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Erosion Wear in Al_2O_3–Cr_3C_2 Composites

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Abstract: The erosive wear behaviour of Al_2O_3–Cr_3C_2 ceramic composite with particulate Cr_3C_2 phase ranging from 10 vol% to 40 vol% was investigated. Experimental results showed that the erosive rate of the composite decreased linearly with increasing Cr_3C_2 content and was lower by a factor of 2–3 than that in high-purity alumina, the most widely-used erosive-resistance material. This finding suggested that Al_2O_3–Cr_3C_2 composites can be considered as candidate materials for erosion resistance applications. The erosive wear behaviour of the composites was well described by the theory developed by Wayne and Buljan by taking the hardness, fracture toughness, and microstructure of the composite into consideration simultaneously. The composite microstructure was found to have a profound effect on the erosive wear of the Al_2O_3–Cr_3C_2 composites. © 1996 Elsevier Science Limited and Techna S.r.l.

1 INTRODUCTION

It has been noted that Al_2O_3–Cr_3C_2 ceramic matrix composite demonstrated fracture strength and fracture toughness over twice as much as those in pure alumina.[1] An earlier study[2] revealed that this composite material showed attractive high-temperature mechanical properties and good resistance to oxidation at temperatures as high as 1320°C. All these findings suggest that such a newly-developed composite material possesses great potential for structural uses. More recently, in an attempt of cutting the composite by means of an EDM (electro-discharge machining) technique, the experimental observations demonstrated satisfactory results, which allows the composite materials to be machined into complex geometry with ease.[3] As a candidate material for engineering purposes, one possible application is to apply this composite to those places subjected to considerable erosion.

Erosive wear behaviour of brittle solids by solid particles is rather complex due to its relation with a number of mechanical properties and microstructure features of the target materials,[4,5] angle of impingement, and particle properties such as size,[4] shape,[6,7] hardness and fracture toughness.[8] In view of these parameters, two elastic–plastic theories have been proposed based on the assumption that lateral cracks propagate in a quasi-static manner due to the residual stresses induced by particle impact. The model proposed by Evans *et al.*[9] is expressed by

$$\Delta v \propto V^{3.2} R^{3.7} r^{1.3} K_c^{-1.33} H^{-0.25} \quad (1)$$

where Δv is erosion rate, V is particle velocity, R is particle radius, r is particle density, K_{1c} is the fracture toughness and H is the hardness of the target materials. Ruff and Wiederhorn[10] also proposed a model by assuming that the kinetic energy of particles is absorbed completely by plastic flow when the particles impact the surface and they gave

$$\Delta v \propto V^{2.4} R^{3.7} r^{1.2} K_{1c}^{-1.3} H^{0.11} \quad (2)$$

Both eqns (1) and (2) display similar power-law correlation which relates the erosion rate (Δv) to particles (V, R, r) and target materials (H, K_{1c}). Under fixed particle parameters, the erosion rate of a target material can generally be expressed by

$$\Delta v = C K_{1c}^{m} H^{n} \quad (3)$$

where the exponents m and n have negative value and C is a proportional constant. Recently, Wada[11] reported the erosive wear of a number of brittle materials including monolithic ceramics and ceramic composites in terms of eqn (3) and he obtained different values of m, n and C for different materials. Although the prediction of Wada by using the expression of eqn (3) is good, the values of m, n and C empirically obtained for each material may have little physical meaning. More recently, Wayne and Buljan[12] indicated that the uncertainties in the wear prediction for brittle ceramics can not be fully reflected by cumulative properties such as hardness and fracture toughness of target materials, particularly for composites, the influence of microstructure is essentially important and should be considered simultaneously. They modified eqn (1) by further taking a factor λ, the average spacing between secondary-phase particulates, into account and which simply yields a form,

$$\Delta v = C\lambda / K_{1c}^{1\cdot 33} H^{0\cdot 25} \quad (4)$$

and

$$\lambda = G\frac{2}{3}\left(\frac{1 - V_f}{V_f}\right) \quad (5)$$

where V_f is the volume fraction of inclusion phase, G refers to the average grain size of inclusion, and C is a constant to be determined. The prediction by eqn (4) combining mechanical properties–microstructural parameter provided fairly consistent results with those measured experimentally, for ceramic–ceramic[12,13] and ceramic–metal composites.[14]

