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ABSTRACT

Solid-particle erosion has been measured in several ceramic matrix whisker-reinforced composites: Al_2O_3+SiC(w), Si_3N_4+Si_3N_4(w) and 3 mol.% Y_2O_3-stabilized zirconia+Al_2O_3(w). The steady-state erosion rate was investigated for normal incidence with an impact velocity of 100 m/s using four types of erodents with varying hardness. Steady-state erosion rate depends on the type of erodent, with the rate being fastest for the hardest particles. Whisker reinforcement of the ceramic matrix increases the fracture toughness, but does not, in all cases, increase the erosion resistance. Microstructural details also play an important role in determination of erosion resistance.

INTRODUCTION

Inclusion of fine, strong whiskers to ceramic matrices has been shown to significantly increase the fracture toughness, K_{IC}, of composites by crack deflection, whisker sliding, crack bowing and/or microcracking [1]. For example, K_{IC} has been approximately doubled in Al_2O_3 by the addition of 20 vol.% SiC [2] and in Si_3N_4 by the addition of 20 wt.% SiC whiskers [3]. This new class of tough

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ceramic composites could find applications in environments in which they would be subjected to solid-particle erosion.

Erosion of a brittle solid occurs by formation and propagation of lateral cracks which form as a result of residual stresses caused by the elastic-plastic zone under the impact site [4]. For normal incidence, steady-state erosion rate, ΔW (in g/g), of a monolithic ceramic is related to the impact velocity, V, and particle size, D, by $\Delta W \propto V^n D^p$, where the particle-size exponent, p, equals 2/3 and the velocity exponent, n, depends on whether dynamic [4] or quasi-static [5] contact conditions apply. The erosion rate also depends on $(1/K_{IC})^{4/3}$ [4], but varies only slightly with target hardness, H_t, as $H_t^{-1/4}$ for dynamic contact conditions [4] and as $H_t^{0.11}$ for quasi-static contact conditions [5].

It has been shown recently that ΔW depends on the ratio H_t/H_p [6,7], where the erodent hardness is given by H_p. When $H_t/H_p < 1$, erosion is higher and occurs classically by means of the lateral crack formation described above. However, if $H_t/H_p > 1$, erosive loss is lower; softer particles can crush or fragment upon impact. The basic loss mechanism of formation and propagation of lateral cracks probably operates, but damage accumulation is required to supply the threshold stress for lateral crack nucleation [6].

The objective of this work was to explore some of the above ideas. In particular, steady-state erosion rates of three whisker-reinforced composites, Al_2O_3 + SiC(w), Si_3N_4 + Si_3N_4(w) and 3 mol.% Y_2O_3-stabilized ZrO_2 + Al_2O_3(w) were measured.

EXPERIMENTAL

The Al_2O_3 composites used for these tests were obtained from Advanced Composite Materials, Greer, SC. Compositions were supplied with 0, 5, 15 and 25 wt.% SiC whiskers. Whiskers were approximately 1 μm in diameter with an average length of 30 μm. Fracture toughness varied from 3.8 to 6.8 $MPam^{1/2}$ as the whisker concentration increased to 25 wt.% [8].

The Si_3N_4 composites were fabricated from powders and Si_3N_4 whiskers by hot-pressing using 2.5 wt.% MgO as a sintering aid. The K_{IC} varied from 6.4 to 7.5 $MPam^{1/2}$ as the 0.6 μm diameter whiskers concentration was increased from 0 to 15 vol.% [9].

Zirconia composites were prepared by hot-pressing mixtures of 3 mol.% Y_2O_3 tetragonal-stabilized zirconia (TZ3Y) with 4-7 μm diameter Al_2O_3 whiskers. The K_{IC} values were 8.6, 7.5 and 10 $MPam^{1/2}$ for the 0, 15 and 25 vol.% compositions, respectively [10].

Experiments were carried out in a slinger-type apparatus [11]. A fixed velocity of 100 m/s and normal incidence was used for the four types of sharp 100 grit (143 μm diameter) abrasives (listed in Table 1) purchased from Norton, Worcester, MA. The abrasives had a hardness variation of about two.

RESULTS AND DISCUSSION

The steady-state erosion rates of the composites are shown as a function of composition for the four abrasives in Fig. 1. Figure 1A presents the results for the Al_2O_3 composite, while Figs. 1B and 1C contain the results for the Si_3N_4 and the TZ3Y composite, respectively. It is apparent that the two types of Al_2O_3 abrasives (Alundum 38 and Dynablast) give identical results for all three ceramic matrix composites. Furthermore, ΔW measured using the hardest abrasive, Crystolon 37 (SiC), is always larger than ΔW measured for the other abrasives, while the Alundum ZS, having the lowest hardness, produces the lowest ΔW. These results are consistent with the idea, proposed by Srinivasan and Scattergood [6], that particle fragmentation or crushing will occur for particles whose hardness is less than that of the target. Indeed, SEM micrographs of indicate that the single-impact damage sites of the various abrasives are different (Fig. 2). The micrographs were taken from the surface of the Si_3N_4 matrix after impact with SiC (Fig. 2A) and Al_2O_3 (Fig. 2B) and indicate that the softer erodent has been crushed.

