Lawrence Berkeley National Laboratory

Recent Work

Title

DOE-BES EROSION-WEAR RESEARCH NEWSLETTER

Permalink

https://escholarship.org/uc/item/789174cs

Author

Lawrence Berkeley National Laboratory

Publication Date

2018-01-04

eScholarship.org Powered by the California Digital Library
University of California

DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

For Reference
Not to be taken from this room

PUB-363

DOE-BES EROS ON-WEAR RESEARCH Newsletter

LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA 94720

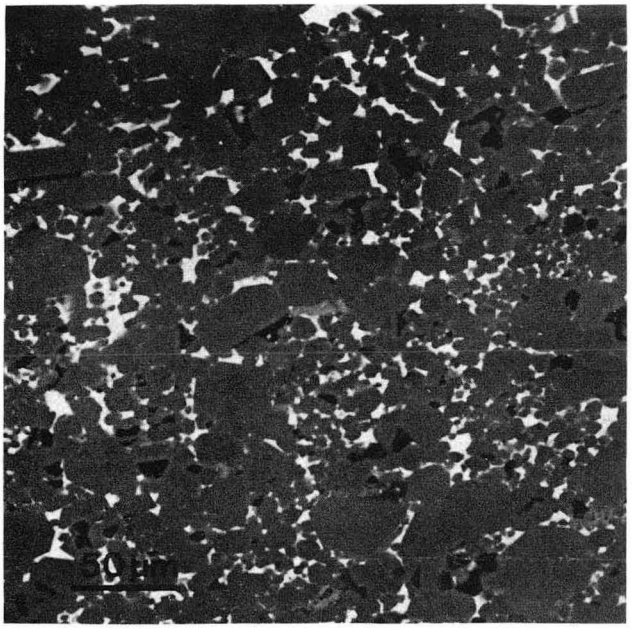
Volume 1, Number 2 October 1980

EROSION OF TiB_2-Ni COMPOSITES

Principal Investigators: C. S. Yust,
G. W. Clark,
C. B. Finch,
V. J. Tennery
Metals and Ceramics Div.,
Oak Ridge National Lab.
Oak Ridge, TN 37830
(615)/574-4812

The high hardness of titanium diboride has long suggested its application as a wear and erosion resistant material, but the utility of this material has been hampered by insufficient fracture resistance. Improved properties for titanium diboride are being sought in research at ORNL through preparation of composities in which hardness is retained while fracture sensitivity is lessened. We are currently investigating the system TiB_2-Ni, in compositions ranging from 10 to 20 mol % nickel. This discussion summarizes the results of the initial erosion tests and scanning electron microscopy of eroded surfaces.

The erosion samples are cut from discs prepared by a liquid phase hot pressing process. The microstructure of the samples consists of titanium diboride grains, a bonding phase or phases, and residual porosity (samples are about 95% of theoretical density). At present, the bonding phases have not been fully characterized, but they are tentatively identified as nickel, titanium and boron bearing compounds. A typical microstructure is shown in Fig. 1, scanning electron microscope view of a polished section of a sample containing 20 mol % nickel.



XBB 809-11125

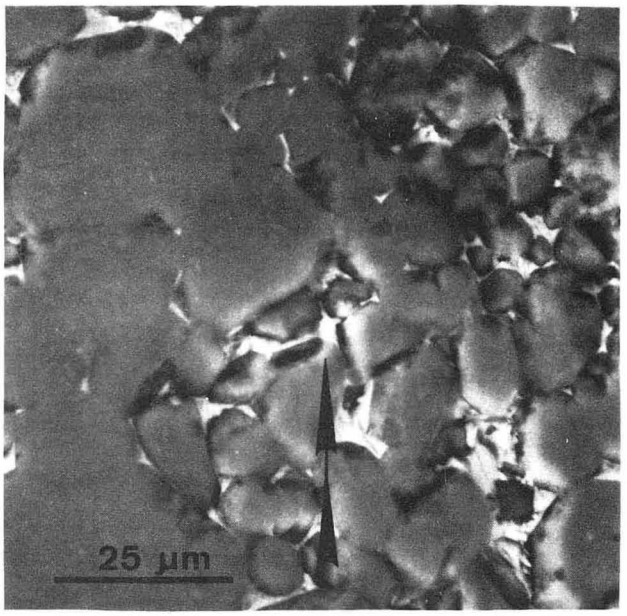
Fig. 1. Scanning electron photomicrograph (backscattered electron mode) of a typical titanium diboride-nickel composite microstructure. The light phase is the nickel rich bonding phase, the black regions are pores. This specimen contains 20 mol % nickel.

Samples containing 10, 15, and 20 mol % nickel have been exposed to erosion by gas-borne alumina particles at the Bureau of Mines Laboratory at Albany, Oregon. The erosion test is a three-minute exposure to 27 μm alumina particles moving at a velocity of 170 m/s, and impinging on the sample surface at 20 or 90° angles. The erosion resistance of these samples was as good as or slightly better than two cemented tungsten carbide reference compositions. The condition of the as-eroded surfaces of the sample containing 20 mol % nickel is shown in Fig. 2. An interesting feature of this eroded region is the lack of apparent mechanical damage at the surface. Typically, eroded surfaces show evidence of particle interaction with the surface by the presence of localized fractures or plastic deformation. This surface reveals only a selective removal of some of the bonding phase.

The titanium diboride-nickel composites have also been subjected to erosion by oil-coal slurries at the Battelle Columbus Laboratories. In this instance, the samples were exposed to a jet of slurry composed of SRC I product dissolved

Supported by the Division of Materials Sciences, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract W-7405-ENG-48.

PUB 363

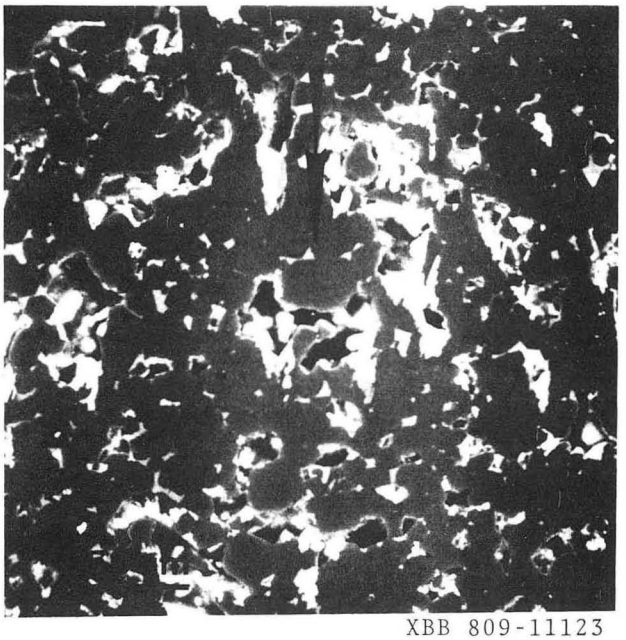


XBB 809-11122

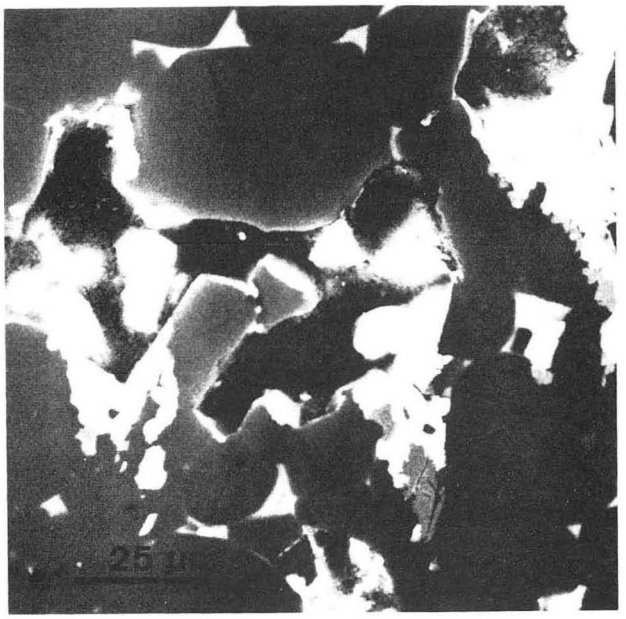
Fig. 2. SEM photomicrograph of the surface of a TiB_2-Ni composite eroded by alumina particles. The arrow indicates the direction of particle motion. The bonding phase is selectively removed, but the diboride grain surfaces show little damage.

in anthracene oil to give a solids content of 24 wt %. The jet is impinged on the sample surface at an angle of 20° for one hour. The jet velocity was 100 m/s and the slurry temperture was 343°C. Under these conditions, the titanium diboride-nickel composites were inferior in performance to cemented tungsten carbide reference material. A typical portion of the eroded surface of the 20 mol % nickel sample is shown in Fig. 3. The surface in this instance is also free of apparent mechanical damage. This experiment exposes the specimen to particulate matter contained within a chemically active liquid rather than an inert gas and the particle surface interaction may be modified under these conditions. The bonding phase does not show evidence of selective removal, Fig. 3a, but a granular material is found in many of the pores, Fig. 3b. Analysis of the composition of the granular constituent indicates that it is composed principally of titanium and nickel, suggesting that it is an erosion and/or corrosion residue rather than an accumulation of coal slurry particles in the pores.

Additional samples of titanium diboride-nickel composites are undergoing erosion testing. These samples include microstructural variations introduced through



XBB 809-11123



XBB 809-11124

Fig. 3. (a) SEM photomicrograph of the surface of a TiB_2-Ni composite eroded by a coal-oil slurry. The pores are filled with a graunlar material, but the bonding phase is not selectively removed. The arrow indicates the direction of slurry flow. (b) The pore filling and bonding phase (arrowed) are shown more clearly at higher magnification.

processing modifications. In all samples, electron microscopy will be a key tool in investigating the erosion mechanism

through studies of surface and subsurface damage. Studies of the subsurface damage resulting from controlled scratches on diboride-nickel composites are being initiated to provide basic information on abrasion and erosion damage mechanisms in this material.

