Materials Research Express

PAPER

Fabrication and mechanical characterization of YAG ceramic-composite with alumina nanoparticles using slip casting and sintering process

M Torki 1, B Movahedi 1, S Ghazanfari 2, and M Milani 3

1 Department of Nanotechnology, Faculty of Chemistry, University of Isfahan, Isfahan, 81746-73441, Iran
2 Department of Materials Engineering, Isfahan University of Technology, Isfahan 84156-83111, Iran
3 Department of Advanced Materials and Renewable Energies, Iranian Research Organization for Science and Technology, Tehran 33131-93685, Iran

E-mail: b.movahedi@ast.ui.ac.ir

Keywords: ceramic-matrix composites, nanostructures, ceramics

Abstract

The aim of this study was to fabricate a YAG/Al2O3 ceramic composite with different alumina nanoparticles using slip casting and the atmospheric sintering process. In addition, some mechanical properties such as hardness and elastic moduli of this ceramic were evaluated using the nanoindentation technique. The results showed that the rheological behavior of the slurry was optimized to the solid loading of 55 wt%; also, the relative density of the green body was enhanced up to 65%. Relative density was increased to 99.5% after sintering at 1700 °C for 12 h; further, the pore size (150 nm) was reduced to half of that of powder particles. It should be, however, noted that the optimum amount of alumina nanoparticles as a reinforcing agent in the matrix was less than 5%wt and the composite hardness was increased to 7.3%, as compared to the pure YAG ceramic.

1. Introduction

Advanced ceramic composites consisting of Al2O3/Y3Al5O12 have been used in aerospace engineering, such as components for the jet motors in the airplane industry and machining tools [1–3]. Alumina is one of the most common materials. Its good mechanical properties, particularly fracture toughness, can be improved by applying second phase additions. Creep behavior and mechanical properties of alumina ceramics can be improved by dispersing yttrium aluminum garnet (YAG) inclusion in the alumina matrix [4]. The presence of the YAG phase increases the hardness of the composite, as compared to the pure alumina [5]. Some studies have successfully developed Al2O3/YAG composites with a low yttria dopant by slip casting and injection molding. Sommer and et al [6], for instance, studied alumina composites containing 5, 10 and 20 vol% YAG and made by a slip casting process. The Alumina composite with 10 vol% YAG had the best mechanical properties, so further increase of the YAG phase did not result in an increase of the mechanical properties. Due to the prevention of the YAG particles penetrating process, the density of the samples was decreased. Previous studies have been focused on developing Al2O3/YAG composites by dry axial pressing [7] or isostatic pressing [8].

Less work has, however, been done on the mixtures of YAG and alumina [9–12]. Slip casting is a simple method that can produce a homogeneous and dense green body [13–16], especially for multiple or composite systems. Homogenization of suspensions and the slurry rheological behavior play an important role in determining the process of slip casting and the microstructure of the final product [17]. A dispersed slurry can be obtained by choosing an optimal concentration of the dispersant [18]. In some systems, the rise of linear density with increasing the solid load has been observed, although there is no relationship between solid loading and green density in the systems [19–21]. It has been reported that the porosity distribution of a slip-cast green body depends on the properties of the used slurry, such as rheological properties and solid loading of the suspension [22]. These researchers have investigated many effective parameters, such as the effects of the dispersant concentration and solid loading content on the rheological behavior of YAG slurries and mechanical properties.

© 2020 The Author(s). Published by IOP Publishing Ltd
In all of these studies, YAG has been used to improve the mechanical properties of the alumina composites. The purpose of this study was, therefore, to increase the hardness of the YAG matrix by adding alumina nanoparticles. In fact, the effects of solid loading on the rheological behavior of the slurry in the slip casting process and sintered bodies, as well as the mechanical properties, have not yet been evaluated for the YAG/Al₂O₃ composites. The fracture surface and hardness of ceramic composites with 2, 5 and 8%wt alumina nanoparticles were investigated in detail. The optimum amount of alumina nanoparticles as a reinforcing agent in the YAG composite was reported less than 5 wt%.

