THE SURFACE FAILURE OF FLUORAPATITE SINGLE CRYSTALS*

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SUMMARY

Single crystals of various material are used for basic studies of friction and wear because of their simplicity. Single pass sliding enables one to sort out the effects influencing wear such as anisotropy and environment. A review of the literature is given for studies with metallic single crystals, diamond, magnesium oxide, and sapphire. Results are presented for studies on fluorapatite single crystals. Frictional anisotropy was found to be similar to that in MgO single crystals even though fluorapatite and MgO have different lattice structures. A new finding is the fact that repeated sliding at contact stress states above a threshold value causes catastrophic surface damage after the second pass even though very little damage appeared on the first pass. Most previous studies report the results of single passes. In practical sliding systems where repeated sliding is always occurring, wear of brittle materials must be dominated by the catastrophic mechanisms found on the second pass rather than by the events that occurred during the first pass.

INTRODUCTION

The study of wear and surface damage of materials is very difficult. An alternative method to studying the gross wear of a material is to investigate the frictional behavior and surface failure of a simplified or model system. Single crystals represent the most attractive simplified systems because the test results are confused by fewer variables in material structure. In the past decade a number of papers have appeared which report on the nature of surface failure of single crystals under conditions of rubbing. The major conclusions of these papers will be reviewed. Recently the experimental approach in a number of the above reviewed

papers was applied to an in-depth investigation of the influence of sliding direction, environment and multi-pass sliding on the mode of surface failure of fluorapatite (FAP) single crystals[1-3]. The main conclusions of the recent investigation are given in this paper. The major new contribution of the recent work is some findings on multi-pass sliding. Previously published papers report conclusions from single pass sliding experiments.

The ultimate goal of the recent experiments was to provide insight into the mechanism of wear of dental enamel[4]. However, the results obtained on the FAP model system indicated the power of such an experimental approach to obtain new information on the basic mechanisms of surface failure.

WEAR OF SINGLE CRYSTALS: A REVIEW OF THE LITERATURE

It is a convenient approximation to regard the frictional forces between solids as being made up of two components: the force required to shear the adhering junctions in the region of surface contact and the force required to deform the underlying bulk material[5]. With an elastic solid, the deformation term may be due mainly to an elastic hysteresis loss; but if plastic flow occurs, the deformation term will represent the force required to produce bulk deformation or to drag surface irregularities through the solid and to plow out a track[6].

Inherent in this representation of friction is the distribution of stress at and below the surface of the solid. On an atomic level, dislocation movement and the intersection of slip planes may in part determine the deformation process. A cleavage mode of stress relief might be expected to occur in cases where the active slip systems of the material are misaligned with respect to the resolved shear stress or where the slip systems are pre-empted by energetically favorable cleavage planes. Consequently, surface damage (cracks, wear particles, or material pile-up) can be expected to occur in a frictional process.

Single crystals (metallic and non-metallic) represent a basic system for the study of frictional anisotropy and surface damage in that grain boundaries, which may serve to hinder dislocation movement and crack propagation, are eliminated. In addition, since crystallographic orientation of a single crystal is possible, a fundamental relationship between friction and surface failure may be observable.

In early work, King and Tabor[7] demonstrated that brittle materials could exhibit plastic deformation in the region of surface contact and they showed that conclusions drawn from friction studies on metallic single crystals may be applicable in a limited way to a study of non-metallic single crystals. Accordingly, the frictional anisotropy of metallic single crystals will be briefly reviewed. Specific consideration will then be given to the investigations of diamond[8-12], magnesium oxide[9-11,13], sapphire[14-18], fluorapatite[19-21], and several miscellaneous crystals[22-26]

1. Metallic single crystals
      Friction and deformation research on metallic single crystals has been pursued by a number of investigators. The rolling and sliding friction of copper [face centered cubic (fcc)] has been extensively studied by Gwathmey and his associates[27,28], by

Courtel and his associates[29], by Dyer[30], and by Takagi and Tsuija[31]. Brass has been studied by Steijn[25]. Research on the body-centered cubic (bcc) metals includes work by Agarwala and Wilman[32] on iron crystals and by Buckley[33] on tungsten. Buckley has also contributed work on the frictional behavior of aluminum[34], as well as the hexagonal metals: beryllium[35], cobalt[36], magnesium[37], and titanium[38].

Buckley[39] has observed that friction coefficients (with limited plowing components) for a number of metals in sliding contact with metals were lowest on the preferred slip or glide planes in the preferred slip direction. Steijn[25] observed that plowing friction on cube faces of fcc and bcc metals was larger in the [101] direction than in the [100] direction, whereas track widths were larger in the [100] direction. He found that hillocks were found to be formed when sliding in the [101] direction, and as a result the resolved shear stress on the active slip planes was reduced. This explains the higher friction in this direction.