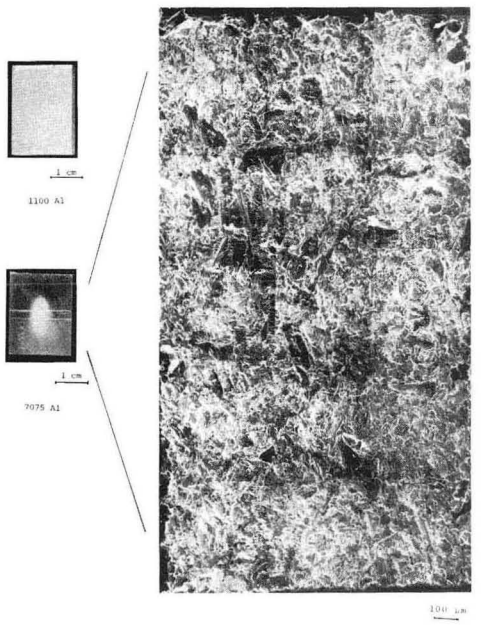
PLATELET MECHANISM OF EROSION OF DUCTILE METALS

Principal Investigator: Alan Levy,
Material & Molecular
Research Division
Lawrence Berkeley Lab.
Berkeley, CA 94720
(415) 486-5822
FTS 451-5822

Ever since small particle impingement erosion of ductile metals has been modelled, starting in the late 50's, the model has been based on a micro-machining physical mechanism.[1-3] The micro-machining models have predicted the effect of impingement angle on erosion, but could never consistently predict erosion rates nor account for several major anamolies, such as a threshold period or increasing erosion with apparent workhardening. Recently completed work in our lab using the SEM to sequentially observe the physical mechanism of erosion has determined that erosion in at least some single and 2 phase alloys occurs by a mechanism of a combined forging extrusion of platelets which are subsequently knocked off the surface, rather than by micro-machining.

The change from micro-machining to forging-extrusion of platelets makes it possible to account for many existing anamolies and accurately represents what is actually seen on the eroded surface of a ductile metal, but it makes it more difficult to develop an analytical model. In the case of the single step micro-machining mechanism, an equation of motion of a particle's tip as it contacts and moves through the surface area of a target, removing material ahead of it, is relatively easy to represent numerically. We are still looking for a way to numerically describe the multi-step activity of initially forging-extruding a platelet from a shallow crater, then further flattening and extending it by additional impacts and finally knocking it off the surface.

The evidence in support of the formation and removal of platelets as the active mechanism was carried out using a 1/8" dia nozzle erosion tester directing 600μm SiC particles in air at 0.75" x 2.5" x .125" specimens of 1100-0 and 7075-T6 aluminum alloys at a velocity of 100 fps and impact angles of 30° and 90°. Figure 1 shows the specimen with scribe marks denoting the magnified area shown in the figure. Approximately 500 particles (0.1 gm) were impacted on the specimen between removals from the tester and observation in the SEM. Sometimes 1 gm of particles was used between observations. When it was desired to observe sequential behavior on a steady-state erosion surface, the specimen was impacted with 500 gm of particles before SEM observations were initiated.

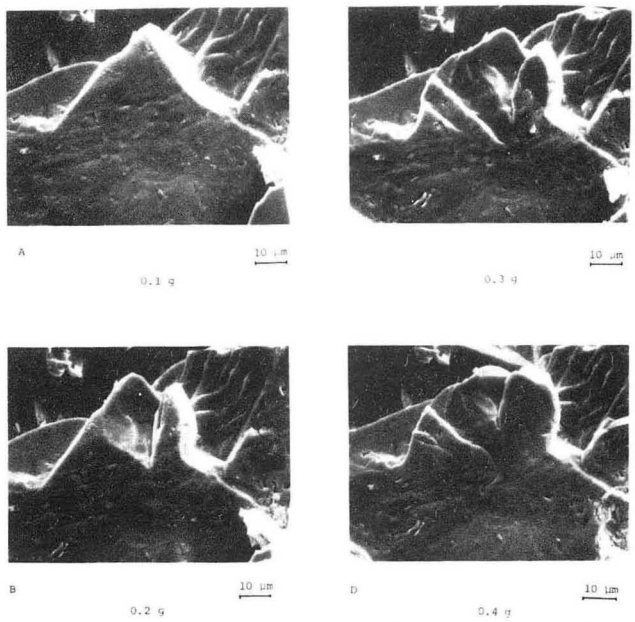


XBB 806-7868

Fig. 1. Test specimens of 1100-0 and 7075-T6 aluminum.

Representative sequences of platelet formation and removal are shown in Figs. 2-5. Figure 2 shows an area of 1100-0 at the beginning stages of erosion after four 0.1 gm of particle impacts. The appearance of the triangular area depicts the type of deformation that occurs in the threshold period where craters and platelets are being formed and extended but where no material loss occurs.

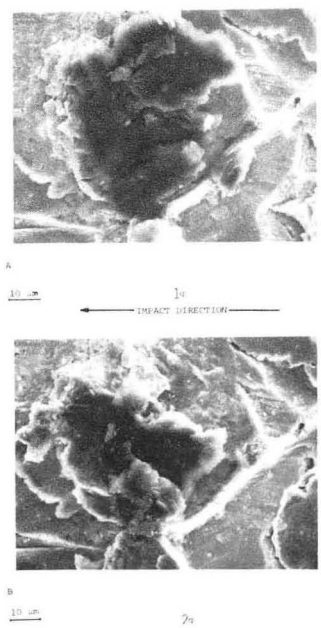
Figures 3 and 4 show subsequent 1 gm of particles sequences after steady state erosion has been reached on 7075-T6. The modification and loss of platelets can be readily seen. The formation of a platelet can be seen on the left hand side of Fig. 3 between A and B pictures. By the time 4 gm of particles had impacted the



XBB 7910-13300A

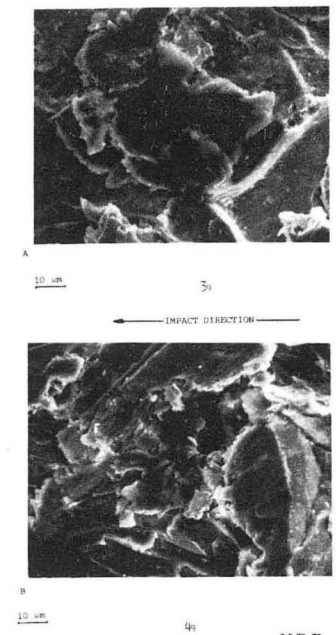
Fig. 2. Initiation of platelet formation in 1100-0 aluminum.

steady state surface shown in Fig. 1, the particular area documented in Figs. 3 and 4 had all of the initially observed platelets removed and new ones formed beneath them. Many other sequences indicating the same mechanism were documented.



XBB 7910-13307A

Fig. 3. Sequential platelet removal from a smear crater.

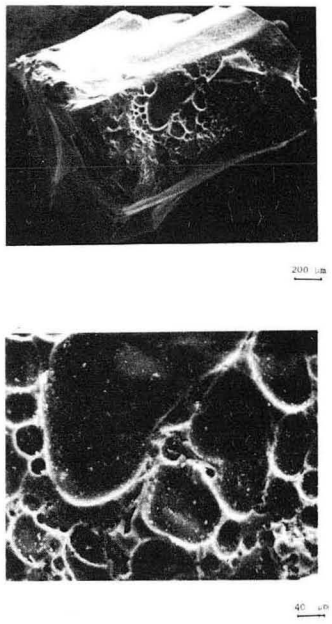


XBB 806-7864

Fig. 4. Sequential platelet removal from a smear crater.

The extensive deformation observed on the eroded surface with no evidence of fracture surfaces where platelets would have separated from the surface when they were knocked off indicated extreme distressing of individual platelets prior to their removal. Since the extent of formation of platelets was the same for both 1100-0 and the 6 times stronger and lower ductility 7075-T6 aluminum it was thought that some degree of heating of the erosion surface had occurred to equalize their plastic deformation behavior. Evidence for surface heating of the target surface, all the way to melting, [4-5] has appeared in the literature. No evidence of melting was ever observed on the target surface in our tests. However, small amounts of aluminum that became attached to the eroding particles did show evidence of melting, or at least the ductile fracture dimples that would have had to occur at a relatively high temperature.

Figure 5 shows the surface of a SiC particle that had been in direct contact with the aluminum specimen. The combined action of the plastic deformation of the aluminum and the friction between the target and particle surfaces resulted in enough heating to weld considerable aluminum to the SiC and probably melt it immediately after the particle lost contact with the target surface. The deposits of aluminum occurred on a large percentage of



XBB 806-7863

Fig. 5. Surface of used SiC particle showing evidence of melted or severely hot formed aluminum on its impacting surface.

recovered SiC particles, probably all those that actually caused erosion.

