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Erosion of a reaction bonded silicon nitride

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Many potential applications of silicon nitride involve solid particle erosion at elevated temperatures. The typical examples of such applications are the key components in the hot section of a gas turbine engine. One variety of such silicon nitride is the reaction bonded silicon nitride. Though the mechanical properties of this material are not particularly outstanding at room temperature, they are known to be retained up to very high temperatures since this material typically does not contain a grain boundary phase that softens and degrades the properties at elevated temperatures.

The temperature dependence of erosion rate has been reported for sintered and hot pressed silicon nitrides [1, 2]. The temperature increases the erosion rate of hot pressed silicon nitrides [1], whereas it decreases the erosion rate in sintered silicon nitride [2]. Thus, it is difficult to predict erosion behavior of reaction bonded silicon nitride at elevated temperatures based on these results. In addition, the hardness and fracture toughness that are known to control the erosion of ceramics are much lower for this material compared to hot pressed and sintered silicon nitrides. In this report, the effects of temperature, impact velocity and impact angle on the erosion rate of a reaction bonded silicon nitride were investigated.

The target material used in this investigation is a high purity reaction bonded silicon nitride supplied in disc form with the following properties: density $\rho = 2.4$ g·cm^{-3}; hardness $H = 7.8$ GPa; fracture toughness $K_{\mathrm{IC}} = 2.5$ MPa·m$^{1/2}$. This is a porous material with density of 75% of theoretical. The discs were cut into pieces to give specimens of dimensions $20 \times 20 \times 5$ mm^3. The specimens were mechanically ground and polished successively using diamond paste up to 3 μm. After grinding and polishing, the specimens were fired at 400 °C for 24 hrs to remove the oil-based grinding and polishing fluids.

Erosion tester used for this work consists of a screw-type particle feeder, gas heater and resistance heated furnace. The carrier gas, either air or N_2, is heated to the desired temperature and passed through an acceleration tube, and then mixed with particles before reaching the 4 mm internal diameter alumina nozzle. The acceleration tube, nozzle and the specimen holder are all housed in a 3-zone furnace which is heated to test temperature. The particle velocity is controlled utilizing the gas pressure and measured using the rotating double discs [3].

Erosion tests were conducted at 22, 300, 500, 700 and 900 °C using 50 g of angular silicon carbide particles of mean diameter 100 μm. Air was used for accelerating these particles. After completion of the test, the specimen was furnace cooled to room temperature either in air or N_2 atmosphere and then weighed to an accuracy of 10^{-5} g using a microbalance. Erosion rate was calculated by dividing the specimen mass loss by the total mass of erodent particles impacted.

Fig. 1 shows the variation in the erosion rates of reaction bonded silicon nitride with temperature at an impact velocity of 70 ms^{-1} under normal impingement condition. The erosion rate of this material decreases with increasing temperature in contrast to the result of hot-pressed silicon nitride, but is consistent with that of sintered silicon nitride. The erosion rate of reaction bonded silicon nitride decreases sharply by increasing temperature to 300 °C, but is very little affected by temperatures between 300 and 700 °C. There is again a larger drop in erosion rate at 900 °C. The erosion rates at 300 and 900 °C are approximately 50 and 30% of that at room temperature, respectively.

The temperature dependence of erosion rate for reaction bonded silicon nitride may be related with the variation of fracture toughness and hardness of this material with temperature as a quasi-static model predicts [4]. According to this model, the erosion rate of brittle materials follows the power-law relations, $\Delta E \propto (\mathrm{KIC})^{-4/3}(H)^{0.11}$, where, K_{IC} and H are the fracture toughness and hardness of the target material, respectively. The fracture toughness of a similar reaction bonded silicon nitride with a density of 2.32 g cm^{-3} (73% of theoretical) has been reported to increase up to 900 °C with increasing temperature [5]. The fracture toughness of the reaction bonded silicon nitride at 900 °C was larger by about 6% than that at room temperature. In addition, hardness of reaction bonded silicon nitride can be presumed to decrease with increasing temperature as reported in a similar purity silicon nitride [6]. This can be confirmed indirectly from the size of indentation formed during erosion at 900 °C, which is much larger than that at room temperature.

