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Simultaneously achieving high tensile strength and fracture toughness of Ti/Ti-Al multilayered composites

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ABSTRACT

Ti/Ti-Al multilayered composites with different volume fractions of α-Ti layer were fabricated by hot press sintering. Microstructural observation indicates that the phase compositions in all the composites are α-Ti, Ti_3Al, TiAl, $TiAl_2$ and $TiAl_3$. The tensile strength and fracture toughness of Ti/Ti-Al multilayered composites are influenced by the volume fraction of α-Ti layer. The composite with 53 vol% Ti presents the highest tensile strength and suitable ductility at room temperature, and its fracture toughness can reach 47.6 $\text{MPa}\sqrt{\text{m}}$, which is much higher than that of TiAl intermetallic alloy and Ti/Al_3Ti composites. Fracture analysis reveals that a certain volume fraction of Ti layers can effectively prevent the crack propagation when the crack is extended to the interface, resulting in high tensile strength and acceptable ductility at the same time. The improvement of toughness is associated with crack deflection and crack bridging provided by the appropriate thickness of remaining α-Ti layer.

1. Introduction

TiAl based intermetallic alloys have been considered to be potential high-temperature materials in aerospace and automotive industries due to high specific yield strength, good oxidation resistance and good creep properties at elevated temperatures [1–6]. However, their poor ductility and formability at room temperature are still the barriers to their extensive application as structural materials. To date, numerous efforts have been made to improve ductility and formability of TiAl based intermetallic alloys at room temperature [7–10]. Three methods can be used to improve ductility at room temperature: (1) Alloying with Cr, V, Mn, Nb, etc. to form disordered and plastic secondary phases [11–14]. By changing the alloy composition and microstructure, some developed alloys exhibit good workability and acceptable tensile properties, and the tensile fracture strains of the alloys are in the range of 1–3% at room temperature. (2) Refining the microstructure through hot isostatic pressing (HIP), forging and complex heat treatments [15–17]. For example, S. Bolz et al. [18] reported that the γ-TiAl alloy exhibits relatively high tensile strength and an acceptable tensile elongation of 1–2% at room temperature after a single-step forged process. Nevertheless, the high cost of thermo-mechanical processes need to be taken into consideration. (3) Introducing of ductile particles, fibers or layers to form TiAl composite [19–21]. Ritchie et al. [22] found that by adding ductile TiNb and Nb particles, the toughness of γ-TiAl composite was increased to 40 $\text{MPa}\sqrt{\text{m}}$ (in comparison with 8 $\text{MPa}\sqrt{\text{m}}$ of the monolithic γ-TiAl), due to crack trapping, crack nucleation and extensive crack bridging by the ductile TiNb and Nb reinforcements.

As demonstrated in many composites [23–25], incorporating one or more ductile phase into the brittle matrix is the most potential way to increase the energy-absorbing capability. In the $MoSi_2$/Nb composite, the morphology of Nb reinforcement has an obvious effect on toughening ability, and the layered structure exhibits the best capability for enhancing ductility [26]. Nb layer and NiCoCrAl layer were introduced individually to fabricate TiAl-based multilayer composites by R.B. Zhang [27] and the composites showed improved mechanical properties at both high and room temperatures, indicating a positive role of the ductile layer in strengthening and toughening composites. In recent years, more and more attentions are forced on Ti-Al multilayered or laminated composites, in particular on the $Ti\text{-}Al_3Ti$ metal-intermetallic multilayered composites, which are potentially used in honeycomb or sandwich components of airplanes [28–35]. The $Ti\text{-}Al_3Ti$ multilayered composite can be easily obtained by reactive sintering in vacuum using Ti and Al foils with different initial thickness [33]. It was suggested that

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the residual ductile Ti is helpful in mitigating Al_3Ti damage and preventing delamination, thus improving the strength and toughness by crack bridging and crack deflection [34]. In addition, different volume fractions of residual Al in Ti-Al_3Ti laminate composites were studied to show the Al content can have an important effect on the mechanical property. This means that the content of ductile phase must be taken into consideration in fabricating Ti-Al composite. Sun [36] also manufactured the various macrostructures of Ti-Al composites at different temperatures and revealed that flexural strength of multilayered Ti-Al composite is better than that of the homogeneous TiAl, indicating that the layered macrostructure is helpful for increasing the mechanical properties of the Ti-Al composite. However, few works have been focused on the effect of Ti content on the mechanical properties of multilayered Ti-Al composites. Since the Ti-Al aluminides have different physical properties [37], the strength and toughness of Ti/Ti-Al layered composite will be greatly influenced by its detailed microstructure, such as the phase composition, volume fraction and interface bonding of brittle and ductile phases. In this work, not only high strength but also high toughness of Ti/Ti-Al multilayered composite was achieved by forming multi-phases of α-Ti, Ti_3Al, TiAl, $TiAl_2$ and $TiAl_3$ in hot press sintering. The influences of α-Ti volume fraction on the tensile strength and fracture toughness were investigated in detail, and optimal volume ratio of Ti to Ti-Al intermetallic was obtained.

2. Experimental procedure

Elemental Ti foils with four different thickness (99.8 at%, 45 μm, 90 μm, 135 μm and 180 μm) and elemental Al foils (99.99 at%, 54 μm) were used to fabricate Ti/Ti-Al multilayered composites. The foils were cut in the form of rectangle pieces of 40 mm × 80 mm, cleaned ultrasonically in alcohol, and wire brushed. After surface treatment, 50 Ti layers and 49 Al layers were stacked alternately according to the sequence shown in Fig. 1 and then placed in a graphite die with internal dimension of 40 mm × 80 mm. The stacked Ti-Al multilayers were pre-sintered in the vacuum furnace under 50 MPa for 30 min at 500 °C in order to enhance the Ti/Al interface bonding. The stacked specimen prepared was then subjected to heat treatment at 900 °C for 30 min in vacuum condition without pressure, so as to consume Al completely to form Ti-Al intermetallics. During heat treatment process, the stacked specimen was kept in the graphite die in order to keep the specimen in specific shape.

