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THE NATURE OF SURFACES AND THEIR INFLUENCE IN WEAR MECHANISMS

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ABSTRACT

The wear of materials is strongly dependent upon the nature of the solid surfaces in contact. their properties and the nature of the films on them. Oxide films, orientation, crystal transformations, adhesive binding, crystal structure, hardness and the presence of alloying agents are all shown to effect one or more of the forms of wear. The three most common forms of wear, adhesive, abrasive, and corrosive, are discussed in terms of the way each is affected by various material properties. Results presented indicate how wear can be optimized by concern for properties of materials.

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WHERE TWO SOLID SURFACES are in contact and then separated, wear or the loss of material from one or both solids can and frequently does occur even when the surfaces are well lubricated. Wear can occur when there is relative motion between the solids such as sliding or rolling. It can also occur on the simple touch contact of the solids as in electrical switches. In general wear is an undesirable process and engineering design seeks to avoid it. There are industrial processes, however, which seek to maximize material removed such as in the abrasive wear associated with the grinding process.

Whether the objective is minimize wear as in bearings, gears, or seals or to maximize it as in the grinding process understanding the fundamental mechanisms of wear is important if optimized objective results are to be achieved.

The objective of the present paper is to review some of the wear mechanisms, the importance of surfaces and surface layers of materials in the wear process and to discuss some typical properties of solids in contact which effect wear. The representative classes of materials to be discussed will include metals, polymers, carbons and ceramics.

DEFINITION OF WEAR

Wear is generally thought of as involving the removal of material from a solid surface and has been defined as "the progressive loss of substance from one operating surface of a body occurring as a result of relative motion at the surface" (1).[*]

There are, however, situations where material is not actually removed or lost from a surface but one of the surfaces has undergone a permanent topographical change. For example, when an aluminum surface is polished with diamond paste, the diamond particles can score the aluminum surface and become

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[*] Numbers of parentheses designate References at end of paper.

permanently embedded in the aluminum so indicated in Fig. 1. The SEM photomicrograph of Fig. 1 indicates the diamond abrasive particle embedded and the destruction of the aluminum surface caused by that particle.

While the events of Fig. 1 do not meet the accepted definition of wear, they do produce a permanent surface change which could result in the destruction of operating tolerances in close tolerance mechanical components just as effectively as an abrasive or adhesive wear particle. The surface of Fig. 1 incidently has become the essence of a grinding surface (hard particle embedded in soft matrix) and it can abrasively wear surfaces that might be brought into contact with it.

SURFACE EFFECTS IN VARIOUS WEAR MECHANISMS

ADHESIVE WEAR – When two solid surfaces are brought into contact and the surfaces are covered with surface films (e.g., metal oxides, adsorbed layers and/or lubricants) any one of a number of surface actions can occur. In those situations where the loads are relatively light so as not to deform the surfaces at the asperities plastically, relatively weak forces of interaction may develop across the interface (i.e., Van der Waals) and very littie change in the surfaces may occur as a result of the contact.

Where loads for surfaces in contact are sufficiently high so that asperity contact occurs through the surface films or the surface films are dissipated due to relative motion nascent solid to solid contact can occur. Under such conditions strong bonds such as metallic, ionic or covalent may occur across the interface. Most frequently these adhesive bonds which form across the interface are stronger than the cohesive bonds in the weaker of the two materials and with motion fracture will occur in the weaker of the two materials giving rise to the generation of an adhesive wear particle. This event repeated many times results at the contacting surfaces in the formation of wear debris of an adhesive nature.

The foregoing concept of adhesive wear can be most effectively demonstrated experimentally by examining atomically clean surfaces where nascent contact occurs over a large area. For example, in Fig. 2 gold is shown transferred to silicon surface after simple touch contact and separation of the solids. No tangential motion was involved. The surfaces were simply sputter cleaned in vacuum prior to contact.

In Fig. 2 gold the cohesively weaker of the two solids transfers to silicon the cohesively stronger material. The adhesive gold to silicon bonds formed at the interface are stronger than the cohesive bonds in the gold and the gold transfers to the silicon resulting in adhesive wear of the gold. The photomicrograph of Fig. 2 indicates the presence of transferred material and the X-ray map identifies the transferred material elementally as gold.

The presence of contaminating surface films such as oxides appreciably reduces the amount of interfacial bonding. This is demonstrated in the data of Fig. 3 for copper contacting iron. Data are presented in Fig. 3 for both a clean and oxidized copper surface. For a given load in Fig. 3 the adhesive bonding force with the clean metal is markedly higher than it is for that containing the surface oxide.

While the presence of the oxide in Fig. 3 reduces the measured adhesion forces, there is still binding across the interface. This binding results from deformation of the copper with nascent metal being exposed for bonding. At the very light loads the oxide film is not disrupted and the adhesion force remains low. As the load is increased penetration of the oxide film occurs and continued with further increases in load. This continued exposure of metal is reflected in the increase in the adhesive bond force measured. Strong adhesive bond forces have been measured for a number of metals in adhesive contact with other metals resulting in adhesive transfer of the cohesively weaker to the stronger (2).

The foregoing discussion deals with the matter of adhesion and adhesive wear on simple touch contact. With sliding or rubbing the interfacial activity can and generally does become more complex. Rubbing or sliding contact under load results in the generation of considerable frictional heat at the interface. Heating will bring about chemical reactions and interactions not normally encountered in simple touch contact.

