

Spontaneous Coagulation Casting and Comprehensive Properties of ZTA ceramics

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received March 25, 2024; received in revised form April 7, 2024; accepted April 9, 2024

Abstract

Spontaneous coagulation casting (SCC) has been proved to be a forming method for producing green bodies with high density and high uniformity. In this work, ZTA (zirconia toughened alumina) composite ceramics with different YSZ (yttria partially stabilized zirconia) content were prepared by means of SCC for the first time. A systematic comparative study was carried out to investigate the green body properties, mechanical properties, friction and wear properties of ZTA ceramics prepared with SCC and dry pressing (DP) forming methods. ZTA ceramics prepared by means of SCC have higher green body density and superior mechanical properties as well as friction and wear properties compared to those formed with the DP method. In addition, with the increase of YSZ content, the flexural strength of the ZTA ceramics gradually increases, while the fracture toughness decreases and the Vickers hardness first increases and then decreases. Meanwhile, the average friction coefficient gradually increases, and the wear rate exhibits the opposite change trend to the Vickers hardness, reaching the lowest value when the YSZ content is 20 wt%.

Keywords: ZTA ceramic, spontaneous coagulation casting, mechanical properties, friction and wear property

Introduction

Ever since Garvie's discovery of the toughening effect in ZrO_2 during the 1970s, zirconia toughened alumina (ZTA) ceramics have gained significant attention due to their exceptional strength, hardness, abrasion resistance, and high fracture toughness^{1–3}. Because of these characteristics, they are very helpful in applications like cutting blades, ceramic liners, and biomedical components^{4–6}. The typical forming methods for these ceramic components include dry pressing, slip casting, injection molding, and gelcasting, etc.^{7–10}. As a near-net-shape forming method, gelcasting is suitable for preparing complex-shaped ceramics, and the microstructure of the ceramics prepared by means of gelcasting is usually more uniform, resulting in superior comprehensive properties of the ceramics^{11–13}. These advantages are very beneficial for the preparation of ZTA composite ceramics, ensuring the uniform distribution of the two phases, which has attracted the attention of many researchers. For example, Ganesh *et al.* introduced a method called “hydrolysis-induced aqueous gelcasting” (GCHAS), in which a dispersing agent (Dolapix CE 64), and other organic additives including MAM (methacrylamide), MBAM (methylenebisacrylamide), NVP (n-vinylpyrrolidinone), an initiator APS (ammonium per-sulphate) and a catalyst TEMED (tetramethylethylenediamine) were added to the

slurry. Improved fracture toughness and bending strength of ZTA ceramics resulted¹⁴. Pietrzak reported the synthesis of a novel monomer, diglyceryl acrylate (DGA), and its application in the preparation of ZTA composites using the gelcasting method, resulting in high-solid-loading slurries, uniform phase distribution, and excellent mechanical properties of the ZTA ceramics¹⁵. Compared to the conventional gelcasting method using many organic additives, a new type of gelcasting method called the SCC (Spontaneous Coagulation Casting) method has been developed in recent years, using a single additive to achieve slurry dispersion and solidification, where Isobam, a copolymer of isobutylene and maleic anhydride, acts as both the dispersant and the coagulation agent. SCC method has received great attention in the field of ceramic forming in the past ten years because of its low addition, nontoxicity and universality¹⁶. To date, the SCC method has been extensively applied to fabricate various ceramics, such as dense alumina, YAG, MgAl_2O_4 and Y_2O_3 ceramics^{17–20}, as well as porous ceramics such as Al_2O_3 ²¹ and SiC²². On account of the obvious advantages of SCC, it has been employed for the forming of ZTA green bodies.

Furthermore, in order to investigate the excellent mechanical properties of ZTA composite ceramics, it is necessary to optimize the content of ZrO_2 . Bartolome²³ found that the wear rate of ZTA with 22 vol% zirconia was two orders of magnitude higher than those with 14 and 7 vol% zirconia, at a relatively low normal load (20 N). However, some studies have shown that a ZrO_2 phase above 20 wt%

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led to a decrease in wear rate, hardness, and other mechanical properties of ZTA composites due to the coarsening of ZrO_2 grains^{24,25}. Gafur²⁶ *et al.* found that with the increase of ZrO_2 content from 0 to 20 vol%, the flexural strength and fracture toughness of ZTA ceramics both showed the change rule of first increasing and then decreasing, and reached their highest value when the zirconia content was 10 vol%. Kren²⁷ found that the stabilizer content in ZTA ceramics containing 17 vol% zirconia varied between 0.6–2 mol% Y_2O_3 and that fracture resistance reached a maximum close to stress-neutral state, where phase transformation stresses balanced the residual cooling stresses and the compressive stresses in the alumina matrix favored higher strength. Previous studies have shown that with the increase of zirconia content, the research related to the change rule of mechanical properties and friction and wear properties of ZTA ceramics is not systematic and in-depth. In this work, ZTA composite ceramics with different zirconia contents were prepared. Also, the green body properties, mechanical properties and friction and wear properties of the ZTA ceramics prepared with the SCC forming method and traditional dry-pressing forming method were compared. This study is expected to lay the foundation for the practical application of ZTA composite ceramics.

II. Experimental Procedure

(1) Preparation of ZTA ceramics

The initial powders comprised alumina powder (AES-11, 99.8 % purity, $D_{50} = 0.45 \mu\text{m}$, specific surface area = $6.4 \text{ m}^2/\text{g}$, Sumitomo Chemical Co., Ltd., Japan) and 3 mol% yttria partially stabilized zirconia powder (YSZ, CYZ, 99.9 % purity, $D_{50} = 0.19 \mu\text{m}$, specific surface area = $15 \text{ m}^2/\text{g}$, Saint-Gobain ZirPro Co., Ltd., Handan, China). The Isobam-600AF (Ib600AF) and Isobam-104 (Ib104) (molecular weight: 5 500–6 500 and 55 000–65 000, respectively; Kuraray, Osaka, Japan) were utilized as both dispersants and gelling agents. Polyvinyl alcohol (PVA, Sino Chemical Reagent Co., Ltd., Shanghai, China) was used as a binder.

