

Enhanced Fracture Strength and Toughness of Zirconia by Coating the Pre-Stressed Mullite-Zirconia

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Abstract

In this work, we prepared mullite-zirconia/zirconia pre-stressed composites with excellent mechanical properties by means of pressureless sintering. Both the strength and toughness of zirconia could be significantly enhanced with the application of a pre-stressed coating. The optimal mechanical properties were obtained when the content of mullite in the coating was 40 wt%. The corresponding flexural strength and fracture toughness were 1250.48 ± 43.81 MPa and 12.39 ± 0.87 MPa·m^{1/2}, an improvement of 39.15 % and 26.8 % compared with the values of zirconia, respectively. Basis for this reinforcement mechanism is that the achieved residual compressive stresses in the mullite-zirconia coating can simultaneously improve the strength and prevent crack propagation. The outstanding properties of mullite-zirconia/zirconia pre-stressed composites make these promising candidates for advanced manufacturing.

Keywords: Pre-stressed strengthening, zirconia ceramics, mechanical properties, mullite

I. Introduction

Zirconia ceramics have excellent properties such as high hardness, high-temperature resistance, excellent corrosion resistance, and outstanding wear resistance. These qualities have led to the widespread use of zirconia ceramics in various fields, including aerospace, vehicles, electronics and information technology, and biomedical applications^{1–2}. However, the brittleness of ceramic materials significantly restricts the broader utilization of zirconia ceramics. To overcome this limitation, researchers have developed various methods for strengthening and toughening³. Currently employed toughening techniques for ZrO₂ ceramics include fiber/whisker reinforcing^{4–6}, particle toughening^{7–9}, phase transformation toughening^{10–13}, among others. Nevertheless, these methods exhibit certain drawbacks. Firstly, none of these approaches can simultaneously enhance both strength and toughness. Secondly, the effectiveness provided by different methods is limited and they are constrained by process conditions such as cost considerations or limitations related to shape and size requirements¹⁴. These aforementioned issues can be effectively addressed with the pre-stressed coating method.

Pre-stressed design necessitates fulfillment of several criteria. In order to achieve surface compressive stresses during the cooling process, a lower coefficient of expansion but a higher modulus of elasticity are required for the

coating material compared to that of the matrix material. Moreover, the coating material must be compatible with sintering processes while being suitably matched with matrix material. Bao *et al.*^{15–17} utilized the coating method to apply a coating with a low coefficient of thermal expansion onto a ceramic matrix, followed by pressureless sintering to obtain pre-stressed coated ceramic composites. During the cooling process, a layer of highly compressive stress can be formed on the surface of the composite due to the difference in shrinkage volume between the matrix and coating. Pre-stressed ZrO₂ ceramics coated with Al₂O₃ achieved a flexural strength of $(1\,330 \pm 52)$ MPa, which was 45 % higher than that of uncoated counterparts. Similarly, the flexural strength of building porcelain tiles increased by 70 %, from (67 ± 3) MPa to (114 ± 5) MPa¹⁵. Hao *et al.*¹⁸ employed this simple preparation method to enhance the flexural strength of mullite-aluminum pre-stressed ceramics by 37.19 % (from 400 MPa to 549 MPa), demonstrating excellent resistance against thermal shock and high-temperature flexural strength. Compared with other toughening methods, pre-stressing is more effective in enhancing materials while maintaining simplicity.

Because the thermal expansion coefficient of mullite is $4 \sim 5.5 \times 10^{-6}$ K⁻¹, lower than that of zirconia (11.27×10^{-6} K⁻¹ at 1 100 °C), and Young's modulus of mullite is 210 GPa, higher than that of zirconia (205.76 GPa), and the mullite coating material is compatible with zirconia during sintering processes, the mullite-zirconia coating was selected to improve the strength and toughness of zirconia. In this study, the green bodies of ceramic composites were obtained by immersing the zirconia matrix

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Table 1: Physical and chemical indicators of fused mullite.

Material	Density(g/cm ³)	Al ₂ O ₃	SiO ₂	Fe ₂ O ₃	TiO ₂	CaO	MgO
Fused Mullite	3.02	72.6%	25.6%	0.01%	0.01%	0.17%	0.08%

Table 2 The mass ratio of zirconia to mullite in coating of each group.

Sample	Zirconia(g)	Mullite(g)	PVB(g)	Castor oil(g)	Ethanol (mL)
S1 (0 wt%)	/	/	/	/	/
S2 (20 wt%)	16	4	1	0.1	80
S3 (30 wt%)	14	6	1	0.1	80
S4 (40 wt%)	12	8	1	0.1	80
S5 (50 wt%)	10	10	1	0.1	80

in mullite-zirconia slurry, followed by pressureless co-sintering to produce pre-stressed composites. Systematic investigations were conducted on the mechanical properties of the composites, as well as performance parameters such as the density, Young's modulus and thermal expansion coefficient of both the composites and matrix. Furthermore, residual stress was calculated to explain the enhancement mechanism of pre-stress coating.

