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Influence of Machining on the Strength of $SiC–Al_2O_3–Y_2O_3$ Ceramic

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Abstract: The influence of surface machining on the mechanical strength of SiC ceramics was investigated in terms of surface roughness, residual stress, and surface morphology observation. Experimental results showed that the mechanical strength of the SiC ceramic appears to correlate with the surface roughness of the ceramics: the lower the surface roughness, the higher the flexural strength. An average four-point bending strength of as high as 700 MPa, which is higher by a factor of 1.8 than the ceramic with as-fired surface, can be achieved after the surface of the specimens is polished with a 600-grit fine diamond wheel. More extensive surface polishing deteriorates the strength by forming large surface pores which act as failure origins. Machining-induced compressive residual stress in the thin surface layer of the ceramic appears to increase the fracture stress to only a limited extent.

1 INTRODUCTION

The requirement of fabrication of high-strength advanced ceramics is increasingly important in modern advanced applications and is a subject of constant interest for many ceramic researchers. Unfortunately, their inherent brittleness makes them extremely sensitive to microstructural defects, particularly those defects on the surface of ceramic products. Since the strength of brittle materials is virtually a weak-link process, those surface defects, particularly with size greater than some critical value, promote the fracture process by stress concentration on loading. Therefore, optimum processing for a substantial reduction of the defect size either within the matrix or on the surface of ceramics has become critically important.

Machining is an unavoidable, and usually the final-stage, process for the requirements of both dimensional control and surface quality control of the final ceramic products. Surface damage would frequently be introduced during the machining and consequently reduced materials' reliability, resulting in poor service performance. In the study of machining-induced mechanical properties, particularly fracture strength, several investigations have correlated surface roughness parameters[1,2] and/or residual stresses[3–5] with the resulting strength data. Recently, Frei and Grathwohl[5] investigated the effect of machining on the strength of Al_2O_3, $ZrO_2–Al_2O_3$, and Si_3N_4 ceramics and they found that the strength for Al_2O_3 and Si_3N_4 ceramics can be correlated with the surface roughness rather than the compressive residual stresses. For instance, a residual stress as high as $\sim$1000 MPa near the Si_3N_4 surface was detected, but showing a negative influence on the strength. However, for $ZrO_2–Al_2O_3$ composite, extensive compressive residual stress due to machining-induced phase transformation enhanced the resulting strength. In the machining of SiC ceramic, Dutta[6] indicated, after different levels of surface treatment, that the influence of machining on the strength value is negligibly small for the SiC body containing large voids near to the ceramic surface. In this investigation, α-SiC with the addition of Al_2O_3 and Y_2O_3 as sintering aids was fabricated, which has recently been reported to exhibit prominent fracture toughness.[7] The strength behaviour and associated surface properties of the specimens machined with different levels of diamond wheel were discussed.

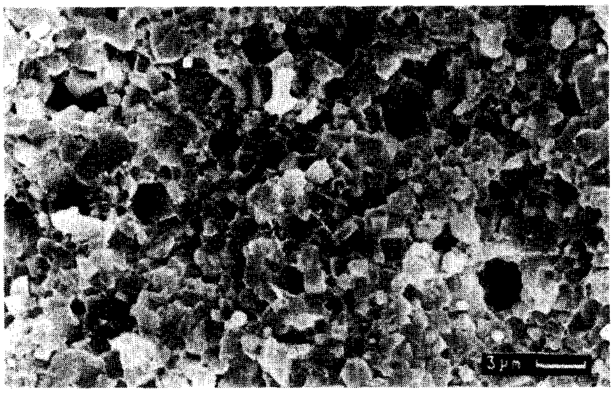

Fig. 1. SEM observation of the fractured surface of the SiC–Al_2O_3–Y_2O_3 ceramic.

