Pulse Electric Current Sintering of Transition Alumina/Zirconia Composite Powders Prepared by a Novel Sol–Gel Route

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Zirconia-dispersed alumina ceramics were fabricated by pulse electric current sintering (PECS) using transition alumina/zirconia (ZrO$_2$ = 5.7–21.0 mass%) composite powders. The composite powders were prepared through a novel sol–gel route using polyhydroxoaluminum (PHA) and polyhydroxozirconium (PHZ) solutions as starting materials. PHA–PHZ composite gels were calcined at 800–1100°C and then ground by a planetary ball mill. Upon heating, the PHA–PHZ composite gels transformed into mixed phases of $\gamma$- and $\beta$-alumina and tetragonal ZrO$_2$, depending on the temperature and ZrO$_2$ content. In the case of low calcination temperature and/or low ZrO$_2$ content, $\beta$-ZrO$_2$ was highly dispersed in transition alumina matrix as nanocrystallites. PECS was effective in transforming the composite powders into fully dense sintered bodies at 1250–1500°C under a uniaxial pressure of 40 MPa. Sinterability depended strongly on calcination temperature: the temperature required for full density decreased as calcination temperature increased. The incorporation of ZrO$_2$ into the alumina matrix through the sol–gel route was very effective in inhibiting grain growth of alumina, leading to finer microstructures. Using composite powders calcined at 1000°C, bending strengths as high as 1.2 GPa were obtained through PECS at 1350°C by the addition of a small amount of ZrO$_2$ (5.7 mass%). With increasing ZrO$_2$ content, the bending strength gradually increased up to 1.4 GPa.

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1. Introduction

High wear resistance and good mechanical properties of ceramic materials have been required in order to use structural applications. Alumina (Al$_2$O$_3$) ceramics with good mechanical properties have been used as structural materials because of their superior chemical and thermal stability. However, the bending strength of commercially available alumina ceramics is ~300 MPa, which restricts the applications of alumina ceramics. To obtain high-strength dense alumina ceramics composed of nanosized grains, studies were conducted on densification of alumina, focusing on the use of transition alumina nanopowders as starting material. Thus, we focused on the fabrication of alumina ceramics using polyhydroxoaluminum (PHA) gel-derived transition alumina and attained a relatively high bending strength of 860 MPa by pulse electric current sintering (PECS) under optimized conditions.

PHA solutions used for fabrication of alumina ceramics were prepared by dissolving Al metal in HCl and have such properties as a high OH/Al ratio and a high content of the highly polymerized Keggin Al$_{13}$ ion ($\left[\text{Al}_{13}\text{O}_{24}\left(\text{OH}\right)_{24}\right]$) species. The PHA gel obtained by drying PHA solutions can be transformed into transition aluminas by heat-treatment. Transition aluminas with controlled polymorphs and pore properties have also been obtained by using PHA composite gels containing organic additives such as polyethylene glycol and quaternary ammonium ions. Studies on the fabrication of alumina ceramics using PHA solutions revealed that the calcination temperature, polymorph of the starting powders, purity of the milling media used for pulverization and sintering temperature all significantly affected the densification behavior, microstructure and mechanical properties of the resulting alumina ceramics.

As is well known, the mechanical properties of alumina ceramics are enhanced by the presence of ZrO$_2$ particles dispersed in the alumina matrix as a second phase. Thus, the present study extends the potential applications of the PHA sol–gel process to the fabrication of zirconia-dispersed alumina ceramics with high mechanical strength by PECS. Transition alumina/zirconia composite powders were prepared via a novel sol–gel route using PHA and polyhydroxozirconium (PHZ) solutions as starting materials. The aims of the present study are (1) to investigate the effect of ZrO$_2$ addition on properties of composite powders obtained from PHA–PHZ composite gels, (2) to clarify the effect of calcination temperature, ZrO$_2$ content and sintering temperature on the densification behavior of composite powders, the microstructure and mechanical properties of sintered composites and (3) to enhance the mechanical properties of the sintered composites.

