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Contact wear of Low-Zirconia Toughened Alumina (ZTA) produced by a colloidal process

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This study focuses on the wear and related mechanical properties of zirconia-toughened alumina (ZTA) composites with 4.7-30 vol% yttria doped-TZP (YTZP) particulates. A colloidal process was used to achieve a homogeneous distribution of fine TZP grains in an alumina matrix. Mechanical properties, flexural strength, hardness, fracture toughness, and contact wear were measured. Quantified microstructures by SEM are also reported. A wear-resistant ZTA with a low-zirconia content (< 5%) was obtained by improvements in microstructural homogeneity and optimization.

Key words: ceramics, composites, colloid process, wear, mechanical properties.

Introduction

Zirconia toughened alumina (ZTA) is a kind of binary composite, of where zirconia is added to an alumina matrix as a boundary phase. Due to the effect of stress-induced phase transformation toughening performed by the t-ZrO_2 phase, the mechanical properties of ZTA are greatly improved and superior to pure Al_2O_3. The past literature, [1-4] has shown that fracture toughness, flexural strength, bio-compatibility, and the tolerance to inner flaws can be effectively improved by adding 25 vol% t-ZrO_2 in Al_2O_3 matrix.

In this study, two compositions of ZTA with 5-10 vol% yttria zirconia particulates (denoted by A90Z* and A95Z), were investigated, and compared to ZTA composites normally with 25 vol% or more zirconia. We tend to keep the best dispersion of YTZP particles in the Al_2O_3-ZrO_2 colloidal system and create an optimal microstructure with good homogeneity in the sintered body, and thus investigate the mechanical properties, especially the contact wear and wear mechanism as a function of the zirconia dopant.

Experimental Procedure

Al_2O_3 (AKP-30, Sumitomo, Japan) and 3Y-TZP (TEAMCera Co., ROC) powders were individually dispersed to aqueous slurries using an ammonium poly- methacrylate anionic dispersant (Darvan C, Venderbilt Co., USA) and an ammonium homopolymer of 2-propenoic acid (D-134, Dai-ichi Kogyo Seriyaku Co., Ltd., Japan) as the dispersing agent, respectively. The slurries were ball-milled for 16-20 h until the powders were fully dispersed*. After the slurries were mixed together in specific ratios (A90Z, A95Z, A85Z, or A70Z), the water in the mixed slurry was eliminated by a pressure filtration method to give green bodies with dimensions 5 × 4 × 50 mm^3. Finally, the green bodies were sintered in air, with a heating rate of 10K/min up to 1600°C and held for 1 h. The detail procedures are reported in a previous document [5].

The sintered body density was measured by Archimedes method. The flexural strength was measured by a 4-point bending test method. [6] The hardness was measured by a Vickers Hardness tester (AKASHI, MVK-EII Hardness tester), indentation loads of 264 N were applied for 15 s. The plane strain fracture toughness (K_{IC}) was measured by an indention fracture method. A block-on-wheel testing method was used for the contact wear tests. The specimens were tested with a multi-purpose friction and wear tester (TE52/7891, Plint & Partners, England).

The microstructures were observed by FESEM (Field Emission SEM, LEO Instrument 1530, England). The grain sizes were measured by a linear interception method. More than 200 grains were analyzed from the SEM images to ensure the statistical significance.

Results and Discussion

Microstructure

The SEM images of polished surfaces of A90Z and A95Z are shown in Fig. 1. The bright grains are zirconia and the dark ones are alumina grains. Nearly all the zirconia grains are located at alumina grain boundaries. The important microstructural and mechanical properties of ZTA with different contents are summarized in Table 1, which shows that the average grain size of ZrO_2 in A95Z is 0.15 μm smaller than the others, because the ZrO_2 particles were mono-dispersed in