SEM of the surfaces eroded into steady state further reflects the differences between the abrasives. Typical SEM micrographs of the surface of a Al_2O_3 + 25 wt.% SiC composite eroded using a hard (Crystolon 37) and a medium (Dynablast) erodent are shown in Fig. 3. The surface of the composite eroded by the harder material has sharper features and contains more cracks.

Fragmentation occurs for all types of abrasives as indicated in the series of SEM micrographs (Figs. 4,5 and 6) taken of the as-received and the impacted (on Si_3N_4 matrix at the standard conditions) abrasives. Indeed, it has recently been shown that fragmentation is more severe for larger than for smaller SiC erodents [12]. This results in a near saturation of ΔW vs D plots for high K_{IC} targets.

It is beyond the scope of this note to quantify the effect of abrasive hardness on the erosion resistance of these hard, brittle materials. It is sufficient to say that the data indicate that the differences in erosion rate do not scale exactly with the ratio of hardnesses. The ratio of the maximum-hardness to that of the minimum-hardness particle is 1.7, while the ratio of ΔW measured with the hardest particle to that measured with the softest particle varies, for a given material, between 4 and 30. It is likely that fragmentation (which clearly depends on the toughness and the hardness of the erodent) and micro-structural effects of the target play a significant role.

Another interesting materials aspect of this investigation has been recently addressed [12] and will be briefly reviewed. The predicted dependence of ΔW on target K_{IC} is approximately observed for the Al_2O_3 + SiC(w) composite for all erodents, thereby explaining the decrease in ΔW with whisker concentration shown in Fig. 1A. However, the situation is more complex for the Si_3N_4 or the TZ3Y composites. The fact that the erosion resistance does not depend on K_{IC} as expected and is hence not a function of whisker concentration in the latter two composites, despite some, albeit not spectacular toughening, can be attributed to microstructural features as a result of the fabrication process.

The Si_3N_4 composites had highly textured distributions of whiskers, with the whiskers aligned primarily in the plane normal to the hot-pressing direction and to the erodent steam. While these whiskers provide bridging or deflection sites for radial cracks, they are inefficient for deflection of the lateral cracks responsible for the erosive loss. In fact, the propagation of lateral cracks tends to remove the Si_3N_4 whiskers. Therefore, the increase in erosion resistance as a result of the slight increase in K_{IC} is compensated by the decrease in erosion resistance because of the propensity for whisker removal as a direct result of the texture. The end result, shown in Fig. 1B, is that ΔW increases slightly with whisker concentration.

The case of the TZ3Y composite is also not in accord with classical conceptions since, as shown in Fig. 1C, ΔW is nearly independent of whisker concentration, while K_{IC} increases. The Al_2O_3 whiskers used in the TZ3Y composite are larger, less perfect and, therefore, considerably weaker than the other reinforcing whiskers. Furthermore the steady-state erosion rate of commercial Al_2O_3 [6] is higher than, for example, SiC [13] or a toughened ZrO_2 [14]. Thus, large whiskers exposed at the surface will erode quickly. Therefore, the expected increase of erosion resistance due to the increase in K_{IC} is balanced by the poor erosion resistance of the whiskers.

SUMMARY

Solid-particle steady-state erosion rates depend on the hardness and the friability of the erodent. Harder particles cause more erosive loss than do softer particles. Whisker reinforcement of the ceramic matrices studied increases fracture toughness, but not always the erosion resistance. The decrease in erosion rate caused by the increasing toughness is sometimes balanced by microstructural features which enhance lateral crack formation and propagation which result in larger erosive losses.

REFERENCES

[1] R.W. Rice, Ceram. Eng. Sci. Proc., 2, 661-701 (1981).

[2] P.F. Becher and G.C. Wei, J.Am. Ceram.Soc., 67, 298-304 (1984).

[3] J.P. Singh, K.C. Goretta, D.S. Kupperman, J.L. Routbort and J.F. Rhodes, Adv. Ceram. Mater., 3, 357-60 (1988).

[4] A.G. Evans, M.E. Gulden and M.E. Rosenblatt, Proc. Roy. Soc. London, Ser. A361, 343-65 (1979).

[5] S.M. Wiederhorn and B.R. Lawn, J. Am. Ceram. Soc., 62, 66-70 (1979).

[6] S. Srinivasan and R.O. Scattergood, Wear, 128, 139-52 (1988).

[7] S. Wada, N. Watanabe, T. Tani and O. Kamigaito, Proc. Mater. Res. Soc. Inter. Conf. on Advanced Materials, in press.

[8] M.T. Sykes, R.O. Scattergood and J.L. Routbort, Composites, 18, 153-163 (1987).

