Influences of TiO$_2$ or Y$_2$O$_3$ doping on the homogeneity of polycrystalline Al$_2$O$_3$ produced by pulsed electric current sintering

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**ABSTRACT**

Influences of TiO$_2$ or Y$_2$O$_3$ dopants on pressure-assisted sintering of polycrystalline Al$_2$O$_3$ were investigated to control the microstructure of sintered Al$_2$O$_3$ as well as to improve the homogeneity of transparent Al$_2$O$_3$ samples. The transparent polycrystalline Al$_2$O$_3$ samples with and without the dopants were fabricated by two-step pulsed electric current sintering (TS-PECS). By the grain boundary segregation by the dopants, both TiO$_2$ and Y$_2$O$_3$ depressed the densification and grain growth processes during the sintering of polycrystalline Al$_2$O$_3$. The principle originalities of this work include the relationship between the homogeneities of microstructure and of optical transmittance of large-size polycrystalline Al$_2$O$_3$ and the consequent doping strategy for controlling of homogeneity of transparent polycrystalline Al$_2$O$_3$ prepared by two-step PECS. Doping of Y$_2$O$_3$ dramatically reduced the grain size of polycrystalline Al$_2$O$_3$ and improved its optical transparency. The homogeneity of the microstructure and the optical transparency of the large-sized polycrystalline Al$_2$O$_3$ with 0.1 mol% Y$_2$O$_3$ was improved. The addition of TiO$_2$ also slightly retarded densification and reduced the grain size of the sintered Al$_2$O$_3$ samples. However, TiO$_2$ dopant is not good for applications of transparent Al$_2$O$_3$ because it caused a dark color in transparent polycrystalline Al$_2$O$_3$ samples by uncertain reasons.

**KEYWORDS**

Transparent polycrystalline Al$_2$O$_3$; microstructure controlling; homogeneity; two-step pulsed electric current sintering; doping of TiO$_2$ and Y$_2$O$_3$

1. Introduction

Transparent polycrystalline Al$_2$O$_3$ ceramics have a high potential to replace the single crystal sapphire in many industrial applications. Besides its good mechanical properties as well as good optical transparency, the main advantage of polycrystalline Al$_2$O$_3$ is the simpler production method along with the lower cost by various sintering techniques such as pulsed electric current sintering (PECS) or hot isostatic pressing (HIP) [1–5]. Moreover, with the sintering techniques, the polycrystalline Al$_2$O$_3$ samples can be shaped much more easily while the single crystal sapphire normally requires machining for shaping after the production of a large bulk. Because of the excellent mechanical properties of sapphire, machining and shaping of sapphire is not a simple task. Replacement of the single crystal Al$_2$O$_3$ by the polycrystalline bulk fabricated by sintering techniques also helps to reduce the machining cost of the final products.

Although having a high potential, transparent polycrystalline Al$_2$O$_3$ ceramics have not been used widely in industries because of their limitations at the optical transparency and the sintering size. Especially, the transparent polycrystalline Al$_2$O$_3$ ceramics fabricated by the PECS techniques have limited size and homogeneity. The difficulty of sintering polycrystalline Al$_2$O$_3$ by the PECS processes is to control the microstructure of the polycrystalline Al$_2$O$_3$. Some studies reported on the heterogeneity of polycrystalline Al$_2$O$_3$ produced by PECS [6–8]. Because of the anisotropic crystal structure, the grain size of polycrystalline Al$_2$O$_3$ has a strong influence on the optical transparency. In order to obtain full densification with insignificant grain growth for PECS of Al$_2$O$_3$, Kim et al. used slow-heating PECS, 2°C/min, and consequently very long sintering period [9]. In the other route, Grasso et al. used a special punch-die device to conduct PECS at extremely high pressure, 500 MPa, and low temperature, 1000°C, at which the grain growth was not significant [10]. Using that special punch-die setup has limitation in the sample size. Our group has studied PECS with two-step temperature profile, referred as two-step PECS (TS-PECS) to fabricate transparent polycrystalline Al$_2$O$_3$ [2,3,5]. The meaning of the first step at lower temperature is for additional densification with limited grain growth. Therefore, grain growth in overall sintering process is suppressed and the homogeneity can be improved. TS-PECS can produce high transparency for polycrystalline Al$_2$O$_3$ in a shorter sintering period without any special punch-die devices.

