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SELECTION AND USE OF WEAR TESTS FOR METALS

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Foreword

The symposium on Selection and Use of Wear Tests for Metals was presented at November Committee Week of the American Society for Testing and Materials held in New Orleans, La., 17–21 Nov. 1975. Committee G-2 on Erosion and Wear, Subcommittee G02.30 on Wear, sponsored the symposium. R. G. Bayer, IBM Corporation, presided as symposium chairman and served as editor of this publication.

Related ASTM Publications

Impact Testing of Metals, STP 466 (1970), $21.25, 04-466000-23

Instrumented Impact Testing, STP 563 (1974), $21.75, 04-563000-23

A Note of Appreciation to Reviewers

This publication is made possible by the authors and, also, the unheralded efforts of the reviewers. This body of technical experts whose dedication, sacrifice of time and effort, and collective wisdom in reviewing the papers must be acknowledged. The quality level of ASTM publications is a direct function of their respected opinions. On behalf of ASTM we acknowledge their contribution with appreciation.

ASTM Committee on Publications

Editorial Staff

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Introduction

In the last decade, the fields of lubrication, friction, and wear have matured into the science of tribology. Along with this maturity, the number of books, periodicals, and conferences concerned with this subject has grown, making available to the engineer a variety of material. Such publications provide references, particularly in terms of the phenomena involved and design approaches, for the engineer and designer occasionally concerned with tribological problems as well as the specialist. However, with this growth, little attention has been devoted to the specific areas of wear testing.

Because of this lack and ASTM's special interest in testing, the ASTM Subcommittee on Wear (G02.30) of the Erosion and Wear Committee (G-2) felt it appropriate that the consideration of wear testing be encouraged and stimulated. As a means of doing this, it was decided to sponsor symposia on the subject of wear testing and to document the papers in ASTM special technical publications. It is intended that these publications would provide useful state-of-the-art references on the subject of wear testing. As such they would provide a ready summary of current techniques and problems for the experienced tribologist. They will also be useful to the occasional investigator and those new to tribology in the selection and use of wear tests and for the assessment of their relevance to machine applications.

While there are many ways to subdivide or categorize wear testing, it was decided that a subdivision based on type of material tested was most appropriate. It was also decided, because of the relative maturity of the area of metal wear testing, that this area be the subject of the first symposium and special technical publication. As a result, this publication contains the majority of papers presented at the Symposium on the Selection and Use of Wear Tests for Metals, held 20 Nov. 1975, in New Orleans, La.

All papers at the symposium were invited with the intention that such an approach would ensure a well rounded coverage of the subject. The aim was to have the subject of wear testing of metals treated not only from the standpoint of the desired results but also in terms of the various modes of wear and applications for which the testing is done. The papers presented in this publication accomplish this aim.

M. B. Peterson's article considers the general objective and approaches to wear testing. Articles by K. R. Mecklenburg and R. J. Benzing, F. Borik, and F. G. Hammitt treat the problems associated with adhesive, abrasive, and erosive wear testing. The area of wear testing for light equipment application is covered by R. C. Tucker, Jr. and A. E. Miller, while R. G. Bayer and A. K. Trivedi consider the specific area of testing for office and data processing equipment. The final article by K. Ludema discusses the use of wear debris in tests and applications to establish simulation.

The main theme of the papers is the development of a state-of-the-art summary of these various aspects, with emphasis on sliding wear situations. It should be noted that while there are many similarities in the equipment used in the evaluation of lubricants and wear testing, they are distinct areas. In lubricant evaluation, the properties of the lubricant and its ability to control friction and wear are of primary concern. In these tests, the wear generated is frequently used as a measure of a lubricant's ability to exert this control. However, in wear testing the primary goal is the determination of specific and relative wear rates of various materials under specific conditions of applications and their dependencies. This difference in goals results in different test techniques and evaluation procedures, while the test equipment may be similar. The distinction between these two area will be evident from the considerations contained in this publication.

ASTM Subcommittee G02.30 previously had sponsored a symposium on the "Significance of Wear," with the papers being published in the Sept. 1974 issue of *ASTM Standardization News*. These papers are:

"Understanding Wear," M. B. Peterson, M. K. Gabel, and M. J. Devine
"The Perspective on Wear Models," K. C. Ludema
"The Physics and Chemistry of Surface," E. Rabinowicz
"The Design and Wear of Sliding Bearings," J. McGrew
"Design for Wear of Lightly Loaded Surfaces," R. G. Bayer

Copies of *ASTM Standardization News* are available from ASTM Headquarters and are recommended as companion articles to those contained in this special technical publication. The primary emphasis in those articles was on wear phenomena and design approaches, which are complimentary to the area of wear testing.

It is hoped that this publication will not only provide a useful state-of-the-art guide in the selection and use of wear tests, but also will stimulate further activity and discussions in this vital area.

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M. B. Peterson[1]

Wear Testing Objectives and Approaches

REFERENCE: Peterson, M. B., "**Wear Testing Objectives and Approaches,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, pp. 3–11.

ABSTRACT: Wear tests are performed for a variety of reasons: to gain an understanding of the wear process, to determine the effects of variables, to characterize materials, and to select materials for specific applications. Selection of test rigs and procedures is only difficult where simulation of an application is necessary. Under these circumstances it is necessary to consider the important variables which affect the wear process; primary consideration should be given to the surface temperature. Many types of test rigs are available to make such evaluations. The development of a standard wear test is considered to be urgently needed.

KEY WORDS: wear tests, metals, wear, friction factor

Wear has been a subject of practical interest for at least a thousand years, yet it has not received a great deal of theoretical attention. The thought is prevalent that it is easier to replace the part when it wears rather than to provide adequate life in design. This may have been true at one time; however, in the present economic climate it is a very costly practice for the following reasons.

1. Maintenance is expensive; it is not just the cost of the part and its replacement but also the fact that a maintenance staff must be available at all times waiting for maintenance actions.
2. Parts and materials are in short supply; accordingly, equipment is out of service longer or larger inventories must be maintained.
3. Worn parts cause secondary problems such as increased vibration (leading to fatigue), shock loading, misalignment, and accelerated wear.
4. Down time for part replacement due to wear causes a loss of productivity and associated manpower.

Recently, because of more effective cost accounting, industry has begun

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to realize that wear control is important, and new information is being sought which will allow adequate designs for wear. However, they find the field of wear, unlike corrosion and fatigue, very confusing in that it appears to lack organization in both principle and practice. For example: (*a*) wear is not adequately defined, and it means different things to different people. (*b*) There is a lack of a collected body of information or unified organization of that which is available. Each investigation seems to stand alone, unconnected to the whole. Mechanisms by which wear occurs have not been adequately defined and are still the subject of controversy. (*c*) A variety of test equipment is used, and there has been little attempt at standardization or correlation. (*d*) Most important, no simple design tools or techniques are available which allow present information to be easily applied.

Those engaged in wear research and testing must "come to the rescue" and assist in the organization and definition of their field. To start, three questions must be addressed.

1. Is there an adequate definition of wear?

2. Is sufficient information available to adequately identify and classify different unique mechanisms by which wear occurs?

3. Could we adopt a standard test device or procedure which would allow a collective body of knowledge to accumulate?

In the following sections, these three questions are discussed. The conclusion drawn is a qualified yes to all three questions.

Definition of Wear

The dictionary definition and the general concept of wear is "to impair by usage." This, of course, is much too broad for a technical definition. The American Society of Lubrication Engineers (ASLE) and others have accepted the definition as "removal of material by mechanical action," while the Organization for Economic Cooperation and Development (OECD) Research Group on wear of engineering materials defines wear as the "progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface." In both of these definitions, the concept of removal has been introduced. Implied in both definitions is the idea of unwanted removal to differentiate wear from other forms of removal, such as machining. These definitions are limiting, however, since they do not consider the results of corrosive, chemical, or fluid action. Most researchers would consider this to be a predominate form of wear. Thus, it seems appropriate to define wear as the "unwanted removal of material by chemical or mechanical action."

Such a definition is not precise since plastic flow may occur, clearances become larger, and, for all practical purposes, wear has occurred even though no material has been removed. However, we may adopt the point of view that all definitions are approximations, and some inaccuracies will occur. With this point of view in mind, the latter definition appears to be adequate.

Classification of Wear Processes

There have been many attempts to classify wear processes. The conventional method is what might be called "process" descriptions where the classification is based upon a physical description of the process: abrasion, adhesion, deformation, fretting, thermal, etc. This clearly identifies the process, but lacks uniqueness since wear may take place by the same method in several of the described processes; for example, fretting and adhesion. The *Metals Handbook* (Vol. 1, 1961) classified wear by materials, that is, metal versus nonmetal or abrasive, metal versus metal, or metal versus liquid or vapor. In addition, the distinction is made between lubricated or nonlubricated wear. Such a classification, based upon conditions, is of limited use; however, some conditional classifications are valuable. For example, "high stress" abrasion and "low stress" abrasion can be used to classify materials for certain applications.

Kislik [*1*][2] uses a classification based upon sliding processes: (*a*) mechanical destruction of interlocking asperities, (*b*) asperity fatigue, (*c*) failure due to working, (*d*) flaking of oxide films, (*e*) molecular interaction, and (*f*) mechanical destruction due to high temperature.

Kragelskii [*2*] suggests that the proper classification should be based upon the way the junctions are broken; that is, elastic displacement, plastic displacement, cutting, destruction of surface films, and destruction of bulk material. Archard [*3*] suggests a classification which distinguishes between elastic and plastic deformation of the contact area and between surface and bulk material effects. This classifies wear into four main groups.

Wear has also been classified into categories based upon the results achieved. Archard and Hirst [*4*] use "mild" and "severe" which distinguishes whether a material combination can or cannot be used. Other such terms used include excessive, normal, etc. Although this classification is useful, what might be severe for one application could be mild for another.

Peterson [*5*] suggests that the classification should be based upon how the particle is removed and whether the event takes place at the asperity level, in bulk, or via a surface film. The following methods of removal were suggested: adhesion and shear of junctions, surface fracture or break up, fatigue, cutting, melting, reactions, plastic deformation, scraping loose reaction products, and tearing.

The advantage of this classification is that it conforms to the definition of wear as a removal process. Even more important, it allows the

[2] The italic numbers in brackets refer to the list of references appended to this paper.

application of established fundamental quantities to each process, that is, fracture mechanics to surface fracture, thermal quantities to melting, etc. The difficulty with this classification is that it is a cumbersome one from a practical point of view. For example, abrasion, erosion, and fretting are well understood and distinguishable processes yet do not receive a unique category because they are each composed of several removal processes.

Unlike the definition where some vagueness is understandable, the lack of a clear cut classification of wear processes leads to the impression that the subject is hopelessly complicated and few improvements are possible.

In reviewing the classifications, the author is still of the opinion that wear classifications should be related to the mechanism of particle removal but should be modified as follows: adhesion, cutting, plastic deformation, fatigue, fracture, tearing, chemical reaction (erosion), corrosion film wear, melting, electrochemical, and dissolving.

It is quite possible that as more is understood of wear processes, these may be changed. For example, plastic deformation and fatigue wear may be essentially the same process, that is, particle removal by the generation and movement of surface cracks.

Whatever classification system might be adopted, it is felt that one is essential for the orderly collection of scientific information, the adoption of standard test devices and procedures, and the solution of service wear problems.

Wear Testing Objectives

The selection of a wear test depends not only on the mode of wear being investigated but also on the objective of the test. Wear tests are run for a variety of reasons; however, they generally fall into one of the following four categories: fundamental understanding, determination of the effect of variables, characterization of materials and lubricants, and selection of materials for a specific application.

In the first two categories the type of test rig is less important than how it is used or what information is gathered and what is now needed. In the last two categories, the type of test rig is of primary importance. These different categories are discussed in the following sections.

Fundamental Understanding

If we accept the particle removal process as a unit wear event, then the primary fundamental efforts should be directed to the description and classification of unique removal processes. Typical examples of such studies are the work of Lancaster [*6*], who has described the adhesion wear process, and more recently, the work of Suth [*7*] in describing deformation wear. Once a wear particle process is adequately defined, it can be quantified either theoretically or empirically, and test devices or conditions, which emphasize that form of wear, can be selected.

Considerable information has been acquired as to adhesion and cutting wear processes. Attention should now be directed to understanding the deformation (plastic, fatigue, fracture) and the corrosion processes. It is necessary to describe the unit wear event, and then relate this event to the operating conditions. Such studies eventually will allow a more rigorous description of unique wear processes.

The type of rig used is relatively unimportant as long as the conditions are adequately controlled. Careful observation of the wear process is much more important. Many new microscopic tools are available and can be used to the benefit of wear research. Examples are the scanning electron microscope, electron probes, particle size analyzers, and variations of electron diffraction. Using such techniques, for example, has allowed the National Aeronautics and Space Administration (NASA) to describe unique wear processes [*8*].

Effect of Variables on Wear

Fundamental understanding of the wear processes may take a long time. In the meantime, it is necessary to know the affect of the different variables. Those variables which are known to be important are given in Table 1.

TABLE 1—*Wear variables.*

Temperature	Atmosphere
Load	Material properties
Velocity	Types of lubrication
Contact area	Finish
Shape	Vibration
Sliding distance	Type of motion

If one adopts the point of view that wear is a practical subject and it is now time to reduce such principles as are available into design techniques, then it is necessary to collect information on variables which can be changed by design. Of these, three lack sufficient information—contact area, shape, and material properties. The role of contact area and shape is necessary to determine the extent to which bench test wear rates can be extrapolated into service where different geometries and shapes (usually larger) exist. Hopefully, wear rate will be independent of such factors so our wear test data will be applicable generally; however, this issue must be settled for each predominate wear mode.

Second, the effect of specific material properties on wear would aid in the material selection process. For example, Lancaster [*9*] investigated the wear rates of a variety of plastic materials and showed that the best correlation can be obtained (when there is no transfer) between wear resistance and toughness (tensile strength times elongation). These data give not only the wear rate for a given combination of materials but also show how variations in material can improve the situation.

The type of test rig is not particularly significant for such investigations as long as the desired type of wear or wear condition predominates. The selection is usually based on the type of service condition under study, such as high temperature, high velocity, reciprocating motion, etc.

Characterization of Materials and Lubricants

The solution to many wear problems could be resolved with relative ease if tabular wear rates were available on different material combinations. Such data can be used by the designer in initial material selection and as a guide by the supplier for materials development and improvement. This information is available for corrosion resistance, fatigue resistance, impact resistance, strength, thermal behavior, dimensional stability, and numerous other properties so it is not exactly an exciting new concept.

Of course, it has been said that a tremendous amount of data would be required. If we start with say five major forms of wear and multiply that by all the possible material combinations, including their potential surface coatings and modifications, then we would have to run each material combination a number of times to account for all lubricants, along with the effect of load, speed, temperature, type of motion, etc. Furthermore, several tests may have to be run at each condition to establish reproducibility. Thus, it appears to be an almost impossible task.

However, it is not this complicated. Everything does not have to be run, only those materials which are commonly used for wear resistant application. Typical lubricants can be used. One set of test conditions can be used as a standard to give reference wear data. Unusual conditions would be up to the individual using the standard wear data as a guide. The most important question to be decided is what type of test rig should be used for this purpose. The test rig, of course, will be dictated by the following: the type of wear, the specimen geometry, the selected operating conditions, the type of motion desired, and the need for multiple testing. If we assume that continuous motion is desired under moderate operating conditions and that multiple testing will be necessary, then the test rig becomes a function of the specimen geometry and the wear mode.

Erosion and two body abrasion apply special conditions and should be considered independently; however, one rig operating under different conditions (or geometries) should suffice for the types of wear commonly found in machine elements.

The following factors should be considered in the selection of the test geometry: uniformity of surface conditions, removal of wear debris, ease of wear measurement, ease of specimen fabrication, and multiple testing.

Uniformity of Surface Conditions—Almost all sliding geometries used in test devices consist of a small area specimen (pin) loaded against a larger specimen (disk, cylinder, flat). This geometry, although convenient, introduces unusual surface conditions in that the pin is in continuous contact and the surface goes in and out of contact. Thus, different temperature distributions are established in each specimen. Also, the surface which is out of contact for a large percentage of the time is more able to react with the environment, so surface films are more likely to appear on it than on the pin. If the pin's sliding surface has a spherical or cylindrical end, its area will change with time as wear occurs; this changes the surface temperature, pressure, and the shape of the contact. It can also change the lubricant film thickness and the type of lubrication at the interface. Although the same thing happens in most applications, it is desirable to avoid such a situation if possible in a standard test. With test devices which use the ring-on-ring geometry (with the faces in contact), no such conditions exist since both specimens are identical. Once the specimens have "worn in," all test conditions remain the same throughout the test.

Removal of Wear Debris—With the pin-disk geometries, the wear debris is removed easily from the surface. For the ring-on-ring configuration, it is not. Thus, the wear rates will be different, and their relative order will depend upon whether the wear debris is detrimental or not. The point-contact pins are influenced less by such considerations as the line-contact machines and area-contact machines.

