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Design and fabrication of porous ZrO_2/(ZrO_2 + Ni) sandwich ceramics with low thermal conductivity and high strength

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ABSTRACT

3Y–ZrO_2/(3Y–ZrO_2 + Ni) sandwich ceramics were fabricated through cold isostatic pressing and pressureless sintering. Porous 3Y–ZrO_2 ceramics with large connecting open pores and permeability were used as interlayers for insulation, whereas outer metal–ceramic layers were used as bearing loads. Microstructures and properties of the porous ZrO_2 and ZrO_2/(ZrO_2 + Ni) sandwich ceramics were investigated in detail. The ZrO_2/(ZrO_2 + Ni) sandwich ceramics exhibited better mechanical properties than the monolithic porous ZrO_2 ceramics at the same low thermal conductivity (approximately 0.85 W/m K). The mechanical properties of the sandwich ceramics were influenced by metal toughening and sintering-induced residual thermal stress.

1. Introduction

With the development of modern technology, porous zirconium ceramics have demonstrated a wide range of attributes, including high melting point and stability, high strength and toughness resulting from stress-induced phase transformation, and good insulation and erosion resistance for structural and functional applications (e.g., as support for catalysts, artificial bones, ceramic filters, and light-weight parts used at high temperature) [1–4].

Most structural ceramics including ZrO_2 are brittle and sensitive to superficial defects, flaws, and pores induced by sintering, finishing, and working processes. These factors, which can result in unexpected catastrophic failure, have long prevented these materials from being more extensively used. To overcome such problems, the major approach is to introduce a toughening phase, such as metal, ceramic particle, whisker and fiber, into the ceramic matrix to form a ceramic matrix composite [5–7]. Minet et al. [5] prepared ZrO_2-based composites through chemical vapor infiltration densification from preforms made of alumina and carbon fibers consolidated with a small amount of alumina, pyrocarbon, or hex-BN to improve mechanical properties. Unidirectional carbon fiber-reinforced calcium-stabilized zirconia composites were prepared through slurry infiltration and hot-pressing methods [6]. A high fracture toughness of 15.4 MPa m1/2 parallel to the fiber direction for the composite hot pressed at 1500 °C was attributed to the fiber pull-out. In our previous work, 3Y–ZrO_2–BN composites were prepared via hot pressing with different contents of BN particles to improve thermal shock resistance of the composites [7].

Multilayer structure design (such as functionally graded structure or sandwich structure) is a good candidate method for effective toughening [8–11]. Most researchers on metal–ceramic functionally graded materials focus on dense materials with high mechanical properties [12,13]. However, these studies neglect porous ceramics with suitable strength and good thermal insulation. No studies have been reported to date on the production methods or multi-functionality of porous metal–ceramic sandwich material for high-temperature insulation.

Various methods are available for manufacturing multilayer structures that can be used to develop new components and structures with good performance. These production methods include slip casting [14], tape casting [15], combustion [16], and dye pressing, followed by cold isostatic pressing [17]. The sintering techniques that can be employed include pressureless sintering [18], hot pressing [19], and hot isostatic pressing [20]. Among the foregoing, cold isostatic pressing and pressureless sintering (CIP-PLS) are relatively simple, widely used techniques that enable accurate control of the composition of each layer.

In this paper, we studied the microstructure, as well as the mechanical and thermal properties, of porous 3Y–ZrO_2/(3Y–ZrO_2 + Ni) sandwich ceramics fabricated through CIP-PLS. We also characterized the mechanical properties of porous 3Y–ZrO_2 ceramics in detail to illustrate the effect of the sandwich

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structure on the mechanical behavior of porous 3Y–ZrO_2/(3Y–ZrO_2 + Ni) sandwich ceramics.

2. Experimental procedures

2.1. Preparation

Commercially available raw materials were used to prepare the ZrO_2/(ZrO_2 + Ni) sandwich ceramics composites by CIP-PLS in this study. The Ni powder (purity > 99.9%) with a mean size of 2 μm was supplied from General Research institute for Nonferrous Metals. The ZrO_2 (1 μm, purity > 99.5%, Fanmeiya Powders Co., Ltd., Jiangxi, China) used here were 3 mol.% Y_2O_3 partially stabilized zirconia prepared by the co-precipitation method. The powder mixtures with different Ni contents are listed in Fig. 1. The different powder mixtures were first blended by ZrO_2 ball milling for 24 h. After milling, the slurry was dried with a rotary evaporator and then subjected to pestle and sieving with 100 mesh. Powder mixtures with varying volume fractions of Ni (0, 15, 30 vol.% Ni) were prepared, such that both homogeneous and graded composites could be fabricated. Moreover, five layers were considered for the present porous ZrO_2/Ni FGMs, as shown in Fig. 1. The first layer, marked as L1, was composed of ZrO_2–30 vol.% Ni. Metal Ni was added to improve the sinterability of ZrO_2. The L2 layer was composed of ZrO_2–15 vol.% Ni. The L3 layer was composed of ZrO_2 without the addition of Ni. These layers were fabricated through die and cold isostatic pressing. To improve the green strength of the layers, 1 wt.% PVA was added as binder to each layer before die pressing.

