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The mechanical properties and microstructure of the bionic alloy–ceramic laminated composite

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ABSTRACT

In the present work, the bionic alloy–ceramic laminated composite was fabricated by electron beam–physical vapor deposition method. The ingots of Ni–20Co–12Cr–4Al (wt.%) and ZrO_2–8 mol%Y_2O_3 were used as the sources of the alloy layer and ceramic layer, respectively. The laminated composite was generally destroyed within the ceramic layer when the interlaminar strength was determined, which revealed that the excellent interface bonding between the ceramic layer and the alloy layer. The obvious diffusion interfaces between the ceramic and alloy layers were readily detected, which was favorable to the mechanical properties of the laminated composite. In the heat treatment process, the diffusion of the flaws within the ceramic layer and/or alloy layer to the interface between the ceramic layer and alloy layer was easier compared with the occurrence of interlaminar diffusion. It was confirmed by the X-ray diffractometer that the reaction of the ceramic layer with alloy layer was simple physical diffusion. The tensile strength of the laminated composite increased first and then decreased as the heat treatment time increased, which was attributed to the mutual reaction of the increase in the relative density with the formation of the flaws located at the interface.

1. Introduction

A major problem in the service of ceramics as structural materials is their low toughness [1]. Even though many attempts have been used to increase their toughness, including incorporation of fibers [2], whiskers [3] or particles reinforcements [4], and ZrO_2 phase transformation reinforcing and so on [5], up to date the brittleness of ceramics has not been overcome in nature. In the research on the structure of natural biomaterials, such as turtleback, shell and nacres, it has been found that these natural biomaterials have very reasonable laminated structures which give them many excellent properties, such as good carrying capacity, good toughness and so on [6–9]. Over the past two decades, bionics has had a profound influence on the material science and engineering, because the unique structures, compositions and correspondingly excellent properties of biology gave researchers many clues to improve the properties of materials or increase the reliability of structural components [10]. One way of preventing properties of ceramic component is to design a structure with dense and strong layers separated by weak or soft layers of the different materials [11]. The weak interface in these laminated composites serves to deflect the propagating crack and reduces its stress intensity. Another way of increasing reliability is the use of intermittent interlayer [12]. One of the requirements for achieving high properties of the laminated composites is the good chemical and physical bonding between the interface materials.

Electron beam–physical vapor deposition (EB–PVD) is one of the advanced techniques for the fabrication of the thin coatings [13]. In the late 1980s, EB–PVD techniques was being used to deposit the top coat onto rotating blades [14]. This deposition method resulted in a columnar microstructure with the columns running perpendicular to the work piece surface, which imparted a high degree of strain tolerance making them ideal for applications involving frequent thermal cycles [15].

In the present work, the bionic alloy–ceramic laminated composite was fabricated by EB–PVD. The ingots of Ni–20Co–12Cr–4Al (wt.%) and ZrO_2–8 mol%Y_2O_3 were used as the sources of the alloy layer and ceramic layer, respectively. The mechanical properties and microstructure of the alloy–ceramic laminated composite were investigated in detail. Furthermore, the laminated composite was heat treated in order to improve the tensile strength through reducing residual stress.

2. Experimental procedure

During deposition process, the stainless steel substrate with the diameter of 1 m and surface roughness of 1.0 rotated at 6 rpm

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around the vertical axis and the substrate temperature was maintained at 650 °C approximately. The process pressure was in the range of 6–10 × 10^{-3} Pa. The ingots of Ni–20Co–12Cr–4Al (wt.%) and ZrO_2–8 mol%Y_2O_3 were used as the sources of the alloy layer and ceramic layer, respectively. The ingots of ZrO_2–8 mol%Y_2O_3 and Ni–20Co–12Cr–4Al (wt.%) were evaporated alternately to produce the alloy–ceramic laminated composite and the thicknesses of the different layers were controlled by their deposition time. The tensile strength tests were carried out by an INSTRON-5569 universal materials testing machine with a crosshead displacement speed of 0.05 mm/min at room temperature. Nanoindentation was performed using a Hysitron TriboIndenter (Hysitron Inc., Minneapolis, MN) with a 100 μm conospherical diamond fluid tip. The laminated composite was heat treated at 1050 °C for different times in Ar atmosphere, and heating rate of 10 °C/min and cooling rate 5 °C/min was lower than the heating cooling rates of the laminated composite in the fabrication process, respectively. The indenter tip is connected to the transducer, which was displacement-controlled, and data were presented as load versus displacement plots for loading, hold, and unloading. For all samples, indentation started with the nanoindenter tip approaching the sample from off contact. In this work, five specimens were tested to get an average value. The microstructures of the specimens were examined using SEM (FEI QUANTA200). Moreover, the phase composition of the laminated composite was determined by X-ray diffractometer (Philips, X'Pert-MRD). The interlaminar strength was evaluated according to GB-T3903.8-2005.

