**PROCESSING AND CHARACTERIZATION OF TRANSFORMATION-
TOUGHENED CERAMICS WITH STRENGTH RETENTION TO
ELEVATED TEMPERATURES**

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R. A. Cutler, C. B. Brinkpeter, A. V. Virkar and D. K. Shetty

ABSTRACT

Monolithic and three-layered Al_2O_3 -15 vol. % ZrO_2 composites were fabricated by slip casting aqueous slurries. The outer and inner layers of three-layer composites contained unstabilized and partially stabilized ZrO_2 , respectively. Transformation of part of the unstabilized ZrO_2 led to surface compressive stresses in the outer layers. Strain gage, x-ray, indentation crack length, and strength measurements were used to determine the magnitude of residual stresses in the composites. The strength of the three-layer composites (≈ 1200 MPa) was 500-700 MPa higher than that of the monolithic outer layer composites at room temperature and 350 MPa higher at 750°C . The strength differential decreased rapidly above the m $\rightarrow$ t transformation temperature. Three-layered composites showed excellent damage resistance and improved reliability. Cam follower rollers were fabricated to demonstrate the applicability of this technique for making automotive components.

INTRODUCTION

Transformation of ZrO_2 from the partially stabilized tetragonal polymorph to the equilibrium monoclinic form has been successfully used to toughen a variety of ceramic matrices[1]. Transformation of the metastable tetragonal ZrO_2 in the near surface regions of ceramics has also been used to produce compressive residual stresses and, thus, strengthen ceramics containing ZrO_2 [2,3]. The techniques developed to date for this purpose, such as grinding[3] or partial removal of the stabilizer[4], produce only modest thickness (≈ 30 μm) of the compressive stress zones. These ceramics do not sustain the improved strength under severe damage conditions that may produce a flaw larger than the compressive stress zone. The compressive stress produced by grinding can also be irreversibly lost by a high-temperature exposure and reverse transformation of the monoclinic ZrO_2 to the tetragonal form.

Virkar[5] patented a simple technique for introducing residual stresses in ceramics using transformation-induced stresses. Virkar, et al.[6] showed that significant

compressive residual stress can be introduced in Al_2O_3 -10 vol. % ZrO_2 with surface compression zones of the order of 300 to 1000 μm . The technique involves fabrication of three-layer composite ceramics consisting of outer layers that contain unstabilized ZrO_2 in an oxide matrix, and an inner layer that contains ZrO_2 (partially stabilized with an oxide additive such as Y_2O_3) dispersed in the same oxide matrix. On cooling from the fabrication temperature, a large fraction of the ZrO_2 in the outer layer transforms to the monoclinic form, while nearly all of the ZrO_2 in the inner layer is retained metastably in the tetragonal form. This selective transformation of the ZrO_2 (with the accompanying volume expansion) in the outer layers and the constraint of the bulk inner material leads to significant compressive stress in the outer layers and balancing tensile stress in the bulk. The residual stress will not decrease with temperature until the monoclinic to tetragonal transformation temperature is reached, since monoclinic and tetragonal ZrO_2 polymorphs have nearly the same coefficients of thermal expansion.

Cutler et al.[7,8] have successfully applied the three-layer technique to Al_2O_3 - ZrO_2 composites. Using dry pressing to form the sandwich composites, a compressive stress of 400 MPa was produced in the outer layers of Al_2O_3 -15 vol. % ZrO_2 composites with an outer layer thickness of 375 μm . During the first two years of ORNL funding[9] it was demonstrated that: 1) three-layer composites could be made with retention of a significant fraction of this residual stress (≈ 200 MPa) to temperatures of 750°C [7,8], 2) residual stresses could be detected by strength testing[7,8], strain gage measurements[10], characterization of monoclinic content by x-ray diffraction[7], or indentation/strength measurements[11], 3) the three-layer composites have excellent damage resistance[11], and 4) significant (300-400 MPa) residual compressive stress which is not transformation-induced can be introduced by grinding monolithic Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3).

This report summarizes highlights of a two year subcontract extension with objectives to: 1) increase the use temperature of three-layer composites by substituting HfO_2 for ZrO_2 , 2) develop aqueous slip casting techniques for three-layer composites in order to obtain better layer uniformity and to maximize residual compressive stress by optimizing the outer layer thickness, 3) superimpose temperature stresses on transformation-induced stresses in three-layer composites, and 4) demonstrate improved thermal shock resistance and damage resistance in optimized composites.

EXPERIMENTAL PROCEDURES

Al_2O_3 -15 vol. % ZrO_2 composites were prepared by dry pressing using techniques discussed previously[7-11] and by slip casting[12,13] using Al_2O_3 (ERC-DBM, Reynolds Metal Co., Bauxite, AR.) and ZrO_2 (DK-1, Daiichi Kagaku Kogyo Co. Ltd, Osaka, Japan) as starting materials for the outer layer monolithic material. The inner layer monolithic material used the same source of Al_2O_3 but partially stabilized (3.0 mol. % ZrO_2) ZrO_2 (HSY-3.0, Daiichi) was used in place of unstabilized zirconia. The two slips were dispersed using 0.5 wt. % citric acid and 2.0 wt. % Darvan C (R. T. Vanderbilt, Norwalk, CT.) in an aqueous slip at 70 wt. % (35 vol. %) solids. The slips were vibratory milled 16 hours with ZrO_2 (3.0 mol. % Y_2O_3) media and degassed prior to slip casting. Three-layer composites were slip cast in plaster molds by first casting the outer layer slip for a given time period and then pouring out the outer layer slip and quickly pouring in the inner layer slip. The inner layer slip was allowed to remain in the mold when making solid plates or cylinders. When hollow tubes for cam followers were fabricated, the inner layer slip was drained followed by introduction of the outer layer slip for a second time. The thickness of the layers was controlled by the slip casting times of the outer layers. The slip cast parts were dried under controlled conditions and sintered at 1587°C for 30 minutes. The sintered parts were subsequently HIPed in 200 MPa Ar at 1550°C for 30 minutes.

Unstabilized HfO_2 and coprecipitated HfO_2 (4 mol. % Y_2O_3) powders were supplied at no cost to the program by Teledyne Wah Chang Albany. Solid solution HfO_2 -50 mol. % ZrO_2 powder was prepared by milling the Teledyne HfO_2 powder with Daiichi DK-1 powder, calcining at 1700°C for 1 hour, and remilling the calcined solid solution.

Characterization for slip cast materials[13] was similar to that used previously for dry-pressed samples[6-11]. Strength testing was generally performed on bars in four-point bending. Thermal shock testing was performed on 6.5 mm diameter by 50 mm long rods. The samples were heated to various temperatures prior to quenching in ice water (0°C). Strength was measured in three-point bending at room temperature for thermally shocked rods.

Ceramic cam followers were ground (Advanced Materials Technology, Inc. (AMATEC), Georgetown, S.C.) to Chrysler Motor Co. drawing SK-783-50201 (revision D). Impact testing at Chrysler consisted of running the rollers on a motorized 2.2 liter cylinder head at 2750 rpm for five minutes with a 0.635-0.762 mm lash between the roller and the base circle of the cam.