In Fig. 4(a) a photomicrograph is presented for the wear scar on an aluminum rider after having slid on a copper surface. The aluminum has undergone adhesive wear and was found transferred to the copper disk surface (3). X-ray mapping of the wear scar of Fig. 4(a) revealed that copper had also transferred to the aluminum surface as indicated in Fig. 4(b).

The cohesive binding energies for aluminum and copper are very close (4). Thus, transfer may be anticipated to go either way. Further, frictional heating can cause interfacial surface alloying which accounts for the fairly uniform distribution of copper on the aluminum rider surface.

Just as the adhesion of metals on touch contact is sensitive to the presence of surface films, so it is also with sliding. Surface films can and are generated by the interaction of the surface with environmental constituents such as oxygen in air. Excluding oxygen from the environment will markedly accelerate adhesive wear as demonstrated in Fig. 5 with surface profiles of iron. The profiles were obtained after sliding various numbers of passes across an iron surface in air and in argon. It is evident that adhesive wear is much greater in argon. Considerably more metal has been removed from the iron surface in argon than in air.

Adhesive wear not only occurs for metals in contact with metals but also for metals in contact with other materials such as polymers and carbons. These types of interactions are important because of the increasing use of polymers and carbons in tribiological systems.

Of all the polymers presently used where reductions in friction and adhesive wear are desired, polytetrafluoroethylene (PTFE) has been probably the most successful. Even with relatively inert materials like PTFE, however, adhesive wear can be a problem where the polymer is in rubbing contact with metals. Adhesion of the polymer to metals can and does occur.

Wear experiments have been conducted with PTFE contacting a variety of metals including aluminum (5, 6). With aluminum adhesion is very strong and transfer of aluminum to PTFE is observed.

A PTFE wear surface is presented in the photomicrographs of Fig. 6 after the PTFE had been in rubbing contact with aluminum. Close examination of the PTFE wear surface reveals the presence of an embedded particle of aluminum. Adhesion of the PTFE to the aluminum resulted in the transfer of a particle of aluminum to the PTFE.

The transferred aluminum particles indicated in Fig. 6 become highly strained and harden sufficiently to act as cutting tools and machine curls of aluminum out of the parent annealed aluminum crystal surface from which they came.

This adhesive wear behavior of the PTFE in contact with aluminum is highly anisotropic with the crystallographic orientation of the aluminum exerting a marked influence on observed results. Adhesive wear of the aluminum is greatest for the lowest atomic density-highest surface energy planes.

Adhesive wear under certain conditions can be beneficial. For example, with certain self-lubricating solids which contact metals, it is necessary to develop a transfer film of the self-lubricating solid to the metal surface. Once such a film developes the self-lubricating material is sliding or rubbing on itself and wear is then reduced to some minimal value.

A self-lubricating solid frequently used in such mechanical components as seals and electrical brushes is graphtic carbon. In seals the carbon body is frequently contacting a chrome plated surface. A graphitic-carbon transfer film to the chrome is necessary to maintain low wear of the graphitic-carbon.

Rubbing experiments have been conducted with the use of Auger emission spectroscopy analysis to monitor adhesion and adhesive wear of the graphitic-carbon. Figure 7 contains three Auger emission spectroscopy traces indicating the transfer of the graphitic-carbon to a chromium surface.

Figure 7(a) indicates the elements present on the chromium surface prior to the initiation of sliding. The oxygen is due in part to the presence of chrome oxide. The carbon comes from the adsorbed gas.

After 50 sliding passes over the same surface a large carbon peak due to transfer of the graphitic-carbon has grown in the spectrum of Fig. 7(b). This is accompanied by a decrease of both the oxygen and chromium peaks. The oxygen and chromium decrease because the graphitic-carbon is covering the surface. Upon completion of 100 passes the only peak remaining in the Auger spectrum is that for carbon (Fig. 7(c)). The surface is covered with a graphitic-carbon film.

The plot of Auger spectroscopy carbon peak intensity as a function of the number of passes over the surface is presented in Fig. 8 for graphitic-carbon sliding against chromium. Adhesion of the graphitic-carbon occurs initially and the film continues to grow with repeated passes over the surface until approximately 50 passes have occurred whereupon the transfer of graphitic-carbon does not appear to increase markedly with additional passes. A film has transferred and adhesive wear of the graphitic-carbon is arrested.

ABRASIVE WEAR - Adhesive wear can occur for a wide variety of different classes of materials brought into contact. Abrasive wear, however, is limited to those situations where a very hard material contacts a softer material or hard particles are sandwiched between two softer surfaces (e.g., particles of sand in a bearing). Abrasion occurs by the cutting or micromachining of the softer surface by the harder whether by another surface or particle.

It might be intuitively anticipated that the resistance of a material to abrasive wear is strongly a function of the hardness of the surface being abraded. The harder the surface the greater could be the resistance to abrasive. This has been experimentally demonstrated to be the case. The harder the surface the greater is the resistance to wear (7).

In Fig. 9 resistance to wear is plotted as a function of hardness for the surface of various metals. The data of Fig. 9 indicate a direct relation between the hardness of the metal being abraded and its abrasive wear resistance.

The abrasion of solid surfaces involves wear to the abrasive as well as wear to the surface being abraded. For example, with such relatively hard abrasive materials as single crystal aluminum oxide (sapphire) and titanium dioxide (rutile), the resistance to wear of these abrasive materials themselves is very much a function of their orientation. With certain atomic planes contacting steel wear resistance of the abrasive substance is greater than for other orientations. This is demonstrated in the data of Fig. 10 for titanium dioxide.