2. Experimental procedure

2.1 Preparation and characterization of composite powders

A PHA solution having an Al$_2$O$_3$ concentration of 23.4 mass% and OH/Al ratio of 2.50 was prepared by dissolving Al metal in a HCl solution. A commercially available PHZ solution (Zirconol ZC–2, ZrO$_2$ concentration: 35.2 mass%, Daichikigensho) was used as a ZrO$_2$ source. The PHZ solution was added to the PHA solution in different proportions, eventually yielding Al$_2$O$_3$/ZrO$_2$ composites containing 0, 5.7, 11.0
and 21.0 mass% ZrO₂. The solutions were mixed thoroughly by stirring at room temperature. The mixed PHA–PHZ solutions were held at 60°C for >2 d for gelation. The resultant PHA–PHZ composite gels were ground into <150 μm powders using an alumina mortar and pestle, and then calcined at 800–1100°C for 6 h. The calcined powders were pulverized using a planetary ball mill (LA–PO₄/2, Ito Works), which consisted of a high-purity (99.99%) alumina pot and balls, for 24 h in ethanol. After pulverization, the suspensions were dried and sieved to ~140 mesh (<106 μm) to obtain the starting composite powders for PECS. The Al₂O₃/ZrO₂ composite powders were abbreviated as AZP–0, −5.7, −11 and −21 for a ZrO₂ content of 0, 5.7, 11.0 and 21.0 mass%, respectively.

Particle size distribution of AZPs was measured using a laser diffraction/scattering particle-size analyzer (LA–920, Horiba Works). The phases of AZPs before and after pulverization were investigated using X-ray diffraction (XRD, XR6000, Shimadzu Corp.) with Cu Kα radiation. The BET specific surface area and pore volume of AZPs were calculated from N₂ adsorption-desorption isotherms at liquid nitrogen temperature using a specific surface area/pore distribution analyzer (ASAP 2000, Micromeritics). The textures of AZPs were observed by transmission electron microscopy (TEM, JEM–2010, JEOL). The α-transformation temperature of the AZPs was determined by differential thermal analysis (DTA).

### 2.2 PECS and characterization of the sintered bodies

AZPs (4 g) were filled into a graphite mold with an inner diameter of 20 mm and sintered under vacuum using a PECS apparatus (SPS–2050, Sumitomo Coal Mining Co., Ltd.). PECS was performed at 1250–1550°C under a uniaxial pressure of 40 MPa. A heating rate of 200°C/min was used. The holding time at the final sintering temperature was 3 min. For bending strength measurements, 18 g of AZPs were sintered using a graphite mold with an inner diameter of 30 mm under similar conditions. Bulk density of the sintered bodies was measured by the Archimedes method. Microstructure of the sintered bodies was observed using scanning electron microscopy (SEM). The specimens were polished and thermally etched prior to SEM observation. Three-point bending tests with a span of 18 mm were carried out by a strength tester in accordance with JIS R 1601, using 3 × 4 × 23 mm specimens prepared by cutting and polishing the sintered bodies. Fracture toughness was evaluated using a three-point bending test by the SEPB (Single-edge precracked beam) technique.

### 3. Results and discussion

#### 3.1 Properties of composite powders

**Figure 1** shows the XRD patterns of AZP–11 calcined at different temperatures. AZP–11 calcined at 800°C consisted of a mixed phase of γ- and χ-alumina. In addition to these transition aluminas, tetragonal ZrO₂ (t-ZrO₂) was observed in AZP–11 calcined at 900°C, and the diffraction peak intensities of t-ZrO₂ increased with increasing calcination temperature. The t-ZrO₂ phase observed presumably corresponds to solid solutions of the type Zr₃₋ₓAl₂O₃₋ₓ by Balmer et al., which the Al content of the t-ZrO₂ phase is unknown. This was supported by the fact that the PHZ mixed with ~50 mass% PHA yielded a single phase, namely t-ZrO₂, upon heating above 800°C. A similar phase change behavior was observed for AZP–5.7 and AZP–21, but the formation temperature of t-ZrO₂ depended on the ZrO₂ content: it was higher for AZP–5.7 (1000°C) than for AZP–21 (800°C). The reflection of the transition aluminas at around 67° (Cu Kα) shifted to slightly lower diffraction angles with increasing ZrO₂ content. This suggests that solid solutions were formed having a low concentration of Zr cations in the crystal lattice of γ- and χ-alumina. At above 800°C, t-ZrO₂ crystallized from the remaining amorphous phase, depending on the ZrO₂ content of the composite powders.