3. Results and discussions

3.1. Microstructure

The laminated composite was generally destroyed along the ceramic layer, as shown in Fig. 1A, when the interlaminar strength was determined, which revealed that the ceramic layer appeared to be well bonded with the alloy layer. The outstanding interface bonding was favorable to the mechanical properties of the laminated composite. It could be seen from Fig. 1A that 8 mol%Y_2O_3 stabilized ZrO_2 particles appeared to be uniformly deposited on the alloy layer. Furthermore, the flaws, such as pore and pit, were not observed in the ceramic layer. Fig. 1B shows the SEM image of the fractured surface perpendicular to the alloy–ceramic interface of the laminated composite. The ceramic layer of uniform thickness was separated by the alloy layer of uniform thickness.

Fig. 2 shows the SEM images of the polished cross section of the laminated composite before and after the heat treatment. No flaws, such as pore and crack, were observed in the ceramic layer of the polished cross section of the laminated composite before and after the heat treatment, which also revealed that ceramic particles appeared to be uniformly deposited on the alloy layer. The obvious diffusion interfaces between the ceramic layer and alloy layer were readily detected, which also indicated the excellent interface bonding between the ceramic layer and the alloy layer. As heat treatment time increased, the obvious flaws such as pit and pore occurred in the interface between the ceramic and alloy layers and the amount of the flaws increased gradually. The formation of the flaws was attributed to the diffusion of the particles during high temperature heat treatment [16]. In the heat treatment process, the diffusion of the flaws within the ceramic layer and/or alloy layer to the interface between the ceramic layer and alloy layer was easier compared with the occurrence of the interlaminar diffusion [17]. In the heat treatment process, the diffusion of the flaws within the ceramic layer and/or alloy layer to the interface between the ceramic layer and alloy layer was favorable to improve the relative density of the ceramic layer and/or alloy layer, whereas was unfavorable to the interface bonding between the ceramic layer and alloy layer.

Fig. 3 shows the XRD spectra obtained from the polished cross section of the laminated composite before and after the heat treatment. Apparently, the phase analysis indicated the predominant phases for the laminated composite were t-ZrO_2 for the ceramic layer and γ-Ni phase for the alloy layer. Compared with the XRD spectra for the polished cross section of the laminated composite before the heat treatment, the obvious change in the XRD spectra was not detected as the heat treatment time increased. Such result indicated that the reaction of the ceramic layer with alloy layer was simple physical diffusion.

The SEM images of the fractured surfaces of the tensile specimen for the laminated composite are shown in Fig. 4. The staged fracture mode resulted from the crack deflection prior to final failure of the tensile specimen were readily observed. Such fracture mode would dissipate a lot of energy and improve the mechanical properties of the laminated composite [3]. Many flat fracture regions resulted from the brittle fracture mode in the fractured surfaces of the tensile specimen for the laminated composite were also detected in the fractured surfaces, as shown in Fig. 4B. The obvious plastic deformation was not observed in the flat fracture region, which was ascribed to the weak grain boundary bonding of the alloy particles [18]. Furthermore, the fractured surface of the alloy layer was blade-like shrank, which indicated the ductile fracture of the laminated composite. The interface debonding phenomenon was easily observed in the ductile fracture region of the alloy layer, whereas the interface debonding did not occur in the brittle fractured region, which revealed that the ceramic layer was well bonded with the alloy layer in the brittle fractured region. The columnar crystals with sharp edges and corners were observed in ceramic layer, which were the typical characteristics of brittle intergranular fracture [19], as shown in Fig. 4C. The ceramic layer was fractured to many fragments due to the crack initiation and

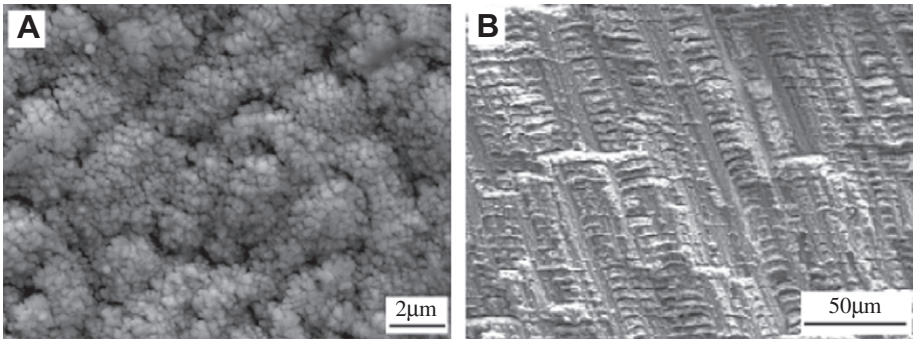

Fig. 1. The SEM images of the fractured surface parallel (A) and perpendicular (B) to the alloy–ceramic interface of the laminated composite.