Ease of Wear Measurement—It is much easier to measure the wear rates with those pin-disk geometries that have spherical or cylindrical surfaces. Since the diameter of the wear scar increases rapidly with the volume, wear rates can be determined in hours instead of days as in the case of the ring-on-ring. For the ring-on-ring, weight loss measurements must be made which introduce additional problems (weight changes not associated with wear).

However, with the pin-disk geometries it is much harder to measure the wear of the disk. This has caused many erroneous conclusions to be drawn in the literature. With the ring-on-ring, the wear of both specimens are measured.

Ease of Specimen Fabrication—Hemispherically tipped pins combined with steel disks are easy to fabricate with most materials; rings are somewhat more difficult and expensive. One also does not have the problem to decide which material to use to make the pin and the ring.

Multiple Testing—The pin on disk geometries lend themselves to multiple testing in that a large number of pins can be slid simultaneously against a common disk or shaft. For the ring-on-ring, a different rig will be necessary for each test. However, the test rig for the ring-on-ring can be very inexpensive. Most investigators have used banks of drill presses for this purpose. The manufactured portion of the rig consists mainly of the holders for the specimens. Based upon these considerations it is not easy to choose a standard rig.

In any case, a standard test device is needed as a reference point and should be developed. Of course, it will not make other rigs obsolete but merely will add a point of commonality to the field of wear testing.

A review of wear test rigs from which one can be chosen has been published by the Wear Subcommittee of ASLE [*10*].

Selection of Materials for a Specific Application

Since the selection of a material is based upon many considerations, other than sliding behavior and other sliding characteristics than wear, usually only a few materials must be evaluated. This simplifies the process to a large extent. However, unless expensive component tests are run, one must answer the question, "Does this bench test simulate the application?"

It will simulate the application if all the variables listed in Table 1 are the same in the bench test as in the application. This presents no particular problem in most instances. The shape is selected to be very similar to the application, and the tests can be run at the same velocity, ambient temperature, atmosphere, using the same materials, lubricants, and finishes. If extraneous vibrations are eliminated, then it becomes a matter of choosing the proper load and area since wear rate is considered to be independent of sliding distance. For light-loaded applications, there is no problem since similar loads and areas can be used. This is, however, impossible for most heavy-loaded applications since most wear test rigs in use have too little power. Generally, the same pounds per square inch loading is used; however, this means that a much smaller area of contact is used. Since it has not been shown that the wear rate is independent of wear rate *for all types* of wear, this introduces an element of uncertainly into the simulation. If research efforts were directed to this point, simulative wear testing would be greatly enhanced.

It should be pointed up, however, that much of the wear which occurs in service is due to abrasive dirt or wear particles in the lubricant. There also may be occasions when there is insufficient lubricant. Both of these factors must be taken into account in simulative testing.

All things considered, the state of wear knowledge has not advanced to the status where a large amount of confidence can be placed in predicting service wear from bench tests.

Conclusions

A cooperative effort is needed to provide improved organization to the field of wear and wear testing. Some of the most critical needs are as follows.

1. An improved classification of wear processes based upon mechanisms must be established.

2. Considerable basic research in needed to better define wear mechanisms, particularly in the areas of wear caused by deformation, fatigue, and corrosion.

3. Further wear testing is necessary to assist in the translation of wear data into service. Most important parameters are the effects of contact area and shape. The influence of specific material properties on wear for a well defined wear mechanism would also be extremely helpful.

4. Wear coefficients for important material combinations obtained with a standard test device are badly needed by industry, since very little data exist.

5. The development of a standard wear test is considered to be the most important contribution which could be made presently.

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K. R. Mecklenburg[1] *and R. J. Benzing*[2]

Testing for Adhesive Wear

REFERENCE: Mecklenburg, K. R. and Benzing, R. J., "**Testing for Adhesive Wear,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, pp. 12–29.

ABSTRACT: This paper presents a technical definition of adhesive wear, comparing adhesive wear to abrasive, erosive, corrosive, fretting, and other forms of wear. The effects of various material factors and test parameters on adhesive wear are described. How to select materials and test conditions to produce the maximum adhesive wear are outlined. Test repeatability and accuracy are included.

KEY WORDS: wear, wear tests, mechano-chemical wear, thermal wear, adhesion, abrasion, fatigue (materials), erosion, corrosion, thermal shock, adhesive wear testing

Testing for adhesive wear of metals is a complex task involving many variables. In this paper, some of the various factors affecting wear will be discussed, including physical property considerations and test geometry configurations. When the adhesive wear process has been distinguished from other wear processes, how to tailor the test element configuration and environment to produce specific wear results can be explained.

The first thing to do is to define what adhesive wear is and how adhesive wear differs from other forms of wear. Then material factors affecting this wear process will be discussed, including the effects of hardness, grain size, and surface finish. Next, the effects of test element geometry will be mentioned, including how to select the best geometry for a specific result. The repeatability and reproducibility of these results will be discussed from an engineering viewpoint, including the problems associated with converting laboratory data into information for practical application.

Definition of Wear

Wear has been defined as "to impair, waste, or diminish, by continual attrition, scraping, or the like; ... to exhaust or lessen the strength of ..." [*1*].[3] That is one definition but not necessarily the best. In the technical

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[3] The italic numbers in brackets refer to the list of references appended to this paper.

literature, wear is defined variously as "deterioration of surface due to use" [2], "the undesired removal of material due to mechanical action" [3], and "the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface" [4]. Only from the last reference is there any mention that wear may not always be bad, "wear is usually detrimental, but in mild form may be beneficial, e.g., during running-in."

The process of wear has not been clearly established. There are various investigators who have their own versions as to how wear occurs, for example, Bowden and Tabor [5], Tabor [6], Kragelskii [7], and Landheer and Zaat [8]. There is no unilateral agreement as to what occurs, but they all agree that the "flat" surface is not really flat but composed of asperities (minute peaks), even on a generally flat surface. As such, contact between two surfaces produces a condition as shown in Fig. 1. The apparent area of contact is the entire surface; the real area of contact is

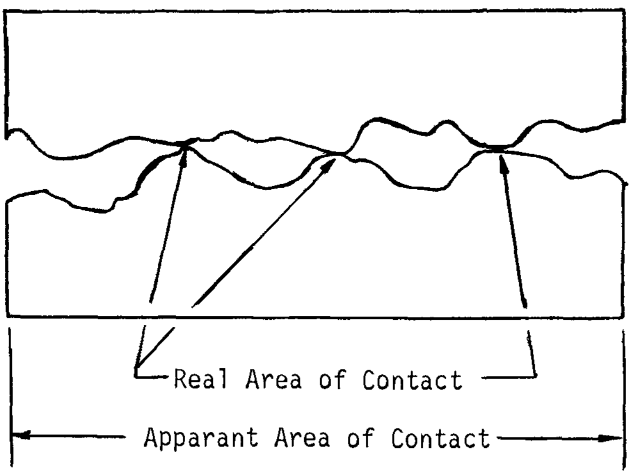

FIG. 1—*Asperity contact.*

the asperity contact. Deformation of the asperities occurs until the real area of contact increases to support the load. The amount of asperity deformation is related to the strengths of these two contacting materials and includes both plastic (nonreversible) and elastic (reversible) deformation. Other factors, such as environment, load, sliding velocity, and temperature, also affect the amount of deformation, but there does not exist, as yet, any single mathematical relationship containing combinations of more than three of the factors that influence the amount of asperity deformation.

Wear can be categorized as mechanical, mechano-chemical, or thermal. Mechanical wear is defined as "removal of material due to mechanical processes under conditions of sliding, rolling, or repeated impact" [*4*]. Mechanical wear includes adhesive, abrasive, fatigue, and fretting wear. Mechano-chemical wear is wear in which both mechanical and chemical factors are important, usually each facilitating the other. Mechano-chemical wear includes fretting corrosion, erosive, and corrosive wear. Thermal wear is defined as "removal of material due to softening, melting, or evaporation during sliding or rolling" [*4*]. Wear by diffusion of separate atoms from one body to the other, at high temperatures, is sometimes denoted as thermal wear. Also, thermal shock, thermal fatigue, and high-temperature erosion may be included in the general description of thermal wear.

Wear can also be categorized according to the degree or amount of wear, without regard to the specific type of wear process involved. Wear can be normal, mild, or severe, with no firm delineation from one to the other. Normal wear is the loss of material within the design limits expected for the specific intended application [*4*]. Normal wear also depends upon economic factors, such as the expendability of the worn part. Mild wear is a form of wear characterized by the removal of material in very small fragments [*4*]. The term "mild wear" is an imprecise term that is frequently used and generally contrasted with severe wear. Severe wear is defined as "a form of wear characterized by removal of material in relatively large fragments" [*4*]. "Mild" and "severe" are often used when the phenomena being studied are related to the transition from small to large wear debris particles.

Other terms frequently encountered in dealing with wear are scratching, scoring, scuffing, galling, ploughing, ridging, rippling, pitting, scabbing, spalling, and shelling. These terms are related to the appearance of the surface after relative motion has produced the wear. *Scratching* is the formation of fine scratches in the direction of sliding. Scratching may be due to asperities on the harder slider, to hard particles embedded in one of the materials, or to hard particles between the surfaces. *Scoring* is the formation of severe scratches in the direction of sliding and may be due to local solid-phase welding or to abrasion. *Scuffing* is a synonym for scoring, and the condition is more severe than scratching. *Galling* is a form of severe scuffing associated with gross surface damage or failure of the part. Galling is used generally when the actual wear process has been masked by the gross surface damage. *Ploughing* is the formation of grooves by plastic deformation of the softer of two surfaces in relative motion. Ploughing is usually the displacement of material, differing from scratching which is associated with the removal of material. *Ridging* is a deep form of scratching in parallel ridges and is caused usually by plastic flow of the subsurface layer. *Rippling* is the formation of periodic ridges and valleys transverse to the direction of motion. *Pitting* is any removal or displacement of material resulting in the formation of surface cavities.

Scabbing is the formation of bulges in the surface. *Spalling* is the separation of particles from a surface in the form of flakes, usually a result of subsurface fatigue and generally more extensive than pitting. *Shelling* is a term used in railway engineering to describe an advanced phase of spalling.

These terms all relate to the appearance of the worn surface. Scratching, scoring, scuffing, and galling are basically degrees of severity in material removal associated with one dimension, length. Ploughing, ridging, and rippling are material displacement characteristics, again associated with one dimension, length, with ridging and rippling being along and across the length dimension. Pitting, scabbing, spalling, and shelling are degrees of severity of material removal in basically three dimensions (irregularly shaped volume removal), with scabbing and pitting being somewhat related as male and female.

Adhesive Wear

Adhesive wear is defined as "wear by transference of material from one surface to another during relative motion, due to a process of solid-phase welding" [*4*]. Adhesive wear also means "damage resulting when two metallic bodies rub together without the deliberate presence of an abrasive agent" [*3*].

The formulation of a working definition or understanding of adhesive wear includes the concepts that the rubbing of the surface asperities of two metallic specimens causes surface oxide films to be broken, resulting in intimate contact between the two metal surfaces. When the adhesive forces between the two materials are greater than the body forces of either of the specimens, adhesive wear occurs. The adhesively formed junction causes part of the surface of the (generally) weaker material to be removed. The removed material may remain attached at the adhesive junction, causing metal transfer, or may become dislodged and remain between the two surfaces as wear debris, causing further damage as an agent for abrasive wear.

Other Wear Processes

In order to discuss adhesive wear, distinctions must be made between adhesive wear and other types of wear. The following definitions, basically from Ref *4*, are presented to enable the distinctions to be made.

Abrasive Wear—Abrasive wear (or abrasion) is wear by displacement of material caused by hard particles or hard protuberances.

Scouring abrasion is caused by the presence of hard particles between two surfaces in relative motion or by the presence of hard protuberances on one or both of the relatively moving surfaces. The abrasive particles may be embedded in one of the surfaces. Scouring abrasion may occur in a dry state or in the presence of a liquid.

Abrasive erosion is due to relative motion of solid particles which are entrained in a fluid, moving nearly parallel to a solid surface.

Fatigue Wear—Fatigue wear is the removal of particles detached by fatigue arising from cyclic stress variations and is thought by some to be the most predominant wear mechanism in most practical machine components.

Fretting Wear—Fretting is a wear phenomena occurring between two surfaces having oscillatory relative motion of small amplitude. The term "fretting wear" should not be used to describe fretting corrosion.

Fretting corrosion is a form of fretting in which chemical reaction predominates. Fretting corrosion is often characterized by the removal of particles and subsequent formation of oxides, which themselves are often abrasive and so increase the wear. Fretting corrosion can also involve other chemical reaction products which may not be abrasive.

Erosive Wear—Erosive wear is loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles. When the relative motion of the solid particles is nearly parallel to the solid surface, the wear is called abrasive erosion. When the relative motion of the solid particles is nearly normal to the solid surface, the wear is called impact erosion or impingement erosion.

Fluid erosion is wear due to the action of liquid or gas streams containing liquid droplets. Fluid erosion can be intensified by chemical action and normally does not include cavitation erosion.

Cavitation erosion is wear of a solid body moving relative to a liquid in a region of collapsing vapor bubbles which cause local high impact pressures or temperatures. Cavitation erosion is the wear process and should not be confused with cavitation, which refers only to the formation and collapse of cavities within the fluid.

Corrosive Wear—Corrosive wear is a wear process in which chemical or electrochemical reaction with the environment predominates. Corrosive wear is usually a mild form of wear but may become serious at high temperatures or in a moist environment.

Oxidative wear is a corrosive wear process in which chemical reaction with oxygen or an oxidizing environment predominates.

Thermal Wear—Thermal wear is defined as the removal of material due to softening, melting, or evaporation during sliding or rolling. Generally speaking, thermal wear is not as significant as any of the mechanical or mechano-chemical wear processes. Thermal wear includes atomic (or diffusive) wear, thermal shock, and high temperature erosion.

Atomic wear is wear between two contacting surfaces in relative motion attributed to migration of individual atoms from one surface to the other. Diffusive wear attributes the loss of material to diffusion, again an atomic or molecular activity. Both atomic and diffusive wear are augmented by increased temperature and increased atomic activity.

Thermal shock can produce unwanted material removal (wear) from the surface if the surface temperature is rapidly changed, causing differential thermal expansion between surface layers and the body of the material.

High temperature erosion has also been listed as a mechanism of wear. Increased molecular activity and reduced material strengths with increased temperature allow erosion to occur at a greater rate than at normal temperatures. Whether or not the process should be classified separately is questionable.

Material Factors Affecting Adhesive Wear

Many factors affect the amount of wear that is generated in a situation of relative motion between two bodies. There are two basic categories of factors used in the presentation. These categories are materials factors and test parameter effects. The first deals with the materials aspect of adhesive wear; the second deals with the conditions imposed upon the materials.

Both categories have been subdivided into factors that can be discussed individually.

Basic Material Selection

In testing for adhesive wear, care must be exercised in the selection of materials to be used for the wear studies. If wear is to be avoided or minimized, the specimen materials should have tensile strengths that are quite different from one another, as babbitt on steel. If wear is to be enhanced, the specimen materials should have tensile strengths that are nearly equal, such as the same material for each of the relatively moving specimens [*9,10*].

Adhesive wear exists because the metal-to-metal contact junctions form cold welds (solid-phase welding) at the sliding interface. These welded junctions must have greater strength than the body strength of at least one of the specimens, so that the shearing of material that must happen in the vicinity of the sliding interface occurs within the body of the weaker material. The strongest welds form when the surface films on both solids are penetrated. This generally occurs when identical materials are used; the conditions which disrupt one surface are equally capable of disrupting the other.

Wear occurs as material is removed from one of the specimen surfaces. If the welded junction completely or even partially deteriorates, the removed material may become wear debris, actively causing abrasive wear (if still between the surfaces) or merely fall free of the specimens.

Another example of the care that must be exercised in the selection of materials can be found in the disposition of the wear debris. If one of the two materials in relative motion happens to be considerably softer than the other, a site for debris accumulation may exist. In the example of steel rubbing on babbitt (one of the possible combinations for minimal wear), the babbitt can also be impregnated with some wear debris without having the debris become abrasive to the steel [*3, 9, 10*].

Surface Finish

Generally speaking, the rougher the surface, the higher the wear rate, as the asperity contact is more intense. That is, for a given load, the number of asperities in contact is less with a rough surface than with a smooth surface, resulting in greater loads per asperity for the rough surface.

On the other hand, very smooth surfaces lose the ability to store contaminants or wear debris due to the absence of the valleys found between the relatively large asperities of a rough surface [*10*]. Also, smooth surfaces may result in higher molecular interaction forces, as more of the two surfaces are in close proximity, where the greater attractive forces can contribute to adhesive wear.