RESULTS AND DISCUSSION

CHARACTERIZATION OF RESIDUAL STRESS

A schematic of the three-layer composites is shown in Figure 1. Both the outer and inner layers consist of Al_2O_3 -15 vol. % ZrO_2 so that thermal expansion coefficients are similar. The main difference is that the ZrO_2 in the outer layers is unstabilized and the ZrO_2 in the inner layer has been coprecipitated with 3 mol. % ZrO_2 . Upon cooling from sintering temperatures ($\approx 1600^\circ\text{C}$) where ZrO_2 in both outer and inner layers is tetragonal, most of the unstabilized ZrO_2 in the outer layers transforms to monoclinic with an accompanying volume expansion. The constraint of the inner layer puts the outer layers under compression and the inner layer in tension (see Figure 2). Assuming a square wave stress distribution the accompanying residual compressive stress, σ_1 , in the outer layers is

$$\sigma_1 = -\Delta\epsilon_0 E d_2 / [(1-\nu)d] \quad (1)$$

where $\Delta\epsilon_0$ is the unconstrained strain in the outer layers from the transformation of ZrO_2 , E is Young's modulus, d is thickness, ν is Poisson's ratio and the subscripts 1 and 2 refer to the outer and inner layers, respectively. Correspondingly, the residual tensile stress, σ_2 , in the

Figure 1. Schematic of three-layer Al_2O_3 -15 vol. % ZrO_2 composites with unstabilized ZrO_2 in outer layers and partially stabilized ZrO_2 in inner layer.

Figure 2. Schematic of three-layer sample showing unconstrained outer and inner layers as well as constrained length of composite.

inner layer is

$$\sigma_2 = 2\Delta\epsilon_o E d_1 / [(1-\nu)d] \quad (2)$$

Based on fracture of three-layer composites from within the outer layers, as would be expected in flexure, the failure strength, σ_f , is

$$\sigma_f = \sigma_o + \Delta\epsilon_o E d_2 / [(1-\nu)d] \quad (3)$$

where σ_o is the failure strength of the outer layers in the absence of residual stress. A plot of strength as a function of normalized inner layer thickness (d_2/d) would be expected to follow a linear relationship with slope of $\Delta\epsilon_o E / (1-\nu)$ and intercept equal to σ_o . Experimental verification of Equation (3) has been demonstrated for samples with flaw populations typical of "as-sintered" samples[7], as well as for samples with well characterized indentation flaws[8,11]. The value of $\Delta\epsilon_o$ determined from these measurements agree with estimates from x-ray measurements[7].

Virkar[14] has developed a technique for determining the residual stress profile of sintered ceramics using inexpensive strain gages. A strain gage is attached to one side of a three-layer ceramic which initially has outer layers of equal thickness. One side is then incrementally ground off (see

Figure 3) and the strain (ϵ) is measured as a function of thickness removed (δ). Using simple beam theory it is possible to predict the shape of the strain vs thickness removed[14] for a three-layer composite (see Figure 4). Considering a symmetric stress profile ($\sigma_{xx} = \sigma_{yy}$) so that residual stress is a function of z (thickness direction of a three-layer composite) only, the measured strain, $\epsilon_M(\delta)$, vs δ data can be used to determine the residual stress profile. For $0 \leq \delta \leq d_1$

$$\epsilon_M(\delta) = \{\Delta\epsilon_0 d_2 \delta (2d + \delta) / (d - \delta)^2 d\} \quad (4)$$

so that the residual stress can be calculated as

$$\sigma_1 = -\Delta\epsilon_0 d_2 E_1 E_2 / \{(2E_1 d_1)(1 - \nu_1) + (E_2 d_2)(1 - \nu_2)\} \quad (5)$$

The expected tensile strain in the inner layer, for $d_1 \leq \delta \leq d_1 + d_2$, is given by

$$\epsilon_M(\delta) = \Delta\epsilon_0 \{[(d_1^2 - (d_2 - \delta)^2) / (d - \delta)^2] + (d_2 / d)\} \quad (6)$$

Verification of this predicted response is shown for experimentally determined curves in Figure 5. As expected, the monolithic outer and inner layer composites show no change in strain as a function of thickness of material removed, while the three-layer composites show significant residual compressive stress in the outer layers. The bend in $\epsilon_M(\delta)$ vs δ occurs at $\delta = d_1$ (the interface between outer and inner layers). The magnitude of $\Delta\epsilon_0$ was measured to be 1.2×10^{-3} giving a calculated compressive residual stress in the outer layers of ≈ 520 MPa[10].

Figure 3. Schematic showing the three-layer sample with a strain gage mounted on one face. The other face is incrementally ground off and the strain is recorded as a function of the thickness ground off.

Figure 4. Analytically determined normalized strain for three-layer composite with $d_1=1$ and $d_2=4$ as a function of thickness removed[10].

Figure 5. Measured strain vs thickness removed for monolithic and three-layer Al_2O_3 -15 vol. % ZrO_2 samples. Monolithic samples show no residual stress while three-layer sample shows compressive stress in outer layer[10].

In the discussion of residual stress above, it was assumed that an equibiaxial state of stress and strain exists in the three-layer composites. In order to verify this assumption, longitudinal and transverse strains were measured on both bend bars (≈ 4.5 mm in width and thickness) and plates (20 mm square-shaped samples) as a function of thickness removed. As shown in Figure 6, the strain in the transverse direction was lower by about 20% than the strain in the longitudinal direction for bar shaped samples. As expected, the longitudinal and transverse strains were similar for the square-shaped sample (see Figure 7). These data suggest that the assumption of equibiaxiality is reasonable.

The influence of residual stresses present in the three-layer composites can also be shown by measuring indentation cracks. Assuming a simplistic analysis for indentation behavior, the indentation crack length, c_0 , in the absence of residual stress is given by

$$c_0 = [0.016(E/H)^{1/2}(P/K_{IC})]^{2/3} \quad (7)$$

In the presence of residual stress, σ_R , the half-penny crack after indentation is shorter in the outer layers which are under uniform compressive stress or longer in the inner layer which is under a lesser tensile stress. The crack length, c , in the presence of residual stress may be calculated by

$$(c_0/c)^2 - (c_0/c)^{1/2} + \gamma = 0 \quad (8)$$

where $\gamma = A\sigma_R[(P/K_{IC}^4)(E/H)^{1/2}]^{1/3}$ and A is a nondimensional constant[11]. Previous work has confirmed the validity of crack lengths which occur in the outer layers of three-layer composites by comparing indentation cracks on the outer surfaces of three-layer composites in relation to the indentation cracks on the outer surfaces of monolithic bars.