The sintering conditions certainly affect to the microstructure of the polycrystalline Al$_2$O$_3$, both in grain size and the heterogeneity. However, in order to obtain polycrystalline Al$_2$O$_3$ with homogeneously
2. Experimental procedure

In this study, a commercial $\alpha$-Al$_2$O$_3$ powder (TM-DAR, Taiimei Chemicals Co., Ltd.) was used as the starting powder. Undoped polycrystalline Al$_2$O$_3$ sample was sintered by the TS-PECS process. The Al$_2$O$_3$ powder of approximately 10 g was introduced into a graphite die with inner diameter of 30.4 mm to make a disk-shaped sample with thickness approximately 3.5 mm. The whole inner surface of die and contacting surfaces between powder and punches were covered by 0.2-mm-thickness graphite sheets for easily removing samples after sintering. The die was covered outside, except a hole on the outer surface, by graphite wool to reduce heat losses due to the radiation. In TS-PECS processes, the temperature of die surface was recorded and controlled by a pyrometer equipped in PECS. The hole on the die outer surface, having 1.8 mm diameter and 3 mm depth, acted as a focus point for the pyrometer. In the TS-PECS processes for undoped Al$_2$O$_3$, the temperature of the first holding step was 930°C and that of the second holding step was 1130°C. The holding time of the first and the second holding steps was 1 h and 10 min, respectively. The heating rates for both steps was 10°C/min. The applied uniaxial pressure was 100 MPa. All PECS processes were conducted in high vacuum condition, below $5 \times 10^{-3}$ Pa. The electric pulse was set with ON-OFF pattern of 12:2, and each pulse duration was 3.3 ms.

The precursor for TiO$_2$ dopant, titanium isopropoxide Ti(OC(CH$_3$)$_2$)$_4$ (Nacalai Tesque), was mixed with Al$_2$O$_3$ powder in ethanol at the concentration of 0.1 mol%. The aqueous solution was mixed well by ball milling for 1 d and was calcined in air at approximately 400°C for 2 h. The dried powder was milled manually by a mortar and a pestle. After that, the TS-PECS processes were conducted similarly to the undoped Al$_2$O$_3$ powder. The sintering temperature for TiO$_2$-doped Al$_2$O$_3$ powder was 930 or 1000°C in the first holding step and 1130 or 1200°C in the second holding step. Other conditions of the TS-PECS processes were similar to those of the undoped Al$_2$O$_3$.

The precursor for Y$_2$O$_3$ dopant, yttrium nitrate Y(NO$_3$)$_3$·10H$_2$O (Wako Pure Chemical Industries, Ltd.), was mixed with Al$_2$O$_3$ powder in distilled water at the concentration of 0.1 mol% of Y$_2$O$_3$, followed by ball milling for 1 d. The aqueous solution was calcined in air at approximately 400°C for 2 h. The dried powder was milled manually by a mortar and a pestle. Because of the strong agglomeration in Y$_2$O$_3$-doped powder after the calcination, the powder was treated with polyethylene glycol (PEG) as a dispersant. 4 mass% of PEG was mixed with the Y$_2$O$_3$-doped Al$_2$O$_3$ powder in distilled water and the slurry was ball-milled for 1 d. The
slurry was dried in air at 120°C in 12 h. After manual milling by a mortar and a pestle, annealing process was conducted at 600°C for 2 h to reject CO₂ and H₂O from the PEG dispersant. The TS-PECS was conducted similarly to the undoped Al₂O₃ powder. The sintering temperature for Y₂O₃-doped Al₂O₃ powder varied from 930 to 1150°C in the first holding step and from 1130 or 1350°C in the second holding step. Other conditions of the TS-PECS process were the same. Table 1 summaries the sintering temperatures of PECS processes for all three powders and the notations of samples.