In spite of the variations of mechanical properties on the scale of erosion process and in some cases possible chemical interactions may proceed during impact, there are two major erosion mechanisms, i.e. fracture mode and scratching mode, which are frequently observed in erosive wear of brittle solids. Therefore, the development of high-toughness and high-hardness materials to overcome the occurrence and/or to minimize the initiation of any possible failure from erosion becomes increasingly important in material design criteria. The purpose of this study is to investigate the solid particle erosion behaviour of Al_2O_3–Cr_3C_2 composite, based primarily on the concept proposed by Wayne and Buljan.

2 EXPERIMENTAL PROCEDURES

A powder mixture containing fine Al_2O_3 (0·4 μm, Alcoa, A16-SG) and 10–40 vol% (with 10% increment) of Cr_3C_2 powder (1·5 μm, H. C. Stark, grade A) was prepared by ball-milling for 24 h with deionized water as a medium solution. After drying, the mixed powder was sintered by hot-pressing at 1400°C for 1 h in Ar atmosphere under a uniaxial pressure of 30 MPa. The density of the sintered composites was determined to be ~99.2% of theoretical density by using the Archimedes method.

The erosion tests were carried out by means of a sand blasting method, shown in Fig. 1. The target specimens having dimensions of 20×20×5 mm³ were placed in position, a fixed distance of 3·2 cm away from the B_4C nozzle having an inside diameter of 5 mm. The 120-mesh SiC particles (~150 μm) were used as impacting abrasives (Fig. 2). Specimen surfaces were subjected to a normal impaction of 600 g of the SiC abrasive grit at

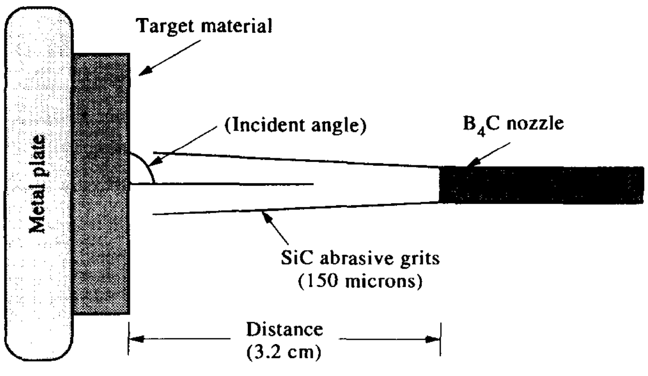

Fig. 1. Schematic drawing of the apparatus for erosive wear test.

Fig. 2. SiC abrasive grits used in this study.

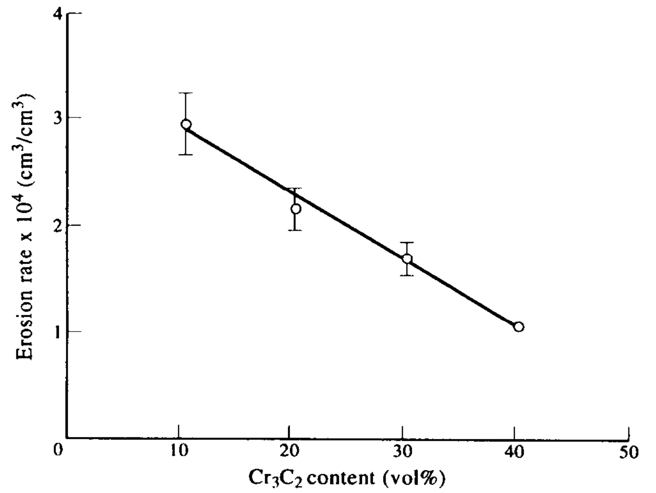

Fig. 3. Erosion rate of the Al_2O_3-Cr_3C_2 composites as a function of Cr_3C_2 content.

an average velocity of approximately 95 m/s at ambient temperature. Erosion rate (Δv), obtained by averaging the data of four specimens for each composition, was determined by calculation of the volume loss of the composite divided by the volume of SiC abrasive used. The as-eroded surface was examined by scanning electron microscopy (Cambridge Instruments, S-360). The microstructure of the composite was examined using transmission electron microscopy (Joel, 400).