Indenting cross-sections shows the effect of strong residual stresses more dramatically (see Figure 8). Assuming typical values[11] of toughness ($4.3 \text{ MPa}\cdot\text{m}^{1/2}$), Young's modulus (340 GPa), hardness (17 GPa), compressive stress (-500 MPa) in the outer layers and balancing tensile stress (100 MPa) in the inner layer ($1/12$ - $5/6$ - $1/12$ bars), Equations (7) and (8) give $c_0=115 \text{ }\mu\text{m}$ and $c=73.7 \text{ }\mu\text{m}$ in the outer layers and $c=140.8 \text{ }\mu\text{m}$ in the inner layer. By aligning cracks parallel and perpendicular to the surface (and interface), it is possible to see shorter cracks in the outer layers perpendicular to the interface/surface (i.e., in the direction where the residual compressive stress is closing the crack tip) and longer cracks in the inner layer perpendicular to the interface/surface (i.e., in the direction where the residual tensile stress is opening the

Figure 6. Measured strain as a function of thickness removed for bar-shaped three-layer composites[10].

Figure 7. Measured strain as a function of thickness removed for square-shaped three-layer composites[10].

(a)

(b)

Figure 8. Optical micrographs of cross-sections of three-layer (Outer layers of Al_2O_3 -15 vol. % ZrO_2 and inner layer of ZrO_2 (3 mol. % Y_2O_3)-40 vol. % Al_2O_3) composites with indents oriented with cracks parallel and perpendicular to the interface/surface. Note change in crack lengths between outer (top) and inner (bottom) layers.

(c)

(d)

Figure 8 (cont). (c,d). Cracks in three-layer Al_2O_3 -15 vol. % ZrO_2 after removing surface of indentation cracks to make cracks more visible. Crack lengths are strongly influenced by residual compression (outer layers) and residual tension (inner layer).

crack tip). These cracks are shorter (outer layers) and longer (inner layer) than the cracks in the absence of residual stresses, as predicted by the simple analysis above.

It is interesting to note, however, the resulting difference in crack length parallel to the interface for indentation cracks in the outer and inner layers. The cracks parallel to the interface are longer in the outer layers and shorter in the inner layer. The longer crack length in the outer layers is due to the spontaneous energy release when the crack parallel to the interface extends.

The integrity of the smooth interface obtained by slip casting is also seen by aligning indentation cracks with the interface. There is no tendency for the cracks to run along the interface (see Figure 8).

The above observations with indentation cracks further explain why strength is high when failure occurs within the outer region and may be low when defects initiate failure within the inner layer. These results give another method for identifying materials with substantial residual stresses and also provide a means for identifying interfaces in three-layer materials without phase contrast.

COMPARISON OF SLIP CAST AND DRY PRESSED COMPOSITES

The advantages of slip casting three-layer $\text{Al}_2\text{O}_3\text{-ZrO}_2$ composites compared to dry pressing the same layered composition are improved uniformity in outer layer thickness, and better particle packing prior to sintering resulting in reduced flaw populations after densification. The disadvantages of slip casting are that the thickness of components is limited and the cycle times are increased due to drying constraints.

Figure 9 shows a comparison of cross-sections of a three-layer composite where the inner layer has been made with higher ZrO_2 content such that the interface is easily seen in the SEM. Figure 9(a) shows the interface of dry pressed composites where spray dried agglomerates are readily observed. Note how much more uniform the interface is for the same composition when slip cast (Figure 9(b)). Figure 10 shows a strength comparison between monolithic and three-layer $\text{Al}_2\text{O}_3\text{-15 vol. \% ZrO}_2$ composites made by dry pressing (followed by isostatic pressing) and slip casting. The 10 to 20% strength improvement is due to the advantages of slip casting outlined above.

Figure 11(a) shows the strength improvement at room temperature for monolithic and layered composites which occurred during the contract. The higher strengths were the result of improved processing including limiting defects (i.e., agglomerates, pores, inclusions), improved interface control, and optimization of drying/sintering schedules.

(a)

(b)

Figure 9. SEM micrographs of cross-sections of (a) dry pressed and (b) slip cast three-layer (outer layers of Al_2O_3 -15 vol. % ZrO_2 and inner layer of ZrO_2 (3 mol. % Y_2O_3)-40 vol. % Al_2O_3) composites. Note smooth interface in slip cast composites and remnants of spray dried agglomerates in dry pressed outer layer.

Figure 10. Room temperature flexural strength comparison of Al_2O_3 -15 vol. % ZrO_2 fabricated by dry pressing (followed by isostatic pressing) and slip casting.

Improved strength was also achieved by controlling the grinding process as described below. High temperature (1000°C) strength also improved, as shown in Figure 11(b), during the same time period due to improved processing. The strength, however, decreases dramatically at elevated temperature for both the monolithic and three-layer composites due to the absence of transformation toughening. The key to increasing the use temperature for transformation-induced stress is the successful substitution of HfO_2 for ZrO_2 (see section below on elevated temperature testing).

EFFECT OF GRINDING ON STRENGTH

The strength of the monolithic inner layer material (Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3)) nearly doubled upon grinding as shown in Table 1. The strength degraded slightly with temperature (see Table 1) but testing at 750°C (after

(a)

(b)

Figure 11. Strength improvement between 1986 and 1989 for monolithic and three-layer Al_2O_3 -15 vol. % ZrO_2 composites. (a) Room temperature, (b) 1000°C.

cooling from 1200°C) showed that transformation-induced stresses are not the primary strengthening mechanism since strength was identical to that measured upon heating to 750°C. This is consistent with x-ray diffraction data which showed no transformation to monoclinic zirconia upon grinding (see Table 2). Specimens polished to a one μm finish without grinding showed only a moderate strength improvement (strength of 551 ± 49 MPa) despite a significant improvement in surface finish, demonstrating that grinding does more than improve surface finish. In order to see if it is possible that grinding introduces compressive stresses due to plastic deformation, Al_2O_3 , ZrO_2 , monolithic outer layer material (Al_2O_3 -15 vol. % ZrO_2) and three-layer composites were all tested (see Table 2) in the unground (edges chamfered before HIPing) and ground state (220 grit wheel at down feed of 2.5 microns/pass before sparking out). The strength increased (by 30-67%) for all specimens, although the magnitude of the strength increase was greatest for ZrO_2 and the monolithic inner layer specimen. Fractography showed alumina, zirconia, and monolithic outer layer bars all failed from the tensile surface, whereas monolithic inner layer and three-layer bars showed a large percentage of bars failing from near the chamfers.