Bailey and Gwathmey[27] in their study of copper single crystals reported similar observations. They suggested that slip and plastic deformation when sliding in the [110] directions caused the metal to build up in front of the slider, so that friction was increased. Their observations substantiated those of Dyer[30].

2. Diamond

Bowden and his associates[8,9] have studied the adhesion component of friction of diamond by sliding a hemispherical diamond on a (111) diamond face in air and in vacuum (5×10^{-10} torr). Although no frictional anisotropy was observed, surface damage in the form of cracking and fragmentation was considerable in vacuum, whereas in air no damage was perceptible. The effect on surface damage of the adhesion component of friction was shown to be highly dependent on the absorbed gas film. Under high vacuum conditions, the bulk elastic deformation of the diamond was unable to relieve the high stresses at the interface caused by high adhesion, thus the energy was expanded in forming new surfaces via a cleavage mode of failure. In air, adhesion was severly limited by adsorbed gas contamination, and surface damage was not observed.

Bowden and his associates[10,11] have studied the plowing friction (one traverse) of diamond by sliding conical diamonds with various apical angles on a (001) diamond surface. Using a cone with a 60° apical angle, they found the friction in the [100] directions to be three times that in the [110] directions. It was observed that surface damage in the low friction directions was low, whereas considerable cracking was found in the [100] sliding directions. Further examination indicated that high friction directions were those allowing the deepest penetration of the slider (or the surface irregularities on it) and maximum deformation and cracking of the bulk crystal. A similar observation was made by Seal[12], who noted that directions of higher friction were directions of easy abrasion.

3. Magnesium oxide

Early work on magnesium oxide was done by Steijn[13], who observed that cracks formed by sliding on a (001) surface in the [110] direction were on (110) planes. Surface cracks resembling chevrons were evident.

Bowden and Hanwell[9] slid a MgO slider on a (001) plane in the [110] direction of MgO in a vacuum (2×10^{-9} torr). After etching, chevrons indicating

cracking on (110) planes were observed, although considerable deformation obscured any central cracks. Etching of areas of subsurface deformation indicated slip on those (110) planes which intersected the (001) planes at 45°. Some normal slip was indicated on those (110) planes normal to the sliding surface.

Bowden and his associates[10,11] have extensively studied the frictional anisotropy and surface damage of MgO where plowing occurred. With a hemispherical slider moving 0.1 mm/sec on a cleaved (001) plane of MgO under load of 30 g, considerable plastic deformation beneath the crystal surface was noted[10]. The process of fracture which governed the formation of wear debris was found to occur both on and beneath the surface. Slip had taken place predominately on those (110) planes which intersected the deformed surface at an angle of 45°, although some slip occurred on those (110) planes at 90° to the surface involved.

When conical diamond sliders were used, a low and a high friction regime were observed[11]. With the apical angle of the cone larger than 120°, low friction was found over a range of loads between 10 and 350 g. Little surface damage was evident and the friction was isotropic. With smaller apical angles, two distinct friction regimes were noted. Below a critical load, the surface behavior was found to be similar to that observed with wide angle cones; however, above this load the friction and surface damage increased. The friction was then anisotropic with higher friction observed in the [100] directions than in the [110] directions. Examination of tracks made in the high friction regime indicated that they were wider and deeper in the [100] directions.

In the low friction regime, etching of surface deformation of MgO produced by sliding in [100] and [110] directions on the (001) surface revealed both edge and screw dislocations[11]. It was observed that plastic flow took place beyond the actual wear track; that cracks were formed within this region on (110) planes; and that a small central wear track was plowed out by a slider. The dislocation density on the (011) planes was greater than that on the (101) planes.

In the high friction regime, large chevron type cracks were formed with a specific orientation with respect to the sliding direction. Chevron formation was preceded by the nucleation of cracks which developed in front of and to the side of the slider. The complete chevron was formed by the interaction of tensile cracks developed on (100) cleavage planes with subsurface shear cracks.

4. Sapphire

The surface damage of corundum (α-Al$_2$O$_3$) has been studied by Steijn[14], who rubbed sapphire balls on sintered tungsten carbide blanks in reciprocating motion under a load of 1550 g. He found that rubbing on a prismatic plane in a direction parallel to the c-axis resulted in severe chipping and conchoidal fracture. Rubbing in the [2$\bar{1}\bar{1}$0] direction gave a smooth wear surface. It was found that the wear of the basal plane was the least damaging and was, furthermore, independent of the sliding direction.

The type of wear characterized by conchoidal fracture and chipping as encountered on prismatic wear planes was explained by a resolved shear stress of zero along the slip direction. As none of the slip systems could become operative, brittle fracture ensued. Wear on the basal plane was considered to be ductile in nature due to a process of basal slip.