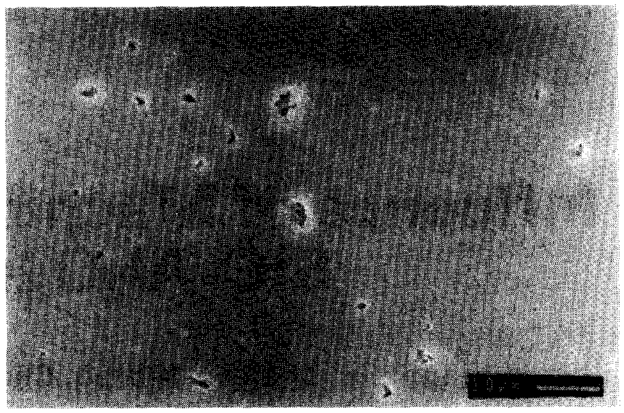

Fig. 2. Surface morphology of the specimen after 1200-grit diamond polishing.

2 MATERIALS PREPARATION

To avoid or minimize the formation of microstructure defects within both green and fired compacts, a colloidal process is employed. Ceramic slip containing 90% α-SiC (Showa Denko, Japan, 0.48 mm in diameter), 6.2% Al_2O_3 and 3.8% Y_2O_3 powders, deionized water and commercially available dispersing agent was prepared by ball milling in a polyethylene jar for several tens of hours. The slip was then poured slowly on to the plaster mould to form a green cake of 7-mm thickness and 50-mm diameter. A more detailed procedure and characterization for the preparation of the slip and green compact have been described separately.[8,9] After drying and heat-treating to remove the volatiles, the cakes were sintered at 1900°C for 2 h, then further increase of the temperature to 2000°C for 30 min in Ar atmosphere. The fired density of the specimens was measured using the Archimedes method.

The fired cakes were cut into bending bars and followed by polishing with 200-, 600-, 1200-, and 3000-grit diamond wheel (Taiwan Diamond Co.) at a constant loading of 4 MPa and at a wheel speed of 300 rpm. Five to seven specimens were collected and chamfered after each step of machining and examined with surface roughness (Hommelwerke, Model LV-50E) and scanning electron microscopy (Cambridge Instruments, Model S360). The fracture strength of the specimens having dimensions of approximately 3 mm × 4 mm × 40 mm was measured using a four-point bending fixture with 10 mm top and 30 mm bottom spans (Instron, Model 1361). X-ray residual stress analysis with CuK_α radiation (Philips, Model 1700) was employed to determine surface residual stress of the specimens after different levels of polishing.

3 RESULTS AND DISCUSSION

In a previous investigation,[9] the green microstructure of the cast body has been examined extensively and is shown to be homogeneous, with a green density of ~68% of theoretical density. No large voids can be found within the green compacts.

The sintered density of these compacts was measured to be 98.7– 99.2% of theoretical density (3.29 g/cm^3). Figure 1 shows that the sintered body exhibits a fairly uniform microstructure with an average grain size of approximately 2–3 μm but with a few intergranular voids of 1–3 μm in size. After different levels of machining, Table 1 summarises the surface roughness parameters of the specimens. It is interesting to note that a minimum surface roughness is obtained by machining with 600-grit diamond wheel, but the roughness increases on further machining with 1200- and 3000-grit fine diamond wheel. This increase of surface roughness is probably due to the formation of machining-induced surface pores during polishing. An SEM

Table 1. Surface roughness parameters (units in μm) for the SiC–Al_2O_3–Y_2O_3 ceramic after different levels of surface machining

	As-fired	200-grit	600-grit	1200-grit	3000-grit
R_a	4.24	0.31	0.02	0.02	0.09
R_{max}	25.47	1.29	0.29	0.53	0.85
R_z	23.25	1.14	0.2	0.41	0.58