Relative density of sintered samples was measured by Archimedes’ method. The heterogeneity of microstructure and transparency of polycrystalline Al₂O₃ samples were investigated by the same methods with our previous study [19]. Microstructure of sintered Al₂O₃ samples was observed on the fractured surfaces by a scanning electron microscope (SEM), at three positions along the radial axis, at the center (inner area), near the edge of the samples (outer area) and at the middle of those two points (middle area). The transparent samples were polished well both faces to measure the optical transmittance. The apparent transmittance of Al₂O₃ samples was evaluated by a mobile laser power meter (Sanwa, Mobiken series, LP1) and a green laser with the wavelength of 532 nm, the power of 1 mW and the beam diameter of approximately 1 mm. The laser head was fixed with a vertical stand with 50 mm in distance from the sensor surface of laser power meter. At the beginning of each measurement, reference value of optical intensity was recorded by emitting laser beam directly to the laser power meter. After that, each transparent specimen was placed on the surface of laser sensor and absolute value of optical intensity transmitting through the sample was measured. Relative transmittance of a sample was determined by the ratio of the absolute value to the reference value. During all measurements, the system was put in a black box to eliminate noises from external light. The measurements of optical transmittance were conducted at three areas along the radial axis of each sample: inner, middle and outer areas. XPS analysis was conducted to investigate the chemical states of dopants (Y and Ti) in the synthesized powder before sintering and on the polished surfaces of the sintered samples by an X-ray photoelectron spectroscopy analyzer (ULVAC PHI, PHI5000 VersaProbe).

3. Results and discussion

3.1. Appearance and relative density of sintered samples

Figure 1 shows the appearance of undoped and TiO₂-doped Al₂O₃ samples. With the same sintering temperature, 930°C in the first holding step and 1130°C in the second holding step, the undoped Al₂O₃ sample was transparent while the TiO₂-doped one was opaque. Increasing the sintering temperature up to 1000°C in the first holding step and 1200°C in the second holding step, the TiO₂-doped sample became transparent.

Figure 2 shows the appearance of Y₂O₃-doped Al₂O₃ samples. Polycrystalline Al₂O₃ sample was opaque at the sintering temperature pattern of 930–1130°C, became translucent at the pattern of 1100–1300°C and finally transparent at the pattern of 1150–1350°C.

Figure 3 shows the influences of sintering temperature on the relative density of polycrystalline Al₂O₃.

Table 1. Notations of polycrystalline Al₂O₃ samples.

| Dopant | Sintering temperature 1ˢᵗ – 2ⁿᵈ step | Notation |
|--------|--------------------------------------|---------|
| -      | 930–1150°C                           | Undoped |
| TiO₂ (0.1 mol%) | 930–1130°C, 1000–1200°C | Ti1130 |
| Y₂O₃ (0.1 mol%) | 930–1130°C, 1000–1200°C | Y1130 |
|        | 1100–1300°C, 1150–1350°C | Y1300 |
|        |                                     | Y1350 |

![Figure 1. Appearance of Undoped, Ti1130 and Ti1200 samples.](image-url)
samples. The undoped sample was fully densified at the sintering temperature of 930–1130°C. However, the sintering temperature of the TiO₂-doped sample for fully densification was 1000–1200°C and that of the Y₂O₃-doped sample was much higher, 1150–1350°C. These results are compatible with the appearance of polycrystalline Al₂O₃ samples. At low sintering temperatures, the TiO₂-doped and Y₂O₃-doped samples were opaque or translucent because of low relative density, as shown in Figures 1 and 2.

Doping TiO₂ or Y₂O₃ increases the sintering temperature for full densification of polycrystalline Al₂O₃. In the case of TiO₂ dopant, the sintering temperature increased only 70°C for a transparent sample. However, the increment of sintering temperature to obtain highly transparent Y₂O₃-doped polycrystalline Al₂O₃...
3.2. Heterogeneity of microstructure and optical transmittance of sintered samples

The influences of sintering temperature on the grain size of polycrystalline $\text{Al}_2\text{O}_3$ samples is shown in Figure 4. At the sintering temperature pattern of 930–1130°C, the addition of TiO$_2$ or Y$_2$O$_3$ performed an obvious influence of depressing grain growth. The grain size in the inner areas of Ti1130 and Y1130 samples was significantly smaller than that of the undoped sample. The Y$_2$O$_3$ dopant exhibited a strong influence while the grain growth did not occur severely with polycrystalline Y$_2$O$_3$-doped Al$_2$O$_3$ samples until a sintering temperature of 1300°C.

The heterogeneity distribution of grain size in the radial direction was shown more clearly in Figure 5. In this figure, only three fully densified samples were shown: the undoped sample, TiO$_2$-doped sample sintered at 1000–1200°C and Y$_2$O$_3$-doped Al$_2$O$_3$ sintered at 1150–1350°C. Typically, the grain size of polycrystalline Al$_2$O$_3$ was larger at the center than near the edge of the samples. This behavior is supposed to derive from the heterogeneity of the temperature distribution during sintering process. Various studies reported the heterogeneity of temperature distributions during PECS processes as well as the heterogeneity of grain size of sintered samples [6–8]. Among three samples, the TiO$_2$-doped one had the smallest grain size. The heterogeneity of grain size of three samples was quite similar. The difference of grain size between the inner area and the outer area was approximately 0.02 μm for all three samples.

