

Strength and Phase Stability of Yttria-Ceria-Doped Tetragonal Zirconia/Alumina Composites Sintered and Hot Isostatically Pressed in Argon–Oxygen Gas Atmosphere

Yttria-ceria-doped tetragonal zirconia ((Y,Ce)-TZP)/alumina (Al₂O₃) composites were fabricated by hot isostatic pressing at 1400° to 1450°C and 196 MPa in an Ar-O₂ atmosphere using the fine powders prepared by hydrolysis of ZrOCl₂ solution. The composites consisting of 25 wt% Al₂O₃ and tetragonal zirconia with compositions 4 mol% YO_{1.5}-4 mol% CeO₂-ZrO₂ and 2.5 mol% YO_{1.5}-5.5 mol% CeO₂-ZrO₂ exhibited mean fracture strength as high as 2000 MPa and were resistant to phase transformation under saturated water vapor pressure at 180°C (1 MPa). Postsintering hot isostatic pressing of (4Y, 4Ce)-TZP/Al₂O₃ and (2.5Y, 5.5Ce)-TZP/Al₂O₃ composites was useful to enhance the phase stability under hydrothermal conditions and strength. [Key words: zirconia, alumina, ceria, yttria, hot isostatic pressing.]

I. Introduction

YTTRIA-CONTAINING tetragonal zirconia polycrystals¹ (Y-TZP) are currently being applied for use as structural ceramics because of their high strength and fracture toughness. However, it has been reported that Y-TZP is greatly reduced in strength by low-temperature aging at 200° to 300°C.²⁻⁴ This result is believed to be due to the formation of microcracks accompanied by tetragonal-to-monoclinic $(t \rightarrow m)$ phase transformation during the aging. This phenomenon starts from the surface, and $t \rightarrow m$ phase transformation is greatly accelerated by water.⁵ A number of studies have been conducted to eliminate the degradation phe-nomenon due to the transformation.^{6,7} It has been reported that Ce-TZP (12 mol%) showed very high fracture toughness and resistance to phase transformation during low-temperature aging.⁸ It has also been reported⁹ that the $t \rightarrow m$ phase transformation in Y-TZP during low-temperature aging was fully controlled by doping with ceria, but the fracture strength of ceria-doped Y-TZP was greatly reduced to less than that of Ce-TZP. Postsinter procedures for eliminating porosity are attractive for improving the fracture strength. The strength of Y-TZP can be enhanced by using the hot isostatic pressing technique. Although Ce-TZP and Ce-TZP/Al₂O₃ composites were fabricated by postsintering hot isostatic pressing, their fracture strengths were lower than that of pressureless sintered Y-TZP.¹⁰ On the other hand, ultrafine monoclinic zirconia particles are known to be formed by prolonged heating of ZrOCl₂ solution at the boiling temperature. This hydrolysis reaction is accelerated by addition of H₂O₂ and NH₄OH.¹¹

In the present study, Y_2O_3 -CeO₂-ZrO₂ powders were prepared by using the sol containing ultrafine monoclinic zircoMasanori Hirano and Hiroshi Inada

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nia particles formed by hydrolysis of $ZrOCl_2$ solution. Using the powders prepared by the hydrolysis technique, (Y, Ce)-TZP/Al₂O₃ composites were fabricated by postsintering hot isostatic pressing in an Ar-O₂ gas atmosphere. The stability under hydrothermal conditions at 180°C and 1 MPa and the fracture strength of the composites were evaluated.

