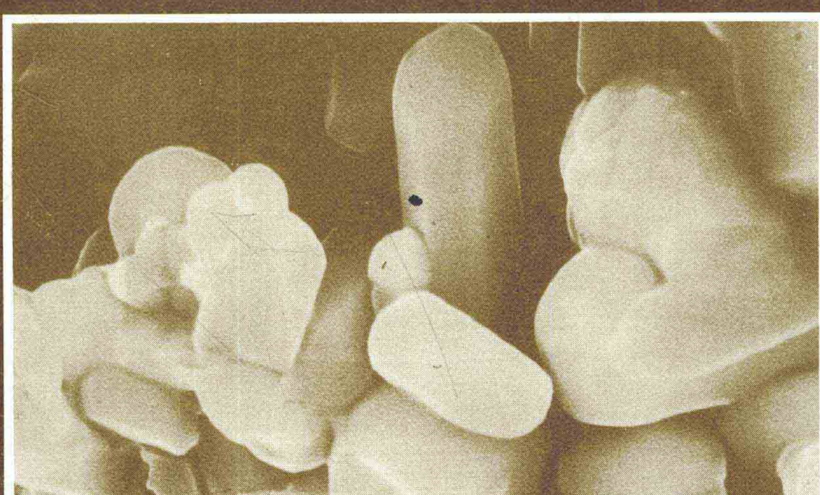
Wear Testing of Advanced Materials



Divakar/Blau, editors

STP 1167

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Ramesh Divakar and Peter J. Blau, editors

ASTM Publication Code Number (PCN)
04-011670-27

ASTM
1916 Race Street
Philadelphia, PA 19103

Library of Congress Cataloging-in-Publication Data

Wear testing of advanced materials / Ramesh Divakar and Peter J. Blau, editors.
(STP ; 1167)
Symposium on Wear Testing of Advanced Materials presented in San Antonio on 14 Nov. 1992 and sponsored by ASTM Committee G-2 on Wear and Erosion.
"ASTM publication code number (PCN) 04-011670-27."
Includes bibliographical references and index.
ISBN 0-8031-1476-1
1. Mechanical wear—Congresses. 2. Composite materials—Testing—Congresses. 3. Aluminum oxide—Testing—Congresses. 4. Ceramic materials—Testing—Congresses. I. Divakar, Ramesh, 1959- II. Blau, P. J. III. ASTM Committee G-2 on Erosion and Wear. IV. Series: ASTM special technical publication; 1167.
TA418.4.W43 1992
620.1'1292—dc20 92-2357
CIP

Peer Review Policy

Each paper published in this volume was evaluated by three peer reviewers. The authors addressed all of the reviewers' comments to the satisfaction of both the technical editor(s) and the ASTM Committee on Publications.

The quality of the papers in this publication reflects not only the obvious efforts of the authors and the technical editor(s), but also the work of these peer reviewers. The ASTM Committee on Publications acknowledges with appreciation their dedication and contribution to time and effort on behalf of ASTM.

Printed in Philadelphia, PA
August 1992

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Overview

There is a continuing interest in extending the reliability and materials capabilities in mechanical systems, both at ambient and elevated temperatures. Tribological applications are excellent examples of situations where stringent requirements have mandated that materials perform at levels previously believed to be unrealistic. Such demanding requirements have served as an impetus for new material development. Taken as a group, advanced materials have been, in many cases, successfully deployed in areas in which conventional materials are no longer satisfactory.

Broadly defined, advanced materials include intermetallic alloys, advanced polymers, engineering ceramics, composites based on metal, polymer, or ceramic matrices. Composites may be classified further into particulate, whisker, and continuous fiber-reinforced varieties. Despite significant advances in materials research, testing techniques and evaluation methodology have not developed at the same pace. As in many other instances, an understanding of material limitations and suitability to task has come by way of an empirical approach at best. Each individual designer/engineer or organization/group has used his/her unique methodology to find advanced materials solutions for a particular problem. While this may be a reasonable practice on a small local scale, communication with the rest of the world, of the success or failure of a material, based on results from this "homemade" approach is not always helpful to others in solving similar, but not identical, problems. Needless to say, to an engineer interested in using these materials in his/her design or application, the lack of standardization poses a difficult problem. As the world economies become increasingly interdependent, and international trade increases, a global consensus on materials testing issues would be extremely beneficial to all parties concerned. More specifically, in light of the potential uses of advanced materials in severe service wear applications, it is vital that their evaluation be done in a systematic, universally acceptable fashion.

