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SOLID–PARTICLE EROSION OF AN Al2O3–SiC–TiC COMPOSITE

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ABSTRACT

An electrodisscharge-machinable Al2O3–SiC–TiC composite developed by Industrial Ceramic Technology, Inc., has a high fracture toughness, 9.6 ± 0.6 MPm1/2, as measured by indentation techniques, and a Vickers hardness of 20.3 ± 0.6 GPa. Additionally, the composite’s resistance to solid-particle erosion was measured for 143-μm-diameter SiC particles impacting at angles between 20 and 90° and at velocities from 50 to 100 m/s. The erosion rate exhibited a maximum for normal incidence, and the erosion resistance was better than that of commercial Al2O3. Scanning electron microscopy indicated that material wastage was by a combination of brittle fracture and microplasticity.

INTRODUCTION

Ceramic–matrix composites are being pursued as materials for structural applications in various industries, including automotive, aerospace, and utilities, chiefly because of the combination of high strength and toughness provided by these composites at both room and elevated temperatures [1]. One of the problems preventing more wide–spread application is that machining costs for complex parts are high, limiting mass production. Parts usually have to be ground by a diamond tool, which requires frequent dressing, and the amount of material removed per cut is limited. One possibility would be to find a tough, high–strength ceramic composite which could be machined by an alternative technique.

Such a ceramic has been developed by Industrial Ceramic Technology, Inc [2]. This composite has sufficiently high electrical conductivity (ρDC = 0.009 Ω-cm at 20°C) that it can be machined by an electrical discharge machine (EDM). With a wire saw the composite cuts 3 to 4 times faster than a carbide or a titanium alloy and cuts about as fast as aluminum or tool steel. EDM might allow the formation of shapes which could not be readily produced by grinding.
It is the purpose of this paper to characterize some of the important properties of this ceramic composite, namely hardness and fracture toughness. Additionally, we have chosen to characterize the solid–particle erosion resistance of this composite because possible applications could include fuel nozzles or pump vanes. The properties will be compared to those of Al₂O₃ monoliths and to other composites, where appropriate.

EXPERIMENTAL DETAILS

Material

The composite was a commercial material (CRYSTALOY 2311EDX) supplied by Industrial Ceramic Technology, Inc. The composition consisted of ≈ 30.9 vol.% SiC whiskers, 23.0 vol.% TiC, with the balance Al₂O₃. The composite was ≥ 98% of theoretical density. The scanning electron micrograph (SEM) taken in the backscattered mode shown in Fig. 1 indicates that the TiC (white phase) is ≈ 5 μm and uniformly dispersed in the matrix. Figure 2 shows that the whiskers are about 0.5 μm in diameter and 10 μm long. The initial whisker length was ≈ 50 μm. There is some evidence for a reaction between the Al₂O₃, and the SiC whiskers.

Fig. 1 SEM taken in the backscattered mode showing a uniform distribution of TiC (white phase).

Fig. 2. SEM taken in the secondary mode of fractured surface showing SiC whiskers.
Mechanical Testing

Fracture toughness (KIC) was determined from cracks produced by a Vickers indentation [3], while the hardness (HV) was determined from the size of the same indentation. Solid-particle erosion at ambient temperature was performed with 143-μm-diameter SiC particles accelerated by a slinger [4] at angles of impact of 20, 45, and 90°C and velocities of 50, 70, and 100 m/s. Steady-state erosion rate was determined from weight loss versus dose measurements. A typical curve is shown in Fig. 3. The rates were calculated from the slope.

![Graph](image)

**Fig. 3.** Weight loss versus dose measured for 143-μm-diameter particles impacting at 50 m/s angles of incidence: solid triangles – 90°, open triangles – 45°, and open diamonds – 20°.

RESULTS AND DISCUSSION

The results for hardness and KIC are summarized in Table 1 where they are compared to average literature values for Al2O3 and an Al2O3 reinforced with 25 wt.% SiC whiskers; see, for example, [5, 6]. It is recognized that there is great variability in KIC and HV for materials such as Al2O3 because these parameters also depend on density, grain structure, purity, etc. It is seen that CRYSTALLOY 2311EDX has both a high fracture toughness and hardness compared to the Al2O3, although values of HV > 14 are routinely reported for specially prepared aluminas [6]. One would expect that KIC for the CRYSTALLOY 2311EDX would be higher than Al2O3 simply because it contains 27.4 wt.% SiC whiskers which act to increase the toughness. There is no way to separate the effect of the whiskers and
the TiC particles. One would also expect that Hv of the CRYSTALOY would be higher than both Al₂O₃ and Al₂O₃ + 25 wt.% SiCₖₜ because TiC is harder than Al₂O₃ or SiC.