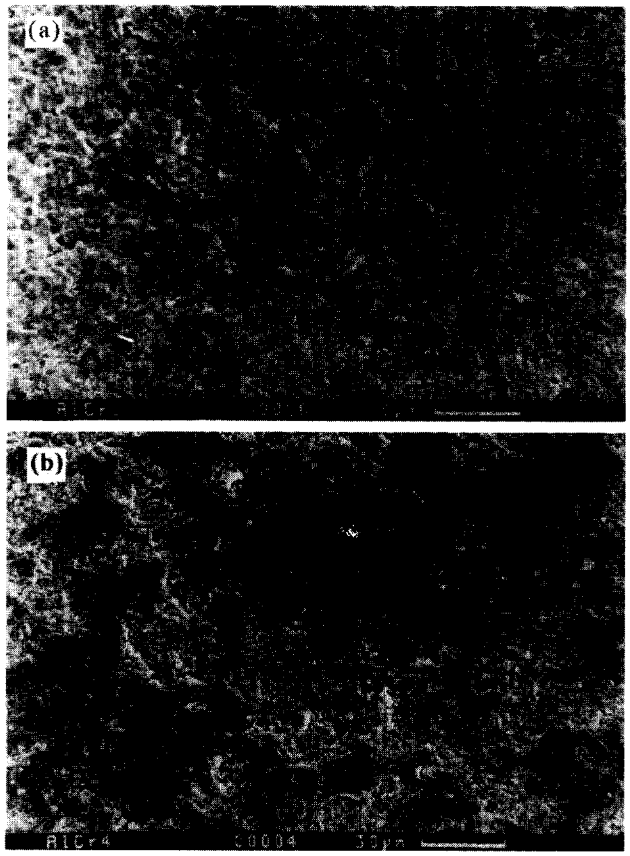

Fig. 4. SEM examination of the as-eroded surface for the composites containing (a) 10 vol% and (b) 40 vol% Cr_3C_2.

3 RESULTS AND DISCUSSION

Figure 3 illustrates that the erosion rate of the composites decreased linearly with increasing Cr_3C_2 content. In view of the existing models accounting for the erosive wear behaviour in brittle solids, material losses are primarily caused by brittle fracture and scratching mode. Therefore, improved fracture toughness as well as hardness of brittle materials should enhance the resistance to abrasive erosion. For the Al_2O_3–Cr_3C_2 composite, both the toughness and hardness increased with Cr_3C_2 content up to 30% and decreased slightly after further increase of Cr_3C_2 content to 40%, as given in Table 1.[1] Accordingly, the erosion rate of the composites is expected to increase at 40% Cr_3C_2 with respect to models described earlier. However, this contradicts experimental observation whereupon a decreased erosion rate at 40% was seen. By examining the eroded surface, using 20 g of the SiC abrasive grits, Fig. 4(a) and (b) showed somewhat distinct surface morphologies for 10% and 40% Cr_3C_2 phase, respectively. Both compositions were subjected to a material loss by fracture mode, mainly intergranular (as correspondingly depicted at a larger magnification in Fig. 5(a) and (b)). However, scratch traces are frequently seen at 10% but only a little at 40% by SEM examination. The actual reason for this difference is not well understood at present. The greater value of hardness at 40% compared to that at 10% may

Table 1. Hardness (H_v)* and fracture toughness (K_{1c})# of the Al_2O_3–Cr_3C_2 composites and microstructure parameters for various Cr_3C_2 volume fractions[1]

Cr_3C_2	H_v (GPa)	K_{1c} ($MPa.m^{0.5}$)	G (μm)	λ (μm)
10	18·98	6·1	1·15	6·88
20	20·63	7·2	1·74	4·59
30	22·65	7·8	2·85	4·39
40	21·83	7·5	2·95	2·95

* Hardness of the composites was determined using Vicker's indentation method with 300 g load for 15 s.
\# Fracture toughness of the composites was measured by means of single-edge-notched beam technique.