Riesz and Weber[15] slid sapphire on sapphire under a vacuum of 10^{-6} torr from 25° to 1550°C at a speed of 50 μm/sec. Their results suggested that at lower temperatures, fracture was induced by strong adhesive forces, whereas at higher temperatures, wear was the result of bulk surface deformation. It was suggested that at elevated temperatures, friction appeared to be related to the number and motion of dislocations. The basal plane was found to be most susceptible to wear.

Duwell[16, 17] has studied the friction and wear of sapphire on steel continuously wet with water at sliding speeds of 140 m/min under a 650 g load. He found the least wear resistant orientation of the sapphire to occur when the c-axis was nearly perpendicular to the plane of sliding and tilted towards the direction of sliding. The most wear resistant orientation occurred when the direction of sliding was reversed 180°. Wear rates were lower on prismatic planes with maximum wear occurring in the direction in which plastic deformation was easiest. Brittle type wear on the prismatic planes was not observed. It was found that the friction force increased as the wear rate increased. It was suggested that when a high wear orientation occurred, plastic flow of the sapphire produced an exceedingly smooth surface that permitted enlargement of the real area of contact and an increase in friction.

Buckley[18] has conducted friction experiments of sapphire on sapphire in a vacuum (10^{-10} torr) at temperatures to 575°C. At a sliding speed of 0.013 cm/sec under a load of 250 g, the friction coefficient for the basal orientation (0001) [11$\bar{2}$0] was less than half that obtained for the prismatic orientation (10$\bar{1}$0) [0001]. It was found that with the basal orientation, a lower coefficient of friction was observed in the preferred [11$\bar{2}$0] slip direction. Marked evidence of plastic deformation of the crystal was found. Higher coefficients of friction in the prismatic orientation than in the basal orientation were anticipated owing to the larger number of active slip systems in the prismatic orientation.

5. Fluorapatite

A quantitative method for characterizing the surface failure of fluorapatite single crystals under sliding has been evaluated by Powers and Craig[19]. The method consisted of sliding a diamond of specific geometrical design on the basal surface of natural fluorapatite single crystals in air. The variables, track width, track depth and area, were found to be effective in ranking data obtained under varying conditions of slider speed, load and slider design.

The frictional behavior of natural fluorapatite single crystals under sliding has been evaluated by an examination of the variables, friction force and the coefficient of friction[20]. The coefficient of friction data were observed to be more reliable in discriminating among differences in load and slider design than were the friction force data.

No strain rate effect was observed for the coefficient of friction under the conditions examined. This suggested that friction was more related to crack *initiation*, whereas the variables measuring wear were more related to crack *propagation*.

Low values of the coefficient of friction of 0.20 were observed with low values of penetration (< 0.65 μm). This suggested that friction under these conditions was composed of an adhesive component and a deformation component. Plastic deformation was probably the primary mechanism of strain energy release

under these conditions, although some cracking indicated that a cleavage mechanism was initiated.

High values of the coefficient of friction of 0.45 were observed with high values of penetration (1.0–25 μm). Under these conditions cleavage and chevron formation were suggested as the major mechanism of strain energy release.

The modes of surface failure observed for natural fluorapatite single crystals under sliding in air have been classified and related to the wear and frictional behavior[21].

The basal plane of fluorapatite was found to behave in a ductile manner for large diameter sliders over the range of loads studied and for small diameter sliders at lower loads. At higher loads this behavior transformed to a brittle mode of failure with tensile cracking followed by chevron formation. It was suggested that the interrelationship between load and slider design influenced the mode of surface failure.

A ductile to brittle transition was observed to occur between penetrations of 0.3 to 0.5 μm for the basal plane of fluorapatite. At penetrations greater than 1.0 μm, chevron formation and high friction were observed. This suggested that a strain corresponding to a penetration of 0.3 to 0.5 μm could be accommodated by plastic deformation. Above this strain, tensile cracks would occur immediately upon passing of the slider. At much greater penetrations, chevron formation would be immediately initiated.

6. Miscellaneous studies

The frictional anisotropy and surface damage of titanium dioxide (rutile) has been studied by Steijn[22,23]. The anisotropy of rutile single crystals was measured by using a 0.001 in. diameter diamond stylus as a slider under loads of 30–40 g. It was concluded that flow on the (100) and (110) planes was more difficult in a direction parallel with the c-axis than at right angles to it. Knoop indentation observations indicated least penetration in the direction of highest friction. With larger diameter styli, no frictional anisotropy was detected.