2. Experimental procedure

High-purity α-Al₂O₃ nanoparticles (99.99%, 50 nm, US-Nano Research) and Y₂O₃ (99.99%, 70 nm, Baikowski SAS-France) were used as the raw materials. The purity of the powders was determined by Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) (Optima-4300 DV, PerkinElmer Inc., MA, USA) analysis. Yttria powder was dissolved in high-purity nitric acid to obtain the transparent solution of Y(NO₃)₃. To describe briefly, Y(NO₃)₃, and urea (Merck 99.5%) were dissolved in distilled water to make a solution. Urea was applied as a precipitating agent at a urea: Y¹⁺ ratio of 33:1. The α-Al₂O₃ nanoparticles solution was added to the mixed solution and dispersed using ultrasonication (probe ultrasonic, 20 kHz, 300w, Topsonics, Iran). The mixed turbid liquid with a Y/Al ratio of 3/5 was homogenized using a hot plate magnetic stirrer with 800 rpm at 90 °C for 3 h. The suspension was washed with a suction filter, 3 times with deionized water, and 1 time with ethanol. The powder was dried in an oven at 100 °C, for 24 h. Then, the powder was calcined at 1550 °C for 3 h to synthesize the YAG phase [23, 24]. YAG nanocomposite powders containing 2, 5 and 8 wt% alumina nanoparticles were mixed using high-energy planetary ball-milling. Alumina balls (10 mm) were used; the milling duration was 2 h and the ratio of the ball/powder was 5/1 (by weight); also, the ratio of ethanol/powder was 3/1.

Ammonium polyacrylate (Dolapix CE64, Zschimmer & Schwarz Chemical Co., Ltd Germany) was used as the dispersant. The optimum amount of the dispersant was obtained by plotting viscosity as a function of the dispersant concentration. At first, for optimizing Dolapix, the solid load was constant; then, different amounts of dolapix (0.5, 1, 1.5 and 2 wt%) were tested, obtaining low viscosity. After that, to optimize the amount of alumina nanoparticles, the amount of Dolapix was constant (in the optimum value); so, different amounts of Alumina nanoparticles (2, 5 and 8 wt%) were examined. For viscosity measurement, a rotary viscometer was used (Model LVDV-II; Brookfield, Middleboro, USA). The viscosity of the slurry was measured by a rotational stress-controlled rheometer with a shear rate of 264 s⁻¹.

A 3D-mixture (Savis sanit Sepehr Iranian) was also used to homogenize the slurry. The slurries were milled for 3, 6, 9 and 12 h with the ball (half of them were 10 mm and the others were 5 mm) ratio of 1:3 (by weight) and at the speed of 45 rpm. After slip casting, the bodies were dried in the air and the organic additives were removed by heating the samples at 600 °C for 2 h in the air. The density of the green bodies was measured by the Archimedes method, using deionized water as the immersion medium [25]. The pore size distribution of the slip-cast samples was addressed by using the Mercury porosimetry (PoreSizer 9320, Micromeritics Instrument Corp, USA).

The microstructure of the composite powders before and after ball-milling was studied by using field emission scanning electron microscopy (FESEM, TESCAN, MIRA3, Czech Republic). The calcined synthesized composite powder at 1550 °C was characterized by using a Philips XPERT MPD x-ray diffractometer with Cu-Kα radiation. Ceramic composite samples were sintered at 1700 °C for 12 h in the air atmosphere furnace (AZAR-F3L 1800, Iran). The microstructures of the YAG/Al₂O₃ composite after sintering were examined on the fracture surfaces by using scanning electron microscopy (SEM, JEOL 6510). Finally, the indentation test was performed on the YAG/Al₂O₃ composite samples and the pure YAG by using CSM nanoindenters instruments (SA, Peseux, Switzerland) with a Berkovich diamond tip (less than 10 nm in diameter, type 4/03). In the load schedules employed, the load at constant rate was first ramped up to a peak value of 40 mN and then unloaded. Each test was performed three times based on the ASTM E2546 standard [26].

3. Results and discussion

3.1. XRD and FESEM characterizations of the YAG/Al₂O₃ nanocomposite powder

According to the x-ray diffraction pattern (figure 1), YAG (00-033-0040 JCPDS file) was formed.

The main peaks match the pattern and no additional peaks are seen. It means that no intermediate phases such as yttrium aluminium monoclinic (YAM) or yttrium aluminium perovskite (YAM) were existed. Figure 2(a) and (b) shows the field emission scanning electron microscope (FESEM) images of the YAG/Al₂O₃ nanocomposite powder before and after milling. After milling, the agglomerates were broken and less
agglomeration would be suitable for slip casting because the particle size distribution was effective in determining the density and pore size distribution [27].