The evidence of the platelet mechanism of erosion presented herein and additional evidence contained in our LBL report 10289, leads to the following description of the erosion mechanism in ductile metals:

> Particles initially impact a stress-free surface and cause craters to form. As the particles continue to impact there is a general microscopic roughening of the surface because of plastic deformation caused by the large localized stresses in the immediate areas of the particle impacts. In the process of forming craters, platelets of metal that are locally attached to the crater rim are forged-extruded. Some of the impact kinetic energy is converted into thermal energy which heats the immediate surface area about each crater resulting in warm or even hot working of the surface and the development of a heated surface zone. This enhances the formation of the platelets. At some depth below the surface the metal temperature decreases to the level where the plastic deformation caused by the particle impacts results in a gradual work hardening of the metal. This sub-surface zone of work hardened material has been measured using a 5 gm load microhardness tester.
>
> Eventually the particle impact craters and their attendant platelets completely cover the surface. At this time particles no longer have a fresh surface to impact against and there starts a gradual increase of smear type craters with platelet formation and measurable erosion (actual material loss) now occurs.
>
> As the work hardened zone and the soft surface zone further develop, the resistance of the subsurface work hardened zone to penetration by the impacting particles concentrates the plastic deformation in the soft surface layers. This increases extrusion of metal in the softened zone between the impacting particles and the hardened subsurface region which enhances the generation of platelets. As more platelets are available to be knocked off, erosion increases. When the development of the heated surface and cold worked subsurface zones is completed, the incubation period is over and further erosion occurs by the steady state mechanism of indentation, smearing, platelet formation and extension, and the knocking off of platelets. It has been observed that from 4 to 8 particle impacts in a specific area cause all of the elements mentioned to occur.

The platelet mechanism accounts for the observed surface of the eroded material as well as anamolies such as the threshold period of no measurable erosion that occurs. Much work remains to be done. The applicability of the mechanism to erosion at elevated temperatures, to surfaces that are undergoing simultaneous corrosion, to multiphase alloys of various morphologies, and to alloys that are much stronger than aluminum alloys is still to be determined. Also, the approach to developing a numerical model based on the forging-extrusion mechanism still has to be established.

References

1. Finnie, I., "Erosion of Surfaces by Solid Particles", Wear 3 (1960), 87-103.

2. Bitter, J.G.A., "A Study of Erosion Phenomena", Parts 1 and 2, Wear 5, (1963).

3. Neilson, J. H. and Gilchrist, A., "Erosion by a Stream of Solid Particles", Wear 11, (1968), p. 11.

4. Winter, R.E., and Hutchings, I.M., "The Role of Adiabatic Shear in Solid Particle Erosion", Wear 34, (1975), 141-148.

5. Christman, T., and Shewmon, P. G., "Erosion of a Strong Aluminum Alloy", Wear 52, (1979), pp. 57-70.

Lawrence Berkeley Laboratory
ALAN V. LEVY, Editor
Erosion-Wear Research
University of California
Berkeley, CA 94720

Non-Profit Org.
U.S. Postage
PAID
Berkeley, CA
Permit No. 1123

PUB-363

DOE-BES
EROS ON-WEAR RESEARCH
Newsletter

LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA 94720

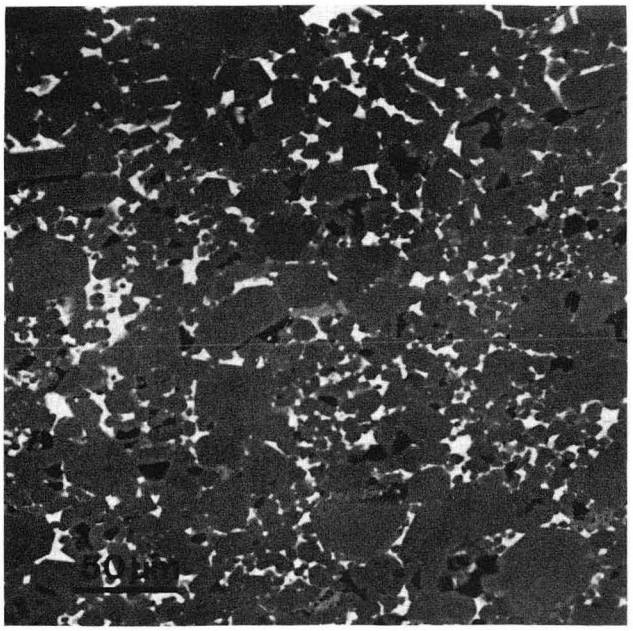
Volume 1, Number 2 October 1980

EROSION OF TiB_2-Ni COMPOSITES

Principal Investigators: C. S. Yust,
G. W. Clark,
C. B. Finch,
V. J. Tennery
Metals and Ceramics Div.,
Oak Ridge National Lab.
Oak Ridge, TN 37830
(615)/574-4812

The high hardness of titanium diboride has long suggested its application as a wear and erosion resistant material, but the utility of this material has been hampered by insufficient fracture resistance. Improved properties for titanium diboride are being sought in research at ORNL through preparation of composities in which hardness is retained while fracture sensitivity is lessened. We are currently investigating the system TiB_2-Ni, in compositions ranging from 10 to 20 mol % nickel. This discussion summarizes the results of the initial erosion tests and scanning electron microscopy of eroded surfaces.

The erosion samples are cut from discs prepared by a liquid phase hot pressing process. The microstructure of the samples consists of titanium diboride grains, a bonding phase or phases, and residual porosity (samples are about 95% of theoretical density). At present, the bonding phases have not been fully characterized, but they are tentatively identified as nickel, titanium and boron bearing compounds. A typical microstructure is shown in Fig. 1, scanning electron microscope view of a polished section of a sample containing 20 mol % nickel.



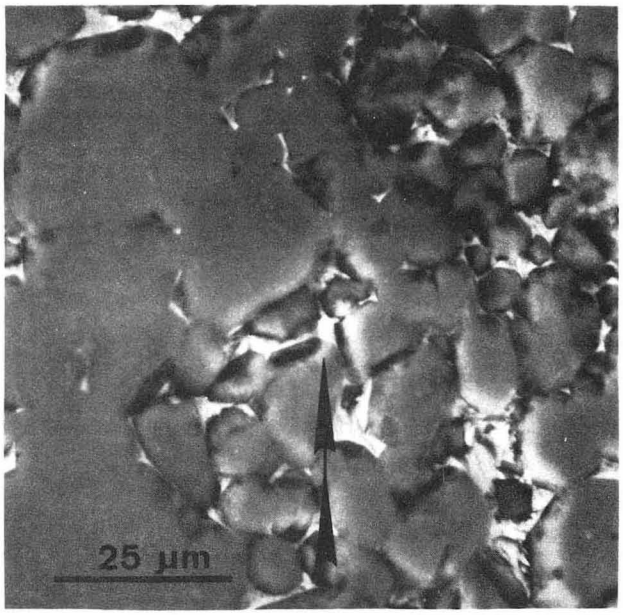
XBB 809-11125

Fig. 1. Scanning electron photomicrograph (backscattered electron mode) of a typical titanium diboride-nickel composite microstructure. The light phase is the nickel rich bonding phase, the black regions are pores. This specimen contains 20 mol % nickel.

Samples containing 10, 15, and 20 mol % nickel have been exposed to erosion by gas-borne alumina particles at the Bureau of Mines Laboratory at Albany, Oregon. The erosion test is a three-minute exposure to 27 μm alumina particles moving at a velocity of 170 m/s, and impinging on the sample surface at 20 or 90° angles. The erosion resistance of these samples was as good as or slightly better than two cemented tungsten carbide reference compositions. The condition of the as-eroded surfaces of the sample containing 20 mol % nickel is shown in Fig. 2. An interesting feature of this eroded region is the lack of apparent mechanical damage at the surface. Typically, eroded surfaces show evidence of particle interaction with the surface by the presence of localized fractures or plastic deformation. This surface reveals only a selective removal of some of the bonding phase.

The titanium diboride-nickel composites have also been subjected to erosion by oil-coal slurries at the Battelle Columbus Laboratories. In this instance, the samples were exposed to a jet of slurry composed of SRC I product dissolved

Supported by the Division of Materials Sciences, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract W-7405-ENG-48.

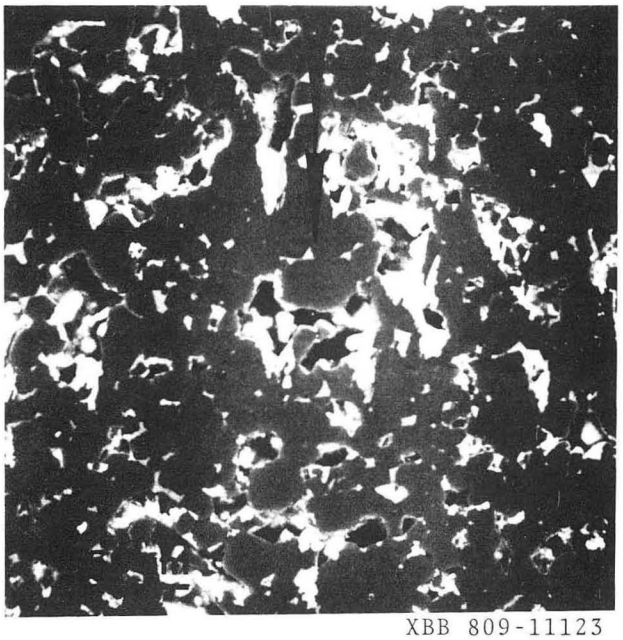


XBB 809-11122

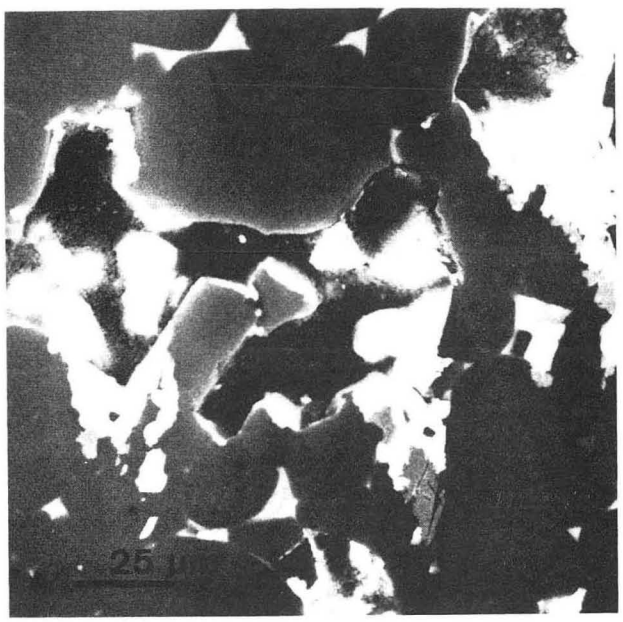
Fig. 2. SEM photomicrograph of the surface of a TiB_2-Ni composite eroded by alumina particles. The arrow indicates the direction of particle motion. The bonding phase is selectively removed, but the diboride grain surfaces show little damage.

