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Ceramic Tribology: Assessment of Needs in Measurement Methods and Standards

C. S. Yust
S. M. Hsu
T. M. Levinson

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CERAMIC TRIBOLOGY: ASSESSMENT OF NEEDS IN MEASUREMENT METHODS AND STANDARDS

C. S. Yust, S. M. Hsu, and T. M. Levinson

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CONTENTS

ABSTRACT 1
EXECUTIVE SUMMARY 1
THE CURRENT STATE OF THE ART 2
WEAR TEST PROCEDURES AND THE FACTORS AFFECTING WEAR RESULTS . . . 2
PROS AND CONS OF STANDARDIZATION 4
STANDARDIZATION PROCESSES 6
INTRODUCTION 7
ECUT TRIBOLOGY PROGRAM AND WORKSHOP OBJECTIVE 8
OVERVIEW OF THE ECUT TRIBOLOGY PROGRAM 8
WORKSHOP OBJECTIVE 10
TECHNICAL SESSIONS 12
SESSION SUMMARIES 12
Current Test Systems 12
Relationship of Ceramic Wear Mechanisms and Testing 13
Wear Test Methodologies 13
The Role of Surfaces in Wear Testing 14
Sliding Wear Tests 14
Rolling Wear Tests 15
Prospects for Testing Standards 16
CURRENT TEST SYSTEMS 16
Presentation 16
Discussion 17
RELATIONSHIP OF CERAMIC WEAR MECHANISMS AND TESTING 19
Presentation 19
Discussion 21
WEAR TEST METHODOLOGIES 25
Presentation 25
THE ROLE OF SURFACES IN WEAR TESTING 27
Presentation 27
Discussion 28
SLIDING WEAR TESTS 32
Presentation 32
Discussion 32

ROLLING WEAR TESTS 36
Presentation 36
Discussion 38
PROSPECTS FOR TESTING STANDARDS 40
Presentation 40
Discussion 42
SUMMARY AND ADJOURNMENT 43
CONCLUSIONS AND RECOMMENDATIONS 44
ACKNOWLEDGMENTS 45
Appendix A. WORKSHOP PROGRAM 47
Appendix B. CURRENT WEAR TEST SYSTEMS 51
Appendix C. COMMENTS AND QUESTIONS TO STIMULATE DISCUSSION 57
Appendix D. COMPILATION OF FRICTION AND WEAR TESTS 63
Appendix E. LIST OF ATTENDEES, WORKSHOP ON TRIBOLOGICAL TEST DEVICES AND PROCEDURES FOR CERAMICS, APRIL 23–24, 1985 67

CERAMIC TRIBOLOGY: ASSESSMENT OF NEEDS IN MEASUREMENT METHODS AND STANDARDS*

C. S. Yust, S. M. Hsu,† and T. M. Levinson‡

ABSTRACT

This report is a summary of discussions held at the Workshop on Tribological Test Devices and Procedures for Ceramics, which was convened to review ceramic wear test practices and to assess the prospects for agreement on standardized wear test methods and test machines. The workshop was held within a framework of six presentations intended to focus the discussion on specific wear testing issues. Wide-ranging views on wear testing and standardized wear tests were expressed and are presented in this report. Both positive and negative aspects of wear test standardization were discussed. By the close of the discussion a consensus developed that recognized the need for and feasibility of standardized wear tests but that also recognized a continued necessity for the use of nonstandard tests and test systems for research on fundamental wear mechanisms. The nonstandard test arrangements, however, should be well defined and the test conditions closely controlled. The suggestion was made that a small group initiate efforts to prepare test procedures and standards for review by the wear community.

EXECUTIVE SUMMARY

Among the topics discussed during the Workshop on Tribological Test Devices and Procedures for Ceramics were the state of the wear testing art, wear test procedures, the pros and cons of standardization, and standardization processes.

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†National Bureau of Standards, Gaithersburg, Maryland.

‡Department of Energy, Conservation and Renewable Energy, Office of Energy Utilization Research, Washington, D.C.

There was a general consensus at the end of the workshop that standardization is desirable and is needed for ceramic tribology at this time. However, standardization should be in specific areas of application and not in basic research or mechanistic studies. More complete reporting procedures and control of test parameters are strongly encouraged to achieve meaningful measurements.

THE CURRENT STATE OF THE ART

There was general consensus that current wear testing procedures for ceramics and the results reported in the literature are not sufficiently well defined to allow data comparisons, and sometimes assessment of the significance of the reported data is difficult. Ceramics have high hardness, low thermal diffusivity, and low density; they behave differently from metals in traditional wear tests.

The attainment of satisfactory levels of repeatability and reproducibility of results with current wear test systems was considered to be a major challenge. Repeatability refers to the precision with which experimental results can be obtained on a given machine by a single operator. Reproducibility refers to the spread of results between laboratories trying to perform essentially the same test. The repeatability of some of the commercial test machines for well-defined metal systems was given as 30 to 40%. This spread in repeatability was seen as excessive by some, while others contended that real test results are often much worse. It was noted that repeatability and reproducibility were not determined by the type of machine but were related to maintenance of the machine and/or to human factors in the use of the machine. It was indicated that careful test set-up by experienced operators and proper attention to details could achieve repeatability of less than 10%. Field test results are often widely varied, as much as two or three orders of magnitude.

WEAR TEST PROCEDURES AND THE FACTORS AFFECTING WEAR RESULTS

The precision and significance of wear test results depend on the wear tester used, operating conditions, and test procedures. Many questions arose regarding specific aspects of the use of particular test machines. The effect on wear results of the continuous change in contact

area generally encountered in pin-on-disc tests was questioned, and several comments were made regarding possible alternate geometries for pin-on-disc tests. Most of the alternate arrangements also had significant disadvantages. It was suggested that pin-on-disc tests could be used to advantage if the contact area growth was limited to 7% or less. Flat-on-flat test configurations may alleviate the problem of variation of contact area, but they introduce temperature gradients, velocity gradients, and the probability of trapping debris in the interface. Debris retained in the sliding interface may agglomerate and/or deform, yielding debris particles that may be misleading with regard to wear mechanisms.

An important aspect of most of the test systems that might not have received adequate attention is the dynamic behavior of the system. The physical configuration of both the machine and the test samples can influence the inherent stiffness of a given system and determine the frequencies and form of resonant vibration modes. Data were presented which demonstrated that the dynamic response of the test system can dramatically influence wear test results. In general, wear test systems are not well characterized in this respect, primarily because of the limited appreciation of the problem. The dynamic effects can be especially acute with ceramics because of the high probability of forming roughened fracture surfaces at the test interface.

The significance of surfaces was emphasized during the discussion. Chemical and mechanical characterization before testing were found to be important. It was noted that mono-molecular levels of contaminants can alter the initial surface response of ceramics, and the humidity level of the test atmosphere can alter the wear process. Wear results were cited demonstrating that wear rate and wear mechanisms of ceramics can be greatly altered by the extent to which water vapor is present. A major conclusion of the discussion was the need to consistently report relative humidities with ceramic wear test results.

Mechanical aspects of surfaces are also significant. The surface topography should be characterized, including directional anisotropy of topographical features. Near-surface defects are critical, and surface residual stresses should be evaluated, particularly since such stresses may be either positive or negative with respect to surface behavior.

Ceramic surfaces will be chemically active, even at low temperature. Evidence of tribochemical effects at low temperature was reported, and

elevated-temperature application will certainly increase the potential for surface chemical effects. Ceramic wear test surfaces need to be well characterized before, during (if possible), and after testing.

Lack of knowledge of the influence these parameters could have on wear test results might lead to incorrect conclusions and data interpretation. Standardization to eliminate these problems therefore is desirable.

PROS AND CONS OF STANDARDIZATION

Throughout the workshop, the various pros and cons of wear standardization were expressed. Much of the initial discussion centered around the lack of appropriate definitions and a concept of standardization as one single test for all applications. By the close of the workshop, a much wider consensus for standardization was evident, as it became clear that some degree of uniformity was desirable and necessary, that a series of standardized tests would be required, and that those tests would not replace more individualized tests for research needs.

A range of views was offered regarding the feasibility of standardized wear tests. On one hand, it was stated that standardized tests to improve communication among researchers was a distant goal. Standard wear tests tended to emphasize one wear mechanism, thereby departing from reality in which multiple mechanisms were active. A concern was also expressed that a standardized test will not provide sufficient information to permit effective assessment of the value of a material as a working component. A comment was made that it was more important to identify and develop novel concepts for improved tribological performance of ceramics than to standardize testing. An example cited of such a possibility was the concept of adjusting surface residual stress levels. A major concern was that an excessive reliance on standardized tests might have a negative effect on innovative thinking, or that too much time and effort might be expended on standardization efforts at the expense of innovation. The point was also made that some caution should be observed in setting requirements for acceptable wear testing. If the requirements become too onerous, progress will be inhibited rather than enhanced.

On the other hand, a significant number of participants subscribed to the view that standard tests are not only possible but needed, and they

pointed to the experience of standard tests effectively already in existence for metals. Some standard tests might require only slight modification to account for the unique characteristics of ceramics. There would not and should not be a single standard test, but rather many such tests. There was broad agreement that whatever standard tests were adopted would have to be related to a specific application problem. Standard tests in existence for metals evolved from the effort to solve specific wear problems, and ceramic wear tests will likewise be applications related. There was general agreement that standardized test procedures would be valuable and could aid in achieving more uniform characterization of test and material parameters. Additional test devices per se are not required; the five or six common geometries in use are sufficient.

The difference between applications-oriented testing and basic research testing was discussed. It was noted that a hierarchy of test types exists, ranging from fundamental studies such as bench tests and culminating in full-system tests. The degree of reality of the test increases as the system test is approached, although the degree of mechanistic knowledge correspondingly decreases. The applications-oriented tests should be specifically related to a particular system. Bench test configurations and conditions should be determined to reproduce the wear process observed in the practical case under study. It is important to determine that the operative wear mechanism in the test used is the same as that of the real system of concern. The selection of the test system and test conditions should be determined by the ability to reproduce the material damage under study. Once these factors are identified, standardization of test procedures with the participation of researchers from industrial, academic and laboratory backgrounds would accelerate materials development and innovation.

Basic research tests are concerned with detailed analysis of a tribosystem behavior under well-defined and closely controlled test conditions. The general view was that such tests should be well characterized and minimum standards for information might be prescribed, yet test geometries should not be fixed. It was noted that while better reporting of results

and test methods should be sought, the scientist doing basic research should be "left to his/her own devices." However, utilization of a standard data reporting form such as that described in the West German Standard DIN 50320 would be helpful.

STANDARDIZATION PROCESSES

The suggestion was made at several points that a small group, possibly U.S. Department of Energy (DOE) contractor personnel, should make an effort to prepare wear test procedures and standards for review by the wear community. It was noted that the American Society for Testing and Materials (ASTM) committee G-2 is already engaged in such efforts and would welcome additional participants. A view was offered that the G-2 process is too slow and that something should be done in the 6 months following this meeting.

The question of the availability of standard reference materials for wear test system evaluation arose several times during the discussion. Private internal reference materials exist to a greater extent than is realized, and these materials are qualified to have certain properties with respect to a specific test. Standard materials and tests must go together. While some standard materials for metals exist, there is a strong need for publicly available standard ceramic reference materials. It was suggested that something should be done quickly to provide such materials.

A consensus was reached that a task group be formed to examine these issues and to initiate actions that will lead to voluntary standardization on prioritized topics.

Suggestions were made that wear test data could be usefully assembled in a data bank and classified with respect to the manner in which the data were obtained. Other suggestions indicated the desirability of providing research data in a manner comprehensible to designers and in a manner that provides an overall view of the information available, and of the major areas in which data are not available. The development of a tribological data base to satisfy these needs is presently under study by the Energy Conversion and Utilization Technology (ECUT) Tribology Program.

INTRODUCTION

The tribological characteristics of ceramics have received increasing attention in recent years. Advanced ceramics are corrosion resistant and strong at elevated temperatures and, consequently, are receiving serious consideration for applications such as advanced heat engines, high-speed bearings, wear parts, and cutting tools. The friction and wear characteristics of this new class of material are very important criteria for many of these applications.

Advanced heat engine concepts have the potential to achieve significant energy savings and thereby preserve valuable natural resources. Ceramics are very attractive material candidates for use in the new heat engine designs. Although many studies have been performed in the past several years to determine the friction and wear properties of various ceramics, much of the reported data is contradictory and generalization of the results has been difficult.

The ECUT Division of DOE recognized through its Tribology Program activities the need to address the technical issues in test procedures and possible test standardization. The Oak Ridge National Laboratory (ORNL) and the National Bureau of Standards (NBS), both under contract to DOE, cosponsored an invited workshop to examine and discuss the state of the art in ceramic wear measurement. Attendees included materials scientists, tribologists, mechanical engineers, physicists, chemists, and chemical engineers from government laboratories, industries, and universities. The workshop was held on April 23 and 24, 1985, at Arlington Heights, Illinois. It was co-chaired by Mr. Charles Yust from ORNL and Dr. Stephen Hsu from NBS.

This report is the result of two days of deliberation. The program was divided into specific technical sessions. However, in the course of discussion some topics emerged in several sessions, and the comments on a single subject should be interpreted within the context of the total proceedings. The workshop proceedings were recorded on audio and video tapes, from which this report was prepared. In order to provide a useful, readable summary, both the formal presentations and the open discussion have been summarized. Every effort has been made to retain the sense of the original remarks.

The executive summary was derived from the discussions of the entire meeting. The individual session summaries include invited presentations and the subsequent discussions. The persons who made comments are identified at the close of each comment. The persons who attended the workshop are listed with their affiliations in Appendix E.

Most of the figures used during the presentation have been omitted for brevity.

A complete review of the discussion indicates that a general consensus exists with respect to several conclusions and recommendations.

In a workshop of this type, it is not possible to cover all areas and all aspects of the issues relating to ceramic wear testing. We hope that this report will catalyze further discussions and thoughts on the subject, and we welcome input from all interested parties to further the cause of this very important area.