Not only depressing the densification of polycrystalline Al2O3, the dopants of TiO$_2$ and Y$_2$O$_3$ also depressed the grain growth during sintering processes. Figure 6 shows SEM images of the inner areas of undoped sample and Ti1200 sample. As shown in Figure 6 and in the graph in Figure 5, the sample Ti1200 had smaller grain size than the undoped sample, even though it was sintered at the higher temperature. The Y$_2$O$_3$ dopant rendered the obviously stronger influences on depressing densification and
grain growth than the TiO$_2$ dopant. The polycrystalline Y$_2$O$_3$-doped Al$_2$O$_3$ required much higher temperature for full densification, up to 1150°C and 1350°C for the first and the second holding steps, respectively. Although the sintering temperature of sample Y1350 was 220°C higher than that of the undoped sample, the grain size of sample Y1350 was approximate to that of the undoped sample. The microstructure in the inner area of Y1350 sample, as shown in Figure 7, is similar with the microstructure in the inner area of the undoped sample, showing in Figure 6. Other Y$_2$O$_3$-doped samples, Y1130, Y1200 and Y1300, had comparable or smaller grain size than the undoped ones sintered at 1130°C.

The optical transmittance of three samples was shown in Figure 8. With Y$_2$O$_3$ dopant, polycrystalline Al$_2$O$_3$ sample could obtain the highest and the most homogeneous transparency.

The influences of the dopants on the densification and the grain growth of polycrystalline Al$_2$O$_3$ was explained in various studies [11,15–18]. The molecules of the dopants stay on the surfaces of the Al$_2$O$_3$ grains within the starting powder, which becomes grain boundaries in Al$_2$O$_3$ bulks after sintering. During sintering process, the occurrence of densification and grain growth theoretically depends on the diffusion of matter along the grain boundaries as well as the diffusion of the grain boundaries. The dopants played a role as the grain boundary segregation. The influences of the dopants on the grain boundary segregation are typically explained by the pinning effect, in which the migration of grain boundary will be ceased when it is pinned by a sufficient number of second-phase particles [20]. Consequently, the diffusion of matter was prohibited and the rate of both densification and grain growth was slowed down. Depending on the solubility of the dopants in the base material, the influences of dopants on the densification and grain growth rate may be weak or strong. If the dopant’s solubility in Al$_2$O$_3$ matrix is low, it strongly segregates at the grain boundaries and strongly prohibits the diffusion processes of matter. The solubility of TiO$_2$ in Al$_2$O$_3$, at a few mol %, was reported by Winkler et al. [21] and Unno et al. [22]. Some studies on sintering of TiO$_2$-doped Al$_2$O$_3$ also mentioned the reduction of TiO$_2$ to Ti$_2$O$_3$ during sintering in reductive atmosphere [18,21,22]. With the same corundum structure, Ti$_2$O$_3$ might be easily dissolved into Al$_2$O$_3$, leading to the reduction in the effectiveness of Ti-dopants as a grain boundary segregation. On the other hand, Y$_2$O$_3$ has

Figure 7. Microstructure in the inner area of Y1350 sample.

Figure 8. The apparent optical transmittance of three fully densified polycrystalline Al$_2$O$_3$ samples.

Figure 9. XPS spectrum for 0.1 mol% Y$_2$O$_3$ doped Al$_2$O$_3$ powder.
been known to have a much lower solubility in $\text{Al}_2\text{O}_3$, only at level of 10 ppm [23–25], which makes the influences of $\text{Y}_2\text{O}_3$ dopant on grain boundary segregation stronger than TiO$_2$. The results proved that $\text{Y}_2\text{O}_3$ dopant has a strong potential for grain growth controlling in polycrystalline $\text{Al}_2\text{O}_3$. Because of the enhanced densification at much higher sintering temperature with limitation of grain growth, the sample Y1350 had a higher and more homogeneous optical transmittance, as shown in Figure 8.