II. Experimental Procedure

In the present experiments, 45 L of zirconium oxychloride $(ZrOCl_2 \cdot 8H_2O)$ solution (0.2 mol/L), to which 500 mL of H_2O_2 (30 wt%) and 750 mL of NH₄OH (28 wt%) had been added, was heated at 98° to 100°C for 48 h to produce a sol containing ultrafine monoclinic zirconia particles. The sol was uniformly mixed with cerium chloride (CeCl₃ · 7H₂O) solution and yttrium chloride (YCl₃·6H₂O) solution and added with stirring to diluted ammonia water. The ZrO₂ particles were sedimented, together with the $Ce(OH)_3$ and $Y(OH)_3$ formed. The sediments were filtered, washed free from chloride, dried, pulverized, calcined at 1050°C in air, and ball milled with zirconia balls for 48 h in ethanol. Thus, fine powders with compositions 4 mol% $YO_{1.5}\text{--}4$ mol% $CeO_2\text{--}ZrO_2$ and 2.5 mol% YO_{1.5}-5.5 mol% CeO₂-ZrO₂ were prepared. The Al₂O₃ powder^{*} used had a particle size of 0.2 μ m and a purity of 99.99%. The (Y, Ce)-TZP and Al₂O₃ powders were mixed by ball milling with zirconia balls, followed by drying in air. The powders were uniaxially pressed at 19.6 MPa to form plates and then isostatically cold-pressed at 196 MPa. The green compacts were sintered at 1300° to 1400°C for 2 h in air to obtain the presintered bodies. The sintered bodies obtained were hot isostatically pressed at 1400° to 1450°C and 196 MPa for 1.5 h in a gas atmosphere containing 96 to $97 \ vol\%$ Ar and 4 to 3 vol% $O_2.$ The schematic time schedule of hot isostatic pressing used in this experiment is shown in Fig. 1.

Specific surface areas of as-synthesized zirconia powders were determined by the BET method. Particle sizes and morphologies of powders were estimated by using SEM and TEM. The bulk densities of both presintered and hot isostatically pressed bodies were measured by the Archimedes technique. Fracture strength was measured in three-point bending on a universal testing machine,[†] using a span of 30 mm and a crosshead speed of 0.5 mm/min. The samples were 3 mm high, 4 mm wide, and 40 mm long. Fracture toughness was determined by the indentation fracture method,¹² employing an indentation load of 98 N. Vickers hardness values were determined by using the microindentation method (load = 9.8 N).

To evaluate the resistance to phase transformation during low-temperature aging, the specimens ground using 140-grit diamond wheels were aged at 250°C in air and under saturated water vapor pressure at 180°C (1 MPa) in an autoclave

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Fig. 1. HIPing treating schedule.

vessel. Phase identification was carried out by powder X-ray diffraction analysis of the surface of the specimen. Scans of 2θ between 27° and 33° were conducted to determine the monoclinic-to-(tetragonal + cubic) zirconia ratio.¹³ The microstructure of the fracture surface of as-sintered samples was analyzed by SEM.

III. Results

A TEM photograph of the ZrO₂ particles formed by heating of $ZrOCl_2$ solution is shown in Fig. 2. The starting ZrO_2 particles formed by heating of ZrOCl₂ solution at the boiling temperature were angular and porous, with platelike secondary particles of about 50 nm \times 50 nm consisting of severalnanometer primary particles. The particles were identified by XRD as monoclinic ZrO₂ of 4.5 nm in crystallite size. A SEM photograph of the calcined powder with composition 4 mol% $YO_{1.5}-4$ mol% CeO₂-ZrO₂ is shown in Fig. 3. There is some degree of agglomeration in the calcined powders. The specific surface area of as-synthesized powders was 165 to 180 m²/g. The surface area of the as-synthesized zirconia powders was very high, so we calcined the powders between 900° to 1150°C and studied their sinterability. In the present study, we used the powders calcined at 1050°C, and their specific surface area was 26 to 27 m²/g. The bulk densities of (Y, Ce)-TZP/Al₂O₃ composites presintered at 1400°C were 97.5% for (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composites and 98.5% for



Fig. 2. TEM photograph of monoclinic ZrO_2 particles formed by boiling $ZrOCl_2$ solution.



Fig. 3. SEM photograph of the powders calcined at 1000°C.

(2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites. Presintered bodies were densified to almost full theoretical density by hot isostatic pressing at 1400° and 1450°C. Figure 4 shows the density of (Y,Ce)-TZP/Al₂O₃ composites before and after hot isostatic pressing. This result indicated that the densities of hot isostatically pressed bodies reached the theoretical value, when the relative densities of presintered bodies were more than about 95% of theoretical.