ECUT TRIBOLOGY PROGRAM AND WORKSHOP OBJECTIVE

OVERVIEW OF THE ECUT TRIBOLOGY PROGRAM

The ECUT Program supports generic, long-term, high-risk-directed research and exploratory development, which private enterprise will not or cannot pursue, in conservation technologies for energy conversion and utilization. The program supports researchers in industry, academia, and government to explore ideas or concepts aimed at specific applications. Research is conducted to a stage where private industry or other government programs might carry it into more advanced technology and engineering development. Its goals are to (1) establish feasibility of revolutionary concepts that significantly reduce energy consumption, (2) carry out exploratory development on novel or innovative conservation concepts, (3) evaluate new concepts for improved efficiency or alternative dual use in energy conversion and utilization, and (4) expand the technology base necessary for development of improvements in energy conversion and utilization. The program attempts to be a bridge between basic research and large-scale technology and engineering development in the areas of energy conversion and utilization.

The mission of the ECUT Tribology Program is to provide the base technology to achieve savings, as much as practical, of the United States' annual energy consumption through major tribological advances. This may be achieved through direct energy savings (e.g., reduction of friction), savings in embodied energy (e.g., reduction of wear), savings in critical material (e.g., reduction of wear), improvements in productivity, or advanced system designs where tribology is the critical limiting technology. The introduction of advanced system designs may require tribological systems that have to operate in severe environments such as high temperature, high speed, high loads, corrosive gases/liquids, and combinations thereof. New technologies for these more rigorous environments will also be developed. The program will establish close ties with U.S. industry and universities to determine current and future needs for advances of tribological systems, and to facilitate the transfer of the new technology developed in this program.

The ECUT Tribology Project was initiated in 1982 and was elevated to program status in 1983. Initially the program was managed by Dr. J. J. Eberhardt of DOE and Dr. J. A. Carpenter of ORNL. Currently the program is managed by Ms. T. M. Levinson (DOE) and Dr. M. Kaminsky (Argonne National Laboratory). The program was structured in four major work elements:

1. Mechanisms,
2. Design,
3. Assessments and Initiatives, and
4. Project direction.

Technical projects under each element were structured, and in 1985 a comprehensive program plan was developed as the program expanded to address many technical barriers imposed by the lack of tribological advances.

According to the current program plan, the work element titled *mechanisms* has the following major thrusts: (1) develop novel tribomaterials by design; (2) explore advanced lubrication concepts; (3) study tribomaterial interactions and develop processes for their control; (4) characterize and test tribomaterials/components; (5) develop diagnostic techniques and devices for monitoring the performance of

tribocomponents/systems/assemblies; and (6) develop models for (a) friction and wear of tribomaterials, (b) surface modification/coating processes, (c) advanced lubricant application processes, and (d) tribomaterial interaction processes.

The work element *design* has the following thrusts: (1) develop tribological design data collection and dissemination systems (e.g., data center); (2) develop tribocomponent design models; (3) develop tribosystem design models; (4) develop codes/models for failure prediction of tribocomponents, systems, and assemblies; (5) develop codes/models for failure reduction in tribocomponents, systems, and assemblies; and (6) develop and demonstrate the proof of concept of automated "expert systems" that will take corrective actions to overcome malfunctions of tribocomponents/systems/assemblies.

The work element *assessments and initiatives* serves to identify through assessments and to explore through limited experimentation those innovative ideas that promise to yield significant energy savings through the design of advanced tribological components/systems/assemblies and through improvement of their operating procedures/conditions.

The work element *project direction* deals with the planning and management activities of the Tribology Program. Working panels with participants from U.S. industry, universities, and government laboratories were set up during FY 1985 to help in the preparation of a more detailed research and development (R&D) program plan for the ECUT Tribology Program.

WORKSHOP OBJECTIVE

The objective of the Workshop of Tribological Test Devices and Procedures for Ceramics was to generate ideas on how to provide an effective standardization of wear testing. The standardization effort is an important part of the total ECUT Tribology Program.

The ECUT Program fills the gap between basic research and the end-use sector by taking concepts arising from the basic studies and developing those concepts into methods and/or devices for practical use (Fig. 1). The ECUT interaction with industry serves to highlight those subjects for which research is required.

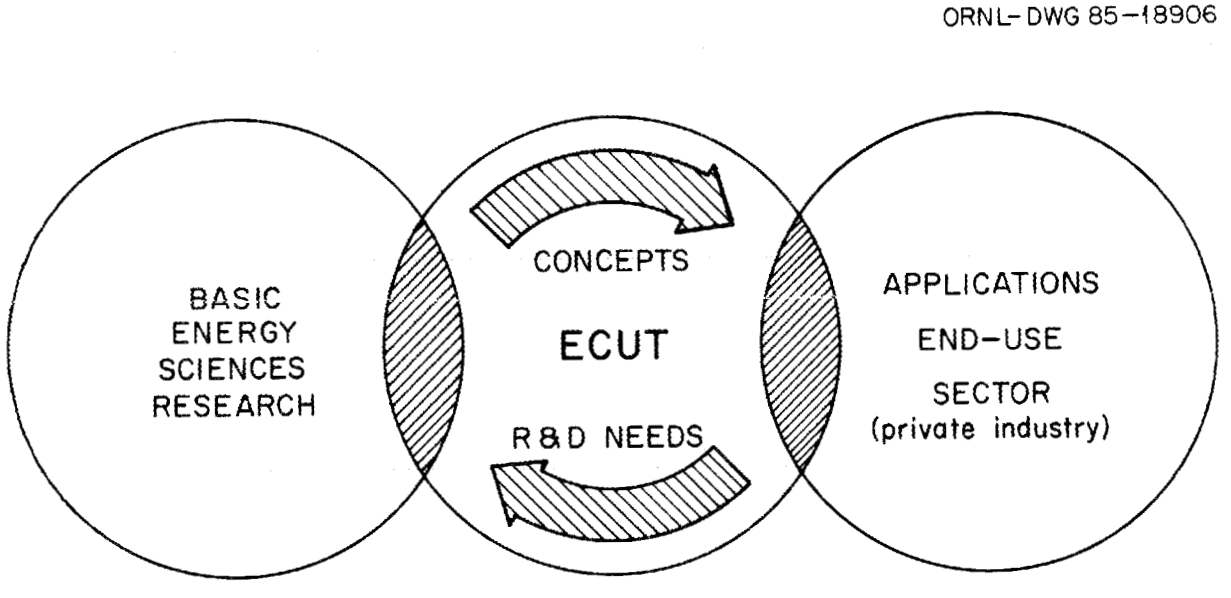

Fig. 1. Research and development system diagram illustrating how ECUT Program transfers technology.

The ECUT Tribology Program utilizes the cooperative efforts of universities and research institutes, governmental agencies, professional societies, and industries; ECUT serves as an intermediary, facilitating the interactions among these groups. The industrial participation is especially important because we are concerned with solving real-world problems.

This workshop was clearly in accord with the long-range objective of establishing meaningful, standardized, laboratory-scale tribological tests and procedures for ceramics. That is an important area in which the government has a definite role.

TECHNICAL SESSIONS

SESSION SUMMARIES

Current Test Systems

The opening presentation by L. R. Heerdt, Falex Corporation, was a discussion of currently available commercial wear test machines. Many machine types were described, including most of the types in general use. The two most commonly used test systems are the pin-on-V-block and the block-on-ring configurations. Commercial machines were cited as offering the advantages of simplicity of operation, use of standard specimens, economy of purchase and operation, and the possibility of the establishment of repeatability and reproducibility standards.

The group discussion considered data variation and whether commercial machines were more accurate or more effective test systems than individually constructed laboratory devices. Inaccuracies in wear data may be due to factors other than the machine itself. A problem with noncommercial systems is the lack of dynamic characterization and lack of recognition of system-related wear effects. The point was made that wear is not a fundamental materials parameter but a consequence of the action of a given system. Successful correlation of laboratory results with field results therefore depends on effective simulation of the real system.

A significant part of the discussion also considered the geometric arrangement of wear test systems. In some arrangements the contact

area varies with time, resulting in stress variation at the interface, while geometries offering constant apparent contact area tend to retain wear debris at the interface.

Relationship of Ceramic Wear Mechanisms and Testing

W. A. Glaeser of Battelle Columbus Laboratories summarized the state of knowledge of wear mechanisms in metals and compared wear damage observed in metals with that observed in ceramics.

Machined metal has a heavily sheared surface layer, but a comparably machined ceramic contains numerous fractures. Ceramics are capable of some plastic deformation, however, as in rolling contact. Metals commonly transfer material between sliding (unlubricated) surfaces, forming a mechanically alloyed interfacial layer. It is not yet clear whether ceramics form a comparable mixed layer. Surface chemical reactions may also play an important role in ceramic wear. A particular feature of ceramic wear is the onset of fracture above a critical load level.

The group discussion considered several factors of importance to wear testing. The desirability of using varied test machines, rather than only one, was noted, as was the need to evaluate the dynamic response of the test system. Several comments were made on the nature of standard wear tests. It was observed that tests are often selected to enhance a particular mechanism, at the expense of reality. The issue of correlation was also raised, exposing a lack of agreement on the appropriate means of demonstrating correlation.

The point was made that it is important to discuss test systems in the context of intended use and application. Most test system consensus derives from efforts to solve a particular problem.

Wear Test Methodologies

A special discussion of wear testing was offered by Dr. H. Czichos of BAM, Berlin. His talk touched on three points: basic parameters relevant to wear testing; the influence of some of the basic parameters, especially the geometric factors, on wear test results; and a review of suggested approaches to wear testing.

The Role of Surfaces in Wear Testing

T. E. Fischer, Exxon Research and Engineering Company, presented research results on silicon nitride illustrating the significance of surface effects on wear behavior. The presence of water vapor was shown to strongly affect the mode and rate of wear of silicon nitride and of zirconium oxide. The effect of moisture can be complex, as illustrated by the diminished wear rate of silicon nitride in high humidity and the increased wear rate of zirconium oxide under the same conditions.

Water vapor also reacts tribochemically with silicon nitride, forming a surface reaction layer of silicon oxide. Other surface chemical reactions with atomic species in the environment may take place; consequently, chemical evaluation of wear surfaces is important. Several tools are available for this task including Auger analysis, SIMS, EDAX, and infrared and Raman spectroscopy.

The group discussion opened with the presentation of further data confirming the chemical activity at tribological interfaces. The significance of only a monolayer of surface contamination was demonstrated. It was also noted that surface modification techniques could be used to develop the desired wear characteristics at a surface.

An effort was made to differentiate between testing for fundamental wear studies and testing for applied problems. The view was expressed that a major difference is that applied tests should use actual components, where possible, and be conducted in a system that closely simulates the application, while basic tests should concentrate on materials response.

It was suggested that standard materials might be used to correlate wear equipment and results. The Versailles Project on Advanced Materials and Standards, an international effort, is attempting to do this.

Sliding Wear Tests

The presentation on sliding wear tests was made by K. F. DuFrane, Battelle Columbus Laboratories. Three types of wear test objectives can be recognized: materials selection for a specific application, wear resistance evaluation, and basic research. The first two categories require extensive engineering judgement in test set-up and evaluation, and they are not likely to be amenable to standard procedures. Some

level of standardization may be achievable in basic research testing (for example, agreement on test element dimensions and documentation of test procedures).

The issue of test standardization was directly addressed in this discussion. Standard tests are considered to be most likely for generic applications, such as piston rings and cylinder liners. It was suggested that standard wear test procedures and standard nomenclature are desirable. Data may also be stored and classified according to the type of source. Availability of standard reference materials for baseline tests was cited as a current need. Classes of tests and end uses might be defined and a matrix of tests and uses formed; tests might then be developed for subsets of the matrix. The predominant feeling was that standard tests would only develop for specific types of systems, rather than as general wear tests. Test procedures and characterization schemes may contribute to improved test documentation.

Rolling Wear Tests

L. D. Wedeven, SKF Industries, made the opening presentation on rolling wear tests. He described the engineer's view of stress distributions in rolling bearings in detail and illustrated the relationship of these stresses to failure modes. The stresses can be viewed on both a macro and a micro scale. The degree to which wear test standardization may be possible varies with the type and scale of the wear phenomenon. For surface macro-stress phenomena, some standardization of testing for surface cracking may be feasible. At the micro-scale contacts, i.e., asperities, the inability to define the contact conditions makes this area unsuitable for standardization. For rolling-contact fatigue, the possibility of providing standard tests is very real. A very important need is a scientific basis for innovation. Standards should not be imposed at the expense of innovation.

During the ensuing discussion it was noted that tests and procedures will be helpful in providing a data base of assured quality. It was suggested that the available data be organized in such a way that the information is readily available and the gaps in the data readily recognized. It was indicated that efforts by the DOE/ECUT Program are under way to provide a tribological data base.

Improved characterization of all elements of wear test systems is desirable. It was suggested that a small group undertake the preparation of test standards.

Prospects for Testing Standards

A. W. Ruff, National Bureau of Standards, made a presentation summarizing the possibilities for wear test standardization. The varied use of test devices makes generalized standardization difficult. Tribological standardization should be related to particular applications. The most likely ceramic applications should be assessed and standards prepared as required for those applications. A number of standard wear tests are presently in use, primarily for metals testing. Some tests exist for ceramics. Other metals tests can be readily modified.

Data variability can be controlled and is lower among experienced testers using a standard test. Factors that will improve tribological data include a standard data format, improved characterization methods, a well documented data base, and improved test methods.

It was noted that some caution should be exercised in setting wear test requirements. Excessive demands on research testing will inhibit the production of results. Among suggestions offered for improved wear testing were more complete reporting of results through better test procedures, use of existing test machines, and use of standard reference samples. It was reiterated that a small group should be convened to prepare standards for consideration by the wear community.

CURRENT TEST SYSTEMS (L. R. Heerdt, Falex Corporation, Aurora, Illinois)

Presentation

In his introductory presentation, Mr. Heerdt outlined the types of machines produced by Falex Corporation. He discussed the pin-on-V-block and block-on-ring tests in some detail and referred briefly to several others, including the four-ball tester, the multispecimen tester, the dry-sand tester, a ball-on-flat system produced in Germany and capable of temperatures of 1000°C, and a high-frequency tester made in England. Advantages of commercial machines cited were simplicity of operation, the use of standard specimens, economy of purchase and operation, and the possibility of establishment of repeatability and reproducibility

standards. The current development of computer programmed control and data acquisition for commercial machines was also mentioned. Test results for commercial test machines vary by 30 to 40%. There are various reasons for this spread of results, including the actions of the operator. While the test system should provide a good correlation with field results, the use of these machines requires a certain level of skill.

