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Tensile and flexural properties of multilayered metal/intermetallics composites

Yanbo Sun [a,*], Jing Chen [a], Fengmei Ma [a], Kei Ameyama [b], Wenlong Xiao [a], Chaoli Ma [a,**]

[a] *Key Laboratory of Aerospace Advanced Materials and Performance of Ministry of Education, School of Materials Science and Engineering, Beihang University, Beijing 100191, China*
[b] *Department of Mechanical Engineering, Faculty of Science and Engineering, Ritsumeikan University, Kusatsu 525-8577, Japan*

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ABSTRACT

The tensile and flexural properties of sintered Ti/Ti–Al intermetallics multilayered composites were investigated and compared with those of multilayered Ti_3Al/TiAl composites and homogeneous Ti–Al intermetallics alloys in this paper. The experimental results indicate that the Ti/Ti–Al composites exhibit superior tensile and flexural strengths because of the unique metal/intermetallics multilayered microstructure. The multilayered Ti/Ti–Al composites also show a high level of damage-tolerant capacity at room temperature. It was found that the multilayered composites with remaining ductile metal layers (Ti layers) behave much stronger under flexural loading compared with tensile loading. The positive effect of metal/intermetallics multilayered structure on the remarkable improvement of bending deflection was interpreted by a simple theoretical model.

1. Introduction

In recent years, the composites with multilayered (or laminated) structure have been the focus of research because of their impressive strength, toughness and other mechanical properties [1–4]. As an important branch of them, the multilayered metal/intermetallics composites are proposed by compositing the high temperature intermetallics with ductile refractory metals [5–8]. The refractory metals play an essential role in toughening, which can effectively restrict the crack propagation *via* crack deflection, blunting, shielding, bridging, trapping, *etc.* [9–11]. Meanwhile, the high temperature intermetallic compounds provide the strength and creep resistance at elevated temperatures. The metal/intermetallics multilayered composites thus are endowed with great potentials in aircraft engine turbine applications [6].

Owing to the high dependence on the microstructure, various mechanical behaviors of metal/intermetallics multilayers have been studied on the basis of the lamellar architecture. For example, Alman et al. [12] and Rawers [13] demonstrated that the tensile behaviors and elastic modulus were closely related to the ratios of thickness between metal and intermetallics for the Ti/Ti–Al intermetallics, Ni/Ni–Al intermetallics and Fe/Fe–Al intermetallics multilayer systems. Vecchio et al. [14] and Li et al. [15] have made a great effort to investigate the mechanical properties of the multilayered Ti/$TiAl_3$ composites which may be used as armor layers in tank or other military vehicles due to their outstanding toughness and ballistic properties. In tension [16], compression [15], bending/R-curve [14], and ballistic [17,18] tests, one common trait observed for this multilayered composites was the failure initiated in the intermetallic layers. Nonetheless, the occurrence of crack bridging, crack deflection, stress redistribution, and crack front blunting could effectively tough the multilayered Ti–$TiAl_3$ composites, which resulted in an excellent combination of specific strength, toughness and stiffness for structural applications.

However, most of the previous works in this field analyze the mechanical behavior simply by the fracture propagation or energy dissipation. Nevertheless, the loading condition also has significant influence on the performance of an identical material, due to the various stress states or strain rates, *etc.* [19,20]. Taking the tension and flexion, two common loading forms in practice, for example, the flexural performance is usually better than the tensile performance for a specific material, even though both of them are destructed in tension form [21–23]. This difference mainly arises from the variable stress states within the investigated material caused by the different loading conditions. In addition, the influence of micro-defects varies with loading condition, *e.g.* the location of defects has relatively limited effect on the tensile strength, while the flexural strength is linked to the location of defects since only half volume of the sample is subjected to tensile stress under bending condition [24]. Therefore, once the microstructure of a material is changed, the different stress distributions and the existence of micro-defects will bring about the apparent disparity between the tensile and bending performance. To our knowledge, the studies about the mechanical properties of multilayered composites from the point of loading conditions are extremely limited.

In the present work, the tensile and bending tests were performed on the materials with multilayered and homogeneous microstructures,

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* Corresponding author.
** Corresponding author. Tel./fax: +86 10 82339772.
E-mail addresses: ybsun1986@gmail.com (Y. Sun), machaoli@buaa.edu.cn (C. Ma).

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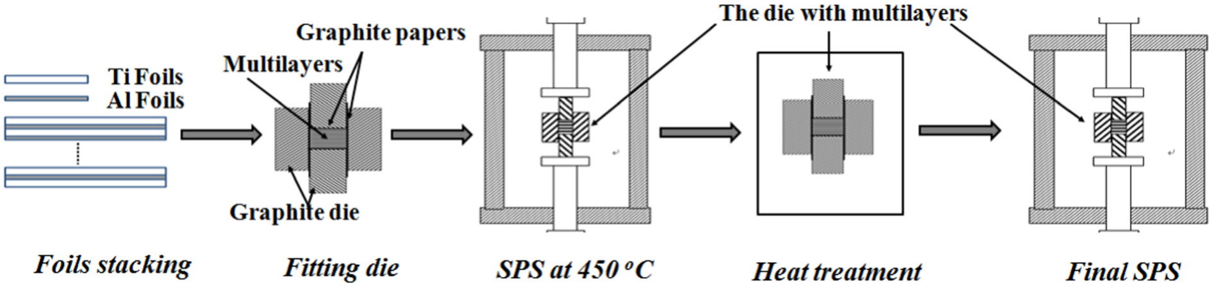

Fig. 1. Schematic illustration of the fabrication process for the Ti–Al intermetallics alloys.

respectively. A particular attention was paid to the effect of multilayered microstructure on the tensile and flexural behavior in Ti/Ti–Al intermetallics composites. The spark plasma sintering (SPS) technique was applied to fabricate the multilayered composites by sintering the alternately stacked foils of Ti and Al, which has been proved to be an efficient way to fabricate a dense compact at low temperature within a short time [25–27].