In the final hot pressing process, a high vacuum of the order of 10^{-3} Pa was applied. The final sintering was carried out at 1050 °C with 10 °C/min heating rate for 60 min under the pressure of 50 MPa. The sintered specimens were cooled with the furnace, and the cooling rate was ~15 °C/min.

Metallographic samples were prepared by standard mechanical polishing. The microstructures of each polished sample were characterized by Cam-3400 Scanning Electron Microscopy (SEM) coupled with energy dispersion spectroscopy (EDS). Phase composition of multilayered specimen was further identified by D/max 2200 PC X-ray diffractometry (XRD) with Cu Ka radiation. Tensile tests based on GB 6397-86 standard were conducted on the sheets using an Instron 8801 testing machine with a crosshead displacement speed of 0.1 mm/min at room temperature. Toughness tests were performed on single edge-notched specimens by using three-point bending tests, and the fracture surface was examined by SEM. All the values of strength and toughness were taken from an average of three samples.

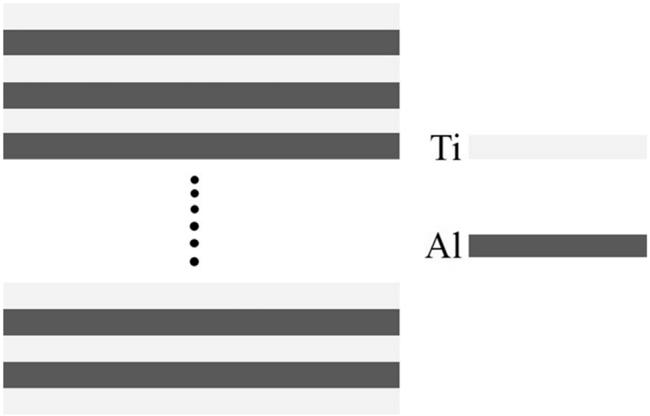

Fig. 1. Stacking sequence of the total 99-layer specimens that will subject to hot pressing.

Single edge-notched bend beams were prepared for three-point bend testing to determine the fracture toughness of the Ti/Ti-Al multilayered composites. The length, width, and height were 20 mm, 2 mm, and 4 mm, respectively. Tests were carried out under displacement control at a rate of 0.1 mm/min. Fracture toughness values, K_{IC}, were calculated for three-point bend loading using [28]:

$$K_{IC} = 3PS/bw^2 \times \sqrt{\pi a} \times f\left(\frac{a}{w}\right) \tag{1}$$

where K_{IC} is the fracture toughness, P is the load, S is the span, b is the specimen thickness, w is the specimen width, a is the crack length, and $f\left(\frac{a}{w}\right)$ is the function defined as:

$$f\left(\frac{a}{w}\right) = \frac{3\left(\frac{a}{w}\right)^{\frac{1}{2}}\left[1.99 - \left(\frac{a}{w}\right)\left[1 - \left(\frac{a}{w}\right)\right]\left[2.15 - 3.93\left(\frac{a}{w}\right) + 2.7\left(\frac{a}{w}\right)^2\right]\right]}{2\left[1 + 2\left(\frac{a}{w}\right)\right]\left[1 - \left(\frac{a}{w}\right)\right]^{\frac{3}{2}}} \tag{2}$$

3. Results and discussion

3.1. Mesostructure

The cross-sectional mesostructures of Ti/Ti-Al multilayered composites prepared through hot pressing are shown in Fig. 2. It can be seen that the interface is straight as the same with the green body between Ti and intermetallic layers. The multilayered composites are well-bonded and besides minor porosity, there are no discernible defects such as cracks or voids, indicating that voids produced due to Kirkendall effect are almost eliminated by hot pressing [38].

Fig. 3 shows the statistical results of the thickness of Ti layer and Ti-Al intermetallic layer of the multilayer specimens after sintered. The volume fraction of Ti was calculated as:

$$\frac{t_{Ti}}{t_{Ti} + t_{Intermetallic}} \tag{3}$$

where t_{Ti} and $t_{Intermetallic}$ refer to the thickness of Ti and Ti-Al intermetallic layer, respectively. After calculation, the Ti volume fractions of the four specimens are 20%, 53%, 66%, and 73%, respectively. Henceforth, the samples are designated by the volume fraction of Ti. For example, 20Ti refers to a specimen with a 20 vol % Ti. Apparently, the individual volume fraction of intermetallic and Ti are dependent on the initial thickness of Al foils and Ti foils. The mesostructure of all four specimens consists of five different contrasted regions, as marked in the inserted high magnification image of Fig. 2(a). The chemical composition of different regions in the four composites was analyzed by EDS, as shown in Table 1. XRD results reveal that the phase compositions in all the specimens consist of hexagonal close-packed (hcp) structured α-Ti solid solution, Ti_3Al, TiAl, $TiAl_2$ and $TiAl_3$ (Fig. 4). By comparing the EDS and XRD results, the phases corresponding to the microstructural features in the interfacial region were identified. The regions from 1 to 5 represent α-Ti, Ti_3Al, TiAl, $TiAl_2$, and $TiAl_3$, respectively, and are aligned in the order from light to dark layers.