Then, the size of five-layer porous sandwich ceramics was designed as ∅8 mm (diameter) × 34 mm (height), and the thickness of Layer 1, Layer 2 and Layer 3 was 8 mm, 4 mm and 10 mm, respectively. The porous sandwich ceramics were stacked layer by layer in a steel die (inner diameter is 10 mm) according to the pre-designed compositional profile. After demoulding, the green bodies were compressed through cold isostatic pressing at 120 MPa. Finally, the porous green bodies were heated with 5 °C/min up to 1200 °C followed by a dwell time of 1–3 h and then cooled down with 5 °C/min to 1000 °C, under pure argon. Low heating and cooling rates were selected in order to relax the mismatch stresses generated in the sandwich ceramics during sintering. For the sake of comparison, the porous ZrO_2 ceramic was also fabricated by the above process.

2.2. Characterization

Open porosities and densities of the sintered samples were determined by the water-immersion technique using the Archimedes method. The density of dried green bodies was calculated from the mass and dimension of samples. The as-prepared products were coated with a thin layer of gold, the microstructural features and fractured surfaces of the composites were observed by scanning electron microscopy (SEM, FEI Sirion, Holland) with simultaneous chemical composition analysis by energy dispersive spectroscopy (EDX, EDAX Inc.). Flexural strength (σ) was tested in three-point bending on 3 mm by 4 mm by 34 mm bars, using a 30 mm span and a crosshead speed of 0.5 mm × min^{-1}. Each specimen was ground and polished with diamond slurries down to a 1 μm finish.

Porous ZrO_2/(ZrO_2 + Ni) sandwich ceramic samples of ∅8 mm × 34 mm were cut off from the as-sintered ceramics, and were loaded at a testing machine (Instron 5569, Instron Corp., Canton, USA) to test the compressive strength, with a crosshead speed of 0.05 mm/min. The samples were machined with the compressive surface perpendicular to the pressing direction. The shear strength of the samples was measured by an Instron-5569 electronic universal testing machine using a specially designed jig, as illustrated in Fig. 2. The samples are inserted into the upper and lower fixture, which have rectangle holes in the middle of them. The shear strength was measured by using rectangle specimen under uniaxial tensile load. The samples of 4 mm × 6 mm × 34 mm were cut off from the as-sintered ceramics in this work. The specimens were water-jet machined and the surfaces were diamond-polished. The arc shape at both ends of the specimen was designed to avoid unsymmetrical stress in the sample. The crosshead speed was 0.55 mm/min during testing. The edges of all the specimens were chamfered to minimize the effect of stress concentration due to machining flaws. In order to obtain the average value, a minimum number of five specimens were tested for each experimental condition and the average value was obtained.

Thermal conductivity of each layer in the ZrO_2/(ZrO_2 + Ni) sandwich ceramics was measured by 5 mm × 5 mm × 3 mm machined specimens with reference to GB/T 22588-2008 [21], using a Thermal Transport Option (TTO) of Physical Properties Measurement System (PPMS, Model 6000, Quantum Design, USA). Each value represented an average of five measurements of five different specimens. Runs on each sample were repeated until three consistent measurements were obtained. Reported results were an average of the three consistent repeat values obtained for each sample. Subsequently, the thermal conductivity, k, was calculated according to the following equation:

$$k = \rho \cdot Cp \cdot \alpha \quad (1)$$

where ρ, Cp and α were the sample density, the specific heat capacity and the thermal diffusivity, respectively.

Finite element analysis (FEA) was used to simulate the thermal stress distribution in the specimen by the commercial finite element package ABAQUS. Here, the FEA model is the same size as the experimentally tested rectangular specimen. The mesh division is performed with 78,040 8-node hex elements (C3D8R). The material properties were shown in Table 1. The temperature-dependent properties of Ni and YSZ were taken from literature [22–25] and the composition-dependent properties against each temperature were calculated using the Vegard's rule [24]

$$M_i = M_A(V_A)_i + M_B * (V_B)_i \quad (2)$$

where M_i is the material property of the ith layer, M_A is the material property of material A, $(V_A)_i$ is the volume fraction of component A in the ith layer, M_B is the material property of material B, $(V_B)_i$ is the volume fraction of component B in the ith layer. The composition-dependent material properties of all the layers used in the present study are given in Table 1.

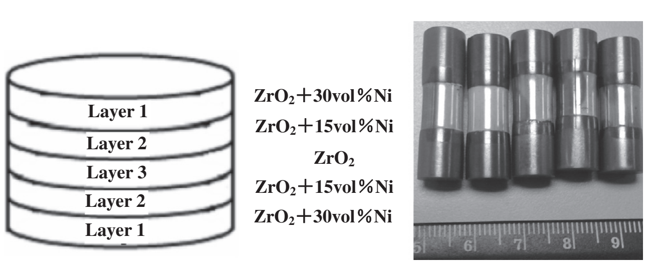

Fig. 1. Schematic composition and optical photograph of porous ZrO_2/(ZrO_2 + Ni) sandwich ceramics.

3. Results and discussions

As shown in Fig. 1, the sintered ZrO_2/(ZrO_2 + Ni) sandwich ceramic samples did not exhibit noticeable macroscopic defects, such