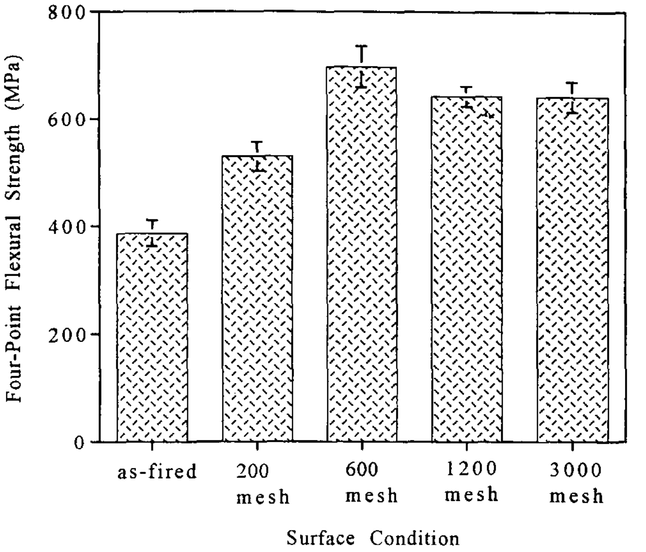

Fig. 3. Four-point flexural strength of the SiC–Al_2O_3–Y_2O_3 ceramics in terms of different levels of surface polishing.

examination of the surface polished with 1200-grit diamond wheel (shown in Fig. 2) reveals the presence of surface pores; some of the pores are large in size, 5–6 μm, and some of them have a size of 2–3 μm, which is equivalent to the average grain size of the SiC ceramic. This finding suggests that some of the surface pores may be generated by means of a grain fall-off mechanism.

Figure 3 shows the flexural strength of the SiC ceramics in terms of different levels of machining. The SiC ceramic with as-fired surface exhibits the lowest strength, i.e. 387 MPa. However, after 200-grit machining the strength increases by ~37%, and reaches the highest value of ~700 MPa (80% increase) while machining with 600-grit diamond wheel. Further surface polishing weakens the flexural strength to approximately 640 MPa. This strength behaviour appears to correlate reasonably with the trend of surface roughness (Table 1) and is similar to the strength–roughness behaviour observed for Al_2O_3 and Si_3N_4 ceramics, whose strength are strongly related to surface flaws irrespective of the formation of compressive residual stress surface layer.[5]

To gain a better understanding of the strength behaviour due to machining, the surface residual stress was calculated by measuring the lattice strain by X-ray diffraction analysis. The measuring conditions and resulting residual stress (within ±15 MPa accuracy) at each corresponding surface layer of the specimens polished by 200-, 600-, and 3000-grit diamond wheel, respectively, are listed in Table 2. The surface stress of the specimens was typically compressive and decreased with penetration depth up to a depth of 140 μm. The magnitude of the surface residual stress appears to reduce upon a higher level of polishing. Since the resulting residual stress is derived directly from lattice strain, the smaller the lattice strain, the smaller the residual stress. Therefore, a higher level of polishing, e.g. 3000-grit diamond wheel, induces a smaller change in near-surface lattice strain and gives rise to a depth of the strain field less than that of a lower level of polishing. This may be the