[9] C.-Y. Chu and J.P. Singh, Proc. of 14th Annual Conf. on Composites and Advanced Ceramics, Cocoa Beach, FL., to be published.

[10] J.M. Roberts, M.S. Thesis, North Carolina State University (1990).

[11] T.H. Kosel, R.O. Scattergood and A.P.L. Turner, Wear of Materials, ASME, NY, (1979), pp. 192-204.

[12] J.L. Routbort, D.A. Helberg and K.C. Goretta, J. Hard Mater., in press.

[13] J.L. Routbort, R.O. Scattergood and A.P.L. Turner, Wear, 59, 363-75 (1980).

[14] S. Srinivasan and R.O. Scattergood, Adv. Ceram. Mater., 3, 345-52 (1988).

Table 1. Characteristics of abrasives used in this investigation obtained from the manufacturer, Norton, Worcester, MA.

Material	Composition(%)		Density (g/cc)	Knoop Hardness
Crystolon 37	SiC	98.06	3.20	2500
Alundum 38	Al_2O_3	99.55	3.95	2000
Dynablast	Al_2O_3 TiO_2	96.6 2.6	3.95	2000
Alundum ZS	Al_2O_3 ZrO_2	75.0 23.0	4.30	1450

FIGURE CAPTIONS

1. Steady-state erosion rate as a function of composition for the three composites, Al_2O_3 (Fig. 1A), Si_3N_4 (Fig. 1B) and 3 mol.% Y_2O_3 stabilized ZrO_2 (Fig. 1C) for the four types of abrasives listed in Table 1. The abrasives are shown as open squares-Crystolon 37, closed triangles-Alundum 38, open triangles-Dynablast and open circles-Alundum ZS.

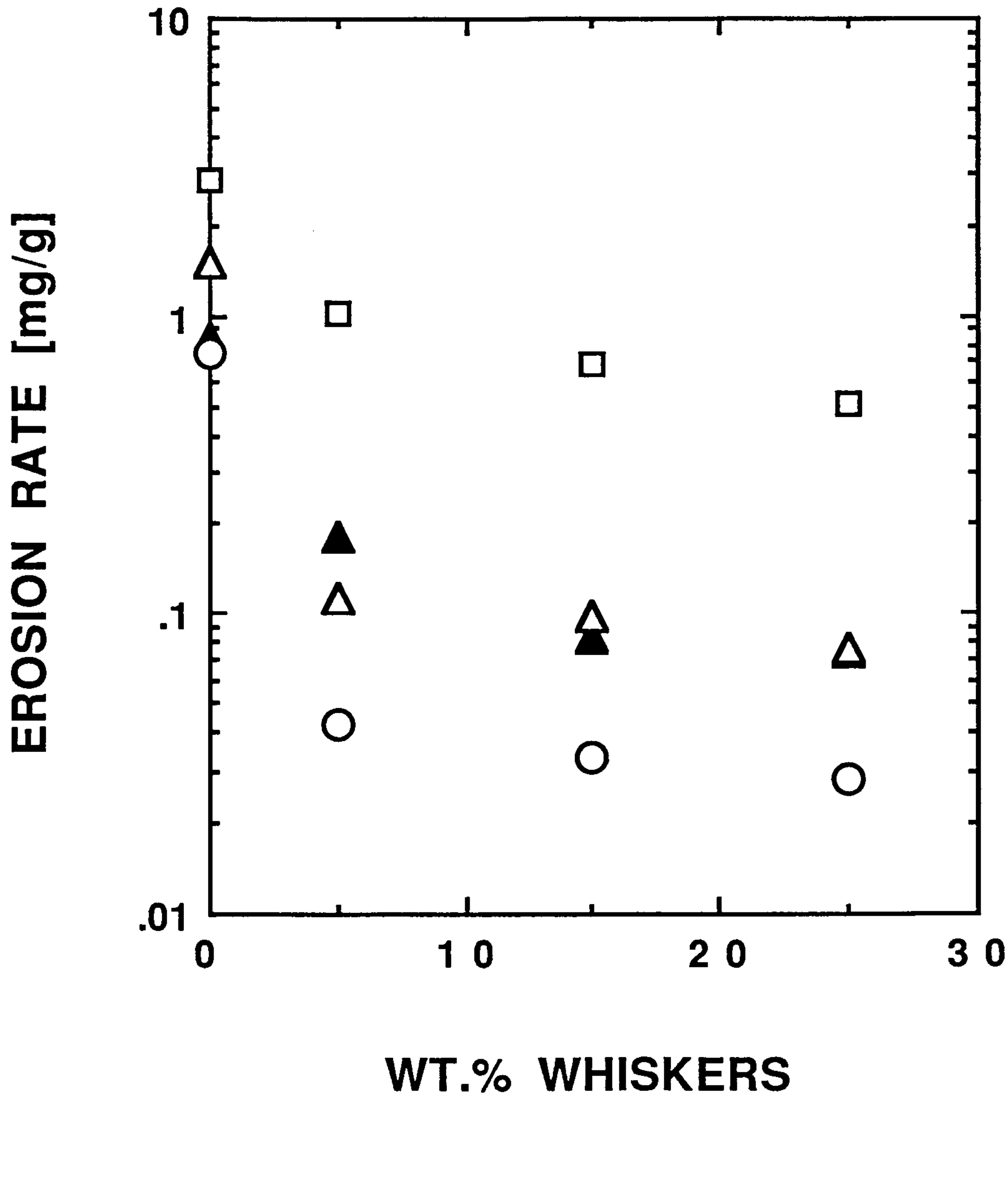
2. Single impact sites for Crystolon 37 (A) and Alundum 38 (B) impacting the surface of the Si_3N_4 matrix.