II. Experimental Method

(1) Preparation of materials

The solvent used in this study was ethanol (Modern Orient Technology Development Co., Ltd., China), and mixtures of fused mullite (Plutonium Casting Materials Co., Ltd., China, D₅₀ = 17 μm, the chemical composition is shown in Table 1) with mass fractions of 20 wt%, 30 wt%, 40 wt% and 50 wt% were combined with 3 mol% yttria partially stabilized zirconia powder (Shanghai Xinchao Welding Material Co., Ltd., China, D₅₀ = 0.02 μm). Polyvinyl butyral (Shanghai Macklin Biomedical Co., Ltd., China) and castor oil (Shanghai Macklin Biomedical Co., Ltd., China) were added to mixture, which was then subjected to ball milling in a planetary ball mill (YXQM-1L, MITR, China) at a speed of 300 r/min for 4 h using a ball-to-material ratio of 10 : 1. This process resulted in the formation of a uniformly dispersed mixture slurry.

A prefabricated 3 mol.% yttria partially stabilized green zirconia substrate with dimensions of 60 mm × 60 mm × 2 mm was prepared with the sol-gel method (Zhisheng Kuangye Co., Ltd., China, D₅₀ = 0.4 μm) and cut into samples measuring 40 mm × 4.5 mm × 2 mm. The surfaces of the substrate were polished and chamfered using 2 000-mesh sandpaper.

The prepared matrix was immersed in the slurry and subsequently dried, with the coating thickness being controlled by adjusting the number of dips. The dried composite ceramics were pressureless-sintered in air at a temperature of 1 550 °C for a duration of two hours, with a heating rate of 5 K/min. Then, they were cooled to room temperature within the furnace. The resulting sintered specimens had dimensions approximately equal to

32 mm × 3.5 mm × 2 mm, with an average coating thickness around both upper and lower sides measuring approximately 25 μm. Specifically, S1 represents the zirconia matrix while S2 – S5 represent pre-stressed ceramic composites prepared using different mullite contents as indicated in Table 2.

(2) Testing and Characterization

The phase structures of the coating and matrix were determined with an X-ray diffractometer (D8 Advance Diffractometer, Bruker, Germany). The morphology observations of the samples were conducted on a scanning electron microscope (SEM, Quanta 250 FEG, FEI Company, American), equipped with energy-dispersive spectrometer (EDS) for elemental composition analysis. The flexural strength and fracture toughness of samples were tested with a microcomputer-controlled electronic universal testing machine (Model C45, MTS, American) with a span of 30 mm and a loading rate of 0.5 mm/min, five samples were tested. Furthermore, the thermal expansion coefficient of samples was measured with a thermal dilatometer (DIL 402C, Linseis, Germany) during stepwise heating from room temperature to 1 400 °C at a heating rate of 5 K/min. The Young's modulus samples were measured with the impulse excitation method (JC/T 2172–2013).

The Archimedes' drainage method was used to obtain the density of the composites and matrix. The relative method¹⁹ was used to test the density of the coating. The calculation formula is:

$$\frac{1}{\rho_c} = \left(\frac{1}{\bar{\rho}} - \frac{k}{\rho_s} \right) \frac{1}{1-k} \quad (1)$$

where $k = \frac{m_s}{m}$; ρ_c is the density of the coating (kg/m³); m_s and m are the dry weights (kg) of the matrix and composites at the same volume; ρ_s and $\bar{\rho}$ are the densities (kg/m³) of the matrix and composites, respectively.

A three-point bending²⁰ test was used to determine the flexural strength of the samples. The fracture toughness of the specimens was obtained using the Single-Edge Notched Bending (SENB) Method. The notch had a depth