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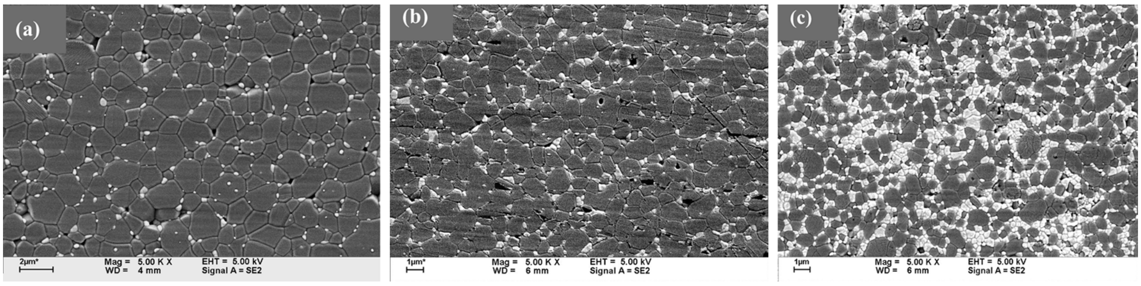

Fig. 1. SEM micrographs illustrating the polished microstructure of ZTA samples (a) A95Z (ave. 4.6 vol%), (b) A90Z (ave. 8.6 vol%), and (c) A70Z (ave. 28.6%). These specimens were sintered at 1600 °C for 1 hr.

Table 1. Properties of A95Z, A90Z, A85Z, and A70Z composites

	A95Z	A90Z	A85Z	A70Z
D_A(µm) [1]	1.41	0.98	0.92	0.71
H_A (%) [2]	45	43	47	45
D_Z (µm) [1]	0.15	0.20	0.50	0.44
H_Z (%) [2]	43	44	50	69
Flexural strength (MPa)	561	594	656	551
Weibull modulus	10.8	7.02	15.1	14.5
Sintered relative density (%)	99.7	99.5	99.8	100.0
Hardness (GPa)	17.7 ± 0.4	17.1 ± 0.2	17.2 ± 0.2	14.3 ± 0.3
K_{IC} (MPam$^{1/2}$)	3.8 ± 0.5	3.9 ± 0.2	4.9 ± 0.3	5.4 ± 0.1
W_r (× 10^{-8} cm^3/Nm)[3]	25.4	18.3	11.3	7.2

Note: [1] D_A and D_Z denote the average grain size of Al_2O_3 and ZrO_2, respectively, At least 200 grains were analyzed from SEM micrographs.
[2] H_A and H_Z represents the degree of homogeneity of Al_2O_3 and ZrO_2 phases, respectively, which is calculated as shown below.

$$H_i = \frac{\sigma}{X} \times 100\ \%$$

is the degree of homogeneity of i phase, σ and X are the standard deviation and average of grain cluster size, respectively.
[3] W_r represents the contact wear rate.

A95Z, compared to some agglomerates found in A90Z and A70Z (Fig. 1(c)). So the grain coarsening of alumina and zirconia hardly occurred, which resulted in smaller ZrO_2 grains.

The degree of homogeneity (H_A) of Al_2O_3 is slightly lower in A90Z than that in A95Z, which may be explained by the fact that abnormal grain growth hardly occurs when the content of the second phase is lower, or most possibly due to the variation of the H_A analysis level.

Mechanical properties

He et al. [7] reported that the wear rate of ZTA was influenced by the grain size, and that the hardness, toughness and Young's modulus of the material, are given by a relation shown below:

$$W_r = G^n K_{IC}^{-1/2} H^{-5/8} (E/H)^{4/5} \tag{1}$$

where W_r represents the wear rate, G is the grain size of alumina, H is the hardness, K_{IC} is the fracture toughness, E is the Young's modulus of the composite, and n varies from 0.5 to 1. The relation also holds in the ZTA samples in this study, as shown in Fig. 2 along with the data for A70Z and A85Z [5]. The SEM image (Fig. 3b) of the worn surface of A95Z clearly appears to show no brittle fracture, which is similar to the samples with 15 or 30 vol% YSZ. The fitting line in Fig. 2 of four ZTA samples show a good linear rela-

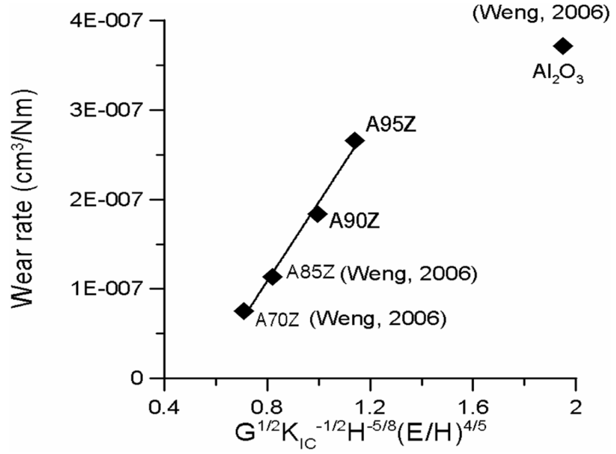

Fig. 2. The relationship between contact wear rate and the combination of material properties reported by [7].