Fracture strength and elastic modulus of specimens fabricated by the normal sintering are shown in Table I. Elastic modulus increased with increasing amounts of Al₂O₃. Fracture strength was also increased by the addition of Al_2O_3 . As shown in Fig. 5, (Y, Ce)-TZP/Al₂O₃ composites fabricated by hot isostatic pressing exhibited extremely high fracture strength. When the specimens were presintered at 1400°C, then hot isostatically pressed at 1400°C in an Ar-O2 gas atmosphere, their fracture strength approached 2000 MPa. As the fracture strength of pressureless sintered bodies sintered at 1500°C showed 1000 to 1100 MPa, significant strength enhancement was achieved by hot isostatic pressing at 1400°C in an Ar-O₂ gas atmosphere. Vickers hardness and fracture toughness of hot isostatically pressed (Y, Ce)-TZP and (Y, Ce)-TZP/Al₂O₃ composites are shown in Table II. Vickers hardness was increased by the addition of Al₂O₃. Although



Table I.Bulk Density, Bending Strength, and ElasticModulus of (Y, Ce)-TZP and (Y, Ce)-TZP/Al2O3 CompositesFabricated by Normal Sintering

Material	Sintering temp (°C)	Bulk density (g/cm ³)	Bending strength (MPa)	Elastic modulus (GPa)
(4Y, 4Ce)-TZP	1500	6.06	840	195
(4Y, 4Ce)-TZP/25 wt% Al ₂ O ₃	1500	5.38	1050	255
(2.5Y, 5.5Ce)-TZP/25 wt% Al ₂ O ₃	1500	5.40	1090	254

the fracture toughness depended on the grain size and sintering conditions, it was decreased by the addition of Al_2O_3 .

Scanning electron micrographs of the fracture surface of (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites hot isostatically pressed at 1400°C in an Ar-O₂ gas atmosphere are shown in Fig. 6. The fracture was intergranular. Figure 7 shows the microstructure of the polished and thermally etched surface of (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composites hot isostatically pressed at 1450°C. The Al₂O₃ grains about 0.5 to 1 μ m were located at the grain boundaries of zirconia grains as indicated in Fig. 7. Although the grain size increased with increase in the hot isostatic pressing temperature and time, the grain size of zirconia in the specimens was decreased from 0.4 to 0.35 μ m by the addition of 25 wt% Al₂O₃. The grain growth of zirconia grains was suppressed by the dispersion of Al₂O₃.

The thermal stability of (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites hot isostatically pressed at 1400° and 1450°C in an Ar-O gas atmosphere was studied by thermal aging in air. All samples of (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites showed no $t \rightarrow m$ phase transformation during 1500-h aging test at 250°C in air as shown in Table III. To estimate the phase stability under more severe conditions, hydrothermal aging was performed by maintaining the specimens in saturated water vapor at 180°C (1 MPa) in an autoclave vessel. The result of the hydrothermal aging test for 20 h is shown in Fig. 8. The amounts of monoclinic phase in the composites hot isostatically pressed in an Ar-O₂ gas atmosphere were below 10% in contrast with 3Y-TZP (3 mol% Y_2O_3 -ZrO₂). The increase in the amount of monoclinic phase was little, and structural degradation was not observed for the composites hot isostatically pressed in an Ar-O₂ gas atmosphere after 35 h hydrothermal aging. The fracture strengths of the specimens obtained before and after hydrothermal aging for 100 h are shown in Fig. 9. The fracture strength of 2Y-TZP and 3Y-TZP decreased from 1100 to 180 MPa and 1050 to 650 MPa, respectively, because of the formation of microcracks accompanied by $t \rightarrow m$ phase transformation during aging. No degradation in strength was observed for (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites hot isostatically pressed at 1400°C in an Ar-O₂ gas atmosphere. (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites were resistant to low-temperature degradation under hydrothermal conditions at 180°C and 1 MPa for 100 h as compared with 3Y-TZP.

IV. Discussion

From the experimental results, hot isostatically pressed (Y, Ce)-TZP/Al₂O₃ composites exhibited high strength and high resistance to low-temperature degradation, which are considered to have been accomplished by (1) the powder processing, (2) the composition of zirconia ((Y, Ce)-TZP), (3) the dispersion of Al₂O₃, and (4) the HIPing treatment conditions as follows. In contrast with yttria-doped zirconia powders, sinterability of yttria- and ceria-doped zirconia powders decreased with increasing CeO₂ contents.¹⁴ To fabricate (Y, Ce)-TZP/Al₂O₃ composites, we used zirconia powders obtained from the hydrolysis technique. As it was reported that high-density monoclinic zirconia sintered bodies (\ge 95% relative to theoretical) were fabricated by sintering at 1100°C without stabilizer addition,¹⁵ zirconia powders obtained from the hydrolysis technique accomposites.





