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Short communication

The flexural strength, fracture toughness, hardness and densification behaviour of various amount of Al_2O_3-doped 8YSCZ/Al_2O_3 composites used as an electrolyte for solid oxide fuel cell

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Abstract

The dependence of flexural strength, fracture toughness, hardness and densification behaviour of 8YSCZ/Al_2O_3 composite on Al_2O_3 content was examined using fine-grained 8 mol% yttria-stabilized cubic zirconia (8YSCZ) doped with 0, 1, 5 and 10 wt% Al_2O_3. The densification behaviour of 8YSCZ/Al_2O_3 composites in the temperature range 1250–1400 °C was studied. It was seen that Al_2O_3 contents up to 1 wt% enhanced densification, but further increase in Al_2O_3 contents led to a decrease in densification. The addition of Al_2O_3 enhanced the hardness, flexural strength and fracture toughness of 8YSCZ/Al_2O_3 composites. The maximum values obtained for hardness, flexural strength and fracture toughness were 1459 kg/mm^2, 330 MPa and 2.41 ± 0.02 MPa/m$^{1/2}$, respectively, for the specimen containing 10 wt% Al_2O_3 while these values were 1314 kg/mm^2, 275 MPa and 1.5 ± 0.03 MPa/m$^{1/2}$ for monolithic 8YSCZ.

Keywords: Cubic zirconia; Densification; Flexural strength; Fracture toughness; Hardness; Alumina

1. Introduction

Solid oxide fuel cells (SOFC) are being used for various applications in the automobile, power generation and aeronautics industries. A single SOFC unit consists of two electrodes (an anode and cathode) separated by a electrolyte. Yttria-stabilized cubic zirconia (YSCZ) with fluorite structure is well known as a solid electrolyte that possesses high oxygen ionic conductivity and chemical stability over wide ranges of temperature and oxygen partial pressure and thus it is widely used as an oxygen sensor, thermal barrier and SOFC [1]. In these applications, not only high conductivity, but also better mechanical (flexural strength and fracture toughness), chemical and electrical stability are required. Cubic zirconia has low mechanical strength at longer working temperatures (higher working temperatures (~1000 °C) are usually needed for SOFC and such a high working temperatures lead to a lower working efficiency), high thermal expansion and low thermal shock resistance. These drawbacks would limit its use as electrolyte, because it may fracture due to thermal stresses, mechanical stresses during operation, lack of transformation toughening and severe grain growth [2]. For SOFC applications, the thin solid electrolyte needs to be strong and tough enough to withstand room temperature assembly stresses and be mechanically stable for long periods at high temperatures in reducing and oxidizing atmospheres [3]. Therefore, the enhancement of mechanical properties of the solid electrolyte is important problem to be solved. Many approaches have been made to enhance the mechanical strength and hinder the severe grain growth

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(It is known that cubic zirconia has large grain sizes and high grain growth rates [4].) in cubic zirconia [5]. One such approach is to use the composite way by dispersing a second phase particles. In the composites, it has been known that the remarkable mismatching of lattice parameters and thermal expansion coefficients between matrix and second phase particles creates grain growth inhibition and thus the enhancement of room temperature mechanical properties. The second phase particles having high elastic modulus and large aspect ratio also give a remarkable shielding effect during crack propagation by crack-bridging and crack-deflection mechanisms. Therefore, the aim of the present study was to investigate the possibility of enhancing the strength and toughness of 8YSCZ/Al_2O_3 composites used as a electrolyte for SOFCs.

2. Materials and procedures

8YSCZ/Al_2O_3 composite containing up to 10 wt% Al_2O_3 were produced from the commercial powders: 8 mol% yttria-stabilized cubic zirconia (8YSCZ) powder, Tosoh, Japan and high purity (>99.999%) α-Al_2O_3 powder, Sumitomo, Japan. The average particle sizes were 0.3 μm for 8YSCZ and 0.4 μm for α-Al_2O_3. The chemical composition of the powders is listed in Table 1. Colloidal processing was used for the mixing of powders in order to achieve an uniform distribution and homogeneous microstructure. The slurries were prepared by dispersing the appropriate amounts of 8YSCZ and α-Al_2O_3 powders in distilled water with a dispersing agent (Dispex A40,UK); the slurries were then ball milled for 24 h to obtain a good dispersion and to break-up agglomerates in a plastic container using zirconia balls. The mixed composite powders were dried by rotary distillation, sieved through a 60-mesh screen to remove hard agglomerate particles and then die-pressed into disks and bars by uniaxial pressing at 40 MPa in a steel die followed by cold isostatic pressing (CIP) at 400 MPa. For lubrication, the interior surface of the dies was coated with a layer of stearic acid.

To determine optimal sintering temperature, the specimens were sintered at different temperatures between 1250 and 1400 °C in air at a constant heating rate of 200 °C/h for 1 h. The density of sintered specimens was determined by the Archimedes method. The theoretical densities of the composites were estimated by the rule of mixtures, using 3.99 and 5.95 g/cm^3 for the theoretical densities of alumina and cubic-zirconia, respectively. The relative density was estimated on the assumption that the sintered body is of the cubic phase and based on the theoretical density of 5.92, 5.81 and 5.67 for the specimens doped with 1, 5 and 10 wt% Al_2O_3, respectively.

For fracture toughness, hardness and density measurements, disk specimens were employed. The dimension of the disk specimen after polishing to a 1-μm diamond finish was 15 mm in diameter and 10 mm in thickness. The hardness and fracture toughness of the specimens were determined to attempt to quantify the effect of Al_2O_3 additions on room temperature mechanical properties. Both hardness and fracture toughness were measured using a Vickers indenter. Vickers hardness measurements were carried out on 8YSCZ/Al_2O_3 composites containing up to 10 wt% Al_2O_3, sintered at 1450 °C for 1 h. Indentations were made on polished specimens with a load of 20 kg held for 15 s. Ten tests were conducted for each composite. The hardness was calculated from the diagonal length of the indentation optically determined for each indentation, using the following equation:

$$H_v = 1.854P/d^2, \quad (1)$$

where H_v is Vickers hardness, P is applied load (kg) and d is mean of the diagonal length (mm). The fracture toughness was determined by the indentation technique. Polished specimens were indented at 10 different locations. Before indentation, a drop of oil was deposited onto the surface of the specimens to minimize moisture-enhanced crack growth. The size of the cracks emanating the indentation centre was measured. Measurements were performed immediately after each indentation in order to avoid any difference in crack length due to the environmental variables such as moisture and time. The indentation fracture toughness was calculated using the formula proposed by Anstis et al. [6] (half-penny crack);

$$K_{IC} = 0.0016(E/H_v)^{1/2}(P/C^{3/2}), \quad (2)$$

where K_{IC} is fracture toughness, E is Young's modulus, H_v is Vickers hardness, P is the load and C is the crack length.

Table 1
Chemical composition of the powders

Materials	Composition in wt%							
	ZrO_2 (+HfO_2)	Y_2O_3	Al_2O_3	SiO_2	TiO_2	Fe_2O_3	Na_2O	CaO
8YSCZ	85.9	13.6	0.25	0.1	0.10	0.003	0.01	0.02
α-Al_2O_3	–	–	99.9	0.04–0.08	–	0.01–0.02	0.08	–