Fine surface markings on the (110), (100) and (001) crystal planes in and near friction tracks were believed to be traces of the [101] (10$\bar{1}$) and [110] (001) rutile slip systems, although complex distortion and lattice rotation was present in the groove. The frictional anisotropy measured was thought to be a direct consequence of the orientation of these slip systems with respect to the applied stress in the region below and adjacent to the sliding indenter. The greater ease of sliding perpendicular to the c-axis as compared to parallel with the c-axis on the (110) and (100) planes was believed to be due to the inclination of the {101} planes with respect to the sliding direction.

Dobson and Wilman[24] have studied the friction coefficient (β) and mass wear rate (M) during abrasion of a (001) cleavage plane of a single crystal of sodium chloride as a function of abrasive particle diameter at a load of 500 g. Three types of (M, β) relationships resulting from abrasion on various grades of dry emery paper were observed corresponding to different ranges of abrasive particles indentation depth. For less than 0.5 μm in depth, fracture appeared to be absent with plastic flow predominating. The (M, β) relationship was found to be approximated by metals of similar hardness. At deeper indentations a linear (M, β) relation was

observed but with greatly increased wear. At depths greater than 5 μm, the wear rate increased rapidly without much increase in the coefficient of friction. A greatly increased spread of fractures around the indenting particles was observed. A modified theory of the friction and wear in the abrasion of such brittle solids was proposed.

Friction tests on cube planes of single crystal of sodium chloride were carried out by Steijn[25] with a sapphire slider under a 200 g load in the [100] and [101] directions. The following surface preparations were examined: as cleaved, chemically polished in a mixture of ethyl and methyl alcohols, mechanically abraded on graded SiC papers, and polished in distilled water. It was observed that the lowest friction was afforded by chemical polishing, the next lowest by water polishing, followed by abrading; the as-cleaved faces exhibited the highest friction. Friction along the [110] directions was consistently higher than that along the [100] directions. Similar effects were examined in crystals of lithium fluoride, potassium bromide and potassium chloride.

Sliding friction experiments were conducted by Buckley[26] on the (111) cleavage face of calcium fluoride single crystals in various environments including hexadecane, oleic acid, water, and dimethyl sulfoxide. A sapphire ball, submerged in fluid, was slid on the (111) planes at speeds of 0.005 to 0.5 mm/sec and loads of 100 to 600 g. Friction was observed to obey Amonton's law in all cases studied, as well as being extremely sensitive to the environment. Track width as observed optically prior to etch-pitting was found to slowly increase with load; however, track deformation as measured by surface dislocation density was observed to increase at a much more rapid rate. In addition, the amount of track deformation was found to decrease with increased sliding speed (increased strain rate).

The number and depth of surface and subsurface cleavage cracks were found to be sensitive to both load and the environmental species present. The subsurface distance for the formation of (111) cleavage cracks increased with increased plasticity of the crystal surface. It was thus suggested that when the applied stress could no longer be accommodated by slip along (100) slip planes, subsurface fracture occurred in the zone of maximum subsurface stress along (111) cleavage planes.

This section has been an attempt to review the engineering literature on the surface failure of single crystals under sliding. It is apparent that surface damage is a complex phenomenon dependent upon variables such as applied stress, environment, slider geometry, sliding speed, and surface preparation, in addition to crystallographic properties such as operable slip and cleavage systems.

EXPERIMENTS ON THE WEAR OF FLUORAPATITE (FAP)

A number of factors influence the wear of FAP. The three most interesting conditions, and those reported here are the influence of sliding direction, the influence of the environment in which the experiment is conducted, and the effect of multiple as compared with single passes.

1. Influence of sliding direction

(a) Materials and methods
A diamond hemisphere (360 μm in diameter) was slid across the basal

Replications : 6 Crystals (natural FAP)
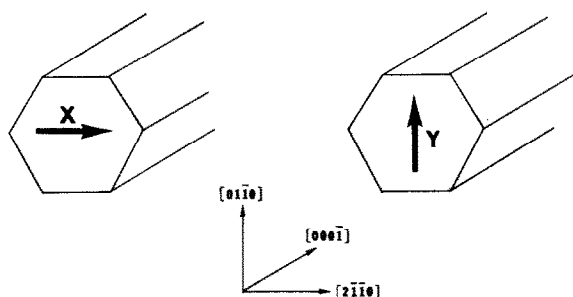**Normal Load : 10 - 150 g (10 g increments)**

Fig. 1. Schematic diagram of experimental procedure for evaluating the influence of sliding direction on surface failure.

surface of natural fluorapatite (FAP) single crystals[1]. Fifteen parallel, one-traversal scratches resulting from sliding a normal load of 10 to 150 g in increments of 10 g were made on the basal plane of each of six crystals in the $[2\bar{1}\bar{1}0]$ direction and subsequently in the $[01\bar{1}0]$ direction as shown schematically in Fig. 1. All runs were made in laboratory air. The single crystals were given a polishing and surface treatment prior to use[19]. The apparatus used for scratching the surface of a specimen and measuring the tangential force has been described in detail earlier[19,20]. The failure classification scale used in the present study has also been reported[21]. From the failure classification data was chosen the normal load (Ω) above which a ductile mode of failure (class 1) was no longer observed. This load is equivalent to the load at which the ductile to brittle transition occurs.

