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Interfacial microstructure and mechanical properties of laminated composites of TiB_2-based ceramic and 42CrMo alloy steel

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ABSTRACT

Based on fusion and interdisffusion of the liquid ceramic and the molten steel, the laminated composite of TiB_2-basedceramic and 42CrMoalloy steel consisting of 3-layer structure with the ceramic matrix, the intermediate and the steel substrate, was rapidly prepared by self-propagating synthesis with centrifugal-casting process, and within the intermediate the continuously-graded microstructures of span-scale-structured (micro-structured → micro-nanostructured → nano-structured) ceramic/alloy network developed while a conherent/particle-conherent relationship was kept in the interface of micro-nano/nanocrystalline TiB_2 and Fe-Ni alloy base. Combining mechanical properties test with FESEM and HRTEM examination, it is considered that the in-situ achievement of the span-scale-structured continuously-graded intermediate of ceramic/alloy network microstructure not only presents the gradient joint with high flexural strength and high fracture toughness, but also presents the laminated composite with strong plastic deformation behavior and high ductility-like capacity during 3-point bending test. Meanwhile, the cooperative action of crack interlocking by fine Ni-based metallic films surrounding TiB_2 platelets in the regions nearby the ceramic with precipitation strengthening by micro-nano/nanocrystalline TiB_2 platelets in the intermediate was considered to contribute to the high interlaminar shear strength of 425 ± 50 MPa.

1. Introduction

Compared with the conventional monolithic ceramics, such as TiC and WC [1], TiC-TiB_2 ceramic composites exhibit not only high hardness and good chemical stability at high temperature, but also enhanced fracture toughness and bending strength. These properties are suitable for a wide range of applications [2–5]. Over the last three decades, dense TiB_2-based ceramics were considered as a potential armor material [6]. However, it is hard to promote the ballistic performance further because of the inherent brittleness of the ceramic. So it is necessary to toughen the ceramic by joining ceramics and metals to meet the special military requirements [7]. Ceramic backed by composite material armor is becoming the subject of many investigations because their performance against small and medium caliber projectiles is outstanding, especially when the weight is a design condition. The ceramic layer function is to blunt and decelerate the projectile and the backing layer keeps the fractured ceramic in its place and absorbs the remnant energy of the projectile [8].

It is well known that, under the high-velocity impact of kinetic energy projectiles, the reflected stress wave in ceramic become tensile when compressive stress wave reach the back surface due to the mismatch of acoustic impedance and thermal expansion between ceramic and metal [9]. As ceramic materials are typically much weaker under tensile loading as compared with their compressive responses, failure initiates where the tensile stress exceeds a critical value. The consequence is a general break-up of the ceramic from the coalescence of the cracks [10]. The idea of functional graded armor composites was advanced, where this new material concept has been proposed to increase adhesion and to minimize the thermal stresses in composites developed to overcome the structural defect. A target with a functional graded layer from ceramic to metal through its thickness combines the superior features of ceramic and metal. Thus, the ceramic-rich side provides good protection against projectiles while the metal-rich side offers toughness and strength to maintain the integrity of the structure as far as possible [11]. As a result, functionally graded materials (FGMs) have brought wide interest recently [12].

However, it is still a challenge to obtain graded structure between ceramic and metal. Furthermore, the low cost and rapid preparation methods for fine grained TiB_2 based ceramics need to be improved [13]. Recently, a rapid and economical processing

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named self-propagating synthesis with centrifugal-casting process has been applied to prepare bulk solidified TiC-TiB_2 ceramics [14]. Based on this technology, joining a ductile metal with a brittle ceramic to constitute laminated FGM has considerable potential for substantial improvements in fracture toughness [12].

In the present work, self-propagating synthesis with centrifugal-casting process is taken to prepare the laminated composite of TiB_2-based ceramic and 42CrMo alloy steel, the interfacial microstructure, mechanical properties, damage and failure mechanisms of the laminated composite are investigated.

2. Materials and experimental procedure

2.1. Materials preparation

Raw materials were prepared from high purity (> 97%) B_4C powder with particle size less than 3 μm, high purity (> 99%) Ti powder with particle size less than 34 μm as well as high purity (> 99.7%) Ni powders with particle size range of 30–63 μm. The molar ratio (Ti to B_4C) of 3:1 was chosen as the starting composition based on Eq. (1), so the composition of the solidified TiC-TiB_2 composite was determined as TiC-66.7 mol% TiB_2. In order to improve the adiabatic combustion temperature, preheating process of 200 °C was introduced. The 10 wt% Ni metallic additive was also added as the bonded phase for increasing the densification.

$$3Ti + B_4C \rightarrow TiC + 2TiB_2 \tag{1}$$

The above powder blends were mechanically homogenized by planetary ball mill (ND8-4L) with 15 Hz for 2 h. The 42CrMo alloy-steel plate with the thickness of 10 mm and the diameter 100 mm was placed at the bottom of the cylindrical graphite crucible as the metallic substrate, and its chemical composition is Fe-0.42C-0.20Si-0.75Mn-1.10Cr-0.22Mo-(< 0.035 S, P, Ni, Cu) wt%, then the crucible was filled with the mechanically-activated raw blends (2.0 kg) under uniaxial cold-press about 200 MPa. After that, the prepared graphite crucibles were fixed on the centrifugal machine. The combustion reaction was triggered with the electrical heat W wire (diameter of 0.5 mm) while the centrifugal machine provided a high-gravity acceleration of 2000g (g=9.8 m/s^2, where g means the gravitational constant). When the combustion reaction was over, the centrifugal machine continued to run for 30 s. After the crucibles were cooled to ambient temperature, the graded composites of the ceramic to steel were obtained by grinding, as shown in Fig. 1.