The variation in the rate of wear of titanium dioxide in Fig. 10 with changes in orientation is marked. Between the minimum and maximum it varies by a factor of seven times. Thus, in abrasion the process can result in wear to the abrasive as well as to the surface to be abraded and the latter can be minimized by giving consideration to properties of the abrasive material.

CORROSIVE WEAR - The surfaces of solids play an extremely important role in corrosive wear. In corrosive wear material is lost from a solid as a direct result of chemical interactions of the solid surface with the environment. The active environmental constituent can be the lubricant, an additive or a component of the surrounding atmosphere. The relative motion between solid surfaces in contact aggravates surface attrition by continuously exposing fresh surface for reaction.

Materials which can be or are very effective lubricants under certain conditions can become extremely reactive under another set of conditions. The lubrication of alloys with halogen containing lubricants is a good example.

In Fig. 11 for a cobalt alloy lubricated by a chlorinated fluorocarbon wear at temperatures to 300° C is extremely low. The values in Fig. 11 are 100 times less than obtained for the unlubricated surfaces. Above 300° C, however, the rate of wear begins to increase markedly. This increase is due to excessive chemical reactivity of the chlorine of the chlorinated fluorocarbon with the cobalt surface.

Examination of the cobalt alloy surface after sliding revealed copious quantities of cobalt chloride. This particular compound is an extremely good solid film lubricant and accounts for the low wear to 300° C. Above that temperature cobalt chloride continues to form but in such large quantities that the cobalt alloys are being consumed as a result of excessive surface reactivity. Thus, effective lubrication is a matter, with solid films of the type described here, of controlled corrosion. It is desirable that a reaction product form to reduce friction and wear as in Fig. 11 but that quantity should be limited.

The data of Fig. 11 also indicate that no correlation between friction and wear can be drawn from information about one or the other. Corrosive wear is an excellent example of this concept. Wear may go up due to the excessive reactivity but friction may go down because of the low shear strength of the reaction product formed.

Corrosive wear can be brought about increasing temperature as in Fig. 11. Similar effects can be produced by increased loading and/or increasing rubbing speed.

EFFECT OF MATERIAL PROPERTIES ON WEAR

A wide variety of material properties effect their wear behavior. As already indicated with reference to Fig. 10, the crystallographic orientation of materials effect wear. This is true not only for the wear of nonmetals but for metals as well (10).

Another property of materials having an influence on wear is crystal structure. Transformation in a metal from one crystal structure to another can result in notable changes in wear. This effect is indicated in Fig. 12 for tin. In Fig. 12 wear track width is plotted as a function of temperature. The wear track width is relatively constant until the temperature for the transformation of tin from a diamond structure (gray tin) to that of the tetragonal (white tin) is approached. At that point wear begins to increase. The tetragonal tin structure has greater ductility than the diamond form.

A further manifestation of the effect of crystal structure is observed when layer lamellar solids are in rubbing contact with metals. With these solids shear readily occurs along basal planes and transfer to the metal surface is readily observed. This can be seen in Table I. In the table pyrolytic boron nitride transfers to all metals except gold and silver. Poor adhesion accounts for the failure of boron nitride to transfer to gold and silver.

In practical engineering applications metals are not used in their elemental form but rather as alloys. The presence of these alloying elements can have varying effects on wear. For example, in Fig. 13 the addition of 10 atomic percent aluminum to copper does not affect its rate of wear. The addition of 10 atomic percent of alloying elements such as silicon, tin, or indium to copper does, however, reduce wear appreciably as indicated in Fig. 13.

The differences in wear behavior for copper alloyed with various elements is maintained even with variations in the concentration of the lubricant additive. This is indicated in Fig. 14 for the alloys copper

10 atomic percent aluminum and copper 10 atomic percent indium. At all concentrations of stearic acid wear is greater with aluminum alloyed with copper than it is for indium alloyed with copper.

CONCLUDING REMARKS

When two solid surfaces are brought into contact, strong bonding can occur across the interface. Frequently adhesive bonds are stronger than the bonds in the cohesively weaker of the two materials and transfer of the cohesively weaker material to the cohesively stronger takes place. In most instances this results in the generation of wear particles and is to be avoided. In certain cases, however, this transfer is desirable to reduce wear as for example with graphitic-carbons in contact with metals.

Various properties of materials affect their adhesive, abrasive, and corrosive wear behavior. Adhesive interfacial bond strength, presence and nature of the surface films, crystallography, surface orientation, hardness, crystal structure, and the presence of alloying elements all affect the wear of materials. With alloying elements certain elements alloyed with a base metal have little or no effect on wear while other elements in equivalent concentrations in the same base metal can pronouncedly reduce wear.