(b) Results and discussion

Frictional anisotropy was observed with the coefficient of friction (β) in the $[2\bar{1}\bar{1}0]$ direction ($\beta = 0.217$) approximately 12% higher than in the $[01\bar{1}0]$ direction ($\beta = 0.193$). The load (Ω) at which the ductile to brittle transition occurred was higher in the $[2\bar{1}\bar{1}0]$ direction ($\Omega = 77$ g) than in the $[01\bar{1}0]$ direction ($\Omega = 15$ g).

The structure[40] of fluorapatite projected on an x, y plane is shown in Fig. 2. The space group and unit cell dimensions of natural FAP are: $P6_3/m$, $a_0 = 9.364$ Å and $c_0 = 6.897$ Å, respectively[41]. Natural FAP has imperfect basal and $\{10\bar{1}0\}$ cleavage[42]. Detailed interpretation of the results in terms of the crystallographic structure of FAP has been reported[43]. Only a summary is presented here.

The degree of anisotropy observed is consistent with observations made by Bowden and Brookes[11] for the frictional behavior of MgO single crystals. They suggested a critical amount of subsurface deformation was necessary for anisotropic friction, a criterion met over the entire load range for FAP. For sliding in the $[01\bar{1}0]$ direction, the complex stress state is such that imperfect cleavage occurs on $\{10\bar{1}0\}$ planes, *i.e.*, those planes oriented at a 30° angle to the direction of sliding. For sliding in the $[2\bar{1}\bar{1}0]$ direction, cleavage again occurs on $\{10\bar{1}0\}$ planes, since cleavage on $\{2\bar{1}\bar{1}0\}$ planes is not energetically favorable due to the overlapping of strongly bound phosphate tetrahedra (see Fig. 2). However, because the $\{10\bar{1}0\}$ planes are oriented at a less favorable angle of 60° to the sliding direction, a larger maximum
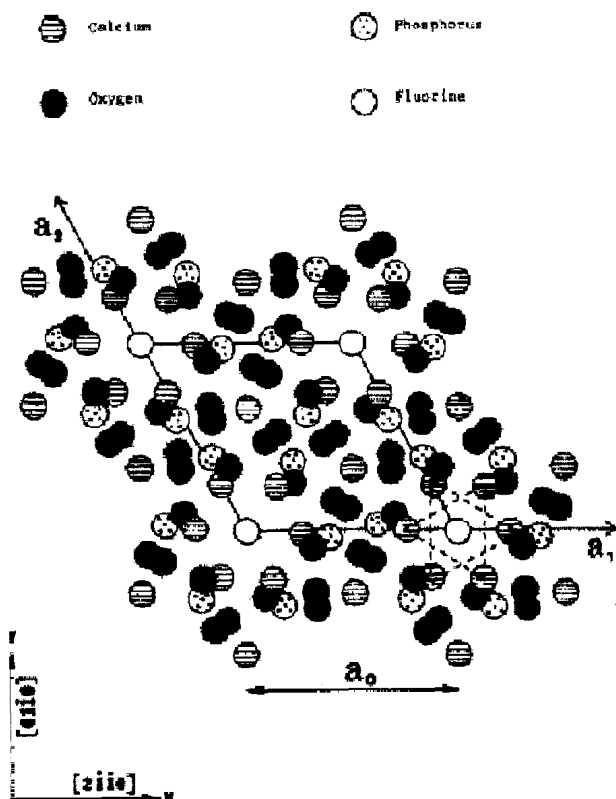
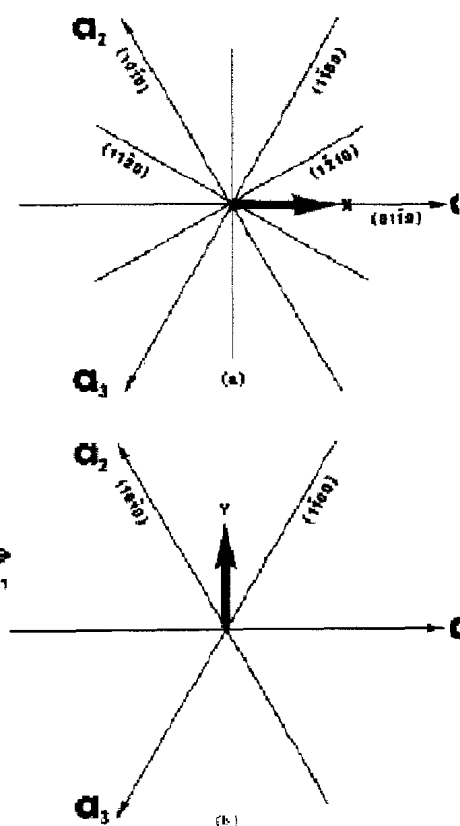Fig. 2. Fluorapatite structure projected on an x, y plane.