The velocity exponents obtained from the slope of log–log plot of the erosion data are presented in Fig. 2. The exponents for normal incidence are 2.4 and 2.0 at 22 and 900 °C, respectively. The value of the velocity exponent is predicted to be 2.4 by quasi-static model [3] and 2.0 by grain ejection model [4]. This suggests that the temperature dependence of the erosion of this material can only be explained roughly by the quasi-static model, since the grain ejection was not observed in this material as will be described later.

For the investigation of the effect of temperature on the exponent in detail, specimens eroded under normal

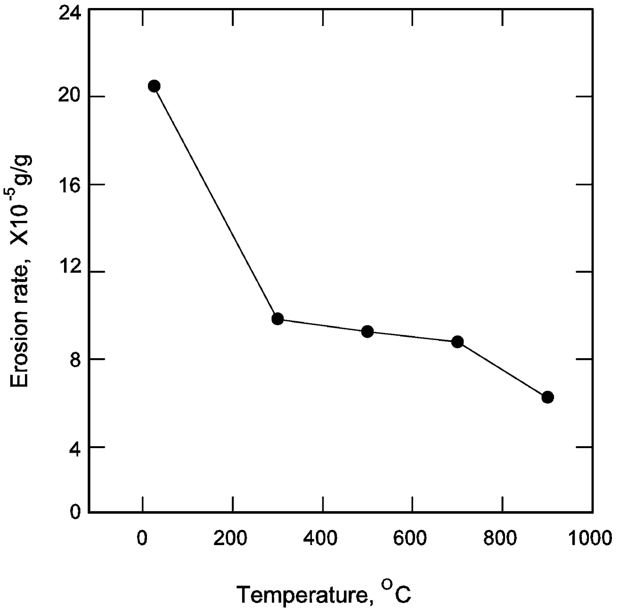

Figure 1 Variation of erosion rate with temperature: impingement angle 90 °; $V = 70$ ms^{-1}.

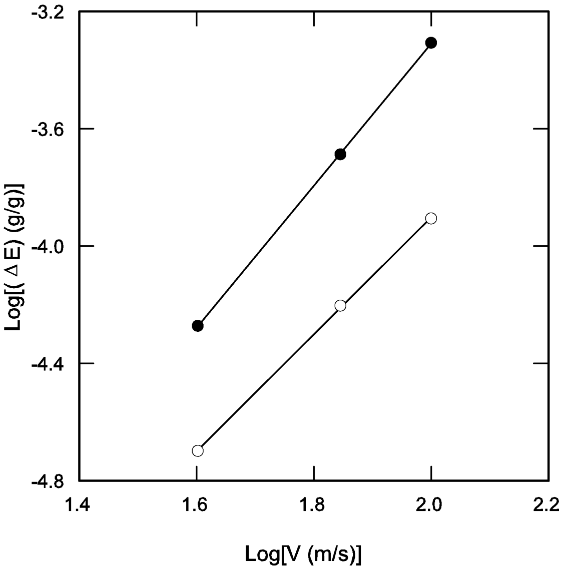

Figure 2 Logarithm of erosion rate versus logarithm of impact velocity plot at 22 °C (●) and 900 °C (○): impingement angle 90 °.

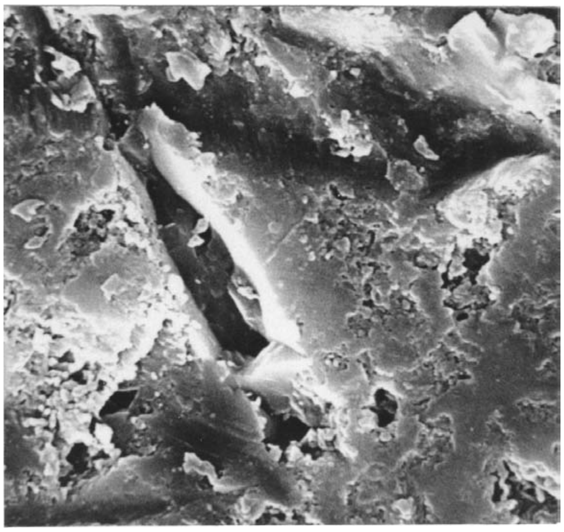

Figure 3 SEM micrographs of a typical surface eroded at 900 °C (4900×): $V = 70$ ms^{-1}; impingement angle 90 °.

impact conditions were examined by SEM. As can be seen in Fig. 3, erosion occurs mainly by cutting and plowing with no evidence of grain ejection at 900 °C. Many grooves are observed, and they are wider and longer for the specimens tested at 900 °C compared to those at room temperature, presumably due to the decrease in hardness with temperature.