A number of factors affect the strength increase including improved surface finish and transformation-induced stresses for the ZrO_2 , monolithic outer, and three-layer specimens. The inner layer monolithic ZrO_2 is unique in that no measurable monoclinic ZrO_2 was observed on the ground or fractured surface (see Table 2). While others [16-19] have seen a strengthening via grinding for transformation toughened ceramics, it has always been accompanied by an

Table 1
Strengthening of Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3)
Due to Grinding

Specimen Preparation	Test Temperature (°C)	Samples Tested	Strength (MPa)
Unground	25	6	452 ± 11
Ground (220 Grit)	25	6	835 ± 85
Ground, 1200°C Anneal	25	5	731 ± 168
Ground, 1600°C Anneal	25	6	666 ± 68
Ground, 1200°C Anneal	750	3	621 ± 47
Ground, 1200°C Anneal	850	3	606 ± 5
Ground, 1200°C Anneal	950	3	528 ± 21
Ground, 1200°C Anneal	1200 $\rightarrow$ 750	3	627 ± 95

Table 2
Strength Comparison of Ground and Unground Bars

Material	Density (g/cc)	Strength (MPa)			m-ZrO ₂ Content ^a (%)		
		Unground ^b	Ground ^c		U ^b	G ^c	F.S. ^d
		# ^e x ^f s ^g	# x s				
Al ₂ O ₃ ^h	3.98	8 308±30	8 434±64	---	---	---	---
ZrO ₂ ⁱ	6.04	8 677±63	5 998±73	<1	1.9	24.8	
Outer ^j	4.29	8 389±23	5 650±59	83.1	85.6	88.5	
Inner ^k	4.32	8 485±34	8 806±52	<1	<1	<1	
3-layer ^l	4.32	7 679±56	4 879±51	--- ^m	--- ^m	--- ^m	

- a. Monoclinic content of ZrO₂ in specimen[15].
b. Chamfered before HIPing with no other grinding.
c. Ground with a 220 grit wheel at a down feed of 2.5 μm/pass before spark out.
e. Number of specimens tested in four point bending.
f. Mean value.
g. Standard deviation.
h. Reynold's ERC-DBM alumina.
i. Daiichi's HSY-3.0 zirconia.
j. Outer layer composition.
k. Inner layer composition.
l. Three-layer composition with outer layers 1/12 total thickness.
m. Not measured but has substantial monoclinic ZrO₂[7,8].

increase in monoclinic content. Stresses introduced during grinding of the inner layer material, however, do not show strength hysteresis dependent on the m<-->t transformation temperatures and ground monolithic inner layer specimens have higher strength than three-layer composites at temperatures in excess of 950°C. The lack of monoclinic zirconia on ground and fracture surfaces, and prior work showing that the effect is not solely due to improved surface finish, suggests that plastic deformation during grinding may account for part of the improved strength of the inner layer composition.

In order to optimize the stresses introduced into the monolithic inner material during grinding, the rate of down feed was varied. Table 3 shows that strengths over 900 MPa were observed when the down feed was increased to 10.2 microns/pass. Furthermore, grinding on the sides of the bar decreased the tendency for the bars to fail from chamfers and increased the strength.

Monolithic Al₂O₃, ZrO₂ (3 mol. % Y₂O₃), Al₂O₃-15 vol. % ZrO₂ and three layer Al₂O₃-15 vol. % ZrO₂ (with and without post HIP grinding) specimens were sent to Rockwell International for determination of residual stresses by x-ray

Table 3
Effect of Grinding Parameters on the Room Temperature
Strength of Al_2O_3 -15 vol. % $\text{ZrO}_2(\text{Y}_2\text{O}_3)$ Composites

Sides Ground ^a	Down feed ^b ($\mu\text{m/pass}$)	Strength (MPa)		
		# ^c	$\bar{x}$ ^d	s ^e
0	2.5	8	485	34
2	2.5	8	806	52
4	2.5	6	876	100
2	5.1	6	749	105
4	5.1	6	862	119
1	7.6	8	806	52
4	10.2	6	926	78
4	15.2	6	849	102

a. Sides of samples ground with a 220 grit diamond wheel. Tensile surface was ground for all samples except for unground bars.

b. Down feed of 220 grit wheel prior to spark out.

c. Number of bars tested.

e. Mean strength.

f. Standard deviation.

diffraction. Dr. Michael R. James performed the Cu K_α x-ray analysis using (416) and (620) planes for Al_2O_3 and ZrO_2 , respectively. When using Cr K_α radiation, (1.1.10) and (331) planes were used for Al_2O_3 and ZrO_2 , respectively. In Al_2O_3 , the respective penetration depths for Cu and Cr radiation are 32 and 10 μm (i.e., 67% of the diffracted radiation comes from a depth less than these values (87 and 27 μm for 95% return)). Thus, the difference in residual stress between the two radiations represents the gradient of residual stress with depth. The penetration depths are slightly less for ZrO_2 since Zr is approximately three times more absorbent than Al.

The measured compressive residual stresses are given in Table 4. Surprisingly, the inner monolithic material which showed a large strength increase with grinding, despite no observable transformation (see Table 2), also showed low residual stress and low dependence of residual stress on depth of penetration. Further work is needed to explain the significant strengthening which occurs upon grinding the inner layer material. The outer layer and three-layer (the outer layer of the three-layer sample was the surface exposed to radiation) materials showed significantly higher residual stresses at shallower penetration and were strongly influenced by grinding. The 98 MPa incremental change in compressive stress for Al_2O_3 using Cr K_α radiation compares with 125-145 MPa as reported by Lange, et al. [18]. $\text{ZrO}_2(3$

Table 4
Residual Stress Determined at Rockwell International
by X-ray Analysis

Composition	Residual Stress (MPa)			
	Cu K α Radiation		Cr K α Radiation	
	unground	ground	unground	ground
Al ₂ O ₃	-136	-135	-101	-199
ZrO ₂ (3 mol. % Y ₂ O ₃)	-44	-15	-81	-271
Al ₂ O ₃ -15 v/o ZrO ₂	-131	-256	-267	-822
Al ₂ O ₃ -15 v/o ZrO ₂ (3 mol.% Y ₂ O ₃)	-131	-203	-173	-261
Three-layer	-486	-711	-570	-1106

mol. % Y₂O₃) showed a strong dependence of residual stress on depth, with residual stress which correlated well with the observed strength increase. There was no overall correlation of compressive stress with strength increase upon grinding for the materials tested. However, the residual stress difference between three-layer and outer layer Al₂O₃-ZrO₂ as determined by x-ray diffraction and strength measurements were both on the order of 300-400 MPa, verifying the substantial residual stress created by the stress-induced transformation in the three-layer composites.

In an effort to determine the depth of compressive stresses introduced by grinding slip cast Al₂O₃-15 vol. % ZrO₂, specimens were prepared for strength/indentation measurements. The strength of ground monolithic inner-layer bars at indentation loads of 16, 37, 64, 125, and 296 N agreed with data for unground samples (see Figure 12), indicating that residual stresses introduced by grinding are very shallow, as expected. The fact that the stresses are shallow, as compared to stresses in three-layer specimens, further supports the need for a protective compressive stress layer of at least 100 μ m[6].

In order to investigate the strengthening which occurs upon grinding Al₂O₃-15 vol. % ZrO₂ (3 mol. % Y₂O₃) (i.e., monolithic inner layer material), slip cast bars in the unground and chamfered state were compared with machine ground and chamfered bars. The difference in strength at room temperature was 500 MPa, decreasing to 270 MPa at 750°C, and 180 MPa at 1250°C (see Figure 13). Ground samples heated to 1250°C, well above the m--->t transformation temperature, and cooled to 750°C, had strength of 762 $\pm$ 129 MPa (6 bars) in comparison to 658 $\pm$ 107 MPa measured for the same material tested at 750°C without the high temperature anneal. These data indicate that residual stresses due to grinding are not completely removed by heating to 1250°C and holding for 30

(a)

(b)

Figure 12. Indentation/strength measurements on ground and unground inner layer material. Strength as a function of (a) indentation load, and (b) inverse cube root indentation load. Note that strength is similar at loads of 16 N.