For the SCC forming method, the alumina and YSZ composite slurries with different YSZ content were prepared as follows: Firstly, different contents of Ib600AF and Ib104 were dissolved in deionized water. Secondly, the alumina and YSZ powders were slowly added and stirred in a stirred mill with alumina grinding balls ($\varnothing 5 \text{ mm}$). After all the powders had been added into the stirred ball mill, the mixed slurries were stirred for another 2 h. Subsequently, the mixed slurries were filtered, degassed and cast into plastic molds. The samples were then dried at 25°C and 80 % relative humidity until the weight of the wet bodies no longer decreased. Next, the green bodies were pre-sintered at 800°C for 2 h to burn out the organic additives in air. Finally, the green bodies were sintered at different temperatures ($1400^\circ\text{C} - 1600^\circ\text{C}$) for 3 h in air. In this work, the mass ratios of YSZ and alumina powder were set as 10:90, 15:85, 20:80, 30:70 and 40:60, and the compositions were denoted 10ZG, 15ZG, 20ZG, 30ZG, and 40ZG, respectively. The amount of Isobam addition, sol-

id loading and viscosity of the composite powder slurries with different YSZ contents are shown in Table 1.

In order to compare the properties of the ZTA ceramics prepared with the SCC method, ZTA ceramics were also fabricated with the traditional DP forming method. The mass ratios of YSZ and alumina powder were the same, and the corresponding green bodies were denoted 10ZD, 15ZD, 20ZD, 30ZD, 40ZD, respectively. Firstly, different amounts of YSZ and alumina powders with 0.5 wt% PVA as binder were ball-milled using alumina grinding balls in ethanol for 24 h. The obtained slurries were then dried in an oven at 60°C for 24 h. Subsequently, the dried powders were sieved on a 100-mesh screen and dry-pressed into blocks ($8 \text{ mm} \times 8 \text{ mm} \times 65 \text{ mm}$) at 20 MPa using stainless steel molds. The blocks were then cold-isostatically pressed at 200 MPa. The obtained green bodies were also pre-sintered at 800°C for 2 h to burn out the organic additives and then sintered at different temperatures ($1400^\circ\text{C} - 1600^\circ\text{C}$) for 3 h in air.

(2) Characterization

The rheological behavior of the slurries was characterized with a rotational rheometer (Haake Viscotester iQ Air, Thermo Electron GmbH, Karlsruhe, Germany) with a parallel plate (20 mm diameter). The bulk density of the samples was determined based on the Archimedes' principle using water as the medium. The theoretical density was determined using the mixing principle, and the relative density of the specimens is equal to the bulk density divided by the theoretical density. The flexural strength of the ZTA ceramics ($3 \text{ mm} \times 4 \text{ mm} \times 36 \text{ mm}$) was measured in a three-point bending test with a span of 30 mm and a crosshead speed of 0.5 mm/min on a universal test machine (Norwood, USA), and ten specimens were tested for each group of samples. The Vickers hardness (H_v) of the ceramics was measured on five specimens for each group of samples with the Vickers indentation technique, and the cracks produced by the previous indentation tests were used to determine the fracture toughness (K_{IC}) of the specimens under a load of 5 kg for 10 s according to the Anis equation.

$$K_{IC} = 0.016 \left(\frac{E}{H_v} \right)^{1/2} \left(\frac{P}{c^{3/2}} \right) \quad (1)$$

where P refers to the applied load (N), E denotes the elastic modulus (GPa), c represents half of the average crack length (mm).

The friction and wear performance of the ZTA ceramics at room temperature was tested with a UMT-2 type friction and wear tester (CETR, USA). A silicon nitride ball with a diameter of 9.45 mm was selected as the friction pair. The test parameters were as follows: applied load of 5 N, sliding speed of 60 mm/s , stroke of 6 mm, and test duration of 30 minutes. The testing was conducted at a room temperature of 23°C and a relative humidity of 52 %. The microstructures of the sintered ZTA ceramics were observed by means of Field Emission Scanning Electron Microscopy (FE-SEM; Magellan 400, FEI, America). The average grain sizes (AGS) of the ZTA ceramics were statistically measured with Nano Measurer software based on the SEM photographs.

III. Results and Discussion

(1) Rheological behavior of the slurries

For the alumina powder chosen in this work, the most suitable addition content of the Ib600AF and Ib104 had already been studied in previous work²⁸. Thus, 56 vol% solid loading and 0.1 wt% Ib104 and 0.2 wt% Ib600AF addition content for the alumina powder slurry was selected. Fig. 1(a) shows the viscosity of the YSZ slurries with varying solid loading and dispersants at 25 °C. When the addition content of the Ib600AF and Ib104 are the same for Slurry I and Slurry II, the viscosity of the slurries decreases with the decrease in the solid loading from 45 vol% to 43 vol%. However, the viscosity of Slurry I is about 2.7 Pa·s at 100 s⁻¹, which is still high for casting. As the Ib600AF with a short chain has a better dispersion effect and the Ib104 with a long chain has a better gelation effect²⁹, when the addition content of Ib600AF is increased to 1.3 wt% with the addition of 0.1 wt% Ib104, the viscosity of the slurry drops to 0.9 Pa·s and it is optimal for casting. According to the above studies for slurries of the alumina and YSZ powders, appropriate solid loading and additive amount for different composite powder slurries were selected in this work (Table 1).

After determination of the solid loading and dispersant, the viscosity of the slurries with five components of 10ZG, 15ZG, 20ZG, 30ZG and 40ZG are configured in Fig. 1(b). It can be seen that all the viscosities of the ZTA composite slurries are suitable for gelcasting. Based on combination of the data in Table 1, it indicates that solid loading of the ZTA composite powder slurry decreases gradually and the viscosity shows an increasing trend with the increase in YSZ content. This is mainly due to the much larger specific surface area of the YSZ powder (15 m²/g) compared to the alumina powder (6.4 m²/g) in this study.

(2) Characteristics of the debinding green bodies

The organic additives in the dried green bodies need to be removed before sintering. An appropriate debinding process should be determined with the TG-DSC method. Fig. 2 shows the TG-DSC curve of the 30ZG green body. The endothermic peaks before 200 °C were main characteristic of free water and bound water. The organic additives (Ib600AF and Ib104) basically completely decompose before 400 °C²¹. In this work, the maximum temperature of the debinding process is set to be 800 °C, which can completely remove the organic additives and ensure that the green bodies have certain strength for handling purposes.

Table 1: The composition and slurry properties for the SCC method.