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TABLE I. - TRANSFER OF MATERIAL FOR VARIOUS METALS IN SLIDING CONTACT WITH PYROLYTIC BORON NITRIDE

Metal	Metal to boron nitride	Boron nitride to metal
Aluminum	No	---
Titanium	No	Yes
Iron	No	Yes
Platinum	No	Yes
Copper	No	Yes
Gold	No	No
Silver	No	No
Tantalum	--	Yes
Niobium	--	Yes
Zirconium	--	Yes
Vanadium	--	Yes
Rhodium	--	Yes

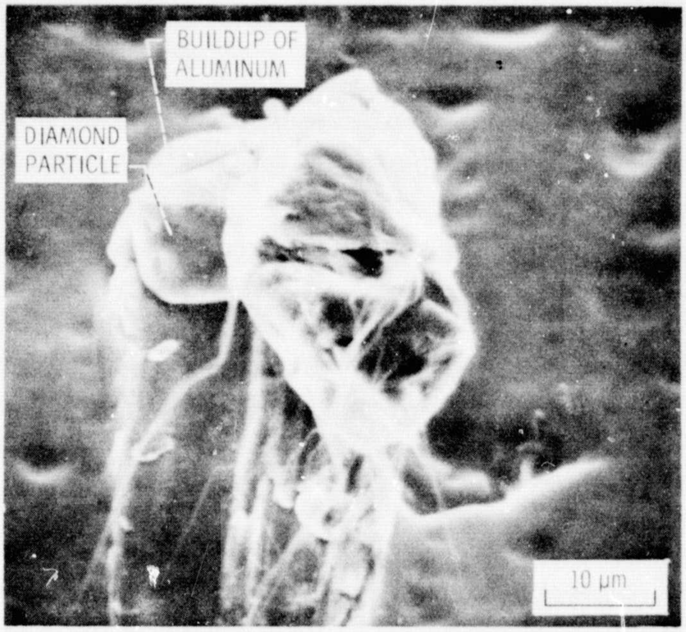
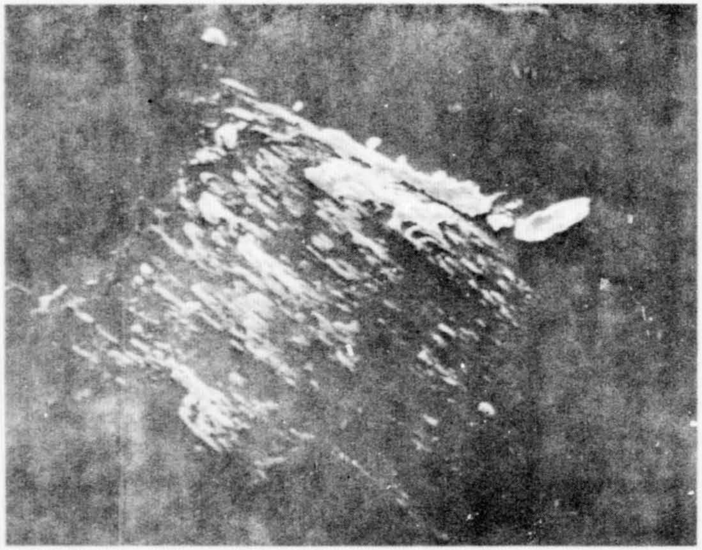
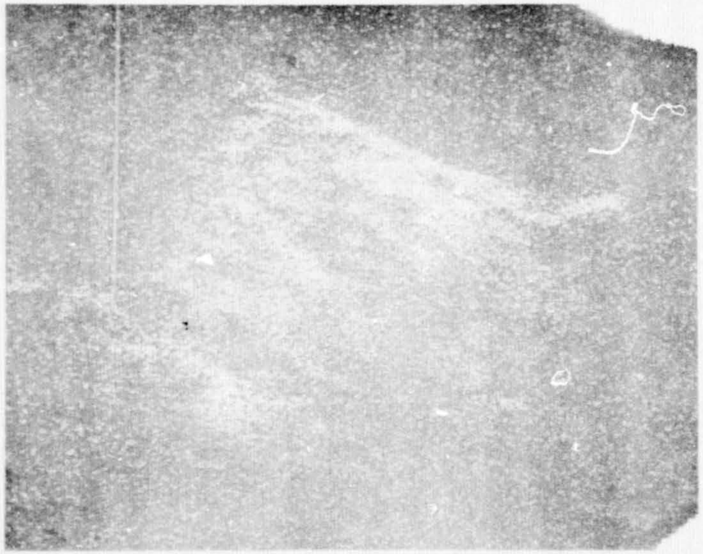


Figure 1. - Termination of score caused by hard diamond particle abrading aluminum.



(a) PHOTOMICROGRAPH.



(b) X-RAY MAP FOR GOLD.

Figure 2. - Photomicrograph and x-ray map for gold transferred to a silicon (111) surface after adhesive contact. Load, 30 gms; sputter cleaned surfaces; 23^{0} C and 10^{-8} N/m^2.