3.2. Rheological behavior of the slurry

Figure 3 illustrates the viscosity of 55%wt of YAG/Al₂O₃ nanocomposite slurries versus shear rate at different dispersant percentages. The slurry showed a pseudo-plastic behavior (the viscosity of slurries was decreased with increasing the shear rates). This behavior would be desirable for many ceramic forming methods because the suspension is flowing in high tensions; however, after removing stress, they can retain their shape [28]. When the amount of the dispersant Dolapix CE64 was 1% wt, the viscosity of the slurry was minimized. By increasing the amount of the dispersant beyond the optimum value, the viscosity was increased due to the formation of a polymer network resulting from the additional dispersant within the slurry [29, 30]. Therefore, in order to create a slurry with suitable viscosity, the dispersant value should be optimized. The slurry behavior indicated that the powder was de-agglomerated and the dispersant was absorbed on the particle surface, leading to the creation of the stable slurry [31, 32].

As shown in figure 4, the viscosity of 55%wt of YAG/Al₂O₃ nanocomposite slurries versus shear rate was measured at different de-agglomeration time. By increasing the de-agglomeration time, big and hard agglomerates were broken and viscosity began to decrease; so, the dispersant could saturate the surface of all particles [13, 27]. According to figure 4, the optimum de-agglomeration time was 9 h to achieve the minimum viscosity. Figure 5 shows the viscosity of 55%wt YAG/2%–8%wt Al₂O₃ nanocomposite slurries versus different shear rates. By raising the amount of alumina (above 2%wt) in the slurry, due to the agglomeration of alumina particles, the viscosity was increased. As a result, slurries with high-viscosity could not be suitable for slip casting.

Figure 1. X-ray diffraction pattern of the YAG powder at 1550 °C.

Figure 2. FESEM images of the YAG/Al₂O₃ nanocomposite powder: (a) before ball-milling, and (b) after ball-milling.
Figure 6 shows the pore size distribution of green bodies obtained by slip casting for three different samples. YAG-8%wt Al$_2$O$_3$ had two peaks; the maximum peak occurred at the pore size of 150 nm, while the other one was at a larger size. This behavior was due to the formation of agglomerates in the slurry [33]. For YAG-2%wt...
Al₂O₃ and YAG-5%wt Al₂O₃, a peak almost half of the particle size was obtained due to the appropriate density. However, the pores of YAG-5%wt Al₂O₃ were larger than those of YAG-2%wt. Therefore, the maximum green relative density of YAG-2%wt was higher than that of YAG-5%wt Al₂O₃ [34, 35].

3.3. Specific characterization of the sintered body

Figure 7 shows the XRD pattern of the YAG/Al₂O₃ ceramic sample. It seems that no phase change between YAG and alumina occurred. This sample was sintered at 1700 °C for 12 h in the air atmosphere furnace. The increase in temperature was due to the alumina infiltration into the YAG and the alumina being in the YAG matrix. Figure 8 shows the relative densities of YAG/2%–8%wt Al₂O₃ composites before and after sintering versus different solid loads. By raising the solid load, in all samples, the green density was increased to the optimal viscosity of the slurry. By further increasing the solid load, the viscosity was raised due to agglomeration. Agglomeration formed large pores, thereby decreasing density [9, 20]. As can be seen, the sample YAG-2%wt Al₂O₃ had the highest green relative density. It could be attributed to the least viscosity of this sample, such that the green relative density was increased from 47% to 65%. After sintering in the air atmosphere at 1700 °C for 12 h, the relative final density was increased from 75% to 99.5%. Compared with YAG-2%wt Al₂O₃, YAG-5%wt and YAG-8%wt had low relative green density; this could be attributed to the inappropriate slurry viscosity and more porosity.

Figure 9 shows the SEM images of YAG/Al₂O₃ ceramics with different percentages of alumina nanoparticles in the YAG matrix. Alumina was mainly located at grain boundaries or triple points in the samples containing 2 and 5%wt alumina. It was distributed uniformly throughout the body, as shown in figure 9(a) and (b). According to the SEM images and relative density (see figure 8), the optimum amount of alumina should be less...
than 5%wt because it could be more homogeneous in structure. Based on evidence, when the alumina particles were in the boundary, the grain boundary was pinned, and alumina particles entered the structure through the grain boundary, improving the mechanical properties \[36, 37\]. In the sample with 8%wt alumina, the reinforcement phase was distributed non-uniformly and accumulated in some parts of the sample, as shown in figure 9(c).