The literature on testing practices and standards for advanced materials is unorganized and uncoordinated. ASTM has sponsored several symposia on this and related subjects. Readers are referred to two resulting publications, namely, ASTM STP 1010, *Selection and Use of Wear Tests for Ceramics*, 1988 (Yust/Bayer, Eds.) and ASTM STP 1105, *Tribological Modeling for Mechanical Designers*, 1991 (Ludema/Bayer, Eds.). Another recently issued, noteworthy publication is *The Tribology of Composite Materials*, 1991 (Rohatgi/Blau/Yust, Eds.). In the hope of further improving the status of wear testing of materials and encouraging the engineering community to explore standardization issues, a symposium on Wear Testing of Advanced Materials was held in November 1990 in San Antonio, TX. The objective of the symposium was to review current practices for testing advanced materials and to explore standardization issues. This symposium, held under the auspices of ASTM Committee G-2 on Wear and Erosion, was attended by a wide variety of international experts from universities, government, and industry. This book represents a select collection of eleven peer-reviewed papers from that symposium.

The papers included in this STP can be roughly classified into two categories, namely, wear test methods for advanced materials specifically related to different applications and analysis and interpretation of results from wear tests. Although not all types of wear testing are covered, the book does give the reader a good overview of the more common tests currently used to characterize advanced materials.

Wear Test Methods for Advanced Materials

The first paper in this section discusses the effect of different test configurations and different counterface materials on the tribological characteristics of alumina. The discussion shows that the wear rate of alumina depends on the test configuration in use and the counterface material, whereas it is not affected by the orientation of the sample or the method of surface preparation (except when the surface was diamond ground).

The next paper details the influence of the mechanical response of the test system on the wear and friction results. The author illustrates how a variation of two orders of magnitude is obtained in the wear rates of alumina as a result of changes in the dominant wear mechanism induced by altering test machine dynamics. Also discussed here is an interesting attempt to correlate mechanical response spectra for different configurations with wear and friction results.

Evaluation of wear coatings for seal applications using an accelerated bench wear test is discussed next. This is followed by two articles related to bearing applications, the first of which deals with the development of a unique wear tester to screen candidate materials for thrust bearing applications. The authors show how this tester is used to screen candidate advanced bearing materials for down-hole drilling applications. The second article discusses the test methodologies used to identify polymer and metal matrix composites and ceramics for self-lubricating journal bearings, bearing liners, and hybrid bearings. Materials are evaluated with pin-on-disc, block-on-ring, and rolling four-ball apparatus in both dry and lubricated tests.

The next paper deals with the friction and wear of high performance polymer composites. The influence of the type of reinforcement and the properties of the counterface used in the fretting wear of continuous fiber-reinforced polymer composites is studied in detail. Two papers on slurry erosion are included. They relate to the development of a slurry jet erosion apparatus and a model to predict abrasive particle trajectories using a streamline analysis. The first paper shows that particle velocity and local impact angles vary along the surface of the target material, depending on fluid viscosity, slurry velocity, and particle size. The second paper uses slurry erosion tests to measure wear coefficients in centrifugal slurry pumps. It also discusses the shortcomings of separately simulating two mechanisms, that is, particle impact and scouring, responsible for slurry erosion wear. The authors give possible reasons for discrepancies in wear coefficients between predictions based on the above mechanisms and actual measurements on components. An alternative approach is proposed, based on the coupling of finite-element modeling of fluid flow and actual wear measurements in pump casings.