Stresses sufficiently high enough to cause deformation and penetration of the surface oxide layers generally are localized and only occur when two asperities on the surfaces come into unusually close proximity. The welds which form during adhesive wear are initially small, and they can only grow to become large if the load is maintained for an appreciable distance of sliding. If the motion is across the direction of the surface finishing lines, the load is less likely to be maintained—and the welds less likely to grow—than if the motion is in the direction of the surface finish [*9*].

Hardness

Resistance to wear generally increases as the hardness increases, provided that other factors remain constant. To understand why this happens requires returning to the asperity contact viewpoint.

A certain amount of plastic deformation occurs in the asperity contacts. The amount of deformation depends upon the strength of the materials, surface roughness, and load, among other factors. Because the asperities tend to come into contact repeatedly as the operating cycle is repeated, small amounts of deformation continue to take place. The result is the work hardening of the asperities with a consequent decrease in the ductility of the metals. After a time, depending upon the amount of deformation at each contact, the asperities become brittle and tend to break off [*10*].

It is not desirable to use fully annealed materials, since fully annealed materials tend to work harden more than hardened materials. If the surface layers become work hardened and adhere strongly to the other body, the deformation induced by sliding will extend to some depth below the surface since the material there is weaker. To reduce wear and especially adhesive wear, the objective is to make the surface layers weaker than the material below so that material rupture occurs at or near the surface [9].

If the surface is a normal surface, an oxide coating exists. Other types of surface films (to be discussed later) can also be used to protect the metals from intimate contact. Without intimate contact, wear by adhesion is not a problem, if it exists at all. If the surface films are penetrated, the surface layers of the materials can be exposed for adhesive bonding and adhesive wear. To keep the surface films from being penetrated, a hardened undersurface is desirable. The hardened undersurface will not flex or deform as much as a softer or unhardened surface. Undersurface flexure can lead to fatigue failure of the surface coating, exposing bare metal.

When one body is considerably harder than the other, wear and surface damage are effectively limited to the softer material [9].

To increase wear resistance, hardness should be increased by alloying or heat treatment [10]. Work hardening fails to increase the resistance of materials to wear. Surface hardening treatments, such as nitriding, are not effective in severe wear conditions (see the section on Surface Coatings).

Grain Size

One of the factors affecting plastic deformation—grain size—will affect the wear of steels. Unlike single crystals which have free boundaries, the grains of a polycrystalline material are influenced by their neighbors during deformation. The constraining action on deformation is least when the average grain diameter is considerably greater than the microscopic areas of contact [11]. Thus, contact over a large number of grains will sharply reduce the wear rate. A large grain size is not desirable.

Welds formed during asperity contact grow during sliding, and anything that can be done to inhibit weld growth is desirable. A discontinuous structure is an advantage. Thus carbon steels, which vary in hardness and composition from point to point, are less prone to build up large welds than are homogeneous materials, such as austenitic stainless steel or pure iron. When carbon steels slide together, their behavior in friction and wear is more characteristic of a pair of dissimilar materials than of similar materials. If austenitic stainless steel is used for both members, the friction is high and the surfaces become badly torn [9].

Surface Coatings

Increasing the hardness of a low-cost steel through heat treatment may be a good method to improve wear resistance, but there are other methods that have applications in mild wear conditions. The other methods for surface alteration to improve wear resistance are electroplating, carburizing, carbonitriding, cyaniding, flame plating, hard facing, chill casting, and flame and induction hardening. These methods should only be used for mild wear conditions, because in vigorous wear applications these coatings wear through too quickly to be effective [*10,12*].

Surfaces can also be protected from wear by the use of protective layers, such as layers of oxide, anodize, phosphating, paints, platings, or other coatings. The purpose of these coatings is to prevent the intimate contact of the metals by interspersing a "contaminating" layer between the asperities. Adhesive wear occurs when the protective layers are penetrated, whether the penetration is a result of surface layer fatigue, abrasion, or chemical attack [*9,10*].

It is also necessary to consider the mechanical properties of the surface layer as well as those of the metal. It is not desirable to use a soft metal which has a hard brittle oxide, for example, aluminum. A hard protective layer on a softer metal is disrupted more easily and penetrated by a contacting metal. The protective layer should be ductile to permit it to conform with the underlying metal and continue to protect it.

Lubricants

Lubrication is the most common and generally the most economical method of reducing wear. Those who deal with lubricants and lubrication cross many lines of discipline in trying to reduce wear. The basic function of lubricants, which may be liquid or solid, is to make the surface layers weaker than the material on which they are used, so that rupture of the asperity contacts occurs at or near the surface.

Test Parameter Effects on Adhesive Wear

The second category of factors that affect the amount of wear generated in a situation of relative motion between two bodies has been termed test parameter effects. These factors are basically ones that are controlled by the experimenter and are not materials related.

Contact Geometry

The effect of contact geometry on wear is not as severe as one might expect. The nature and magnitude of the motion has more effect. When experiments are conceived, considerable attention is given to specimen configuration, often with great efforts being made to assure the experimental specimen conformance to what is expected in the application.

In a recent survey [*13*], over one hundred differenct devices were found that were specifically designed to study friction and wear. A follow-up survey [*14*] revealed that over one hundred additional machines had been designed and built in the five-year period from 1965 to 1970.

The concern over testing in the configuration expected in the application is warranted, as wear seems to be a system function [*11*], at least with the knowledge available today. The multiplicity of the testing apparatuses, with their special geometries, environments, loading systems, and speed ranges, reflect the need to determine wear rates in as close-to-application configuration as possible.

In general, there is little disruption of the surface layers when two surfaces are loaded together normally. When tangential motion is introduced, the surface layers are disrupted, and small welds form and grow as sliding proceeds. Rolling systems are the least prone to suffer adhesive wear, while with sliding systems, adhesive wear is the most usual cause of unwanted surface damage. Gears operate with a combination of rolling and sliding and are intermediate in adhesive wear behavior. Of the gears, worm gears with their greater proportion of sliding are more apt to suffer adhesive wear than either spur or helical gears.

When materials run together dry in equilibrium conditions, the wear, W, may be expressed by the relationship

$$W = \frac{KPs}{p_m}$$

where

P = load,
s = distance of sliding, and
p_m = flow pressure, which for present purposes may be taken as the hardness [*9*].

There is no general agreement on the accuracy and completeness of this relationship. There are several other forms of the wear equation; not all forms use even the same parameters. For this discussion and this wear equation, wear is independent of the apparent area of contact. Thus, contact geometry would have little effect on adhesive wear. In severe wear, the constant, K, may take a value 10^2 to 10^4 greater than the K value found in mild wear conditions. In a practical problem of unsatisfactory wear in unlubricated conditions, the value of K should be determined.

It has been our contention that a constant of proportionality in a mathematical equation should be a constant. To change materials would be to allow the constant to change, but to increase the load or the speed should not change the constant of proportionality, as admitted in the distinction between severe and mild wear. There do seem to be some factors missing from the equation. The knowledge is admittedly not complete, but that is what is presently available.

With the given equation, there is no apparent contact area term as such. However, when load, *P*, is divided by the flow pressure, p_m, an area term does appear, with the area being the real area of contact. So, from the theoretical knowledge presently available, wear is independent of the apparent area of contact. This means that, according to present theory, wear is not affected by whether flats slide on flats or crossed cylinders slide relative to each other. In some limited work with a sphere on a plane, wear of the sphere was found to be linear with time. That is, as the apparent area of contact increased from the hertzian "point" contact of a sphere on a plane to that of a flattened surface (worn spot on the sphere) on a plane, the wear rate was constant [*15*].

Test geometry does affect the presence of wear debris in the contact zone. If the wear debris is not removed from the contact zone, regardless of the method that formed the debris, it can cause further wear by abrasion. This is the general factor that causes the test geometry to affect the wear rate. When a flat surface slides on a flat surface, the wear debris is generally trapped between the surfaces. When a sphere is slid against the underside of a flat surface, the wear debris can readily fall away from the contact zone (see Fig. 2).

Load

Returning to the wear equation, load, *P*, is shown directly related to wear. According to two of the many references on the subject, "wear increases almost proportionally with load" [*10*] and "if the rate of wear is measured, it is found that it increases with load . . ." [*9*]. Continuing from the latter reference, "a critical value [of load] is reached at which it [wear rate] suddenly increases perhaps by as much as two orders of magnitude." The increase in wear rate by as much as two orders of magnitude is the change in the proportionality constant, *K*, as wear moves from mild to severe.

With wear changing from mild to severe, certain phenomena are occurring. These phenomena are related to wear by their influence on the wear rates. As sliding occurs, the surface films (primarily oxide films) are broken, and the resulting intimate contact of the surfaces leads to adhesive wear. If the rate of oxide formation is greater than the destruction of the oxide coating, the wear is termed mild. As the load increases, the rate of oxide film destruction exceeds the rate of healing or regeneration of the oxide film. Then wear becomes severe. As severe wear occurs, frictional heating increases at higher surface temperatures, and the rate of healing may ultimately overtake the increase in the rate of damage. Severe wear can and has been encountered between two regimes of mild wear [*9,16*].

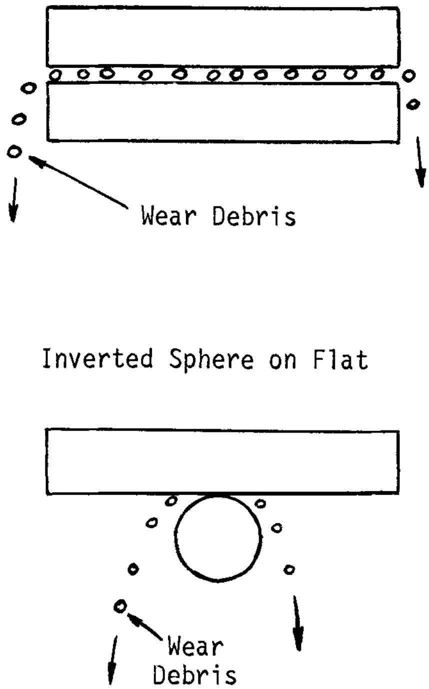

FIG. 2—*Disposition of wear debris.*

Changing load was the only consideration here, but changing speed will demonstrate the same effect. If speed is the variable, at slow speeds there is sufficient time for the healing processes, and at higher speeds frictional heating increases the healing rate.

Relative Velocity

The wear equation shows wear to be directly related to the sliding distance. The equation applies as long as the wear is considered mild (although one might also state that wear is considered mild as long as the equation applies). Further increase in velocity (greater than the velocity used in the mild wear regime) generally decreases wear, due to the increasing frictional heating and resulting large temperature gradient, causing healing of the ruptured surface layers. The effective area of contact may also be reduced as there is less time available for yielding under the applied load [*10*].

In many applications, the sliding is unidirectional. However, there are applications in which reciprocating motion is used. The constant velocity (unidirectional motion) is generally less destructive on surfaces than the varying velocity (magnitude and direction) of reciprocating motion [*11*].

Quite often, too, the amount of motion in reciprocating contacts is small, so that some of the wear debris is retained within the contact zone, augmenting adhesive wear with abrasive wear caused by the debris.

Atmosphere

Not too much can be said about the atmosphere in which the relative motion occurs. An atmosphere of pure oxygen will allow regeneration of protective oxide layers at a rapid rate. The regeneration rate in air will be slightly less. If inert gases are used for the atmosphere, the regeneration rate of oxide surface layers will be reduced greatly (although not eliminated because an absolutely oxygen-free atmosphere is very difficult to obtain).

A more common special atmosphere for adhesive wear testing is that of an ion-pumped vaccum chamber, in which the pressure is reduced to 10^{-8} torr or less. At these pressures, an oxide film (monolayer of oxide coating) may take several seconds to reform. Adhesive testing can be accomplished more easily in a vacuum environment; for once the surface layers are destroyed and removed from the specimens, intimate metal contact can occur, provided the exposure time of the surface is not too great.

Temperature

The effects of temperature have been mentioned throughout the preceding discussion. Some of these effects will be summarized here.

Wear rate, usually determined in cases of mild wear only, generally increases with temperature due to a decrease in hardness plus an increase in the chances of welding, plastic deformation, and corrosion by oxidation [*10*].

The region of severe wear can be reduced by raising the ambient temperature [*9*], allowing the surfaces to heal at a faster rate and thus reducing the severity of the wear.

The increase in temperature due to frictional heating also increases with the speed of sliding, and this effect may overtake the increase in the rate of surface damage with speed.

In fast moving machinery, a considerable amount of heat may be generated in a bearing, especially a journal bearing, and the thermal properties of the materials may become important. Heat dissipation through the bearing may be enhanced by the presence of a flowing liquid lubricant. The lubricant can not only provide the material for the easily sheared-surface junctions but also act as a heat transfer fluid to keep the bearing operating temperature lower.

Operating Time

The total time of operation affects wear, even under stabilized conditions. Both work hardening and fatigue of the metal surface depend on the number of stress cycles, in turn, related to the frequency of operation and the total time. The effects of work hardening and fatigue, both generating weakened surface and body forces resulting in surface wear and damage, have been mentioned previously.

There is another effect of time that should be mentioned. In continuous rubbing, the character of the surface itself is a dynamic thing as wear damages the surface, exposes the underlying material, and then proceeds to damage that material. The rate of wear often changes with time until an equilibrium surface condition is achieved. A process of this kind is known to almost every motorist and is called running-in or breaking-in of an engine. The running-in process involves changes in surface finish and sometimes surface profile, changes in the state of work hardening of the surface layers, and changes in the state of oxidation of the surface. Running-in is clearly a complex process, and no industrial method has yet been devised that is capable of generating a surface as resistant to wear as that produced by running-in [*9*].

Adhesive Wear Testing

Many of the factors affecting adhesive wear have been mentioned. However, the problem under consideration is testing for adhesive wear. Just how is that testing to be done?

First of all, a selection of material needs to be made. If austenitic stainless steel (like Types 301, 302, 304, or 316) is selected—for both members, naturally—adhesive wear will be augmented. Alloyed steels are to be avoided if possible, although some with 3 percent chromium could be used [*16*]. The use of alloyed steels would restrict the wear damage by employing weld-stopping grain boundaries and readily formed oxide coatings. A carbon steel or a hardened tool steel, sliding on babbitt or on a silver- or gold-plated hard surface are also to be avoided, as adhesive wear particles may be difficult to find.

After the specimens have been rough sized, the final surface should be ground to a surface finish of not better than 100 μin. rms, with the grind marks parallel to the expected direction of relative motion. In this manner, the ridges and valleys of the surface will have their greatest contact area. However, if the surfaces cannot be prepared this way, lapping to a superfinish of 0 to 4 μin. rms would work almost as well, providing good conformance, increased potential for many asperity contacts, and no relief for the wear debris. A surface finish of 16 to 64 μin. rms is to be avoided, as this range of surface finish has been found to provide the best adhesion of various solid lubricants with their respective binders. This surface finish range would also provide reservoirs for lubricants to be supplied to the system [*15*] and for debris to be removed from the interface [*10*].

If possible, the specimens should be annealed after grinding to eliminate any work hardening that may have been introduced during rough machining or finish grinding. The annealing operation should be prolonged as long as practical to allow grain growth to occur. If the annealing is done in a good inert atmosphere, the surface oxide formation will be minimized. Of course, if a hardened steel surface is used for adhesive wear experiments, there may be some difficulty generating adhesive wear debris; abrasive wear effects would obsure any adhesive wear effects that might have been present.

After heat treating, the surfaces of the specimens should be thoroughly cleaned; contamination in the form of oils, greases, phosphates, anodizations, or solid lubricants (especially molybdenum disulfide and graphite, if a minute quantity of water vapor is present) should not be permitted. It is also desirable to remove the oxide coating, but the only semi-practical way to do that is to sputter etch the surface in a vacuum environment of at least 10^{-9} torr.

The specimen configuration should employ flat surfaces, sliding together, with rapid oscillating motion of moderate amplitude, under an extremely heavy load. If a vaccum environment is available (an environment of at least 10^{-5} torr) the test atmosphere conditions would be improved. A large drive system would be required, because the welds formed during this type of operation would be extensive, and there would be considerable power required to shear the adhesive welds formed in the contact zone. If the specimens are thermally insulated from the holders, the generated heat can be retained for softening the surfaces and weakening the body forces of the specimens. There would be no need to provide heat to the system; there would be adequate energy dissipation in the form of heat. The time required to complete the experiment would not be great; complete surface welding should occur relatively rapidly.