	10ZG	15ZG	20ZG	30ZG	40ZG
YSZ (wt%)	10	15	20	30	40
Ib600AF (wt%)	0.31	0.365	0.42	0.53	0.54
Ib104 (wt%)	0.10	0.10	0.10	0.10	0.10
Solid loading (vol%)	54.9	54.3	53.7	52.5	51.3
Viscosity (η , @ 100s ⁻¹)	0.45	0.49	0.56	0.73	0.75

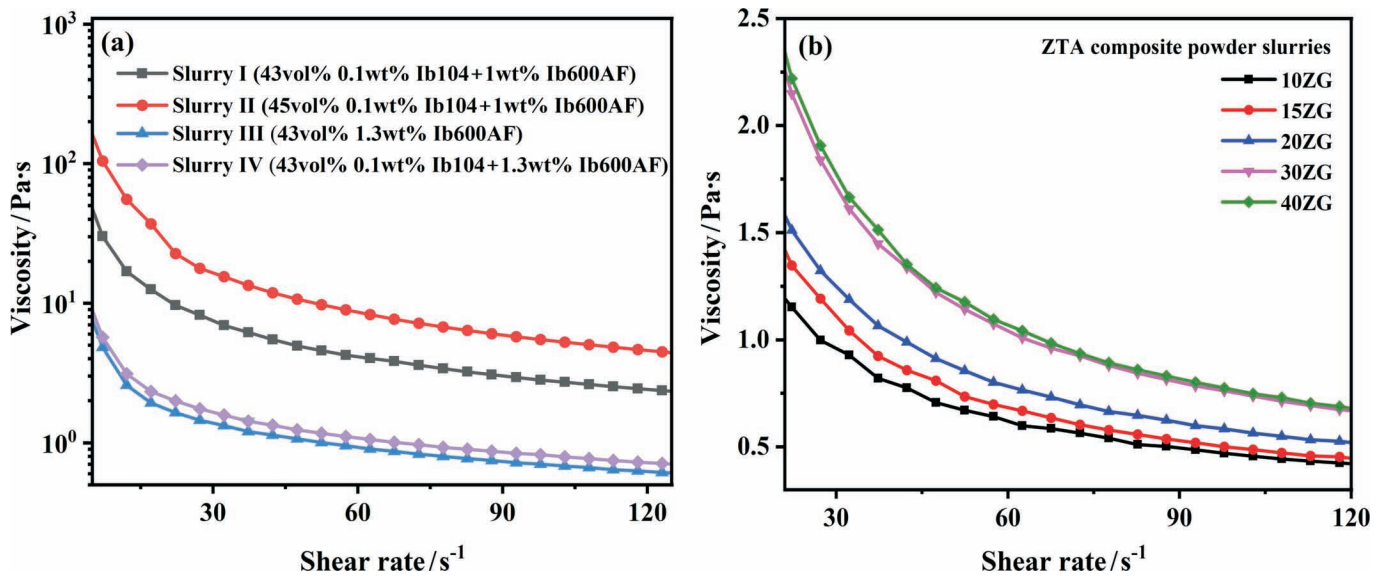


Fig. 1: The viscosity of the slurries of (a) YSZ powder with different solid loading and Isobam contents; (b) ZTA composite powders with different YSZ content (25 °C).

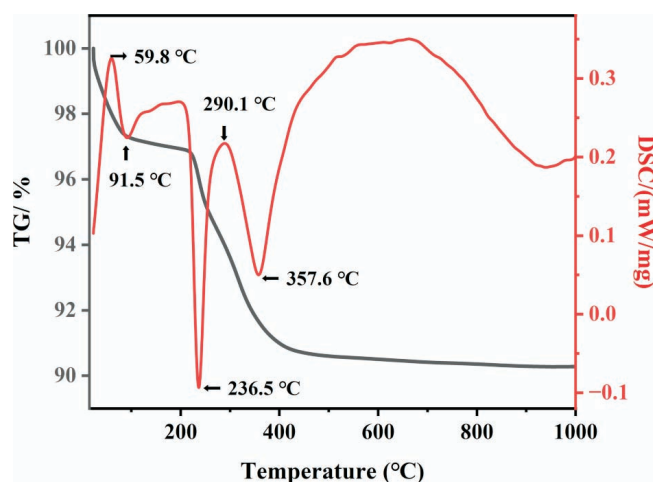


Fig. 2: TG-DSC curve of the 30ZG green body.

Fig. 3 shows the density and relative density curves of the five sets of green bodies prepared with the SCC and DP forming methods after 800 °C debinding. The density of the green bodies increases as the YSZ content increases because of the higher theoretical density of YSZ than that of alumina. It is observed that the relative density of the five components SCC green bodies initially increases and then decreases, peaking for the 20ZG green bodies. Overall, there is little change in relative densities for the five components SCC green bodies.

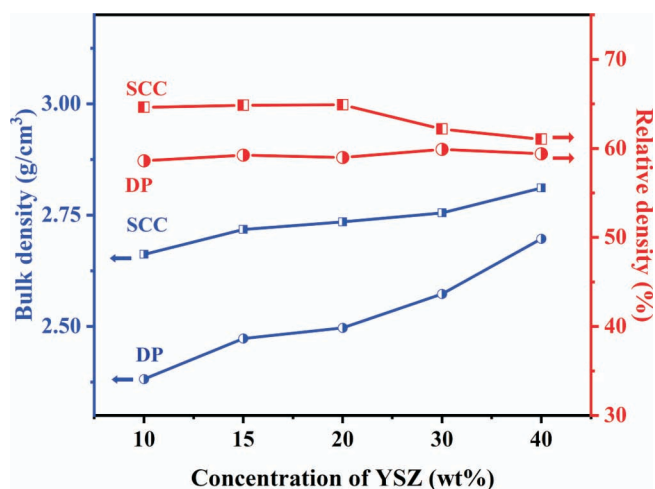


Fig. 3: Bulk density and relative density of ZTA green bodies with different YSZ contents prepared with the SCC and DP forming method, respectively.

(3) Characteristics of sintered ZTA ceramics

Fig. 4(a) shows the bulk density and relative density of ZTA ceramics prepared with two forming methods and sintered at five different temperatures. In brief, the ZTA ceramics with different YSZ contents, whether prepared with the DP or SCC forming method, show a trend of initially increasing density and relative density, followed by a decrease with the rise in sintering temperature. Differently, for ZTA ceramics prepared with the DP method, all samples achieve the highest density after being sintered at 1500 °C. While some of them for the ZTA ceramics prepared by means of SCC reach the highest density after sintering at 1550 °C. Furthermore, for ZTA ce-

ramics prepared with DP, when the sintering temperature is between 1450 °C and 1500 °C, the density of the ZTA ceramics with YSZ content ranging from 10 wt% to 40 wt% is higher than that of ceramics prepared with the SCC method. However, when the YSZ content is between 10 wt% and 20 wt%, the density of the ZTA ceramics sintered at 1400 °C is higher than that of ceramics prepared with the SCC forming method. When the sintering temperature exceeds 1500 °C, the density of all the ZTA ceramics with all compositions prepared with DP is lower than that of ceramics prepared with SCC. Moreover, with the increase in YSZ content, the densities of ZTA ceramics are all increased while the relative densities do not change much and were all around 99 % (Fig. 4f). This also indicates that all ZTA ceramics sintered at 1550 °C have relatively high densities.