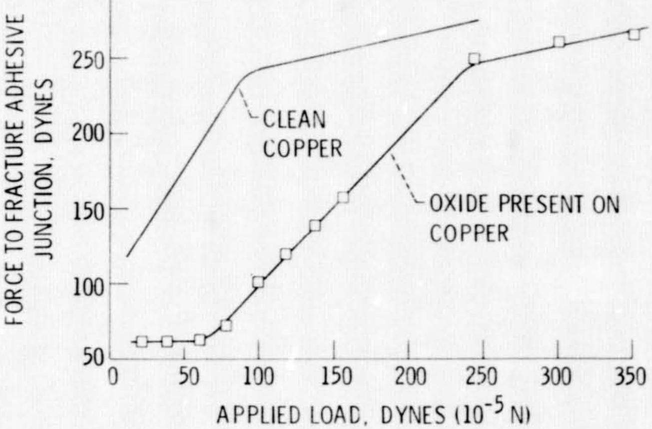
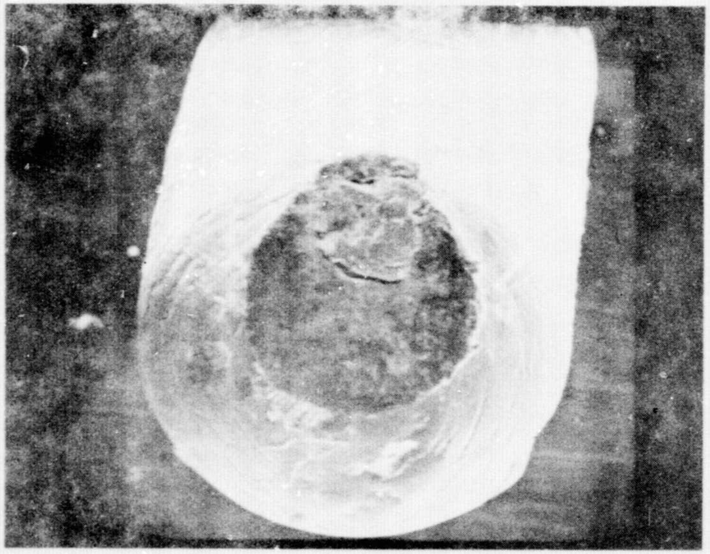
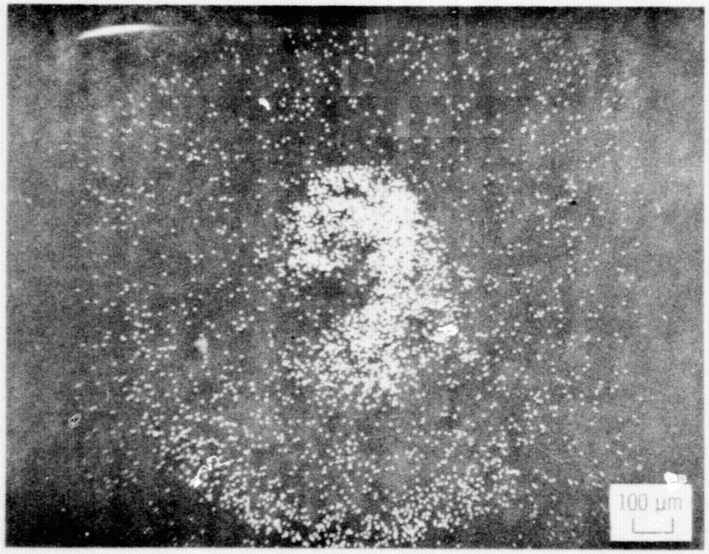


Figure 3. - Adhesion of clean and oxidized copper crystals to iron (011) surface. Experiments conducted in vacuum of 10^{-8} N/m^2.

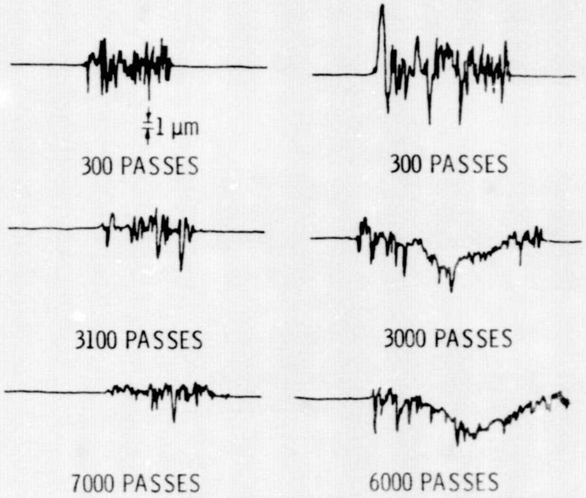


(a) ALUMINUM RIDER.



(b) COPPER K_{α} X-RAY MAP OF ALUMINUM RIDER; 15 000 COUNTS.

Figure 4. - Rider wear scar of aluminum rider after running on copper disk.



(a) IN AIR.

(b) IN ARGON.

Figure 5. - Iron wear track profiles. Sliding velocity 5.18 cm/s; load 500 g; temperature, 23° C.