If the surfaces are curved or segmented, adhesive wear debris can escape from the contact zone. If the specimens are rolling elements, the amount of sliding can be drastically reduced but not eliminated (see Fig. 3). If the velocity is too high, frictional heating will affect adversely the adhesive wear process; if the velocity is decreased too much, the situation can become stick slip, a pheonomenon that is still not entirely explained although many analyses have been proposed. If the amplitude of oscillation is too small, fretting will occur instead of adhesion; if the amplitude is too large, some of the wear debris will become dislodged from the contact zone. Unidirectional motion usually means larger surface involvement; one specimen has to travel further on the other with more opportunity for debris to be removed from the contact zone. Light loading means less deformation of the surfaces, less film rupture, and less fatigue failure. Heavy loads are required to produce more asperity contacts and greater plastic deformation, which are necessary with curved contact surfaces, as the potential for numerous asperity contacts has already been reduced

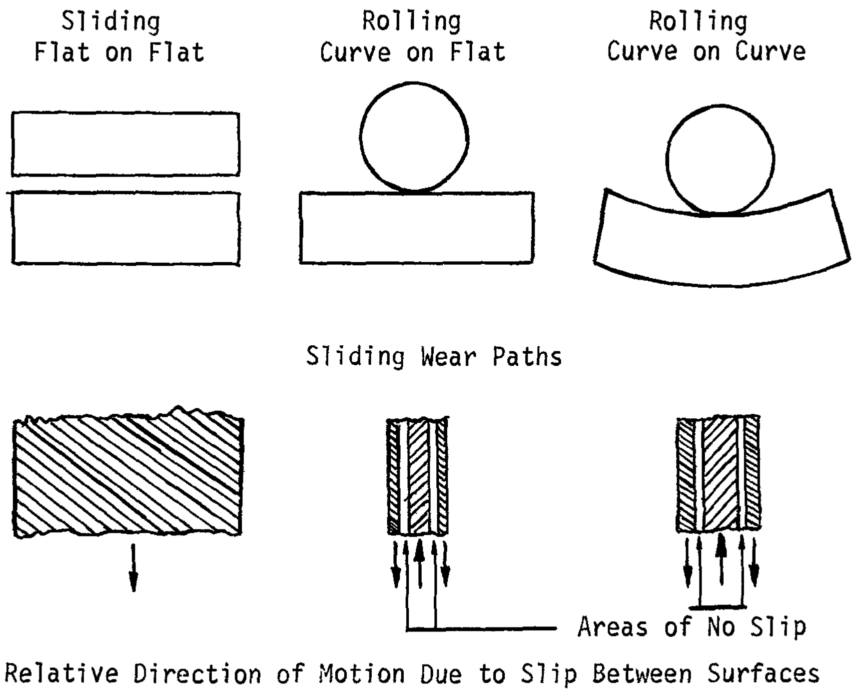

FIG. 3—*Wear paths as a result of relative motion.*

by the geometry of the configuration. There would not be a reduction in the stress level required for plastic deformation, as each asperity would deform until plastic flow occurred and other asperity contacts were made and helped to bear the load.

Reproducibility

A short discussion of the reproducibility of wear rate data seems appropriate at this time. Suppose that a value of wear rate has been obtained from a specific situation; just how reliable and reproducible is that value? If the experiment is repeated, would the same value be obtained? Would the second value (or the third, the tenth, etc.) differ from the first by 10 percent or by 100 percent?

Wear rates for three lubricating compact materials were obtained in a relatively simple, controlled laboratory experiment [*17*]. The wear rates were found to vary even when all controllable parameters were held constant. No explanation was obtained, although attempts were made to study some of the test conditions that were thought to vary. These materials were supposed to wear, as sacrificial lubricating material, so wear could be determined within a reasonable length of time.

The results were that even under identical laboratory conditions, the wear rates were not constant from one time period to another, and there was no trend to the variability of the wear rate. A randomness existed in the data, prompting the use of statistical techniques for data analysis. The result was that the wear rate for any given condition was found to be within a certain range of values and could be expected to be within that range with a specified probability.

The point is that *any* wear rate data presented in the literature should not be taken as gospel. Some variation in the presented value should be expected by the user, and some degree of confidence in the presented value should be given by the author.

Concluding Comments

No specifics of adhesive wear rates were presented, as none were intended to be presented. As stated earlier, the wear processes are system functions, and the material combination that might be a problem in one situation could seemingly run forever in another situation. Some of the factors that influence adhesive wear have been discussed, and an attempt was made to distinguish adhesive wear from some of the many other types of wearing processes. This review of adhesive wear has referenced some very interesting works that in themselves contain additional referenced material, all for further in-depth study.

Acknowledgments

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F. Borik[1]

Testing for Abrasive Wear

REFERENCE: Borik, F., "**Testing for Abrasive Wear,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, pp. 30–44.

ABSTRACT: The abrasive wear of machine components used in mining, mineral dressing, and earth moving machinery has long been recognized as a major problem in material design. This problem has been studied on a laboratory scale using four types of tests which simulate abrasion conditions ranging from severe gouging wear to low-stress erosion. These tests, namely, the jaw crusher test, the pin test, the rubber wheel abrasion test, and the impeller test, are described; the data obtained from the tests are interpreted in terms of the effects of those metallurgical variables that influence the abrasion resistance of an alloy. The results demonstrate the usefulness of the tests in assessing the magnitude of the metallurgical effects and the usefulness of the data for the design of better abrasion-resistant alloys.

KEY WORDS: wear tests, erosion, corrosion, iron alloys, wear, gouging, abrasion

In general, equipment fails in three different ways, namely, fracture, corrosion, and wear. Of these, wear appears to be the most damaging, yet it is the least understood. Wear is characterized as surface damage caused by a loss of material usually associated with plastic deformation. It has four principal forms: adhesive wear (metal-metal contact), abrasive wear (abrasive particle-metal contact), corrosive wear (in moving corrosive media), and surface spalling (surface subjected to cyclic stresses).

This paper focuses on the progress that has been made in the study of abrasive wear, the process which limits the life of equipment and which is of major concern to mining, mineral dressing, and earth moving industries. At the author's laboratory, four tests were developed to determine the abrasion resistance of ferrous materials subjected to conditions of various stress intensities. These conditions are characterized by gouging abrasion, high-stress abrasion, low-stress abrasion, and erosion. The last condition has been modified to also incorporate the effects of corrosion.

In this paper, typical results of the abrasion tests demonstrate the value of these tests in the study of the effects that metallurgical variables have

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on the abrasion resistance of metals, in general, and of ferrous alloys, in particular. The knowledge of these effects is a prerequisite to improved design and selection of abrasion-resistant alloys.

Experimental Procedures

Laboratory Jaw Crusher for Study of Gouging Wear

The type of jaw crusher used in the gouging wear tests was as overhead eccentric, single-toggle jaw crusher. The commercially produced crusher was modified to meet the more stringent requirements of a test apparatus. The essential parts of the crusher are illustrated and identified in Fig. 1. The crusher has a stationary jaw plate (1) which is held against the frame

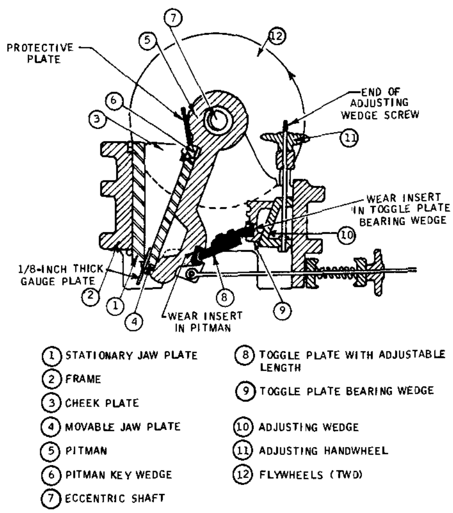


FIG. 1—*Schematic sketch of the main components of the jaw crusher.*

(2) by two cheek plates (3). Two retaining ribs welded on the back side of the stationary plate rest on ledges in the frame and keep the plate from sliding out of the crushing chamber. The stationary plate faces a movable jaw plate (4), which fits into a recess in the pitman (5) and is held in place by a wedge (6). An eccentric shaft (7) rotates in the bronze bearing of the pitman and imparts an oscillating motion to the pitman. The bottom of the pitman touches one end of a toggle plate (8) against which it is spring loaded. The other end of the toggle plate is locked in one of three grooves of the toggle plate bearing wedge (9). The toggle plate pivots around this fixed end as it moves with the pitman; the length of the toggle plate can be adjusted to keep it constant, that is, to compensate for wear on the ends of plate.

The width of the discharge opening can be decreased or increased by moving the adjusting wedge (10) up or down with the adjusting handwheel (11). In all experiments, the discharge opening was set at 0.125 ± 0.010 in. (3.2 ± 0.3 mm) at the point of nearest approach of the plates. The width of the opening was checked by letting the plates take a "bite" on a ¼-in. (6-mm) diameter, soft aluminum wire while the flywheel (12) was manually turned one revolution. The thickness of the compressed portion of the wire was then measured with a micrometer. On the back swing, the opening enlarged to a ⅜-in. (10-mm) wide slit.

The stationary plate (1), approximately 0.9 by 5.4 by 7.5 in. (23 by 137 by 190 mm), is made of a test material, and the movable jaw plate (4), approximately 0.7 by 5.2 by 8.5 in. (18 by 132 by 216 mm), is prepared from a reference material (Type B, ASTM Specification for Pressure Vessel Plates, Alloy Steel, High-Strength, Quenched and Tempered (A 517-74) wrought plate, heat treated to 260 HB).

The testing procedure was detailed in an earlier paper [*1*].[2] The test plate, paired with the reference plate, crushes 1 ton (908 kg) of rock in four 500-lb (227-kg) batches. For each run, the two plates are cleaned and weighed to an accuracy of ±0.1 g before being installed in the crusher. Between the batches, the jaws are reset to a minimum opening of 0.125 ± 0.010 in. (3.2 ± 0.3 mm). When the fourth batch is finished, the plates are cleaned and weighed again. Weight loss due to wear is obtained by subtracting the final from the initial weight. The rock used in the tests is a highly siliceous morainal rock precrushed to a size range of 1½ to 2 in. (38 to 51 mm).

Results are reported as a wear ratio, which is determined by dividing the weight loss of the test plate by the weight loss of the reference plate. This technique minimizes the influence of those inevitable minor variations, such as differences in the size distribution, shape, and composition of the rock. Wear ratios of duplicate runs are averaged. By the nature of the reporting method, low wear ratios are analogous to low wear rates (high abrasion resistance).

Reproducibility tests conducted on a low alloy steel, a maraging steel, Type 304 and 316 stainless steels, and SAE 4340 steel of different heat treatments indicated [*1*] that the variability, in terms of the standard deviation expressed as a percent of the average wear ratio, was within a range of 0.4 and 3.0 percent.

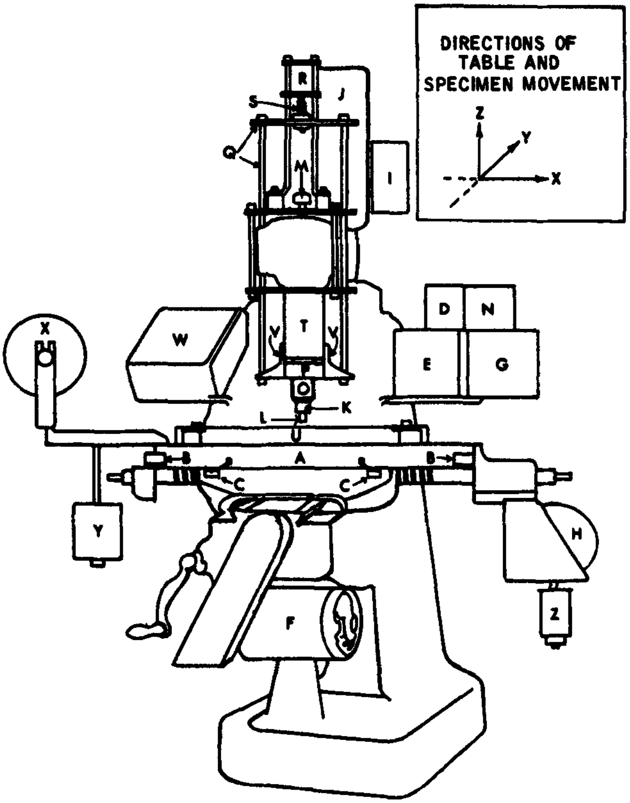
The effects of several metallurgical variables were studied in gouging wear tests of a variety of constructional steels, structural steels, stainless steels (including a maraging steel), cast steels, austenitic manganese steels, and alloyed white irons, most of which were characterized previously in the literature [*1*].

[2] The italic numbers in brackets refer to the list of references appended to this paper.

Pin Test for Study of High-Stress Abrasion

High-stress abrasion tests were conducted using a pin test abrasion testing machine [*2*]. A schematic of the machine is shown in Fig. 2.

In the test, an abrasive cloth of 180-mesh (80-μm) alumina is secured to



A machine table	N counter
B tripping plate	O quill
C limiting switch	P collar
D timer	Q frame assembly
E indexing motor controller	R load cell
F indexing motor	S spring
G table cycling motor controller	T quill housing
H table cycling motor	U platform
I variable speed motor controller	V bearing
J motor	W single channel recorder
K spindle	X roll of abrasive cloth
L pin specimen	Y weight
M drawbar	Z counter weight

FIG. 2—*Schematic of pin test abrasion machine.*

the table (A) with a pressure sensitive tape. The table is moved back and forth in the X direction a distance of about 18 in. (460 mm). At the end of each pass, it is indexed in the Y direction a distance of approximately 0.27 in. (7 mm). As the table moves, a cylindrical pin (L) prepared from a test material to the dimensions of 0.250 in. (6.3 mm) in diameter by about 1 in. (25 mm) is in contact with the abrasive cloth under a force of 15.0 lb (66.5 N) and follows a nonoverlapping pattern for a predetermined distance of 504 in. (12.80 m). During the travel, the pin rotates around its axis at 20 rpm. At the end of the travel, which takes about 7 min, the pin is removed, cleaned in acetone, and its weight is determined. The first test is considered as a run-in. The test is then repeated twice, and the weight losses of the last two tests are averaged. The variability of the results in terms of the standard deviation expressed as a percent of the mean was determined [2] to be within a range of 0.2 and 0.6 percent based on tests conducted on a martensitic high chromium white iron, chromium-molybdenum steel, 2Si-1Mo steel, nickel-chromium white iron, pearlitic chromium-molybdenum steel, and austenitic manganese steels.

The effects of metallurgical variables were studied in pin abrasion tests on a series of structural and constructional steels. The steels comprised plain carbon and low- and medium-alloy steels with carbon contents ranging from 0.05 to 0.84 percent.

Rubber Wheel Abrasion Test for Study of Low-Stress Abrasion

Low-stress abrasion was studied using a rubber wheel abrasion machine as illustrated in Fig. 3. The machine is a modification of a commercial apparatus, described in detail previously in the literature [3]. Essentially, the machine consists of a steel wheel with a ½ by ½-in. (12.5 by 12.5-mm) neoprene rubber rim [7 in. (180 mm) in outside diameter] which rotates through a quartz sand slurry at a speed of 440 surface ft/min (sfm) (134 m/min). In the test, a ¼ by 1 by 2¼-in. (6 by 25 by 57-mm) specimen is pressed against the rubber with a force of 50 lb (222 N).

A new neoprene rubber-rimmed steel wheel is placed in a lathe on an expandable arbor and is ground square with a freshly dressed grinding wheel (5 by ½ by ½) rotating at the speed of 3500 rpm, while the rubber wheel rotates at 86 rpm. The cross feed used is 0.017 in./revolution (0.43 mm/revolution) of the rubber wheel. After the dressing, each rubber wheel is carefully measured to determine the diameter and width of the rubber rim.

The rubber wheel of nominal 45 durometer hardness (the wheel with the lowest hardness of the three hardness levels used) is installed, and its actual hardness is determined with a durometer tester. The hardness reading is repeated at each ⅛ turn of the wheel and averaged. A wheel in which the hardness fluctuates more than ± 1 durometer hardness point

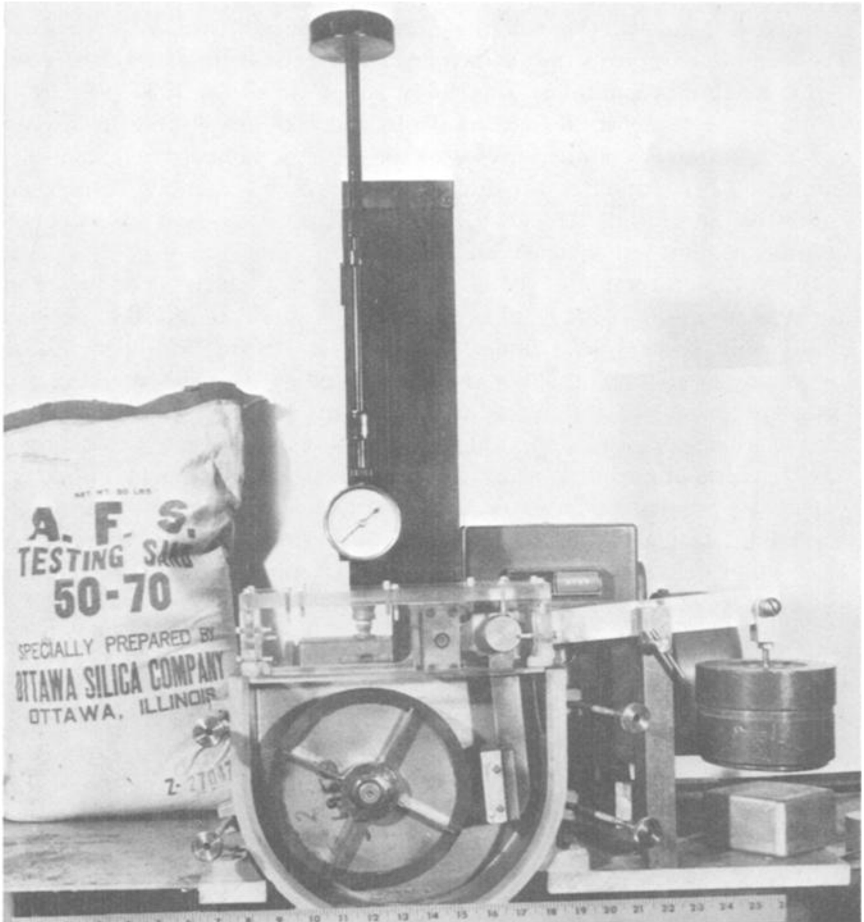


FIG. 3—*Front view of the rubber wheel abrasion machine (front cover of the slurry cage has been removed).*

is rejected. Subsequently, the specimen is installed in a holder which is secured to a lever carrying a dead weight. The specimen is demagnetized, freed of static charge, degreased in acetone, and weighed to the nearest 0.0001 g, before and after each test.