Analysis and Interpretation of Wear Tests

As an introduction to this section, the first paper is a fairly comprehensive report on results of a round-robin series of tests in the sliding wear of alumina. The effect of changes in test conditions, such as load, sliding speed, humidity level, and load on tribological characteristics, are discussed. It is also reported that a decrease in humidity is accompanied by a significant increase in both friction and wear of alumina. This is attributed to the formation of interfacial layers of hydrated alumina. The use of wear maps is illustrated in the sliding wear of silicon nitrides. They show in three-dimensional representation of the dependence of wear rate on different test variables.

The final paper in this book is a discussion of sliding wear testing and data analysis strategies for advanced ceramics. It discusses the advantages and disadvantages of commonly used techniques to measure friction and wear behavior and suggests alternatives to improve the wear characterization of engineering ceramics.

The editors believe that this book will be a valuable and useful reference for scientists and engineers facing friction and wear problems. In conclusion, the symposium chairmen gratefully acknowledge the expert contributions of the authors and reviewers. They also express deep appreciation for the help and sponsorship of ASTM Committee G-2 on Wear and Erosion and the tireless efforts of ASTM staff, Monica Siperko and Rita Hippensteel, in making this STP possible.

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Wear Testing Methods for Advanced Materials

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Effect of Test Variables on the Friction and Wear of Alumina

REFERENCE: Bahadur, S. and Iskandar, I., "**Effect of Test Variables on the Friction and Wear of Alumina,**" *Wear Testing of Advanced Materials, ASTM STP 1167*, Ramesh Divakar and Peter J. Blau, Eds., American Society for Testing and Materials, Philadelphia, 1992, pp. 7–23.

ABSTRACT: The sliding friction and wear behavior of alumina was studied using variations in the test methods and the procedures. The counterface materials against which alumina slid were tool steel, alumina, and zirconia-toughened alumina. Wear tests were performed using the ball-on-flat, block-on-ring, pin-on-disk, washer, and reciprocating arrangements with the alumina specimen constantly in contact with the tool steel counterface. The effects of the orientation of the alumina specimen in molded block, the method of surface preparation, and the variation in counterface material on wear were also studied. It was found that the orientation did not affect wear behavior. As for the surface preparation, alumina specimens were finished by abrasion against 600-grade silicon carbide paper and grinding with alumina and diamond wheels. There was some damage to the surface observed in all of these cases, but only diamond grinding affected the wear behavior adversely. The effect of counterface on the wear behavior was very significant. The effects of the above variations on the test results are examined and interpreted with the help of scanning electron microscopy, energy dispersive X-ray analysis (EDXA), and tribological principles. The significance of the test variables is discussed in the context of anticipated ASTM standards for the testing of ceramics.

KEYWORDS: sliding wear, wear tests, ceramic wear, alumina wear, alumina coefficient of friction, grinding damage in alumina

Wear is not a material property but is instead a system response arising from the conditions at the sliding interface. It is affected by a number of factors that are relevant to both members of the sliding pair and the system as a whole. The variables affecting wear are the materials in contact, the type of relative motion (rolling, sliding, or impact), the system configuration (pin-on-disk, block-on-ring, and so forth), contact stress and stress distribution, sliding speed, surface finish, and so forth [*1,2*]. Because of these variations, different wear rates are commonly reported for the same material in the literature. The principal consideration in using a test set-up is the sliding configuration that conforms to the practical situation. Sometimes, the selection is governed by the availability of the particular test set-up or of the specimen in a particular shape and size [*3*]. This is much more true for ceramics, which can be inherently damaged in machining [*4,5*].