Fig. 5 illustrates the variation in the flexural strength of ZTA ceramics with different compositions as a function of the sintering temperature. The change in flexural strength of the ZTA ceramics with increasing sintering temperature differs depending on the YSZ content and the forming method used. For ceramics prepared with the SCC forming method, as the YSZ content increases from 10 wt% to 15 wt%, the flexural strength of ZTA ceramics increases with the sintering temperature. When the YSZ content reaches 20 wt%, the flexural strength initially increases and then decreases with the sintering temperature, reaching a peak after sintering at 1550 °C. For ceramics prepared with the DP forming method, the change in flexural strength with increasing YSZ content and sintering temperature is similar to that of ceramics prepared with the SCC forming method, except for the samples with YSZ contents of 10 wt%. Overall, the flexural strength of ZTA ceramics prepared with the DP forming method is lower than that of ceramics prepared with the SCC forming method. This indicates that the SCC forming method has an advantage in preparing high-strength ceramics.

Fig. 6 analyzes the variation trends of the flexural strength, fracture toughness and hardness of the ZTA ceramics (sintering temperature: 1550 °C) prepared with the two forming methods with the increase of YSZ content. From Fig. 6a, it can be seen that with the increase in YSZ content, the flexural strength of ZTA ceramics prepared with the two forming methods increases, and the flexural strength of ZTA ceramics prepared with the SCC forming method is higher than that of the ZTA ceramics prepared with the DP forming method. Owing to the high strength, high hardness, and high toughness of ZTA ceramics, the mechanical machining of ZTA ceramics is extremely challenging. The test data of mechanical performance is greatly affected by the quality of ceramic processing, resulting in a high degree of data dispersion in test samples, which in turn weakens the regularity of the test results. As a result, the fracture toughness data in Fig. 6b is not very regular. However, it is generally opposite to the trend of the flexural strength, showing a decrease in fracture toughness with the increase of YSZ content in the ZTA ceramics.

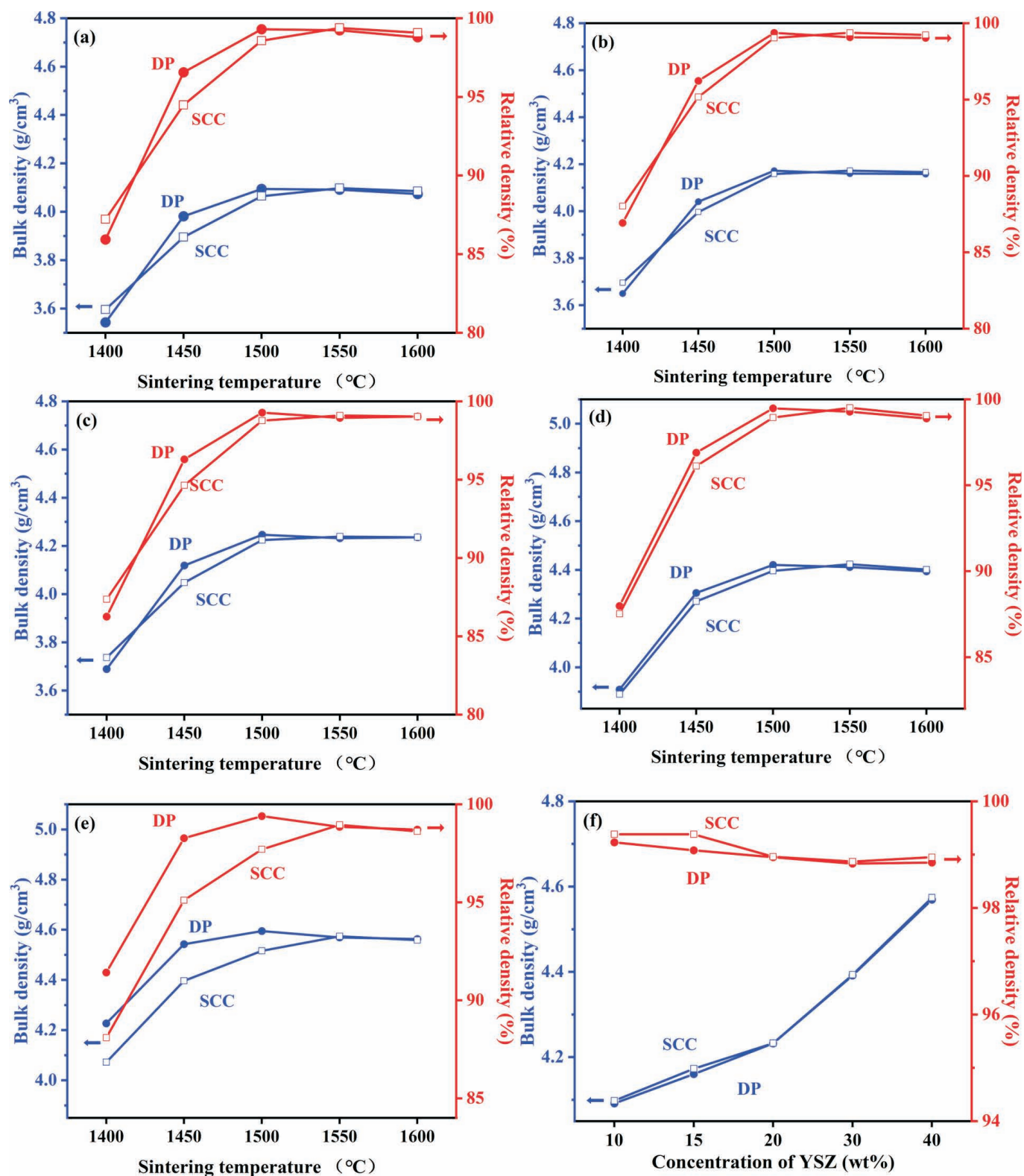


Fig. 4: Effect of sintering temperature on the bulk and relative density of ZTA ceramics with different YSZ content:(a) 10 wt%; (b) 15 wt%; (c) 20 wt%; (d) 30 wt%; (e) 40 wt%; (f) bulk and relative density of ZTA ceramics with different YSZ content sintered at 1550 °C.