The slurry cage is then filled with 1500 g of quartz sand (American Foundry Society (AFS) testing sand 50-70) and 940 g of deionized water at room temperature. The machine is started and the specimen is gently engaged with the rotating rubber wheel to produce a "run-in" wear scar. The wear scar removes the surface layer and exposes material unaffected by the surface preparation. The run-in is continued for 1000 revolutions of the rubber wheel in the case of steels, and 5000 revolutions in the case of white irons. A counter, preset to the desired number of revolutions, automatically terminates the test after the preset number is reached. Following the run-in, the slurry is drained from the slurry case and the specimen is removed, cleaned, and reweighed.

The next step represents the actual abrasion test which is conducted on the same wear scar. Care is taken to install the specimen into the specimen holder with precisely the same orientation as before. This test follows the same procedure as that for the run-in, ending with the weighing of a clean specimen; the difference in the weights before and after the test gives the weight loss of the specimen. This test is repeated twice using rubber wheels of two higher durometer hardness levels of about 55 and 65.

The test results, in terms of the specimen weight loss in grams, are normalized to correspond to the travel of a wheel having a diameter of 7.000 in. (177.8 mm), width of 0.500 in. (12.7 mm), and 5000 revolutions using the following formula

$$\text{normalized weight, loss in grams} = \frac{7.000 \times 0.500 \times 5000 \times \text{actual weight loss in grams}}{[\text{actual diameter (in.)}] \times [\text{actual width (in.)}] \times [\text{actual number of revolutions}]}$$

or

$$\frac{177.8 \times 12.7 \times 5000 \times \text{actual weight loss in grams}}{[\text{actual diameter (mm)}] \times [\text{actual width (mm)}] \times [\text{actual number of revolutions}]}$$

The values of the normalized weight loss (that is, three values for each material) then are plotted on a logarithmic scale against the rubber hardness plotted on a linear scale. The final result is obtained by fitting a least square line to the three data points and solving the equation of the line for the weight loss corresponding to the rubber hardness of 55 durometer. The fitting is done with the computer that is also programmed to calculate coefficients of correlations for the least square lines. The weight loss, referred to the 55 durometer hardness, facilitates making comparisons between materials. The volume loss, although more correct in characterizing the loss of material due to abrasion, is usually not computed because the densities of ferrous materials tested are quite similar.

Results of reproducibility tests conducted on quenched and tempered SAE 4140 steel [3] indicated that the standard error expressed as a percent of the weight loss at 55 durometer hardness ranged between 1.7 to 2.2 percent.

The effect of metallurgical variables was studied on the basis of results obtained for a series of constructional and structural steels, alloyed white irons, and a few nonferrous materials (glass and sintered carbides).

Impeller Test for Study of Erosion

The apparatus used for the study of erosion is illustrated in Fig. 4. It consists of a converted drill press, a stainless steel impeller (not seen in

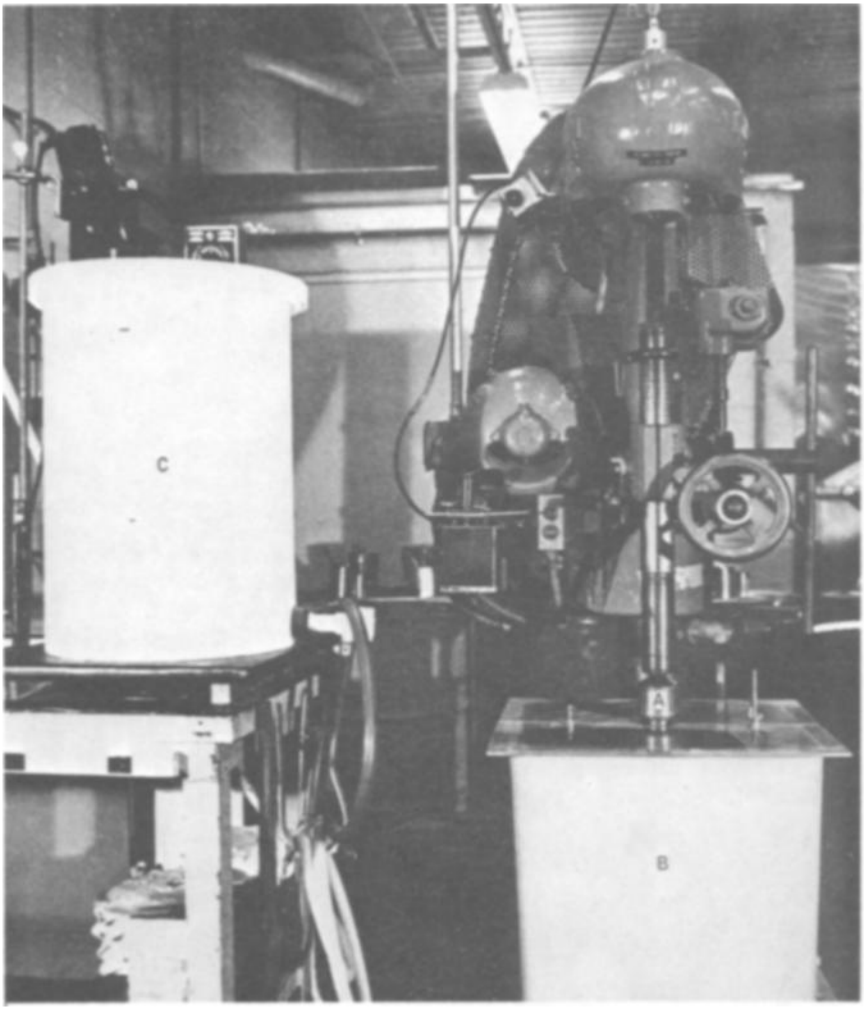


FIG. 4—*Impeller tester (A) chuck that holds the impeller, (B) slurry tank, and (C) container for heating deionized water.*

Fig. 4), and a polyethylene slurry tank. The impeller, shown in Fig. 5, is made of a stainless steel shaft holding four equally spaced stainless steel arms. A Teflon holder containing a specimen is attached to the end of

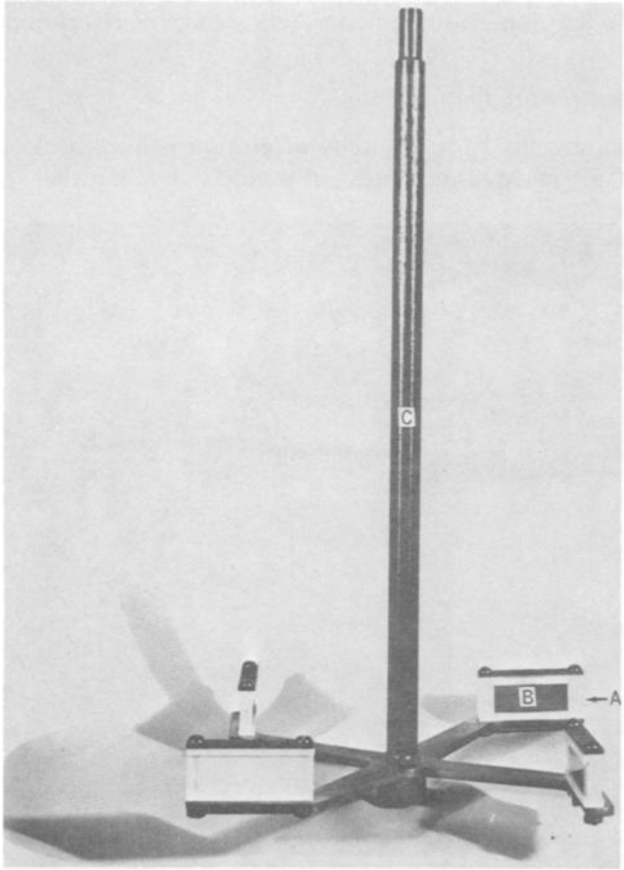


FIG. 5—*Impeller (A) Teflon holder, (B) specimen, and (C) shaft.*

each arm by stainless steel bolts. The shaft of the impeller is held in the chuck of the drill press which rotates the impeller arms through an abrasive slurry.

The procedure requires four specimens, each having overall dimensions of ¼ by 1 by 2¼ in. (6 by 25 by 57 mm). These specimens are carefully ground to a surface finish of about 20 μin. (5×10^{-4} mm) rms, degreased, demagnetized, and weighed with a precision of +0.0001 g. They are installed in the Teflon holders of the impeller which is held in the chuck of the drill press. The assembly is lowered into the slurry tank until it clears the bottom of the tank by ¾ in. (19 mm). The counter on the drill press is preset to 3×10^5 revolutions and the speed set to 260 rpm, allowing the specimens to move through the slurry at a linear speed of 15 ft/s (4.5 m/s). The motor is started and the tank is filled with 30 kg of deionized water (at about 105°F (40°C)) containing chemicals if needed to prepare a slurry with a selected pH value. Subsequently, 20 kg of AFS testing sand 50-70 is poured into the tank. The pH value is determined at the beginning and the end of each test. The impeller is stopped automatically after completing 3×10^5 revolutions. Subsequently, the specimens are cleaned and weighed with a precision of ±0.0001 g. The weight losses of the four specimens are averaged.

The effects of metallurgical variables were studied using test results on a tool steel (M2) and a series of alloyed white irons. The pH values of the water in the slurry were about 5.8 and 3.7. They were achieved, respectively, by preparing buffered solutions using additions of 367-g potassium phosphate, monobasic, (KH_2PO_4) plus 12-g sodium hydroxide (NaOH), and of 423-g potassium hydrogen phthalate ($HOOCC_6H_4COOK$) plus 33.6-g hydrochloric acid (HCl) (concentrated, 37.8 percent), respectively. The variability of results in terms of ±1 standard deviation expressed in terms of the average weight loss ranged between 4 and 7 percent.

Results and Discussion

The results of the jaw crusher tests are illustrated in Fig. 6. Demonstrating the effect of carbon content on gouging abrasion, the figure shows a data band obtained by plotting the wear ratios from numerous tests against the total carbon content of various ferrous materials. Note that the data band shows a sharp decrease of the wear ratio (in other words, a sharp increase in the resistance to gouging wear) in the range from 0 to approximately 0.8C. For alloys with more than 0.8C, wear ratios tend to decrease much more slowly with increasing carbon. This correlation, which reveals the powerful effect of carbon on gouging wear, appears to be a characteristic of many ferrous alloys, ranging from practically carbon-free steels to high-carbon white-cast irons.

The effects of various microstructures on gouging wear have been found to contribute to the spread of the band in Fig. 6 in the vertical direction [*1*]. There is a general tendency for materials with either ferritic or austenitic matrices to be nearer the upper boundary of the band, while alloys with martensitic matrices tend to be closer to the lower boundary. Martensite, under these test conditions, resists gouging wear to a greater degree than ferrite or austenite.

The results of the pin abrasion tests are shown in Fig. 7. They represent weight loss plotted against the original hardness of a series of heat treated low- and medium-alloyed structural and constructional steels identified in the figure by their carbon contents (that is, numerals near data points

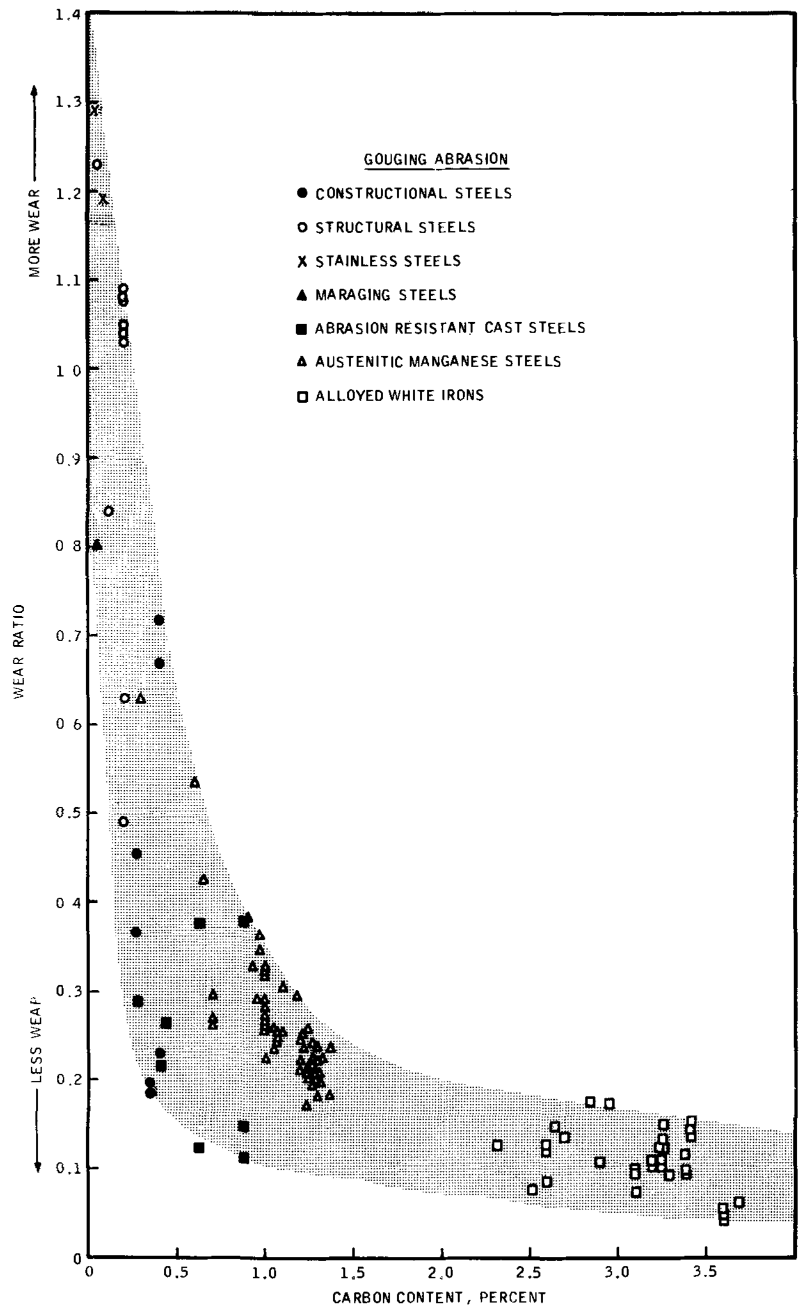


FIG. 6—*Wear ratios obtained in the jaw crusher test, plotted as the carbon content of a variety of ferrous materials.*

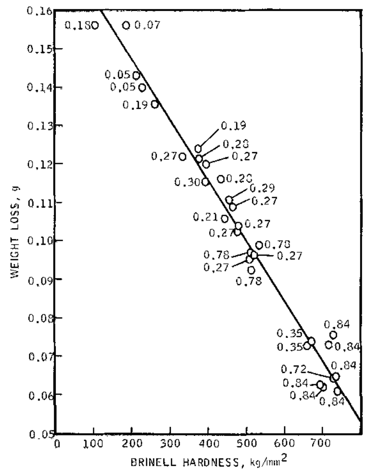


FIG. 7—*Relationship between original hardness of various constructional and structural low alloy steels and the weight loss in the pin abrasion test. Numerials at data points indicate the carbon content in percent.*

are carbon contents in percent). It is clear that for the range of carbon between 0.05 and 0.84 percent weight loss is a linear function of the original hardness. In general, original hardness is not a unique indicator of the abrasion resistance, and it is found [*4*] that the resistance depends rather on the work-hardened hardness of the abraded surface. In this sense, the good correlation exhibited in Fig. 7 is probably limited to materials of similar ferritic (or martensitic) microstructures. The relationship implies that the work-hardened hardness of the abraded surface of these steels is probably a simple function of the original hardness. Inspection of the work by Richardson [*5*] on plain carbon steels of various heat treatments and ranging in carbon content from 0.10 to 0.74 percent shows that such a simple function exists.