<table>
<thead>
<tr>
<th>Material</th>
<th>K_{IC} (MPm^{1/2})</th>
<th>Hv (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRYSTALOY 2311EDX</td>
<td>9.6 ± 0.6</td>
<td>20.3 ± 0.6</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.8</td>
<td>14</td>
</tr>
<tr>
<td>Al₂O₃ + 25 wt.% SiCₖₜ</td>
<td>6.8</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 1. Comparison of fracture toughness and hardness values.

On the basis of the above parameters it might be expected that the erosion resistance of the CRYSTALOY 2311EDX would be higher than that of both Al₂O₃ and Al₂O₃ + 25 wt.% SiCₖₜ because erosion ($\Delta E$, in mass of material removed/mass of material impacting the target) of a brittle material is proportional to [6]

$$\Delta E \propto V^n K_{IC}^{-4/3} H^q,$$

(1)

![Graph](image)

Fig. 4. Variation of the steady–state erosion rate versus impact angle for 143-μm–diameter particles impacting the target at the following velocities: triangles – 40 m/s, circles – 70 m/s, and squares – 100 m/s. A second order polynomial is drawn through the data.
where V is the impacting particle velocity and n and q are exponents which depend on the exact details of the impact conditions. Erosion for brittle materials is a maximum at normal incidence, 90°, because this represents the condition of maximum kinetic energy transfer. As expected, this is indeed the case for the CRYSTALOY 2311EDX, as shown in Fig. 3.

Generally, the velocity exponents, n, are about 2 to 3 for brittle materials [7] and values for Al₂O₃ and Al₂O₃ + 25 wt.% SiCₖ range between 2.48 and 2.0 with the exponent of 2.0 being reported for the 25 wt.% SiCₖ material [8] for a SiC abrasive. Values are somewhat higher if a softer abrasive, such as Al₂O₃, is used [9]. The value of the exponent measured from the slope of Fig. 4 is 2.0, exactly the value obtained under identical conditions (143-μm-diameter SiC particles impacting at 90°) for the Al₂O₃ + 25 wt.% SiCₖ composite. The velocity exponent measured for Al₂O₃ under the same conditions was 2.3 [9].

![Graph showing steady-state erosion rate versus impact velocity for 143-μm-diameter particles impacting the target at 90°.](image)

**Fig. 4.** Steady-state erosion rate versus impact velocity for 143-μm-diameter particles impacting the target at 90°.

The data are compared to published results on Al₂O₃ and Al₂O₃ + 25 wt.% SiCₖ [8] in the same figure. As noted above, the velocity dependence of erosion is nearly the same. More interesting, the erosion rate of the CRYSTALOY 2311 EDM alloy is lower than that of Al₂O₃, as expected on the basis of Eqn. 1 because it is generally found that q is quite small. That is, ΔE depends more strongly on K IC than on Hv. However, Eqn. 1 also predicts that the CRYSTALOY 2311 EDM
should have a higher erosion resistance than Al₂O₃ + 25 wt.% SiC₆. This is not the case.

Some insight can be obtained from SEM of a surface lightly eroded at 100 m/s such that the impacts did not overlap, as shown in Fig. 5. There is clear evidence for microplasticity as the surface was indented with little material loss. A surface eroded into steady state at 100 m/s is presented in Fig. 6. The predominant material failure mechanism was clearly brittle fracture. The impacting particles formed many small cracks that linked together to cause material wastage.

Fig. 5. SEM of a surface impacted by one 143-μm-diameter particle at 100 m/s at normal incidence.

The presence of many fine cracks in the SEM of the eroded surfaces suggests that microcracking contributes to the erosion of this material. This observation can be used to explain why the erosion resistance of the CRYSALOY 2311 EDM is lower than Al₂O₃ + 25 wt.% SiC₆ despite the higher toughness of the former. It was also reported that the erosion resistance of a SiC-whisker-reinforced Si₃N₄ composite was lower than expected on the basis of its fracture toughness [10], where it was suggested that while microcracking increased K_{IC}, it did not necessarily increase erosion resistance. Srinivasan and Scattergood [11] suggested that R-curve effects must be invoked to explain solid-particle erosion of brittle materials and not just the asymptotic values of K_{IC}. Microcracking in the wake of a constrained crack reduces crack propagation, thereby increasing K_{IC}. However, during erosion, material is continually removed and the cracks are not necessarily constrained; thus erosion resistance is decreased.
CONCLUSIONS

The hardness, toughness, and erosion resistance of an electrodischarge-machinable Al₂O₃-SiC-TiC composite has been measured. It is a hard (Hᵥ=20 GPA) and tough (9.6 MPa m¹/²) material and its erosion behavior is similar to that found for other ceramic composites, e.g. maximum erosion rate at normal incidence and velocity exponents ≈ 2. Erosion resistance of the composite falls between that of Al₂O₃ and a Al₂O₃ + 25 wt.% SiC whisker reinforced composite. Fracture and microplasticity contribute to the materials wastage mechanism.

ACKNOWLEDGMENTS

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