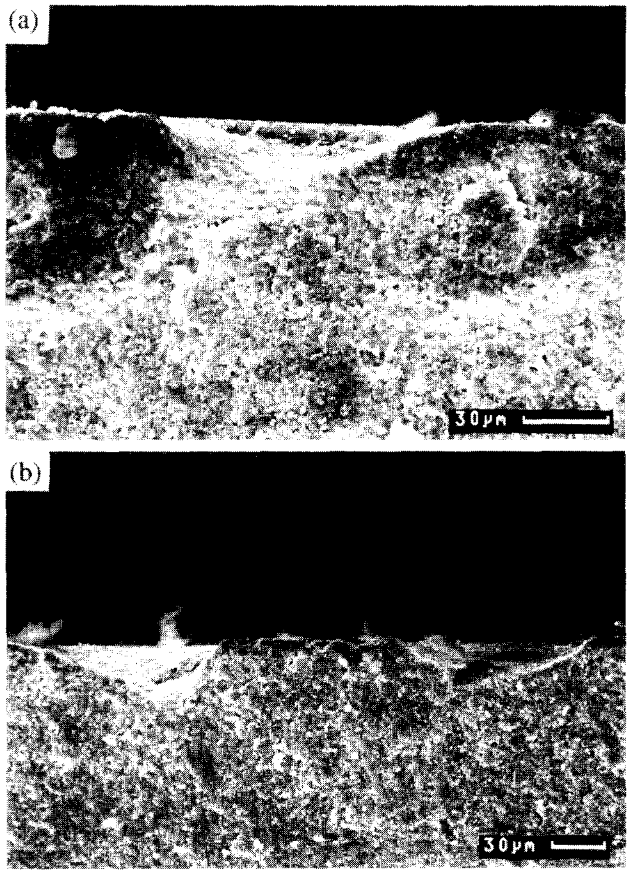

Fig. 4. Fractured surface SEM observation showing the presence of a large surface flaw after (a) 600-grit and (b) 3000-grit diamond polishing.

Table 2. X-ray residual stress analysis data for SiC–Al_2O_3–Y_2O_3 ceramics polished with 200-, 600-, and 3000-grit diamond wheel

Lattice plane	Penetration depth (μm)	Stress (MPa) 200-grit	Stress (MPa) 600-grit	Stress (MPa) 3000-grit
(102)	46	316	280	208
(110)	76	224	208	176
(116)	89	176	152	131
(1016)	132	156	136	115
(2110)	140	103	80	42

reason responsible for the decrease in strength discussed earlier. However, the influence of the residual stress on the strength behaviour can not be satisfactorily explained for the specimens polished with 200- and 600-grit diamond wheel, because the magnitude of their residual stresses is roughly similar. Further analysis of the residual stress at depth, for instance 10–20 μm beneath the surface, failed due to the limitation of the X-ray diffractometry.

The fractured surface of the specimens was examined using SEM. Figure 4(a) and (b) show the presence of surface pores (or flaws) as large as ~ 100 μm at the specimen surface polished with 600- and 3000-grit diamond wheel, respectively. These pores are believed to be machining-induced and are not revealed explicitly by the surface roughness data (particularly the values of R_{max} in Table 1), which is probably due to the nature of the measurement. According to the fracture theory,[10] the flaw size (c) can be determined using $K_{1c} = \sigma (Yc)^{1/2}$, where K_{1c} is the fracture toughness (5.4 $MPa{\cdot}m^{0.5}$)[11] and σ is the flexural strength (700 MPa) of the SiC ceramic, for a halfpenny-shaped flaw. The flaw size is then calculated to be approximately 32 μm, which is much smaller in size than the surface flaws mentioned above. Therefore, these large pores are considered to act as failure flaws. Since the penetration depth of the compressive residual stress is considerably greater in magnitude than the flaw size, the increase of the applied stress is thus necessary to compensate the residual stress, resulting in an increased fracture strength. However, this increase in strength is limited due to the presence of large surface flaws.[12] The lower strength for the specimens with 200-grit diamond polishing compared with that from 600-grit polishing may thus be a result of the presence of large surface flaws.

4 CONCLUSIONS

The effect of machining on the fracture strength of the $SiC–Al_2O_3–Y_2O_3$ ceramic was investigated. The strength behaviour appears to correlate with surface roughness: the lower the surface roughness, the higher the resulting strength. Further analysis of surface residual stress and fracture surface observation revealed that the strength may be enhanced by the presence of a compressive residual stress surface layer. However, the enhancement of the strength is inhibited due to machining-induced surface flaws of a size ~ 100 μm, which is considerably larger than the calculated critical flaw size, ~ 32 μm. Although a maximum four-point fracture strength as high as 700 MPa is achievable in the present study, it suggests that the strength of the $SiC–Al_2O_3–Y_2O_3$ ceramic can be further enhanced by diminishing the machining-induced surface flaws with optimization of the machining process and by maximizing the compressive residual stress.

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