in anthracene oil to give a solids content of 24 wt %. The jet is impinged on the sample surface at an angle of 20° for one hour. The jet velocity was 100 m/s and the slurry temperture was 343°C. Under these conditions, the titanium diboride-nickel composites were inferior in performance to cemented tungsten carbide reference material. A typical portion of the eroded surface of the 20 mol % nickel sample is shown in Fig. 3. The surface in this instance is also free of apparent mechanical damage. This experiment exposes the specimen to particulate matter contained within a chemically active liquid rather than an inert gas and the particle surface interaction may be modified under these conditions. The bonding phase does not show evidence of selective removal, Fig. 3a, but a granular material is found in many of the pores, Fig. 3b. Analysis of the composition of the granular constituent indicates that it is composed principally of titanium and nickel, suggesting that it is an erosion and/or corrosion residue rather than an accumulation of coal slurry particles in the pores.

Additional samples of titanium diboride-nickel composites are undergoing erosion testing. These samples include microstructural variations introduced through



XBB 809-11123



XBB 809-11124

Fig. 3. (a) SEM photomicrograph of the surface of a TiB_2-Ni composite eroded by a coal-oil slurry. The pores are filled with a graunlar material, but the bonding phase is not selectively removed. The arrow indicates the direction of slurry flow. (b) The pore filling and bonding phase (arrowed) are shown more clearly at higher magnification.

processing modifications. In all samples, electron microscopy will be a key tool in investigating the erosion mechanism

through studies of surface and subsurface damage. Studies of the subsurface damage resulting from controlled scratches on diboride-nickel composites are being initiated to provide basic information on abrasion and erosion damage mechanisms in this material.

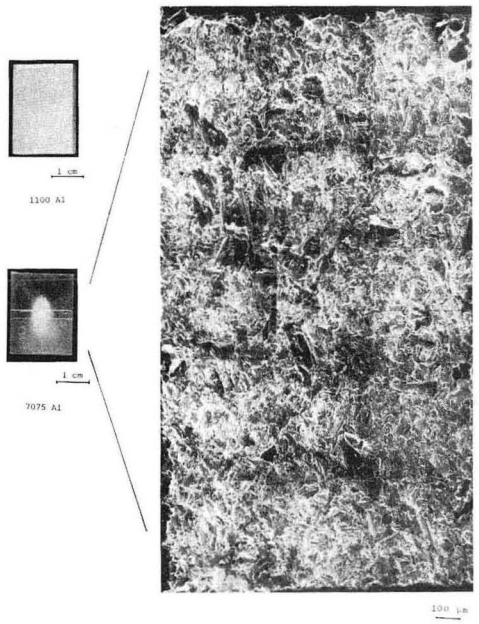
PLATELET MECHANISM OF EROSION OF DUCTILE METALS

Principal Investigator: Alan Levy,
Material & Molecular
Research Division
Lawrence Berkeley Lab.
Berkeley, CA 94720
(415) 486-5822
FTS 451-5822

Ever since small particle impingement erosion of ductile metals has been modelled, starting in the late 50's, the model has been based on a micro-machining physical mechanism.[1-3] The micro-machining models have predicted the effect of impingement angle on erosion, but could never consistently predict erosion rates nor account for several major anamolies, such as a threshold period or increasing erosion with apparent workhardening. Recently completed work in our lab using the SEM to sequentially observe the physical mechanism of erosion has determined that erosion in at least some single and 2 phase alloys occurs by a mechanism of a combined forging extrusion of platelets which are subsequently knocked off the surface, rather than by micro-machining.

The change from micro-machining to forging-extrusion of platelets makes it possible to account for many existing anamolies and accurately represents what is actually seen on the eroded surface of a ductile metal, but it makes it more difficult to develop an analytical model. In the case of the single step micro-machining mechanism, an equation of motion of a particle's tip as it contacts and moves through the surface area of a target, removing material ahead of it, is relatively easy to represent numerically. We are still looking for a way to numerically describe the multi-step activity of initially forging-extruding a platelet from a shallow crater, then further flattening and extending it by additional impacts and finally knocking it off the surface.

The evidence in support of the formation and removal of platelets as the active mechanism was carried out using a 1/8" dia nozzle erosion tester directing 600μm SiC particles in air at 0.75" x 2.5" x .125" specimens of 1100-0 and 7075-T6 aluminum alloys at a velocity of 100 fps and impact angles of 30° and 90°. Figure 1 shows the specimen with scribe marks denoting the magnified area shown in the figure. Approximately 500 particles (0.1 gm) were impacted on the specimen between removals from the tester and observation in the SEM. Sometimes 1 gm of particles was used between observations. When it was desired to observe sequential behavior on a steady-state erosion surface, the specimen was impacted with 500 gm of particles before SEM observations were initiated.

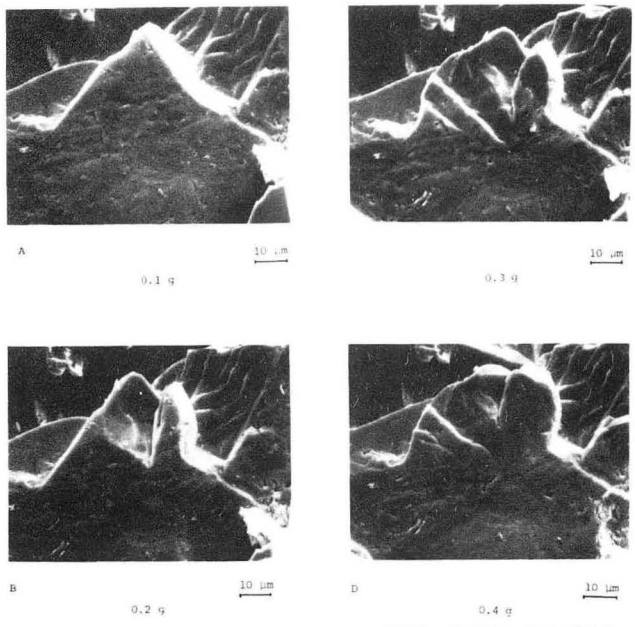


XBB 806-7868

Fig. 1. Test specimens of 1100-0 and 7075-T6 aluminum.

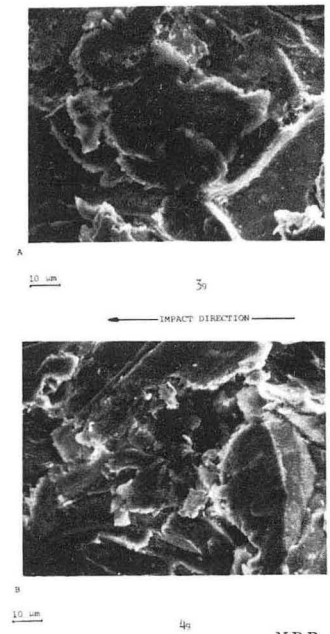
Representative sequences of platelet formation and removal are shown in Figs. 2-5. Figure 2 shows an area of 1100-0 at the beginning stages of erosion after four 0.1 gm of particle impacts. The appearance of the triangular area depicts the type of deformation that occurs in the threshold period where craters and platelets are being formed and extended but where no material loss occurs.

Figures 3 and 4 show subsequent 1 gm of particles sequences after steady state erosion has been reached on 7075-T6. The modification and loss of platelets can be readily seen. The formation of a platelet can be seen on the left hand side of Fig. 3 between A and B pictures. By the time 4 gm of particles had impacted the



XBB 7910-13300A

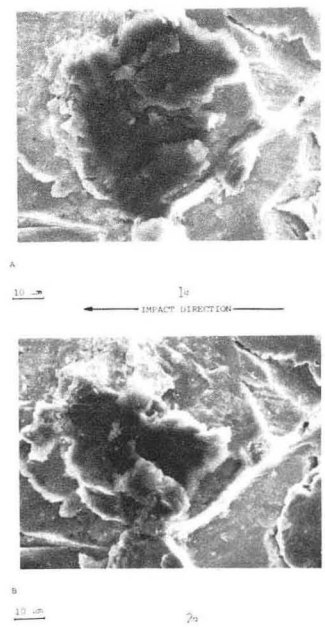
Fig. 2. Initiation of platelet formation in 1100-0 aluminum.



XBB 806-7864

Fig. 4. Sequential platelet removal from a smear crater.

steady state surface shown in Fig. 1, the particular area documented in Figs. 3 and 4 had all of the initially observed platelets removed and new ones formed beneath them. Many other sequences indicating the same mechanism were documented.

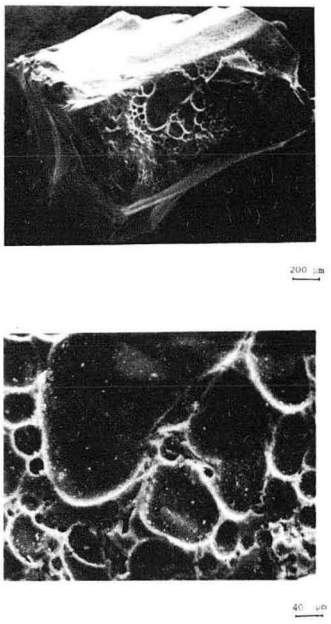


XBB 7910-13307A

Fig. 3. Sequential platelet removal from a smear crater.