Table 2. Erosion rate (Δv), hardness (H_v), and fracture toughness (K_{1c}) of the composites containing 40 vol% Cr_3C_2 of different particle sizes (G, data from supplier), together with the average spacing λ

G (μm)	Δv (cm_3/cm^3)	H_v (GPa)	K_{1c} ($MPa.m^{0.5}$)	λ (μm)
0·5 (0·42)	$1{\cdot}8\times10^{-4}$	22·12	5·8	0·42
1·5 (2·95)	$1{\cdot}2\times10^{-4}$	21·83	7·5	2·95
7·5 (7·40)	$2{\cdot}48\times10^{-4}$	21·7	7·6	7·40

probably be responsible for the enhancement of the composite resistance to particle erosion.

According to the Wayne–Buljan model, composite microstructure parameters, particularly the size of secondary phase, strongly affect the erosion behaviour. In the Al_2O_3–Cr_3C_2 composite, Cr_3C_2 reinforcements of three different particle sizes, i.e. 0·5 μm, 1·5 μm and 7·5 μm (data from supplier), were used to examine the erosion rate of the composites containing 40% Cr_3C_2 under the same erosive condition. The erosion rates (Δv) are listed in Table 2, together with the corresponding mechanical properties. Erosion rate increased for both 0·5 μm and 7·5 μm particulate composites, having a similar value of hardness. According to the Wayne–Buljan model, the increased Δv for 0·5 μm particulate composite is caused by its lower values of fracture toughness, and for 7·5 μm composite, the increased Δv may be explainable as a result of its greater value of λ in spite of its high fracture toughness. Further, an examination of 7·5 μm composite by TEM (Fig. 6) revealed the presence of grain-boundary microcracking which is due to differential thermal contraction between both constituent phases. These cracks may also reduce the resistance of the composite to erosion.

From the standpoints of the experimental observation, as well as theoretical expectation, the material parameters in the Wayne–Buljan model are not independent in relation to the resulting erosive wear behaviour. They are essentially strongly interrelated and it may lead to quantitative error in data interpretation by considering only the mechanical properties or microstructual features for composite materials. Therefore, one may conclude that an optimum design of Al_2O_3–Cr_3C_2 composites

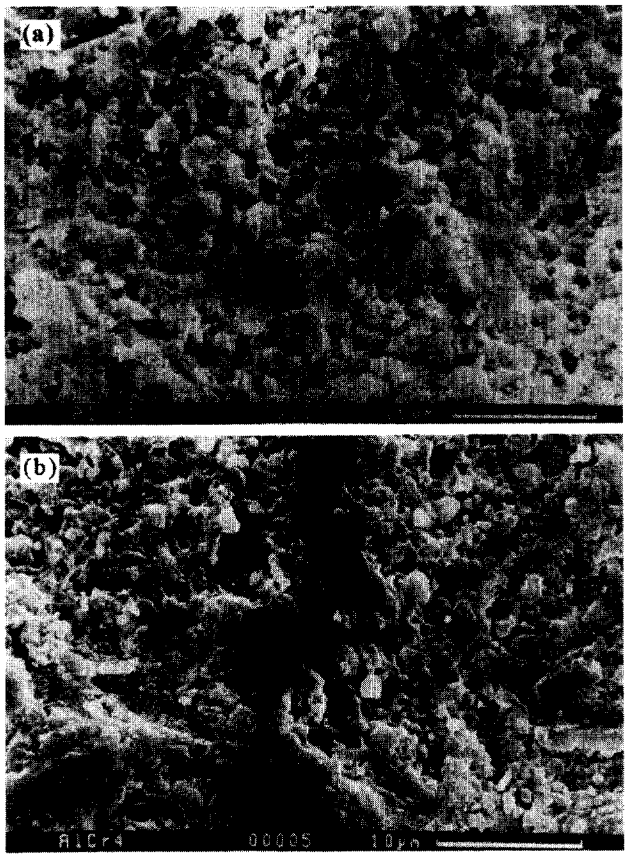

Fig. 5. A larger magnification, corresponding to Fig. 4, for the composites containing (a) 10 vol% and (b) 40 vol% Cr_3C_2.