The most common wear test setup used in laboratories is the pin-on-disk arrangement in which a cylindrical or rectangular pin with either a spherical or flat end rides on a flat disk. Although the spherical end is difficult to produce, it provides better alignment than the flat end. The stress at the contact point of spherical tip with a flat surface in the initial stages of sliding is very high and decreases rapidly with longer sliding times. A similar contact

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stress situation prevails in the block-on-ring arrangement because of the initial line contact between the flat surface and the cylindrical periphery of the ring. To reduce the initial high contact pressure, sometimes a pin-on-ring arrangement is used in which the pin contact surface is machined to a concave shape to make apparently full contact with the ring periphery. Another test set-up variation is the reciprocating arrangement in which a flat pin or a ball rides over a flat surface in reciprocating motion. The relative speed in an eccentric driven system is a function of the stroke location. This configuration is similar to the motion of a piston in a cylinder. As opposed to the above arrangements, in the washer type test set-up there is always full contact between the two mating surfaces so that no part of either surface is exposed to outside atmosphere for cooling.

Because ceramics are brittle materials, they are very sensitive to flaws. Because machining operations, such as cutting, grinding, and so forth, may produce flaws, wear is expected to be affected by surface preparation. It has been reported [*6*] that the nature of the damage in ceramics from grinding depends on factors such as the grinding medium, the coolant, the rate of material removal, and the nature of the ceramic material. The hard third-body particles may also act as abrasive material and influence the surface finish. It has been suggested [*4*] that the grinding particles act as indenters and introduce flaws. The subsurface cracks have been observed [*7*] in both the parallel and the perpendicular directions to the groove axis. The above findings demonstrate that the method of surface preparation is expected to affect wear considerably.

Whereas ceramics are commonly known as brittle materials, plastic deformation and chemical interaction have been observed on the worn surfaces of ceramics [*8*]. The plastic deformation is caused presumably by hydrostatic pressure and excessive temperature rise in the contact zone. The latter promotes chemical interaction between the surfaces and their atmospheres. For example, in the case of sliding between alumina and steel, the possibility of reaction between alumina (Al_2O_3) and iron (Fe) producing oxide of iron and aluminum ($FeOAl_2O_3$) spinel as solid solution has been reported [*9*]. Brown et al. [*10*] found that the spinel structures can range in composition from pure iron oxide to pure alumina. Because of adhesion, this compound can form a layer at the mating surface and affect wear. The composition of the layer material, in general, depends on the counterface material. The counterface material can significantly affect the wear behavior.

From the above discussion, it is obvious that the wear of ceramics is affected by the variations in test conditions and testing procedures. The objective of this work was to study the effect of some of the variations such as the test setup, surface preparation method, the orientation of material in the molded slab, counterface material, load, and speed on the wear of ceramics.

Experimental Procedure

Specimen Preparation

The ceramic materials, alumina[2] (99.5% Al_2O_3 doped with magnesium oxide [MgO]), and zirconia-toughened alumina[3] (ZTA) were supplied by the Champion Spark Plug Co. in the form of 100- by 100-mm-slabs of 6.35-mm thickness. The properties of alumina are specific gravity 3.92, porosity 2%, hardness 1710 VHN, and thermal conductivity 36 W/m · K. The properties of ZTA are specific gravity 3.95, porosity 5%, hardness 1610, and thermal conductivity 23 W/m · K. The specimens were cut out of the slab using a diamond cutter, and normally the surface unaffected by cutting was used in wear experiments. Except for the

[2]Manufacturer's code name M-RCHP-4PD.
[3]Manufacturer's code name ZTA-GF-A.

case when the effect of surface preparation mode on wear was studied, alumina specimens were finished by abrasion against 600-grade emery paper in running water. These were then washed with soap and water and finally with methanol and dried.

In most experiments, the counterface of AISI 02 tool steel (carbon [C] 0.90%, manganese [Mn] 1.6%) was used. It was quench-hardened to 53 Rc and finished by grinding with an alumina wheel to a surface roughness of 0.62-μm center line average (cla). When ceramic was used as the counterface material, the surface as produced in molding without any extra preparation was used.

To study the effect of the surface preparation method on wear, four variations were used. These involved no finishing, abrasion against 600-grade silicon carbide paper, and surface grinding with alumina and diamond wheels. The material was ground using a coolant to a depth of 200 μm with a downfeed of 20 μm. The surface roughness values were 1.35- and 1.85-μm cla in the case of grinding with alumina and diamond wheels, respectively.