3. SEM micrographs of the surface of a Al_2O_3 + 25 wt.% SiC composite eroded into steady-state using Crystolon 37 (A) and Dynablast (B).

4. The as-received (143 μm diameter) Crystolon 37 abrasive particles (A) and the particles after impacting a Si_3N_4 surface at normal incidence and 100 m/s (B).

5. The as-received (143 μm diameter) Alundum 38 abrasive particles (A) and the particles after impacting a Si_3N_4 surface at normal incidence and 100 m/s (B).

6. The as-received (143 μm diameter) Alundum ZS abrasive particles (A) and the particles after impacting a Si_3N_4 surface at normal incidence and 100 m/s (B).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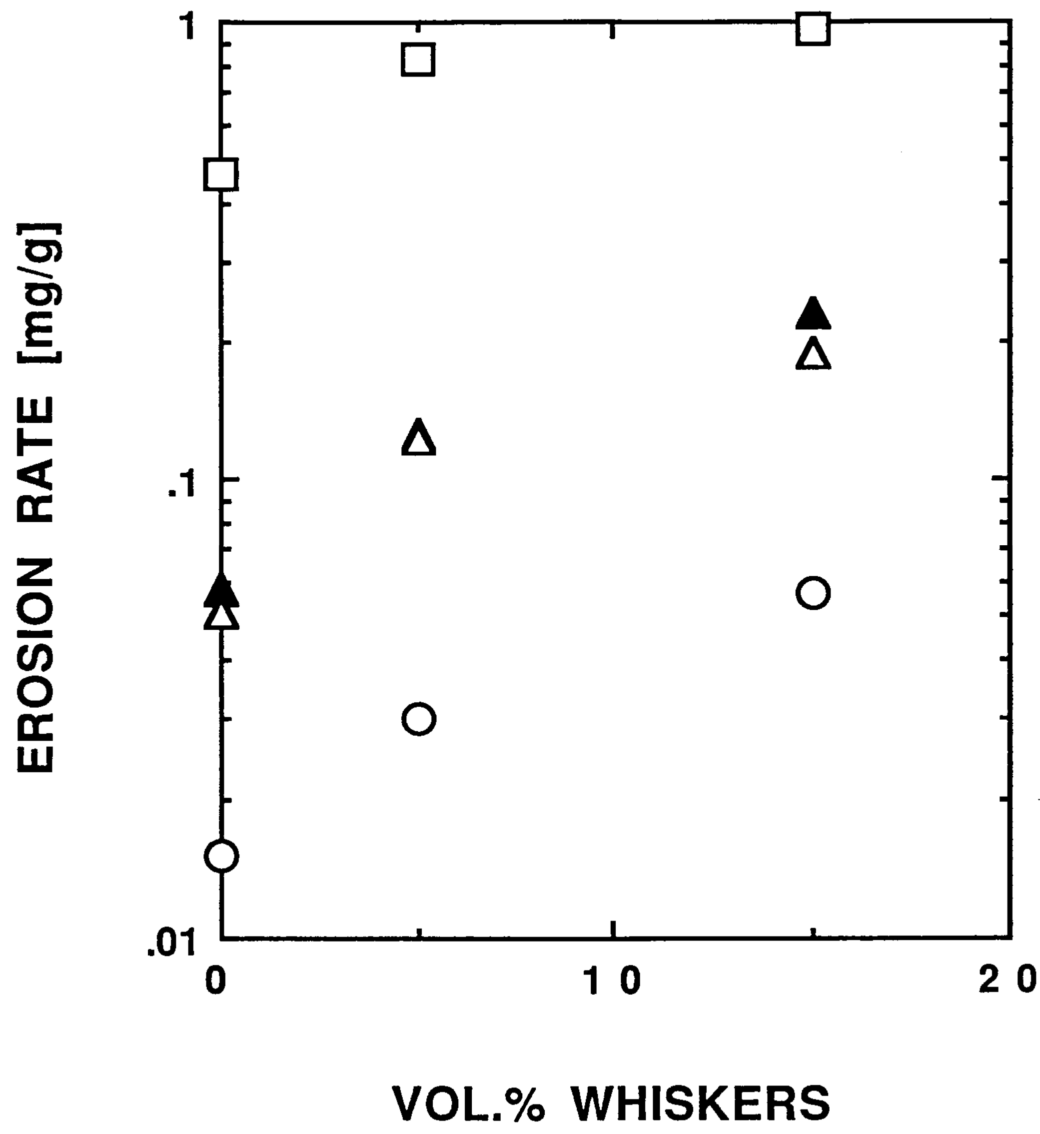
EROSION RATE [mg/g]
WT.% WHISKERS