Fig. 3. Diagram of hexagonal system to show orientation of cleavage planes with respect to sliding directions.

normal stress would be required to initiate cracking in the [2$\bar{1}$10] sliding direction (see Fig. 3).

2. Influence of environment

(a) Materials and methods

A diamond hemisphere (360 μm in diameter) was slid across the basal surface of natural FAP single crystals in the [2$\bar{1}$10] direction. One-traversal scratches were made on the basal plane in environments of air, water and dimethylformamide as shown schematically in Fig. 4. The load range from 10 to 150 g was studied. Further experimental details have been reported elsewhere[2].

(b) Results and discussion

Typical scanning electron photomicrographs of the surface failure observed for sliding in water are shown in Fig. 5. Ductility observed in the center of the wear

Replications : 6 Crystals (natural FAP)

Normal Load : 10 - 150 g (10 g increments)

Environments : Air (adsorbed water) , Water ,
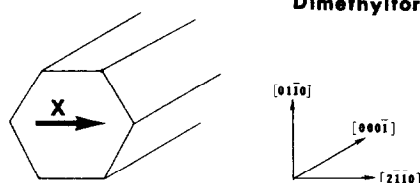
Dimethylformamide

Fig. 4. Schematic diagram of experimental procedure for evaluating the influence of environment on surface failure.

scar for sliding in air or dimethylformamide[43] was not apparent for the majority of tracks formed in water. Tensile cracking was no longer observed above normal loads of 30 g, rather large fragments had chipped from the center of and along the edge of the wear scar. Subsurface failure in the immediate vicinity of each wear scar was considerably more prevalent for sliding in water. The ductile to brittle transition occurred at a lower load ($\Omega = 18$ g) for sliding in water than in air ($\Omega = 77$ g). No difference, however, could be detected among the values of the coefficient of friction (β) for sliding in air, water or dimethylformamide.

The apparent difference in the mechanism of surface failure observed for sliding in water is explained by a surface hardening that requires an interaction between the polar water present in a bulk solution of water and charged near-surface species present in the FAP. Such a model for surface hardening has been explained in detail by Westwood, Goldheim and Lye[44-46]. In fluorapatite the fluorine is located at the center of a calcium triangle (see Fig. 2). The channels formed by these calcium triangles are fairly large and are supported by the rest of the structure, such that one can expect that they provide easy diffusion paths. Presumable, surface-active species could influence the position of the near-surface F^- ions relative to the calcium triangles, thereby modifying the properties of the surface. The observation of decreased track ductility and increasing chipping and flaking support a surface hardening mechanism.

3. Influence of multipass sliding

(a) Materials and methods

The experimental procedure for scratching the basal surface of a fluorapatite single crystal was similar to that described above and has been reported in detail elsewhere[3]. The influence of five types of multipass sliding on the surface failure of the basal plane of FAP was studied as shown in Fig. 6.