Variations of Test Configurations

Wear experiments were performed using five different test configurations. One of the test setups used was the block-on-ring, which was described elsewhere [*11*]. A block of alumina, 17 mm high and with the planar area of 4.9 by 6.35 mm in which the 4.9-mm dimension was parallel to the axis of the ring, rode over a tool steel ring of 68.5-mm diameter and 6.35-mm thickness.

Another test setup used was the pin-on-disk arrangement. Sliding occurred between the face, 4.90 by 6.35 mm, of the pin and the flat surface of the disk in an average track diameter of 36 mm.

The third configuration used was the ball-on-flat arrangement. This test was performed in a pin-on-disk machine. Because ceramic balls were not available, the contact between a ball and flat was approximated by the contact between the corner of a ceramic cube and the flat surface of a tool steel disk. The contact stresses in these two arrangements are fairly identical particularly in the initial stages of sliding. The track diameter here was 28 mm.

The fourth test configuration was the washer arrangement. A tool steel washer 2 mm thick with an inner diameter of 26 mm and an outer diameter of 28 mm rotated about its axis in sliding contact against an alumina disk in the pin-on-disk machine.

The last test setup used was the reciprocating arrangement. An alumina pin with the contact dimensions of 4.90 by 6.35 mm slid in reciprocating motion over a tool steel disk. The reciprocating motion was obtained by connecting a slider to an eccentric mounted on a motor shaft.

Wear experiments were run under dry conditions over a sliding distance of at least 50 km. Sliding was interrupted at suitable intervals for weighing to determine the material loss from wear. In general, the sliding speed and the normal load used in wear experiments were 2 m/s and 14.7 N, respectively. The sliding speed varied as a function of stroke position in the reciprocating experiments.

The worn surfaces were coated with a thin layer of gold and studied by scanning electron microscopy.

Results and Discussion

Effect of Specimen Orientation

The effect of the orientation of specimen in molded block on wear was studied. Wear experiments were carried out with alumina blocks sliding against tool steel rings at 2-m/s sliding speed and 14.7-N load. The wear surfaces corresponded to the three planes marked in Fig. 1. Because the wear data followed a straight line behavior, the slopes of the lines in Fig. 1 provided the wear rates. The wear rates are about the same irrespective of the orientation. The tool steel ring wear was also about the same (1.587×10^{-3} g/km) for all three cases. From the variation of the coefficient of friction with sliding distance in Fig. 1, it is seen that there is no significant difference in the coefficient of friction either.

Effect of Test Configuration

Dry sliding tests were conducted in five different test configurations, as described in the section entitled "Experimental Procedure." Because the contact geometries in these arrangements varied theoretically from a point to a surface in the initial stage of sliding and the contact area changed considerably in some cases, it was not possible to run these experiments under perfectly controlled contact pressure conditions. To get the same contact pressure of 0.472 Pa as in the pin-on-disk arrangement, a load of 39.65 N was used in the washer configuration; in other cases, a constant load of 14.7 N was used. With the exception of the reciprocating arrangement in which sliding speed varied from zero at stroke ends to a maximum of 1.257 m/s in the mid-stroke position, all wear experiments in this section were performed with a sliding speed of 2 m/s. The latter was an average sliding speed because in the pin-on-disk and the washer arrangements sliding speed on the outside track was different from that on the inside track. In the reciprocating arrangement, wear tests were run with 500 strokes/min and the stroke length was 48 mm. In all of these experiments, the counterface material was tool steel.