The extensive deformation observed on the eroded surface with no evidence of fracture surfaces where platelets would have separated from the surface when they were knocked off indicated extreme distressing of individual platelets prior to their removal. Since the extent of formation of platelets was the same for both 1100-0 and the 6 times stronger and lower ductility 7075-T6 aluminum it was thought that some degree of heating of the erosion surface had occurred to equalize their plastic deformation behavior. Evidence for surface heating of the target surface, all the way to melting,[4-5] has appeared in the literature. No evidence of melting was ever observed on the target surface in our tests. However, small amounts of aluminum that became attached to the eroding particles did show evidence of melting, or at least the ductile fracture dimples that would have had to occur at a relatively high temperature.

Figure 5 shows the surface of a SiC particle that had been in direct contact with the aluminum specimen. The combined action of the plastic deformation of the aluminum and the friction between the target and particle surfaces resulted in enough heating to weld considerable aluminum to the SiC and probably melt it immediately after the particle lost contact with the target surface. The deposits of aluminum occurred on a large percentage of



XBB 806-7863

Fig. 5. Surface of used SiC particle showing evidence of melted or severely hot formed aluminum on its impacting surface.

recovered SiC particles, probably all those that actually caused erosion.

The evidence of the platelet mechanism of erosion presented herein and additional evidence contained in our LBL report 10289, leads to the following description of the erosion mechanism in ductile metals:

> Particles initially impact a stress-free surface and cause craters to form. As the particles continue to impact there is a general microscopic roughening of the surface because of plastic deformation caused by the large localized stresses in the immediate areas of the particle impacts. In the process of forming craters, platelets of metal that are locally attached to the crater rim are forged-extruded. Some of the impact kinetic energy is converted into thermal energy which heats the immediate surface area about each crater resulting in warm or even hot working of the surface and the development of a heated surface zone. This enhances the formation of the platelets. At some depth below the surface the metal temperature decreases to the level where the plastic deformation caused by the particle impacts results in a gradual work hardening of the metal. This sub-surface zone of work hardened material has been measured using a 5 gm load microhardness tester.
>
> Eventually the particle impact craters and their attendant platelets completely cover the surface. At this time particles no longer have a fresh surface to impact against and there starts a gradual increase of smear type craters with platelet formation and measurable erosion (actual material loss) now occurs.
>
> As the work hardened zone and the soft surface zone further develop, the resistance of the subsurface work hardened zone to penetration by the impacting particles concentrates the plastic deformation in the soft surface layers. This increases extrusion of metal in the softened zone between the impacting particles and the hardened subsurface region which enhances the generation of platelets. As more platelets are available to be knocked off, erosion increases. When the development of the heated surface and cold worked subsurface zones is completed, the incubation period is over and further erosion occurs by the steady state mechanism of indentation, smearing, platelet formation and extension, and the knocking off of platelets. It has been observed that from 4 to 8 particle impacts in a specific area cause all of the elements mentioned to occur.

The platelet mechanism accounts for the observed surface of the eroded material as well as anamolies such as the threshold period of no measurable erosion that occurs. Much work remains to be done. The applicability of the mechanism to erosion at elevated temperatures, to surfaces that are undergoing simultaneous corrosion, to multiphase alloys of various morphologies, and to alloys that are much stronger than aluminum alloys is still to be determined. Also, the approach to developing a numerical model based on the forging-extrusion mechanism still has to be established.

References

1. Finnie, I., "Erosion of Surfaces by Solid Particles", Wear 3 (1960), 87-103.

2. Bitter, J.G.A., "A Study of Erosion Phenomena", Parts 1 and 2, Wear 5, (1963).

3. Neilson, J. H. and Gilchrist, A., "Erosion by a Stream of Solid Particles", Wear 11, (1968), p. 11.

4. Winter, R.E., and Hutchings, I.M., "The Role of Adiabatic Shear in Solid Particle Erosion", Wear 34, (1975), 141-148.

5. Christman, T., and Shewmon, P. G., "Erosion of a Strong Aluminum Alloy", Wear 52, (1979), pp. 57-70.

Lawrence Berkeley Laboratory
ALAN V. LEVY, Editor
Erosion-Wear Research
University of California
Berkeley, CA 94720

Non-Profit Org.
U.S. Postage
PAID
Berkeley, CA
Permit No. 1123

PUB-363

BES EROSION-WEAR RESEARCH Newsletter

LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA 94720

Volume 1, Number 1 July 1980

INITIATION OF BES EROSION RESEARCH NEWSLETTER

The importance of the need for an increasing understanding of the behavior of materials in erosion-wear environments has been underscored by the occurrence of more failures of components in coal conversion system pilot plants by erosion than by any other single mechanism. The BES program in erosion and wear is a wide ranging one that is aimed at providing knowledge of the basic mechanisms of erosion of several types of materials to those that are endeavoring to eliminate erosion failures by astute materials selection and component and process design.

This newsletter is intended to provide a written information exchange medium for the team of BES erosion-wear researchers to more effectively carry out our programs in close communication with one another. It is planned to periodically have informal meetings to further share our findings and ideas. In these ways, we can collectively make available more basic knowledge of erosion-wear behavior in a timely manner. Issues will be prepared for distribution quarterly.

In this first issue of the newsletter, each of the seven active BES programs is briefly presented to acquaint the reader with the objectives and approaches of the programs. In subsequent issues, it is planned to review the concepts, accomplishments and even problems of individual programs in more depth, still preserving the brevity of this issue. Two or three individual investigators per issue will be able to highlight aspects of their work that will provide knowledge of behavior that has been gained in recent efforts.

A section of the newsletter will be made available for comments by others on the results of the work of individuals reported in earlier issues. Speculations on the meanings of data, correlations with data from other investigators' programs, critical comments on experimental or analytical techniques; in short a forum for investigators to use to enhance each others programs will be provided. Lists of recent publications and reports will be another feature as will be notices of pertinent meetings and other activities.

It is hoped that the newsletter will become a valued tool for both BES investigators and others that will receive it to advance the knowledge of erosion-wear mechanisms.

LOCALIZED CORROSION OF PASSIVE METALS

Principal Investigator: Richard C. Alkire,
Materials Research Laboratory
University of Illinois
Urbana, IL 61801
(217)333-0063 / FTS 957-0063

The purpose of this program is to study the effects of fluid flow on repassivation of metals immersed in aqueous solutions at ambient temperatures. The program focuses on the sequence by which passivity is regained following disturbance of the surface. Mathematical models are used to quantify hypotheses of the mechanism. Experiments aim for controlled variation of system parameters under known corrosion conditions.

Typical disturbances which create loss of passivity include fluid flow, particle impingement/impaction, and cavitation. After birth of local activity, subsequent corrosion processes are invariably influenced by transport phenomena including both mass transfer of aggressive species, ohmic transport of charge, fluid flow, and both heterogeneous and homogeneous reactions. By using mathematical models to test hypotheses of mechanism, this program seeks an improved understanding of corrosion in the presence of erosion. In particular, chemical engineering concepts are incorporated into models of diffusion and convection controlled corrosion processes. By inversion, mathematical models provide a rational basis for predicting conditions under which corrosion may be avoided.

Special attention has been directed to the role which metal salt films play during early stages of repassivation. Under such conditions, the rate of corrosion is so high that a salt film precipitates upon the surface. Subsequent events are thus greatly influenced by diffusive and convective transport processes which influence the behavior of the salt film. On iron in dilute sulfuric acid, for example, the salt film is a necessary precursor to repassivation. High flow rates thus impede repassivation since they prevent precipitation of the salt film. In chloride solution, on the other hand, the presence of a salt film inhibits repassivation; high flow rates thus enhance repassivation.

In order to achieve controlled observations on individual corrosion sites, a new experimental technique has been developed which induces highly localized depassivation at a pre-selected site on

Supported by the Division of Materials Sciences, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract W-7405-ENG-48.

the metal surface. The method uses a low-energy laser beam, focused to <5 μm diameter, to trigger depassivation with a 5-ns pulse. The method simulates an individual impingement event on an otherwise passive surface. Subsequent corrosion events, including repassivation can be observed under controlled hydrodynamic flow conditions. A theoretical analysis of the potential and convective flow fields is being developed to correlate and to scale data from among various experimental systems.

ENVIRONMENTAL EFFECTS ON THE MECHANICAL BEHAVIOR OF BRITTLE MATERIALS

Principal Investigator: R. E. Cuthrell,
Surface Metallurgy Division
Sandia National Laboratories
Albuquerque, New Mexico 87185
(505)264-7554 / FTS 844-7554

Changes in the mechanical behavior of solid materials which are produced by gaseous or liquid environments are known as Rebinder effects after the Russian academician P. A. Rebinder who discovered these chemomechanical phenomena in 1928. Following the extensive though little understood work of many investigators in this field, we have (1) reproduced the results of Westwood who showed that drilling rates in brittle materials depend on the surface charge produced by ions adsorbed from liquid environments, (2) found that ion aggregation in low dielectric constant liquids limits the chemomechanical effects through limiting the availability of the ions for surface interaction, (3) proposed that hydrogen is the ionic species responsible for chemomechanical effects, (4) tested this hypothesis in gaseous hydrogen and hydrogen plasmas in an ultrahigh vacuum chamber and found that the magnitude of the Rebinder effects depends on the hydrogen pressure. Subsequent experiments showed the same dependence of drilling rates on hydrogen availability from liquid environments. Since hydrogen ions are small and highly mobile, a wide variety of materials were expected to exhibit this Rebinder effect. A survey of materials showed the effect in glasses, ceramics, single crystal minerals, rocks, refractory coatings, semiconductors, and metals containing brittle phases.