Although the American Society of Lubrication Engineers (ASLE) compendium of wear test machines lists about 300 devices, only about 10 types of machines are in general use. The most commonly used system is the pin-on-V-block. This system provides four line contacts by loading two V-blocks against a rotating pin. Approximately 1100 of these machines have been built by Falex in the past 50 years. They are often used to evaluate coatings, with an increase in friction being used as the criterion of failure. This type of test has shown good field correlation. Used in oil testing procedures, the device has given rankings of the oil in agreement with field tests.

The next most common system in use is the block-on-ring tester. Approximately 330 of these machines have been produced since they became commercial items about 1960. This system has a greater capability in speed, load range, and temperature than the pin-on-block tester. It may be used for line or area contact, in a linear or a reciprocating mode. Under automatic control, the load can be cycled during the test.

For any of the test systems used, it was noted that a full wear curve should be developed, not just a single determination of the total wear.

Discussion

The discussion opened with a challenge of the idea of using commercial test machines because the admitted spread in data is 30 to 40%, which is quite large. While laboratory-to-laboratory comparisons are better with the use of seemingly identical (i.e., commercial) machines, does the admitted data spread warrant the large investment as compared with use of a home-built device? Furthermore, many persons do not consider commercial machines suitable for basic research (J. Wert). The block-on-ring commercial system is used repeatedly for basic research.

At present, almost all wear data has a 30 to 40% spread, regardless of the machine origin. Commercial machines are no worse, probably better than home-built machines. Inaccuracies are not due only to the machines; poor specimens, poorly maintained machines, or operator errors may contribute to the problem (L. Heerdt). Test machines will not differentiate the type of failure (J. Wert). The machine only reports what happens during the test; the specimen needs to be examined to assess the type of failure (L. Heerdt). Home-built machines are frequently not well characterized, especially with regard to stiffness and vibration characteristics; many home machine builders are not aware of the problems associated with machines. Repeatability, it should be noted, refers to the comparison of successive results in the same laboratory with the same operator. Reproducibility refers to the comparison of results between different laboratories (S. Hsu).

A second point noted is that wear is not a fundamental materials parameter. If it were, then identical results should be obtained on different machines (J. Wert). But tribological pairs have certain characteristics, which include their topography, materials properties, and environment as well as kinematic and solid-mechanics interactions. These parameters are hard to duplicate in a test system (N. Hakim). Wear is the consequence of the system, not a single intrinsic material parameter (S. Hsu).

It was well recognized during the discussion that successful correlations between laboratory and field depend on good simulation of the system to be studied. The key question is how well test systems correspond to real systems (S. Hsu). The test machine should always be selected to model the service condition as well as possible (T. Fischer). Test systems will have to correlate quantitatively with field systems before they replace real component testing (N. Hakim).

But a point of major concern was that of test geometry. This point arose through a question on the effect of a continuously changing pin tip area on test results for pin-on-disc testing (A. Levy). Pin-on-disc tests are poor, but people want them (L. Heerdt). It was suggested that the pin area can be kept constant by using a right cylinder configuration (H. Hawthorne). But it was noted that, even with right cylinders or thrust washer tests, a run-in period was required to obtain a

true alignment (J. Wert). Using a thrust washer, one has to be concerned about debris retention on the wear surface (H. Hawthorne). Grooves in the washer face can help remove debris from a washer test (J. Wert). The pin-on-disc test is all right if it is used properly. It provides an accurate measure of the wear but must be limited in area growth to about 7% increase (G. Tennenhouse). It is necessary to be careful about debris origins. A block-on-ring test may produce extrusions from the exit zone of the block if the block is soft with respect to the ring. The extruded material has a platelike form, unlike any debris observed at the wear interface. There is a need to be concerned about such effects in a standard test (W. Glaeser). A reciprocating flat-on-flat machine offers good repeatability of results, but all parameters must be controlled (V. Aronov).

A further point was raised concerning the use of statistically designed experiments that include quantitative indication of precision limits of the data. Single-point tests are inadequate (N. Hakim). It was also noted that a need exists for a test system that will measure oil film thickness during tests (M. Covitch). Finally, it was noted that, in technological pursuits, it is almost a natural law that progress is promoted by the user rather than by the provider of the technology. It is necessary that researchers seek improved test machine designs (T. Fischer). Falex will build what industry requires (L. Heerdt).

Regarding the economy of the purchase of a commercial test machine, it was noted in closing that the millions of dollars associated with wear- and energy-related problems certainly warrant the expenditure of thousands for good wear test equipment (L. Heerdt).

RELATIONSHIP OF CERAMIC WEAR MECHANISMS AND TESTING (W. A. Glaeser, Battelle Columbus Laboratories, Columbus, Ohio)

Presentation

Mr. Glaeser summarized the state of knowledge of wear mechanisms in metals and compared the observations in metals with those obtained to date in ceramics. Some speculations were offered on what might be anticipated in ceramic wear, and some indications were made of how wear

mechanisms relate to the design of wear test machines. Mr. Glaeser emphasized that devising a wear test machine without a knowledge of the wear mechanism is "operating in the blind."

Examples of wear damage effects in both metals and ceramics were reviewed. While the machining of metals leaves a heavily sheared surface layer containing continuous grooves, a comparably machined ceramic surface commonly contains fractured pull-out regions and microfractures. Some plastic deformation of ceramic surfaces is observed, as in early stages of rolling contact. Subsurface dislocation networks may form; an example was shown of such a network in MgO, which, while similar to that in a metal, was composed of large cells with less tightly knit dislocation walls. Metals commonly transfer material between sliding (unlubricated) surfaces, ultimately forming a mechanically alloyed interfacial layer containing very fine grains. Although some transfer layers have been reported in ceramics, it is not yet known if a process comparable to that in metals, which forms a mechanical mixture of the sliding constituents, is operating.

Further ceramic wear observations illustrated the potential for surface reaction, plastic deformation, and thermal effects. A surface of SiC subject to sliding at high temperature was found to have a glassy oxide phase at the surface. The consequence of limited slip systems in MgO was shown to be fracture induced by dislocation pile-up. Thermal shock was also found to yield a finely cracked surface, which rapidly degrades under further mechanical stressing.

The onset of fracture in ceramics was discussed in terms of a critical load required to initiate cracks. At loads lower than the critical level, plastic deformation accompanies scratching rather than fracture. This was illustrated by the example of a ball pressed onto a ceramic surface and was extended to sliding contact by illustrating the moving asperity as a translating ball contact point. Factors that influence the critical load value were noted to be friction force, fracture toughness, hardness, and microstructural features such as grain size. Velocity and consequent heating effects can also influence the critical load effects, particularly through the onset of thermomechanical instability, the process in which asperities are heated and subsequently spall off because of thermal shock.

Finally, creep was considered as a possible response to imposed stress. In addition to a general surface deformation, creep might lead to void formation on grain boundaries and subsequent fracture along those boundaries. A tabulation was presented to summarize the varied anticipated wear mechanisms and the test system parameters related to those mechanisms (Table 1).

Discussion

Four needs in wear testing were cited at the outset of the discussion: (1) reproducibility by unskilled test performers; (2) correlation with practical applications, which requires skilled participants; (3) differentiation in testing of lubricants and materials; and (4) research needs, a principal one being the need to use varied machines in research because intermachine correlation is poor. There is a long way to go in obtaining standard wear testers to facilitate communication with one another (K. Ludema).

The significant factors that must be considered in designing a wear test device were discussed. They include initial surface condition for sample and counterface, type of surface contact, type of relative motion, length of run, contact stress, and relative sliding velocity. The properties of the test materials and the effects of the environment are also critical. Wear is complex — there are no shortcuts to proper test design (S. Rice).

The importance of the dynamic response of the test system was noted, and data were presented illustrating the large effects that can be attributed to system stiffness. Change in the length-to-diameter ratio of the test pin can result in dramatic changes in the wear result. All too often apparatus-specific effects are not reported, possibly because they are not sufficiently recognized as a problem (S. Rice). It was also noted that wear rate and friction coefficient numbers are given frequently without sufficient background; it is difficult to comprehend their meaning (L. Heerdt).

The question of the adequacy of current ceramic wear test systems for wear evaluation was raised (S. Hsu). An answer given was that the question is premature — first the mechanisms must be understood to see

Table 1. Ceramic wear mechanisms and tester design

Wear mechanism[a]	Mechanism effect[a]	Significance of material properties[a]	Tester parameters
Lateral fracture $p^* = \left(\frac{K_c^a}{H^b}\right)(E/H^c)$	Above threshold load Wear changes mode Wear rate jumps	Grain size of same material influences depth of fracture Surface cracks influence threshold p^*	Contact geometry (state of stress) Area of contact
TMI $V^* = \frac{K\rho c J^2}{(\mu\alpha E)^2}$	Above threshold velocity Microfracture Local high-temperature effects	Thermal properties of specimen influence TMI	Maximum sliding velocity (specimen diameter, wear acceleration)
Thermal shock $W = \frac{\mu p^c}{R^a D^b}$	Above ΔT^* wear mode becomes fracture and wear rate jumps	Thermal properties influence ΔT^*	Heat transfer characteristics Quenching mechanisms
Creep: plastic flow $\epsilon = A(\sigma/E)^n \exp(-Q/RT)$	Above 0.6 T_m; creep void formation and void growth	Grain boundary chemistry influences. Ashby deformation mechanism maps should be consulted	Maximum Hertz shear stress Operating temperature Length of time at laod Extent of load reversal
Transfer	Contact geometry will influence concentration and compaction of debris	Compatibility, diffusion, and solution of materials in contact	Debris trapping geometry?
Decomposition	Localized heating during rubbing contact leads to surface chemical reactions, diffusion, and solution between contacting species	Oxidation (Si, Si_3N_4, etc.) Oxidation rate Glassy surface phase	Gaseous environment Shear stress Length of dwell under load

[a]Symbols:

p^* = Critical load for lateral fractures
V^* = Critical velocity for thermal instability
ΔT^* = Critical temperature drop to cause fracture
T_m = Melting point, absolute
W = Wear rate
μ = Coefficient of friction
E = Young's modulus
H = Hardness
K_c = Fracture toughness
R = Thermal stress resistance
D = $K/\rho c$; ρc = heat capacity per unit volume
Q = Activation energy
TMI = Thermal mechanical instability
K = Thermal conductivity
α = Thermal expansion coefficient
J = Mechanical equivalent of heat
ρ = Density
c = Heat capacity

how they affect parameters to be designed into the machines (W. Glaeser). Enumerating the factors that must be taken into account in designing a test or a test machine is only defining those factors that must be well characterized (standardized) in a given test (C. Yust). Standardization is an effort to reduce the system to a manageable size, but standardization is only valid for a short time for a particular problem — never for a total field (T. Fischer). By keeping some factors constant we seek to identify the rate-controlling mechanisms; we also want to define operative parameters, even if we cannot control them (G. Tennenhouse). The worst thing about a wear test is to have an uncontrolled test — no one should get the idea that standardization means one test at one condition (S. Hsu). In this discussion of standardization, we need to consider people in industry who need immediate answers of the type "A is better than B which is better than C," and not just people doing research on mechanisms (L. Heerdt).

Further questions were raised about the significance and/or validity of standardized tests. What do we want to standardize? First, the purpose of the tests should be established (J. Wert). It was also noted that the use of the tests will influence the selection of the operating parameters (W. Glaeser). Furthermore, all too often tests are selected to enhance the mechanism being studied, thereby departing from reality (K. Ludema). As we get into developing wear tests, we will have to simulate contacting conditions, test environments, and so on (S. Rice).

The issue of correlation of results, among test machines as well as between bench test and field tests, arose again in this discussion period. What is correlation? Working with the Archard equation and data from several machines, one finds a range of values for the exponential factors (K. Ludema). In response it was noted that correlation is not exponents in equations but a ranking of material performance that will correspond to field experience (L. Heerdt). The test conditions that reproduce field rank orderings have to be found empirically. A procedure of increasing interest is that of producing the same wear debris and the same surface damage in a laboratory test as in field service, thereby providing the test that simulates field service. This approach was recommended (K. Ludema).

It was noted that a 30% variation in results was really very good — many tests should be run to improve data (F. Carignan). Control of surfaces, flatness, and alignment was cited as a means of reducing data spread (J. Bierlein). A question was raised about the extent to which wear models incorporating known brittle fracture modes had been tested (I. Singer). A recent literature survey suggests that little has been done on model evaluation in the past five years (W. Glaeser).

Relatively little time during the discussion was devoted to the issue of wear mechanisms. An answer to the question "What is a wear mechanism?" was sought; it was noted that a transition from mild wear to structural failure had been presented (N. Hakim). Additionally, mild wear relates to plastic deformation as opposed to fracture processes (in the severe regime) (W. Glaeser). [A response to Hakim's question was offered in writing by O. Vingsbo after the meeting and appears at the end of this subsection.] The simulation of a tool bit mechanism by a pin-on-disc test was mentioned (G. Tennenhouse). The mechanism was determined to be that of diffusion of an element to the surface at which chemical reaction produced a liquid reaction layer. Removal of the liquid layer, the rate-determining step, could be duplicated in the pin-on-disc test.

Finally, it was mentioned that it is important to put discussion of a test system into the context of intended uses and applications. Most efforts toward mechanical system consensus derive from a specific problem. What problem applications are we concerned with (A. Ruff)? The question was not answered in this session.

Response by O. Vingsbo, University of Houston, to question by N. Hakim ("What is a wear mechanism?"):

"There is consensus today that wear is defined as the loss of material from a tribo surface. Based on this definition a wear mechanism is then defined as a microevent, by which wear takes place. Consequently, the basic element of a wear mechanism must be some kind of surface fracture. It has been suggested that only a small number of such surface fracture machanisms — tribofracture mechanisms — are sufficient for a good description of wear. For example, at the ASM Materials Science Seminar in Pittsburgh in October 1980, four tribofracture mechanisms were discussed for the case of metals: shear fracture

of adhesive joints, microcutting, impact cracking, and cracking due to surface fatigue. This list can be modified and extended but can always be kept very short.