The results of these tests are plotted in Figs. 2 and 3. For the washer type setup, only one data point over a sliding distance of 50.4 km was taken because of the difficulty in repositioning and leveling the ceramic disk. The data for the pin-on-disk, the reciprocating, and the block-on-ring configurations are plotted separately from the others because of the considerably lower wear rates in these three cases. The reason for much lower wear in the first two cases is considerably lower contact pressure than in the ball-on-flat and the block-

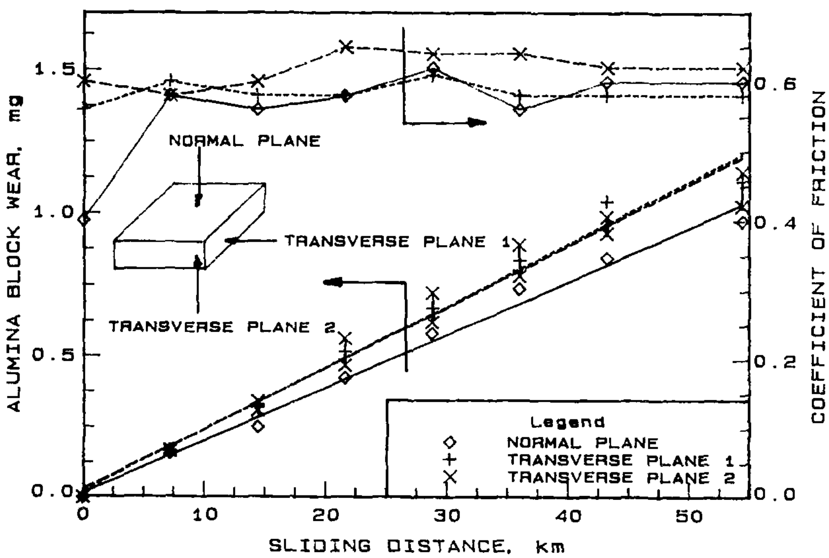

FIG. 1—*Alumina block wear and coefficient of friction versus sliding distance for three different planes in the molded block rubbing against tool steel ring (sliding speed: 2 m/s, normal load: 14.7 N).*

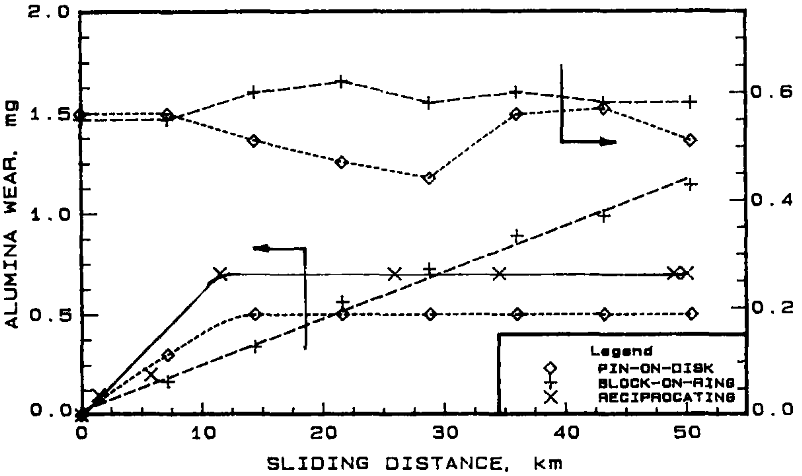

FIG. 2—*Wear and coefficient of friction versus sliding distance for three different configurations with alumina rubbing against tool steel (sliding speed: 2 m/s, normal load: 14.7 N; sliding speed varied with stroke for reciprocating arrangement).*

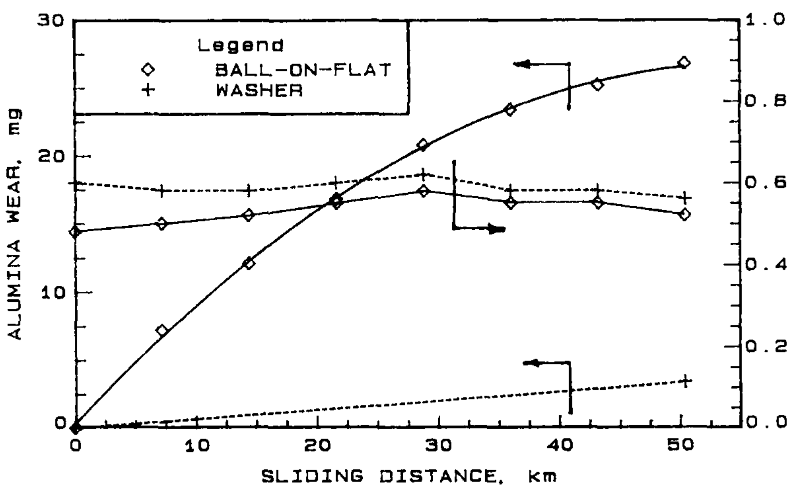

FIG. 3—*Wear and coefficient of friction versus sliding distance for two different configurations with alumina rubbing against tool steel (sliding speed: 2 m/s, normal load: 14.7 N).*