Subcritical crack growth rates in Pyrex and soda-lime glass exhibit similar hydrogen dependence both in the gaseous and liquid environments. These results suggest that the chemomechanical effects depend on the rate of diffusion of hydrogen relative to the rate of fracture in the near surface region of brittle materials. The observed time dependence of Rebinder effects in silicon were consistent with estimated hydrogen permeation rates at room temperature. Exposure to hydrogen during the preparation of erosion resistant coatings by chemical vapor deposition may determine their resistance to cracking. Hard CVD coatings are currently under study using exoelectron emission and photon emission to detect crack initiation under bending loads.

CVD HARD COATINGS PROGRAM

Principal Investigator: E. Randich,
Surface Metallurgy Division
Sandia National Laboratories
Albuquerque, New Mexico 87185
(505)264-7554 / FTS 844-7554

This program is a study of the chemical vapor deposition of refractory hard borides of the group IV and V metals. As coatings, these materials are of interest in erosion and wear applications. Specific borides which have been studied include TiB_2, ZrB_2, TaB_2, and alloys of the form $(Ti,Ta)B_2$ and $(Ti,Zr)B_2$. The program involves three areas: (1) theoretical and experimental studies of the CVD processes used to deposit the materials, (2) characterization of the deposited materials and their interaction with various substrate materials, and (3) erosion and wear testing of both laboratory specimens and prototype valve hardware for coal conversion systems.

Present work includes: (1) the thermodynamic prediction and experimental verification of the Ti-B-Cl-H and Ta-B-Cl-H systems which are used to deposit TiB_2 and TaB_2 respectively, (2) pole figure analysis to determine the effects of CVD parameters on preferred orientation of the coating, and (3) construction of a pressurized coal slurry test loop to evaluate coating material for high pressure letdown service in coal liquefaction systems.

EROSION/CORROSION AND WEAR OF SYNTHETIC FUELS PROCESS EQUIPMENT MATERIALS

Principal Investigator: Alan V. Levy,
Materials & Molecular Research Division
Lawrence Berkeley Laboratory
Berkeley, California 94720
(415)486-5822 / FTS 451-5822

The operating environments of the materials used in many of the components of synthetic fuels production plants are detrimental to their chemical and mechanical surface stability. The three principal destructive forces occurring in such elevated temperature and pressure processes as coal gasification and liquefaction and oil shale retorting are corrosive attack by sulfur and oxygen, erosion wear by solid particles, and abrasive wear resulting from the pulverization and transport of solid particles of coal and minerals into the reaction zones. My group is carrying out a comprehensive, integrated research program to gain an understanding of these corrosive, erosive and abrasive forces. Metals, ceramics, and protective coatings are all being studied. We want to learn how process operating conditions and construction materials' composition and properties can be coordinated to result in economical, long lived components.

Erosion

The presence of small (1 - 500 μm) solid particles of coal and char entrained in flowing gases or liquids in coal conversion processes introduces

a destructive mechanism, erosion, into the operating environment of the materials containing the reactions. Erosion has become a major consideration in the design of coal conversion equipment. We are conducting an indepth investigation of the erosion behavior of metals, ceramics and their coatings. There are many interrelated variables active in the erosion process. They include such factors as the size, shape, mass and friability of the particles; their velocity and direction upon impact with a solid surface; the hardness, strength, ductility and work hardenability of the target; and the temperature and composition of the gases and liquids that carry them to the target surface. The study is broken down into two major areas of investigation: the fluid mechanics of the particle containing flows and the mechanisms of erosion when the particles impact the target surface. In addition, since the fluids carrying the particles to the surface are corrosive in nature, combined erosion/corrosion investigations are being conducted. Analytical models based upon the mechanisms of erosion that are microscopically observed using the latest instruments are being developed. These mechanisms have been found to be considerably different from those used in earlier modeling efforts reported in the literature.

Fluid Mechanics

In all circumstances where small particles carried to material surfaces by fluids such as gases or liquids are studied, the fluid mechanics of the two-phase flow is a very important aspect of the overall behavior. How the particles impact the surface in terms of velocity, impingement angle and mass loading are major variables in the erosion mechanism. We are conducting both analytical model and experimental wind tunnel studies to gain a sufficient understanding of how entrained particles move in a fluid stream over various flow surface shapes to accurately define the actual condition of the particles when they impact containment surfaces. The similarities and differences observed in erosion of metals by gas-solid particle streams and by liquid slurries are clarified as the result of the fluid mechanics work.

Corrosion

We are trying to understand the combined degradation of the containment surfaces of synthetic fuels process plant components operating at elevated temperatures in gas-solid particle flows where the gases are highly reactive. It is necessary to know what the nature of the materials that form on their surfaces as the result of corrosion mechanism are before any practical understanding of the complete mechanisms can be gained. While each process for converting coal or oil shale to clean, efficient fuels has different components and environments, their corrosion behavior has many areas of commonality. For example, the sulfur present in the coal or oil shale is released at elevated temperatures in a form that results in a high sulfur chemical activity at the surface of a containment material such as in a pipe, pump housing or valve body. The sulfur can be in the form of a gas, H_2S, or a solid, iron pyrite, in coal gasification and oil shale retorting or in an acid in coal liquefaction. By studying the basic corrosion mechanisms of gases containing active sulfur and oxygen at elevated temperature in contact with a metal surface, a knowledge of the behavior of the metals and the characteristic of the scales formed on them that is applicable to several different processes is gained.

Corrosion-Erosion

In a comprehensive program to understand the mechanisms of materials surface degradation in synthetic fuel production plant environments, it is necessary to integrate the corrosion mechanisms with the erosion mechanisms. We are studying the erosion of scales of sulfides and oxides on metals and coatings at various temperatures and times at the sulfur and oxygen activities which occur in synthetic fuels processes. So far this work has given us considerable insight into the mechanisms of erosion of the brittle scale materials on ductile base metals. Factors such as morphology of the scale, adhesion of the scale to the base metal, scale thickness and plastic deformation of the substrate all effect the resultant erosion behavior. Combined erosion-corrosion tests are teaching us more about this complex and very important surface phenomena.

Abrasive Wear

The pulverization of coal and oil shale into particle sizes suitable for efficient reaction and their transport into the reaction vessels to convert them into gaseous and liquid fuels causes considerable abrasive type wear on containment materials. We are investigating the mechanisms of this wear and the ability of materials of different compositions, strengths and morphologies to resist it. Both two-body and three-body type abrasive wear mechanisms are being studied. The differences and similarities of abrasive wear to erosive wear are being determined.

MECHANISMS OF EROSION

Principal Investigators: A. P. L. Turner, J. Routbort, R. Scattergood
Materials Science Division
Argonne National Laboratory
Argonne, IL 60439
(312)972-4985

At the present time, we have active research projects on the mechanisms of erosion of ceramic materials and the nature of erosion processes for corrosion product scales. Although no work is currently being done on metals except in conjunction with the corrosion product scales, we will probably do more work in this area in the future.

The emphasis of our work on ceramics is on understanding the velocity and particle size dependencies of the erosion rate and how they relate to the microstructure. We are investigating the origin of the rapid decrease in erosion rate for abrasive particle sizes less than 20 μm. We have observed this apparent threshold in particle size for erosion of both reaction bonded SiC (RBSiC)

which is a two-phase material with a complex microstructure and for erosion of (111) surfaces of Si single crystals. Therefore the origin of the threshold is apparently not connected with the microstructure but is an inherent feature of the brittle mechanism of erosion. We are also studying the erosion of hot pressed SiC which is single phase. For this material we observe a peak in the erosion rate for particles of size approximately 100 μm. We believe that this anomalous particle size dependence is related to the grain size in the ceramic, but have yet to establish the details of the mechanism responsible for the peak.

The objective of the work on corrosion product scales is to establish the relationship between the erosion resistance of the scales and the chemistry of the corrosive environment in which they were formed. Test samples are coupons of 310 stainless steel that have been corroded at high temperatures in multicomponent gas atmospheres with varying oxygen and sulfur potentials. We are investigating the critical velocities and particle sizes required to cause rapid spalling of the scales, the rates of scale erosion under conditions where spalling does not occur and the erosion rates of subscale sulfur penetrated zones in the 310 substrates. We hope to be able to relate the erosion characteristics to the scale structure, hardness and other physical properties.

Our experiments are carried out in a slinger type erosion apparatus. Particles are accelerated by a rotating hollow arm into which the particles are fed at the center, and then impact the samples arranged around a circle outside the tip of the arm. We have the capability of heating the samples to about 700°C. Experiments are carried out in a vacuum of approximately 0.2 Torr.

STUDIES OF LOW VELOCITY, PARTICULATE EROSION

Principal Investigators: P. S. Follansbee,
G. B. Sinclair and
J. C. Williams
Dept. of Metallurgy & Materials Sci.
Carnegie-Mellon University
Schenley Park
Pittsburg, PA 15213
(412)578-2704

The erosion of copper and copper-aluminum alloys at room temperature by the impact of spherical SiO_2 and angular SiC (50 - 100 μm diameter) particles at velocities less than 30 m/sec is being studied using a combined experimental and analytical approach. The experimental studies employ a technique which incorporates a laser velocimeter for continuously measuring particle velocity and particle concentration (particles/sec). This removes many of the experimental difficulties which have been troublesome in previous erosion studies. The experimental results are to include both surface penetration and weight loss as a function of time, impingement angle and impingement velocity for annealed and cold-worked Cu and Cu-6% Al. Microscopic characterization (SEM) of both the damaged surface and subsurface regions, and of the individual particles which have been removed from the surface are being performed to correlate the erosion rate measurements with physical processes.