It is also clear that this relationship provides an effective aid in selecting steels for service conditions requiring resistance to high-stress abrasion.

Figure 8 presents the results of the rubber wheel tests. The results form a series of parallel lines which are displaced in a vertical direction. The lines correspond to a wide variety of materials, including plate glass, steels, white irons, and sintered carbides.

If the weight losses are converted to volume losses, it can be shown that the 0.18C plain-carbon steel (SAE 1018) in Fig. 8 is twelve times more wear resistant than ordinary plate glass. Hardened SAE 4140 steel, in turn, is four times more abrasion resistant than SAE 1018 steel. The 15Cr-3Mo high-carbon white iron surpasses hardened SAE 4140 steel by a factor of almost eight. Based on volume loss, it can also be shown that sintered tungsten carbide exhibited four times the wear resistance of 15Cr-

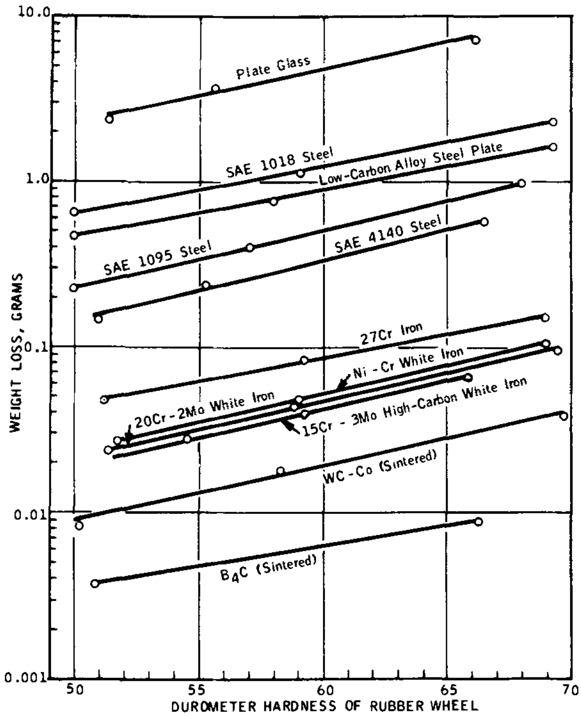


FIG. 8—*Weight loss of various materials as determined from the rubber wheel abrasion test at different levels of rubber hardness.*

3Mo white iron. The data shown in Fig. 8 reveal the wide range of applicability of the rubber wheel abrasion test.

The rubber wheel abrasion test is also useful in the study of the effects of metallurgical factors on the resistance of materials to low-stress abrasion. Figure 9, for example, shows the effects of composition and tempering temperature. As can be seen, the abrasion rate in terms of the volume loss of the two steels increased with decreasing hardness, that is, with rising tempering temperature. The lower position of the curve for SAE 4140 steel is due to its higher carbon content.

Erosive wear is encountered in handling dusty atmospheres and slurries; it occurs at different stress levels depending on the inertia of the particles making contact with a confining surface. The impeller test described in this paper simulated low-stress erosion under corrosive conditions. It should be emphasized that this test is in the early stages of development and the results discussed are preliminary.

The results of some typical impeller tests are summarized in Fig. 10 in which the pH values of the abrasive slurry (linear coordinate) are plotted against the weight loss (logarithmic coordinate). The solid lines in the

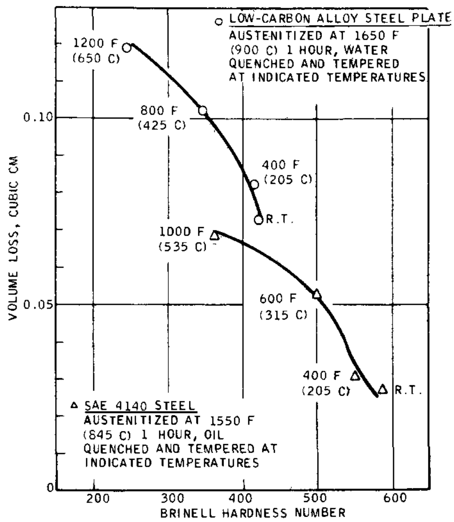


FIG. 9—*Volume loss of two constructional steels plotted against hardness. (Abrasion resistance indicated in terms of volume loss normalized to 55 durometer hardness of the rubber wheel.)*

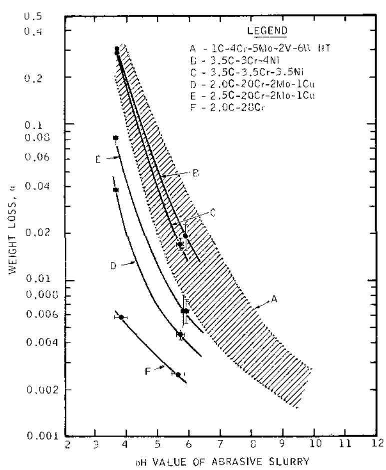


FIG. 10—*Weight loss of a tool steel and several types of alloyed white irons in a low-stress impeller test under the conditions of various pH values.*

figure connect data points resulting from tests in slurries at about 3.7 and 5.8 pH values. The lines were drawn curved to approximately conform with the general trend of the results as indicated by the band bounded by the dotted lines. This band comprises results of numerous tests conducted on M2 tool steel in slurries at various pH values.

It can be concluded by the inspection of the limited data in Fig. 10 that the erosion-corrosion weight loss increases drastically as the pH value is lowered. The increase appears to be more pronounced as the chromium content of the materials is lowered from 28 to 3 percent. As to the effect of carbon, it can be noted that higher carbon level, that is, 2.5 percent compared to 2.0 percent in the chromium white irons, tended to be detrimental. This indicates that the matrix of the higher-carbon iron was depleted of the "protective" chromium which combined with carbon to form more carbides.

Summary

This paper reviews the current status of methods of testing materials for resistance to abrasive wear as developed at the author's laboratory. It also describes abrasion test machines designed to determine the resistance to four types of abrasive wear and the respective test procedures. Types of wear investigated were gouging abrasion, high-stress abrasion, low-stress abrasion, and erosion.

It has been shown that a small jaw crusher is capable of measuring gouging abrasion resistance on a laboratory scale and can yield results of relatively high reproducibility. Information on the resistance of steels to high-stress abrasion can be determined with high precision using a pin test abrasion machine. Equally accurate data on low-stress abrasion resistance can be obtained in the rubber wheel abrasion test. Erosion tests, as conducted in the impeller tester, conveniently yield important data on the effects of erosion combined with corrosion but they are somewhat less reproducible than the other tests described here.

In general, the tests are valuable in ranking materials according to abrasion resistance. In addition, they have proved to be suitable for the study of metallurgical variables affecting abrasive wear. The knowledge and understanding of these effects is essential for a systematic approach to the development of materials with improved abrasion resistance.

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F. G. Hammitt[1]

Erosive Wear Testing

REFERENCE: Hammitt, F. G., "**Erosive Wear Testing,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, pp. 45–67.

ABSTRACT: Fluid-induced erosion, single and multiphase flow induced, is considered according to the various phenomena involved. The basic damage mechanisms are considered and described. The various types of erosion testing devices are described and compared.

KEY WORDS: wear tests, erosion, metals, liquid erosion tests

Erosive wear of a solid surface can take place in a liquid or gaseous medium even without the presence of another phase in the fluid continuum. However, it can be greatly accelerated by the presence of additional phases, as will be discussed later. For the present purpose, we are considering "erosive wear" to be that provoked by fluid flow. It includes particularly, then, the phenomena of solid and liquid particle impact, where the particles may be carried by gas, vapor, or liquid, and liquid "cavitation," which is essentially a phenomenon involving vapor "particles" (that is, pockets or bubbles in liquid). It is not entirely analogous, however, to the other droplet or particle impact phenomena, as will be discussed later. While the main purpose of this article is the discussion of erosive wear testing devices, it is first necessary to clarify what we mean by erosive wear and its various facets. This will be done in the following section.

Mechanisms and Types of Erosive Wear

Erosive Wear Mechanisms

Since we have just excluded chemical or corrosive effects from the

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category of phenomena, it seems intuitively obvious that material removal for this category of phenomena must be due to the imposition on the surface of shear or normal stresses of sufficient magnitude to cause material failure either through single blow effects or through fatigue-type effects. Of course, in most real situations chemical effects are not completely absent, although there are certainly many cases where their effects are relatively negligible. Further, in most cases of erosive wear, the existence of a potentially damaging level of stress can be rationally justified, as will be explained in the following section.

Erosive Wear Phenomena

Single-Phase Flow—General—To provide a logical presentation, single-phase flow phenomena will be considered before multiphase, even though the most important erosive phenomena for reasonably strong materials appear to require the presence of more than one phase of the fluid. Of course single-phase liquid flows are capable of river bank or beach erosion, for example, but phenomena of those types are not the subject of this article. It is concerned rather with the erosive wear of engineering materials such as structural metals, plastics, ceramics, etc. Here we are considering such phenomena as liquid droplet impact in wet steam, for example, to be two-phase phenomena (similarly liquid or solid particle impact in an air or gas continuum). The jetting action of a fire hose, on the other hand, we would consider here to be a single-phase phenomenon, provided it did not involve entrained solid particles, vapor bubbles to provide cavitation, etc.

In the nature of possibly erosive single-phase phenomena, we have the possibility of either very high velocity flows of liquid, vapor, or gas, the latter two being relatively similar in their damage capability. Damaging stresses to be provided on a surface can be included within the categories of shear or normal stress, or both. Solid surface shear should equal fluid shear at the fluid-solid interface and would thus equal the product of viscosity and wall velocity gradient, that is

$$\tau = \mu(\partial u/\partial y)_{\text{wall}} \tag{1}$$

where

u = velocity component parallel to the surface, and
y = distance from it.

Normal stress in the surface is numerically equal approximately to the fluid pressure at the surface. In the case of a steady-state impinging jet, the maximum value this could attain would be the "stagnation pressure" in the fluid, that is

$$\Delta p_{stag} = \varrho V^2/2 \quad (2)$$

where

V = total fluid velocity, and
Δp_{stag} = measured above the ambient pressure.

In the case of a nonsteady liquid jet, the pressure at certain points can attain the approximate magnitude of the "water-hammer" pressure, that is

$$\Delta p_{W.H.} = \varrho VC \quad (3)$$

where C is velocity of sound in the liquid. Of course water hammer phenomena are not pertinent to gas or vapor flows. For relatively low velocity liquid flows, water-hammer pressure can reach values sufficient to cause material surface failure, and hence erosion.

A numerical example at this point may be useful. Suppose a flow of cold water of 500 ft/s, which is a very high velocity for water flow. For the case where this flow is assumed parallel to a wall, assume the "boundary layer thickness" to be 10^{-4} ft, which seems about the minimum conceivable. Then the surface shear stress, stagnation pressure, and water hammer pressure are approximately as listed in Table 1, along with values for 1000 ft/s.

TABLE 1—*Numerical example of fluid stresses high velocity in cold water.*

Velocity	500 ft/s	1 000 ft/s
Shear	<1 psi	<2 psi
Stagnation pressure	1 600 psi	6 400 psi
Water-hammer pressure	32 000 psi	64 000 psi

It is apparent from Table 1 that surface shear stress is not likely to be a damaging mechanism at velocities of interest unless the viscosity were extremely high. It also appears that in most cases the stagnation pressure is also not sufficient to be damaging to most structural materials, so that high velocity impacting liquid jets should not be damaging in most cases of engineering interest, unless nonsteady-state behavior is involved (in which case fluid pressures could attain values of the general order of the water hammer pressure). Another possibility exists if relatively large asperities exist on the surface. Stagnation pressure, rather than shear stress, could be exerted against these. The bending moment against an asperity of sufficient aspect ratio could cause a surface failure.

Examination of Table 1 and Eqs 1 and 2 indicates that it is most unlikely that either shear stress or pressure induced by gas or vapor flows could be sufficient to damage materials such as structural metals, though gas velocities in some applications up to several thousand feet per second are possible. The wall shear stress is only linear with velocity, so that even very high gas velocities would not raise this stress to damaging values. In addition, the viscosity of most gases is much less than that of the cold water used in the Table 1 calculations. The stagnation pressure with gases or vapors is not likely to be damaging either, since it is proportional to density, which for gases or vapors is very much less than the cold water used for Table 1 (factor is $\sim 10^3$ between atmospheric air and water).

Actual single-phase applications—Several single-phase flow applications in which erosive wear has sometimes occurred will be considered. For the most part, these involve high-velocity water flows. However, even for these cases, a consideration of the possible normal and shear stresses induced by liquid flow seem to indicate that erosive wear is impossible in the absence of either corrosive effects or multiphase phenomena such as cavitation, droplet impact, etc. Thus, presumably, in cases where erosion, in fact, has been observed in these applications, it is the author's opinion that one or more of these "extraneous" effects must have been involved.

1. Pelton (hydraulic) turbine—In this application, water jets with velocity up to the order of 600 ft/s impinge upon a rotating turbine wheel equipped with suitably designed "buckets," usually of hardened steel, perhaps of the 400 series. If the design is correct, no significant erosion occurs, at least for thousands of operation hours. In some cases, however, prohibitive erosion does occur quickly. This is presumably due to such factors as improper blade design leading to cavitation on the blade surfaces or perhaps to entrained sand in the impinging water. In any case, it is not, in the writer's opinion, single-phase erosion.

2. Boiler feed pump—Modern high-performance boiler feed pumps also involve liquid velocities of the order 500 to 600 ft/s. With proper design, again, no substantial erosion occurs. However, there are many cases on record where large erosion has resulted (Fig. 1, for example) in such pumps. This is usually presumed to be due to cavitation, even though it has occurred in some cases in the discharge casing, usually of the first stage. Cavitation in this region is plausible, at least for off-design conditions. Again there is no plausible mechanism for erosion of these materials (probably 400-series steels) under the existing velocity conditions, except through cavitation or corrosion, or both.

3. Valve seats—Very high velocities can exist across valve seats in some cases at least of the magnitudes previously discussed. Resultant erosion,

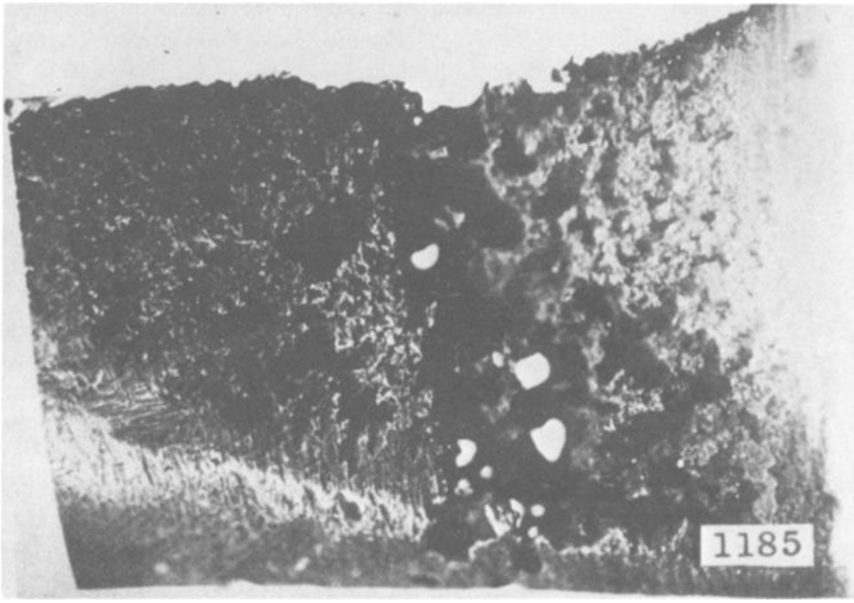


FIG. 1—*Leading edge of a series 400 stainless steel impeller for a boiler feed pump, exhibiting deep local damage caused by cavitation erosion.*

sometimes called "wire-drawing," has been reported for liquid and steam valves. The materials are often hardened steels. Again no plausible mechanism for erosion exists *unless* there is either substantial corrosion (unlikely for proper material choice), or multiphase phenomena are involved, such as cavitation (for liquid-handling valves) and possible water droplet impingement for steam valves, assuming that wet steam may be involved.

Multiphase Flow—General—As indicated in the foregoing it seems most probable that in most engineering cases involving erosive wear, multiphase flow phenomena must be involved. These can involve a liquid gas or vapor continuum with solid or liquid particles (droplets), a liquid continuum with entrained vapor (cavitation), or entrained gas. These cases will be discussed briefly in the following section with reference to the stress-raising mechanisms involved.

Solid particle impingement—High velocity solid particle impingement can certainly provoke erosive wear in many well-known cases, for example, dust erosion of helicopter blades, propellor blades, helicopter drive gas-turbine compressor blades, etc. In these cases, the phenomenon considered is that of the rapid motion of the eroded material through a continuum of gas with entrained solid particles. Other less clear-cut cases involving erosive solid particle impingment are liquid or gaseous slurry flows. Tests have certainly indicated that such flows are far more erosive than single-phase flows of the same velocity, but the precise mechanism of erosion at this point is not entirely clear.