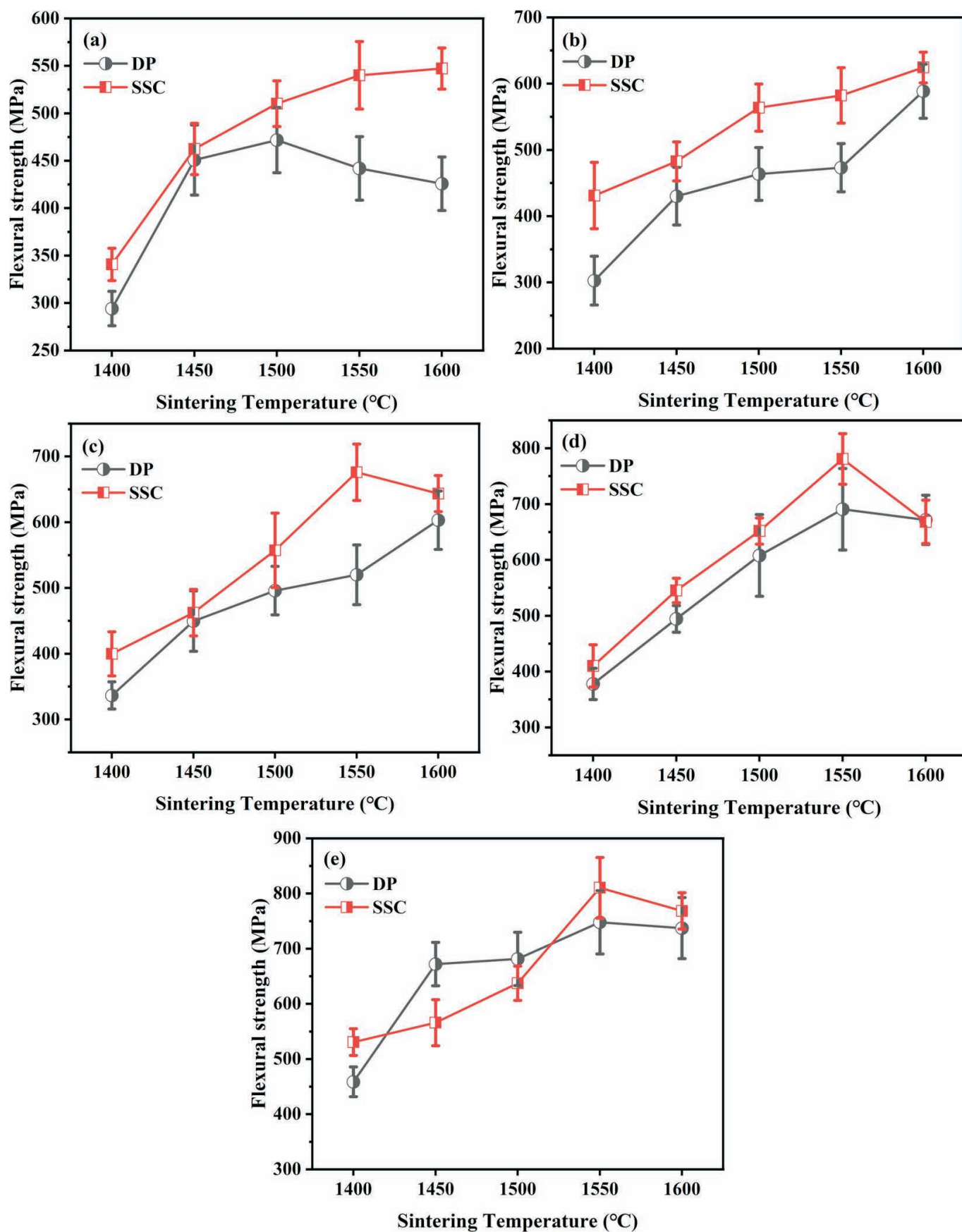


Fig. 5: Effect of the sintering temperature on the flexural strength of ZTA ceramics prepared by means of DP and SSC with different YSZ content: (a) 10 wt%; (b) 15 wt%; (c) 20 wt%; (d) 30 wt%; (e) 40 wt%.