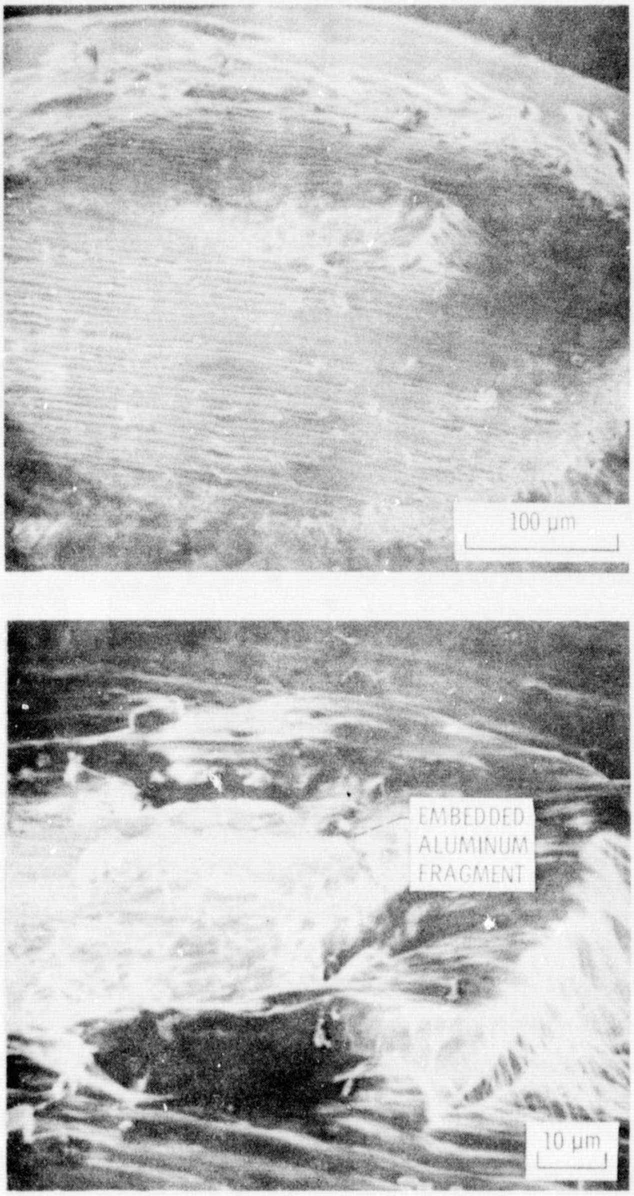
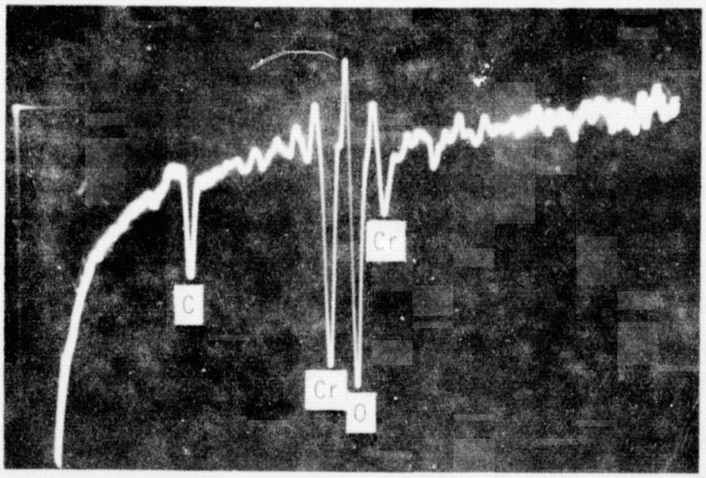
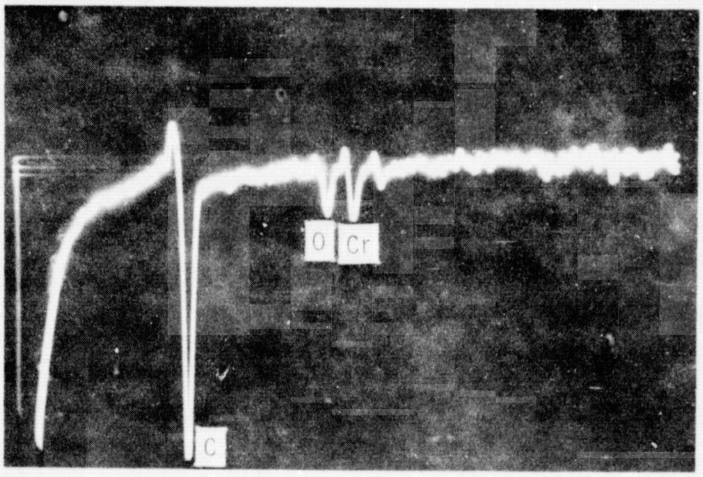


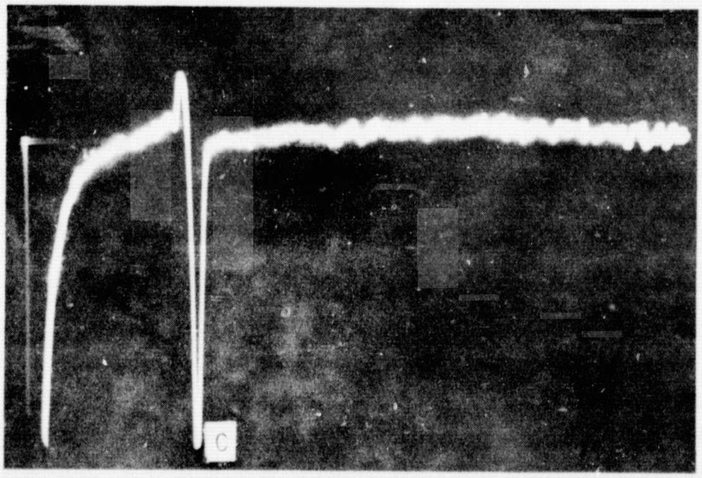
Figure 6. - PTFE-rider wear scar showing lodged metal fragment. Run on (110) surface; single pass; 200-gram load.



(a) BEFORE SLIDING.



(b) AFTER 50 SLIDING PASSES.



(c) AFTER 100 SLIDING PASSES.

Figure 7. - Photographs of oscilloscope display of oxide-covered chromium surface film and the development of a graphite transfer film.

