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ELECTRON MICROSCOPIC STUDIES OF THE MICRO-EROSION IN BRITTLE SOLIDS

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Erosion is a form of wear caused by particles impinging against a target face and removing material. The erosive action of fast moving particles is of importance in many engineering applications. In the pneumatic transportation of solids, the enclosing ducts may suffer severe damage. In gas turbines, blade erosion by particles leaving the combustion chamber, may considerably shorten the life of machine. In rocket engines, part of the surface damage to the exhaust nozzle wall is attributed to the action of particles from the combustion chamber. However, there are the useful applications of erosion: shot peening, sand blasting and erosive drilling of hard materials.

The major factors which affect the erosion: (i) Impact regime variables: particle impingement angle, particle velocity, distribution of velocity of impinging particles, temperature at which erosion occurs; (ii) Target variables: nature of target includes ductility, hardness etc; (iii) Contaminant variables: Particle size, shape and hardness.

Various studies have been reported on the importance of above variables and interrelation among them obtained for both ductile and brittle solids.¹⁻¹⁰ Sheldon¹¹ and Sheldon and Finnie¹² investigated the behavior of brittle targets subjected to homogeneous erosive agents.

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They correlated erosion rate with the Weibull flaw parameter, size and speed of the particles and found that, as the size of the particles decrease and/or their speed increases, the transition from brittle to ductile erosion takes place. They also observed that, for ductile targets, the maximum erosion rate occurred at small impact angles; for brittle targets, the maximum rate occurred at normal impact. However, still the knowledge about the basic mechanism of the erosion is very limited. The purpose of this note is to emphasize the need for electron microscopy to determine the nature of the damage introduced during erosion process. This will help understand the mechanism of erosion better and consequently theories will have a sound basis. The results reported here are the part of the continued program on electron microscopy of erosion.

High purity MgO single crystals (impurities in PPM: Al-200; Si-200, Fe-30) with 100 faces were used as the target and bombarded by Al_2O_3 microspheres ($0.3\mu - 27\mu$) at angles between 80 to 90° from the surface. Crystals contained relatively low dislocation density $10^5 - 10^6 \text{ cm/cm}^3$. A crystal ($2 \times 2 \times 0.2 \text{ cm}$) was first chemically thinned from both sides in hot phosphoric acid ($150-160^\circ\text{C}$) to a thickness about 0.05 cm . The crystal was then immersed in the solution (5 parts of saturated ammonium chloride, 1 part of sulphuric acid and 1 part distilled water) for about 15 min. at room temperature to reveal the damage on the surfaces of the crystal. Conical pits develop where dislocations emerge through surfaces. After confirming that there was no major damage in the crystals, they were bombarded from one side by Al_2O_3 particles using a pressurized gun at 65 lbs. The crystals were cleaned by air,

water and methyl alcohol and then re-etched. The damaged surface was photographed using Zeiss optical microscope at 400x. To get electron microscope samples, these crystals were thinned from the undamaged side using a jet polishing technique.¹³ The Berkeley 650 kV Hitachi high voltage microscope was used to make observations. High voltage microscopy has the advantages of better resolution and higher penetration thickness than ordinary (100 kV) microscopes.

Figure 1 shows an optical microscope picture of a bombarded (27μ Al_2O_3 particles at $\sim 85^\circ$ from the crystal surface) and subsequently etched surface. A points A, B, C, D, E and F (Fig. 1), micro-erosion and associated plastic flow is revealed. Plastic flow with almost no erosion is shown at G, H, I and J (Fig. 1). When the areas with plastic flow are observed in the electron microscope, a typical substructure as shown in Fig. 2, is revealed. Figure 2 was photographed using the diffraction vector¹⁴ $[200]$. Therefore, the damage on the slip planes (101) , $(\bar{1}01)$ and (110) , $(\bar{1}\bar{1}0)$ is in contrast. The electron beam was very close to $[001]$ direction of the specimen. Most of the plastic damage along $[110]$ is on $(\bar{1}\bar{1}0)$ and along $[\bar{1}\bar{1}0]$ is on (110) slip plane. The damage along $[0\bar{1}0]$ is on (101) and $(\bar{1}01)$ slip planes. Figure 3 is for the diffraction vector $[\bar{2}20]$. Therefore the damage on slip planes (110) ; (011) , $(0\bar{1}1)$ and (101) , $(\bar{1}01)$ is in contrast. Most of the plastic damage on (110) is along $[\bar{1}\bar{1}0]$; damage on (011) and $(0\bar{1}1)$ is along $[100]$; and on (101) and $(\bar{1}01)$ is along $[010]$.

As mentioned earlier, the crystals were bombarded at about 85° from their $\{001\}$ surfaces, i.e., at about 5° from $[001]$. Therefore, most of the damage should be contained on (011) , $(0\bar{1}1)$, and (101) , $(\bar{1}01)$

slip planes and little on (110) ($\bar{1}10$) planes because the resolved shear stress on the latter planes along Burgers vector is very small. That this is true can be seen from high dislocation density slip bands along $[0\bar{1}0]$ in Fig. 2; and along $[100]$ and $[010]$ in Fig. 3. (MgO has rock salt structure with six $\{110\} \langle \bar{1}10 \rangle$ slip systems, each slip system having only one slip vector).

Most of the damage is in the form of dislocation dipoles (two closely spaced dislocations of opposite nature). See A and B in Fig. 2; and A in Fig. 3.

Experiments done for particles $< 27\mu$ (10μ , 1μ , 0.3μ) showed no difference in the nature of the damage except in degree. As the particle size decreased for the same velocity, the amount of damage was less. Experiments have been done on thin electron microscope foil where the same area was photographed in the electron microscope before bombarding. There was no difference in the nature of the damage.

These results indicate that the electron microscope is a very powerful tool to study the damage introduced during erosion. From the dislocation can be better understood. From the knowledge of initial energy of the particles and the dislocation density, fractions of the energy used in plastic flow and erosion can be estimated. The knowledge of the latter is very important in the theories of erosion. It is further suggested that by controlling the size and velocity of impinging particles, the surface can be cold worked (like points G, H, I and J in Fig. 1). The cold worked surface should be much more resistant to further erosion.

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FIGURE CAPTIONS

- Fig. 1. Erosion with plastic flow at points A, B, C, D, E and F; plastic flow with almost no erosion at points G, H, I and J.
- Fig. 2. Micrograph using diffraction vector $(g) [200]$. The plastic deformation in the form of dislocations and dislocation dipoles on (110) plane (shown along $[\bar{1}10]$), on $(\bar{1}10)$ (shown along $[110]$); and on (101) and $(\bar{1}01)$ slip planes (shown along $[0\bar{1}0]$). Note dislocation dipoles at A and B. The electron beam is along $[001]$ of the specimen. So the plastic damage shown is the projection on (001) plane.
- Fig. 3. Micrograph using diffraction vector $[\bar{2}20]$. Most of the plastic damage on (110) plane is along $[\bar{1}10]$, the damage on (011) and $(0\bar{1}1)$ plane is along $[100]$; and on (101) $(\bar{1}01)$ is along $[010]$. Note the dislocation dipoles, typical of MgO plastic damage.¹³

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Fig. 1

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Fig. 2.

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Fig. 3.

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