The number 90 means the volume percent of the zirconia particulate. Same notation used in the following sample abbreviations.

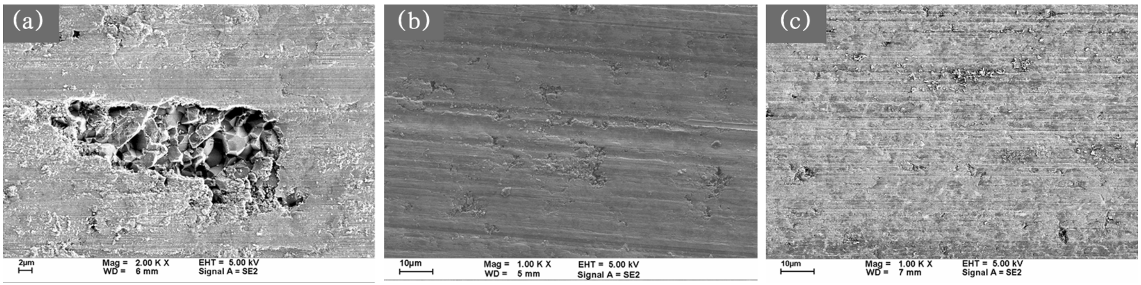

Fig. 3. SEM micrographs showing the worn surfaces of (a) pure alumina, (b) A95Z, and (c) A85Z samples test at applied normal load of 42 N and a sliding velocity of 0.63 m/s.

tionship to their material properties, implying the wear mechanism of these ZTA samples is identical, but different from that of pure alumina.

The variation of flexural strength with composition can probably be interpreted differently reasons from a microstructural viewpoint. In general, ZTA samples with a higher zirconia content exhibit higher fracture strengths, which corresponds to the rising trend of strength from A95Z to A85Z in Table 1. An increase in the strength when the composition varies from 30 to 15 vol% ZrO_2 is uncommon. This may be because the mean size of the ZrO_2 grains in A85Z is closer to the "critical size" [8], so that the phase-transformation toughening is more active than it is in A70Z. However, the strength of A95Z and A90Z are still greater than that of A70Z and pure alumina [9]. This may be a ZrO_2 grain-size effect, because the ZrO_2 grain sizes are far smaller than the critical size, so the toughening effect will be limited. The other possibility, of a finer Al_2O_3 grain size, is not effective in this comparison (A95Z vs. A70Z).

The contact wear is improved because as the alumina grain boundaries are reinforced by zirconia particles. ZrO_2 particulates, either as agglomerates or freely dispersed, may act as crack-front deflectors, [3, 8] which is proper for the quasi-plastic deformation of alumina grains. The worn microstructure of A95Z (Figs. 3(b) and 3(c)) is representative and different from the brittle fracture seen on alumina worn surfaces. Apparently, the decrease in ZrO_2 agglomerate size by the colloidal processing effectively improves the fracture strength and fracture mode of the ZTA composites.

Conclusions

The mechanical properties of ZTA are closely related to its microstructure. The wear rate of four ZTA samples shows a linear relationship as a specific function of several material properties. Quasi-plastic deformation and similar worn surfaces were found for ZTA com- posites with the zirconia content as small as 4.7 vol%.

Fracture strength is controlled by complex factors, such as grain size, and fracture origin, etc. In this study, the strength was found to maintain a level higher than 550 MPa when the fine-grain YSZ is in a well-dispersed condition. The low-level-YSZ ZTA samples give a strength 100-150 MPa higher than that of high-quality Al_2O_3. The degree of homogeneous dispersion in the colloidal stage is important in fine-turning the sintered-body microstructure and mechanical properties.

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The state means that the particle size measurement should reach single-mode distribution and the average particle size did not decrease.