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Strength and residual stresses of functionally graded Al_2O_3/ZrO_2 discs prepared by electrophoretic deposition

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Abstract

Biaxial strength testing of functionally graded Al_2O_3/ZrO_2 discs revealed that the strength of such discs, prepared by electrophoretic deposition, was almost doubled from 288 MPa for pure Al_2O_3 to 513 MPa for the graded discs; this was due to the compressive surface residual thermal stresses in the Al_2O_3 surface layer caused by the graded compositional profile. The surface compressive stress measured by means of X-ray diffraction was compared with the analytically calculated stress distribution in the graded component.

Keywords: Functionally graded materials; Bending test; Residual stresses; Electrophoretic deposition

1. Introduction

As in many joining applications and composites, the non-homogeneity of functionally graded materials (FGMs) has a large effect on the residual and thermal stresses arising from non-uniform shrinkage due to the thermal expansion mismatch between the different phases [1]. Moreover, the residual stress distribution in FGMs strongly influences the mechanical and tribological properties of the component [2], e.g., judicious design of the composition gradient can generate compressive stresses at those locations that are loaded in tension during operation.

Electrophoretic deposition is a suitable technique to produce FGMs by means of colloidal processing because it is a low cost process allowing the generation of well controlled continuously graded profiles in FGM components. Continuously graded materials in the Al_2O_3/ZrO_2 [3], ZrO_2/WC [4], and WC/Co [5] systems, for example, have already been explored.

In this paper, the strength and residual surface stresses in Al_2O_3/ZrO_2 FGM discs processed by electrophoretic deposition is explored.

2. Experimental procedure

Homogeneous Al_2O_3 and Al_2O_3/ZrO_2 FGM discs were made by electrophoretic deposition. The starting materials are commercially available 3 mol% Y_2O_3 co-precipitated ZrO_2 powder (Daiichi grade HSY-3U, Japan) with an agglomerate size of 0.35 μm and a crystal size of 30 nm, and α-Al_2O_3 powder (Baikowski grade SM8, France) with an average crystal and particle size of 0.60 μm. Technical grade methylethylketone (MEK, 99%, Acros, Belgium) and *n*-butylamine (Acros, 99.5%, Belgium) were used as the suspension media. A detailed description of the suspension preparation and the electrophoretic deposition process is provided elsewhere [3]. After at least 1 day of drying in air, the green bodies were sintered for 1 h at 1550 °C in air (Nabertherm, Germany) and hot isostatically pressed (HIPed) at 1390 °C in argon for 20 min at 140 MPa (Bodycote HIP, Chesterfield, UK).

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Sintered cross-sectioned discs were ground and polished for microstructural analysis. The compositional profile was measured quantitatively by means of electron probe microanalysis (EPMA, JEOL Superprobe 733, Japan). Density measurements were performed on sintered bodies according to the Archimedes method in ethanol. X-ray diffraction analysis (XRD, Siemens D500, Germany), using Cu K_α radiation (40 kV, 40 mA), was used for residual stress determination in the alumina surface layer of the graded discs according to the d-$\sin^2 \psi$ method [6]. The {1 4 6} reflection of α-Al_2O_3 was used for stress investigation. ψ^2 was varied from 0 to 0.6 in steps of 0.1, whereas 2θ was varied between 134 and 138° in steps of 0.02. A Poisson ratio, $v_{\{146\}}$, and Young's modulus, $E_{\{146\}}$, of 0.27 and 356 GPa, respectively, were used, corresponding with X-ray elastic constants S_1 and S_2 of -0.76×10^{-6} MPa^{-1} and 3.57×10^{-6} MPa^{-1}, respectively [7].

Ring-on-ring biaxial strength experiments were performed on ground homogeneous and FGM discs ($\phi = 36$ mm, $h = 4$ mm) according to ISO 6474 [8].

3. Results and discussion

3.1. Electrophoretic deposition of discs

Five-millimetre thick homogeneous Al_2O_3 and semi-symmetrical graded Al_2O_3/ZrO_2 discs were processed by means of electrophoretic deposition, as described elsewhere [3].