**Figure 2** shows the XRD patterns of AZP–11 after planetary ball milling for 24 h. Calcination temperature: (a) 1100°C, (b) 1000°C, (c) 900°C, (d) 800°C. ▪ γ-Al₂O₃, ▲ χ-Al₂O₃, ● α-Al₂O₃, □ t-ZrO₂, ○ m-ZrO₂.
moted as the ZrO$_2$ content and the calcination temperature increased.

Figure 3 shows TEM photographs of the calcined AZP–5.7 and AZP–11 after planetary ball milling. The TEM image of the powder calcined at 1100°C (Figs. 3(b) and (c)) consisted of light and dark sections; the former were probably transition aluminas, and the latter ZrO$_2$. The segregation of ZrO$_2$ was also observable with smaller particle sizes at lower temperature. Indeed, XRD patterns of the AZP–11 calcined at 900°C gave very weak ZrO$_2$ diffraction peaks. This would indicate that transition aluminas and ZrO$_2$ particles were intimately mixed at the nanometer scale when the AZPs were calcined at lower temperatures. Transition alumina and ZrO$_2$ crystals grew to $\sim$20 nm at higher calcination temperatures.

The abrasion powder, which consisted of fine $\alpha$-alumina particles, was incorporated into the composite powders during planetary ball milling. Thus, the temperature of transformation of AZP into $\alpha$-alumina was lowered in the case of AZP–11, $\sim$100°C lower after milling because of the seeding effect induced by the fine $\alpha$-alumina particles dispersed in the composite powders; the exothermic peak, which is ascribable to the transformation of transition aluminas into $\alpha$-alumina, in DTA curves appeared around 1100°C (refer to Table 1). The decrease in the $\alpha$-transformation temperature promotes densification and the formation of a homogeneous fine-grained microstructure at lower sintering temperature.$^{3,11,12}$

The particle size of the abrasion powder collected by planetary ball milling in the absence of the sample powder was estimated to be $\sim$20 nm by TEM. The BET surface area and total pore volume were 46 m$^2$/g and 0.22 cm$^3$/g, respectively. The abrasion powder content was determined by XRD to be similar to that in our previous study$^{11}$ ($\sim$5 mass%) because the same pulverization conditions were used.

Table 1 summarizes the powder characteristics of the AZPs after planetary ball milling. The mean particle size of the AZPs in the milled suspension ranged from 0.4 to 0.7 μm. Regardless of the calcination temperature, the particle size distribution was similar to those reported in previous studies.$^{3,11,12}$ The mean particle size measured here corresponds to the size of the agglomerates in the suspension, which consists of transition alumina primary particles and ZrO$_2$ particles, as shown in the TEM photographs (Fig. 3). This indicates that the strongly aggregated particles of as-calcined powders could be ground into fine particles by planetary ball milling. The particles, however, reagglomerated during evaporation of the dispersion medium from the milled suspension. Thus, all milled AZPs were crushed and sieved prior to PECS. After crushing, the mean particle size of all samples was 13–16 μm. This represents the mean agglomerate size of AZPs used for PECS.

The BET surface area and total pore volume of AZP–11 calcined at 900°C was 33.7 m$^2$/g and 0.15 cm$^3$/g, respectively. These values, especially the BET surface area, gradually decreased with increasing calcination temperature and ZrO$_2$ content. The decrease in BET surface area is due to the grain growth of transition aluminas and ZrO$_2$ particles. The pore diameter of AZPs ranged between 3 and 100 nm (highest

<table>
<thead>
<tr>
<th>Sample</th>
<th>ZrO$_2$ content / mass%</th>
<th>Calcination temperature / °C</th>
<th>Mean particle size of agglomerate / μm</th>
<th>BET surface area / m$^2$/g$^4$</th>
<th>Total pore volume / cm$^3$/g$^4$</th>
<th>Transformation temperature / °C</th>
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<td>900</td>
<td>0.55</td>
<td>55.2</td>
<td>0.23</td>
<td>961</td>
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<td>AZP–11</td>
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<td>35.4</td>
<td>0.20</td>
<td>1116</td>
</tr>
<tr>
<td>AZP–21</td>
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<td>1100</td>
<td>0.61</td>
<td>30.4</td>
<td>0.12</td>
<td>1114</td>
</tr>
</tbody>
</table>

$^4$Measurement value for composite powders in milled suspension before drying.