Figure 13. Strength of ground (open) and unground (solid) inner layer material (Al_2O_3 -15 vol. % ZrO_2 (3 mol.% Y_2O_3)) as a function of temperature.

minutes. Since the inner layer material does not contain monoclinic ZrO_2 , it does not show any strength hysteresis.

The difference in strength between ground and unground inner layer material is not due to transformation-induced stress as in the three-layer material. The larger surface flaws on the unground surfaces account for part of the difference in strength, but the experiments described above showed that polishing unground samples to a high surface finish did not result in comparable strengths to the ground bars.

The high strength ground inner material, however, is susceptible to surface damage, showing similar strength to unground inner material at indentation loads as low as 16 N (see Figure 12). These data indicate that the depth of compressive stress, due to surface grinding, is shallow and does not provide protection against surface flaws. This is

consistent with shallow surface compression measured in Si_3N_4 -based ceramics after grinding[20]. As shown below, a primary advantage of layered composites is their greatly enhanced damage resistance.

DAMAGE RESISTANCE

Indentation/strength testing of slip cast monolithic and three-layer Al_2O_3 -15 vol. % ZrO_2 was performed in order to determine their response in comparison to the dry pressed bars tested previously[11]. The main differences between the dry pressed and the slip cast bars were the improved strength of all three slip cast materials and the increased uniformity of the outer layer thickness in the three-layer slip cast bars (see Figure 9). In addition, the thickness of the outer layers of slip cast three-layer bars was $\approx 250 \mu\text{m}$ in comparison to dry pressed bars with outer layer thickness of $\approx 375 \mu\text{m}$. The indentation/strength response of three-layer composites was compared with theoretical expectation based on superposition of stress. It can easily be shown[11] that the strength expected for three-layer composites which have been indented with a Vickers indenter of load P is given by

$$\sigma_f = CK_{IC}^{4/3} / ((E/H)^{1/6} P^{1/3}) + \Delta \epsilon_0 E d_2 / (1-\nu) d \quad (9)$$

where C is a constant equal to 2.02[20,21], K_{IC} is fracture toughness and H is hardness. According to Equation (9), a plot of σ_f vs $P^{-1/3}$, as shown in Figure 14, should yield a straight line with a slope related to K_{IC} and an intercept giving the compressive residual stress, σ_1 . Taking values of $E=340 \text{ GPa}$, $H=17 \text{ GPa}$, linear regression of the data for monolithic specimens gave slopes corresponding to K_{IC} values of 5.35 and 5.03 $\text{MPa}\cdot\text{m}^{1/2}$ for outer and inner materials, respectively. Both materials had intercepts near zero, showing that they were free of residual stress (see Figure 14). A linear regression of the data for the three-layer composites gave a slope corresponding to a fracture toughness of 5.75 $\text{MPa}\cdot\text{m}^{1/2}$, similar to the monolithic materials, as predicted previously[11]. It is interesting to note, however, that there was very little decrease in strength at high indentation loads (greater than 125 N) suggesting that the three-layer material has even better damage resistance than predicted by Equation (9). The intercept from the linear regression gave a value of -588 MPa for the compressive stress. This value of σ_1 is higher than the difference in strength of -497 MPa when comparing the unindented bars. These data confirm the superior damage resistance of

(a)

(b)

Figure 14. Fracture stress (σ_f) versus (a) load (P) and (b) inverse cube root load ($P^{-1/3}$) plots for the slip cast three-layer and monolithic Al_2O_3 -15 vol. % ZrO_2 ceramics.

materials made using the three-layer concept and show that improved resistance to contact damage can be expected for ceramic components made using this technique.

In order to show the practical extension of this technology, totally encapsulated ≈ 5 mm diameter rods were fabricated by slip casting such that pits on the order of 50-250 μm were prevalent on the surface but were rarely present in the bulk. The outer layer of the rods was ≈ 425 μm thick and surface compressive stress was on the order of 400 MPa. The strength (5 rods broken in 4-point bending using an inner span of 20 mm and an outer span of 40 mm) of the "as-HIPed" material was 908 ± 116 MPa, as compared to strength of $1,211 \pm 123$ MPa for three-layer rods which were ground to a 30 μm surface finish. In contrast, monolithic outer layer rods had strength of 476 ± 84 MPa in the "as-HIPed" state and 830 ± 27 MPa in the ground state. The change in strength between the three-layer and monolithic outer layer materials was improved at larger flaw sizes. This means that as long as the outer layer thickness of the three-layer composite is sufficiently larger than the surface flaws, that strength improvement consistent with the indentation/strength data can be expected in components.

In order to further explore the use of three-layer composites, monolithic and three-layer (outer layer $\approx 1/12$ th the total thickness of the ceramic) composite cam followers were fabricated and tested by Chrysler Motor Corp. The o.d. of the roller was ≈ 17.8 mm, the i.d. was ≈ 7.59 mm, and the length ≈ 12.7 mm. Ceramtec had previously tested Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3) cam followers of similar geometry which failed the lash test where high impact loads are applied. The test consisted of running the rollers on a motorized 2.2 L cylinder head at 2750 rpm for five minutes with a 0.635-0.762 mm (0.025-0.030") lash between the roller and the base circle of the cam. Previous tests were run at 3000 rpm, but due to limitations of the test fixture used at Chrysler only 2750 rpm were applied.

Fifteen rollers were supplied and eight were selected for testing. One monolithic outer roller broke during setup, most likely due to expansion of the pin during welding. Of the seven rollers tested, six of them passed the lash test. This is in stark contrast to the previous testing of the inner layer material made by dry pressing where three out of three rollers failed the lash test. Two of each of the three types of materials (i.e., monolithic outer, monolithic inner, and three-layer) tested survived five minutes of the lash test. The only material to fail was a three-layer roller which was terminated after 18 seconds.

Due to the fact that the monolithic materials survived the lash test, it was requested that a larger lash be applied to see if the compressive stress in the outer layer of the

three-layer material allowed improved damage resistance. Additional testing was not performed by Chrysler for two reasons: 1) the coefficient of friction for Si_3N_4 is lower than $\text{Al}_2\text{O}_3\text{-ZrO}_2$ and wear is consequently improved for silicon nitride rollers compared to oxide-based rollers (no wear measurements were done on the slip cast rollers sent), and 2) the cost per ground roller was \$0.50/roller and Chrysler was only interested in testing rollers from suppliers who were serious about getting into this business (At the time the rollers were tested, Si_3N_4 supplied by Sullivan Mining Co. looked very promising and Ceramatec was not committed to competing in this market). To the best of the authors' knowledge, these are the only tests performed where aluminum oxide-based ceramics have passed the impact test.