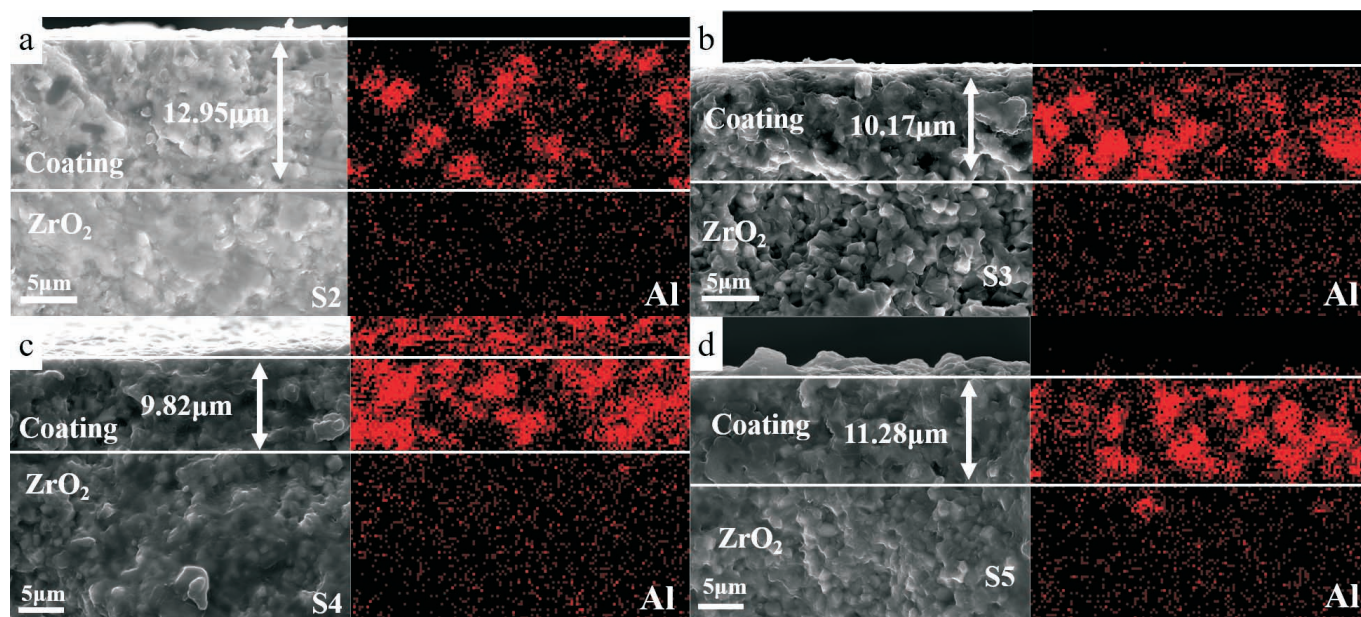


Fig. 3: SEM and EDS images of the fracture surface of each coating group.

coating and substrate, indicating that the coating and matrix were closely bonded. The EDS surface scanning results reveal a uniform distribution of aluminum within the coating, with an increasing content of aluminum observed as the mullite content increases.

Fig. 4 shows the SEM image of matrix after three-point bending experiments. The fracture of the composites was mainly transgranular and intergranular. There were only a few pores present in the matrix after sintering, further indicating dense sintering. Furthermore, its grain size was approximately 1 μm , which was small and can enhance the material's density, reduce pores and cracks, and contribute to improving its strength and toughness.

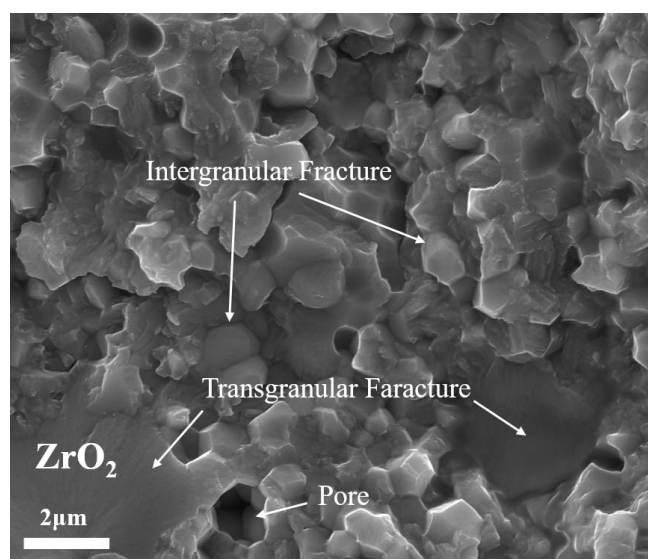


Fig. 4: Scanning electron microscope images of the matrix.

(2) Mechanical properties

Fig. 5 shows the flexural strength and fracture toughness of the pre-stressed ceramic composites prepared with

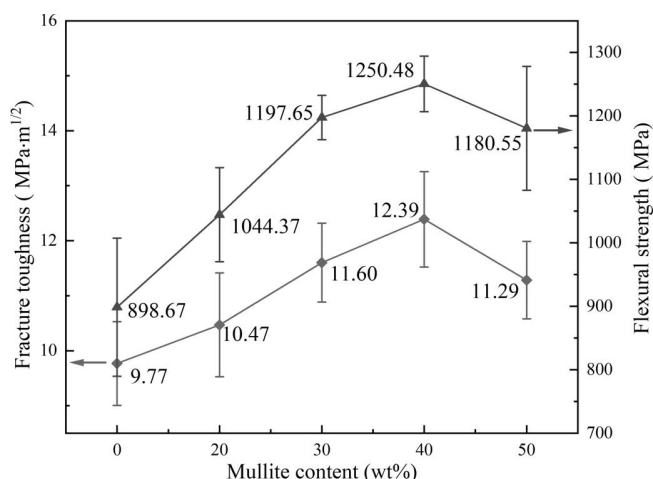


Fig. 5: Curves of flexural strength and fracture toughness as a function of mullite content.

different content of mullite and zirconia matrix at room temperature. The flexural strength and fracture toughness of the ceramic composites increases significantly with the support of pre-stressed coating. With the increase in the content of mullite in the coating, the flexural strength and fracture toughness of the pre-stressed composites showed a trend of increasing and then decreasing. The highest pre-stressed enhancement was achieved when the content of mullite in the coating was 40 wt%, the flexural strength increasing to (1250.48 ± 43.81) MPa, which was 39.15 % higher than that of the zirconia matrix (898.67 ± 108.69) MPa. The fracture toughness of the pre-stressed ceramic reached (12.39 ± 0.87) MPa·m^{1/2}, which was 26.8% higher than that of the zirconia matrix (9.77 ± 0.76) MPa·m^{1/2}. It should be noted that the fracture toughness results obtained using the SENB method may potentially exhibit an overestimation. When the content of mullite was increased to 50 wt%, the flexural strength and fracture toughness began to decrease. The improved

strength and toughness of the composites can be attributed to the presence of residual compressive stress in the coating. This compressive stress counters the applied tensile stress, inhibiting the expansion of microcrack tips. This effectively enhances the composite's overall strength and toughness.

