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Fracture behavior of Ti/Al_3Ti metal-intermetallic laminate (MIL) composite under dynamic loading

Yang Cao [a], Chunhuan Guo [b], Shifan Zhu [a], Ningxia Wei [b], Raja Ahsan Javed [a], Fengchun Jiang [b,*]

[a] College of Mechanical and Electrical Engineering, Harbin Engineering University, Harbin 150001, China
[b] Key Laboratory of Superlight Materials & Surface Technology Ministry of Education, Harbin Engineering University, Harbin 150001, China

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ABSTRACT

Ti/Al_3Ti metal-intermetallic laminate (MIL) composite is fabricated using Ti and Al foils through the vacuum sintering process. The fracture behavior of the MIL laminate composite under dynamic loading is investigated via modified Hopkinson bar loaded three-point bending fracture test. An experimental–numerical hybrid method is used to simulate the fracture behavior of MIL composite. In this method, the brittle damage model and plastic kinematic model are employed to represent the dynamic responses of the brittle intermetallic matrix Al_3Ti and ductile reinforcement of Ti, respectively. As the boundary condition, displacement data obtained from dynamic three-point bending fracture test are imported into the finite element software package for simulation. Finite element model is validated through the comparison of the load–displacement curves from numerical simulation and the Hopkinson bar loaded three-point bending test. In addition, the dynamic damage evolution behaviors of the laminate composite, including crack deflection, delamination, plastic deformation, and brittle fracture are investigated using the post-process technique of finite element software package. The current study demonstrates that the MIL composite has excellent damage tolerance due to the multiple energy-absorbing mechanisms.

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1. Introduction

Owing to its unique properties, such as high strength, high stiffness, high modulus and low density, metallic–intermetallic laminate composite Ti/Al_3Ti is considered as a potential candidate in aerospace engineering and lightweight structural armor plating [1–4]. As a structural material in engineering, the mechanical response [1,5–11], fatigue [12], fracture behavior [1,11–14], damage evolution of this laminate composite under different stress states [5,6,15], etc. have been investigated theoretically and experimentally until now. For example, the crack resistance (R-curve) and fracture toughness behaviors in both divider and arrester orientations (parallel and perpendicular to the laminate layer orientation) of the Ti/Al_3Ti MIL composites with different volume fractions of Ti have been explored via three-point bending test using single-edge notched specimens [14]. The fracture toughness and fatigue crack propagation of the MIL composite were also investigated in both crack arrester and crack divider orientations [16]. In addition, the elastic properties and anisotropy of the laminates were calculated and successfully compared with the resonant ultrasonic spectroscopy (RUS) measurements [5]. The tensile and compressive mechanical responses of the material under quasi-static and high strain rates were also determined using various experimental methods. The overall tensile mechanical properties were measured by the Brazilian disk test [15]. And the experimental result indicated that the in-plane tensile strength of Ti/Al_3Ti MIL composite is much higher than that in the through-thickness orientation due to the effect of the reinforcing Ti layers. The effects of the residual Al in preparation on fracture and failure modes of these MIL composites were studied using the samples with varying amounts of residual Al by four-point bending tests under quasi-static and high-rate loading conditions [12]. To utilize this composite as a new type of structural material, its mechanical properties and fracture behaviors under various loading conditions must be understood thoroughly. However, until now, only a few studies associated with the fracture behavior of the MIL composite have been performed under quasi-static loading conditions using notched fracture specimen [14,16]. Most of the studies in this field focus on the various processing techniques and mechanical properties of the intermetallic laminate composites under quasi-static loading. The material properties and failure mechanisms under dynamic bending conditions are being investigated now.

* Corresponding author. Tel.: +86 045182569890.
E-mail address: fengchunjiang@hrbeu.edu.cn (F. Jiang).

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The objective of this study is to investigate the fracture property and damage evolution of Ti/Al_3Ti laminate composites under dynamic bending stress state. To this end, Ti/Al_3Ti MIL composite is fabricated using titanium alloy and commercial pure Al foils in a vacuum furnace. The fracture behavior of the laminate composite is investigated via three-point bending fracture tests performed on a modified Hopkinson bar loading fracture experimental setup. The toughening mechanisms including crack deflection and delamination were proposed in this work based on the analysis of the crack distribution and the load–displacement history of the three-point bending sample. In order to further study the damage evolution process, finite element model associated with a three-point bending test is established. The load history as a function of displacement is also obtained by the computing program to make a comparison with the experimental results. The damage evolution behaviors, such as transverse cracks, deflection, and delamination corresponding to different loading instants are studied using finite element analysis techniques.