THERMAL SHOCK TESTING

Fracture strengths of monoliths and three-layer rods after thermal shocking over different temperature ranges are displayed in Figure 15. The as-HIPed strengths were 830 ± 27 MPa, 1185 ± 109 MPa, and 1206 ± 36 MPa for outer, inner and layered composite rods, respectively. These strengths are similar to those reported above for bars in four-point bending. The inner layer rods had a ΔT of slightly less than 300°C , the outer layer rods had a ΔT of $\approx 325^\circ\text{C}$ and the layered rods had a ΔT of $\approx 425^\circ\text{C}$. The exposed ends of the layered rods were the regions most susceptible to thermal shock and totally encapsulated rods would likely have resulted in a higher ΔT for this material. Individual layered composite rods had strengths greater than 1200 MPa at temperatures up to 425°C . Since thermal shock under severe cooling conditions generally initiates from the outer surface of monolithic components, the increase in thermal shock resistance of the three-layer rods over the outer layer rods is of interest. This increase of 100°C can be compared with what would be expected for the strength improvement due to the surface compressive layer. The compressive stress, σ_1 , in the outer case and the balancing tensile stress, σ_2 , in the inner core can be easily calculated assuming a square-wave stress distribution. These stresses are approximately given by

$$\sigma_1 = -(A_2/A) E \Delta \epsilon_0 / (1-\nu) \quad (10)$$

and

$$\sigma_2 = (A_1/A) E \Delta \epsilon_0 / (1-\nu) \quad (11)$$

Figure 15. Thermal shock behavior of monolithic and "three-layer" Al_2O_3 -15 vol. % ZrO_2 quenched in ice water. Layered rods with surface compressive stress of ≈ 400 MPa have critical ΔT 100°C higher than monolithic rods.

where A is the cross-sectional area of the rods. The outer case thickness was approximately 0.375 mm or $1/12$ th the diameter of the rods. Taking values of $4.86 \times 10^{-6} \text{ m}^2$, $1.10 \times 10^{-5} \text{ m}^2$, and $1.59 \times 10^{-5} \text{ m}^2$ for A_1 , A_2 , and A , respectively, E of 340 GPa, $\Delta \epsilon_0$ of 1.3×10^{-3} and Poisson's ratio of 0.25 , results in a compressive residual stress of 409 MPa in the case and a residual tensile stress of 180 MPa in the core. The calculated compressive stress is in good agreement with the increase in room temperature strength between the outer and the layered composite rods of 376 MPa.

Based on the early work of Hasselman[23,24] it is possible to explain the improved thermal shock resistance of the Al_2O_3 -15 vol. % ZrO_2 ceramics having substantial compressive surface stresses as compared to the monolithic ceramics of similar composition, modulus and thermal

expansion. The expected increase in ΔT_c , the critical temperature difference to which the rods are subjected in order to initiate crack growth and decrease strength, for a material with compressive residual stress is given by

$$\Delta T_c = \Delta T_c^0 + [\sigma_c(1-\nu)/\alpha E]f(k/ha) \quad (12)$$

where ΔT_c^0 is the temperature differential in the absence of residual stress given by $[\sigma_f(1-\nu)/\alpha E]f(k/ah)$, where σ_f is the unquenched strength, α is linear coefficient of thermal expansion, k is the thermal conductivity, h is the surface heat-transfer coefficient and a is the characteristic heat transfer length. The work of Becher et al.[25] investigating the effect of sample size on the thermal shock resistance of ceramics shows the need to take the Biot modulus (ah/k) into account in calculating ΔT_c . For a conservative prediction, a relatively high heat transfer coefficient, $h=10 \text{ W/cm}^2\cdot\text{C}$ was assumed. With $a=0.225 \text{ cm}$ and $k=0.25 \text{ W/cm}\cdot\text{C}$, the Biot modulus equals 9. For this value of β , $f(k/ah)=0.433$. From Equation (12), the predicted increase in thermal shock resistance for three-layer rods is 243°C for $\sigma_1=-376 \text{ MPa}$. The increase obtained in experiments was $\approx 100^\circ\text{C}$. The reason for this discrepancy is likely related to the fact that the ends of the rods were not encapsulated. The reason for the low values for ΔT_c ($300-425^\circ\text{C}$) measured in the present study in contrast to the high values ($\Delta T_c > 800^\circ\text{C}$) reported by Becher[26] for monolithic $\text{Al}_2\text{O}_3\text{-ZrO}_2$ composites is believed to be due to the more vigorous quench of the ice water as compared to boiling water[27] and to the difference in sample thickness between the two studies.

Improved thermal shock resistance of the three-layer composites is expected due to the presence of residual compressive stresses. These results show that residual compressive stress of substantial depth in layered composites not only increases strength, apparent toughness[7], and damage resistance, but also makes the materials more resistant to thermal shock.

IMPROVED RELIABILITY

Superposition of temperature stress (due to difference in thermal expansion) on transformation-induced stress (due to volume expansion differences between monoclinic and tetragonal ZrO_2) was demonstrated using $\text{ZrO}_2(3 \text{ mol. \% } \text{Y}_2\text{O}_3)\text{-40 vol. \% } \text{Al}_2\text{O}_3$ as the inner layer material in three-layer

slip cast composites. The temperature-induced stress enhance the strength of three-layer composites at low temperatures.

The expected compressive residual stress in the outer layer of the bars is the combination of transformation-induced and temperature-induced stresses. The transformation-induced compressive stress, σ_1 , in the outer layer, assuming a square wave stress distribution, is

$$\sigma_1 = \frac{-(E_1 E_2 d_2 \Delta \epsilon_0)}{[(1-\nu)(2E_1 d_1 + E_2 d_2)]} \quad (13)$$

in an analogous manner to Equation (1). The temperature induced stress, σ_1 , in the outer layer, also assuming a square wave distribution, is given as

$$\sigma_1 = \frac{-(E_1 E_2 d_2 \Delta T)(\alpha_2 - \alpha_1)}{[(1-\nu)(2E_1 d_1 + E_2 d_2)]} \quad (14)$$

where ΔT is the temperature difference over which stress builds up and α is the coefficient of linear thermal expansion. By superposition, the expected residual stress in the outer layer is

$$\sigma_1 = \frac{-(E_1 E_2 d_2)(\Delta \epsilon_0 + \Delta T(\alpha_2 - \alpha_1))}{[(1-\nu)(2E_1 d_1 + E_2 d_2)]} \quad (15)$$

Taking E_1 as 340 GPa, E_2 as 275 GPa, $\Delta \epsilon_0$ as 1.3×10^{-3} , ΔT as 1000°C , $\alpha_2 - \alpha_1$ as $1 \times 10^{-6}/^\circ\text{C}$, ν as 0.25, d_1 as 500 μm , and d_2 as 5 mm, the expected compressive residual stress in the outer layer is slightly over 1,000 MPa. The corresponding residual tensile stress in the inner layer is approximately 200 MPa. Strain gage measurements resulted in a measured compressive stress of 1,100 MPa, in excellent agreement with prediction.

The room temperature fracture strength of three-layer composites was 1,275 MPa as compared to a strength of 549 MPa for the outer layer bars. The compressive stress of -725 (difference between inner and three-layer bars) is 70% of the predicted value. More importantly, it shows that high strengths can be achieved in layered ceramic composites using a combination of transformation and temperature-induced stresses, as expected.