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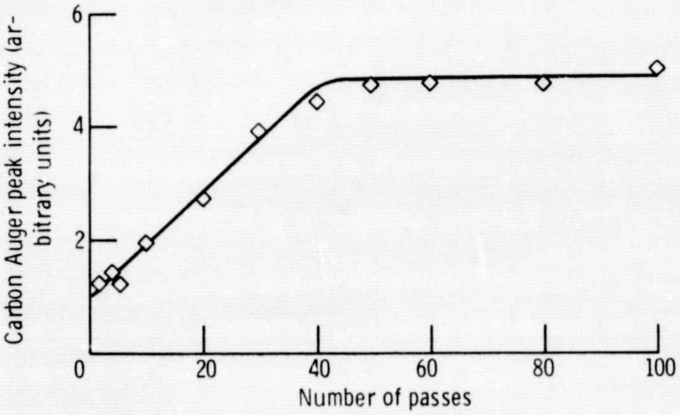

Figure 8. - Carbon peak intensity as a function of the number of sliding passes for graphitic carbon sliding on a sputter-cleaned chromium surface. Sliding velocity, 30 centimeters per minute; load, 500 grams; ambient temperature 23^0 C; ambient pressure, 10^{-10} N/m^2.

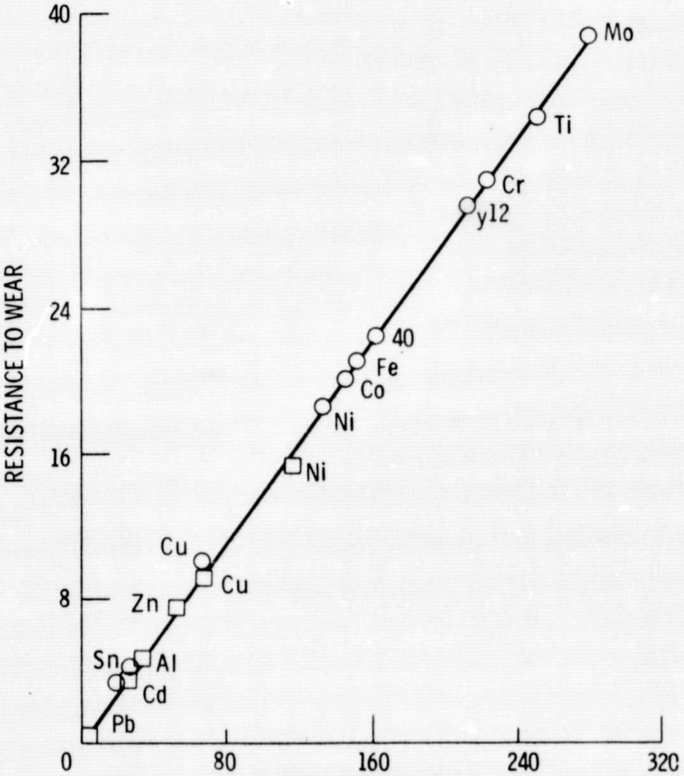

Figure 9. - Resistance to wear as a function of hardness. (Ref. 7).

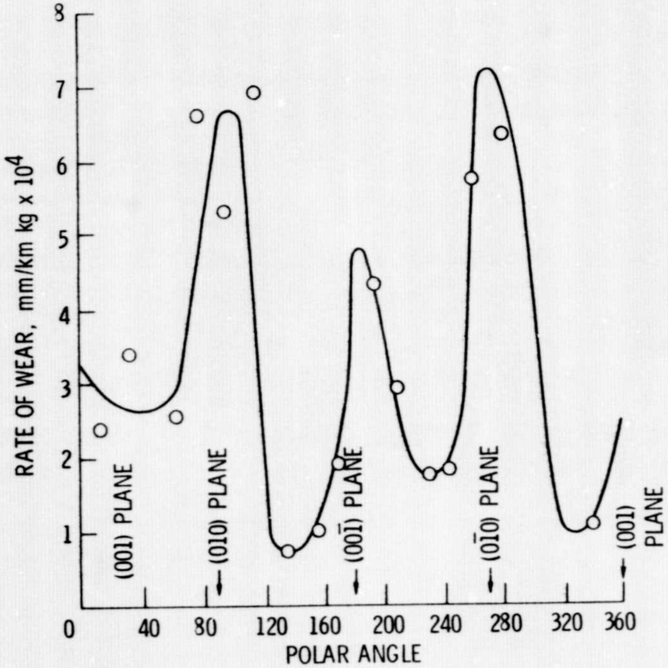

Figure 10. - Rate of wear of a rutile single-crystal sphere on a great circle in the plane of the a- and c-axes. The c-axis is normal to plane of sliding at 0 and 180°. Slide direction in plane of the great circle.[8]

