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Enhanced fracture toughness of TiB_w/Ti_3Al composites with a layered reinforcement distribution

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ABSTRACT

The prospect of combining laminated structure design and tailored reinforcement distribution to toughen brittle materials is investigated. TiB_w/Ti_3Al–Ti_3Al laminated composites consisting of alternating TiB_w/Ti_3Al and Ti_3Al layers were fabricated by reaction annealing of stacked, alternating foils of TiB_w/Ti and Al. Enhancement in the fracture toughness is experimentally observed, which is attributed to stress redistribution and stress state change in laminated composites. Theoretical prediction of fracture toughness depending on a shear ligament toughening model agrees well with the experimental value. It is expected that the design strategy can be extended to other brittle intermetallic compounds, such as Ni–Al, Fe–Al, and Nb–Al systems.

1. Introduction

Titanium aluminides (α_2-Ti_3Al) and their composites are of engineering significance due to the potential for high temperature services [1,2]. However, the addition of reinforcements generally leads to poor ductility and fracture toughness of the composites [3]; in other words, high strength and high toughness are usually mutually exclusives in many engineering materials [4]. Great endeavors have been made to pursue the strength-toughness synergy [5–7]. Recently, Lu et al. [8,9] proposed that the overall properties (especially for toughness) of the composites can be enhanced by tailoring the distribution of reinforcements in a controlled way to form novel multi-scale hierarchical structures, compared with a conventionally homogeneous composite structure. This material design strategy has been successfully applied into metal matrix composites, where simultaneous improvements in the strength and toughness were found [10,11]. However, no particular attention is placed on the matrix of brittle Ti_3Al intermetallic compounds, and the effect of the reinforcement distribution on the fracture toughness of brittle materials is still unclear. Because the mechanical properties depend strongly on the microstructure, we undertook to investigate the hypothesis that it is feasible to adjust the reinforcement distribution to achieve more optimal combinations of strength and toughness, and that one can reinforce a brittle matrix with a brittle phase to enhance toughness.

Among these multi-scale inhomogeneous reinforcement distributions, laminated structure, i.e., in form of layered reinforcement distribution, stands out because of the relatively simple preparation process and highly controlled architecture [12,13]. Easy fabrication of laminated composites can be processed by reaction bonding of metal foils, an approach that permits variations in the layer thickness and phase volume fractions through the selection of initial foil thickness [11,14].

The aim of this work is to explore the possibility of tailoring the reinforcement distribution to toughen brittle materials. The matrix is selected as brittle Ti_3Al intermetallic compounds, and TiB whisker (TiB_w) with a high length/diameter ratio is the reinforcement. The layered distribution of TiB_w is achieved by reaction annealing of pure Al foils and TiB_w/Ti foils, and the reaction process and synthesis mechanism of the composites are described in details. Three-point bending tests are performed to measure the fracture toughness of as-fabricated composites. The contribution of layered TiB_w distribution on the fracture toughness is also discussed.

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2. Experimental procedures

2.1. Sample preparation

Commercial pure Al foils (99.7% purity, $30 \times 50 \times 0.1$ mm^3) and 3 vol% TiB_w/Ti composite foils ($30 \times 50 \times 0.4$ mm^3) were employed to prepare $TiB_w/Ti_3Al–Ti_3Al$ laminated composites. These foils were chemically etched in 10 wt% NaOH and 10 vol% HF solutions, respectively, water flushed, alcohol cleaned, and dried. Subsequently, the stacked laminates of alternating TiB_w/Ti and Al foils were hot-pressed at 515 °C for 1.5 h under 40 MPa to obtain $TiB_w/Ti–Al$ composites with well-bonded interfaces, and then annealed in a vacuum furnace as follows: (i) an initial annealing was carried out at 700 °C for 1 h to convert all elemental Al into $TiAl_3$; (ii) in order to eliminate the Kirkendall voids formed in the initial annealing stage, a necessary densification process was conducted under 40 MPa at 1200 °C for 3 h, and finally, (iii) the composite was annealed at 1250 °C for 2 h to further reaction-diffusion and obtain the desired microstructure composed of alternating Ti_3Al and TiB_w/Ti_3Al layers. The spatial coordinate system of the samples is represented by rolling (RD), normal (ND), and transverse (TD) directions.

2.2. Microstructure characterization

Polished cross-sections were prepared after every annealing process and examined by scanning electron microscopy (SEM, FEI Quanta 200F) and X-ray diffraction (XRD, Philips X'Pert) for microstructure observation and phase identification, respectively. Three-point bending tests (sample dimensions: $2 \times 4 \times 20$ mm^3 according to ASTM E1820 standard, with a notched depth of 1 mm parallel to the loading direction) were employed to study the crack propagation behavior at room temperature (RT). The fracture profile was also examined by optical microscopy (OM) using a sample etched by 5% HF + 5% HNO_3 + 90% H_2O (vol.%) solution for 30 s.