In the analytical studies, modeling of the particle impact event is being conducted using an elastoplastic, finite element, stress analysis. This analysis has been applied to the normal incidence impact of a rigid spherical projectile. Preliminary results for a single impact show that the fracture stress is not exceeded upon impact of a 50 μm diameter particle at 30 m/sec. Therefore, a material removal criterion based on the accumulated damage of multiple impacts is required and the present thrust of the research program is to develop such a model and supporting experimental evidence.

EROSION AND WEAR OF CERAMICS

Principal Investigator: Charles Yust,
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830
(615)574-4812 / FTS 624-4812

The BES erosion study at ORNL is concerned with the study of damage mechanisms at particle impact sites in ceramics, principally by direct observation of such damage. Electron microscopy, both scanning and transmission, is the tool by means of which impact damage is observed and characterized. The initial thrust of this study has been directed toward the creation of controlled damage in single crystal aluminum oxide specimens by impingement of silicon carbide particles. The early observations suggested that the local damage was the consequence of very high strain rate deformation processes at the impact point. Some effort has been expended, therefore, on analysis of another comparable high strain rate damage process in alumina, i.e., explosive compaction. The results of study of an explosively compacted alumina body seem to be consistent with some features of the individual erosion impacts in alumina and should contribute significant background for analysis of erosion damage.

The erosion study is also being extended to include study of TiB_2-Ni composites. These materials are being produced as part of a study of hard materials for wear resistance. Consequently, we will evaluate the erosion resistance of these compositions, and produce specimens for detailed characterization of the erosion process.

At present, our in-house erosion facility consists of a simple gas gun device for the acceleration of small batches of particles onto a specimen surface. Angles of impingement of 0 to 90 degrees, temperatures to approximately 1000°C, and a controlled environment are available in the system. A particle velocity measurement is not part of the system, but is estimated from the gas gun characteristics. The velocity range is approximately 50 - 200 m/sec. The system is designed for small samples to be used for electron microscopy.

PUB-363

BES EROSION-WEAR RESEARCH Newsletter

LAWRENCE BERKELEY LABORATORY, UNIVERSITY OF CALIFORNIA, BERKELEY, CALIFORNIA 94720

Volume 1, Number 1 July 1980

INITIATION OF BES EROSION RESEARCH NEWSLETTER

The importance of the need for an increasing understanding of the behavior of materials in erosion-wear environments has been underscored by the occurrence of more failures of components in coal conversion system pilot plants by erosion than by any other single mechanism. The BES program in erosion and wear is a wide ranging one that is aimed at providing knowledge of the basic mechanisms of erosion of several types of materials to those that are endeavoring to eliminate erosion failures by astute materials selection and component and process design.

This newsletter is intended to provide a written information exchange medium for the team of BES erosion-wear researchers to more effectively carry out our programs in close communication with one another. It is planned to periodically have informal meetings to further share our findings and ideas. In these ways, we can collectively make available more basic knowledge of erosion-wear behavior in a timely manner. Issues will be prepared for distribution quarterly.

In this first issue of the newsletter, each of the seven active BES programs is briefly presented to acquaint the reader with the objectives and approaches of the programs. In subsequent issues, it is planned to review the concepts, accomplishments and even problems of individual programs in more depth, still preserving the brevity of this issue. Two or three individual investigators per issue will be able to highlight aspects of their work that will provide knowledge of behavior that has been gained in recent efforts.

A section of the newsletter will be made available for comments by others on the results of the work of individuals reported in earlier issues. Speculations on the meanings of data, correlations with data from other investigators' programs, critical comments on experimental or analytical techniques; in short a forum for investigators to use to enhance each others programs will be provided. Lists of recent publications and reports will be another feature as will be notices of pertinent meetings and other activities.

It is hoped that the newsletter will become a valued tool for both BES investigators and others that will receive it to advance the knowledge of erosion-wear mechanisms.

LOCALIZED CORROSION OF PASSIVE METALS

Principal Investigator: Richard C. Alkire,
Materials Research Laboratory
University of Illinois
Urbana, IL 61801
(217)333-0063 / FTS 957-0063

The purpose of this program is to study the effects of fluid flow on repassivation of metals immersed in aqueous solutions at ambient temperatures. The program focuses on the sequence by which passivity is regained following disturbance of the surface. Mathematical models are used to quantify hypotheses of the mechanism. Experiments aim for controlled variation of system parameters under known corrosion conditions.

Typical disturbances which create loss of passivity include fluid flow, particle impingement/impaction, and cavitation. After birth of local activity, subsequent corrosion processes are invariably influenced by transport phenomena including both mass transfer of aggressive species, ohmic transport of charge, fluid flow, and both heterogeneous and homogeneous reactions. By using mathematical models to test hypotheses of mechanism, this program seeks an improved understanding of corrosion in the presence of erosion. In particular, chemical engineering concepts are incorporated into models of diffusion and convection controlled corrosion processes. By inversion, mathematical models provide a rational basis for predicting conditions under which corrosion may be avoided.

Special attention has been directed to the role which metal salt films play during early stages of repassivation. Under such conditions, the rate of corrosion is so high that a salt film precipitates upon the surface. Subsequent events are thus greatly influenced by diffusive and convective transport processes which influence the behavior of the salt film. On iron in dilute sulfuric acid, for example, the salt film is a necessary precursor to repassivation. High flow rates thus impede repassivation since they prevent precipitation of the salt film. In chloride solution, on the other hand, the presence of a salt film inhibits repassivation; high flow rates thus enhance repassivation.

In order to achieve controlled observations on individual corrosion sites, a new experimental technique has been developed which induces highly localized depassivation at a pre-selected site on

Supported by the Division of Materials Sciences, Office of Basic Energy Sciences of the U.S. Department of Energy under Contract W-7405-ENG-48.

the metal surface. The method uses a low-energy laser beam, focused to <5 μm diameter, to trigger depassivation with a 5-ns pulse. The method simulates an individual impingement event on an otherwise passive surface. Subsequent corrosion events, including repassivation can be observed under controlled hydrodynamic flow conditions. A theoretical analysis of the potential and convective flow fields is being developed to correlate and to scale data from among various experimental systems.

ENVIRONMENTAL EFFECTS ON THE MECHANICAL BEHAVIOR OF BRITTLE MATERIALS

Principal Investigator: R. E. Cuthrell,
Surface Metallurgy Division
Sandia National Laboratories
Albuquerque, New Mexico 87185
(505)264-7554 / FTS 844-7554

Changes in the mechanical behavior of solid materials which are produced by gaseous or liquid environments are known as Rebinder effects after the Russian academician P. A. Rebinder who discovered these chemomechanical phenomena in 1928. Following the extensive though little understood work of many investigators in this field, we have (1) reproduced the results of Westwood who showed that drilling rates in brittle materials depend on the surface charge produced by ions adsorbed from liquid environments, (2) found that ion aggregation in low dielectric constant liquids limits the chemomechanical effects through limiting the availability of the ions for surface interaction, (3) proposed that hydrogen is the ionic species responsible for chemomechanical effects, (4) tested this hypothesis in gaseous hydrogen and hydrogen plasmas in an ultrahigh vacuum chamber and found that the magnitude of the Rebinder effects depends on the hydrogen pressure. Subsequent experiments showed the same dependence of drilling rates on hydrogen availability from liquid environments. Since hydrogen ions are small and highly mobile, a wide variety of materials were expected to exhibit this Rebinder effect. A survey of materials showed the effect in glasses, ceramics, single crystal minerals, rocks, refractory coatings, semiconductors, and metals containing brittle phases.

Subcritical crack growth rates in Pyrex and soda-lime glass exhibit similar hydrogen dependence both in the gaseous and liquid environments. These results suggest that the chemomechanical effects depend on the rate of diffusion of hydrogen relative to the rate of fracture in the near surface region of brittle materials. The observed time dependence of Rebinder effects in silicon were consistent with estimated hydrogen permeation rates at room temperature. Exposure to hydrogen during the preparation of erosion resistant coatings by chemical vapor deposition may determine their resistance to cracking. Hard CVD coatings are currently under study using exoelectron emission and photon emission to detect crack initiation under bending loads.

CVD HARD COATINGS PROGRAM

Principal Investigator: E. Randich,
Surface Metallurgy Division
Sandia National Laboratories
Albuquerque, New Mexico 87185
(505)264-7554 / FTS 844-7554

This program is a study of the chemical vapor deposition of refractory hard borides of the group IV and V metals. As coatings, these materials are of interest in erosion and wear applications. Specific borides which have been studied include TiB_2, ZrB_2, TaB_2, and alloys of the form $(Ti,Ta)B_2$ and $(Ti,Zr)B_2$. The program involves three areas: (1) theoretical and experimental studies of the CVD processes used to deposit the materials, (2) characterization of the deposited materials and their interaction with various substrate materials, and (3) erosion and wear testing of both laboratory specimens and prototype valve hardware for coal conversion systems.

Present work includes: (1) the thermodynamic prediction and experimental verification of the Ti-B-Cl-H and Ta-B-Cl-H systems which are used to deposit TiB_2 and TaB_2 respectively, (2) pole figure analysis to determine the effects of CVD parameters on preferred orientation of the coating, and (3) construction of a pressurized coal slurry test loop to evaluate coating material for high pressure letdown service in coal liquefaction systems.