3.3. Existence of $\text{Y}_2\text{O}_3$ in Y-doped synthesized powder and sintered sample

For further information of the influences of the dopants, XPS experiments were conducted to confirm the state of the dopants in the synthesized powders and in the sintered bodies. The XPS spectrum of the sintered samples were collected on the polished surfaces. Figures 9 and 10 shows the XPS results of synthesized $\text{Y}_2\text{O}_3$ doped powder and Y1350 sample. In both XPS results for the powder and the sintered sample, peaks of Al2p at around 74 eV and of O1s at around 531 eV [26–29], indicated the binding energy of Al and O within Al2O3, were observed. Besides the peaks of Al and O, the doublet peaks of Y3d were clearly observed in the synthesized powder at 159.7 and 157.9 eV. It was reported that the doublet XPS peaks of Y3d of $\text{Y}_2\text{O}_3$ were at 158.9 and 156.8 eV [26,30]. In this study, the doublet positions of Y3d peaks showed a positive shift of approximately 1 eV. This positive increment in binding energy of Y implies that Y atoms may be bonded to an element of a group with higher electronegativity. Similar positive shift of Y3d peaks was also reported in other studies [31,32]. Y-containing surface was reported to react with ambient moisture to form Y-OH sites. Those Y-OH bonds are vulnerable for the further reactions with CO$_2$ to form Y-OC sites. Both of Y-OH and Y-OC sites may produce the positive chemical shift in the binding energy of Y [31]. The XPS spectrum in Figure 9 indicate that $\text{Y}_2\text{O}_3$ was formed after the calcination process. The low ratio of signal/noise intensity of binding energy peaks of Y element came from the low concentration of $\text{Y}_2\text{O}_3$ at 0.1 mol%, which was the typical detectable limitation of XPS method. On the other hand, the two Y3d peaks were not detected on the polished surface of the sintered sample. However, the existence of $\text{Y}_2\text{O}_3$ could be confirmed by the binding energy peak of Y3p at 302.1 eV, as shown in Figure 10. The Y3p peak in $\text{Y}_2\text{O}_3$ was reported at 300.5 eV by Bethge et al. [27]. Again, there might be a formation of Y-OH or Y-OC sites on the sample surface which caused the positive shift in the binding energy of $\text{Y}_2\text{O}_3$.

The possible reason why the doublet peaks of Y3d were not detectable is the low concentration of $\text{Y}_2\text{O}_3$. Although it was 0.1 mol% in the synthesized powder, but the actual surface concentration of $\text{Y}_2\text{O}_3$ on the polished surface of the sintered sample should be much lower. Figure 11 shows an illustration of XPS analysis on the surface of powder compact and on the polished surface of the sintered body. Fundamentally, the molecules of the dopants cover the $\text{Al}_2\text{O}_3$ particles, which creates a thin layer of the dopants on the surface of the powder compact in XPS measurements. Inside the sintered sample, the dopants’ molecules/atoms/ions exist only at the grain boundaries with the typical thickness of a few nanometers, leading to a sufficiently low surface concentration on the polished surface. Because of that, the doublet peaks of Y3d were detected in the powder but could not be detected in the sintered sample. The peak of Y3p, which is theoretically stronger, was still detectable. The XPS results clearly indicated the existence of $\text{Y}_2\text{O}_3$ in both synthesized powder and sintered sample and implied its influences on densification and grain growth of polycrystalline $\text{Al}_2\text{O}_3$.

3.4. Existence of TiO$_2$ in Ti-doped synthesized powder and the demerit of Ti- doped sintered sample

Although sample Ti1200 had full relative density and smaller grain size than the undoped sample, its optical
transmittance was lower than that of the undoped sample. In Figure 8, the optical transmittance of sample Ti1200 showed a reverse direction—lower at center and higher near the edge—in comparison with that of undoped sample. This result seems to be inconsistent with the results of grain size showed in Figure 5, in which sample Ti1200 and undoped sample have similar heterogeneity of grain size. The reason for this inconsistency is still unclear.

Regardless of the results on the heterogeneity of grain size, the optical transmittance of the above two samples demonstrated the worse actual appearance of sample Ti1200. Figure 12 shows the appearance of the undoped sample and Ti1200 sample putting together without the backlight. Ti1200 sample had noticeably darker color that the undoped sample. This dark color of Ti1200 sample is possibly generated by the following factors: the formation of Al₂TiO₅ during sintering process and/or the change of valence state of Ti⁺⁴. The phase diagram of Al₂O₃-TiO₂ system which was reported by Jung et al. showed that the formation of Al₂TiO₅ might occur at 1264°C [33]. During the sintering process of Ti1200 sample at 1200°C, the temperature inside the powder compact possibly attained higher and caused the formation of Al₂TiO₅. That reaction, if really occurred, not only generated second-phase matter in the sintered samples but also created micro-scaled or nano-scaled cracks due to its uniquely anisotropic thermal expansion coefficient. Both of them might become the reason for the dark color of sample Ti1200.