2.3. Finite element simulation

Two models of monolithic Ti_3Al and $TiB_w/Ti_3Al–Ti_3Al$ laminated composites were developed to qualitatively reveal the effects of laminated structures on the stress distribution under flexural loading. Model geometries are set up similar to the experimental standard specifications of the ASTM E1820 [15], and performed only within the linear regime. The model, specimen geometric configurations, and material parameters were shown in Supplementary materials. This 3D model consisted of several rectangular prisms stacked together to represent the different layers/components, and the thicknesses of both components refer to real imaging of the final microstructure. 3D solid elements were used in meshing and were arranged in an assembly that matches the material system's layout definition. Generally, cohesive elements were used to simulate damage behavior, however in our work, particular emphasis was placed on the elastic response. Therefore tie constraint, which is simply a constraint that keeps the model intact forever (not like cohesive elements that can split into two), is used. The boundary and loading conditions of the model were shown in Supplementary Fig. S3. The translation in z axis (axis coordinates shown in Supplementary Fig. S1) was fixed as $T_3 = 0$. The indenter pins were restrained to move only in Y direction. Frictionless contact condition was applied between the three indenter pins and the specimen body.

The aim of finite element simulation is to reveal the elastic response and stress state of monolithic Ti_3Al and $TiB_w/Ti_3Al–Ti_3Al$ laminated composites under flexural loading, and we pay more attention on the *xx* normal stress, not von Mises stress, so that quantitative statistic of stress intensity is not strongly recommended. Also, tie constraint was chosen only for elastic deformation. In the future, combining quantitative stress/strain analysis, performing nonlinear simulation, and the choice of cohesive elements is suggested to provide a more comprehensive understanding in dynamic stress/strain evolution process.

3. Results

3.1. Microstructure evolution

Fig. 1 shows the microstructure evolution of $TiB_w/Ti–Al$ composites during reaction annealing. In the initial stage, the annealing was performed at 700 °C to melt the aluminum (melting point: 660 °C) and reduce the annealing period due to the higher diffusion rate of liquid Al compared with that of solid Al. After 1 h, the microstructure consisted of newly formed $TiAl_3$ layers (dark grey region, Fig. 1a) and residual TiB_w/Ti layers (white region, Fig. 1(a)). The porous morphology and growth kinetics of $TiAl_3$ can be found in our previous work [16], and not given here. After this initial annealing, all the Al was transformed to $TiAl_3$, and numerous voids with radius of a few microns were left in $TiAl_3$ layers owing to the Kirkendall effect [17,18]. These pores were eliminated by the subsequent densification process under 40 MPa at 1200 °C for 2 h, and then the laminate was composed of alternating layers of $TiAl_2$

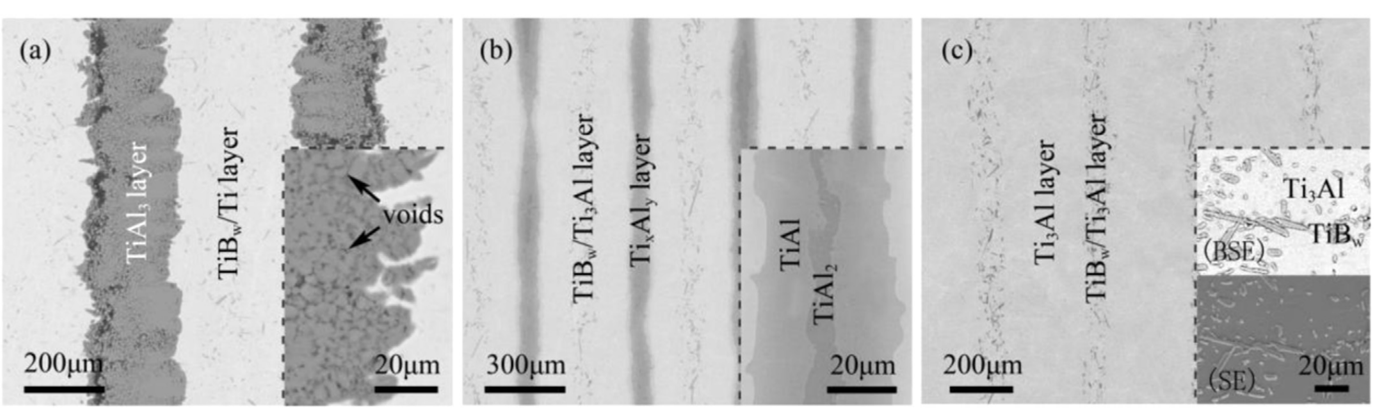

Fig. 1. Scanning electron microscopy (SEM) images showing typical microstructures of $TiB_w/Ti–Al$ composites treated by (a) an initial annealing at 700 °C for 1 h; (b) a densification process under 40 MPa at 1200 °C for 3 h after (a); (c) a further reaction-diffusion annealing at 1250 °C for 2 h after (b). Inset indicates the morphology of $TiAl_3$ (a), microstructure evolution (b), and the interface between TiB_w inclusions and Ti_3Al matrix (c). All images were captured by backscattered electrons (BSE), except for the bottom right one operated on secondary electron (SE) mode.