In addition, embedded erodent particles are observed for the specimens tested at 900 °C. Particle embedding is known to have a significant influence on the erosion process. The locations containing embedded particles are known to exhibit different mechanical properties than surrounding materials. The raised material or lip formed by the particle embedding was reported to be more susceptible to fracture and removal from the surface once it is exposed [8]. However, the lip is not well developed in the reaction bonded silicon nitride and the penetration of particles into the material is deep, presumably due to low hardness and high porosity in this material. Thus, embedded particles may not contribute to the increase of susceptibility to the fracture or the removal of material in reaction bonded silicon nitride. Rather, the embedded particles may have contributed to a larger decrease of erosion rate at 900 °C by increasing the weight of the specimen. This may also be responsible for the decrease in the velocity exponent at this temperature. Particle embedding may lead to less effective erosion at higher impact velocities, since it is expected to occur more extensively as the particle velocities increase.

Fig. 4 shows the angular dependence of erosion rate of reaction bonded silicon nitride at a particle velocity of 70 ms^{-1}. Maximum erosion occurs for normal incidence both at room temperature and at 900 °C. This indicates that erosion occurs by a brittle fracture mechanism for reaction bonded silicon nitride at both temperatures, though the erosion was found to occur mainly by cutting and plowing as in Fig. 3. Note that erosion is known to peak at lower impact angles for ductile type

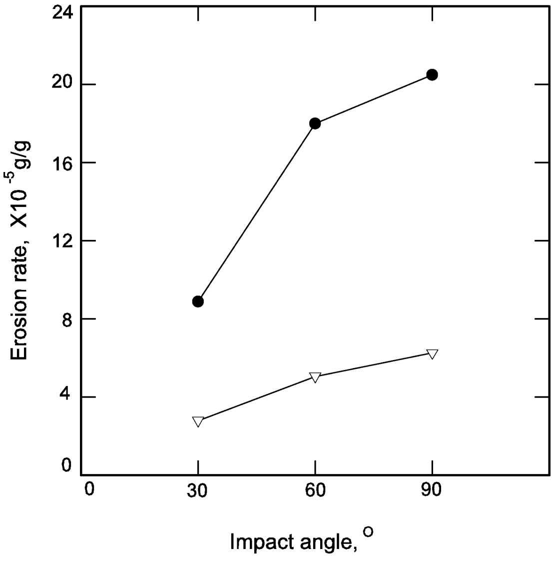

Figure 4 Impingement angle dependence of erosion rate at 22 °C (●) and 900 °C (▽): $V = 70$ ms^{-1}.

erosion. However, maximum erosion has been reported to occur for normal incidence even for the materials including hot-pressed silicon nitride in which erosion occurs in a ductile fashion [1, 9].

In summary, erosion rate of reaction bonded silicon nitride decreases with increasing temperature, in consistence with the prediction of quasi-static model. The velocity exponent is lower at 900 °C than that at 22 °C presumably due to the particle embedding, and maximum erosion is observed for normal impact conditions in the temperature range investigated though erosion is observed to occur mainly by cutting and plowing.

References

1. S. M. WIEDERHORN and J. B. HOCKEY, *J. Mater. Sci.* **18** (1983) 766.
2. J. E. RITTER, S. R. CHOI, K. JAKUS, P. J. WHALEN and R. G. RATEICK, *ibid.* **26** (1991) 5543.
3. A. W. RUFF and L. K. IVES, *Wear* **35** (1975) 195.
4. S. M. WIEDERHORN and B. R. LAWN, *J. Amer. Ceram. Soc.* **62**(1/2) (1979) 66.
5. A. S. JAYATILAKA and J. A. LEAKS, *Proc. Brit. Ceram. Soc.* **25** (1975) 311.
6. K. NIHARA and T. HIRAI, *Powder Met. Int.* **6**(5) (1984) 223.
7. J. K. RITTER, P. STRAZEPA, K. JAKUS, L. ROSENFELD and K. J. BUCKMAN, *J. Amer. Ceram. Soc.* **67**(11) (1984) 769.
8. L. K. IVES and A. W. RUFF, ASTM STP (1979) vol. 664, p. 5.
9. J. J. KIM, D. J. KIM and S. J. CHO, *J. Mater. Sci. Lett.* **20** (2001) 427.

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