Table 3 summarizes related articles on different toughening methods of ZrO_2 ceramics and mullite- ZrO_2 composites. Their preparation conditions and mechanical properties are also listed. The comparison of the results of this

work with that of other researchers is shown in Fig. 6. It is observed that in the methods of previous work, the improvement of flexural strength and fracture toughness cannot be taken into account at the same time, and often only one of the two properties clearly improved. Notably, the pre-stressed method not only achieves the purpose of both strengthening and toughening, but is also able to achieve a higher rate of improvement compared to other methods.

Table 3: Different toughening methods for ZrO_2 ceramics and mullite- ZrO_2 composites.

Toughening method	Sintering process	Materials	Sintering method	Relative density (%)	Mechanical properties		References
					$\sigma_f(\text{MPa})$	$K_{Ic}(\text{MPa} \cdot \text{m}^{1/2})$	
Phase transformation toughening	1 500 °C (5 h, air)	$\text{Al}_2\text{O}_3/\text{ZrO}_2$	Pressure-less sintering	98.4	/	5.4	23
	1 200 °C (4 h, air)	$\text{TiO}_2/\text{Ca-TZP}$	Pressure-less sintering	99.1±0.2	730±20	9	24
	1 450 °C (1 h, vacuum)	2YSZ	Hot-pressed sintering	99	1269	10.7	25
Fiber/whisker reinforcing	1 200 °C (10 min, 30 MPa, vacuum)	$\text{Al}_2\text{O}_3/\text{YSZ}$	SPS	/	593	5.5	26
	1 400 °C (1 h, 25–35 MPa, air)	ZrO_2 whisker/ ZrO_2	Oscillatory pressure sintering	/	1376	6.7	27
	1 550 °C (1 h, 27.5–32.5 MPa, vacuum)	SiC whisker/ $\text{Al}_2\text{O}_3/\text{ZrO}_2$	Oscillatory pressure sintering	98.54	528±20	6.67±0.33	28
	1 600 °C (2 h, air)	Al_2O_3 short fiber/YTZP	Pressure-less sintering	98	760	9.2	29
	1 200 °C (10 min, 30 MPa, vacuum)	Al_2O_3 fiber/YSZ	SPS	/	277±43	15.93±0.75	30
	1 600 °C (5 h, air)	mullite/ ZrO_2	Pressure-less sintering	96.2±0.2		3.9±0.2	31
Particle toughening	1 500 °C (2 h, argon)	Ta/ ZrO_2	Pressure-less sintering	95	697±21	14±0.47	32
	1 400 °C (1 h, 45 MPa, argon)	Nb/YTZP	Hot pressed sintering	/	800±10	/	33
	1 550 °C (30 min, 30 MPa, vacuum)	$\text{HfB}_2/\text{ZrO}_2$	Hot pressed sintering	/	1093.06±24	8.17±0.18	34
	1 550 °C (2 h, air)	mullite/ ZrO_2	Pressure-less sintering	>93	268.23	4.05	35

Toughening method	Sintering process	Materials	Sintering method	Relative density (%)	Mechanical properties $\sigma_f(\text{MPa})$	$K_{Ic}(\text{MPa} \cdot \text{m}^{1/2})$	References
	1 500 °C (3 h, air)	mul- lite/3Y-TZP	Pressure- less sintering	98.9	890.4	10.2	36
	1 450 °C (3 h, air)	Mul- lite/Y-TZP	Pressure- less sintering	99.6	780	5.4	37
Pre-stressed toughening	1 500 ° C(2 h, air)	Al ₂ O ₃ /ZrO ₂	Pressure- less sintering	/	1330±52	/	15
	1 550 °C (2 h, air)	mul- lite/ZrO ₂	Pressure- less sintering		1250.48± 43.81	17.91±1.19	This work

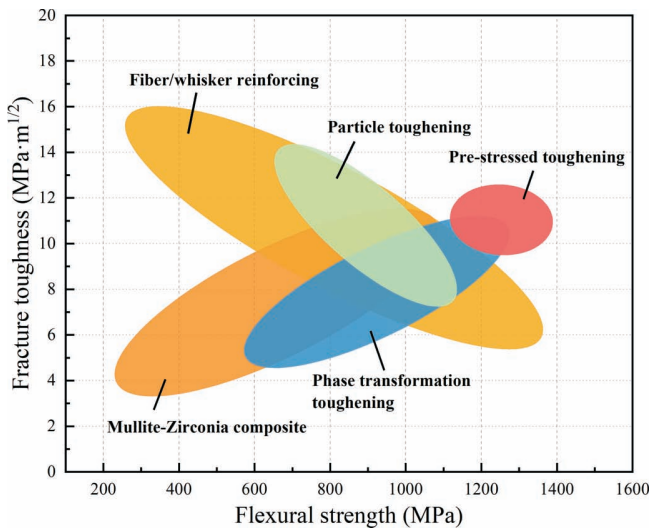


Fig. 6: Comparison of strength and toughness of ZrO₂ ceramics toughened with different methods 15, 23–37.