Fig. 3. TEM photographs of calcined AZP–5.7 and AZP–11 after planetary ball milling. ZrO$_2$ content: (a) and (b) 5.7 mass%, (c) 11.0 mass%. Calcination temperature: (a) 900°C, (b) and (c) 1100°C.
proportion of pores around 50 nm), showing a broad distribution as a result of planetary ball milling. These results indicate that the AZPs are tertiary agglomerates formed from the secondary aggregates of the primary transition alumina particles and ZrO₂ particles.

The temperature of transformation into α-alumina, as determined by the DTA exothermic peak, increased with calcination temperature and ZrO₂ content. This is presumably caused by the t-ZrO₂ formed in the early stage below 1000°C. The α-transformation was hindered when the t-ZrO₂ phase separation accelerated, i.e., the calcination temperature and/or ZrO₂ content increased. Moreover, t-ZrO₂ segregation at high temperature is presumably accompanied with the expulsion of α-alumina; hence, the shift of α-transformation to higher temperatures.

The amounts of impurities in AZP–0 were SiO₂=0.049 mass%, Na₂O=0.078 mass%, CaO=0.014 mass% and Fe₂O₃=0.017 mass%. The amounts of impurities in AZP–11 were SiO₂=0.045 mass%, Na₂O=0.069 mass%, CaO=0.013 mass% and Fe₂O₃=0.014 mass%. The difference in purity between the two AZPs results from the difference in purity between the PHA and PHZ solutions used as starting materials: the PHZ solution was somewhat purer. The use of milling media made of high-purity alumina can minimize the deterioration in the purity of AZPs.

### 3.2 Densification of composite powders by PECS

Figure 4 shows the relationship between sintering temperature and bulk density of sintered bodies obtained by PECS using AZP–11 calcined at different temperatures. All samples have completely transformed into α-alumina and t- and m-ZrO₂. Sinterability of AZP–11 strongly depended on calcination temperature. AZP–11 calcined at higher temperatures could be densified at lower sintering temperatures: AZP–11 calcined at 1100°C attained full density (>99.0% of theoretical density) at ~1300°C, while that calcined at 800°C attained full density at ~1500°C. At a sintering temperature of 1500°C or above, the bulk density of the sintered AZP–11 converged on 4.12 g/cm³, regardless of the calcination temperature. Sinterability of AZP–5.7 and AZP–21 showed a calcination temperature dependence similar to that of AZP–11. The dependence of calcination temperature can be explained in terms of the degree of t-ZrO₂ phase separation and the difference in primary particle sizes of transition aluminas and t-ZrO₂ in the composite powders. The difficulty in densification of AZPs calcined at lower temperatures can be ascribed to the highly dispersed ZrO₂ particles, which hinder sintering and grain growth of α-alumina at the initial stage of sintering, and hence, densification. Calcination at higher temperatures promotes phase separation of t-ZrO₂ as well as grain growth of transition aluminas and t-ZrO₂. The grain growth of the primary particles of transition aluminas and t-ZrO₂ also leads to less aggregated particles, which is conducive to low-temperature densification.

Figure 5 shows the relationship between sintering temperature and bulk density for sintered AZPs–5.7, AZP–11 and AZP–21, all calcined at the same temperature, namely 1000°C. At any given ZrO₂ content of the composite powders, bulk density of all sintered specimens increased with sintering temperature and attained full density at ≥1350°C. Bulk density increased with ZrO₂ content because ZrO₂ has a higher theoretical density than Al₂O₃. Sinterability of AZPs depended strongly on calcination temperature, and not as strongly on ZrO₂ content.

When PECS of AZPs was performed without planetary ball milling, the sintering temperature required to attain full density was ~150°C higher than the values shown in Figs. 4 and 5. This remarkable lowering of the densification temperature by planetary ball milling is due to the seeding effect of the abrasion powder generated during milling. The use of high-purity (99.9%) milling media also contributed to the low-temperature densification of the milled AZPs because the inclusion of impurities such as SiO₂ was prevented.  