"On the contrary, a practically unlimited number of interactive phenomena (plastic deformation, corrosion diffusion, etc.) can be identified. Those mechanisms are, however, not exclusively characteristic of friction and wear situations, but, together with the relevant tribofracture mechanisms, they can be useful for describing the tribo system in question.

"In ceramic materials fracture is essentially brittle, and another handful of tribofracture mechanisms must be considered, such as intragranular or intergranular cracking, parallel or perpendicular cracks, etc. The list will, however, still be short. Likewise, the interactive phenomena will be dominated by non-plastic mechanisms, e.g., phase transformations."

WEAR TEST METHODOLOGIES (H. Czichos, Bundesanstalt für Materialprüfung, Berlin, FRG)

Presentation

A special discussion of wear testing offered by Dr. Czichos touched on three points: (1) basic parameters relevant to wear testing; (2) the influence of some of the basic parameters, especially the geometric factors, on wear test results; and (3) a review of suggested approaches to wear testing.

The wear characteristic of a material may be contrasted with the several properties of a material. Strength, for example, can be understood and characterized as a material property. Wear resistance, however, depends on the materials in contact, the load, the motion, and other aspects of the test system. Wear is, therefore, a characteristic of a given system rather than a bulk characteristic of a material. The system can be viewed as having four elements: the two partners in contact, the interfacial material, if any, and the environment. These elements represent the system structure.

The physical operating variables, such as load, velocity, etc., that act on the system structure represent a second set of influential

parameters. A third set of parameters includes the friction force, friction coefficient, noise, vibrations, temperature, wear rate, and the contact conditions. Instrumentation presently available allows the determination of these operating variables and of the resultant data, although temperature may be a special problem.

An effort was made in 30 European laboratories in the 1960s to do comparative tests on copper and iron. The tests were pin-on-disc tests performed under an agreed set of conditions, with materials that originated in the same master batch. The wear results, however, differed significantly, one case yielding adhesion and transfer of copper from the pin to the ring, another resulting in the oxidation and formation of a protective reaction layer. These results indicate the need to have a well-considered test system structure.

This point is further confirmed by results of a fretting motion of ceramics against a stationary 52100 steel ball. After approximately 5 million cycles, a wear groove is observed on the ceramic surface, and profilometry reveals a varied behavior among the four ceramics (alumina, silicon nitride, partially stabilized zirconia, and siliconized silicon carbide). A wear coefficient can be determined for each ceramic, for its mating ball, and for the total system ball and ceramic. The observed ranking of the materials depends on whether the individual or combined wear coefficient is used. Wear testing must take into account the significance of the structural geometric arrangement of the system.

Another aspect of the geometric contact to be considered is the tribocontact parameter, the ratio of the contact area to wear track area. This parameter accounts for the disparity in contact time that may arise between two surfaces, such as those in a pin-on-disc test, where the pin surface is in constant contact with the disc but a specific part of the disc is only in contact with the pin on an intermittent basis. This parameter also illustrates that a wear test is a two-sided experiment, and attention must be paid to the effects on each side of the interface.

The approaches to wear test standardization in West Germany were discussed. Examples of two "wear standard" documents were presented. The most recent document is a proposed wear standard that defines wear

testing goals and several categories of wear testing (DIN 50322). The gearbox of a truck, for example, can be tested as a complete unit (1) in a field test, i.e., in an operating truck on the street; (2) on a proof stand, i.e., as a truck operating in a controlled proof stand arrangement; or (3) as a gearbox unit on a test stand; alternatively, elements of the gearbox can be tested as a model system (4) with actual components of the gearbox; (5) with similarly stressed test components; or (6) with simple test components with arbitrary shapes. Category (1) corresponds to a function-oriented test, and category (6) is a wear-mechanism-oriented test. The series of test types represents a "test chain"; i.e., a series of tests ranging from the application to fundamental study of the interface. Transfer of information from one stage of the test chain to another, however, must be done with great care and requires demonstration of correlation between steps of the test series.

A second standard (DIN 50320) has been in effect since 1979 and defines wear terms, types of wear, wear mechanisms, and wear measuring quantities. It also includes a data sheet designed to help organize and facilitate the complete collection of wear data.

THE ROLE OF SURFACES IN WEAR TESTING (T. E. Fischer, Exxon Research and Engineering Company, Annandale, New Jersey)

Presentation

Dr. Fischer began his presentation with a review of silicon nitride research results that illustrate some of the surface effects on wear. Wear surfaces in silicon nitride may be rough and on close examination may show evidence of two kinds of fracture. For silicon nitride tested in dry argon, a fine fracture process produces a very fine particulate debris, while intragranular fracture results in the removal of large flakes from the surface. By contrast, wear experiments in humid air produce a flat, noncrystalline surface layer and a wear rate a factor of 100 lower than that measured in dry argon. The surface layer is amorphous and contains oxygen. The friction coefficient for silicon nitride sliding on itself is about 0.7 to 0.8, generally starting at the lower value and rising toward 0.8 as the test progresses. Humidity also affects the wear rate of zirconium oxide. In this instance, the wear increases by a factor of 100 as the

humidity is increased from 0 to 100%, primarily due to stress corrosion cracking, the effect of moisture on crack propagation rates. These results demonstrate the complexity of ceramic wear processes and the strong influence of water vapor on the wear behavior of silicon nitride.

In addition to fracture effects, water vapor reacts tribochemically with silicon nitride. The tribochemical nature of the reaction is made evident by the fact that reaction does not take place outside the wear path; only along the wear path is the formation of silicon oxide observed. It is also significant that the sliding velocity was very low, and interfacial temperature and the theoretical flash temperature did not exceed 10°C. In contrast, the chemical oxidation of silicon nitride does not begin until the temperature exceeds 700°C.

The surface topography influences the operative wear mechanism. Unlike metal surfaces, the irregularities on a silicon nitride surface will not deform in the early run-in stages, producing a well-mated surface. Fracture will occur at asperity tips, maintaining a rough surface. Smooth ceramic surfaces must be prepared during the manufacturing process.

Ceramics are very tribochemically active, and may react with many of the other environmental constituents in addition to water. The evaluation of the wear surface composition is therefore essential, and it is a guide to chemical effects during wear. Many techniques are available for surface analysis, but the low electrical conductivity of many ceramics may complicate the use of some of the techniques. Auger analysis, SIMS, EDAX, infrared spectroscopy, and Raman spectroscopy are among the available techniques. A judicious use of wet chemistry may also be of value.

Discussion

The discussion opened with the presentation of results supporting those of the introductory talk (N. Macmillan). For silicon carbide, a bimodal wear-particle distribution is found: fine particles of about 100-nm diameter, apparently formed by brittle fracture, and a coarse particle fraction formed by intergranular fracture. Water affects the appearance of the wear scar on alumina, and silicon carbide tested in

carbon tetrachloride turns the liquid black because of carbon formation by tribochemical reaction. Investigation of the friction coefficient as a function of surface roughness in silicon carbide and zirconia ceramics showed that a friction coefficient of 0.4 was consistently measured at a common surface roughness, this roughness being produced from either a previously smoother or a previously rougher surface. The utility of the continuous measurement of both normal force and friction force was noted, these values providing detailed information on cyclic variations in friction as well as long-term changes in this parameter (N. Macmillan).

The significance of surface contamination was emphasized by reference to the effects of a monolayer of stearic acid on the response of glass sliding against sapphire; the monolayer molecules delay the onset of fracture from 2 or 3 cycles to 200 cycles (I. Singer). Similarly, surface structure modifications can alter the frictional behavior. An example of a metallic glass was discussed for which the magnitude of the friction force in sliding is observed to diminish significantly at the crystalline transition temperature. Subsequent surface analysis revealed that a segregation of impurities to the surface accompanies the structural change. Ion implantation can also modify surface properties. An example of the effect of ion implantation on silicon carbide was shown; at a sufficiently high implantation dose the surface material becomes amorphous and plastically deforms in the path of a diamond stylus, and the usual fracture behavior is suppressed. It was emphasized that concern should be directed toward selection of surface modifications that might be used to minimize wear (I. Singer).

The idea of fully characterizing surfaces was endorsed, but the question was raised of the possibility of assessing surface properties and composition at elevated temperatures (W. Glaeser). With regard to elevated temperature composition, mass spectrometry was suggested as a means of analyzing the gas phase (T. Fischer). Silicon carbide was reported as showing evidence of large-scale subsurface plastic deformation (J. Wert), and sliding wear results that illustrate different interfacial effects at elevated temperatures were mentioned (A. Levy).

Generally, fracture will be the interfacial failure mode in ceramics, unless there are environmental effects to mitigate it (T. Fischer).

The influence of surface texture on strength and rolling contact fatigue was mentioned, as was the effect of porosity on fatigue strength (T. Yonushonis). The idea of an influence of surface texture on wear was affirmed, and porosity was cited as a possible initiation site for unrepresentative surface effects (N. Macmillan).

Referring to the suggestion that complete system characterization is desirable, it was indicated that as many as 80 variables would have to be ascertained in such an effort (K. Ludema). The only hope for doing this is by grouping the variables into manageable lots. Selection of a given material, for example, fixes those variables related to materials properties. As far as defining all the system variables is concerned, a central model is needed — a framework to guide the development and use of standard tests. Agreement on standard tests will require a framework in terms of what we are trying to learn with the tests (K. Ludema).

The suggestion was made that the multiplicity of variables reflects an inability to reduce the problem to its lowest terms. Mathematical modeling might offer some guidance in identifying a minimal number of pertinent variables (M. Zlotnick).

Returning to the question of surface roughness, experiments were cited which indicate that surface finish does influence wear (I. Singer). The present discussion has offered several illustrations of procedures that might be used to alleviate surface finish effects. The important point is to seek notions from basic research results and apply those notions to real problems (I. Singer).

The discussion turned to a consideration of surface analytical tools. The applicability of these techniques to ceramics was questioned (H. Czichos). Some difficulties may be encountered in the poorly conducting ceramics; sometimes conducting layers can be utilized, but in other cases this is not successful (T. Fischer). Under some conditions, the wear service, i.e., engines, may leave a conducting surface film of metal or carbon (N. Macmillan). The environment is critical in wear behavior, producing surface layers that

influence tribological properties positively or negatively; cigarette smoke may contribute sulfur to the environment (H. Hintermann). Defect structures in the surface and in the near-surface region are also significant in that they can contribute to the enhancement or the minimization of surface cracking through residual stress effects (M. Kaminsky).

The difference between wear tests for fundamental understanding and wear tests to evaluate real applications was considered. Regarding basic research, all system parameters should be determined, and any test system that reproduces the situation to be studied can be used; for applications tests, a full determination of all system parameters should likewise be made, and a test system should be designed that simulates the real system as closely as possible (T. Fischer). The principal feature of both approaches seems to be as complete a characterization of system parameters as possible (C. Yust). A major distinction between basic and applied tests is that applied tests should use actual components intended for service, tested in a system as nearly identical to the real system as possible, while basic tests should concentrate on the materials aspects (H. Czichos). One feature distinguishing service tests from laboratory tests is the ability to control the parameters in a laboratory test, whereas in service tests only a full determination of the parameters is possible (O. Vingsbo).

Attention was directed to a surface analytical technique not previously mentioned. Spectroscopic ellipsometry, which does not require a vacuum for application, can be used to investigate liquids on surfaces and offers the possibility of identifying adsorbed species (N. Macmillan). It was also indicated that ceramics have been found to be chemically active with respect to liquid lubricants, and surface reaction products become an important issue in lubricated ceramic behavior. A distinction was made between testing the wear behavior of ceramic materials and testing means of preserving the surfaces during wear by some type of lubrication (S. Hsu). Reference was also made to the necessity to be aware of the potential for changes in the surface with time at elevated temperature (I. Singer).

Finally, it was suggested that baseline tests with standard materials be considered as a means of correlating wear equipment and

results (F. Lockwood). The international Wear Test Methods activity of the Versailles Project on Advanced Materials and Standards (VAMAS) intends to pursue this point (H. Czichos).

SLIDING WEAR TESTS (K. F. Dufrane, Battelle Columbus Laboratories, Columbus, Ohio)

Presentation

Mr. Dufrane noted that wear is a system process not easily separated into individual elements. Reviewing recent ceramic wear papers, it can be seen that a variety of wear tests are being used to evaluate the wear behavior of ceramics, including pin-on-disc tests, abrasion tests by a variety of devices even though there is an ASTM standard abrasion test, ring-on-block tests, functional tests such as drilling and machining, and varied specialized tests.

There are three reasons for doing wear tests: (1) selection of materials for a specific application, (2) study of the basic mechanisms of wear, and (3) evaluation of the wear properties of a new material. Category (1) is an engineering test to find the optimum temperature, speed, and sliding direction. Some aspects of basic testing might be suitable for standardization, such as agreement on the dimensions of the pin in a pin-on-disc test or ranges of operating speeds in an effort to establish some uniformity in test performance. Full documentation of test procedures and conditions is desirable.

The category (3) tests are also a specialty area in which much engineering judgement and experience are required, and it is unlikely that standardization would be advantageous in this area.

Discussion

The initial discussion comments concerned the issue of wear test standardization (P. Sutor). Agreement with the presentation on reasons for wear testing was noted; materials selection tests will vary with the application, and fundamental tests may be any well-described configuration. The important feature of basic tests is that an intelligent question be asked and that well-documented, interpretable experiments be used to provide an answer.

Standardization is an effort to find a means of ranking materials for a given end use, and the development of standards will be little different for ceramics than for metals. Some standardization may evolve for applications of a generic type, such as piston rings and cylinder liners or rolling-contact bearings. More attention should be addressed to fundamental models and to test and specimen characterization (P. Sutor).

Data were offered on the sliding wear of surfaces simulating the piston ring-cylinder wall interface (A. Levy). The test configuration was a washer and disc arrangement in a system capable of being heated to 730°C. Examples of elevated-temperature interfaces were shown, as were wear rate data for several ring-liner combinations. The data illustrated the changes that ceramic surfaces and wear rates experienced with changing temperature (A. Levy).