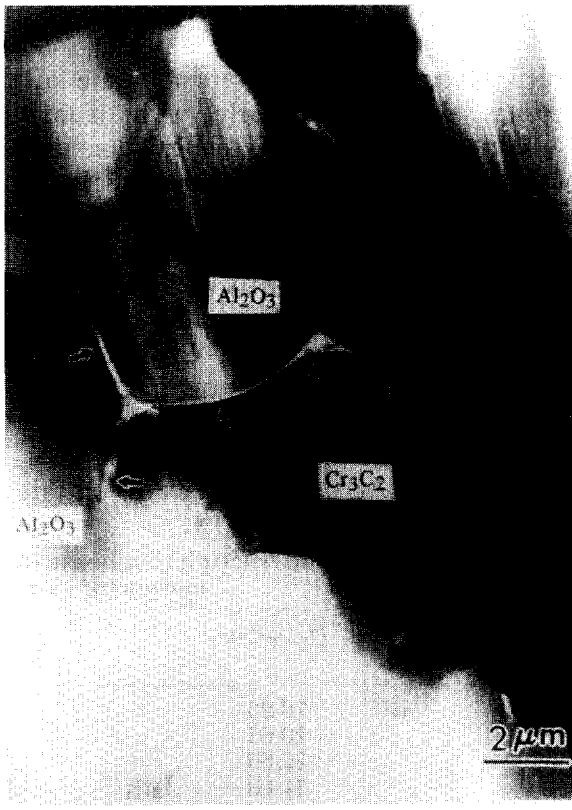

Fig. 6. Spontaneous microcracking occurs at the Al_2O_3/Cr_3C_2 interface and triple junction.

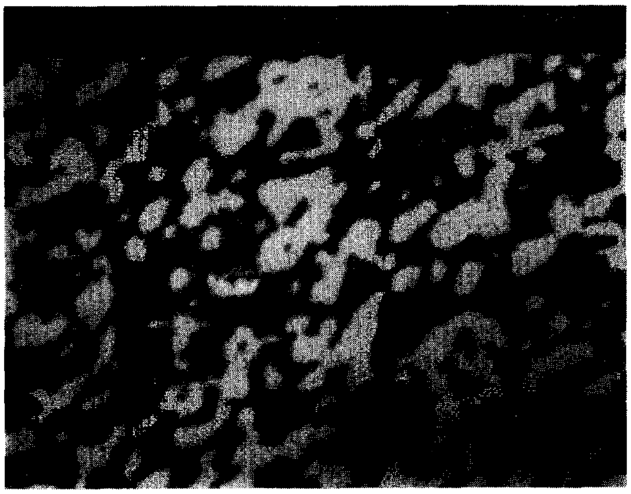

Fig. 7. Scanning electron micrograph of a polished surface of the composites containing 40% Cr_3C_2, with some of the Cr_3C_2 particulates interconnected to form larger-size grains.

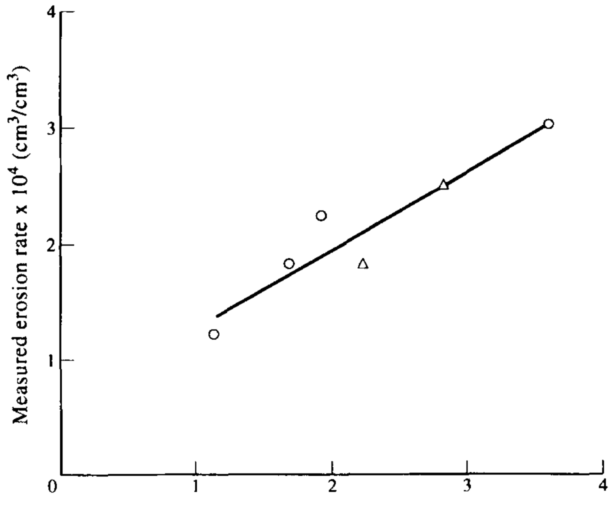

Fig. 8. Correlation between experimental measurement and eqn (6). (The circle symbols represent the composites containing 10–40 vol% Cr_3C_2 phase and the triangle symbols denote the composites containing 40 vol% Cr_3C_2 phase of different mean particle sizes.)

toward a satisfactory erosion wear performance can be achieved by optimization of both the mechanical properties and microstructural features. In practice, for Al_2O_3–Cr_3C_2 composites the selection of Cr_3C_2 particulate size of approximately 3 μm is encouraging to be more effective in erosion wear resistance.