on-ring arrangements. The wear in the washer arrangement is also fairly low because of low contact pressure but much higher than in the pin-on-disk and the reciprocating cases because, unlike these two cases, the ceramic material here comes in progressive contact with hot tool steel counterface. The wear for the block-on-ring case is much lower than for the ball-on-flat because the initial line contact in the former case soon changes to a large area contact.

Among all the test configurations, the ball-on-flat arrangement exhibited the maximum alumina wear because of the highest contact pressure. Figure 4*a* shows the features on the worn alumina surface after 2 h of sliding. The surface is covered with grooving marks, is plastically deformed, and is also severely cracked. Some of these cracks and the fragmentation of material are shown at higher magnification in Fig. 4*b*. A very high contact pressure and the accompanying localized high temperature rise are obviously responsible for this. Because the

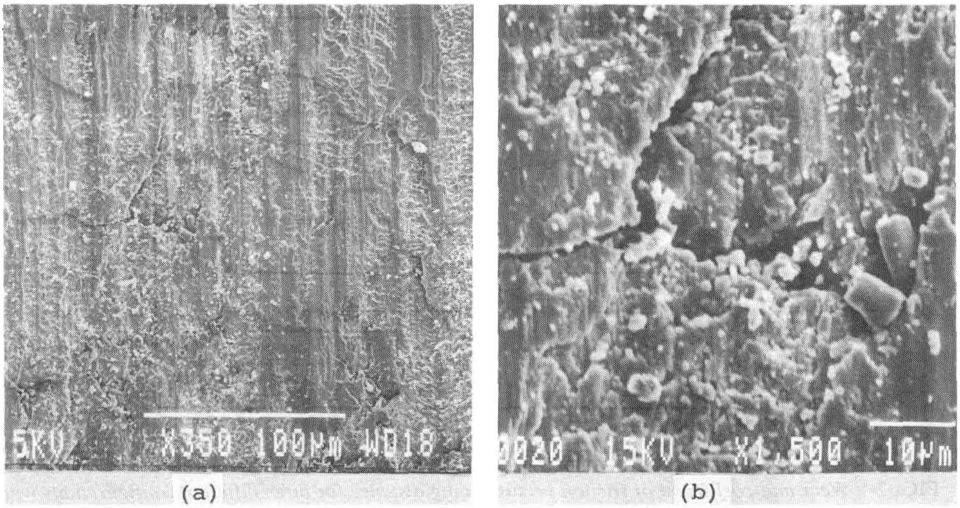

FIG. 4—(a) *Wear surface features on alumina ball in case of ball-on-flat configuration with alumina ball rubbing against tool steel flat,* (b) *magnified details of damage shown in* (a).

thermal conductivity of ceramics is extremely low, the localized temperature rise in these materials is much higher than in other materials and so they are prone to thermal cracking. Such cracking was not observed on the wear surfaces in other configurations.