The need to obtain the identical mechanism in a bench wear tester as in an applied system under study was pointed out. It was suggested that the same mechanism must be demonstrated in the test system as is operative in the applied system if the test system is to have any validity in ranking materials for the application (S. Hsu).

A researcher interested in data will use whatever is available, regardless of type of specimen. Possibly stored data could be classified according to type of source, i.e., standardized or special test. There is also a need to standardize the use and definitions for wear coefficients (R. Burton). A need for standard means of reporting wear results was noted (C. Wu). A developing test machine was described; it is intended to be as universal a machine as possible, encompassing many types of motion and test geometries as well as temperature and environmental control (S. Gray).

It was suggested that it will be very difficult to standardize wear tests, but there is a good opportunity to standardize wear test procedures; possibly we should be working toward standard nomenclature and standard test procedures (J. Wert). The point was again raised concerning the availability of a standard specimen that could be used as a reference material (J. Wert). It has been proposed that a common material be provided to serve as a reference for ceramic wear research, but this has not as yet been realized (S. Hsu). A European

group has previously devised a systemization of sliding wear effects; might this apply to ceramics (I. Singer)? Failure criteria and the failure boundaries for lubricated sliding metal contacts were defined for some metals (in the European work), but it is not certain that this applies to ceramics; it may be important to study failure transitions in ceramics (H. Czichos). Is it possible to set up some generalized standard test to rank materials? Although it would not particularly interest researchers, many people would find such a test useful (M. Peterson).

The discussion turned to the question of exactly what is desired from this meeting (R. Burton). The response was that the consensus of the wear community is desired on whether or not standard tests for ceramic wear are feasible or desirable, and if so, how they might be developed (C. Yust). It was suggested that classes of tests and classes of end uses might be defined and a matrix of tests and uses be formed; tests might then be developed as standard tests for some subsets of the matrix. A test might be developed for piston ring—cylinder liner evaluation, but not for adhesion or abrasion for all systems (M. Kaminsky). The comment was made that better reproducibility of data will come with more careful work, full characterization is something that all should do, and correlation of bench and field results is not likely in the near future; there is also no reason to expect a single test method to be developed for ceramics (S. Jahanmir). But users of materials want to know what tests to use to evaluate materials (M. Peterson). A test system that is designed with the end use in mind and that yields the same wear mechanism as the real application is the best test system (T. Fischer). Perhaps there should be special tests of individual components (J. Wert). The development of one test is not the object of this discussion (S. Hsu).

This is not the proper time for traditional standards, but standard procedures and characterization schemes may help improve the documentation of the work (K. Dufrane). Component testing and materials selection tests will continue to be determined by end use; a standard reference material should be seriously considered (P. Sutor). A group of DOE-related people should consider preparing a standard procedure for review by the wear community and/or ASTM G-2. The German standard data form would aid in achieving a greater uniformity of data (J. Wert).

ROLLING WEAR TESTS (L. D. Wedeven, SKF Industries, Inc., King of Prussia, Pennsylvania)

Presentation

Dr. Wedeven illustrated the normal progression of wear tests, from bench tests through rig, component, and finally systems tests. Progression through the series from bench to system increases time and cost, becomes less generic and more system specific, and provides a greater proof of concept but less fundamental understanding. Analytical procedures to evaluate stress distribution must also accompany testing to avoid misinterpretation of the observations. We are confronted by two basic needs, one being design tools to predict wear performance, the other being an efficient method for full development and evaluation of new opportunities. If standard tests help to bridge the gap between knowledge and application, they can be useful, but if they inhibit innovation, then they should be avoided.

The rolling-bearing contact zone was discussed in detail. The engineer's view of stress and stress concentrations in a bearing, including a detailed discussion of the effects of topography, microstructure, and lubrication, was presented. Examples of the effects of stress on the subsurface zones and the relationship of those effects to failure were discussed. With regard to testing for subsurface zone effects, it was noted that it is important to test with good lubrication (to eliminate surface effects) to be able to define the macrostress distribution so that the fatigue resistance of the material of concern may be evaluated. Numerous test systems exist to evaluate fatigue resistance; they include four-ball, five-ball, and disc-and-rod machines.

Distribution of the surface macrostress has been analyzed, and tensile stress components are noted at the surface at both the back edge and sides of the contact zone. Cracking can occur at the tensile stress sites, especially in brittle ceramics. A full understanding of these processes requires comprehension of both slip and rolling processes in the contact zone. The materials properties of concern are tensile strength and those related to the initiation and propagation

of cracks. These properties may be difficult to evaluate for the near surface region in which microstructural and chemical variations with time under stress are not well understood. There may be a possibility for standardization of testing for surface cracking behavior, and that standardization would focus on very good control of the macrostress and the friction in the macrostress zone. A disc-and-ball apparatus that can be used to control the velocity distribution within the macrocontact zone was described and discussed.

Stresses at asperity contacts are also significant. In steels, asperity deformation can lead to micropitting, and the micropits may serve as stress concentrators leading to cracks and spalls. In ceramics, fracture of asperities may occur, and the pit formed becomes part of the wear mechanism. Efforts have been made to characterize ceramic surfaces by stylus evaluation of the surface roughness. Models for surface contact have been applied to estimate the real area of contact, contact pressure, and proportion of ceramic contacts that will fracture. This information has been combined with other ceramic tribology data in an effort to estimate ceramic performance. Some results were presented for silicon nitride; at high temperatures it was observed that oxidation of the surface changed the surface properties, that synthetic seawater may have induced an amorphous surface layer, and that cleaning of the silicon nitride balls removed surface films and resulted in higher friction and greater wear. Many unknowns remain in the study of asperity contact effects, and this is not an area in which standardization would be desirable.

For rolling-contact fatigue, for which failure initiates below the surface and is primarily a material response, the possibility of providing standardized tests and procedures is very real. Test devices, common in the industry although not formally standardized, are readily available. Evaluation of the effects of stress at the edge of the contact zone is more difficult because of the complication of dealing with the poorly characteried near-surface region. Nevertheless, there is some possibility of standardized testing for macrostress effects, although for asperity site investigations it seems impractical to think of standardized tests and procedures.

The most important area for emphasis is the need for innovation. Many things can be done to surfaces to improve performance; new ideas for lubrication are required if ceramics are to successfully applied. A scientific basis for innovation is needed. General guidelines for good testing and good experimentation are desirable, but standard tests and procedures should not be imposed at the risk of inhibiting innovation. Scientific notions and suggestions are needed regarding what may work or what may not, rather than a narrow focus on one aspect of the problem. While we should be concerned for every variable in a given situation, we should retain a general view of the problem and be alert for innovative approaches to a solution.

Discussion

The discussion opened with a consideration of the elastic events that occur beneath the surface of a rolling contact (L. Keer). The subsurface characterization includes the role of voids, inclusions, and cracks. Two-dimensional analyses can include the effect of the quiescent zone on cracks. Very good stress codes are available for three-dimensional subsurface stress characterization, even yielding exact solutions for the case of elliptical Hertzian contact. Calculation codes are developing for more general stress conditions and flow inclusion, which should contribute to progress in modeling of tribological phenomena (L. Keer).

Rolling-contact fatigue tests can successfully give rank ordering of materials for contact fatigue resistance (T. Yonushonis). The information derived from such tests, however, has to be greatly extended before the material will be utilized as components. More information is required than can be derived from one standard test (T. Yonushonis).

The major problem in wear testing is to simulate real components and their system behavior in a meaningful, repeatable, and low-cost manner (S. Gray). Various test machines are currently available and were discussed in detail. Ceramic wear surfaces are often very rough and may induce high levels of vibration in the test machine; accelerometers may be of value in assessing this problem. A possible approach to ceramic wear test standardization is to review the real needs for

ceramics, review current test systems, formulate designs for testers, and then initiate preliminary standard specifications (S. Gray).

The introduction of standardized test procedures does not necessarily mean that innovation would be denied (C. Yust). The concern is that excessive effort will be dedicated to development of standard samples, procedures, and devices; the primary purpose should be to bridge the gap between science and application and provide innovative ideas for evaluation (L. Wedeven). When trying a new idea, a standard procedure may be useful to demonstrate that something valid is being accomplished (M. Peterson). Ball-bearing testing is a very uniform procedure, and standards are not necessary there (O. Vingsbo). Are the codes mentioned earlier for stress analysis and materials response to applied stresses under rolling conditions readily available (V. Tennery)?

An aspect of wear testing that has not yet been addressed is the test endpoint (W. Glaeser). Rolling tests have a defined endpoint, a surface spall, but this is not so clear for other types of tests. Before a test system is designed, the desired endpoint should be defined (W. Glaeser).

Possibly this discussion started with the premise that a standardization could be achieved, but that is too far in the future (J. Bierlein). A desirable result would be the organization of tribology data, possibly as some type of map that illustrates interrelationships of data and absence of data. The information from this meeting could be the initial data (J. Bierlein). But standards and procedures are needed to get reliable data for the map (H. Czichos). It would be useful to have information on standard reference materials (K. Kim). Reference materials can only be qualified to have particular properties with respect to a particular test; materials and tests must go together (A. Ruff). Agreement was expressed for standard tests and reference materials; possibly a small committee should prepare initial standards for consideration (F. Lockwood). One way to encourage innovation is to broaden the base of participants and to encourage technology transfer; recommended procedures would help to include the broadest possible group of research participants (F. Larson). Reference to technology transfer raises the question of how

information can best be transferred from fundamental research or development avenues to designers in a form that is readily understood (S. Jahanmir). Efforts are under way to establish a tribological data base in the near future (T. Levinson). Some measure of wear test standardization would enhance technology transfer between tribologists and would provide improved data for the tribological data bank (C. Yust).

With regard to a data map, it was suggested that a paper-study design for a specific wear test system would highlight information needs and problem areas (W. Glaeser).

In addition to improved test procedures, we need characterization of the materials tested, including the lubricants involved and residual stresses in the test surface. Material characterization is as important as a good definition of test parameters (M. Kaminsky). In response to the foregoing comment, it was pointed out that surface residual stress and the potential for modifying surface stresses or other surface properties is the type of innovative idea that should be pursued. The opportunity to adjust surface conditions to a particular need and useful methods to make such adjustments are required for technological advances (L. Wedeven). But are not standards necessary to help improve the comparability of wear data (C. Yust)? Standards improve horizontal relationships (among researchers), but improvements are necessary in the vertical relationships (between basic and applied interests) (L. Wedeven). An example presented was a gear test in which much effort was expended to improve agreement among workers. The resultant test is infrequently used because it is too expensive and is more of an inhibition than an aid to innovation (L. Wedeven). There is a real value in having standard tests available; they do improve interlaboratory agreement. Possibly DOE should form a small group to initiate the preparation of a pin-on-disc or a cylinder wall-ring standard test (J. Wert).

PROSPECTS FOR TESTING STANDARDS (A. W. Ruff, National Bureau of Standards, Gaithersburg, Maryland)

Presentation

Dr. Ruff indicated that he is inclined by background to support the idea of voluntary standards. He sees no limitations in the means

of obtaining data in standards and is optimistic about the prospects for ceramic wear test standards.

With reference to standard definitions and standard terms, it was noted that ASTM has prepared a list of terms and definitions for wear, although possibly modifications or new terms are needed for ceramics. Wear coefficient definitions might also be required.

The rationale for performing bench tests varies from research on wear mechanisms to wear rate prediction and service correlation. An ASTM standard for a common bench test, the pin-on-disc test, has not been prepared because the range of conditions used in such testing is so broad. The discussion of this meeting has indicated a need for agreed-upon bench tests.

It was pointed out in this meeting that a test machine helps us to ask questions. Very often, the answer obtained depends on the question asked. Different test machines ask different questions; consequently, more can be learned by using several approaches. Key parameters must be involved in the test, such as stress and velocity. Most ASTM tests concentrate on a small number of parameters.

Tribological standardization has to be related to particular applications. The most likely applications for ceramics should be assessed, and such standards as required should be prepared for those applications. Standard tests should relate to specific wear problems; a prescribed procedure must have a connection to a use or a service experience.

Data were presented illustrating difficulties encountered in wear rate prediction. Atmosphere and temperature effects can induce nonlinear wear rates, and changes in wear rate with time as materials pass through transitions are possible. Uniform test methodologies may yield improved data and contribute to improved lifetime prediction.

A number of standard wear tests are presently in the U.S. literature, and some have been used for ceramics. Only minor modifications would be needed to make some of them fully appropriate for ceramics. Although some of the discussion at this meeting suggested that standards will not be soon agreed upon, those cited here are now available or nearly so (see Appendix D). The use of standard tests would not inhibit fundamental testing; in fact, it may be very useful for mechanisms research. Modelers would benefit from a narrow band of data from many researchers.

Referring to precision in wear testing, data were cited which were produced according to ASTM G65 (1981), the dry sand abrasion test. The data are from several laboratories experienced in the use of this test. The internal variability of the data ranged from 2.1 to 6.7%. Among a larger group of laboratories, the data range is larger. Experience is an important factor in obtaining the best results.

Recently a panel assembled by DOE evaluated tribotesting of materials. The findings of that panel are generally in agreement with the comments and emphasis heard at this meeting. The needs cited include a standard data reporting format, improved characterization methods, an expanded and well-documented data base, and improved test methods. Interlaboratory test comparison will also be important, and an international effort of this type is presently under way. Possibly some wear standards will emerge from the cooperative international tests.

Discussion

In discussion of the presentation, it was observed that some caution should be exercised in establishing requirements for wear research. If all the factors cited in the current discussion must be attended to in detail, then progress will be limited (W. Winer). Concerning repeatability of data, it was noted that physical property data often contain a spread in values of 30 to 50%; therefore, this same range of results for wear data is quite acceptable. A single standard wear test is unlikely; in fact, several such tests have been cited. Different tests for either specific applications or different classes of applications will be necessary. Whatever procedures are used, it will be necessary to map out a range of behavior over a reasonable range of variables.