### 3.4. Mechanical properties of the sintered body

The results related to nanohardness (H), elastic modulus (E), the maximum displacement of the nanoindenter (h$_{\text{max}}$), the final indentation depth (h$_{f}$), and the h$_{f}$/h$_{\text{max}}$ ratio for the pure YAG ceramic sample reinforced with various ratios of alumina nanoparticles are summarized in table I. It was evident that the maximum penetration depth (h$_{\text{max}}$) was decreased by raising the amount of alumina content in the matrix, probably indicating that the higher hardness appeared in the reinforced YAG ceramic. The measured hardness of the pure YAG ceramic was 2246 Hv, while it was 7550 Hv for the sample with 8%wt alumina nanoparticles. The higher hardness of the latter could be associated with a high amount of nanoparticles distributed in the matrix. The hardness values reported here were slightly higher than those measured by the conventional microindenters, probably because of the indenter size effect at small load levels \[38\].

---

**Figure 8.** Relative densities of YAG/2%–8%wt Al$_2$O$_3$ composites versus different solid loads, before sintering at 600 °C and after sintering at 1700.

**Figure 9.** SEM images of YAG/Al$_2$O$_3$ ceramics with different percentages of alumina. (a) 2%wt, (b) 5%wt, and (c) 8%wt.
The value of this ratio was found to be decreased for the sample with 8 wt% alumina. As it is evident from figure 9(c), in the sample with 8 wt% alumina, hardness at three points differed greatly due to the accumulation of alumina and the absence of the homogeneous distribution in some parts of the ceramic microstructure. Based on the results summarized in table 1, with values less than 5 wt% alumina, the reinforcing phase was almost uniformly distributed in the matrix, increasing the hardness up to 7.3%. Despite the fact that the YAG ceramic, in its turn, could be a suitable choice for many applications, it has poor mechanical properties. Therefore, in this study, the alumina phase was added to the YAG matrix in order to enhance the mechanical properties.

### 4. Conclusions

In this study, a YAG/Al₂O₃ ceramic composite with different amounts of alumina nanoparticles was fabricated using slip casting and the atmospheric sintering process. The slurries of the YAG/Al₂O₃ nanocomposite with the solid loading of 75 wt% at the lowest viscosity (8 mPas) were prepared. The relative density of the green body and the ceramic composite after the sintering process with no pressure at 1700 °C was about 65% and 99.5%, respectively. The optimum amount of alumina nanoparticles was less than 5 wt% due to the uniformity and absence of agglomeration in the ceramic microstructure. As the hardness of alumina was higher than that of YAG, by using alumina nanoparticles as a reinforcing agent, hardness and elastic modulus were increased, as compared to the pure YAG ceramic.

### ORCID iDs

B Movahedi @ https://orcid.org/0000-0001-7737-9117

### References

[1] Ochiai S, Ueda T, Sato K, Hojo M, Waku Y, Nakagawa N, Sakata S, Mitani A and Takahashi T 2001 Deformation and fracture behavior of an Al₂O₃/YAG composite from room temperature to 2023 K Compos. Sci. Technol. 61 2117–28

[2] Parthasarathy T, Mah T and Matson L E 2004 Processing, structure and properties of alumina-YAG eutectic composites J. Ceram. Process. Res. 5 380–90

[3] Palmero P, Simone A, Esnouf C, Fantozzi G and Montanaro L 2006 Comparison among different sintering routes for preparing alumina-YAG nanocomposites J. Eur. Ceram. Soc. 26 941–7

[4] Torrecillas R, Schel M, Diaz L A, Menendez I L and Moya J S 2007 Creep behaviour of alumina/YAG nanocomposites obtained by a colloidal processing route J. Eur. Ceram. Soc. 27 143–50

[5] Lach R, Wojtczko K, Dudek A and Pędzich Z 2014 Fracture behaviour of alumina-YAG particulate composites J. Eur. Ceram. Soc. 34 3373–8