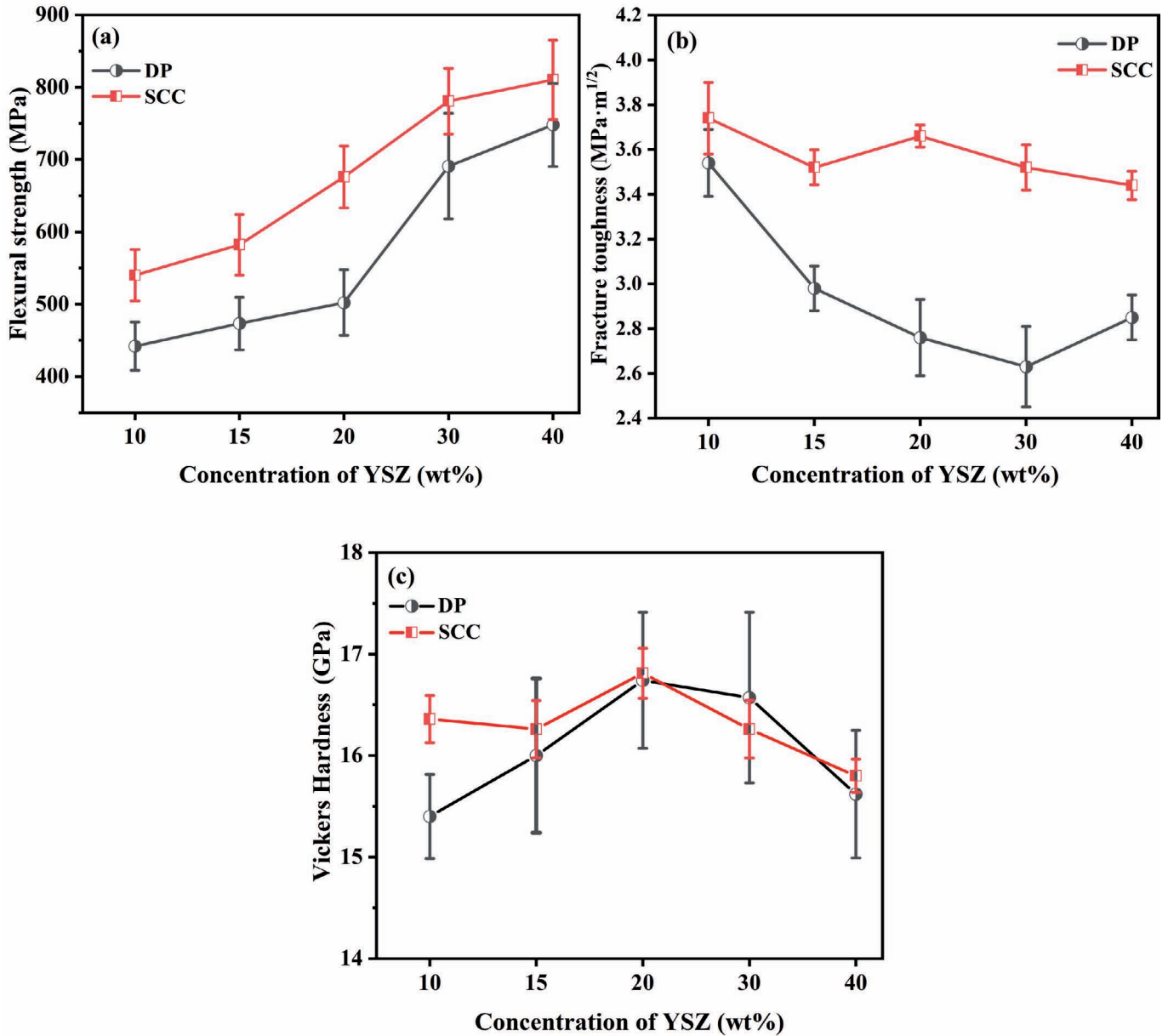


Fig. 6: (a) Flexural strength, (b) fracture toughness and (c) Vickers hardness of ZTA ceramics sintered at 1550 °C.

Usually, zirconia ceramics have higher flexural strength and fracture toughness than alumina ceramics, and hence are usually added into alumina ceramics to form ZTA composite ceramics to increase the strength and toughness of the ceramics. In the present work, the flexural strength of ZTA ceramics increases gradually with the increase in YSZ content, but their fracture toughness tends to decrease. This is mainly due to the fact that the grain size of zirconia shows an increasing trend with the increase in YSZ content, which leads to a deterioration in its toughening effect. In addition, the Vickers hardness (Fig. 6c) of the ZTA ceramics prepared with the two forming methods showed a trend of initially increasing and then decreasing with the increase in YSZ content, except for the 15ZG sample. Meanwhile, the Vickers hardness of the ZTA ceramics prepared with the two forming methods reached the highest value when the YSZ content is 20 wt%. In general, alumina ceramics have higher hardness than zirconia ceramics. However, the hardness is also affected by the grain size

(Hall-Petch relation, $H_v \sim 1/L^{1/2}$, where L is grain size)²⁶, and usually the smaller the grain size, the higher the hardness of the ceramic. As the YSZ content increases in this work, the size of the alumina grains gradually decreases (Fig. 7), but the alumina content also decreases. When the YSZ content is less than 20 wt%, the effect of the grain size is dominant, thus the hardness of ZTA ceramics increases with the increase in YSZ content. When the YSZ content is higher than 20 wt%, the effect of the alumina content dominates, and the hardness of ZTA ceramics gradually decreases with the increase in YSZ content. Ceramic hardness and flexural strength are closely related to the material porosity and grain size. Suzuki *et al.* reported that in the initial sintering stage, Vickers hardness is related to porosity, while in the later sintering stage, Vickers hardness is related to grain size³¹. With the increase in YSZ content, the alumina grains are refined, enhancing the flexural performance by constraining the matrix, as shown in Fig. 7. However, when the YSZ content exceeds 20 wt%,

the ZrO_2 grains become enlarged, leading to a weaker pinning effect of ZrO_2 grains at grain boundaries, resulting in a decrease in hardness and wear resistance.

SEM images of the thermally etched surface and grain sizes of the ZTA ceramics sintered at 1550 °C are shown in Fig. 7. The thermal etch of the polished ceramic surface was carried out in a muffle furnace at 1450 °C for 2 h. From Fig. 7a – 7e, it can be seen that the grain sizes of the two phases in the ZTA ceramics formed with SCC change with the increase in YSZ content. The average grain size of the alumina (the dark grains) gradually de-

creases from 1.07 μm to 0.86 μm , while that of zirconia (the white grains) gradually increases from 0.37 μm to 0.52 μm . The above results are similar to the findings of Gafur²⁶. When the YSZ content is increased from 30 wt% to 40 wt%, the changes in grain size of alumina and zirconia are very small. It is evidenced that the addition of zirconia to alumina ceramics can inhibit the growth of alumina grains. It was also found that the inhibition effect of zirconia grains on the growth of alumina grains gradually diminished with the increase in YSZ content^{32,33}. In addition, when the YSZ content is 40 wt%,