In order to quantitatively estimate or predict the erosive wear of materials, the influence of microstructure has to be considered when a two-phase composite was used as a model material. According to eqn (4), the average composite inclusion spacing λ has to be determined. The mean grain size (G) of the Cr_3C_2 particulates was measured by a linear intercept method on a polished surface and had values of 1·15 μm (smaller than the supplier's value), 1.74 μm, 2·85 μm and 2·95 μm for 10%, 20%, 30% and 40% Cr_3C_2, respectively. The Cr_3C_2 particulates, particularly at higher concentrations, tend to coarsen into a larger-size particulate phase during sintering, as evidenced by examining a polished surface of 40% Cr_3C_2 phase shown in Fig. 7. Some of the particulates were considerably larger in size than the critical value, i.e. ~3.2 μm, above which internal microfracture occurs spontaneously.[1] It can thus be ascertained that some microcracks should exist, preferentially located at interfaces and/or triple junctions. By substituting the calculated spacing λ (listed in Tables 1 and 2) together with the mechanical properties into eqn (4), the constant C can then be determined and eqn (4) can be rewritten in a more quantitative manner as

$$\Delta v = 124\,\lambda/K_{1c}^{1\cdot 33}\,H^{0\cdot 25} \quad (6)$$

A plot of the measured erosion rate (Δv) in terms of the calculated value ($124\,\lambda/K_{1c}{}^{1\cdot 33}\,H^{0\cdot 25}$) yields a straight line with a correlation coefficient of 0.88 as depicted in Fig. 8. The triangle symbols denoted the data calculated for 0·5 μm (measured value 0·42 μm) and 7·5 μm (measured value 7·40 μm) Cr_3C_2 particulates, which were fairly well described by eqn (6). It is concluded that eqn (6) provides not only a more reasonable and physically meaningful description for the erosion behaviour of the composites than in eqn (3), but also readily involved the effect of microstructure imperfections, i.e. internal microcracking and residual porosity.

However, in spite of their tendency to form microcracks (particularly at higher volume fractions), the erosion resistance property of the Al_2O_3–Cr_3C_2 composites was still promising. Table 3 lists the erosion wear results of a number of widely-used materials for comparison purposes (under the same testing conditions).

Table 3. A comparison of erosive wear rate for different brittle materials. Samples were tested under the same erosion conditions as described in the text for comparison purposes

Materials	Erosion rate (cm^3/cm^3)
Composite (10% Cr_3C_2)	$2{\cdot}98\times10^{-4}$
Composite (20% Cr_3C_2)	$2{\cdot}22\times10^{-4}$
Composite (30% Cr_3C_2)	$1{\cdot}8\times10^{-4}$
Composite (40% Cr_3C_2)	$1{\cdot}2\times10^{-4}$
Al_2O_3 (99.9% purity)	$3{\cdot}32\times10^{-4}$
Al_2O_3-A[a]	$3{\cdot}63\times10^{-4}$
Al_2O_3-B[b]	$4{\cdot}41\times10^{-4}$
Al_2O_3-C[c]	3.73×10^{-4}
SiAlON[d]	$1{\cdot}2\times10^{-4}$

[a,b,c] Commercially available Al_2O_3 tiles.
[d] Fabricated in this laboratory with α-phase ~20% and β-phase ~80%.

4 SUMMARY

The erosive wear behaviour of the newly-developed Al_2O_3–Cr_3C_2 composites with particulate Cr_3C_2 phase ranging from 10 vol% to 40 vol% was investigated. The erosion rate decreased linearly with increased fractions of Cr_3C_2 particulates. The erosion mechanisms of the composites were described by the model proposed by Wayne and Buljan, and which was strongly related to mechanical properties and microstructure of the composites. The influence of composite microstructure was also found to play an important role in erosive wear behaviour. A mechanical properties–microstructural correlation was quantitatively established, i.e. 124 $\lambda/K_{1c}{}^{1.33}\ H^{0.25}$, which showed a satisfactory prediction on the erosion wear behaviour of the Al_2O_3–Cr_3C_2 composites. The excellent wear-resistant property of the composites comparable to other types of commercially-available materials suggests it could be a prime candidate material for erosion resistance applications.

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