(b) Results and discussion

It was observed that multipass sliding produced considerably more wear than did a single pass, although at very low loads and at very high loads the effect was not obvious. For example, when a pass was made with a load of 50 g that was
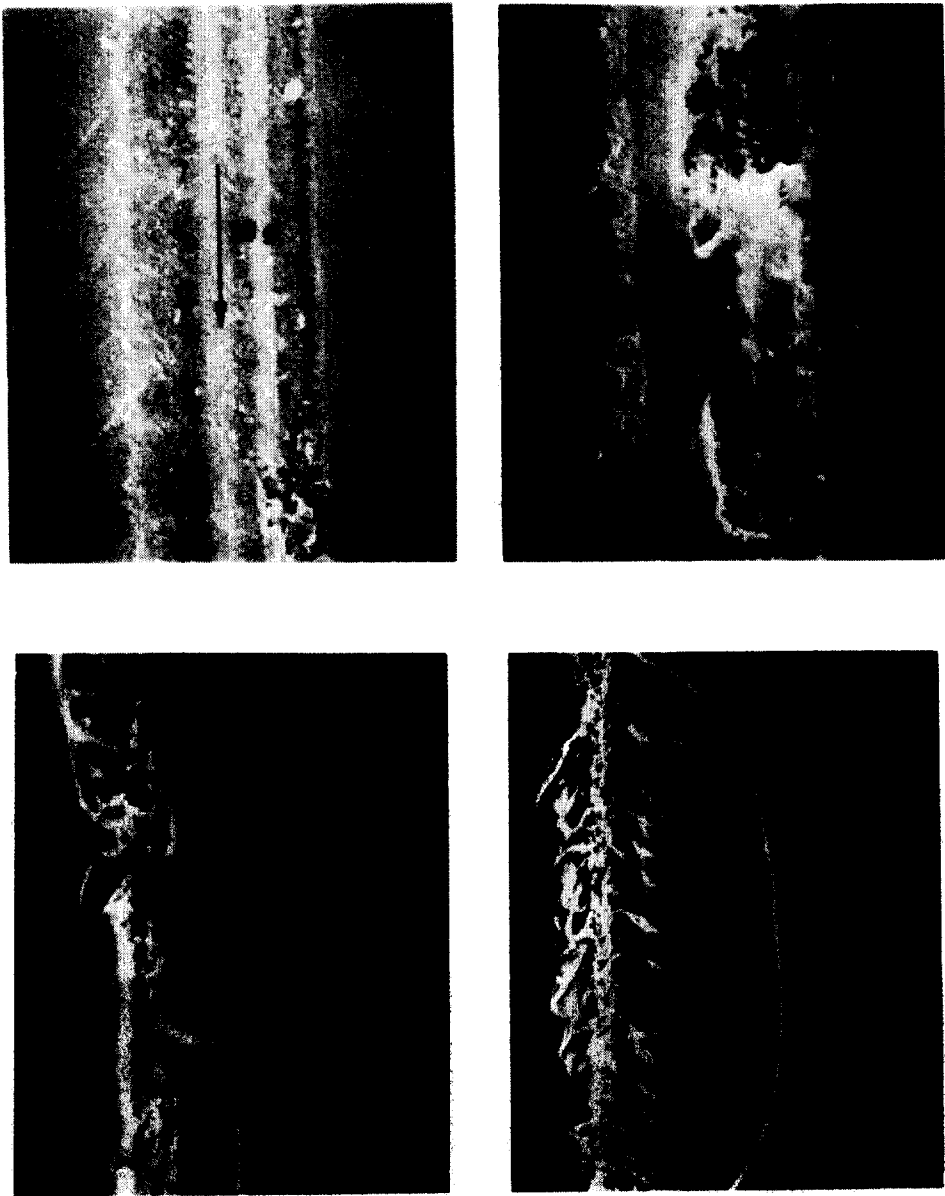
Fig. 5. Scanning electron photomicrographs of surface failure observed for sliding in water.

subsequently crossed by a pass with a 10 g normal load, no unusual surface failure was seen as shown in Fig. 7(a). When the second pass was made with a load of 50 g, however, considerable damage resulted (Fig. 7b).

Increased damage was observed where a pass was repeated on a previous wear scar in the same direction as the first pass. Even at low loads as shown in Fig. 8, the resulting damage from the second pass was apparent. The most destructive com-
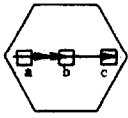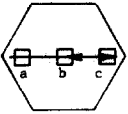
Wear I: Two, one-traversal scars exactly
          superimposed on one another in
          the same sliding direction.*
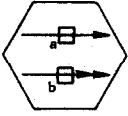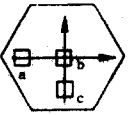
Wear II: A single pass scar followed by a
          double pass scar adjacent to it
          in the same sliding direction.
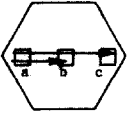
Wear III: Two, one-traversal scars almost
          superimposed on one another in
          the same sliding direction.

Wear IV: Two, one-traversal scars exactly
          superimposed on one another but
          in opposite sliding directions.

Wear V: One-traversal scars in the x-
          sliding direction crossed with
          one-traversal scars in the y-
          sliding direction.