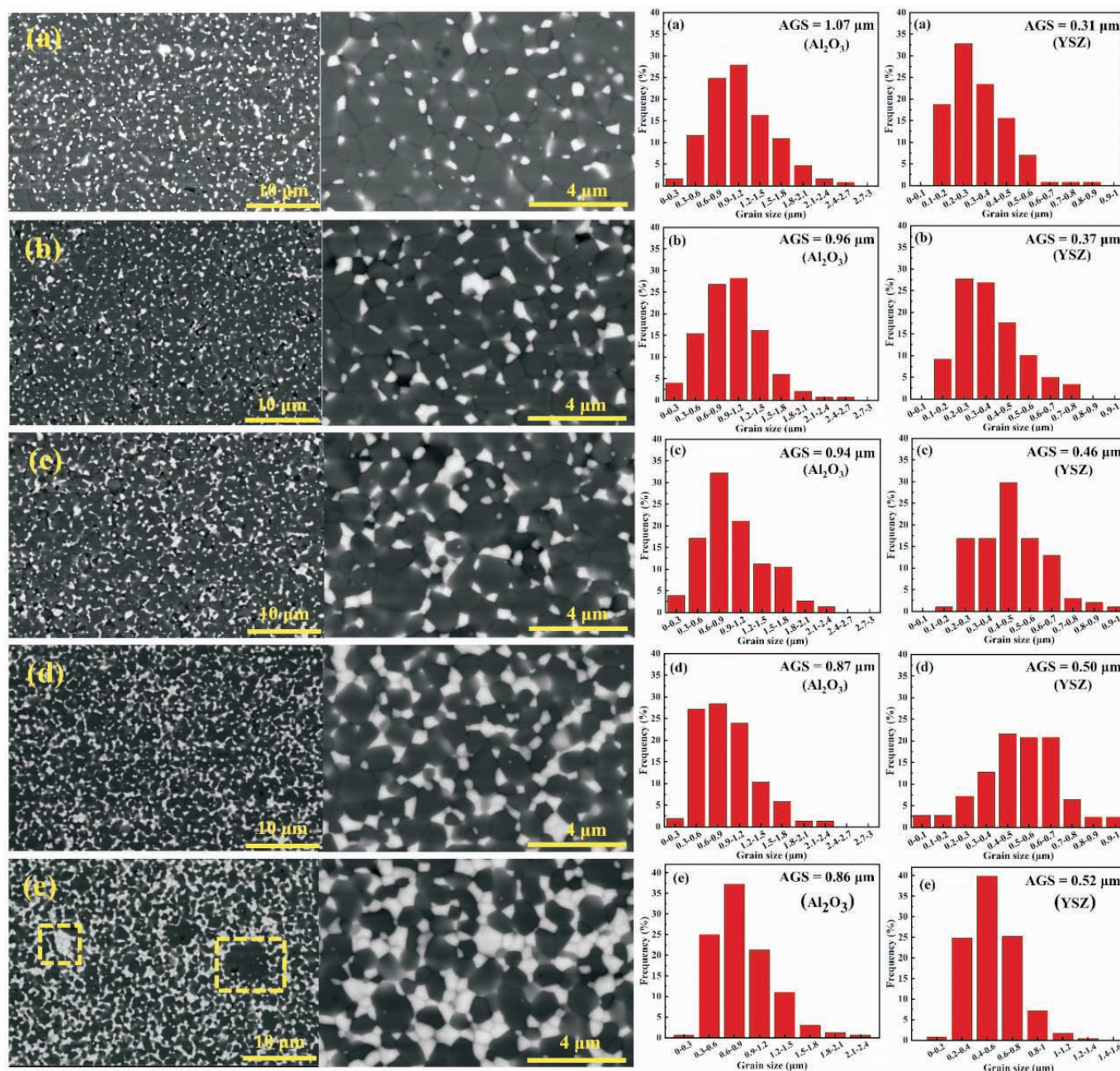


Fig. 7: SEM images of the thermally etched surface and grain sizes of (a) 10ZG, (b) 15ZG, (c) 20ZG, (d) 30ZG, (e) 40ZG and (f) 40ZD ZTA ceramics sintered at 1550 °C.

there are some enriched zones of alumina and zirconia grains in the ZTA ceramics, which suggests that the slurry 40ZG used for SCC forming is not very homogeneous with regard to the dispersion of the two powders due to the high viscosity, and there are agglomerates of particles that have not been dispersed completely and homogeneously. This enriched area is a region of accumulation defect and porosity³⁴. Therefore, the SCC process for ZTA ceramics of this composition needs to be further optimized.

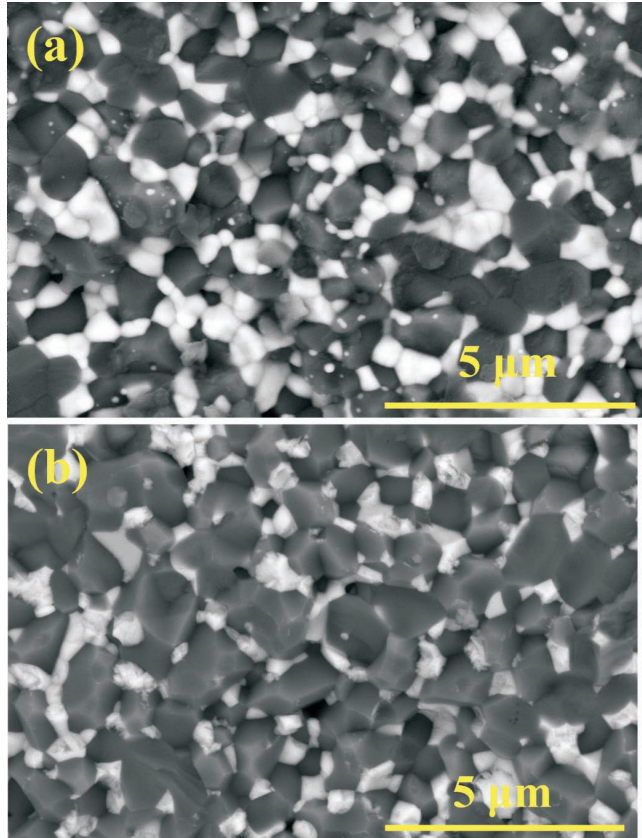


Fig. 8: SEM images of the fracture surface of (a) 20ZG and (b) 20ZD ZTA ceramics sintered at 1550 °C.

Fig. 8 shows the SEM images of the fracture surface of 20ZG and 20ZD ZTA ceramics sintered at 1550 °C. It can be observed that the fracture mode of the 20ZG and 20ZD ceramics is different. In the 20ZG ceramic, the fracture mode of zirconia grains is mainly transgranular fracture, while in the 20ZD ceramic, the zirconia grains mainly exhibit intergranular fracture. Niihara³⁴ classified nanocomposites into three types: intragranular, intergranular, intragranular/intergranular, and discovered that the mechanical properties of the composite materials are significantly improved by the complex structure within the grains. A large amount of intragranular ZrO_2 is present in the alumina grains of 20ZG, while it is hardly observed in the fracture surface of 20ZD. Studies have shown that

the intragranular zirconia structure not only helps stabilize the grain boundaries of alumina but also effectively inhibits the growth of alumina grains. This structure can undergo phase transformation under external stress, providing a certain shielding effect. Additionally, the intragranular zirconia structure can induce a “nano-scale effect”, generating a large number of subgrains and multiple subgrain boundaries within the matrix, effectively hindering the propagation of microcracks. The presence of this structure significantly enhances the flexural strength and fracture toughness of ceramics^{35, 36}. This is one of the reasons for the higher flexural strength of ZTA ceramics prepared with the SCC method compared to the DP forming method (Fig. 5).