Figure 16 shows linearized Weibull plots of fracture stresses of monolithic outer, monolithic inner and three-layer composites with transformation-induced stresses,

Figure 16. Linearized Weibull plots of fracture stress of monolithic and three-layer composites. Slip cast composites have both transformation-induced and temperature-induced residual stress. Note higher modulus of three-layer composites compared to monoliths, indicating enhanced reliability.

fabricated by dry pressing, as well as slip cast three-layer composites with both transformation-induced and temperature-induced stresses. It is noted that the three-layer composites exhibit both increased strengths as well as improved Weibull moduli relative to the monolithic ceramics. Improvements in uniformity in the thickness of the layers by slip casting is the main reason for the improved strength of the slip cast composites. The improvement in Weibull modulus is due to superposition of stress[7]. Residual compression

deliberately introduced into the near surface regions of structural ceramics can be a viable approach to increase Weibull modulus and reliability.

ELEVATED TEMPERATURE TESTING

Strength measurements as a function of temperature are shown in Figure 17 for monolithic outer, inner and three-layer samples. At room temperature the three-layer composites have a strength of 1150 MPa as compared to a strength of 660 MPa for the outer layer monolithic bars. The strength differential between the three-layer and outer layer bars, as shown in Figure 18, is due to the compressive

Figure 17. Strength of three-layer Al_2O_3 -15 vol. % ZrO_2 composites as a function of temperature, in comparison to monolithic inner (Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3)) and outer (Al_2O_3 -15 vol. % ZrO_2) layer materials.

Figure 18. Strength differential between three-layer and outer layer materials. Strength differential is due to compressive residual stress in the outer layers of the three-layer composite.

residual stress in the outer layers of the three-layer bars. The experimentally observed value of -490 MPa from strength testing agrees well with the value of -520 MPa from strain gage measurements.

The residual stresses are effective in strengthening the three-layer composites until the monoclinic to tetragonal (m-->t) transformation is completed at a temperature above 750°C (see Figure 18). Dilatometric studies of the outer layer material show the A_s temperature as $\approx 900^\circ\text{C}$ and the A_f temperature as $\approx 1000^\circ\text{C}$. The M_s temperature was $\approx 600^\circ\text{C}$ and the M_f temperature was $\approx 500^\circ\text{C}$. Since these temperatures are dependent on the constraint of the ZrO_2 in the outer layers, these temperatures may be shifted slightly lower in the three-layer composite. Figure 19 shows the strength

Figure 19. Strength hysteresis for three-layer Al_2O_3 -15 vol. % ZrO_2 composites as a function of temperature cycling. Open symbols represent samples heated to the test temperature. Solid symbols represent samples heated to 1250°C and then cooled to the test temperature. Note that when layered composites are heated above A_s , the martensitic start temperature during heating, that strength is not fully recovered until the samples are cooled below the M_f , the martensitic finish temperature during cooling.

hysteresis measured for three-layer composites cycled above the A_f temperature and tested on cooling above the M_s temperature. These results are in excellent agreement with expectation and show that layered composites cycled above the A_s temperature will have decreased strength during cooling until they are cooled below the M_f temperature. This limits the use of layered Al_2O_3 - ZrO_2 ceramics with high damage resistance to temperatures not exceeding $\approx 800^\circ\text{C}$ (see Figures 18 and 19).

Substituting HfO_2 for ZrO_2 is the most straightforward approach for increasing the use temperature of layered composites. Al_2O_3 -15 vol. % HfO_2 , Al_2O_3 -15 vol. % HfO_2 (4 mol. % Y_2O_3), and HfO_2 (4 mol. % Y_2O_3) compositions were dry pressed, sintered and HIPed using hafnia powders received from Teledyne Wah Chang Albany. X-ray diffraction showed that the sintering temperature of 1600°C was not high enough to fully convert the monoclinic $\text{HfO}_2(\text{Y}_2\text{O}_3)$ to tetragonal. Approximately 60 % of the $\text{HfO}_2(\text{Y}_2\text{O}_3)$ was monoclinic after holding for two hours at 1600°C . The $\text{HfO}_2(\text{Y}_2\text{O}_3)$ with no Al_2O_3 added had a strength of 329 ± 28 MPa. Monolithic outer (Al_2O_3 -15 vol. % HfO_2), monolithic inner (Al_2O_3 -15 vol. % HfO_2 (4 mol. % Y_2O_3)) and three-layer composites had strengths of 458 ± 30 MPa, 437 ± 22 MPa, and 492 ± 31 MPa, respectively. The thermal expansion of the monolithics materials were both $\approx 8.4 \times 10^{-6}/^\circ\text{C}$ over the temperature range 25 - 1000°C . The slightly higher strength of the three-layer composites is not likely due to transformation-induced stresses since sintering occurred in the monoclinic stability range for the unstabilized HfO_2 .

In an effort to lower the m $\rightarrow$ t transformation temperature, $\text{HfO}_2\cdot\text{ZrO}_2$ powder was made and x-rayed to verify that a solid solution had formed. Al_2O_3 -15 vol. % ($\text{HfO}_2\cdot 50$ mol. % ZrO_2) was used as the outer layer and Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3) was the inner layer in three-layer composites. The room temperature strength of the three-layer composite was 947 ± 164 MPa and the strength at 1000°C was 523 ± 23 MPa. The strength at 1000°C is not improved over the strength of 644 ± 51 MPa measured at the same temperature for three-layer Al_2O_3 -15 vol. % ZrO_2 composites. While the concept of improving the high temperature strength of three-layer composites by substituting HfO_2 for ZrO_2 is sound, improved HfO_2 or $\text{HfO}_2\cdot\text{ZrO}_2$ powders will be required before this concept is realized in practice.

SUMMARY AND CONCLUSIONS

Three-layer oxide ceramics with compressive residual stress ranging between 300 and 600 MPa in the outer layers were fabricated using dry pressing and slip casting. The outer layer thickness was controlled in the green state. The outer layer protected against damage due to surface flaws or sliding contact.

Transformation-induced stresses were present at temperatures in excess of 750°C . Stress due to the thermal expansion mismatch between inner and outer layers were superimposed to give strength increases greater than 500 MPa at room temperature.

Slip casting was used to improve the uniformity of the interface between layers to allow composites with outer layer thicknesses of 200-300 μm to be fabricated. The room temperature strength of Al_2O_3 -15 vol. % ZrO_2 composites increased from 825 MPa to 1150 MPa and the strength at 1000°C increased from 320 MPa to 640 MPa. Strength in excess of 1200 MPa at room temperature was achieved by superimposing temperature stress on transformation-induced stress. Both monolithic and layered cam rollers fabricated by slip casting survived the impact testing required for cam followers in automobiles.

In addition to strength measurements, residual stresses were detected by strain gage measurements, characterization of monoclinic content as a function of temperature by x-ray diffraction, strength and indentation/strength measurements, indentation crack length measurements, and thermal shock testing.

Grinding dramatically improves the strength of Al_2O_3 -15 vol. % ZrO_2 (3 mol. % Y_2O_3) without creating substantial transformation-induced stresses detectable by standard x-ray techniques. These monolithic materials do have surface induced residual stresses which do not protect against surface damage. In contrast, three-layer composites, with outer layers exceeding 100 μm , have excellent damage resistance. Further work is needed to identify applications where layered composites are cost effective in replacing monolithic ceramics due to their improved damage resistance.