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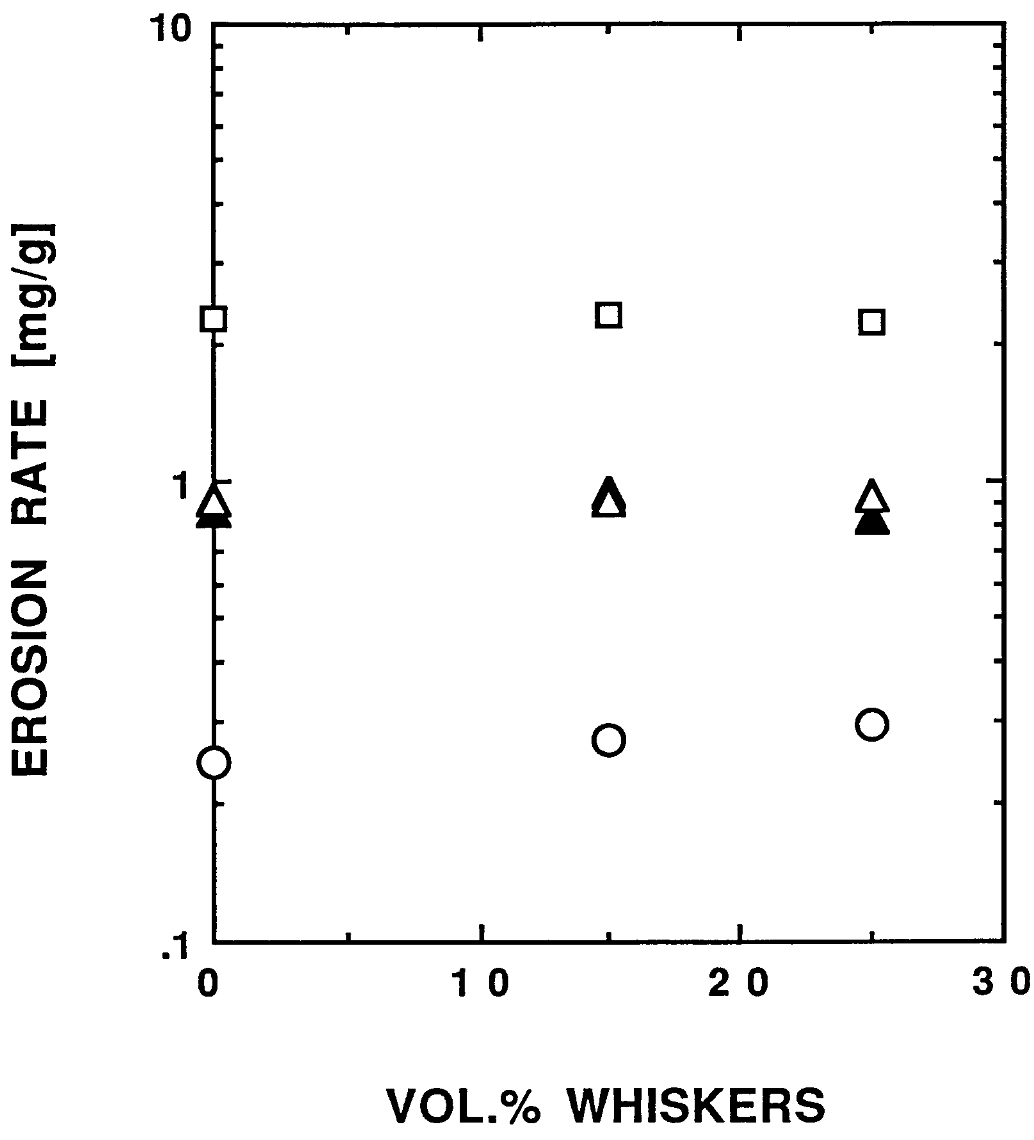