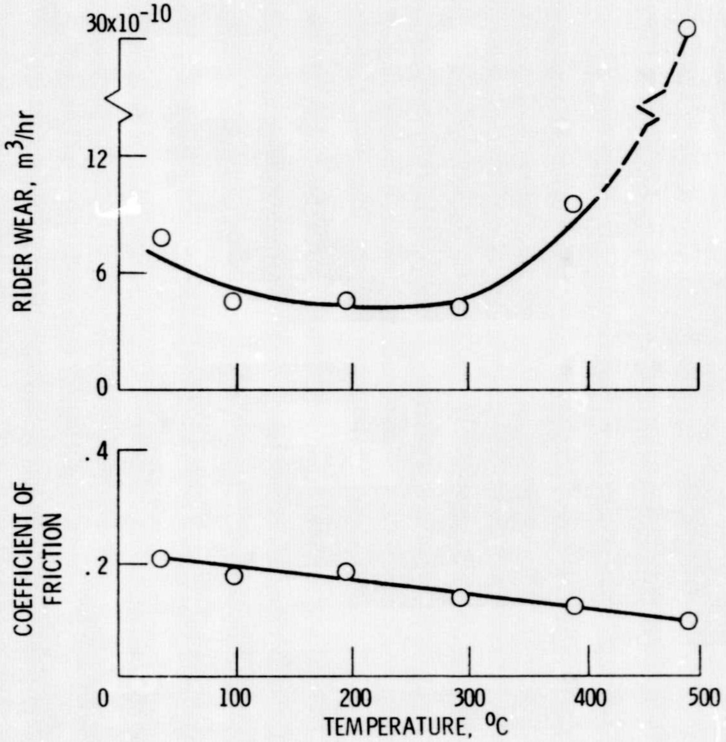

Figure 11. - Friction and wear of cobalt alloy sliding on itself at various temperatures and lubricated with a chlorinated fluorocarbon.

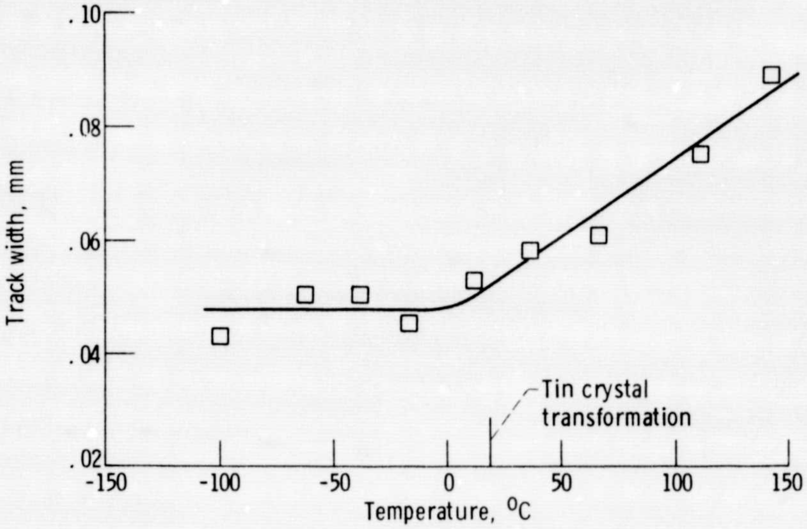

Figure 12. - Track width on tin single-crystal surface as function of temperature. Sliding velocity, 0.7 mm/min; load, 10 g; pressure, 10^{-8} N/m^2 (10^{-8} N/m^2); rider, iron (110); single pass.

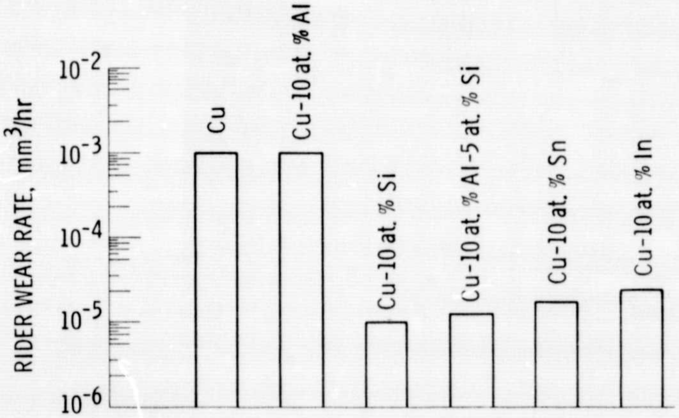

Figure 13. - Coefficient of friction and rider wear for various copper alloys sliding on themselves in hexadecane containing 0.1 volume percent stearic acid. Load, 250 grams; sliding velocity, 300 centimeters per minute; temperature, 25° C.

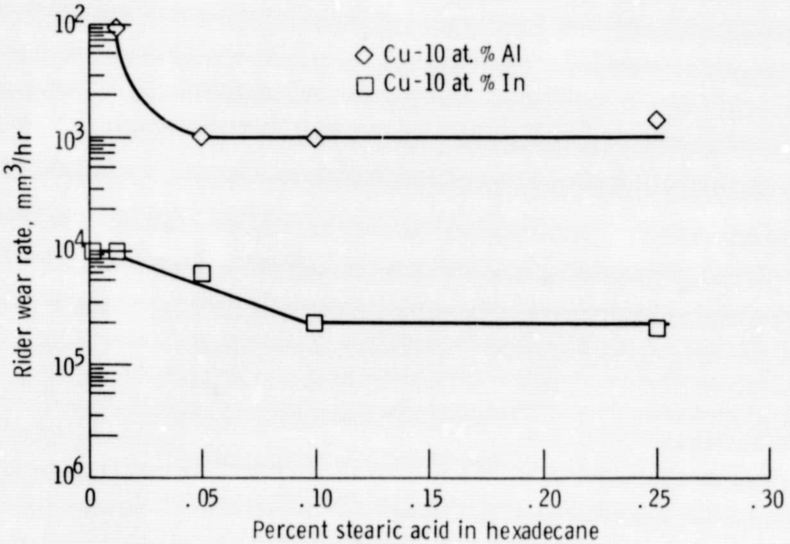

Figure 14. - Rider wear rate for two copper alloys sliding on themselves with various concentrations of stearic acid in hexadecane as lubricant. Load, 500 grams; sliding velocity, 300 centimeters per minute; temperature, 25^0 C.

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