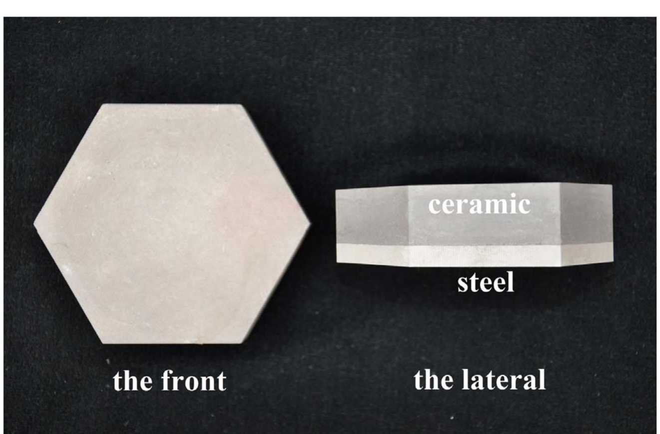

Fig. 1. Hexagonal product of laminated composite of TiB_2 based ceramic and 42CrMo steel.

2.2. Composites characterization

The phase composition was identified by X-ray diffraction (XRD; RigakuD/max-PA, Japan) with a step of 0.02° and a scanning rate of 2°/min. The microstructure and fracture morphology of the composite were examined by field emission scanning electron microscopy (FESEM; Ultra55, ZEISS, Germany). Electron probe microanalysis (EPMA) was conducted by energy dispersive spectrometry (EDS; Ultra55, ZEISS, Germany). The crystal structures and inter-phase interfaces in the composite were determined by transmission electron microscopy (TEM; Tecnai F30, FEI, USA).

The composite discs were cut and ground into the rectangular bars measuring 3 mm (width) × 4 mm (height) × 36 mm (length) to determine the flexural strength (half ceramic and half steel). The flexural strength was measured by the three-point bending method with a cross-head speed of 0.5 mm/min and a span of 30 mm (CMT5105 Universal Testing Machine). The hardness of the composite was measured using Vickers hardness tester (HVS-50) under 196 N load. Fracture toughness K_{IC} of the composites was determined using a direct crack measurement method. Accordingly, the fracture toughness was estimated using equation $K_{IC} = 0.018\alpha l^{-0.5}HV^{0.6}E^{0.4}$ [15], where l is the Palmquist crack length, E is the Young modulus, HV is the Vickers hardness number, and α is the half-diagonal of the Vickers indent.

Meanwhile, the composites of TiC-TiB_2 ceramic and 42CrMo steel were cut and ground into six rectangular bars measuring 8 mm (width) × 5 mm (height) × 20 mm (length) for determining the interlaminar shear strength (CMT5105 Universal Testing Machine), and the interlaminar shear strength was evaluated by equation $\tau_b = P_b/A$, where τ_b is the interlaminar shear strength of the joint, P_b is the actual breaking load and A is the initial area of samples.

3. Results

3.1. Phase composition, microstructure and gradient interface

The XRD patterns of the samples showed that as the part of the laminated composite, the ceramic was mainly composed of TiB_2 primary phases, TiC secondary phases and a few Ni metallic binder, as shown in Fig. 2. Meanwhile, HRTEM micrographs of the ceramic confirm the morphology and validity of the TiB_2 platelets and the approximate spherical TiC grains, as shown in Fig. 3 and Fig. 4. In addition, the metallic binders of Ni were distributed at the discontinuous network or triangularly-shaped gain-boundaries, as shown in Fig. 5.

It was observed by FESEM that there was only the microstructure transformation rather than a clear and strict joint interface between the ceramic and the alloy steel, as shown in Fig. 6. After corrosion, there is a lot of cast dendrite growth near the alloy

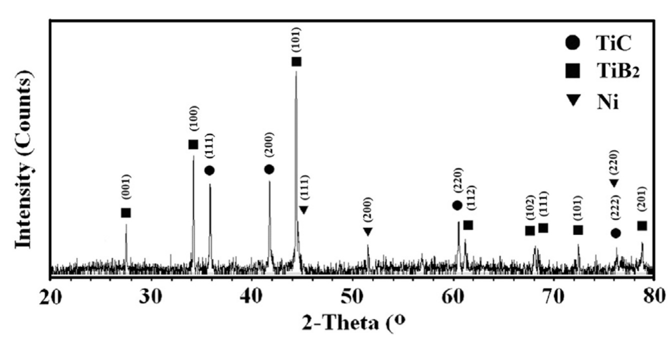

Fig. 2. XRD pattern of TiB_2 based ceramic matrix powder of the laminated composite of TiB_2 based ceramic and 42CrMo steel.