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Bending behaviors and fracture characteristics of laminated ductile-tough composites under different modes

B.X. Liu [a, b, c], L.J. Huang [a, *], X.D. Rong [a], L. Geng [a], F.X. Yin [b, c]

[a] School of Materials Science and Engineering, Harbin Institute of Technology, P.O. Box433, Harbin 150001, China
[b] Research Institute for Energy Equipment Materials, Hebei University of Technology, TianJin 300132, China
[c] TianJin Key Laboratory of Materials Laminating Fabrication and Interfacial Controlling Technology, China

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ABSTRACT

The bending load-deflection curves and fracture characteristics of a range of laminated Ti–(TiBw/Ti) composites were investigated under five modes. The results show ductile-brittle transition with decreasing Ti layer thicknesses and increasing volume fractions of TiBw, which is attributed to the constrained plastic deformation mechanism accompanying with high stress traixiality and tensile stress. The laminated composites with weak interfaces display superior fracture toughness under notched crack arrested orientation, which is related to the delamination cracks and multiple tunnel cracks. Moreover, single tunnel crack propagation and periodic multiple tunnel cracks were observed in the laminated composites under mode IV, which depend on the thickness and ultimate strength ratio of ductile Ti layer and tough TiBw/Ti composite layer. There are many interfacial delamination cracks and multiple tunneling cracks presented under mode V, playing an effective role in toughening the laminated composites. In addition, with decreasing the Ti layer thickness, laminated composites reveal obvious size effect characterized by more tunnel cracks.

1. Introduction

Examples of whisker-, fiber- and particulate-reinforced titanium matrix composites have been extensively investigated in the past 30 years [1]. However, due to the incorporation of reinforcements by both ex-situ and in-situ methods, titanium matrix composites (TMCs) usually exhibit low ductility, workability, formability and toughness, which greatly limit their practical application. Lu [2] proposed an idea that the mechanical properties of composites can be enhanced by tailoring reinforcement distribution to form novel multi-scale structures far beyond the homogeneous composite structure. Recently, laminated [3], gradient [4] and novel network structures [5] resulted in a significant strengthening, toughening and plasticizing effect of metal matrix composites.

Laminated composites have been extensively studied for a number of potential applications in structural components, such as aerospace, automobile, vehicle and armor sectors. Typical laminated composites such as ceramic-ceramic, metal-metallic glass, metal-ceramic, metal-metal and metal-ceramic-intermetallic systems have shown desirable structural properties as a result of many layers and interfaces [6–9]. These systems allow for the possibility of combining the good ductility and toughness of the soft layer with the high strength of hard layer. Several processing techniques, such as adhesion bonding, chemical deposition, diffusion bonding, hot accumulative rolling, flake powder metallurgy and reaction hot pressing can be used to fabricate these laminated systems [10–17].

In our previous work [15–21], the tensile properties of laminated Ti–(TiBw/Ti) composites with two-scale structures were investigated in detail, revealing high strength and superior fracture elongation under the unaxial tensile testing. However, laminated composites used for structural materials always afford complex stress states, such as bending condition. Ohashi et al. [13] proposed that laminated steel-brass composite achieved remarkable bending ductility without failure. Sun. et al. [22] reported that laminated Ti/Ti–Al intermetallics composites benefited more bending strength and ductility from the multilayered microstructures compared with tensile properties, which is due to appearance of more micro-cracks. Yanagimoto et al. [2,23] revealed that laminated 420J2/304 stainless steel composites can obtain superior bending formability by delaying necking of 420J2 stainless steel layer. Therefore,

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[*] Corresponding author.
E-mail address: huanglujun@hit.edu.cn (L.J. Huang).

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the laminated composite will be more suitable to be used under the bending loading conditions on the basis of their fracture mechanics and deformation mechanisms.

Up to date, most of studies of laminated composites were devised to improve either impact toughness or fracture toughness under bending condition with a chevron notched crack [24]. It is demonstrated that the enhanced fracture toughness of laminated composites is related to extremely high resistance to crack propagation by delamination cracks, crack deflection, tunnel cracks, micro-cracks and compression stress state accompanying with many toughening mechanisms, such as blunting, shielding, bridging and trapping effects [19,25,26]. There are two distinct tunnel crack modes ahead of notched crack tip of laminated metal/ceramic composites with strong interfaces: the first mode is multiple tunnel cracks, which are nucleated in the ceramic layer either side of the notched crack, and the second crack mode-with single tunnel crack propagates by renucleation in successive ceramic layers following an approximately co-planar path. Obviously, multiple tunnel cracks mode is more benefits for absorbing fracture energy and improving fracture toughness, and many studies revealed that transition behavior from single tunnel crack into multiple tunnel cracks is depend on structural parameters, such as layer thickness ratio $\left(\frac{t_c}{t_m}\right)$, fracture strength ratio $\left(\frac{\sigma_c}{\sigma_m}\right)$ of ceramic layer and metal layer, notched crack size and interfacial bonding strength et al. Therefore, the effects of structural parameters on transition behavior are complex and not completely understood [27–36]. Meanwhile, the deformation behavior of metal layer is constrained by the adjacent hard phase layer, and the fracture strength and fracture morphology is different from the monolithic metal samples, which may be related to metal layer thickness, plastic deformation of the adjacent layer and interfacial bonding strength [37–60]. According to Hsia, Suo and Yang's theoretical model, the confined ductile layer with thin thickness makes dislocations pile up at interface, and even the pre-existing dislocations with low number are unlikely to blunt the tunnel crack tip, which results in the transition from ductile to brittle behavior with decreasing ductile layer thickness [60].