The materials designer, the mechanical designer, and the tribologist interact in a continuum of needs. The materials designer wants to find a use for his materials, the mechanical designer seeks materials for his designs, and the tribologist is interested in the basic behavior of materials. These needs do not necessarily overlap, but the tribologist can improve the interaction by providing useful, rather than discouraging, advice. Suggestions were made for each group for improving interactions (W. Winer).

The suggestion was made that this would be an appropriate point to offer a few specific recommendations (M. Peterson). Research results should be more completely reported, especially regarding how tests were run, but researchers should be free to use any test device. For development tests, standard machines and standard tests exist; new machines are not required. While some standard reference materials exist, there should be more, including ceramics. There is a general agreement that better test procedures are needed, including information on what tests should be run and how they should be run. It will be important to be aware of the intended end-use of ceramics and to develop test procedures directed toward those specific applications. Surface damage reporting needs to be quantified, and a standard surface damage criterion is required. In sum, better test procedures are required but not better test machines. Most existing procedures have been worked out for metals, but ceramics may need emphasis on different variables, and contamination may be more important (M. Peterson).

SUMMARY AND ADJOURNMENT

The session chairman (S. Hsu) summarized the ideas expressed during the course of the meeting as he perceived them:

1. Ceramic wear tests and testing procedures do not give adequate comparability of data.
2. There is a need for reference materials and reference procedures for guidance and calibration for application-specific testing and mechanistic study.
3. Parameters to be reported and controlled include
   - characterization of materials,
   - characterization of test machines,
   - tribochemistry,
   - surface characteristics,
   - temperature, and
   - wear debris.
4. Standardized tests may not be desirable for research. Guidelines may be possible for uniform characterization and measurement.

5. Standardization is useful and desirable for simulation testing for screening purposes. Laboratory-to-field correlation should guide such development. Standardization is best done under auspices of an established industrial or governmental body.

It was reiterated that a small group should be convened to define the near-term ceramic applications and define suggested procedures (A. Levy). It was noted that a group already exists for procedure development, that group being Committee G-2 of the ASTM. Many people are not aware of the extent of G-2 activities, but everyone is welcome to become an active ASTM member and join in procedure development (L. Heerdt). Possibly we should agree on a minimum standard of characterization, for example, all tests should specify relative humidity quantitatively (T. Fischer). The ASTM is too slow; an ad hoc procedure should appear in six months (A. Levy). Reference was made to the data map concept, which may serve as a guide to thinking on what may or may not be critical (J. Bierlein).

The meeting adjourned at this point, after some brief closing remarks by T. M. Levinson and C. S. Yust.

CONCLUSIONS AND RECOMMENDATIONS

1. Current testing procedures and reporting requirements on ceramic wear are not sufficiently well defined for data comparison. Better definition and better control of the test parameters are desirable and should be reported. The parameters reported should include:

(a) material characterization of the test specimens, e.g., composition, microstructures, material properties;

(b) environmental control such as humidity, specimen cleaning, procedures, and lubricant compositions;

(c) surface characterization such as surface roughness and surface conformity before and after the wear test;

(d) bulk temperature and actions directed toward control of the system temperatures; and

(e) wear debris analysis including both particle morphology and chemical transformations.

2. Standardization is desirable and needed for ceramic tribology. Multiple standard procedures for various applications are urged, and standard tests once established should not exclude other tests for the purpose of research and development. For every application-oriented standard test, reference materials and data should be made available for data comparison and system calibration.

3. For basic research and mechanistic studies, standard test procedures and specimens may not be possible or desirable. A common guideline for testing, including a requirement for parameters to be controlled during tests, is desirable. Data precision is important and should be reported.

4. The significance of standard wear tests should be supported by laboratory-to-field correlation data. Standardization should be achieved through established voluntary consensus processes by government, industries, and academia.

5. In the long term, the standardization should be accomplished through ASTM. In the short term, an ad hoc group should be established under joint government-industry-academia sponsorship to resolve key issues in a timely fashion.

ACKNOWLEDGMENTS

The authors express their appreciation for the financial support from the DOE ECUT Tribology Program and their thanks to all the workshop speakers, panelists, and attendees for their contributions. Special thanks are expressed to F. M. Foust for preliminary organizational work, and to H. G. Corbett for follow-up work and for serving as registrar and treasurer at the workshop. E. L. Long, Jr., and J. M. Leitnaker reviewed this report and provided helpful suggestions. This report was drafted by C. A. Valentine, edited by O. A. Nelson, and prepared for publication by A. R. McDonald.

Appendix A

WORKSHOP PROGRAM

Tuesday, April 23, 1985

8:40 — 8:45 a.m. Welcoming Remarks
C. S. Yust, Oak Ridge National Laboratory

8:45 — 9:00 a.m. ECUT Tribology Program and Workshop Objectives
T. M. Levinson, Department of Energy

Session 1

Chairman: C. S. Yust, Oak Ridge National Laboratory

9:00 — 10:30 a.m.

A. Current Test Systems
L. R. Heerdt, Falex Corporation

B. Panel Discussion
N. Hakim, Genral Motors Corporation
S. M. Hsu, National Bureau of Standards
J. J. Wert, Vanderbilt University

C. Open Discussion

Session 2

Chairman: S. M. Hsu, National Bureau of Standards

10:45 — 12:15

A. Relationship of Ceramic Wear Mechanisms and Testing
W. A. Glaeser, Battelle Columbus Laboratories

B. Panel Discussion
F. J. Carignan, Advanced Mechanical Technology, Inc.
K. C. Ludema, University of Michigan
S. L. Rice, University of Central Florida

C. Open Discussion

Session 3

Chairman: C. S. Yust, Oak Ridge National Laboratory

1:30 — 2:00 p.m. Wear Test Methodologies
H. Czichos, Bundesanstalt für Materialprüfung

2:00 — 3:30 p.m.

A. The Role of Surfaces in Wear Testing
T. E. Fischer, Exxon Research and Engineering Company

B. Panel Discussion
N. H. Macmillan, Pennsylvania State University
I. Singer, Naval Research Laboratory

C. Open Discussion

Session 4

Chairman: S. M. Hsu, National Bureau of Standards

3:45 — 5:15 p.m.

A. Sliding Wear Tests
K. F. Dufrane, Battelle Columbus Laboratories

B. Panel Discussion
A. V. Levy, Lawrence Berkeley Laboratory
P. Sutor, Midwest Research Institute

C. Open Discussion

Wednesday, April 24, 1985

Session 5

Chairman: C. S. Yust, Oak Ridge National Laboratory

8:45 — 10:15 a.m.

A. Rolling Wear Tests
L. D. Wedeven, SKF Industries, Inc.

B. Panel Discussion
S. Gray, Mechanical Technology, Inc.
L. Keer, Northwestern University
T. Yonushonis, Cummins Engine Co.

C. Open Discussion

Session 6

Chairman: S. M. Hsu, National Bureau of Standards

10:30 — 11:50 a.m.

A. Prospects for Testing Standards
A. W. Ruff, National Bureau of Standards

B. Panel Discussion
M. Peterson, Wear Sciences Corporation
W. O. Winer, Georgia Institute of Technology

C. Open Discussion

Remarks

C. S. Yust, Oak Ridge National Laboratory
S. M. Hsu, National Bureau of Standards

12:00 Adjourn

Appendix B

CURRENT WEAR TEST SYSTEMS

L. R. Heerdt

Many of the friction and wear test systems commercially available today may have application in evaluating ceramic material. These systems have helped to standardize testing within various industries by improving precision limits and providing verification of test results between laboratories. Because parameters for a given test can be preset or varied, the operator can design a laboratory test that correlates accurately with actual field conditions, thus eliminating much of the expense of full-scale evaluations.

The following test systems have been used successfully in many applications involving wear between two sliding objects. The user should determine if the test varibles of the machine are applicable to his field application.

Falex Pin and Vee Block Test Machine

Specimens:	AISI 1137 vee block against SAE 3135 journal
	Steel on steel (other materials available)
Contact:	Four-line contact
Motion:	Rotating, oscillating (sliding)
Speed:	20 to 5600 rpm
	1 to 350 cpm
	0.67 to 188 ft/min (0.23 to 57.3 m/min)
Specimen load:	3000 lbf (1364 kgf) max
Temperature:	375°F (190°C) max
Environment:	Liquid, semi-fluid, dry
ASTM Standards:	D-2670, D-2625, D-3233
First machine:	1932

Number of machines in use:	1100
General use:	Evaluates wear life and load carrying capacity of lubricants and other materials: metals, composites, or combinations of these. Most widely used bench test.

Falex Block On Ring Test Machine

Specimens:	SAE 4620 ring, SAE 01 tool steel block (other materials available)
Contact:	Line, area, point
Motion:	Roatating, oscillating (sliding)
Speed:	5 to 7411 rpm 17 to 1600 cpm 1.8 to 2668 ft/min (0.55 to 813 m/min)
Load:	1300 lbf (591 kgf) max
Temperature:	700°F (371°C) max
Environment:	Liquid, semi-solid, dry-pressure chamber to 150 psig
ASTM Standards:	D-2714, D-2981, D-3704, D-2509, D-2782, C-77
First machine:	1960
Number of machines in use:	330
General use:	Extreme pressure properties of lubricants. Will differentiate between low, medium, and high levels of extreme pressure properties. Used for friction and wear studies of lubricants and various metallurgies.

Falex Multi-Specimen Test Machine

Specimens:	Thrust washer, four-ball, pin-on-disc, vane, gear, liquid erosion, stock-slip
Contact:	Variable

Motion:	Rotating, oscillating (sliding/sliding-rolling/rolling)
Speed:	20 to 7411 rpm 1 to 1600 cpm
Load:	807.5 lbf (367 kgf) max
Temperature:	500°F (260°C) max
Environment:	Fluid, solid film, semi-solid
ASTM Standards:	D-3702, D-2266
First machine:	1972
Number of machines in use:	100
General use:	Measures friction and wear characteristics of lubricants, metals, and composites.

Falex Abrasion Test Machine

Specimens:	Metal or composite material coupons
Contact:	Area
Motion:	Sliding
Speed:	7 to 350 rpm
Load:	75 lb max
Temperature:	Ambient
Environment:	Dry abrasive, liquid slurry
ASTM Standards:	G-65
First machine:	1981
Number of machines in use:	14
General use:	Measures wear characteristics under an abrasive condition.

Falex Crossed Cylinder Test Machine

Specimens:	Two cylinders
Contact:	Rotating
Motion:	Rotating

Speed:	25-450 rpm
Specimen load:	50 lb max
Temperature:	Ambient
Environment:	Dry, liquid
ASTM standards:	G-83
First machine:	1981
Number of machines in use:	Six
General uses:	Measures friction and wear characteristics.

Falex Four-Ball Wear Test Machine

Specimens:	E-52100 steel on steel
Contact:	Three-point
Motion:	Rotating (sliding)
Speed:	1 to 10,000 rpm
Specimen load:	396 lbf (180 kgf) max
Temperature:	350°F (176°C) max
Environment:	Liquid, semi-solid, dry atmosphere environmental chamber
ASTM standards:	D-2266, D-4172
First machine:	1950
Number of machines in use:	200
General use:	Measures friction and wear characteristics of lubricants. Widely used for gear oil, greases, and engine oil.

Optimol SRV Test Machine

Specimens:	Two cylinders against needle rollers (rolling friction). Ring on surface (fretting corrosion and galling). Ball on surface (mechanical abrasive wear tests).

Contact:	Point, line, area
Motion:	Relative oscillatory sliding motion of variable amplitude and frequency.
Amplitude:	0 to 3500 μm
Frequency:	10 to 150 Hz
Contact load:	270 lbf (0-1200 N) max
Temperature:	1000°C
First machine:	1975
Number of machines in use:	60
General use:	Measures friction and wear in high-speed oscillation.

Plint High-Frequency Friction Test Machine

Specimens:	Steel on steel
Contact:	Point, area
Motion:	Relative oscillatory sliding motion of variable amplitude and frequency.
Speed:	2.5-50 Hz
Load:	56 lbf (250 N) max
Temperature:	1110°F (600°C) max
Environment:	Open chamber or enclosure
First machine:	1978
Number of machines in use:	15
General use:	Boundary, transition, and full hydrodynamic lubrication.

In his presentation, Mr. Heerdt discussed these standardized commercially available friction and wear test machines, including design considerations, test conditions, and applications. In addition, he described a new machine designed specifically for testing ceramics.

Appendix C

COMMENTS AND QUESTIONS TO STIMULATE DISCUSSION

(Circulated before the meeting)

C. S. Yust and S. M. Hsu

Tribology testing, in one form or another, can probably be traced to the earliest use of tools and mechanical devices. The original test system was most likely the operating device itself (full component testing), observed in operating by the manufacturer or user, who sought to correct observed deficiencies (i.e., goatskin thong is a better joining medium than dried grapevine). One can even imagine that the very earliest wear tests involved ceramics, as a stone-age craftsman carefully applied the first motions of a newly fashioned tool, testing the degree of preparation and suitability of operation.

In more recent times, evidence of interest in friction and wear testing is offered by the large number of meetings and symposia on this topic. Of most direct interest to the present discussion is a series of symposia sponsored by the American Society for Testing and Materials (ASTM). In 1967, a symposium on the relationship of testing and service performance was held, and, in 1968, an ASTM symposium discussed the subject "Evaluation of Wear Testing".[1,2] Beginning in 1975 a symposium series has reviewed the state of the art in wear testing of metals, plastics, and coatings.[3-5] Generally, these discussions have concluded that standardization of tribology testing would be desirable, while noting that the complexity of wear might prevent the use of only a few standard tests.

The 1968 meeting expressed the hope that steps leading to the invitation of activity on tribology test standards would be the result of that meeting. That hope has been partially realized in that some tribology test standards are presently incorporated in the ASTM standards. A listing of friction and wear test standards has been compiled by P. J. Blau, and it includes six standards for testing of ceramics.[6] As Blau notes, some are specialized and have little

general applicability. Others, however, represent an initial effort to provide standardized methods for wear testing. Two examples are ASTM G77-83, a standard practice for sliding wear using the block-on-ring test, and ASTM D3702-78 (reapproved in 1983), a standard test method for a thrust washer test machine application.

This workshop examined the prospects for ceramic tribology test standards. What types of ceramic tribology tests are amenable to standardization? What tribology test devices should be applied in standard tests? How can we begin to formulate and apply standards?