(3) Analysis of reinforcement mechanism

To further explore the effects of pre-stressed coating on the mechanical properties of composites, the residual stress in the coating was analyzed with the relative method. The thermal expansion coefficient and Young's modulus of coating were firstly calculated with Eq. (5)³⁸ and Eq. (6)³⁹, respectively. Subsequently, the residual stress in the coating was derived according to the uniform stress model.

$$\alpha_c = \alpha_f - \frac{E_s h_s}{E_c h_c} (\alpha_s - \alpha_f) \quad (5)$$

$$E_c = \frac{(1+2R)^3 E_f - E_s}{8R^3 + 12R^2 + 6R} \quad (6)$$

where α_f , α_c , α_s , E_f , E_c , E_s , h_c , h_s , R are the coefficient of thermal expansion of the composites, the coefficient of thermal expansion of the coating, the coefficient of thermal expansion of the substrate, Young's modulus of the composites, Young's modulus of the coating, Young's modulus of the substrate, the thickness of the coating, the thickness of the substrate, and the thickness ratio of the coating to the substrate, respectively.

It can be known from Eq. (5) and Eq. (6), the thermal expansion coefficient and Young's modulus of the coating

were derived from the measured results of matrix and composites. Fig. 7 exhibits the elongation of each group samples as a function of temperature in the temperature range of 25 °C to 1 400 °C, and the results of the calculation of the coating thermal expansion coefficient are summarized in Table 3. The thermal expansion coefficient of the zirconia matrix at 1 100 °C was $11.27 \times 10^{-6} \text{ K}^{-1}$. Notably, there was a reduction in the coefficient of thermal expansion for each group's samples after the production of the mullite pre-stressed coating. However, this reduction did not follow a simply decreasing rule with the increase in the content of mullite. When the content of mullite was higher than 50 wt%, the coefficient of thermal expansion changed to increase, it can be inferred that the strong bond is formed between the coating and matrix when the mullite content is at a low level, leading to the low thermal expansion coefficient. As the mullite content increased, the degree of interface bonding gradually weakened, resulting in the increase of thermal expansion coefficient. In addition, when the temperature exceeded 1 100 °C, the elongation rate of each group of samples began to slow down and the coefficient of thermal expansion began to decrease gradually. This phenomenon is probably due to the fact that the monoclinic phase zirconia in the coating began to change into tetragonal phase at high temperatures. The phase change affects the residual stress left after sintering. Therefore, the coefficient of thermal expansion of each sample at 1 100 °C was chosen as the critical temperature ΔT for the residual stress calculated.

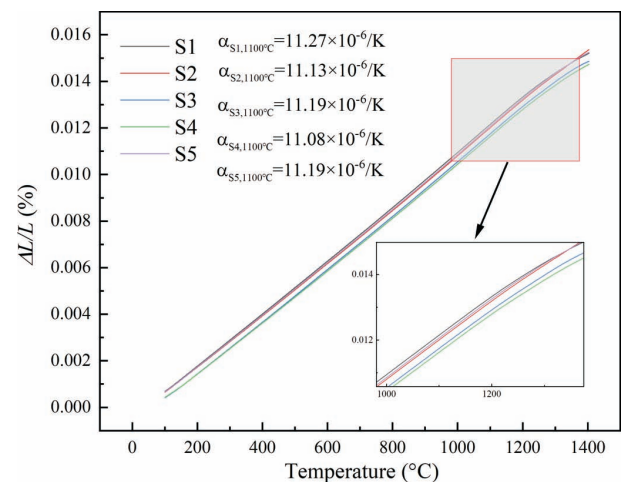
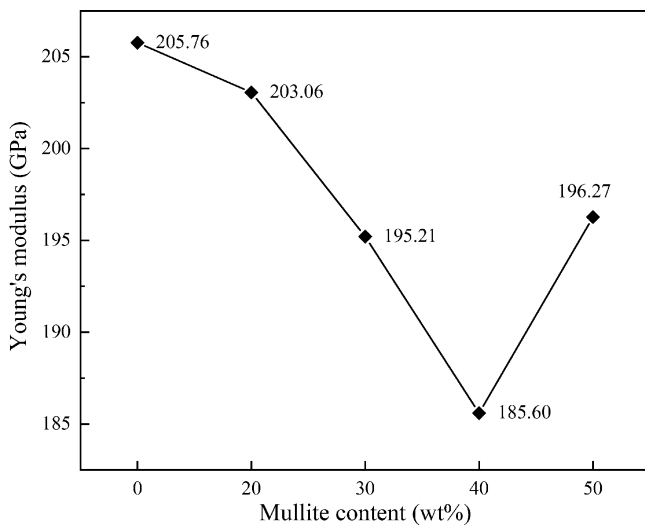


Fig. 7: Linear thermal expansion coefficient curves measured from room temperature to 1 400 °C.