The state of the art at this time does not provide methods for specifying the state of stresses on the eroded material surface (even to the extent possible for liquid impact as already discussed) resulting from impact by particles of irregular shape, which is the usual case of interest. It is obvious of course that both shear and normal stresses of substantial magnitude will be provoked by such impacts, but no generalized governing relations are available as yet to the author's knowledge.

The situation for slurry erosion is even more obscure than that for direct solid particle impact with respect to being able to specify the stresses or the detailed mechanisms causing the erosion. This is particularly true for liquid slurries, since the velocities are normally relatively low so that stresses from direct impact would not be of damaging magnitude. An extremely damaging situation, nevertheless, is that provided by cavitating slurries which sometimes have occurred in pumps (dredging pumps, for example) or in solids-bearing transport pipelines (ore-bearing, for example).

Liquid droplet impingement—Liquid droplet impingement erosive wear applications usually involve the rapid motion of the eroded material through a gaseous or vapor continuum with entrained liquid droplets. Important examples are the motion of high-speed aircraft or missiles, propellor or helicopter blades, through air, or the motion of steam turbine blades through a vapor continuum including relatively large water droplets. A somewhat similar situation can occur for aircraft gas turbine compressor blades under atmospheric rain conditions. Inverse cases, where the droplets are projected against relatively stationary target materials, are not usual because it is not possible generally to accelerate liquid droplets of potentially damaging size to damaging velocities without droplet disintegration, that is, a critical Weber number from the viewpoint of droplet stability is involved.

The stress regimes applying for liquid droplet impact erosion can be estimated much more closely than those applying for the solid particle or slurry cases discussed here. In general, the order of magnitude of normal stresses can be obtained from the water hammer relation (Eq 3). Some improvement can be made if the result is corrected for the nonrigidity of the target material and for the effects of liquid compression on liquid shock[2] velocity and density. Droplet shape also affects the stress regime, as shown by various recent numerical and experimental studies, some from our own laboratory [*1–4*].[3] The last of these is a numerical study where the target material was assumed elastic rather than rigid as in the

[2] Not identical to but less than sonic velocity.

[3] The italic numbers in brackets refer to the list of references appended to this paper.

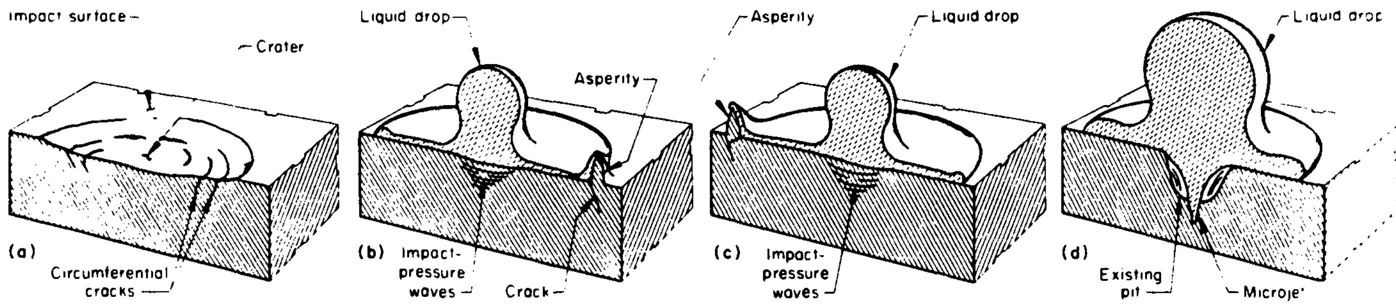
earlier cases, so that realistic target material stresses could be computed [*4*]. However, the precise state of the analysis of liquid droplet impact is beyond the scope of the present article, and will not be discussed further here. Suffice it to say that the general level of stress magnitudes computable (and measured) for this case is sufficient to explain and justify the erosion observed.

Another interesting point which can be made with regard to droplet impact erosion is that radial velocities along the impacted surface are generated by droplet impact which can be several times the original impact velocity. It has been previously supposed that the shear stress caused by this high-velocity flow parallel to the surface might be an important contribution to the damage. However, this hypothesis seems unlikely considering the numerical results in Table 1 and the form of Eq 1. Even though the radial velocity in an extreme case might be ten times that used for the example of Table 1 (500 ft/s), the shear stress induced by this flow would still be very small, since it is proportional only to velocity to the first power. However, the impingement of this high-velocity radial flow against a small asperity raised from the surface could create failure. This process as well as that of the droplet impact in general is well illustrated in Fig. 2, which is taken from Ref *5*. This recent article well summarizes the droplet impact and cavitation processes discussed here.

Cavitation—Whereas droplet and solid particle impact involve liquid and solid particles, respectively, in a gas or vapor continuum, cavitation involves vapor (with some gas content) particles in a liquid continuum. However, since these particles involve only relatively low density material with little mass, their "impact" with target material is not in general a likely cause of erosion. Of course, this statement may not apply to the combined phenomenon case of a cavitating slurry (mentioned earlier).

Though particle impact *per se* is not the presumed cause of cavitation erosion, a combination of shock waves in the liquid and liquid "microjet" impact upon the eroded surface, represents at this time, in the author's opinion, the most likely detailed mechanism for cavitation erosion. This problem is thoroughly discussed in a recent book [*6*] and summarized in Ref *5*, as well as in research articles too numerous to mention here. Bubble collapse adjacent to a surface with development of microjet is shown schematically in Fig. 3 (from Ref *5*). The shock waves emitted during the bubble "rebound" which often follows original collapse (Fig. 4) are believed to provide, in many cases, important assistance to the damaging process originating from the microjet impact. At least the liquid pressures upon a neighboring wall during bubble collapse appear to be considerably less than those during rebound [*8*] and appear to be in fact of sufficient magnitude to contribute to damage for most materials.

Actual calculation of the stress regime applied to an eroded surface by



(a) Solid surface showing initial impact of a drop of liquid that produces circumferential cracks in the area of impact, or produces shallow craters in very ductile materials. (b) High-velocity radial flow of liquid away from the impact area is arrested by a nearby surface asperity, which cracks at its base; (c) subsequent impact by another drop of liquid breaks the asperity. (d) Direct hit on a deep pit results in accelerated damage, because shock waves bouncing off the sides of the pit cause the formation of a high-energy microjet within the pit.

FIG. 2—*Processes by which a material is damaged by liquid-impingement erosion.* (By permission, from *Metals Handbook,* Vol. 10. Copyright American Society for Metals, 1975.)

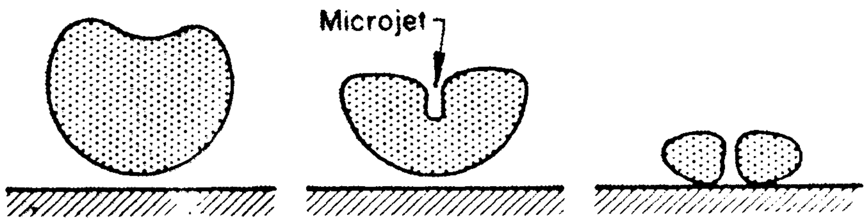


FIG. 3—*Schematic representation of successive stages of nonsymmetrical cavity collapse with microjet impingement against a metallic surface.* (By permission, from *Metals Handbook,* Vol. 10. Copyright American Society for Metals, 1975.)

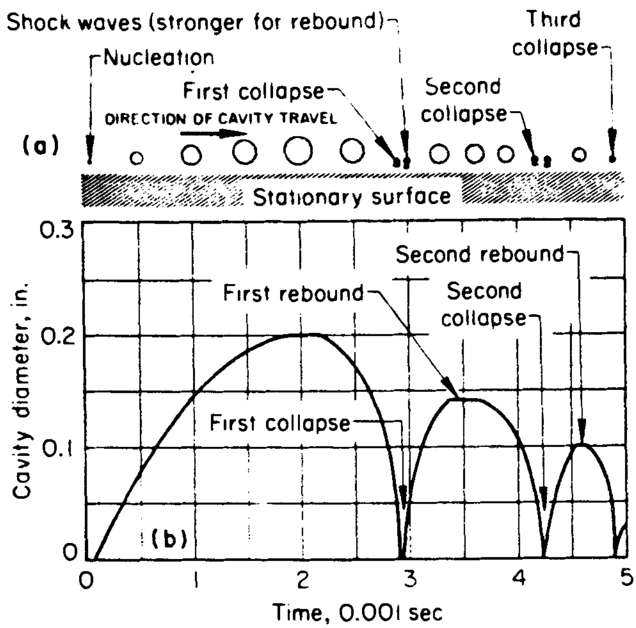


FIG. 4—(a) *Schematic representation of successive stages of growth, collapse, and rebound of a single traveling cavity.* (b) *Graph of cavity diameter as a function of time for the cavity in* (a) [5,7].

cavitation is not yet possible in the present state of the art. This is certainly not surprising when one considers the complex mix of processes which are involved (not to mention the important contribution of corrosion in many cases). The problem of stress calculation appears even more difficult, as compared with that of droplet impingement, when it is realized that the size and position of the collapsing bubbles, to which the damage is presumably due, is not fixed or well known in most cases. Natural cavitation fields include bubbles which cover a large range of diameter. In the usual engineering case, neither range of diameter, distribution over this range, or number of bubbles involved is known to any degree of precision. Hence, for the general engineering case, estimation of the stress regimes to which a cavitated surface will be exposed by a given flow regime is essentially impossible, whereas for the droplet impact case quite reasonable estimates can be made as was previously discussed. For laboratory cavitation erosion test devices, the situation is only slightly less obscure (depending upon the type of test device) as will be discussed later. While from numerical analyses [*6,8–10*], it can be shown that the potentialities for sufficient stress magnitudes to account for the observed damage exist, it is still true that the best evidence of the stress regimes to which cavitated surfaces have been exposed can be obtained from examination of the damaged surfaces themselves. Since the damage surfaces from cavitation and droplet impact often have a very similar appearance, it can be presumed that the two processes are quite similar in their effects upon surfaces. Of course in most cases the attack by cavitation is on a smaller and finer scale so that individual-blow craters from cavitation have a diameter typically of only a few mils (Ref *11*, for example), and it is presumed that the microjet diameter is typically only a few microns (Ref *12*, for example). Typical individual-blow cavitation craters on stainless steel are shown in Fig. 5. In a typical case, such craters presumably cover the entire surface by an essentially "random" bombardment, so that large scale fatigue failure eventually occurs, producing eventual large-scale failure (Fig. 1).

Erosive Wear Testing Devices

Applications

The applications for erosive wear testing devices can be subdivided in the following manner. This division is not entirely parallel to that based on erosion phenomena previously discussed, since the test devices attempt, in general, for practical reasons, to model one primary factor of the application involved, rather than the phenomenon itself.

1. High fluid velocity devices should be applied where "single-phase" erosion only is to be evaluated. If cavitation of droplet or particle impact occurs, it is unintentional, but may be instrumental in the results. Such devices are intended for the study of erosion in steam or liquid ("noncavitating") valves, that is, wire-drawing, boiler feed pump casings, etc.

2. Solid particle or droplet impact devices cause the material to be eroded to rapidly traverse a field of essentially stationary particles or droplets. In most cases, the target material is whirled through a field of falling particles or droplets, but in some cases a translational motion is

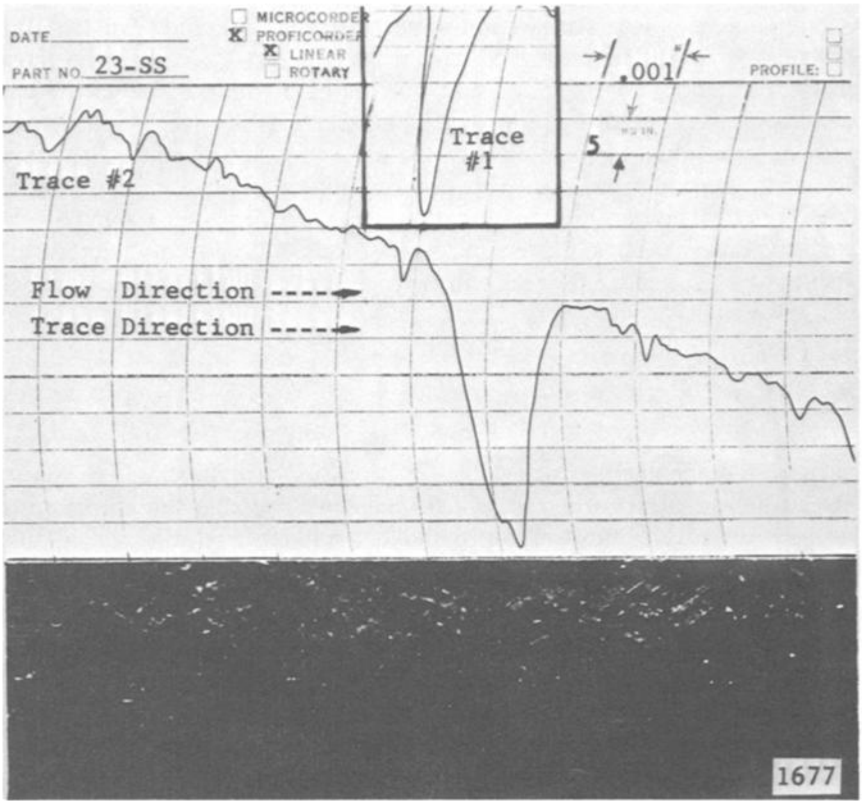


FIG. 5—*Individual blow cavitation craters on stainless steel.*

used. In some cases, liquid jets rather than droplets are impacted. Impacting liquid devices can sometimes generate secondary cavitation, which may contribute importantly to the damage, but usually this is not intentional.

3. Flowing cavitation devices cause cavitation by converting pressure "head" into kinetic head. Numerous geometries have been used for this purpose as will be discussed later. In general these could be characterized under the terms "venturi," "rotating disk," and "miscellaneous." These devices are meant to obtain cavitation erosion under flow conditions as realistic as possible, since damage modeling laws are highly uncertain.

4. Vibratory cavitation devices cause cavitation in an essentially static fluid, as opposed to the flowing cavitation devices just discussed. Such a device, sometimes called a "magnetostriction" or "ultrasonic" tester, usually relies on the rapidly reciprocating motion of a submerged test plate, at a relatively high frequency, to provoke cavitation by pressure oscillation in an essentially static liquid. The necessary pressure oscillation

is due to a very high acceleration imposed upon the liquid. This type of device is used for the study of cavitation damage, since it is the most economical, both for purchase and operation, of the possible cavitation damage devices. It also is a strongly "accelerated" device in that it can provide substantial damage on even the most resistant of materials within relatively short test periods. However, its major disadvantage is that it does not, by its nature, relate cavitation damage to flowing system parameters such as velocity and pressure, so that the conversion of "vibratory" results to projected performance in field devices is extremely uncertain, if not impossible.

Actual Test Devices

High-Velocity Single-Phase Erosion Wear Test Devices—Various tests have been made at times to evaluate high velocity single-phase erosion in cases where this has occurred in field machines, so that laboratory tests seemed warranted. However, no relatively standardized machine of this type appears to exist. A case in point was the work at Detroit Edison in the 1940s to evaluate erosion in boiler feed pump casings and regulating valves [*13,14*] which were exposed to relatively high velocity but supposedly not cavitation. Some corrosive contribution no doubt was also included with some of the materials used (carbon steels, etc., but also including the 400 and 300 series later used in this application). High velocities (~200 ft/s) were attained by accelerating the pressurized water through a small slit formed by the materials to be tested. Back pressure was limited by the equipment available for the test, so that although the absence of cavitation was one of the test objectives, it is nevertheless quite likely, in my own opinion, that it contributed importantly to the results, which included considerable erosion of most materials tested. As previously discussed, without cavitation (or corrosive attack, probably not important for the stainless steels tested), there is no plausible mechanism to explain the erosion observed.