Fig. 5. Relation between bending strength and sintering temperature of (A) (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composites and (B) (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites fabricated by (a) postsintering hot isostatic pressing in an Ar-O₂ gas atmosphere, and (b) postsintering hot isostatic pressing in Ar gas (Ref. 17).

$(\mathbf{Y}, \mathbf{Ce})$ -1ZP and $(\mathbf{Y}, \mathbf{Ce})$ -1ZP/Al ₂ O ₃ Composites					
Material	Sintering temp (°C)	Vickers hardness (GPa)	$\frac{K_{\rm IC}}{(\rm MPa \cdot m^{1/2})}$		
(4Y, 4Ce)-TZP	1400 HIPing*	12.6	5.2		
(4Y, 4Ce)-TZP/25 wt% Al ₂ O ₃	1500 HIPing* 1400 HIPing [†] 1450 HIPing [†]	11.8 15.0 14.6	10.6 5.9 6.3		
(2.5Y, 5.5Ce)-TZP/25 wt% Al ₂ O ₃	1450 HIPing [†]	14.3	6.1		

Table II. Vickers Hardness and Fracture Toughness of (Y, Ce)-TZP and (Y, Ce)-TZP/Al₂O₃ Composites

*In Ar. [†]In Ar–O₂ atmosphere.





Fig. 6. SEM photographs of the fracture surface of (A) (4Y, 4Ce)-TZP/25 wt% Al_2O_3 and (B) (2.5Y, 5.5Ce)-TZP/25 wt% Al_2O_3 composites hot isostatically pressed at 1400°C in an Ar- O_2 gas atmosphere.



Fig. 7. SEM photograph of the polished and thermally etched surface of (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composite hot isostatically pressed at 1450°C in an Ar-O₂ gas atmosphere.

drolysis technique have high sinterability. As densification (almost full theoretical density) can be achieved by normal sintering at low temperature below 1400° C, Al_2O_3 powders used have also high sinterability.

Recently, it has been reported that the fracture strength of $12Ce-TZP/Al_2O_3$ composites increased from 500-580 to 620-760 MPa following postsintering hot isostatic pressing.¹⁰ But the fracture strength of $12Ce-TZP/Al_2O_3$ composites fabricated by hot isostatic pressing is lower than that of pressureless sintered Y-TZP. In the present study, the strengths of (4Y, 4Ce)-TZP/Al_2O_3 and (2.5Y, 5.5Ce)-TZP/Al_2O_3 composites were above those of Y-TZP and came near those of hot isostatic pressing temperature between 1400° and 1450°C in an Ar-O₂ gas atmosphere, it is desirable that hot isostatic pressing is performed at 1400°C to eliminate the grain growth and to enhance the resistance to phase transformation during low-temperature aging.

The enhancement in strength of hot isostatically pressed (Y, Ce)-TZP/Al₂O₃ composites is considered to be due to the following effects. The microstructures consisting of the small grains with no large pores were achieved by using the sinterable fine powders and hot isostatic pressing. The defects such as pores were eliminated, and the densities of the composites reached the theoretical value by hot isostatic pressing at lower treating temperature than that of the normal sintering. The

Table III. Results of Thermal Aging at 250°C in Air

	Sample	Sintering	Monoclinic ZrO ₂ (%)	
Material	preparation	condition	After 500 h	After 1500 h
(4Y, 4Ce)-TZP/25 wt% Al ₂ O ₃	HIP	1400°C in Ar-O ₂	0	0
(4Y, 4Ce)-TZP/25 wt% Al ₂ O ₃	HIP	1450°C in $Ar-O_2$	0	0
(2.5Y, 5.5Ce)-TZP/25 wt% Al ₂ O ₃	HIP	1400°C in $Ar-O_2$	0	0
(2.5Y, 5.5Ce)-TZP/25 wt% Al ₂ O ₃	HIP	1450°C in $Ar-O_2$	0	0
3Y-TZP	NS*	1500°C in Air	12	20
3Y-TZP	NS	1550°C in Air	28	30
4510				

*NS: normal sintering.

grain growth of zirconia grains was suppressed and the elastic modulus increased by the dispersion of Al_2O_3 into (Y, Ce)-TZP.