2. Experimental procedures and numerical models

2.1. Experimental procedures

The foils of commercial pure aluminum 1100 and titanium alloy Ti–6Al–4V are used as initial components in the fabrication of the Ti/Al_3Ti MIL composite. The thicknesses of aluminum and titanium alloy are 1.1 mm and 0.6 mm, respectively. Before sintering, surface of both the foils are polished with silicon carbide papers and cleaned in alcohol bath using ultrasonic cleaning machine to remove the contaminations and oxide layers and dry rapidly. Then the cleaned foils are stacked in alternate layers and placed in a vacuum furnace to allow them to react with each other and controlled by temperature, pressure, and time. The final sintering product is the laminate composite containing the alternate layers of the newly-generated Al_3Ti and residual titanium only. The laminate composite plate prepared in current study has 17 layers in total, including 9 layers of reinforcement ductile phase Ti and 8 layers of brittle intermetallic matrix Al_3Ti. Both top and bottom layers are Ti alloys. The single-edge notched bending specimens with the length of 55 mm and width of 10 mm are directly cut from the MIL plate using an electrical discharge machining (EDM). The specimen thickness is identical with the MIL plate without any machining, which is around ~10 mm. All the specimens are machined along crack-arrester orientation, i.e., both the crack orientation and the loading direction are perpendicular to the layers [16]. Bending specimens are notched to around ~2 mm long using a EDM method (wire diameter ~0.2 mm), thus the notch length/width ratio (a/W) is around ~0.2, the notch tip is near the interface between the layers, but exactly locates in the intermetallic Al_3Ti layer as shown in Fig. 1.

In order to investigate the fracture behavior of MIL composite under dynamic loading, split Hopkinson pressure bar test system is modified to conduct the dynamic three-point bending experiment. Loading configuration is shown in Fig. 2, in which the classical transmission bar is replaced with an aluminum transmission tube and two cylindrical pins are assembled in the tube as supports with a span of 40 mm for supporting the specimen. In addition, the Hopkinson bar loaded three-point bending fracture experimental setup also includes a gas gun, a striker bar, an incident bar, and a data acquisition system. The striker and incident bars have the same diameter of 14.5 mm but different lengths that are 190 mm and 800 mm, respectively. The transmission tube with a length of 2000 mm is made of a high strength aluminum alloy with 60 mm outside diameter, 40 mm inside diameter. There are two grooves in the front end of the tube for supporting two pins to slide in (see enlarged illustrations in Fig. 2 for details).

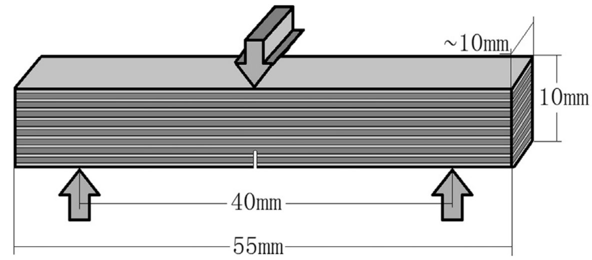

Fig. 1. The diagram of three-point bending specimen whose dimensions are ~55 mm (length) × 10 mm (width) × 10 mm (thickness). Here, the gray layers are Ti and the dark layers are Al_3Ti.

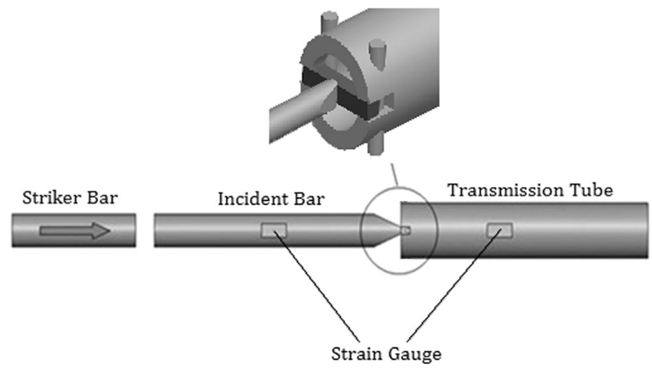

Fig. 2. The schematic diagram of Hopkinson bar loaded three-point bending fracture system, including a steel striker bar, a steel incident bar, and a hollow aluminum transmission tube. The three-point bend fracture specimen is supported by two pins fixed in the transmission tube.

The dynamic fracture test is conducted by shooting the striker bar from the gas gun. The striker bar impacts the incident bar to generate a compressive stress pulse, $\varepsilon_I(t)$, of which the amplitude and duration can be well-defined by adjusting the impact velocity and the length of the striker bar. The loading pulse propagates along the incident bar towards the notched fracture specimen until reaching the interface between the loading edge of the incident bar and the intact side of the notched specimen. At this moment, part of the incident pulse, named transmitted pulse, $\varepsilon_T(t)$, transmits into the specimen to produce deformation and fracture for the specimen. Meanwhile the other part reflects back into the incident bar as a tensile stress pulse, $\varepsilon_R(t)$. The incident and the reflected pulses are captured by a pair of strain gauges glued at the midpoint of the incident bar. The transmitted pulse is captured by another pair of strain gauges mounted on the transmission tube. The dynamic loads $P(t)$ and deflection $\delta(t)$ of the specimen are calculated using the incident, transmitted and reflected pulses proposed by Tanaka et al. [17] in terms of the stress-wave loading method.

$$P(t) = A_2\sigma_T \tag{1}$$

$$\delta(t) = \int_0^t \left\{ \frac{2}{\rho_1 C_1}\sigma_I - \frac{1}{\rho_2 C_2}\left(1 + \frac{A_2\rho_2 C_2}{A_1\rho_1 C_1}\right)\sigma_T \right\} dt \tag{2}$$

where

A_1 and A_2 — cross sectional areas of incident bar and transmission tube, respectively;

C_1 and C_2 — longitudinal wave velocities in incident bar and transmission tube, respectively;

ρ_1 and ρ_2 — densities of the incident bar and transmission tube, respectively.

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