Table 4: Calculation results of residual stress in pre-stressed coating of each group.

Sample	E_c/GPa	E_s/GPa	$\alpha_c/10^{-6}\text{K}^{-1}$	$\alpha_s/10^{-6}\text{K}^{-1}$	H_c/mm	H_s/mm	$\delta T/^\circ\text{C}$	σ_c/MPa	σ_s/MPa
S2(20 wt%)	189.34	205.76	8.09	11.27	0.025	1.95	1 100	-907	26
S3(30 wt%)	130.01	205.76	6.13	11.27	0.025	1.95	1 100	-1 013	25
S4(40 wt%)	83.97	205.76	6.10	11.27	0.025	1.95	1 100	-2 220	64
S5(50 wt%)	137.34	205.76	6.40	11.27	0.025	1.95	1 100	-1 014	23

The Young's modulus of each group of samples is shown in Fig. 8. As the content of mullite increases, the Young's modulus of the composites showed a trend of decrease and then increase. The lowest Young's modulus of 185.6 GPa was obtained corresponding to the content of mullite being 40 wt%. As the content of mullite increased to 50 wt%, Young's modulus started to become larger. This may be due to an increase in the content of mullite with a high Young's modulus in the coating and a decrease in the residual stress in the coating, and the bonding ability between the coating and substrate was weakened as the content of mullite increased. However, Young's modulus calculations for the coatings in Table 4 show that the S4 group has the highest Young's modulus, which was influenced by residual stress in the coating.

**Fig. 8:** Curve of Young's modulus as a function of mullite content.

Based on the calculated results for Young's modulus and the coefficient of thermal expansion, the residual stress in the coating and the matrix for each group of samples were obtained according to the calculations Eq. (3) and Eq. (4) (shown in Table 4). It can be seen from the results that the residual stress in the coating and matrix was positively correlated with the difference in the thermal expansion coefficient ($\Delta\alpha$) between the coating and matrix, and the residual compressive stress in the coating was greatest when the content of mullite was 40 wt%. It is confirmed that the application of the pre-stressed coating can effectively improve the mechanical properties of zirconia ceramics.

IV. Conclusions

In this study, a mullite coating was applied to a zirconia matrix with a co-sintering method. Due to the mismatch of thermal expansion coefficient, compressive stress was formed between the coating and matrix during the cool-

ing process. The results show that residual compressive stress can effectively inhibit crack tip spreading, giving mullite-zirconia/zirconia pre-stressed composites excellent mechanical properties. The maximum residual stress in the coating was achieved when the content of mullite was 40 wt% and the corresponding mechanical properties were most excellent, the flexural strength was (1250.48 ± 43.81) MPa, which was 39.15 % higher than that of zirconia matrix, and the fracture toughness was (12.39 ± 0.87) MPa·m^{1/2}, representing an increase rate of 26%. These high-strength, high-toughness ceramics are expected to be used in advanced manufacturing field.

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References

- Zhang, S.W.: High temperature ceramic materials, *Materials*, **14**, [8], 2031, (2021). doi: <https://doi.org/10.3390/ma14082031>.
- Chang, Y.W., Yao, X.Y., Chen, Y.Y., et al.: Review on ceramic-based composite phase change Materials: preparation, characterization and application, *Compos. Part B-Eng*, **254**, 110584, (2023). doi: <https://doi.org/10.1016/j.compositesb.2023.110584>.
- Shi, G.P.: The Summary of Fiber Reinforced Ceramic Matrix Composites, *Ceramics*, (2009). doi: <https://doi.org/10.19397/j.cnki.ceramics.2009.01.005>.
- Silvestroni, L., Sciti, D., and Melandri, C., et al.: Toughened ZrB₂-based ceramics through SiC whisker or SiC chopped fiber additions, *J. Eur. Ceram. Soc.*, **30**, [11], 2155–2164, (2010). doi: <https://doi.org/10.1016/j.jeurceramsoc.2009.11.012>.
- Wang, X., Guo, A.R., and Liu, J.P., et al.: Effects of in-situ synthesized mullite whiskers on compressive strength of mullite fiber brick, *Ceram. Int.*, **42**, [11], 13161–13167, (2016). doi: <https://doi.org/10.1016/j.ceramint.2016.05.107>.
- Lin, J., Zhang, X.H., Han, W.B., Jin, H.: The hybrid effect of SiC whisker coupled with ZrO₂ fiber on microstructure and mechanical properties of ZrB₂-based ceramics, *Mat. Sci. Eng. A-Struct.*, **551**, 187–191, (2012). doi: <https://doi.org/10.1016/j.msea.2012.05.006>.
- Shen, J.X., Li, X.L., Zou, W.G.: Study on mechanism of Ni₃Al toughened Al₂O₃ ceramic, *Shandong Ceram.*, **3**, 4, (2000). <https://kns.cnki.net/kcms/detail/detail.aspx?FileName=BOWL200003000&DbName=CJFQ2000>.
- Zhao, X.J., Guo, L., Cai, Z.Y., et al.: SiC and ZrN nano-particle reinforced ALON Composites: preparation, mechanical properties and toughening mechanisms, *Ceram. Int.*, **42**, [5], 6072–6079, (2016). doi: <https://doi.org/10.1016/j.ceramint.2015.12.164>.