When the specimens were hot isostatically pressed at 147 MPa and 1400°C in Ar gas, the fracture strengths of specimens were 1700 to 1800 MPa as shown in Fig. 5.¹⁷ In contrast, the specimens hot isostatically pressed at 147 MPa and 1600°C in Ar gas were greatly reduced in strength. Phase transformation from the tetragonal to the monoclinic structure of (Y,Ce)-TZP was observed after postsintering hot isostatic pressing at 1600°C in Ar gas. When the specimens were fabricated by hot isostatic pressing at 1600°C using a graphite heater in Ar gas, the decrease of fracture strength was considered to be caused by treating under a reducing gaseous atmosphere of (CO + Ar) that led to reduction of CeO₂ dopant to Ce₂O₃.¹⁷

The enhancement in phase stability and resistance to lowtemperature degradation can be explained by the following effects. From experimental results and reported data,¹⁴ tetragonal phase stability depended on the grain size, the shape of the grains, stabilizer contents, and relative density. The free energy change of the tetragonal-to-monoclinic phase transformation ($\Delta G_{t \to m}$) can be described by the following equation, proposed by Lange:¹⁸

$$\Delta G_{t \to m} = (G_c^m - G_c^t) + (G_{sc}^m - G_{sc}^t) + (G_s^m - G_s^t)$$
$$= -\Delta G_c + \Delta G_{sc} + \Delta G_s \qquad (1)$$

where G_c^m and G_c^i , G_{se}^m and G_{se}^i , and G_s^m and G_s^i are the chemical free energies, the strain free energies, and the surface free energies in the monoclinic and the tetragonal state. The change in the surface energy is inversely proportional to the grain size as expressed by

$$\Delta G_{s} = (A_{m}\gamma_{m} - A_{t}\gamma_{t})/V$$

= $6(\gamma_{m} - g_{s}\gamma_{t})/d$ (2)



Fig. 8. Tetragonal-to-monoclinic phase transformation resulting from hydrothermal aging at 180°C and 1 MPa for 20 h for (A) 3Y-TZP, (B) (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composites and (C) (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites: (a) normal sintering at 1500°C for 2 h in air; (b) hot isostatic pressing at 140°C and 147 MPa for 0.5 h in Ar gas (Ref. 17); (c) hot isostatic pressing at 1450°C and 196 MPa for 1.5 h in a 96 vol% Ar-4 vol% O₂ gas atmosphere; (d) hot isostatic pressing at 1400°C and 196 MPa for 1.5 h in a 97 vol% Ar-3 vol% O₂ gas atmosphere.

where A_m and A_t are the interfacial surface areas, γ_m and γ_t are the specific interfacial surface energies in the monoclinic and the tetragonal states, $V(V = \pi d^3/6)$ is the transformation volume, d is the diameter of the transformed grain, and $g_s = A_t/A_m$. Therefore, the resistance to the phase transformation increases with decreasing grain size. By both hot isostatic pressing and using fine sinterable powders, sintering was performed at lower temperature. Then grain growth of zirconia grains was suppressed and the densification with almost theoretical density was achieved. The grain growth of zirconia grains was suppressed also by dispersion of Al₂O₃, and the stability of the tetragonal phase increased all the more. The strain energy can be expressed as

$$\Delta G_{\rm se} = E_c (\Delta V/V)^2/6 \tag{3}$$

where E_c and $\Delta V/V$ are the Young's modulus and an isotropic volume expansion by transformation. That is, the greater the elastic modulus of the constraining matrix, the greater the strain energy and, thus, the lower the potential transformation temperature. Release of the strain energy will relieve the internal stresses which stabilize the tetragonal structure and thus decrease the barrier for phase transformation to monoclinic structure. Addition of Al₂O₃ into (Y, Ce)-TZP was useful to increase the tetragonal phase stability, which was explained by increasing elastic modulus and strain energy.