Fig. 9 shows the friction and wear performance data of ZTA ceramics prepared with the SCC and DP forming methods. In Fig. 9a, it is evident that the friction coefficient of all samples shows a “running-in period” followed by a “stable period” as time increases, with the running-in period being within 400 s, followed by onset of the stable period. The friction coefficient in the stable period is relatively stable with small fluctuations. From Fig. 9b, it can be observed that the average friction coefficient of ZTA ceramics prepared with both forming methods increases with the increase in YSZ content. Meanwhile, the average friction coefficient of ZTA ceramics prepared with the SCC method is higher than that of ZTA ceramics prepared with the DP method. From Fig. 9c, it can be seen that the wear rate of ZTA ceramics prepared with the two forming methods first increases, then decreases, and then increases again with the increase in YSZ content. The wear rate of ZTA ceramics prepared with the two forming methods reaches its lowest value at a YSZ content of 20 wt% in both cases. Additionally, when the YSZ content is not higher than 20 wt%, the wear rate of ZTA ceramics prepared with SCC is higher than that of the ZTA ceramics prepared with the DP method. However, when the YSZ content is higher than 20 wt%, the wear rate of the ZTA ceramics prepared with SCC is lower than that of the ZTA ceramics prepared with the DP method. From the combination of the data from Fig. 9 and Fig. 6, it can be established that the ZTA ceramics with a YSZ content of 20 wt% have high hardness and a low wear rate, which is a more suitable compositional choice for application as a wear-resistant material in this research work. The above research results indicate that, compared to ZTA ceramics prepared with the DP forming method, ZTA ceramics prepared with the SCC forming method have more advantages with regard to their mechanical properties. In future work, further optimization of the SCC forming method for preparing ZTA ceramics can be carried out to further enhance the performance of ZTA ceramics.

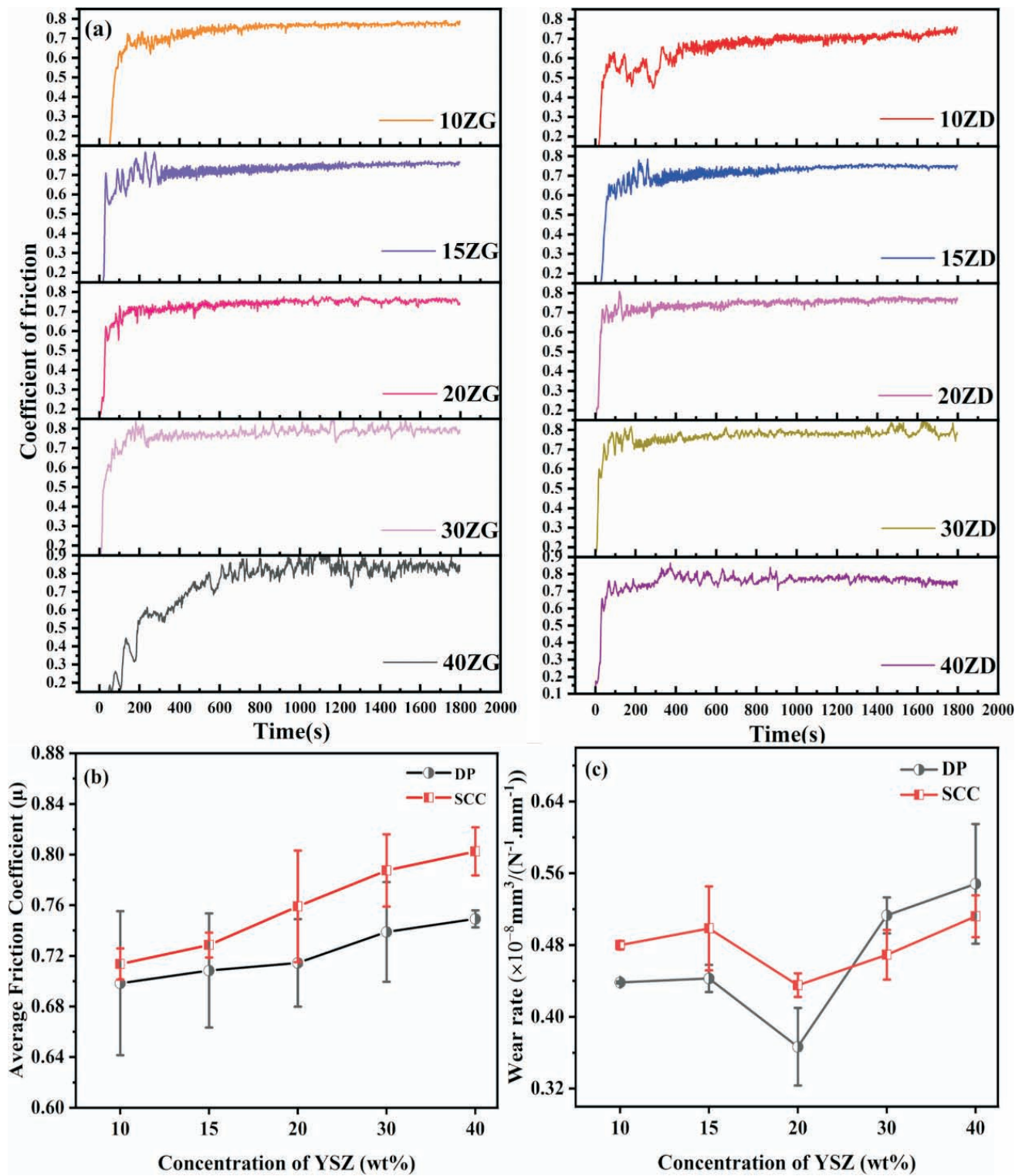


Fig. 9: Friction and wear performance data of ZTA ceramics prepared with the SCC and DP forming methods: (a) friction coefficient vs. time, (b) average friction coefficient, (c) wear rate.

IV. Conclusions

The SCC forming method was used to prepare ZTA composite ceramics for the first time. Based on a systematic comparison of the SCC forming method and the DP forming method for the preparation green bodies and ceramics in terms of density, microstructure, mechanical properties, and friction and wear performance, the following conclusions were drawn: Compared to DP forming method, the SCC forming method can achieve high-

er-density green bodies, and can result in ZTA composite ceramics with excellent mechanical properties, including flexural strength, Vickers hardness, and fracture toughness. In addition, ZTA ceramics prepared with the SCC method have a higher average friction coefficient and wear rate when the YSZ content is below 30 wt%. When the mechanical properties of ZTA composite ceramics with different YSZ contents was compared, it was found that with the increase in YSZ content, the flexural strength of ZTA

ceramics gradually increases, while the fracture toughness gradually decreases, and the Vickers hardness shows a trend of first increasing and then decreasing. The wear rate of ZTA ceramics shows an opposite trend to Vickers hardness, reaching the lowest value at 20 wt% YSZ content, which is promising for the application of ZTA ceramics in the field of wear resistance.

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