To aid discussions, the following questions were formulated:

Current Test Systems

How well do test systems represent real operating components?

Will some type of "standardization" improve bench-to-field correlation?

Will "standard" devices and procedures improve the ability to measure and control test parameters?

Is there one best type of test device for a given wear mode (i.e., sliding, rolling, etc.)?

What is the precision of the current wear test system?

Are the current procedures and wear test systems sufficiently defined to enable users to compare data and draw generalizations on materials?

Are there particular problems associated with ceramic wear testing as compared to metal wear testing?

What are the main uses for the current wear test systems? Is there a need for new wear systems for ceramics?

Wear Mechanisms/Wear Tests

What aspects of ceramic wear testing require special attention as a result of the fracture sensitivity of ceramics?

How does the potential for sudden transitions from mild wear to severe wear affect ceramic wear testing?

How are the operative ceramic wear mechanisms evaluated?

Would procedures for characterization of ceramic wear surfaces help identify wear mechanisms?

What kind of measurements are necessary to understand the mechanisms in ceramics? How to distinguish chemical wear mechanisms vs mechanical processes?

Would wear debris analysis help to understand wear modes in ceramics? Any particular problems associated with ceramic wear debris analysis?

Should wear tests be conducted to evaluate materials under different load, under different speeds, and as a function of time to assess materials?

Should there be different procedures for measuring friction vs wear?

Should there be different procedures for evaluating materials vs evaluating lubricants? If so, how should they be different?

Sliding Wear Tests

What is your approach to performance of a sliding wear test of a ceramic?

Would a "standard" set of guidelines be a help or hinderance?

What should such guidelines include?

Can most real sliding interfaces be represented by a limited number of test geometries?

What speed and load should be used? How does the interface temperature affect the wear results?

What are the vibrational characteristics of the tester and how do they affect the wear results?

Will alignment be maintained throughout the test as wear progresses?

Role of Surfaces in Testing

To what extent should ceramic surfaces be characterized prior to wear testing? From both a mechanical and a chemical standpoint?

If wear is removal of surface material, why is surface characterization of importance?

How to characterize the ceramic surfaces before and after the wear test?

What cleaning procedure and environmental control should be exercised in preparing the ceramic specimen for testing?

What should be the extent of surface topography measurements? Would they help? How?

Rolling Wear Tests

Are the forces and motions of real rolling elements too complex to be adequately simulated in test systems?

Can a limited number of rolling test geometries be used to simulate many real rolling interfaces?

What standards seem possible for rolling element test devices and test procedures?

Prospects for Standardization

What should a wear test standard be?

Will standards conflict with the flexibility required for research experiments?

What existing standards should we be cognizant of in considering further wear standards?

What research and/or development might be necessary for preparation of standards for wear testing?

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Appendix D

COMPILATION OF FRICTION AND WEAR TESTS

Peter J. Blau
Metallurgy Division
National Bureau of Standards
Gaithersburg, Maryland

The American Society for Testing and Materials (ASTM) has witnessed the development of many types of friction and wear tests. Some were developed for very specific technical applications and have limited general applicability, while others are used for analyzing the tribological behavior of various materials combinations, abrasives, and lubricants. As a service to ASTM Committee G-2, Erosion and Wear, and to other interested parties, this summary of ASTM friction and wear tests has been compiled. Of course ASTM standards are constantly revised, replaced, and discontinued. Therefore, the most recent version(s) of each voluntary standard should be used. Comments are invited on this compilation.

Table D.1. ASTM friction tests

Materials[a]	Applications	ASTM Code	b	Comments
MET CER PLS	Gen lab test	D2714	M	LFW 1 block on ring machine
Graphite	Seal matls	C 808	G	Guidelines for reporting data
Coal	Plastic properties	D1812	M	Gieseler plastometer (discontinued)
MET CER PLS	Prostheses	F 732	P	Pin-on-flat, reciprocating device
Paper	Electrical insul	D 202	M	Sliding on inclined plane
Pavement	Field testing	E 303	M	Portable British pendulum device
Pavement	Tires-side force	E 670	M	Side-force "mu meter," full size tires
Pavement	Gen lab test	E 510	P	Small torque motor bench test
Fabrics	Static coef	D3334	M	Inclined plane
Sintered MET	Dry clutch	B 526	M	Flywheel device, break-away torque, temp
Sintered MET	Dry brake drum	B 460	M	Heated brake drum
Sintered MET	Lub brake drum	B 461	M	Heated drum, run-in lube evaluation
Yarn-metal	Textile machines	D3108	M	Yarn wrapped over drum
Yarn-yarn	Self-mated	D3412	M	Twisted strand or hung over capstan
Carbon paper	Static test	F 524	M	Tilting plate
Fiberboard	Correg, solid board	D3247	M	Horizontal plane
Fiberboard	Correg, solid board	D3248	M	Inclined plane
Wood	Finish flooring	D2394	M	Weighted slider
Wax CTG	Self-mated	D2534	M	Friction sled device
PLS	Sheet, films	D1894	M	Five different devices
PLS	Solid, sheet, film	D3028	M	Pendulum device, "frictionometer"
Floor polish	Flooring	D4103	P	How to prepare test surfaces
Rubber, leather	Shoe soles, heels	F 695	P	James machine, data evaluation
Rubber, leather	Shoe soles, heels	F 489	M	James machine, static test
Floor polish	Floor coatings	D2047	M	James machine, static test
Rubber, fabric	Tire skidding	E 707	M	Pendulum device

[a]MET = metals and alloys, CER = ceramics and glasses, PLS = plastics, CTG = coating.

[b]M = method, P = practice, G = guideline.

Table D.2. Lubricants — friction related

Lubricant type	Applications	ASTM Code	a	Comments
Greases	Oscill bearings	D2509	M	Fretting behavior
Greases	E. P. properties	D2716	M	Timken, block-on-ring
Solid lubes	Vacuum performance	D4170	M	Pin-on-flat (discont)
Lubes	MET sheet forming	D4173	P	Drawing fixture

[a]M = method, P = practice.

Table D.3. Lubricants — wear related

Lubricant type	Applications	ASTM Code	a	Comments
Greases	E. P. properties	D2509	M	Block-on-ring, Timken test
Greases	Fretting	D4170	M	Fafnir frict oxid tester
Greases	Anti-wear	D2266	M	Four-ball machine
Greases	Anti-wear	D3704	M	Oscil ring-on-block
Greases	E. P. properties	D2596	M	Four-ball machine
Dry lubes	Wear, load carry cap	D2625	M	Steel pin in V-block
Dry lubes	Wear life	D2981	M	Ring-on-block
Dry lubes	Load carrying cap	D2625	M	Steel pin in V-block
Dry lubes	Adhesion	D2510	M	Tape, anod Al panels
Dry lubes	Thermal shock test	D2511	M	Heat and quench steel panel
Fluid lubes	Anti-wear	D4172	M	Four-ball machine
Fluid lubes	Gears, load carrying	D1947	M	Ryder gear machine
Fluid lubes	E. P. properties	D3233	M	Pin V-block, two methods
Fluid lubes	Seizure, wear	D2670	M	Pin and V-block
Hydr fluid	Pump part wear	D2271	P	Recirc pump system
Hydr fluid	Pump part wear	D2882	M	Recirc pump system

[a]M = method, P = practice, G = guideline.

Table D.4. ASTM wear tests

Materials[a]	Applications	ASTM Code	b	Comments
MET, CER, PLS	Sliding wear	G 77	P	Block-on-ring (D2714)
MET	Slurry abrasivity	G 75	M	Recipro lap in slurry tray
MET	Sliding wear	G 83	M	Crossed cylinders
MET, compos	Jaw crusher wear	G 81	P	Angled crusher plates
MET, CER, PLS	Erosion	G 76	P	Particles against flat
Fabric	Inked ribbon	G 56	M	Ribbon-wrapped drum
MET, PLS	Liquid erosion	G 73	P	Spinning spec, drops, jets
MET, CER, PLS	Cavitation	G 32	M	Vibration in liquid bath
MET	Dry sand abrasion	G 65	P	Flowing sand-rubber wheel
Insulation	Pipeline coatings	G 6	M	Revolving drum
C-graphite	Seals	G 808	G	Guideline on data reporting
MET	Self-lube metals	D3702	M	Falex ±6, thrust washer
MET, CER, PLS	Sliding wear	D2714	M	Set-up of ring-on-block
Textiles	Woven fabrics	D3884	M	Rubbing while flexing
Minrl aggrg	Crushing resistance	C 585	M	See C 131, Los Angeles Mach.
Org CTGs	Floor coverings	F 510	M	Taber Abraser
Org CTGs	Floor coverings	D1395	M	See D 658 and D 968 below
Org CTGs	Paint, lacquer, yarn	D 658	M	Jet abraded coupons
Org CTGs	Paint, lacquer	D 968	M	Falling sand or SiC, coupon
Concrete	Sand blasting	C 418	M	Air driven sand
Concrete	Rotary cutter	C 944	M	Drill press, rotary cutter
Concrete	Abr, sliding, impact	C 779	M	Three machines
CER	Porcel enamel	C 448	M	NBS lapping machine
CER	Refractory brick	C 704	M	Room temp jet erosion
CER	Tile	C 501	M	Taber Abraser
Rubber	Shoe soles, heels	D1630	M	NBS abrasive drum machine
Minrl aggrg	Crushing resistance	C 131	M	Los Angeles Mach., ball mill
Textiles	Clothing wear	D3181	M	Human subjects, data rept'g
Textiles	Abrasion resistance	D3884	M	Taber Abraser
Textiles	Woven fabrics	D3885	M	Rub while flexing
Textiles	Abrasion	D4157	M	Oscillating cylinder
Textiles	Abrasion	D4158	M	Rotary rubbing-Schiefer
Cem carbide	Wet abrasion	B 611	M	Flat against wheel, slurry

[a]MET = metals and alloys, CER = ceramics and glasses, PLS = plastics, CTGs = coatings.

[b]M = method, P = practice, G = guideline.

Appendix E

LIST OF ATTENDEES,
WORKSHOP ON TRIBOLOGICAL TEST DEVICES AND PROCEDURES FOR CERAMICS,
APRIL 23–24, 1985

Jane Adams
IIT Research Institute
Dept. of Materials and
Processing Technology
10 West 35th Street
Chicago, IL 60616
312-567-4417

H. Michael Anderson
Falex Corporation
2055 Comprehensive Drive
Aurora, IL 60505
312-851-7660

V. Aronov
IIT Research Institute
Mechanical Engineering Department
10 West 35th Street
Chicago, IL 60616
312-567-3181

S. Bhattacharyya
Senior Engineer, Materials Dept.
IIT Research Institute
10 West 35th Street
Chicago, IL 60616
312-567-4192

John C. Bierlein
Materials Engineering
Eaton Corporation
Engineering & Research Center
P.O. Box 766, 26201 Northwestern Hwy.
Southfield, MI 48037

Nancy Blehr
David W. Taylor Naval Ship
R&D Center
Code 2832
Annapolis, MD 21402
301-267-3740

Robert N. Bolster
Naval Research Laboratory
Tribology Section Code 6176
Washington, DC 20375-5000
202-767-2920

Joseph Boylan
Pure Carbon Company
441 Hall Avenue
St. Mary's, PA 15857

Michael S. Brenner
The Lubrizol Corporation
Mechanical Engineering
29400 Lakeland Boulevard
Wickliffe, OH 44092
216-943-9400, ext. 2521

Ronald Bunda
The Lubrizol Corporation
Mechanical Engineering
29400 Lakeland Boulevard
Wickliffe, OH 44092
216-943-9400, ext. 2595

Ralph A. Burton
Ralph Burton Technologies, Inc.
PO Box 5676
Raleigh, NC 27650
919-787-1592

Forest J. Carignan
Advanced Mechanical Technology, Inc.
141 California Street
Newton, MA 02158
617-964-2042

Jean-Pierre Chalifoux
Ecole Polytechnique
Mechanical Engineering Dept.
C.P. 6079, SUCC 'A'
Montreal, Quebec, H3C 3A7, Canada
514-340-4909

Ming Chang
John Crane-Houdaille, Inc.
Research and Development
6400 Oakton Street
Morton Grove, IL 60053
312-967-3817

J. X. Cheng
Cummins Engine Company
Technical Center, Box 3005
Columbus, IN 47202
812-377-7102

Michael J. Covitch
The Lubrizol Corporation
Research-Physical Chemistry Section
29400 Lakeland Boulevard
Wickliffe, OH 44092
216-943-4200, ext. 2703

Horst Czichos
Bundesanstalt für Materialprüfung
Unter Den Eichen 87
D-1000 Berlin 45, West Germany

S. Danyluk
University of Illinois
Department of Civil Engineering
Mechanics and Metallurgy
PO Box 4348
Chicago, IL 60680
312-996-2437

James Derby
Manager
Materials Characterization
EG&G SEALOL
50 Sharpe Drive
Howard Industrial Park
Cranston, RI 02920

Charles E. DeVore
Oak Ridge National Laboratory
Metals and Ceramics Division
PO Box X
Oak Ridge, TN 37831
615-574-4560

James Dray
David W. Taylor Naval Ship
R&D Center
Code 2832
Annapolis, MD 21402
301-267-3740 or 2755

K. F. Dufrane
Senior Research Engineer
Battelle Columbus Laboratories
Dynamics Section
505 King Avenue
Columbus, OH 43201
614-424-4618

Traugott E. Fischer
Exxon Research and Engineering
Company
Corporate Research Dept.
Route 22 East
Annandale, NJ 08801
201-730-3045

Edwin A. Frame
Southwest Research Institute
Army Fuels and Lubrication
Laboratory
6220 Culebra Road, PO Box 28510
San Antonio, TX 78284
512-684-5111, ext. 2515

W. A. Glaeser
Battelle Columbus Laboratories
Dynamics Section
505 King Avenue
Columbus, OH 43201
614-424-4619

Stephen J. Goguen
Department of Energy
Office of Vehicle and Engine
R&D
1000 Independence Avenue, S. W.
FORSTL CE-131
Washington, DC 20585
202-252-1505

