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Review

Residual stresses and mechanical properties of Si_3N_4/SiC multilayered composites with different SiC layers

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ABSTRACT

The effect of residual stresses on the strength, toughness and work of fracture of Si_3N_4/SiC multilayered composites with different SiC layers has been investigated. It may be an effective way to design and optimize the mechanical properties of Si_3N_4/SiC multilayered composites by controlling the properties of SiC layers. Si_3N_4/SiC multilayered composites with different SiC layers were fabricated by aqueous tape casting and pressureless sintering. Residual stresses were calculated by using ANSYS simulation, the maximum values of tensile and compressive stresses were 553.2 MPa and −552.1 MPa, respectively. Step-like fracture was observed from the fracture surfaces. Fraction of delamination layers increased with the residual stress, which can improve the reliability of the materials. Tensile residual stress was benefit to improving toughness and work of fracture, but the strength of the composites decreased.

Las tensiones residuales y las propiedades mecánicas de compuestos multicapa de Si_3N_4/SiC con diferentes capas de SiC

Palabras clave:
Compuesto multicapa
Tensiones residuales
Microestructura
Propiedades mecánicas

RESUMEN

Se ha investigado el efecto de las tensiones residuales en la resistencia, dureza y trabajo de fractura de los compuestos multicapa de Si3N4/SiC con diferentes capas de SiC. Puede ser una manera eficaz de diseñar y optimizar las propiedades mecánicas de los compuestos multicapa de Si3N4/SiC mediante el control de las propiedades de las capas de SiC. Los compuestos multicapa de Si3N4/SiC con diferentes capas de SiC se fabricaron por medio de colado en cinta en medio acuoso y sinterización sin presión. Las tensiones residuales se calcularon mediante el uso de la simulación ANSYS, los valores máximos de las fuerzas

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de tracción y compresión fueron 553,2 MPa y −552,1 MPa, respectivamente. Se observó una fractura escalonada a partir de las superficies de fractura. La fracción de capas de deslaminación aumenta con la tensión residual, lo que puede mejorar la fiabilidad de los materiales. La fuerza de tracción residual era beneficiosa para la mejora de la dureza y el trabajo de fractura, pero la resistencia de los compuestos disminuyó.

Introduction

Ceramics, glasses and other inorganic non-metallic composites are characteristically brittle and their application is limited by the poor reliability. Lots of studies have been done to improve their toughness and reliability through phase transformation, addition of whisker or fiber, controlling or designing the microstructure and secondary phases [1–4]. However, high costs in association with low increment of toughness are the disadvantages of these methods.

Artificially multilayered composites with weak interfaces were firstly designed and fabricated by Clegg and co-wokers [5]. Lots of works have been done to fabricate the multilayered composites with weak interfaces which possessed high toughness and work of fracture, however, the strength of the composites were insufficient [6,7]. Liu and Hsu [8] fabricated Si_3N_4/BN multilayered composites by hot pressure sintering at 1750 °C and 30 MPa for 1.5 h. These composites possessed high work of fracture ($5500 \pm 1000\,J/m^2$), but the strength was low (181 ± 51 MPa). Another kind of multilayered composite with strong interface was firstly fabricated by Lange and co-works [9]. The multilayered composites with strong interfaces were difficult to show the crack deflection at the interface or not so significant. Generally the toughness and reliability of the composites were lower than the ones with weak interfaces under the same conditions but the strength was higher. Wang [10] prepared Si_3N_4/BN (SiC whiskers added in BN layers) multilayered composites by hot pressure sintering at 1820 °C for 1.5 h, the strength and fracture of the composite were up to 1124.6 ± 143.2 MPa and $7.8 \pm 0.6\,MPa\,m^{1/2}$ respectively. However, no obvious layer delamination was found and the reliability of the samples was poor.

Residual stresses generated in the multilayered composites with strong interfaces, because of the differences in thermal expansion coefficient, Young's modulus, chemical reactions and phase transformations of the layers [11,12]. The compressive residual stresses developed in both surface and internal layers. The compressive stresses in the surface layer could enhance the strength of the samples, meanwhile, the internal compressive layer was used to design and improve the reliability of the composites [13,14]. Lots of works have been done to discuss the effect of residual stresses on the mechanical properties of multilayered composites, such as alumina–zirconia and alumina–mullite [15–18]. Bermejo and co-workers [15] prepared alumina–zirconia multilayered composites by slip casting. The compressive residual stresses generate by the phase transformation of ZrO_2. The residual stresses were calculated using a 3D finite element model, the sample possessed high apparent fracture toughness (higher than twice of the monolithic material), however, the effects of tensile stresses were not discussed.

As described in this paper, the mechanical properties of SiC/Si_3N_4 multilayered materials can be optimized by adjusting SiC layers. SiC/Si_3N_4 multilayered composites with different SiC layers were fabricated by aqueous tape casting, laminating and pressureless sintering. High residual stresses generated during the sintering and cooling process because of the different thermal expansion coefficient and Young's modulus between Si_3N_4 and SiC layers. The residual stresses were calculated by ANSYS software via the properties of Si_3N_4 and SiC layers such as thermal expansion coefficient, Poison's ratio, Young's modulus and layer thickness. The effect of residual stresses on mechanical properties was discussed.

Experimental

Raw materials

Low cost commercial α-Si_3N_4 powders (3–5 μm, Qinhuangdao Yi-Nuo Nitride Co. Ltd. China) and β-SiC powders (3–5 μm, Qinhuangdao Yi-Nuo Nitride Co. Ltd. China) were used as raw materials. The powder mixture of yttrium oxide (1–3 μm, 99%, Fuguang Co. Ltd. China) and alumina (1–3 μm, 99%, Fuguang Co. Ltd. China) in a weight ratio of 3:5 were used as sintering aids. The total concentration of the sintering aid was 10 wt.% based on Si_3N_4 layers, and the concentration of the sintering aid based on SiC layers were 10 wt.%, 20 wt.% and 30 wt.% respectively. Polyacrylic acid (PAA) (molecular weight 35,000, analytically pure, Fuguang Co. Ltd. China), polyvinyl alcohol (PVA) (molecular weight 1450, 99%, Zhongjia Co. Ltd. China), glycerol (analytically pure, Zhongjia Co. Ltd. China) and n-butyl alcohol (analytically pure, Zhongjia Co. Ltd. China) was used as a dispersant, binder, plasticizer and defoamer, respectively. The simethicone (analytically pure, Zhongjia Co. Ltd. China) was employed to treat the glass slab in order to strip the tapes easily.

Preparation of green tapes and sintered samples

The component of the slurry which was used to prepare Si_3N_4 and SiC green tapes was listed in Table 1. The slurry mentioned above was cast on a glass slab with a blade (LYJ, Beijing Dongfang Co. Ltd. China). The height of blade was 150 μm and the casting speed was 0.2 m/min. Drying process was conducted in open air at room temperature to obtain Si_3N_4 and SiC green tapes. Si_3N_4 and SiC green tapes were cut into roundness

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