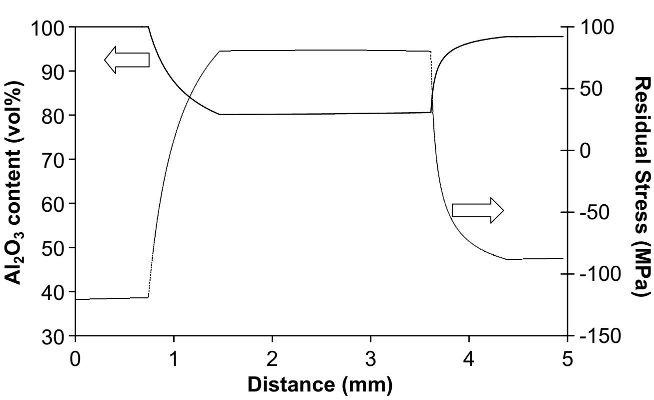

Fig. 1. Cross-sectional Al_2O_3 composition profile and corresponding calculated residual stress distribution for an Al_2O_3/ZrO_2 FGM disc.

The FGM discs were composed of a pure Al_2O_3 outer layer with a sintered thickness of 0.75 mm, a 2 mm thick homogeneous core with 80 vol.% Al_2O_3 and continuously graded 0.75 mm thick interlayers. The tested FGM discs were not perfectly symmetrical since one of the alumina outer layers is actually a homogeneous Al_2O_3/ZrO_2 composite with 96 vol.% alumina, as shown in Fig. 1. Although the FGMs were not perfectly symmetrical, no bending of the plates during sintering was observed.

A backscattered electron contrast micrograph of a cross-sectioned FGM plate is shown in Fig. 2. The bright ZrO_2 and dark Al_2O_3 phases can be clearly differentiated. The average Al_2O_3 grain size in the pure Al_2O_3 phase of both homogeneous alumina and FGM discs was 1.64 μm, as determined by the linear intercept method.

The sintered materials were hot isostatically pressed to eliminate residual porosity and concomitantly increase the strength. The density of the FGM components slightly increased upon HIPing, whereas the pure alumina discs were found to be fully densified after sintering, as shown in Table 1.

3.2. Residual stress calculation

Due to the lower coefficient of thermal expansion of Al_2O_3 ($\alpha = 7.4 \times 10^{-6}$) compared to ZrO_2 ($\alpha = 10.1 \times 10^{-6}$), compressive stresses developed in the Al_2O_3-rich surface and tensile stresses in the core of the graded disc during cooling from the sinter temperature. In fact, a state of equal biaxial loading exists in the regions of the plate away from the free edges. In this biaxial field, the materials undergo normal stresses only in the in-plane directions and

Table 1
Influence of hot isostatic pressing (HIP) on density of the disks

	Before HIP (g/cm^3)	After HIP (g/cm^3)
Al_2O_3	3.91 ± 0.02	3.91 ± 0.01
FGM	4.12 ± 0.03	4.17 ± 0.03

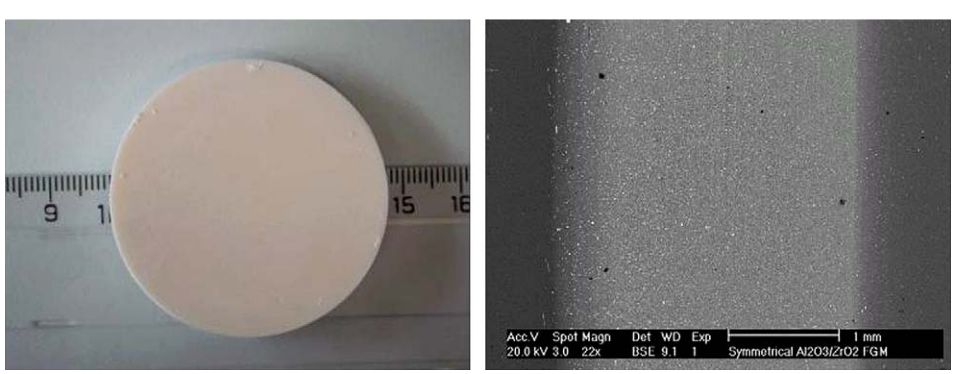

Fig. 2. Overview and SEM micrograph of the cross-sectioned Al_2O_3/ZrO_2 FGM disc.