On the other hand, Yoshida et al. reported the change of valence state of Ti from +4 to +3 during sintering process in a reducing atmosphere, in particular N₂-H₂ atmosphere [18]. A combination of chemical states of Ti after sintering in reductive atmosphere was also reported by other groups [21,22]. In this study, the sintering processes in high vacuum conditions, with the atmospheric pressure at the order of 10⁻³ Pa, and the presence of graphite die and punches produced the reducing environment. If the change of valence state of Ti happens in this case, the secondary phase or oxygen vacancies at the Ti⁺³ sites may be formed in the matrix. They are also possible reasons for the dark color of the sample. In order to clarify the state of Ti dopant, XRD and EDX mapping were conducted. However, because of the low concentration of TiO₂ in the powder mixture, only 0.1 mol%, the existence of TiO₂ or Ti₂O₃ or Al₂TiO₅ was not observed by those analysis methods. Hence, XRD and EDX mapping results were not shown in this article.

XPS analysis of Ti-doped powder and its sintered sample was conducted to confirm the state of Ti dopant in Al₂O₃ powder and bulk body. Figure 13 shows the XPS spectrum for 0.1 mol% TiO₂ doped powder. Similar to the Y₂O₃ doped powder, the Al2p and O1s peaks appeared at around 74 and 531 eV respectively. Within the TiO₂ doped Al₂O₃ powder, the doublet peaks of Ti2p were observed at 464.52 and 458.07 eV. The results of Ti2p peaks are consistent with the other studies [26,28,29,34], indicating that TiO₂ was successfully formed from the precursor after calcination. Similar to the Y₂O₃ doped powder, the ratio of signal/noise
The cation concentration intensity of Ti element was low due to the low concentration of TiO2 in the synthesized powder.

Unfortunately, there was no Ti2p peak observed in the XPS spectra for the polished surface of Ti1200 sample. By that reason, XPS spectrum of TiO2 doped sintered sample are not showed in this manuscript. Regardless of the state of Ti ions in sintered sample, the XPS peaks of Ti could not be detected because of the low surface concentration of Ti as described above with Y2O3 doped sintered sample. Therefore, even the existence of TiO2 in the synthesized powder and its influences on densification and grain growth of polycrystalline Al2O3 were perceived, this study could not confirm any phase transformation of Ti after sintering as well as the cause of the dark color of Ti-doped Al2O3 samples. Although the actual reasons for the dark color of polycrystalline TiO2-doped Al2O3 was not confirmed yet, it could be concluded that the TiO2 dopant is not good for transparent polycrystalline Al2O3 due to the dark color and the degradation of the optical transparency.

4. Conclusions

The microstructure of polycrystalline Al2O3 was controlled by using the dopants. With both dopants, TiO2 and Y2O3, the densification and grain growth of polycrystalline Al2O3 were depressed. However, the influences of TiO2 dopant was not so strong. Moreover, it caused a dark color for polycrystalline Al2O3 samples. The polycrystalline Al2O3 samples with TiO2 dopant had a significantly lower optical transmittance. Therefore, the TiO2 dopant is not suitable for transparent polycrystalline Al2O3, although it has some influences on retarding densification and controlling grain growth during PECS.

On the other hand, the additive of Y2O3 dopant is very excellent to control the microstructure of polycrystalline Al2O3. Even at much higher sintering temperature, the grain size of Y2O3-doped Al2O3 samples was still equivalent with that of the undoped ones. By the influences of Y2O3 dopant, the grain size of polycrystalline Al2O3 samples was homogeneously small. Consequently, the optical transmittance of the Y2O3-doped Al2O3 was high and homogeneous along the radial axis of the Al2O3 samples. Doping of Y2O3 is beneficial to fabricate homogeneously transparent polycrystalline Al2O3 at large sample size with two-step PECS.

From the obviously bad appearance and low optical transmittance of Ti-doped Al2O3 samples, it was suggested that the chemical states of Ti-dopant as well as the phase transformation of TiO2 and/or TiO2 dopants in PECS-sintered polycrystalline Al2O3 should be clarified in future studies.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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