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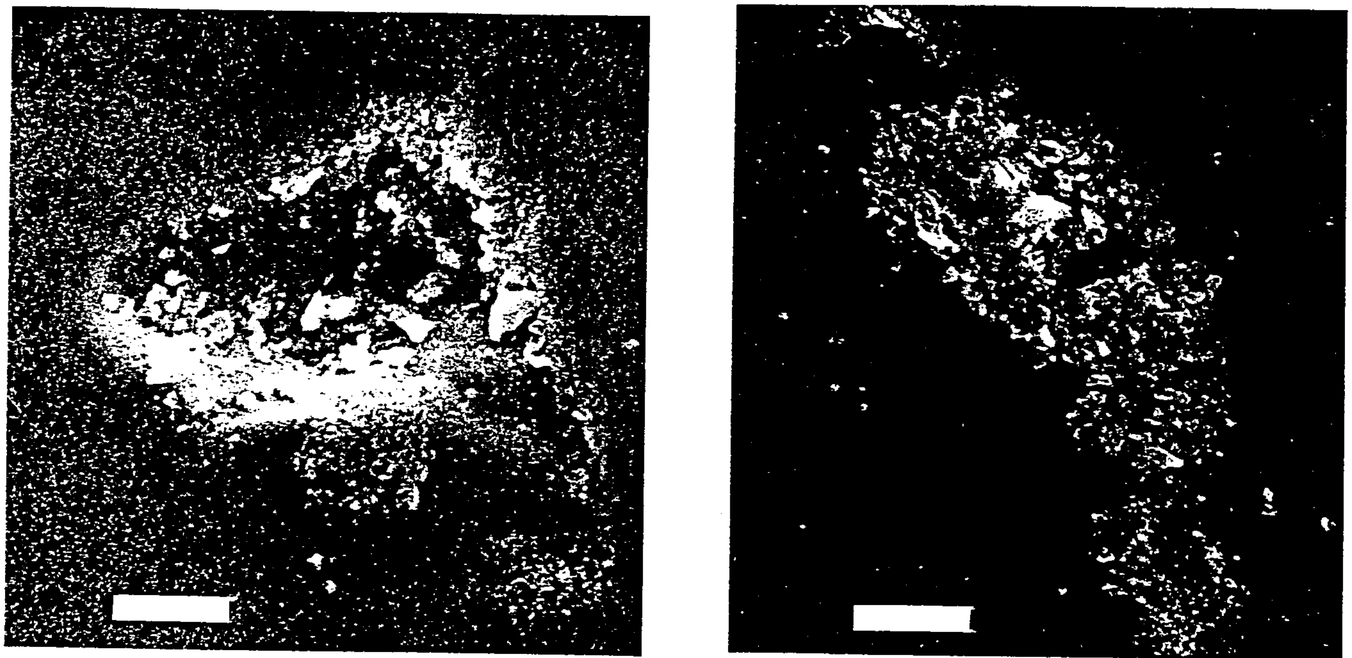

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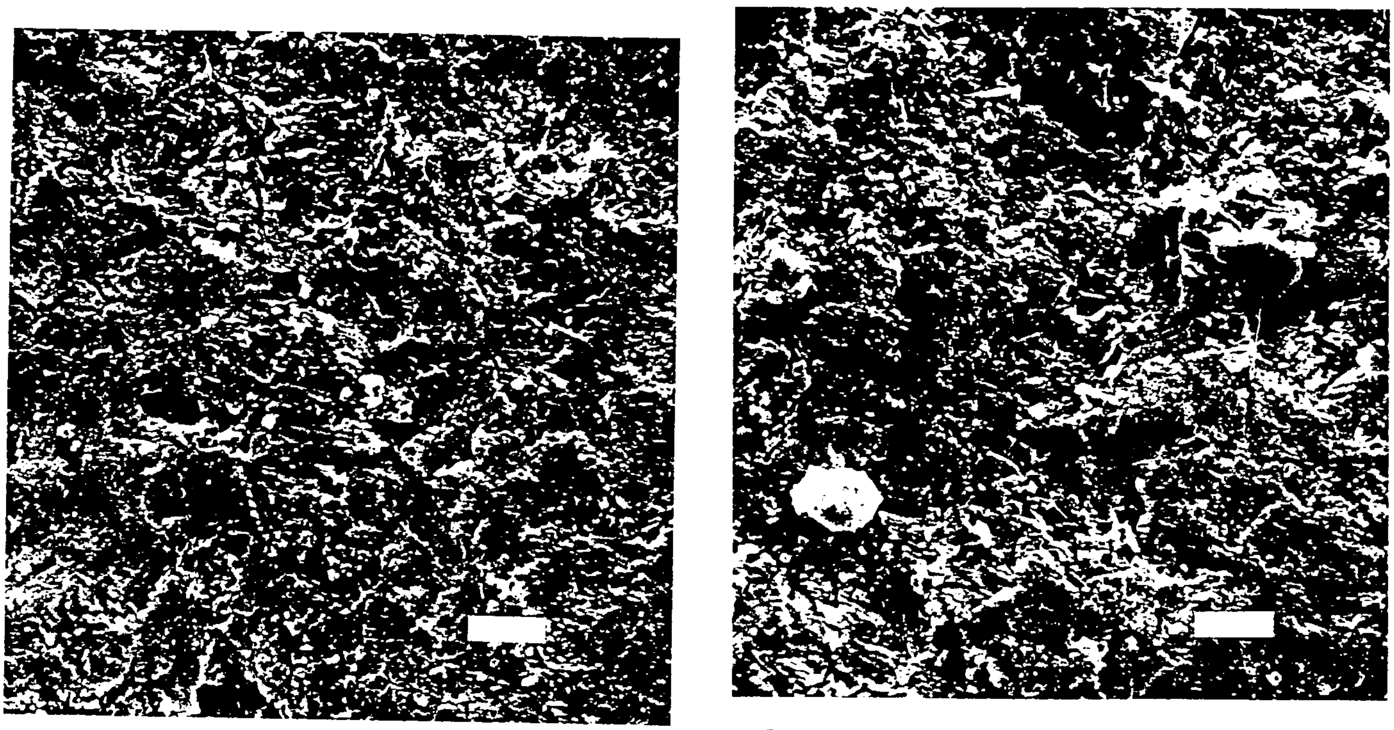