Figure 6 shows SEM photographs of the polished and thermally etched surfaces of sintered bodies obtained by PECS at 1350°C using AZP–0, -5.7, -11 and -21 calcined at 1000°C. Sintered AZP–0 was pore-free and showed a microstructure consisting of somewhat elongated grains with a broad size distribution from 0.4 to 2.0 μm. Sintered AZP–5.7 had more equiaxed α-alumina grains ranging from 0.3 to 1.3 μm. Most of ZrO₂ grains in the sintered specimen were located along the
boundaries of α-alumina grains (intergranular). A relatively small number of nanosized ZrO$_2$ grains (≈0.06 μm) were observed inside the alumina grains (intrgranular). Sintered AZP–11 was also composed of equiaxed α-alumina grains 0.5–1.3 μm in size and exhibited an increased amount of inter- and intragranular ZrO$_2$ grains (∼0.2 μm) as compared with sintered AZP–5.7. Sintered AZP–21 had a uniform microstructure consisting of smaller α-alumina grains (0.3–0.7 μm) and larger ZrO$_2$ grains (∼0.3 μm), as compared with the other sintered AZP specimens. Indeed, sintered AZP–21 showed an exceptionally fine-grained microstructure with homogeneously dispersed ZrO$_2$ grains. The ZrO$_2$ grains in sintered AZP–21 were mainly intergranular, while the increase in the number of intragranular ZrO$_2$ grains was not significant.

AZPs calcined at 1100°C were fully densified at the lowest temperature, namely ∼1300°C (data not shown). Figure 7 shows SEM photographs of polished and thermally etched surfaces of sintered bodies obtained by PECS at 1300°C using AZP–5.7, –11 and –21 calcined at 1100°C. The intergranular ZrO$_2$ grains in the sintered AZP–21 were mainly intergranular, while the increase in the number of intragranular ZrO$_2$ grains was not significant.

AZPs calcined at 1100°C were fully densified at the lowest temperature, namely ∼1300°C (data not shown). Figure 7 shows SEM photographs of polished and thermally etched surfaces of sintered bodies obtained by PECS at 1300°C using AZP–5.7, –11 and –21 calcined at 1100°C. The images are from sections exhibiting homogeneous microstructure; these samples often had sections with nonuniform microstructure containing anomalously large grains and lumps (≈30 μm), as revealed by SEM observation on fracture surfaces. This is caused by the heterogeneity of the composite powders, i.e., the coexistence of excessively grown transition alumina and t-ZrO$_2$ particles resulting from calcination at too high temperature. The uniform region had a finer microstructure than those obtained at 1350°C using AZPs calcined at 1000°C (see Fig. 6) because the sintering temperature was 50°C lower in the former case, which restrained grain growth. The grain size of alumina decreased with increasing ZrO$_2$ content. Most of ZrO$_2$ grains were dispersed in the intergranular region; there were relatively few intragranular ZrO$_2$ grains (∼0.06 μm). The intergranular ZrO$_2$ grains in the sintered bodies obtained at 1300°C using AZPs calcined at 1100°C were rather larger than those obtained at 1350°C using AZPs calcined at 1000°C. This can be explained in terms of the degree of phase separation and grain growth of the AZPs calcined at higher temperature. Thus, optimization of both the calcination temperature and sintering temperature is important for the development of a fine and uniform microstructure.

### 3.3 Bending strength of sintered bodies

Figure 8 shows the relationship between ZrO$_2$ content and bending strength for sintered bodies obtained by PECS at 1350°C using AZPs calcined at 1000°C. The bending strength increased drastically, up to 1.2 GPa in the case of AZP–5.7. With further increase in ZrO$_2$ content, the bending strength gradually increased, reaching 1.4 GPa at 21 mass% ZrO$_2$. This is attributable to the difference in microstructure, in particular, the dispersion of ZrO$_2$ and the size of alumina grains. In addition, the standard deviation clearly increased with ZrO$_2$ content.
content. This can be explained by the degree of ZrO₂ dispersion in the starting AZPs. The bending strength of samples obtained at 1300°C using AZPs calcined at 1100°C was 200–300 MPa lower than that of samples with a corresponding ZrO₂ content obtained at 1350°C using AZPs calcined at 1000°C. As mentioned above, this was due to the heterogeneous microstructure characterized by large lumps (flaws), which act as failure sites. Thus, optimizing the calcination temperature and sintering temperature is also important for achieving high bending strength.