The transformation temperature can also be decreased by decreasing the change in chemical free energy, $|\Delta G_c|$. This can be accomplished by alloying with additives. Urabe *et al.*¹⁹ measured $m \rightarrow t$ temperature (" A_s " temperature) for the monoclinic phase in the system ZrO₂-CeO₂-Y₂O₃. They reported " A_s " temperature for (4Y, 0Ce)-TZP, (6Y, 0Ce)-TZP, (2Y, 5Ce)-TZP, (3Y, 5Ce)-TZP, and (4Y, 4Ce)-TZP were 556°, 539°, 485°, 338°, and 311°C, respectively. From these data, it is clear that the addition of CeO₂ to Y-TZP enhances the stability of the



Fig. 9. Bending strength of 2Y-TZP, 3Y-TZP, (a) (4Y, 4Ce)-TZP/25 wt% Al₂O₃ composites, and (b) (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites as-prepared (sintered at 1500°C or hot isostatically pressed at 1400°C in Ar-O₂ gas atmosphere) and aged under hydrothermal conditions at 180°C and 1 MPa for 100 h.

tetragonal phase. We also investigated the resistance to $t \rightarrow m$ phase transformation for (2.5Y, 4Ce)-TZP, (2.5Y, 5.5Ce)-TZP, and (4Y, 4Ce)-TZP.¹⁴ These (Y, Ce)-TZP were more resistant to $t \rightarrow m$ phase transformation than 3Y-TZP, which is thought to be due to the difference in the change in chemical free energy.

Based on the data presented in this study and previously reported by us,¹⁴ Urabe *et al.*,¹⁹ Tsukuma,⁸ Chen *et al.*,²⁰ and Duh *et al.*,²¹ the characteristic regions and composition areas of zirconia phase for the sintered materials on the ternary system Y₂O₃-CeO₂-ZrO₂ are illustrated in Fig. 10. The materials in the composition area of the region T_1 can exhibit excellent mechanical properties with high values for strength. The mean values of the strength of normally sintered TZP and hot isostatically pressed TZP/Al₂O₃ composites in this composition area can reach more than 800 and 1500 MPa, respectively. TZP in the composition area of the region T_3 is known to be high-toughness material ($\geq 15 \text{ MPa} \cdot \text{m}^{1/2}$). The region T_2 is the more stable area of tetragonal phase. (Y, Ce)-TZP in this region was more stable and was more resistant to $t \rightarrow m$ phase transformation in low-temperature aging than **3Y-TZP.** From the results of this study, the $(T_1 + T_2)$ region is considered the most interesting and practical region for structural ceramics, since the hot isostatically pressed composites consisting of (Y, Ce)-TZP and Al₂O₃ show exceptional strength and high resistance to low-temperature degradation, especially under water vapor pressure at 180°C (1 MPa).

V. Conclusions

(1) Ceramic composites consisting of 25 wt% Al_2O_3 and tetragonal zirconia with compositions 4 mol% $YO_{1.5}$ -4 mol% CeO_2 -ZrO₂ and 2.5 mol% $YO_{1.5}$ -5.5 mol% CeO_2 -ZrO₂ have been fabricated by hot isostatic pressing at 1400° to 1450°C and 196 MPa in an Ar-O₂ gas atmosphere, and the densities of the composites reached the theoretical value.

(2) The mean bending strengths for the composites hot isostatically pressed at 1400°C were 2000 and 2050 MPa for (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃, respectively.



Fig. 10. Schematic illustration of zirconia phase and characteristic regions for the sintered materials on the ternary system Y_2O_3 – CeO_2 -ZrO_2 using data from this study and Ref. 14 (\bullet), Ref. 8 (\blacktriangle), Ref. 19 (\bigcirc), Ref. 20 (\triangle), and Ref. 21 (\square): (T_1) high-strength region, (T_2) more stable area of tetragonal phase, (T_3) high-toughness region.

(3) (Y, Ce)-TZP/Al₂O₃ composites with the present composition hot isostatically pressed at 1400°C showed superior stability and no structural degradation under hydrothermal conditions at 180°C and 1 MPa for 35 h as compared with 3Y-TZP.

(4) Dispersion of Al_2O_3 into (Y, Ce)-TZP was useful to suppress the grain growth of zirconia grains and to increase the fracture strength, Vickers hardness, elastic modulus, and stability of tetragonal phase.

(5) No degradation in strength was observed for (4Y, 4Ce)-TZP/25 wt% Al₂O₃ and (2.5Y, 5.5Ce)-TZP/25 wt% Al₂O₃ composites hot isostatically pressed at 1400°C in an Ar-O₂ gas atmosphere after hydrothermal aging at 180°C and 1 MPa for 100 h.

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