In this paper, it is really interesting to further investigate the bending behaviors and fracture characteristics of the laminated Ti–(TiBw/Ti) composites by adjusting layer thickness, reinforcement volume fraction and interfacial bonding strength, which is useful to further comprehend the relationship between structure and performance and guide the microstructure design for property improvement of laminated composites.

2. Experimental procedures

In order to investigate the effects of structural parameters on bending fracture behaviors of laminated composites, a series of laminated Ti–(TiBw/Ti) composites were successfully fabricated by diffusion welding, the commercial pure Ti sheets (TA1) with 200 μm, 300 μm, 400 μm and 500 μm thickness were selected, and the as-sintered 5vol %, 8 vol % and 10 vol % and 12 vol % TiBw/Ti composites with network microstructure were prepared. The fabrication process of the TiBw/Ti composites with network microstructure was reported in our previous work [18], then the as-sintered composites were cut into many sheets with 200 μm, 300 μm, 400 μm and 500 μm thickness by wire-cut machine. In order to clean the oil and contaminant of the pure Ti and TiBw/Ti composite sheets, the thin sheets were corroded for 2 min in the 2 vol % HF solution and cleaned in water, then dried and alternatively stacked with Ti sheets in a graphite mold. Finally, the stacked green composites were hot pressed in a vacuum atmosphere (10^{-2}) with a heating rate of 10 °C/min, and hold at 1100 °C and 1200 °C under a pressure of 25 MPa for 1 h, respectively. During the sintering process, the laminated Ti–(TiBw/Ti) composites were successfully fabricated by diffusion welding.

Microstructural examination was performed by optical microscopy (OM) and scanning electron microscopy (SEM, Hitachi S-4700) for the laminated composites after etching by 5%HF + 15% HNO_3 + 85%H_2O solution. In order to provide a clear surface, the specimens were glued to a metallic platen and polished using a polishing machine. Transversal tensile tests were carried out using an Instron-5569 universal testing machine at a constant crosshead speed of 2 mm/min. Tensile dog bone samples have dimensions of 18 mm × 5.6 mm × 2 mm. Fracture toughness testing of laminated Ti–(TiBw/Ti) composites in the I, II, III orientation was performed on single edge-notched bend (SENB) specimens ($2 \times 4 \times 20$ mm^3) with a notched depth of 2 mm parallel to the loading direction in accordance with ASTM: E-399-09 [61]. The specimens with a U-shaped pre-notch were machined using electrical discharge machining (EDM). In order to form sharp, narrow crack and accurately load-deflection curves, fatigue pre-crack needs to be done carefully. Fatigue pre-cracking was performed on a servo-hydralic load from by cycling the load between 0 and 150 N, and with the frequency of 100HZ. The rate of loading is discretionary, and the cyclically load is at a ratio of minimum-to-maximum value of 0.1 for about 10^5 cycles. The maximum stress-intensity factor (K_{max}) and the stress-intensity factor range (ΔK) in the initial portion of the fatigue cycle does not exceed 60% of the estimated K_{IC} value of the materials, the load-displacement (F-l) curve was acquired automatically by using an instron-5500 electronic universal test machine at room temperature. Assuming the maximum force, F_{max}, and the values of fracture toughness, characterized by K_{IC} or critical J integral (J_{IC}), and fracture energy (J) can be calculated by the following Equations (1)–(4) [39–42]:

$$K_{IC} = \frac{F_{\max} L}{B^{\frac{1}{2}} W^{\frac{3}{2}}} \times f\left(\frac{a}{W}\right) \tag{1}$$

$$f\left(\frac{a}{W}\right) = 3\left(\frac{a}{W}\right)^{\frac{1}{2}} \times \frac{1.99 - \left(\frac{a}{W}\right)\left(1 - \frac{a}{W}\right)\left[2.15 - 3.93\left(\frac{a}{W}\right) + 2.70\left(\frac{a}{W}\right)^2\right]}{2\left(1 + \frac{2a}{W}\right)\left(1 - \frac{a}{W}\right)^{\frac{1}{2}}} \tag{2}$$

$$J_{IC} = \frac{2\int_0^{F_{\max}} Fdl}{B(W-a)} \tag{3}$$

$$J = \frac{2\int Fdl}{B(W-a)} \tag{4}$$

Where L, B, W, a are span, thickness, width of samples and the length of pre-crack (mm), respectively. The $f\left(\frac{a}{W}\right)$ is a geometry factor based on the dimension of specimen. In this work, $L = 16$ mm, $B = 2$ mm, $W = 4$ mm and $a = 2$ mm, respectively. Meanwhile, bending specimens without notched crack have dimensions of 30 mm × 3 mm × 4 mm and a total of five samples were tested for each mode, and the linear variable differential transformer (LVDT) was pasted to measure the vertical displacement at the center of beam samples. The LVTD had a stoke of up to 5 mm, and the sample rate is 1000 samples per second. The bending testing process was carried out using an instron-5500