2. Experimental procedures

The commercial pure Ti foils (99.8 at.%) with 45 μm in thickness and Al foils (99.99 at.%) with 27 μm in thickness were selected to fabricate the designed materials. Fig. 1 shows the illustrative diagrams of the preparation procedure. Before sintering, the foils were cleaned ultra-sonically in acetone and cut subsequently into Φ15 mm circular pieces. The Ti foils and Al foils were alternately stacked, and then placed in a graphite mold with the internal diameter as Φ15 mm. A graphite paper with the thickness of 0.5 mm was used to insulate the "multilayers" from graphite mold and prevent the interaction between them. As illustrated in Fig. 1, the stacked Ti/Al "multilayers" were primarily sintered at 450 °C under 50 MPa for 10 min in the spark plasma sintering (SPS; DR. SINTER, SUMIMOTO) machine, aiming to enhance the bonding between Ti and Al foils. The pre-sintered "multilayers" were then subjected to heat treatment at 900 °C for 30 min under the argon atmosphere in a tube furnace, leading to the consumption of the surplus pure Al and the formation of Ti–Al intermetallics. During the whole process, the "multilayers" were kept in the graphite mold, which could not only maintain the shape of the multilayered composites but also avoid the leakage of molten Al.

For comparison, the samples were finally SPS s at 950 °C, 1050 °C and 1200 °C, respectively, in order to obtain various microstructures. All of them were sintered with the conditions of a heating rate of 100 °C/min, a holding time of 10 min and a high vacuum of 10^{-3} Pa. The experimental temperature was constantly monitored by focusing an optical pyrometer onto the surface of the graphite die. A maximum pressure of 50 MPa was applied at the holding temperature and unloaded after the process finished. The sintered samples were finally cooled to 300 °C with the rate about 100 °C/min.

The microstructural observation was performed in the JSM-6400 scanning electron microscope (SEM) and the JEM-2100F transmission electron microscope (TEM). Meanwhile, the phase information of the sintered compacts was further confirmed by a D/max 2200PC Automatic

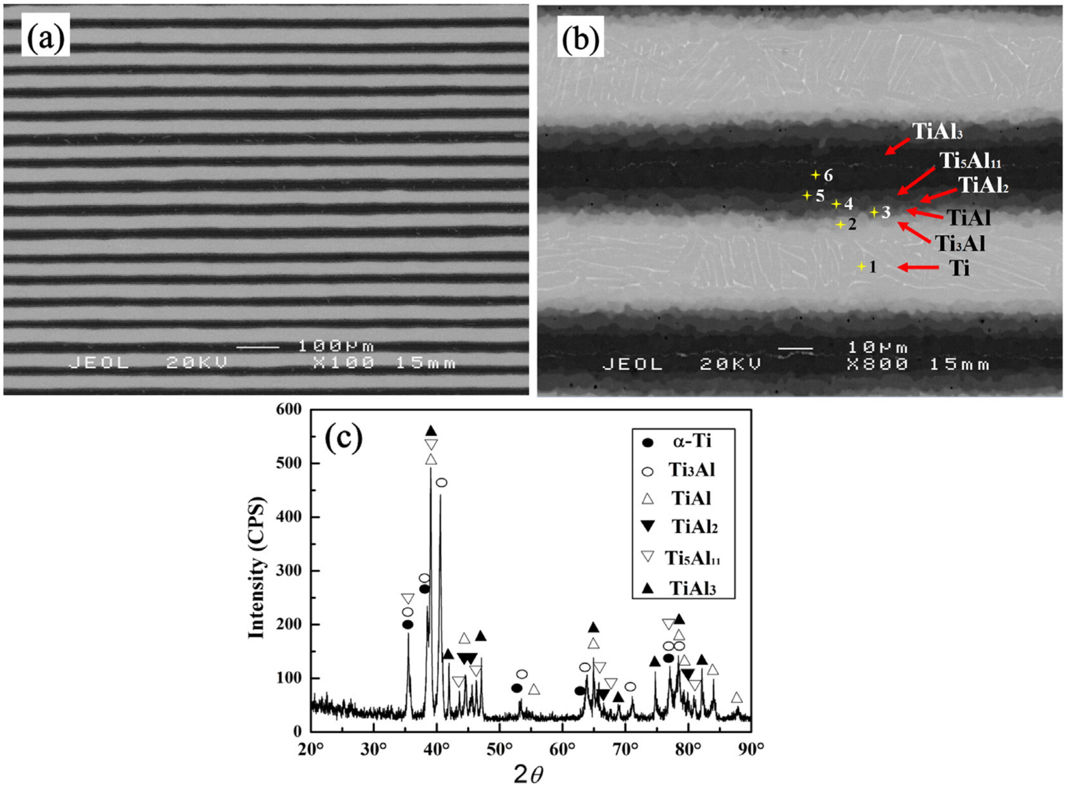

Fig. 2. The back scattered electron (BSE) image for lower magnification (a), BSE image at a higher magnification (b) and X-ray diffraction pattern (c) of the multilayered Ti/Ti–Al intermetallics composites sintered at 950 °C for 10 min under 50 MPa.