The fracture toughness of the samples sintered at 1350°C increased from 3.6 MPa m¹/₂ (AZP-0) to 4.8 MPa m¹/₂ (AZP-21) with an increase in ZrO₂ content. As shown in Fig. 7, the sintered specimens contained intragranular ZrO₂ nanograins. The sintered specimens exhibited an intergranular fracture behavior, that is, the main fracture path was grain boundaries. Thus, presumably, the intragranular ZrO₂ nanograins hardly contributed to the increase in fracture toughness. The increase can be explained by the 20–30% increase in the m-ZrO₂ transformation ratio accompanying fracture, as estimated from XRD patterns of the sample surfaces before the bending test and the fractured surfaces after the bending test. In general, the bending strength is determined by the interaction between the maximum defect size and the fracture toughness. On the basis of the maximum defect size argument and using the measured mechanical properties, the high bending strength achieved in the present study was ascribed to the reduced defect size and increased toughness.

The following bending strengths have been reported for zirconia-toughened alumina containing roughly the same amount of ZrO₂ as that found in the present specimens: 400–700 MPa for specimens sintered in air, 600–1100 MPa for hot isostatically pressed specimens and 700–800 MPa for sinter-forged specimens. In the case of the PECS process, Jayaseelan et al. reported a bending strength of 827 ± 129 MPa for specimens containing 3 vol% ZrO₂, and Takano et al. reported a linear increase in bending strength from ~600 to 1620 MPa with increasing ZrO₂ content up to 50 mol%. The high bending strength of the specimens fabricated by PECS in the present study, especially of those with a low ZrO₂ content (5.7 mass%), implies that the new sol–gel route using PHA and PHZ solutions is effective in improving the mechanical strength. One specimen fabricated by PECS at 1350°C using AZP-21 calcined at 1000°C gave a bending strength of 1700 MPa. Thus, an increase in ZrO₂ content is expected to lead to a steep increase in bending strength if the formation of lumps is entirely avoided.

Alumina-based ceramics with high strength were obtained by PECS using transition alumina/zirconia composite powders consisting of mixed phases of transition alumina and t-ZrO₂. This shows that the new sol–gel route starting with PHA and PHZ solutions is a promising route for obtaining desirable composite powders, and that there is a possibility of tailoring the microstructure and hence mechanical properties by further optimizing PECS conditions and preparation conditions of the composite powders.

4. Conclusions

To fabricate zirconia-dispersed aluminas with high mechanical strength, transition alumina/zirconia (5.7–21.0 mass% zirconia) composite powders (AZPs) were prepared by a novel sol–gel route using polyhydroxaloaluminum (PHA) and polyhydroxozirconum (PHZ) solutions as starting materials. These composite powders were densified by pulse electric current sintering (PECS) at a sintering temperature of 1250–1550°C under a uniaxial pressure of 40 MPa. The effects of ZrO₂ content, calcination temperature and sintering temperature on the densification behavior, microstructure and mechanical properties of the resultant sintered bodies were investigated. The results can be summarized as follows:

1. Upon heating, the PHA–PHZ composite gels transformed into mixed phases of γ-, χ-alumina and t-ZrO₂. The phase separation of t-ZrO₂ proceeded as the ZrO₂ content and calcination temperature increased. A highly dispersion of t-ZrO₂ nanoparticles was obtained in the transition alumina matrix by decreasing the ZrO₂ content and calcination temperature. The starting AZPs contained small amounts of α-alumina originating from the milling media as well as m-ZrO₂, which formed from t-ZrO₂ during planetary ball milling.

2. Dense sintered composites were obtained by PECS at 1300–1500°C under a uniaxial pressure of 40 MPa. Sinterability depended strongly on the calcination temperature of the starting AZPs. The densification temperature decreased as the calcination temperature increased. However, calcination at too high temperature (1100°C) often caused nonuniform densification due to the some exaggerated grain growth of the starting composite powders. The sintered specimens consisted of α-alumina and ZrO₂ grains; the morphology of α-alumina grains changed from elongated to equiaxed with increasing ZrO₂ content, and ZrO₂ was found at inter- and intragranular positions. The incorporation of ZrO₂ into the alumina matrix through the present sol–gel route proved effective in inhibiting grain growth of alumina.

3. Using composite powders calcined at 1000°C, the bending strength of the sintered specimens obtained by PECS at 1350°C reached as high as 1.2 GPa by the addition of a small amount of ZrO₂ (5.7 mass%). The bending strength gradually increased with ZrO₂ content, up to 1.4 GPa at 21.0 mass% ZrO₂. Moreover, the fracture toughness increased from 3.6 to 4.8 MPa m¹/₂.

References