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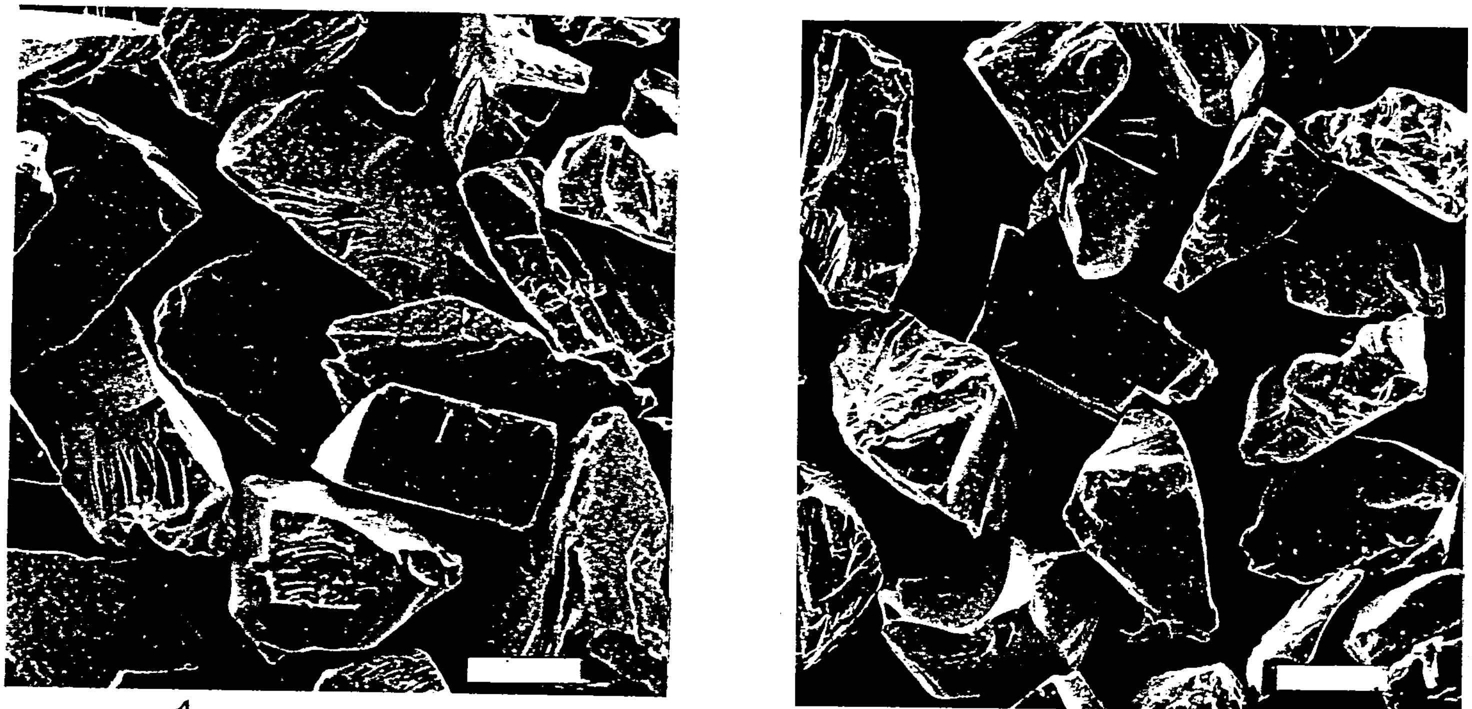
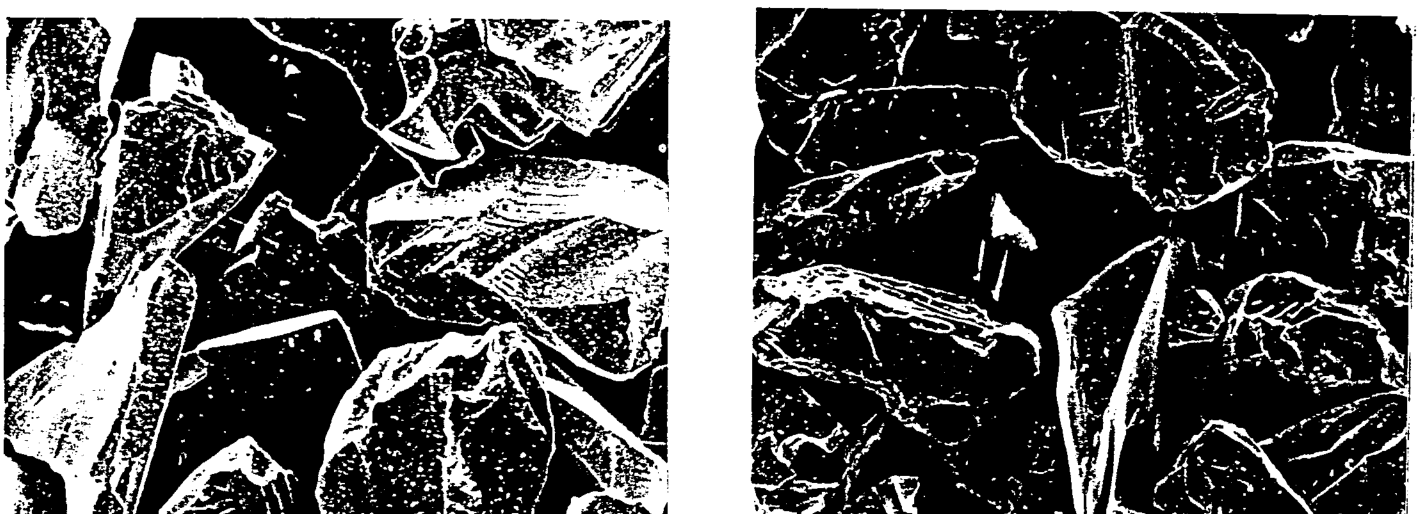