Stanley Gray
Mechanical Technology, Inc.
R&D Division Advanced
Technology Operation
968 Albany-Shaker Road
Latham, NY 12110
518-785-2320

Nabil S. Hakim
General Motors Corporation
Detroit Diesel Allison Division
13400 W. Outer Drive
Speed Code R03B
Detroit, MI 48239
313-595-5581

Howard M. Hawthorne
National Research Council
of Canada
3904 W. 4th Avenue
Vancouver, BC V6S 1B6, Canada

Leslie R. Heerdt
Vice President
Falex Corporation
2055 Comprehensive Drive
Aurora, IL 60505
312-851-7660

John A. Hilaris
EG&G Sealol
Research and Development
442 W. Fullerton
Elmhurst, IL 60116
312-941-1888

H. E. Hintermann
Centre Suisse d'Electronique et de
Microtechnique SA
Case Postal 41, Rue Breguet 2
2000 Newchatel 7, Switzerland

Stephen M. Hsu
National Bureau of Standards
Bldg. 220, Room A215
Gaithersburg, MD 20899

Joseph E. Hunter
General Motors Corporation
General Motors Research Laboratories
Metallurgy Department
12 Mile and Mound Roads
Warren, MI 48090
313-575-2951

Said Jahanmir
National Science Foundation
1800 G Street NW
Washington, DC 20550

S. Johar
Ontario Research Foundation
Sheridan Park Research Community
Mississauga, Ontario, L5K 1BE, Canada

Roger N. Johnson
Technical Director
National Tribology Program
Hanford Engineering Development Lab.
PO Box 1970, W/A 40
Richland, WA 99352
509-376-0715, FTS 444-0715

Manfred Kaminsky
Argonne National Laboratory
Materials Science and Technology
9700 S. Cass Avenue
Building 212
Argonne, IL 60439
312-972-4074

Michael D. Kanakia
Southwest Research Institute
U.S. Army Fuels and Lubricants
Research Laboratory
6220 Culebra Road, PO Box 28510
San Antonio, TX 78284
512-684-5111, ext. 3367

Keith R. Karasek
Signal UOP Research Center
Materials Science Dept.
50 UOP Plaza
Des Plaines, IL 60016-6187
312-391-3341

Leon Keer
Northwestern University
Department of Civil Engineering
Evanston, IL 60201

Paul J. Kennedy
Department of the Navy
Naval Air Development Center
Aeromaterials
Lubricants Code 60612
Warminster, PA 18974
215-441-1567

Rifat Keribar
Integral Technologies, Inc.
415 E. Plaza Drive
Westmont, IL 60559
312-789-0003

Vijay D. Khanna
IBM Research
Magnetic Recording Dept.
PO Box 218, Room 38-107
Yorktown Heights, NY 10598
914-945-1621 or 3498

Ken Kim
Polaroid Corporation
750 Main Street
Cambridge, MA 02139
617-577-2007

Floyd G. Larson
Sii Tungsten Carbide Manufacturing Co.
Research and Development
14451 Myford Road
Tustin, CA 92680
714-832-3013, ext. 421

Gary Leonard
General Electric Company
Corporate Research and Development
One River Road
Schenectady, NY 12301
518-385-8055

Rudy M. Lepp
Chalk River Nuclear Laboratories
Engineering Research Branch
Special Projects Division
Chalk River, Ontario, KOJ 1JO, Canada
613-584-3311, ext. 2598

Terry M. Levinson
U.S. Department of Energy
1000 Independence Avenue, SW
Washington, DC 20585
202-252-1484

Alan V. Levy
Senior Scientist
Lawrence Berkeley Laboratory
Materials and Molecular Research Div.
University of California, M/S 62/203
One Cyclotron Road
Berkeley, CA 94720
415-486-5822

Frances Lockwood
Pennzoil Products Company
Technology Div., Physical Sci. Dept.
1520 Lake Front Circle
Woodlands, TX 77387
713-363-8022

E. L. Long, Jr.
Oak Ridge National Laboratory
PO Box X
Oak Ridge, TN 37831
615-574-5172

K. C. Ludema
University of Michigan
Dept. of Mechanical Engineering and
Applied Sciences
2250 G. G. Brown Building
Ann Arbor, MI 48109-2125
313-764-3364

Norman H. Macmillan
Pennsylvania State University
167 Materials Research Laboratory
University Park, PA 16802
814-863-0180

Jacques Masounave
National Research Council of Canada
75 De Mortagne
Bouchervelle, Quebec, J4B 6Y4, Canada
514-641-2280

B. D. McConnell
U.S. Air Force
Wright Aeronautical Labs.
AFWAL/MLBT
Wright Patterson AFB, OH 45433
513-255-5731

Karl R. Mecklenburg
U.S. Air Force
Wright Aeronautical Labs.
AFWAL/GLXPM
Wright-Patterson AFB, OH 45433
513-255-7174 or 5731

Richard L. Mehan
General Electric Company
Corporate Research and Development
Materials Laboratory
Physical Metallurgy Branch
PO Box 8
Schenectady, NY 12301
518-385-8058

Allan I. Michaels
Argonne National Laboratory
Materials Science and Technology
9700 S. Cass Avenue
Building 212
Argonne, IL 60439
312-972-7785

F. A. Moslehy
University of Central Florida
Department of Mechanical Engineering
and Aerospace Sciences
PO Box 25000
Orlando, FL 32816-0993
305-275-2416

Carl F. Musolff
Cummins Engine Company
Metallurgical Engrg. Dept.
Box 3005, Mail Stop 50183
Columbus, IN 47202-3005
812-377-7082

Malcolm Naylor
Cummins Engine Company
Box 3005
Columbus, IN 47202-300

Roger K. Nibert
Borg-Warner Corporation
Physical Chemistry Dept.
Wolf and Algonquin Roads
Des Plaines, IL 60018
312-827-3131, ext. 432

Marshall Peterson
President
Wear Sciences Corporation
925 Mallard Circle
Arnold, MD 21012
301-261-2342

Gopal Revankar
Deere and Company
Technical Center
3300 River Drive
Moline, IL 61265
309-757-5595

K. T. Rhee
Rutgers University
Department of Mechanical
Engineering
PO Box 909
Piscataway, NJ 08854
201-932-3651

Stephen L. Rice
University of Central Florida
Department of Mechanical
Engineering and Aerospace
Sciences
PO Box 25000
Orlando, FL 32816-0993
305-275-2416

W. N. Rogers
ESSO Petroleum Canada
Research Division
PO Box 3022
Sarnia, Ontario, N7T 7M1,
Canada
519-339-2555

Fred G. Rounds
General Motors Corporation
GM Research Laboratories
Fuels and Lubricants Dept.
12 Mile and Mound Roads
Warren, MI 48090
313-575-3276

A. William Ruff
National Bureau of Standards
Metallurgy Division
B266, Materials Building
Gaithersburg, MD 20899
301-921-2966

A. C. Schaffhauser
Oak Ridge National Laboratory
PO Box X
Oak Ridge, TN 37831
615-574-4826

Eric W. Schneider
General Motors Research Labs.
Analytical Chemistry
30500 Mound Road
Warren, MI 48090
313-575-3022

Lewis B. Sibley
President
Tribology Consultants, Inc.
504 Foxwood Lane
Paoli, PA 19301
215-644-0481 or 684-0234

Irwin Singer
Naval Research Laboratory
Research Center Code 6170
Washington, DC 20375

Ralph Slone
Cummins Engine Company
Box 3005, Mail Code 50165
Columbus, IN 47201
812-377-7527

Louis Socha
Corning Glass Works
Ceramic Development Dept.
Sullivan Park DV-21
Corning, NY 14831
607-974-3744

Thomas N. Strom
NASA Lewis Research Center
Advanced Gas Turbine and
Heavy Duty Transport Tech. Project
21000 Brookpark Road, M/S 23-2
Cleveland, OH 44135
216-433-4000, ext. 6829, FTS 294-6829

Paul Sutor
Midwest Research Institute
425 Volker Blvd.
Kansas City, MO 64116
816-753-7600

Denis J. Taylor
Ontario Research Foundation
Centre for Alternative Fuel
Utilization
Engineering Sciences Division
Sheridan Park Research Community
Mississauga, Ontario, L5K 1B3, Canada
416-822-4111, ext. 418

Gerald J. Tennenhouse
Ford Motor Company
Ceramic Materials Department
PO Box 2053, S-2079
Dearborn, MI 48121
313-594-0982

V. J. Tennery
Oak Ridge National Laboratory
Metals and Ceramics Division
PO Box X
Oak Ridge, TN 37831
615-574-5123

Richard J. Trippett
General Motors Corporation
General Motors Research
Laboratories
Fluid Mechanics Department
12 Mile and Mound Roads
Warren, MI 48090
313-575-3008

Olof Vingsbo
University of Houston
Department of Mechanical
Engineering
Houston, TX 77004
713-749-2448

L. D. Wedeven
SKF Industries, Inc.
1100 First Avenue
King of Prussia, PA 19406-1352
215-265-1900, ext. 298

James J. Wert
Vanderbilt University
Mechanical and Materials
Engineering Department
PO Box 1621, Station B
Nashville, TN 37235
615-322-3583

R. Ted Wimber
Deere and Company
Metals Research Dept.
3300 River Drive
Moline, IL 61265
309-757-5832

Ward O. Winer
Georgia Institute of Technology
School of Mechanical Engineering
Atlanta, GA 30332
404-894-3270

Carl C. Wu
Research Engineer
Naval Research Laboratory
Ceramics Department
4555 Overlook Avenue, SW, Code 6360
Washington, DC 20375
202-767-2007

Marc Yesnik
Borg-Warner Corporation
Wolf and Algonquin Roads
Des Plaines, IL 60018
312-827-3131, ext. 437

T. M. Yonushonis
Cummins Engine Company
Box 3005, Mail Code 50183
Columbus, IN 47202-3005

C. S. Yust
Oak Ridge National Laboratory
Metals and Ceramics Division
PO Box X
Oak Ridge, TN 37831
615-574-4812

Martin Zlotnick
Hudson Research Institute
141 East 88th Street
New York, NY 10128
212-860-9774

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    M. C. Shaw

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    K. F. Dufrane
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    H. E. Hintermann

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    D. W. Richerson

58. CHALK RIVER NUCLEAR LABORATORIES, Engineering Research Branch, Special Projects Division, Chalk River, Ontario, KOJ 1JO, Canada

    R. M. Lepp

59. CORNING GLASS WORKS, Ceramic Development Dept., Sullivan Park DV-21, Corning, NY 14831

    Louis Socha

60–61. JOHN CRANE-HOUDAILLE, INC., Research and Development, 6400 Oakton Street, Morton Grove, IL 60053

    Ming Chang
    John Hamaker

62–66. CUMMINS ENGINE COMPANY, Box 3005, Columbus, IN 47202-3005

    J. X. Cheng
    C. F. Musolff
    Malcolm Naylor
    Ralph Slone
    T. M. Yonushonis

67. DARPA/DSO/MSD, 1400 Wilson Blvd., Arlington, VA 22209

S. G. Wax

68–69. DEERE AND COMPANY, Technical Center, 3300 River Drive, Moline, IL 61265

Gopal Revankar
R. T. Wimber, Metals Research Dept.

70. DOW CHEMICAL U.S.A., Government Contract Research, 566 Building, Midland, MI 48667

P. R. Stoesser

71. EATON CORPORATION, Materials and Engineering, Engineering and Research Center, P.O. Box 766, 26201 Northwestern Highway, Southfield, MI 48037

J. C. Bierlein

72. ECOLE POLYTECHNIQUE, Mechanical Engineering Dept., C.P. 6079, SUCC 'A', Montreal, Quebec, H3C 3A7, Canada

Jean-Pierre Chalifoux

73. EG&G SEALOL, Materials Characterization, 50 Sharpe Drive, Howard Industrial Park, Cranston, RI 02920

James Derby

74. EG&G SEALOL, Research and Development, 442 W. Fullerton, Elhurst, IL 60116

J. A. Hilaris

75. ESSO PETROLEUM CANADA, Research Division, P.O. Box 3022, Sarnia, Ontario, N7T 7M1, Canada

W. N. Rogers

76. EXXON RESEARCH AND ENGINEERING COMPANY, Corporate Research Dept., Route 22, E, Annandale, NJ 08801

T. E. Fischer

77–78. FALEX CORPORATION, 2055 Comprehensive Drive, Aurora, IL 60505

H. M. Anderson
L. R. Heerdt

79. RICHARD S. FEIN ASSOCIATES, 35 Sheldon Drive, Poughkeepsie, NY 12603

R. S. Fein

80. FORD MOTOR COMPANY, Ceramic Materials Department, P.O. Box 2053, S-2079, Dearborn, MI 48121

G. J. Tennenhouse

81–82. GENERAL ELECTRIC COMPANY, Corporate Research and Development, One River Road, Schenectady, NY 12301

Gary Leonard
R. L. Mehan

83. GENERAL MOTORS CORPORATION, Detroit Diesel Allison Division, 13400 W. Outer Drive, Speed Code R03B, Detroit, MI 48239

N. S. Hakim

84–87. GENERAL MOTORS CORPORATION, General Motors Research Labs., 12 Mile and Mounds Roads, Warren, MI 48090

J. E. Hunter
F. G. Rounds
E. W. Schneider
R. J. Trippett

88. GEORGIA INSTITUTE OF TECHNOLOGY, School of Mechanical Engineering, Atlanta, GA 30332

W. O. Winer

89. HANFORD ENGINEERING DEVELOPMENT LABORATORY, National Tribology Program, P.O. Box 1970, W/A 40, Richland, WA 99352

R. N. Johnson

90. HUDSON RESEARCH INSTITUTE, 141 East 88th Street, New York, NY 10128

Martin Zlotnick

91. IBM RESEARCH, Magnetic Recording Dept., P.O. Box 218, Room Room 38-107, Yorktown Heights, NY 10598

V. D. Khanna

92–93. IIT RESEARCH INSTITUTE, 10 West 35th Street, Chicago, IL 60616

Jane Adams
V. Aronov
S. Bhattacharyya

94. INSTITUTE FOR DEFENSE ANALYSIS, 1801 N. Beauregard Street, Alexandria, VA 22311

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