A significant amount of plastic deformation was observed on the alumina surface worn in the washer-type setup (Fig. 5). This could have been caused by the high temperature prevailing at the interface because the alumina surface is always in progressive contact with the heated counterface. The flash temperature estimated for this condition was about 1800°C. Unlike the above case, in the block-on-ring, the pin-on-disk, and the reciprocating configurations the alumina surface always comes in contact with the incoming cool part of the

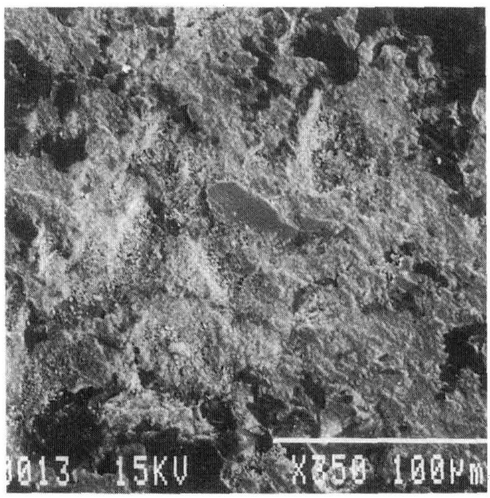

FIG. 5—*Wear surface features on alumina disk in the case of washer configuration with alumina disk rubbing against tool steel washer.*

counterface so that the temperature rise in the contact region is much lower. Consequently, a much lower plastic deformation on the wear surface is expected. This was indeed found to be the case for the pin-on-disk configuration (Fig. 6).

Alumina wear was measured at regular intervals, but it was not feasible to measure counterface wear in this manner. The wear of tool steel counterface was measured only at the end of the test. The counterface wear as measured at the end of sliding over a distance of 50.4 km is shown in Fig. 7. The wear of tool steel counterface was higher than that of alumina in all the cases because the hardness of alumina (1710 VHN) is much higher than the hardness of tool steel (600 VHN). Thus, alumina was capable of abrading the counterface as shown in Fig. 8. Among all the test configurations, the ball-on-flat arrangement exhibited

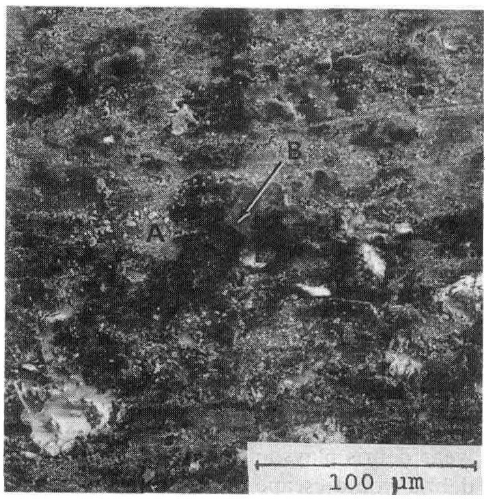

FIG. 6—*Wear surface features on alumina pin in the case of pin-on-disk configuration with alumina pin rubbing against tool steel disk.*

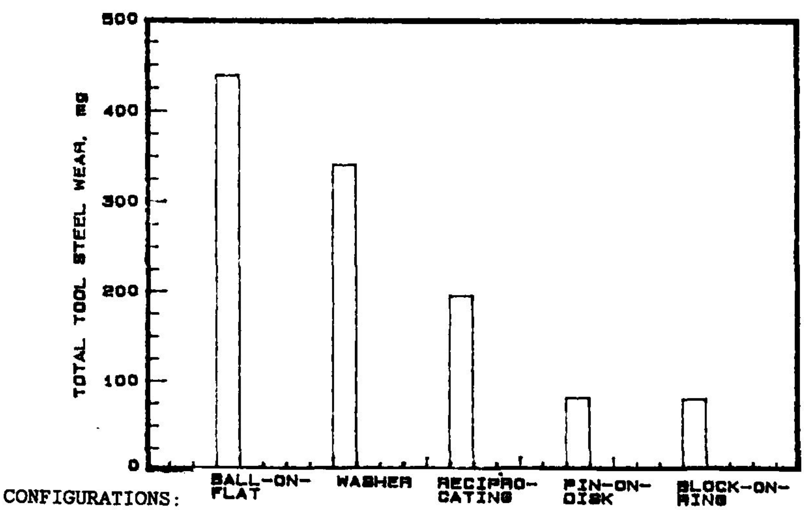

FIG. 7—*Total wear of tool steel counterface for different configurations in sliding over a distance of 50.4 km.*