- 9 Liu, L., Shinozaki K.: Brittle-Ductile transition and toughening of silica glass via ni nanoparticle incorporation at a small volume fraction, *J. Alloy Compd.*, **940**, 168874, (2023). doi: <https://doi.org/10.1016/j.jallcom.2023.168874>.
- 10 Hideaki, T.: Enhancement of transformation toughening of partially stabilized zirconia by some additives, *Ceram. Int.*, **48**, [14], 20675–20689, (2022). doi: <https://doi.org/10.1016/j.ceramint.2022.04.047>.
- 11 Butler, E.P.: Transformation-toughened zirconia ceramics, *Mater. Sci. Tech.-Lond.*, **1**, [6], 417–432, (2013). doi: <https://doi.org/10.1179/mst.1985.1.6.417>.
- 12 Kelly, P.M., Francis Rose, L.R.: The Martensitic Transformation in Ceramics — Its Role in Transformation Toughening, *Prog. Mater. Sci.*, **47**, 463–557, (2002). doi: [https://doi.org/10.1016/S0079-6425\(00\)00005-0](https://doi.org/10.1016/S0079-6425(00)00005-0).
- 13 Hideaki, T.: Design against fracture of functionally graded thermal barrier coatings using transformation toughening, *Mat. Sci. Eng. A-Struct.*, **527**, [13–14], 3217–3226, (2010). doi: <https://doi.org/10.1016/j.msea.2010.01.087>.
- 14 Gong, J.H.: Microstructural Effects in Brittle Fracture of Ceramics, *Adv. Ceram.*, **42**, [5–6], 287–428, (2021). doi: <https://doi.org/10.16253/j.cnki.37-1226/tq.2021.05.001>.
- 15 Bao, Y.W., Kuang, F.H., Sun, Y., et al.: A simple way to make pre-stressed ceramics with high strength, *J. Materiomics*, **5**, [4], 657–662, (2019). doi: <https://doi.org/10.1016/j.jmat.2019.06.001>.
- 16 Bao, Y.W., Sun, Y., Kuang, F.H., et al.: Development and prospects of high strength pre-stressed ceramics, *J. Inorg. Mater.*, **35**, [4], 399–406, (2019). doi: <https://doi.org/10.15541/jim20190360>.
- 17 Bao, Y.W., Wan, D.T., Wang, C.A., et al.: Effects of residual stress on strength and crack resistance in ZrO₂ ceramics with alumina coating, *J. Inorg. Mater.*, **37**, [4], 467–472, (2022). doi: <https://doi.org/10.15541/jim20210412>.
- 18 Hao, H.J., Li, Y.M., Bao, Y.W., et al.: Enhanced flexural strength and thermal shock resistance of alumina ceramics by Mullite/Alumina pre-stressed Coating., *J. Inorg. Mater.*, **37**, [12], 1295–1301, (2022). doi: <https://doi.org/10.15541/jim20220238>.
- 19 Bao, Y.W.: Methods and techniques for the mechanical property evaluation of advanced ceramics; China Building Materials Press: Beijing, China, 130–133, (2017).
- 20 SAC/TC 194. GB/T 6569–2006. Fine Ceramics(Advanced Ceramics, Advanced Technical ceramics)--Test Method for Flexural Strength of Monolithic ceramics at Room Temperature. Beijing: Standards Press of China, 2006.
- 21 SAC/TC 194. GB/T23806–2009. Fine Ceramics (Advanced Ceramics, Advanced Technical Ceramics)-Test Method for Fracture Toughness of Monolithic Ceramics at room temperature by Single Edge Precracked Beam (SEPB) Method. Beijing: Standards Press of China, 2009.
- 22 Bao, Y.W., Su, S.B., Yang, J.J., Huang, Z.R.: Residual stress analysis in unsymmetrical laminated ceramics by non-uniform strain model, *J. Chin. Ceram. Soc.*, **5**, 579–584, (2002). <https://kns.cnki.net/kcms/detail/detail.aspx?FileName=GXYB200205008&DbName=CJFQ2002>.
- 23 Srdi, V., Radonji, L.: Transformation toughening in sol-gel-derived alumina-zirconia composites, *J. Am. Ceram. Soc.*, **80**, [8], 2056–2060, (2005). doi: <https://doi.org/10.1111/j.1151-2916.1997.tb03089.x>.
- 24 Zhigachev, A.O., Rodaev, V.V., Zhigacheva, D.V.: The Effect of Titania Doping on Structure and Mechanical Properties of Calcia-Stabilized Zirconia Ceramic, *J. Mater. Res. Technol.*, **8**, [6], 6086–6093, (2019). doi: <https://doi.org/10.1016/j.jmrt.2019.10.002>.
