanning electron microscopy (SEM, EVO18, ZEISS) and electron probe micro-analysis (EPMA, JXA8100, JEOL), respectively. Additionally, the phase structure at the interface was also determined by X-ray diffraction (XRD-6000, Cu Kα radiation, Rigaku) which was performed at a scanning range of $20° \leqslant 2\theta \leqslant 90°$.

Table 1
The composition (wt%) of the commercially available aluminum matrix and titanium insert used in this experiment.

	Aluminum	Titanium
Si	0.07	
Fe	0.16	0.30
Cu	0.02 max	
Mn	0.02 max	
Mg	0.02 max	
Zn	0.06 max	
Ca	0.03 max	
Others		0.40 max
Ti	0.03 max	Balance
Al	Balance	

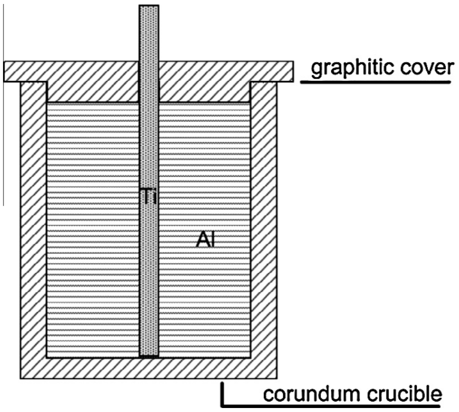

Fig. 1. The schematic sketch of preparing Al/Ti bimetallic compound samples using insert moulding method.

As no ASTM test standard exists for these joint materials, classical push-out testing was chosen to investigate the shear strengths of the joint interface [15,17,18]. A universal testing machine was used to conduct the push-out tests. The tested specimens with thicknesses of 5 mm were put on a supporting platform, with a centered circular hole of 7 mm diameter as shown in Fig. 2. The Ti insert was pushed by a steel cylinder stub punch, which is concentric with the circular hole, with a diameter of 5.5 mm. The displacement rate of cross-head was 0.5 mm/min. In order to keep the interface zone vertical during the whole operation, a steel locater was set up at the central bottom of the specimens. Shear strength of the interface (τ) was calculated using the following equation [15,16]:

$$\tau = \frac{F_{\max}}{2\pi rt} \qquad (1)$$

where $F_{\max}$ is the maximum load, *r* is the radius of Ti insert (i.e., 3 mm), and *t* is the specimen thickness (i.e., 5 mm).

The Vickers hardness was measured by a microhardness tester (Type M tester, Wolpert Wilson Instruments) across the interface layer as well, under the indentation load of 300 g for 15 s. The microhardness value was evaluated by averaging the three mediate values of five indentation measurements.

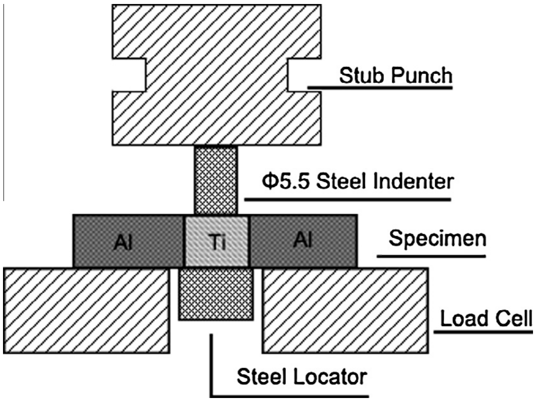

Fig. 2. Schematic sketch of typical setup used for push-out tests.