[6] Lv Y, Zhang W, Liu H, Sang Y, Qin H, Tan J and Tong L 2012 Synthesis of nano-sized and highly sinterable Nd:YAG powders by the urea homogeneous precipitation method Powder Technol. 217 140–7

[7] Corman G S 2009 High-temperature creep of some single crystal oxides 15th Annu. Conf. Compos. Adv. Ceram. Mater. Part 2 2, (New York) (Wiley) 1745

[8] Ikesue A, Kinoshita T, Kamata K and Yoshida K 1995 Fabrication and optical properties of high-performance polycrystalline Nd:YAG ceramics for solid-State lasers J. Am. Ceram. Soc. 78 1033–40

[9] Appignani K A, Messing G L and Dumm J Q 2008 Aqueous slip casting of transparent yttrium aluminum garnet (YAG) ceramics Ceram. Int. 34 1309–13

[10] Studart A R, Amstad E, Antoni M and Gauckler L J 2006 Rheology of concentrated suspensions containing weakly attractive alumina nanoparticles J. Am. Ceram. Soc. 89 2418–25

### Table 1. Comparison of the mechanical properties of the pure YAG ceramic with samples by different alumina.

| Sample      | Hardness (HV) | Elastic modulus (Gpa) | h₀ (nm) | hₘₐₓ (nm) | h₀/hₘₐₓ | Standard deviation of hardness |
|-------------|---------------|-----------------------|---------|-----------|---------|-------------------------------|
| YAG         | 2225 2246 2237| 289                   | 184.1   | 328.2     | 0.560   | 10.53                         |
| YAG-2%wt Al₂O₃ | 2367 2330 2380| 309                   | 176.6   | 319.7     | 0.552   | 25.94                         |
| YAG-5%wt Al₂O₃ | 2438 2229 2325| 317                   | 165.1   | 310.8     | 0.530   | 104.53                        |
| YAG-8%wt Al₂O₃ | 10839 7550 3868| 352                   | 52.7    | 261.6     | 0.201   | 1102.79                       |