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REFERENCES

1. A. G. Evans and R. M. Cannon, "Toughening of Brittle Solids by Martensitic Transformations," Acta Metall., **34**, 761-800, (1986).
2. D. J. Green, R. H. J. Hannink, and M. V. Swain, Transformation Toughening of Ceramics, (CRC Press, Boca Raton, FL 1989).

3. M. V. Swain, "Grinding-Induced Tempering of Ceramics Containing Metastable Zirconia," *J. Mater. Sci. Lett.*, **15**, 1577-79, (1980).
4. D. J. Green, "A Technique for Introducing Surface Compression into Zirconia Ceramics," *J. Am. Ceram. Soc.*, **66**[9], C-178-C-179, (1983).
5. A. V. Virkar, "Ceramic Bodies Having a Plurality of Stress Zones," U. S. Pat. NO. 4,656,071 (April 7, 1987).
6. A. V. Virkar, J. L. Huang. and R. A. Cutler, "Strengthening of Oxide Ceramics by Transformation Induced Stresses," *J. Am. Ceram. Soc.*, **70**[3], 164-70, (1987).
7. R. A. Cutler, J. J. Hansen, A. V. Virkar, D. K. Shetty, and R. C. Winterton, "Strength Improvement in Transformation Toughened Ceramics using Compressive Residual Surface Stresses," pp. 155-63 in Advanced Structural Ceramics Vol. 78, ed. by P.F. Becher, M. V. Swain, and S. Somiya, (Materials Research Society, Pittsburgh, PA, 1987).
8. R. A. Cutler, J. D. Bright, A. V. Virkar, and D. K. Shetty, "Strength Improvement in Transformation-Toughened Alumina by Selective Phase Transformation," *J. Am. Ceram. Soc.*, **70**[10], 713-18, (1987).
9. R. A. Cutler, J. J. Hansen, D. W. Prouse, J. D. Bright, A. V. Virkar, and D. K. Shetty, "Processing and Characterization of Transformation-Toughened Ceramics with Strength Retention to Elevated Temperatures," Final Report, ORNL/Sub/85-22028/1, Martin Marietta Energy Systems, Inc., Oak Ridge Natl. Lab., July 1988.
10. A. V. Virkar, J. F. Jue, J. J. Hansen and R. A. Cutler, "Measurement of Residual Stresses in Oxide-ZrO₂ Three-Layer Composites," *J. Am. Ceram. Soc.*, **71**[3], C-148-51 (1988).
11. J. J. Hansen, R. A. Cutler, D. K. Shetty and A. V. Virkar, "Indentation Fracture Response and Damage Resistance of Al₂O₃-ZrO₂ Composites Strengthened by Transformation-Induced Residual Stresses," *J. Am. Ceram. Soc.*, 1988, **71**[12], C-501-5, (1988).

12. R. A. Cutler, C. B. Brinkpeter, S. L. Bruner, D. W. Prouse, A. V. Virkar, and D. K. Shetty, "Transformation-Toughened Ceramics with Strength Retention to High Temperatures, pp. 155-63 in Proc. 27th Automotive Tech. CCM, (SAE, Warrendale, PA, 1990).
13. R. A. Cutler, C. B. Brinkpeter, A. V. Virkar and D. K. Shetty, "Fabrication and Characterization of Slip-Cast Layered Al_2O_3 - ZrO_2 Composites," pp. 397-408 in Ceramic Materials and Components for Engines, Ed. by R. Carlsson, T. Johansson and L. Kahlman, (Elsevier Applied Science, London, 1992).
14. A. V. Virkar, "Determination of Residual Stress Profile Using a Strain Gage Technique," *J. Am. Ceram. Soc.*, **73**[7] 2100-02 (1990).
15. H. Toraya, M. Yoshimura, and S. Somiya, "Calibration Curve for Quantitative Analysis of the Monoclinic-Tetragonal ZrO_2 System by X-Ray Diffraction," *J. Am. Ceram. Soc.*, **68**[6] C-119-C-121 (1984).
16. T. K. Gupta, "Strengthening by Surface Damage in Metastable Tetragonal Zirconia," *J. Am. Ceram. Soc.*, **63**[1-2] 117 (1980).
17. N. Claussen and M. Rühle, "Design of Transformation-Toughened Ceramics," pp. 137-63 in Advances in Ceramics Vol. 3, ed. by A. H. Heuer and L. W. Hobbs, (The Am. Ceram. Soc., Columbus, Ohio, 1981).
18. D. J. Green, F. F. Lange, and M. R. James, "Residual Surface Stresses in Al_2O_3 - ZrO_2 Composites," pp. 240-50 in Advances in Ceramics Vol. 12, ed. by N. Claussen, M. Rühle, and A. H. Heuer, (The Am. Ceram. Soc., Columbus, Ohio, 1983).
19. D. J. Green, F. F. Lange, and M. R. James, "Factors Influencing Residual Surface Stresses due to a Stress-Induced Phase Transformation," *J. Am. Ceram. Soc.*, **66**[9] 625-629 (1983).
20. D. Johnson-Walls, A. G. Evans, D. B. Marshall and M. R. James, "Residual Stresses in Machined Ceramic Surfaces," *J. Am. Ceram. Soc.*, **69**[1] 44-47 (1986).

21. G. R. Anstis, P. Chantikul, B. R. Lawn, and D. B. Marshall, "A Critical Evaluation of Indentation Techniques for Measuring Fracture Toughness: I, Direct Crack Measurements," *J. Am. Ceram. Soc.*, **64**[9] 533-38 (1981).
22. P. Chantikul, G. R. Anstis, B. R. Lawn, and D. B. Marshall, "A Critical Evaluation of Indentation Techniques for Measuring Fracture Toughness: II, Strength Method," *J. Am. Ceram. Soc.*, **64**[9] 539-48 (1981).
23. D. P. H. Hasselman, "Unified Theory of Thermal Shock Fracture Initiation and Crack Propagation in Brittle Ceramics," *J. Am. Ceram. Soc.*, **52**[11] 600-04, (1969).
24. D. P. H. Hasselman, "Figures of Merit for the Thermal Stress Resistance of High-Temperature Brittle Materials," *Ceramurgia Int.*, **4**[4] 147-50, (1979).
25. P. F. Becher, D. Lewis, K. R. Carman, and A. G. Gonzalez, "Thermal Shock Resistance of Ceramics: Size and Geometry Effects in Quench Tests," *Am. Ceram. Soc. Bull.*, **59**[5] 542-48 (1980).
26. P. F. Becher, "Transient Thermal Stress Behavior in ZrO_2 -Toughened Al_2O_3 ," *J. Am. Ceram. Soc.*, **64**[1], C-37-9 (1981).
27. P. F. Becher, "Effect of Water Bath Temperature on the Thermal Shock of Al_2O_3 ," *J. Am. Ceram. Soc.*, **64**[1], C-17-18 (1981).

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