4 A B



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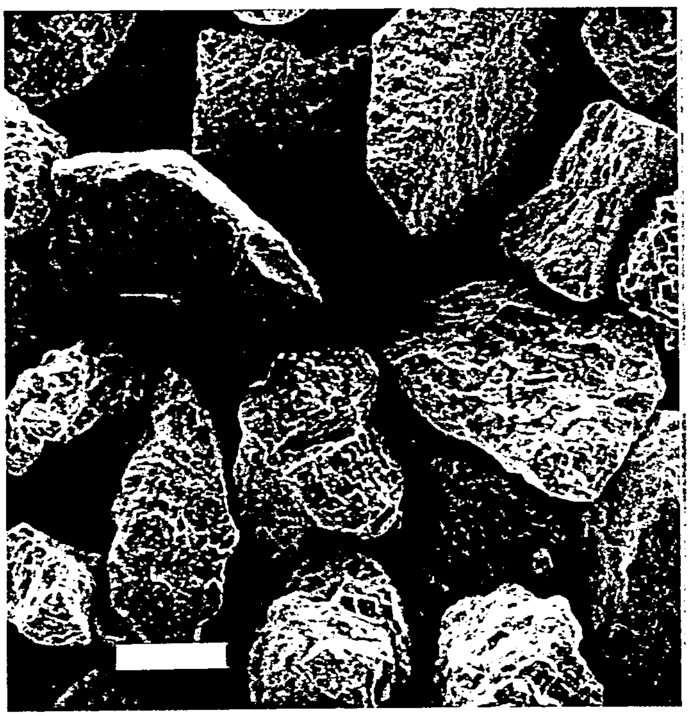
6



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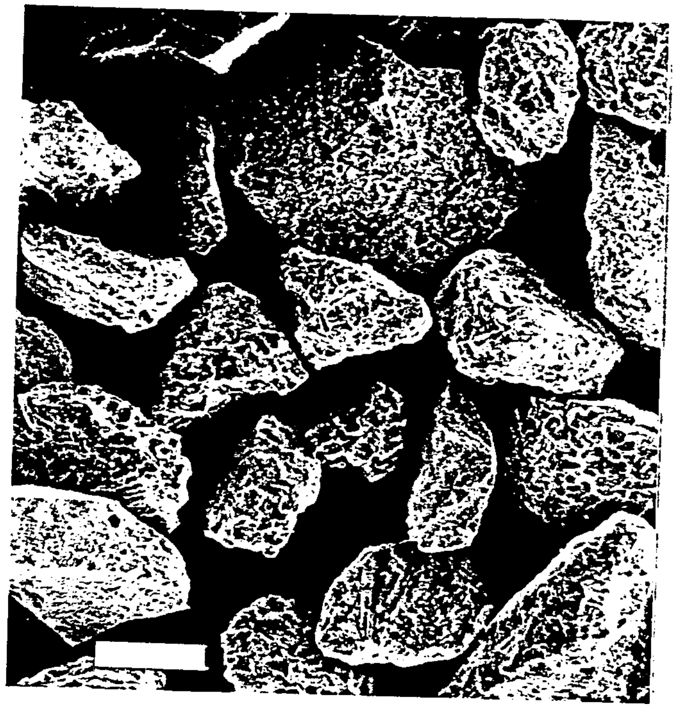

B