Elastic moduli of the reinforced YAG ceramics were found to be higher than those of the pure YAG. The enhancement in elastic modulus was due to the higher elastic modulus of an alumina phase than the YAG matrix [39]. The h₀/hₘₐₓ ratio is one of the important parameters that can be a characteristic of rigid plastic materials. The value of this ratio was found to be decreased for the sample with 8 wt% alumina. As it is evident from figure 9(c), in the sample with 8 wt% alumina, hardness at three points differed greatly due to the accumulation of alumina and the absence of the homogeneous distribution in some parts of the ceramic microstructure. Based on the results summarized in table 1, with values less than 5 wt% alumina, the reinforcing phase was almost uniformly distributed in the matrix, increasing the hardness up to 7.3%. Despite the fact that the YAG ceramic, in its turn, could be a suitable choice for many applications, it has poor mechanical properties. Therefore, in this study, the alumina phase was added to the YAG matrix in order to enhance the mechanical properties.
[11] Mohammadi F, Mirzaee O and Tajally M 2018 Influence of solid loading on the rheological, porosity distribution, optical and the microstructural properties of YAG transparent ceramic Ceram. Int. 44 12098–105
[12] Li X and Li Q 2008 YAG ceramic processed by slip casting via aqueous slurries Ceram. Int. 34 397–401
[13] Ghazanfari S, Torki M, Shaiey A, Milani M and Emadi R 2020 The influence of Y3+ and Mg2+ dopants on the transparency behavior of alumina ceramics Mater. Chem. Phys. 247 122905
[14] Shaiey A, Enayati M H and Al-Haji A 2017 The effect of slip casting parameters on the green density of MgAl2O4 spinel Ceram. Int. 43 6069–74
[15] Rahimian A, Torki M, Ghazanfari S, Movahedi B and Emadi R 2019 Effect of the Evolution of Rheological Behavior over Deagglomeration Time on Optical Transparancy of Polycrystalline Alumina Ceramics J. Ceram. Sci. Technol. 10 73–9
[16] Abbaslo S, Shokrollahi H and Alhaji A 2020 Slip-casting process of MgO–Y2O3 nanocomposite: Investigation of powder synthesis method Mater. Chem. Phys. 254 123387
[17] Rahaman M N 2003 Ceramic processing and sintering 2nd edition (New York: Marcel Dekker)
[18] Tallon C, Limacher M and Franks G V 2010 Effect of particle size on the shaping of ceramics by slip casting J. Eur. Ceram. Soc. 30 2819–26
[19] Ferreira J M F and Diz H M M 1999 Effect of solids loading on slip-casting performance of silicon carbide slurries J. Am. Ceram. Soc. 82 1993–2000
[20] Činar S 2013 Rheological behavior of oxide nanopowder suspensions Iowa State University https://doi.org/10.31274/etd-180810-3609
[21] Mohammadi F, Mirzaee O and Tajally M 2018 Influence of TEOS and MgO addition on slurry rheological, optical, and microstructure properties of YAG transparent ceramic Opt. Mater. (Amst). 85 174–82
[22] Krell A and Klimke J 2006 Effects of the Homogeneity of Particle Coordination on Solid-State Sintering of Transparent Alumina J. Am. Ceram. Soc. 89 1985–92
[23] Kafili G, Loghman-Estarki M R, Milani M and Movahedi B 2017 The effects of TEOS on the microstructure and phase evolutions of YAG phase by formation of alumina/yttria core-shell structures J. Am. Ceram. Soc. 100 4305–16
[24] Kafili G, Movahedi B and Milani M 2016 A comparative approach to synthesis and sintering of alumina/yttria nanocomposite powders using different precipitants Mater. Chem. Phys. 183 136–44
[25] ASTM B962-17 2009 Standard Test Methods for Density of Compacted or Sintered Powder Metallurgy (PM) Products Using Archimedes’ Principle, ASTM International, 2009 Volume 02.05
[26] ASTM E2546-16 2007 Standard practice for instrumented indentation testing, ASTM International, 2007 Volume 03.01
[27] Watanabe H 1999 Critical rotation speed for ball-milling Powder Technol. 104 95–9
[28] Lewis J A 2000 Colloidal processing of ceramics J. Am. Ceram. Soc. 83 2341–59
[29] Xu X, Oliveira M I L L, Fu R and Ferreira J M F 2003 Effect of dispersant on the rheological properties and slip casting of concentrated sialon precursor suspensions J. Eur. Ceram. Soc. 23 1525–30
[30] Dakskobler A, Kočevar K and Kosmač T 2001 Short-range repulsive potential developed by the addition of Mg (II) ions to aqueous alumina slurries J. Eur. Ceram. Soc. 21 2361–8
[31] Ewais E M M 2005 Rheological properties of concentrated alumina slurries: Influence of pH and dispersent agent J. Australas. Ceram. Soc. 41 36–43
[32] Xuewei B A, Jiang L I, Yubai P A N, Jing L I U, Huamin K O U and Jingkun G U O 2013 Optimization of dispersing agents for preparing YAG transparent ceramics J. Rare Earths 31 507–11
[33] Zawrah M F 2004 Investigation of lattice constant, sintering and properties of nano Mg2Al2O4 spinels Mater. Sci. Eng. A 382 362–70
[34] Kim J-M, Kim H-N, Park Y-J, Ko J-W, Lee J-W and Kim H-D 2016 Microstructure and optical properties of transparent MgAl2O4 prepared by Ca-infiltrated slip-casting and sinter-HIP process J. Eur. Ceram. Soc. 36 2027–34
[35] Sommer F, Kern F, El-Maghraby H F, El-Ezz M A, Awaad M, Gadaw R and Naga S M 2012 Effect of preparation route on the properties of slip-casted Al2O3/YAG composites Ceram. Int. 38 4819–26
[36] Wang C-J, Huang C-Y and Wu Y-C 2009 Two-step sintering of fine alumina–zirconia ceramics Ceram. Int. 35 1467–72
[37] Stearns L C and Harmer M P 1996 Particle-Inhibited Grain Growth in Al2O3-SiC: I, Experimental Results J. Am. Ceram. Soc. 79 3013–9
[38] Movahedi B 2017 On the Prospects of using nanoindentation and wear test to study the mechanical behavior of Fe-Based metallic glass coating reinforced by BC4 Nanoparticles Metal. Mater. Trans. A 48 1474–83
[39] Lach R, Haberko K, Bucło M M, Szumera M and Grabowski G 2011 Ceramic matrix composites in the alumina/5–30 vol% YAG system J. Eur. Ceram. Soc. 31 1889–93