EROSION/CORROSION AND WEAR OF SYNTHETIC FUELS PROCESS EQUIPMENT MATERIALS

Principal Investigator: Alan V. Levy,
Materials & Molecular Research Division
Lawrence Berkeley Laboratory
Berkeley, California 94720
(415)486-5822 / FTS 451-5822

The operating environments of the materials used in many of the components of synthetic fuels production plants are detrimental to their chemical and mechanical surface stability. The three principal destructive forces occurring in such elevated temperature and pressure processes as coal gasification and liquefaction and oil shale retorting are corrosive attack by sulfur and oxygen, erosion wear by solid particles, and abrasive wear resulting from the pulverization and transport of solid particles of coal and minerals into the reaction zones. My group is carrying out a comprehensive, integrated research program to gain an understanding of these corrosive, erosive and abrasive forces. Metals, ceramics, and protective coatings are all being studied. We want to learn how process operating conditions and construction materials' composition and properties can be coordinated to result in economical, long lived components.

Erosion

The presence of small (1 - 500 μm) solid particles of coal and char entrained in flowing gases or liquids in coal conversion processes introduces

a destructive mechanism, erosion, into the operating environment of the materials containing the reactions. Erosion has become a major consideration in the design of coal conversion equipment. We are conducting an indepth investigation of the erosion behavior of metals, ceramics and their coatings. There are many interrelated variables active in the erosion process. They include such factors as the size, shape, mass and friability of the particles; their velocity and direction upon impact with a solid surface; the hardness, strength, ductility and work hardenability of the target; and the temperature and composition of the gases and liquids that carry them to the target surface. The study is broken down into two major areas of investigation: the fluid mechanics of the particle containing flows and the mechanisms of erosion when the particles impact the target surface. In addition, since the fluids carrying the particles to the surface are corrosive in nature, combined erosion/corrosion investigations are being conducted. Analytical models based upon the mechanisms of erosion that are microscopically observed using the latest instruments are being developed. These mechanisms have been found to be considerably different from those used in earlier modeling efforts reported in the literature.

Fluid Mechanics

In all circumstances where small particles carried to material surfaces by fluids such as gases or liquids are studied, the fluid mechanics of the two-phase flow is a very important aspect of the overall behavior. How the particles impact the surface in terms of velocity, impingement angle and mass loading are major variables in the erosion mechanism. We are conducting both analytical model and experimental wind tunnel studies to gain a sufficient understanding of how entrained particles move in a fluid stream over various flow surface shapes to accurately define the actual condition of the particles when they impact containment surfaces. The similarities and differences observed in erosion of metals by gas-solid particle streams and by liquid slurries are clarified as the result of the fluid mechanics work.

Corrosion

We are trying to understand the combined degradation of the containment surfaces of synthetic fuels process plant components operating at elevated temperatures in gas-solid particle flows where the gases are highly reactive. It is necessary to know what the nature of the materials that form on their surfaces as the result of corrosion mechanism are before any practical understanding of the complete mechanisms can be gained. While each process for converting coal or oil shale to clean, efficient fuels has different components and environments, their corrosion behavior has many areas of commonality. For example, the sulfur present in the coal or oil shale is released at elevated temperatures in a form that results in a high sulfur chemical activity at the surface of a containment material such as in a pipe, pump housing or valve body. The sulfur can be in the form of a gas, H_2S, or a solid, iron pyrite, in coal gasification and oil shale retorting or in an acid in coal liquefaction. By studying the basic corrosion mechanisms of gases containing active sulfur and oxygen at elevated temperature in contact with a metal surface, a knowledge of the behavior of the metals and the characteristic of the scales formed on them that is applicable to several different processes is gained.

Corrosion-Erosion

In a comprehensive program to understand the mechanisms of materials surface degradation in synthetic fuel production plant environments, it is necessary to integrate the corrosion mechanisms with the erosion mechanisms. We are studying the erosion of scales of sulfides and oxides on metals and coatings at various temperatures and times at the sulfur and oxygen activities which occur in synthetic fuels processes. So far this work has given us considerable insight into the mechanisms of erosion of the brittle scale materials on ductile base metals. Factors such as morphology of the scale, adhesion of the scale to the base metal, scale thickness and plastic deformation of the substrate all effect the resultant erosion behavior. Combined erosion-corrosion tests are teaching us more about this complex and very important surface phenomena.

Abrasive Wear

The pulverization of coal and oil shale into particle sizes suitable for efficient reaction and their transport into the reaction vessels to convert them into gaseous and liquid fuels causes considerable abrasive type wear on containment materials. We are investigating the mechanisms of this wear and the ability of materials of different compositions, strengths and morphologies to resist it. Both two-body and three-body type abrasive wear mechanisms are being studied. The differences and similarities of abrasive wear to erosive wear are being determined.

MECHANISMS OF EROSION

Principal Investigators: A. P. L. Turner, J. Routbort, R. Scattergood
Materials Science Division
Argonne National Laboratory
Argonne, IL 60439
(312)972-4985

At the present time, we have active research projects on the mechanisms of erosion of ceramic materials and the nature of erosion processes for corrosion product scales. Although no work is currently being done on metals except in conjunction with the corrosion product scales, we will probably do more work in this area in the future.

The emphasis of our work on ceramics is on understanding the velocity and particle size dependencies of the erosion rate and how they relate to the microstructure. We are investigating the origin of the rapid decrease in erosion rate for abrasive particle sizes less than 20 μm. We have observed this apparent threshold in particle size for erosion of both reaction bonded SiC (RBSiC)

which is a two-phase material with a complex microstructure and for erosion of (111) surfaces of Si single crystals. Therefore the origin of the threshold is apparently not connected with the microstructure but is an inherent feature of the brittle mechanism of erosion. We are also studying the erosion of hot pressed SiC which is single phase. For this material we observe a peak in the erosion rate for particles of size approximately 100 μm. We believe that this anomalous particle size dependence is related to the grain size in the ceramic, but have yet to establish the details of the mechanism responsible for the peak.

The objective of the work on corrosion product scales is to establish the relationship between the erosion resistance of the scales and the chemistry of the corrosive environment in which they were formed. Test samples are coupons of 310 stainless steel that have been corroded at high temperatures in multicomponent gas atmospheres with varying oxygen and sulfur potentials. We are investigating the critical velocities and particle sizes required to cause rapid spalling of the scales, the rates of scale erosion under conditions where spalling does not occur and the erosion rates of subscale sulfur penetrated zones in the 310 substrates. We hope to be able to relate the erosion characteristics to the scale structure, hardness and other physical properties.

Our experiments are carried out in a slinger type erosion apparatus. Particles are accelerated by a rotating hollow arm into which the particles are fed at the center, and then impact the samples arranged around a circle outside the tip of the arm. We have the capability of heating the samples to about 700°C. Experiments are carried out in a vacuum of approximately 0.2 Torr.

STUDIES OF LOW VELOCITY, PARTICULATE EROSION

Principal Investigators: P. S. Follansbee,
G. B. Sinclair and
J. C. Williams
Dept. of Metallurgy & Materials Sci.
Carnegie-Mellon University
Schenley Park
Pittsburg, PA 15213
(412)578-2704

The erosion of copper and copper-aluminum alloys at room temperature by the impact of spherical SiO_2 and angular SiC (50 - 100 μm diameter) particles at velocities less than 30 m/sec is being studied using a combined experimental and analytical approach. The experimental studies employ a technique which incorporates a laser velocimeter for continuously measuring particle velocity and particle concentration (particles/sec). This removes many of the experimental difficulties which have been troublesome in previous erosion studies. The experimental results are to include both surface penetration and weight loss as a function of time, impingement angle and impingement velocity for annealed and cold-worked Cu and Cu-6% Al. Microscopic characterization (SEM) of both the damaged surface and subsurface regions, and of the individual particles which have been removed from the surface are being performed to correlate the erosion rate measurements with physical processes.

In the analytical studies, modeling of the particle impact event is being conducted using an elastoplastic, finite element, stress analysis. This analysis has been applied to the normal incidence impact of a rigid spherical projectile. Preliminary results for a single impact show that the fracture stress is not exceeded upon impact of a 50 μm diameter particle at 30 m/sec. Therefore, a material removal criterion based on the accumulated damage of multiple impacts is required and the present thrust of the research program is to develop such a model and supporting experimental evidence.

EROSION AND WEAR OF CERAMICS

Principal Investigator: Charles Yust,
Metals and Ceramics Division
Oak Ridge National Laboratory
P.O. Box X
Oak Ridge, TN 37830
(615)574-4812 / FTS 624-4812

The BES erosion study at ORNL is concerned with the study of damage mechanisms at particle impact sites in ceramics, principally by direct observation of such damage. Electron microscopy, both scanning and transmission, is the tool by means of which impact damage is observed and characterized. The initial thrust of this study has been directed toward the creation of controlled damage in single crystal aluminum oxide specimens by impingement of silicon carbide particles. The early observations suggested that the local damage was the consequence of very high strain rate deformation processes at the impact point. Some effort has been expended, therefore, on analysis of another comparable high strain rate damage process in alumina, i.e., explosive compaction. The results of study of an explosively compacted alumina body seem to be consistent with some features of the individual erosion impacts in alumina and should contribute significant background for analysis of erosion damage.

The erosion study is also being extended to include study of TiB_2-Ni composites. These materials are being produced as part of a study of hard materials for wear resistance. Consequently, we will evaluate the erosion resistance of these compositions, and produce specimens for detailed characterization of the erosion process.

At present, our in-house erosion facility consists of a simple gas gun device for the acceleration of small batches of particles onto a specimen surface. Angles of impingement of 0 to 90 degrees, temperatures to approximately 1000°C, and a controlled environment are available in the system. A particle velocity measurement is not part of the system, but is estimated from the gas gun characteristics. The velocity range is approximately 50 - 200 m/sec. The system is designed for small samples to be used for electron microscopy.