- 25 Basu, B., Vleugels, J., Biest, O.V.: Toughness tailoring of yttria-doped zirconia ceramics, *Mat. Sci. Eng. A-Struct.*, **380**, [1–2], 215–221, (2004). doi: <https://doi.org/10.1016/j.msea.2004.03.065>.
- 26 Hideaki, T.: Enhancement of transformation toughening of partially stabilized zirconia by some additives, *Ceram. Int.*, **48**, [14], 20675–20689, (2022). doi: <https://doi.org/10.1016/j.ceramint.2022.04.047>.
- 27 Li, S., Wei, C.C., Wang, Pen, et al.: Fabrication of ZrO₂ whisker modified ZrO₂ ceramics by oscillatory pressure sintering, *Ceram. Int.*, **46**, [11], 17684–17690, (2020). doi: <https://doi.org/10.1016/j.ceramint.2020.04.071>.
- 28 Zhang, J., Zhu, T.B., Cheng, Y., et al.: Fabrication and mechanical properties of ZrO₂-Al₂O₃-SiC(W) composites by oscillatory pressure sintering, *Ceram. Int.*, **46**, [16], 25719–25725, (2020). doi: <https://doi.org/10.1016/j.ceramint.2020.07.048>.
- 29 Ibrahim, O.H., Kolthoum I.O., Ahmed A.H., et al.: Synthesis and mechanical properties of Zirconia-Yttria Matrices/Alumina short fibre composites, *Arab J. Sci. Eng.*, **45**, [6], 4959–4965, (2020). doi: <https://doi.org/10.1007/s13369-020-04542-2>.
- 30 Li, X.W., Fan, X.H., Ni, N., et al.: Continuous alumina fiber-reinforced yttria-stabilized zirconia composites with high density and toughness, *J. Eur. Ceram. Soc.*, **40**, [4], 1539–1548, (2020). doi: <https://doi.org/10.1016/j.jeurceramsoc.2019.12.041>.
- 31 Daniel, T., Vick, M.J., Giuliani, F., Vandeperre, L.J.: High-temperature fracture toughness of mullite with monoclinic zirconia, *J. Am. Ceram. Soc.*, **100**, [4], 1570–1577, (2017). doi: <https://doi.org/10.1111/jace.14637>.
- 32 Smirnov, A., Bartolomé, J.F.: Microstructure and mechanical properties of ZrO₂ ceramics toughened by 5–20 vol% ta metallic particles fabricated by pressureless sintering, *Ceram. Int.*, **40**, [1], 1829–1834, (2014). doi: <https://doi.org/10.1016/j.ceramint.2013.07.084>.
- 33 Bartolomé, J.F., Beltrán, J.I., Gutiérrez-González, C.F., et al.: Influence of Ceramic-Metal Interface Adhesion on Crack Growth Resistance of ZrO₂-Nb Ceramic Matrix Composites, *Acta Mater.*, **56**, [14], 3358–3366, (2008). doi: <https://doi.org/10.1016/j.actamat.2008.03.021>.
- 34 Song, J.P., Cao, L., Jiang, L.K., et al.: Effect of HfN, HfC and HfB₂ additives on phase transformation, microstructure and mechanical properties of ZrO₂-based ceramics, *Ceram. Int.*, **44**, [5], 5371–5377, (2018). doi: <https://doi.org/10.1016/j.ceramint.2017.12.164>.
- 35 Cheng, C., Chen, H., Xue, H.F., Guo, L.C.: Mechanical and thermal behaviour of zirconia-mullite composites, *J. Ceram.*, **31**, [4], 601–606, (2010). doi: <https://doi.org/10.13957/j.cnki.tcx.2010.04.020>.
- 36 Liu, P.F., Zhuan, L., Peng, X., et al.: Microstructure and mechanical properties of in-situ grown mullite toughened 3y-tzp zirconia ceramics fabricated by gelcasting, *Ceram. Int.*, **44**, [2], 1394–1403, (2018). doi: <https://doi.org/10.1016/j.ceramint.2017.09.151>.
- 37 Imose, M., Ohta, A., Takano, Y., Yoshinaka, M., et al.: Low-temperature sintering of Mullite/Yttria-doped zirconia composites in the mullite-rich region, *J. Am. Ceram. Soc.*, **81**, [4], 1050–1052, (2005). doi: <https://doi.org/10.1111/j.1151-2916.1998.tb02447.x>.
- 38 Bao, Y.W., Kuang, F.H., Ma, D.L.: Evaluation of coating properties and design of physical properties of coated composite ceramics based on relative method, *Adv. Ceram.*, **43**, [5–6], 325–334, (2022). doi: <https://doi.org/10.16253/j.cnki.37-1226/tq.2022.06.002>.
- 39 Bao, Y.W., Zhou, Y.C., Bu, X.X., Qiu, Y.: Evaluating elastic modulus and strength of hard coatings by relative method, *Mat. Sci. Eng. A-Struct.*, **458**, [1–2], 268–274, (2007). doi: <https://doi.org/10.1016/j.msea.2006.12.131>.