* a,b and c indicate areas of observation in the SEM

Fig. 6. Schematic diagram of experimental procedure for evaluating the influence of multipass sliding on surface failure.
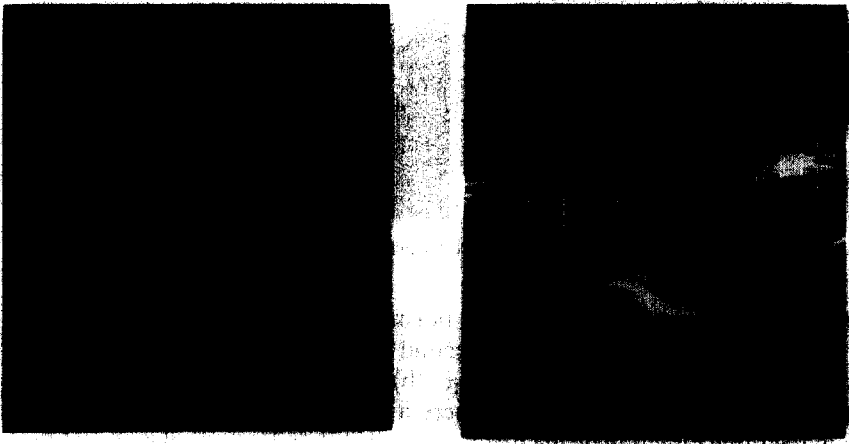
Fig. 7. Scanning electron photomicrographs of surface failure observed under conditions of wear V.
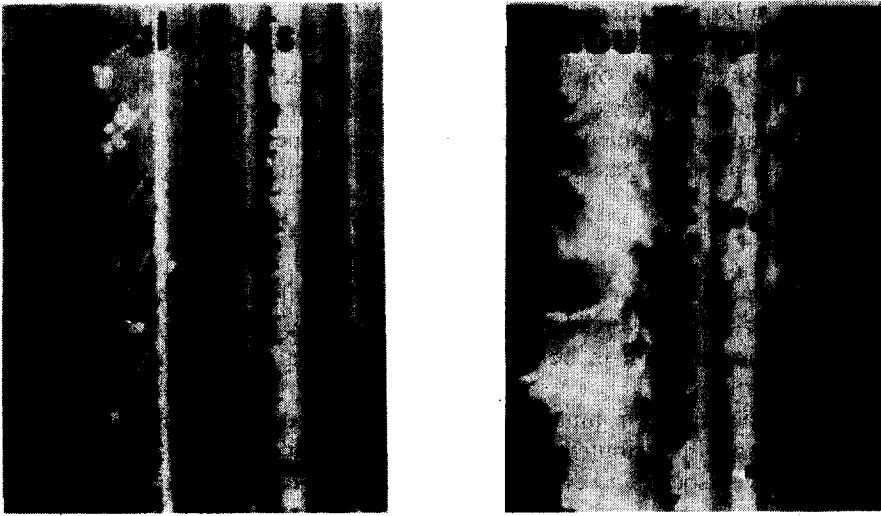
Fig. 8. Scanning electron photomicrographs of surface failure observed under conditions of wear I.
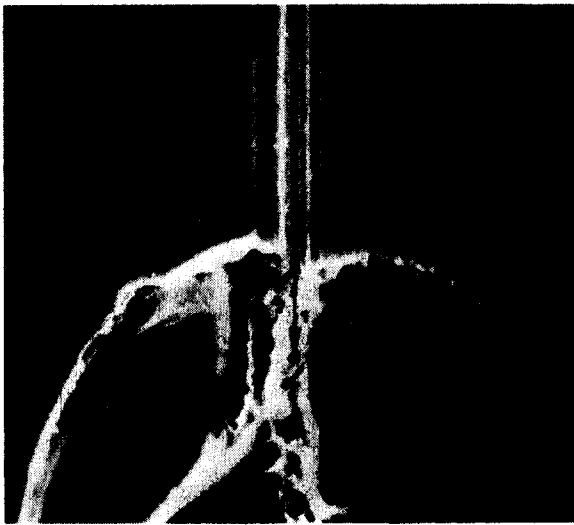

Fig. 9. Scanning electron photomicrographs of surface failure observed under conditions of wear IV.

bination of sliding occurred when the second pass was reversed in direction on a previous wear scar as shown in Fig. 9.

The above examples show that wear of a brittle material under conditions of repeated sliding cannot be predicted on the basis of single-pass sliding. It should be noted that such is the case also for slider passes which are not exactly super-imposed on one another[3].

The precise reason for catastrophic failure due to a second pass has not been determined. However, one may suppose that one pass of a slider does con-

siderably more subsurface damage than is indicated by surface features. In fact when a sliding pass is made on a semi-transparent solid, it is often possible to observe some change in the optical qualities of the material near the wear scar. Presumably, a greater number of very small cracks exist under the wear track. Since the most severe multipass sequence is for reverse sliding, one may also speculate that the cracks from a previous pass are oriented in some particular direction.

CONCLUSIONS

The frictional behavior of fluorapatite single crystals appears to parallel the frictional behavior of MgO single crystals. The influence of sliding direction relative to crystallographic direction in both materials is similar even though they have different lattice structures.

The influence of environment appears in fluorapatite as it does in several other materials, and is attributed to an interaction between polar water on the surface with charged species a very small distance down in the substrate.

Finally, the experiments show that repeated sliding at some contact stress state above a threshold value causes catastrophic surface damage on the second pass, even though very little damage appeared on the first pass. These observations would indicate that, in previous studies of friction and wear of single crystals, simple observation of the surface of the wear track is inadequate for understanding all of the results of sliding. These findings would also indicate that a new approach must be taken in the use of single crystals to predict the gross wear behavior of materials.

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