Another partially pertinent case in point are the "rotating wheel" devices developed originally in the 1930s probably first by Ackeret and de Haller [*15*]. This device is shown schematically in Fig. 6 (from Ref *6*) and consists of a rotating "wheel," to the periphery of which the specimens to be eroded are attached. These are rotated through a relatively low velocity water jet with the direction parallel to the wheel axis. Since the impact velocity for these devices is typically no more than 100 m/s, it is difficult to explain the rapid erosion of some of the hardened materials tested without the contribution of local cavitation, as well as the liquid impact. According to Table 1, the water hammer pressure for this device at 100 m/s would be ~29 000 psi, but even materials such as stellite can be eroded quite rapidly. These devices were originally developed to study

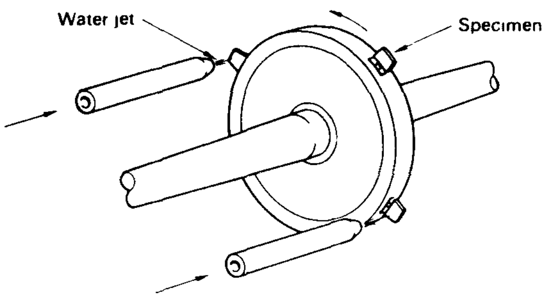


FIG. 6—*Jet impact damage device (schematic).* (By permission, McGraw-Hill, copyright 1970, from Ref *6*.)

erosion of impulse hydraulic turbines such as "Pelton wheels." It was assumed then that this erosion was of a similar nature to that encountered in large steam turbines (which is now clearly known to be a case of liquid droplet impact). Actually the Pelton wheel erosion is probably due to cavitation mainly, but features a very high liquid velocity parallel to the blading surfaces, as previously discussed. Thus, since this rotating wheel test device was developed to study Pelton wheel erosion, which at first glance appears as a case of high-velocity single-phase erosion, its introduction in this article at this point is pertinent.

Solid Particle or Droplet Impact Erosive Wear Test Device—Various devices of this type have been developed and used over the years, including the relatively low velocity rotating wheel device just discussed (Fig. 6). In recent years, solid wheel devices for rotating speeds up to perhaps 500 m/s have been built in various laboratories throughout the world, particularly for the study of the droplet impact problem existing in the low pressure end of large steam turbines. These more modern wheels are generally enclosed within a strong steel casing, both for protection in case of failure and to allow operation under vacuum, both to model more closely the steam turbine problem and to reduce drive power for the device. Relatively low velocity liquid droplets or jets are caused to impact the rotating specimens. Various test facilities of this type existing in England are well described in Ref *16*. Somewhat comparable facilities also exist to the writer's knowledge in this country and in Russia, but little descriptive data have yet been published.

In addition to the wheel devices described here, designed particularly for the steam turbine application where the materials to be tested are generally of highly resistent nature such as stellites, hardened steels, etc., another group of facilities has been developed in recent years for the droplet impact erosion testing, both in this country and Europe, of aircraft and missile component materials where the application is "rain erosion," that is, the erosion encountered when such components are flown through rain storms. For applications where the flight velocity exceeds Mach 1 (~300 m/s) particularly, erosion can occur very rapidly, since the materials involved are not optimum for erosion resistance, but are chosen rather for other prerequisites, that is, for radomes, propeller or helicopter blade, etc. For this application, rotating arms rather than disks are normally used. Relatively large diameters, and hence low revolutions per minute for such a test device is usually required, since very large *g* loads must not be imposed upon the test materials. This requirement is obviously not of such great importance for the very strong metallic alloys to be tested in the turbine application. Also, required test times for the aircraft type device are obviously much shorter. The largest and highest speed device (~900 m/s), to the writer's knowledge, is that at Bell Aerospace [*17*]. The diameter of the rotating element is ~18 ft.

Figure 7 is a schematic of the propeller arm device at the Air Force Materials Laboratory (AFML) at Wright Patterson Air Force Base. Results from these propeller arm devices have been carefully evaluated to show that the relative ratings of materials erosion resistance and the actual modes of erosion failure observed from rotating arm tests are closely the same as obtained in actual flight tests.

Another type of device for the study of air and missile component rain erosion resistance at very high velocity is the rocket sled, where test materials can be driven through an artificial rain field. The largest such device to the writer's knowledge is that at Holloman Air Force Base [*18,19*] where test velocities up to ~Mach 5 (~5500 ft/s or 1700 m/s) have been utilized. This type of device allows higher velocities than rotating arm devices, which are limited by centrifugal stresses in the arm. The rocket sled has the advantage of allowing the test of many material specimens in a single run and, hence, under precisely identical conditions. However, the test is relatively very expensive and has the disadvantage that intermediate observation of the progress of erosion is not practical.

Many of these aircraft component test devices have also been used for dust erosion tests, which is an important present day problem for such applications as helicopter blades.

Flowing Cavitation Devices—General and miscellaneous—Flowing cavitation erosion test devices include machines involving both rotating elements and translatory flows. In general, these are well described in Ref *6*. No really standard device has yet evolved in this field, and a variety of devices have been used. These can be considered under the main headings of venturi and rotating disk devices. However, there exist several miscellaneous devices such as specimens submerged in large water tunnels (used by Knapp et al, Ref *6*) and a vibrating reed in a flowing stream [*20*]. However, since these and other miscellaneous devices are not of major importance to present-day cavitation damage evaluations, they will not be discussed further here.

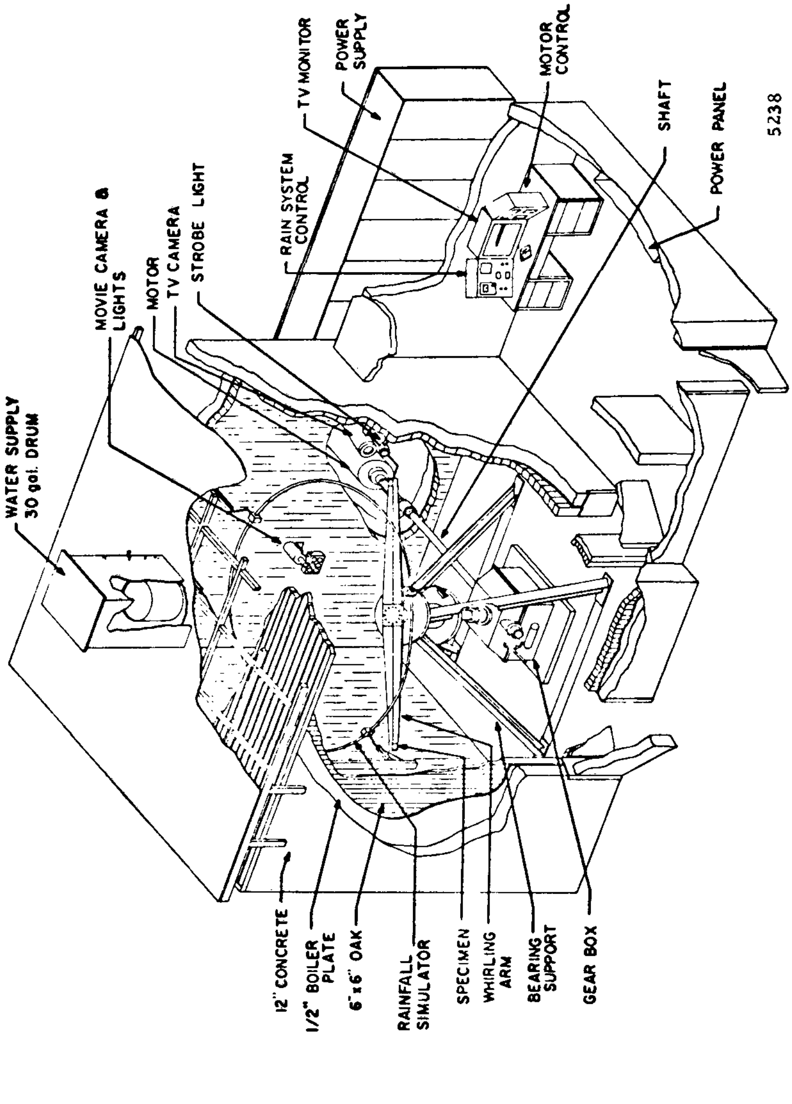


FIG. 7—*AFML rotating arm apparatus.*

Venturi devices—Venturi devices are taken here to include all those flow devices employing a flow restriction to convert pressure into kinetic head, creating a cavitating region when the static pressure falls to the level of the vapor pressure. For damage studies, relatively standard venturis (Fig. 8) as well as several quite special designs have been used. Of these the earliest is probably that of Boetcher reported in 1936 (Fig 8 taken from Ref *6*, see also Ref *21*). As will be noted from Fig. 9, the arrangement is such that the cavitating jet impinges upon the specimen. Such a venturi geometry does provide, in fact, a very intensely damaging regime, as compared, for example, to the University of Michigan design [*11*] (Fig. 8), which, however, does model more closely the usual flow conditions found in hydraulic machines (Table 2).

Another special damage venturi design which has been used somewhat broadly in various countries since its introduction in 1955 [*22*] is that of Shal'nev (see Fig. 10). The flow geometry consists of a rectangular throat of constant flow area across which a small cylindrical pin is placed. Cavitation occurs in the wake of this pin, and the damage specimens are located flush with the wall and downstream of the pin (Fig. 10). The damaging intensity induced by this geometry is also much higher than the University of Michigan design (Fig. 7). However, the flow regime is that of separated vortices, which may model a relatively special type of cavitation quite closely, but is not particularly similar to the more usual flow regimes encountered in flow machinery.

Cavitating disk devices—A rotating disk device (see Fig. 11) developed for the study of cavitation damage was reported in 1955 by Rasmussen [*23*]. The flow geometry consists of a flat disk, fitted with pins or through holes at various radial locations. The disk is caused to rotate in the test liquid which is contained within a circular casing. The casing is fitted with radial baffles to prevent gross rotation of the overall fluid. The traverse of the disk pins or holes through the relatively quiescent surrounding liquid causes cavitation clouds which follow the rotating disk and collapse upon specimens fitted flush with the disk surface. Figure 12 (from Ref *6*) is a schematic of a more recent rotating disk facility built by Pratt and Whitney Aircraft for eventual use with liquid metals [*24*]. Eroded specimens of refractory metal are also shown in Fig. 11.

This type of facility also produces damage very rapidly, more so than the Boetcher and Shal'nev types of venturi (Table 2). In all these cases, however, the flow regimes involved are really quite different. By its very nature that flow regime provided by the rotating disk resembles closely that involved for regions of separated flow in turbomachines.

Another valid comparison between these flowing damage tests is the expense of the facilities involved. The venturis obviously require a loop facility with driving pump and much other instrumentation and controls.

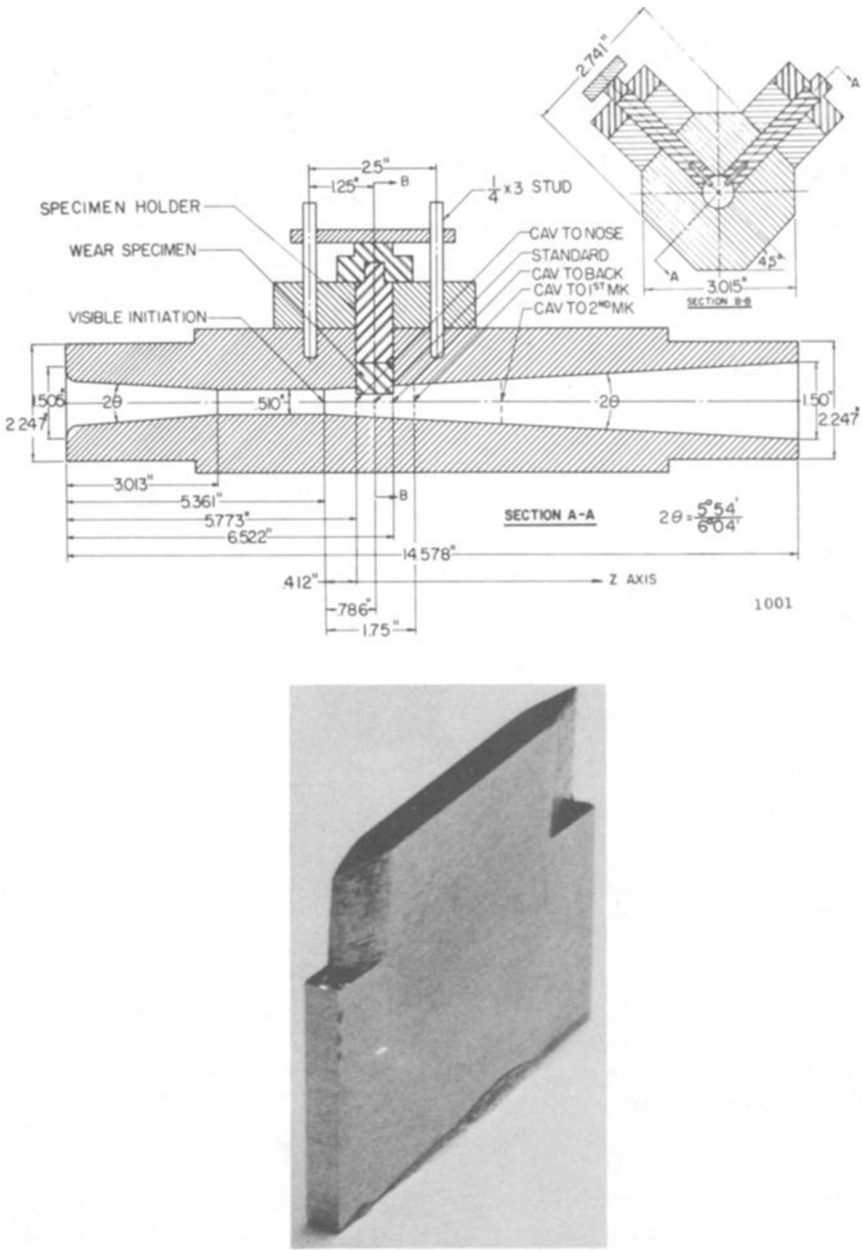


FIG. 8—*Venturi device for cavitation damage tests at the University of Michigan:* (top) *cross section of the venturi device, and* (bottom) *specimen from the venturi device.* (By permission, from Hammitt, F. G., *Journal of Basic Engineering,* American Society of Mechanical Engineers, Vol. 85, 1963, pp. 347-359.)

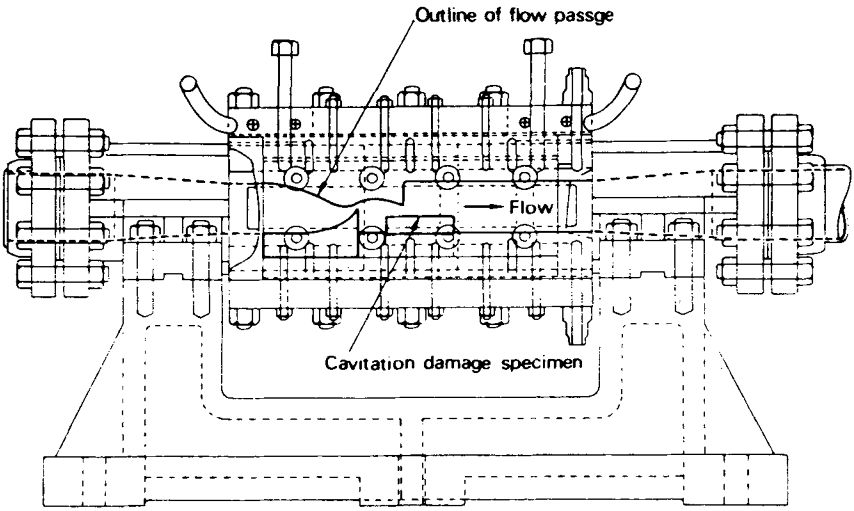
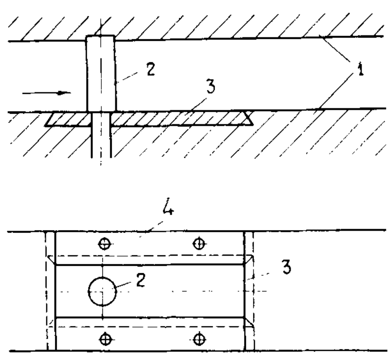


FIG. 9—*Holtwood Laboratory cavitation damage test section* [21].



1. Walls of the experimental chamber
2. Model
3. Specimen
4. Ties of the specimen

FIG. 10—*Diagram of experiments on the erosion of metal specimens caused by the cavitation beyond a circulat profile* [22].

The rotating disk, however, is not a simple or cheap facility in itself, as can be seen from Fig. 12 which shows the actual design drawing for the Pratt and Whitney device [*24*]. An accurate statement comparing the cost of rotating disk and venturi damage facilities is not possible at this time, since too many unknown and complicating factors are involved.

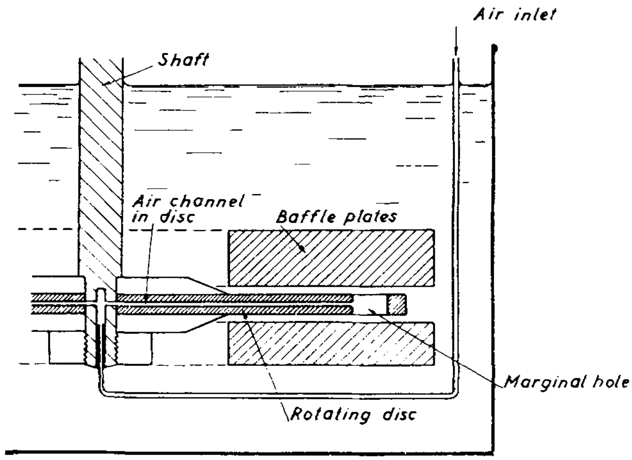
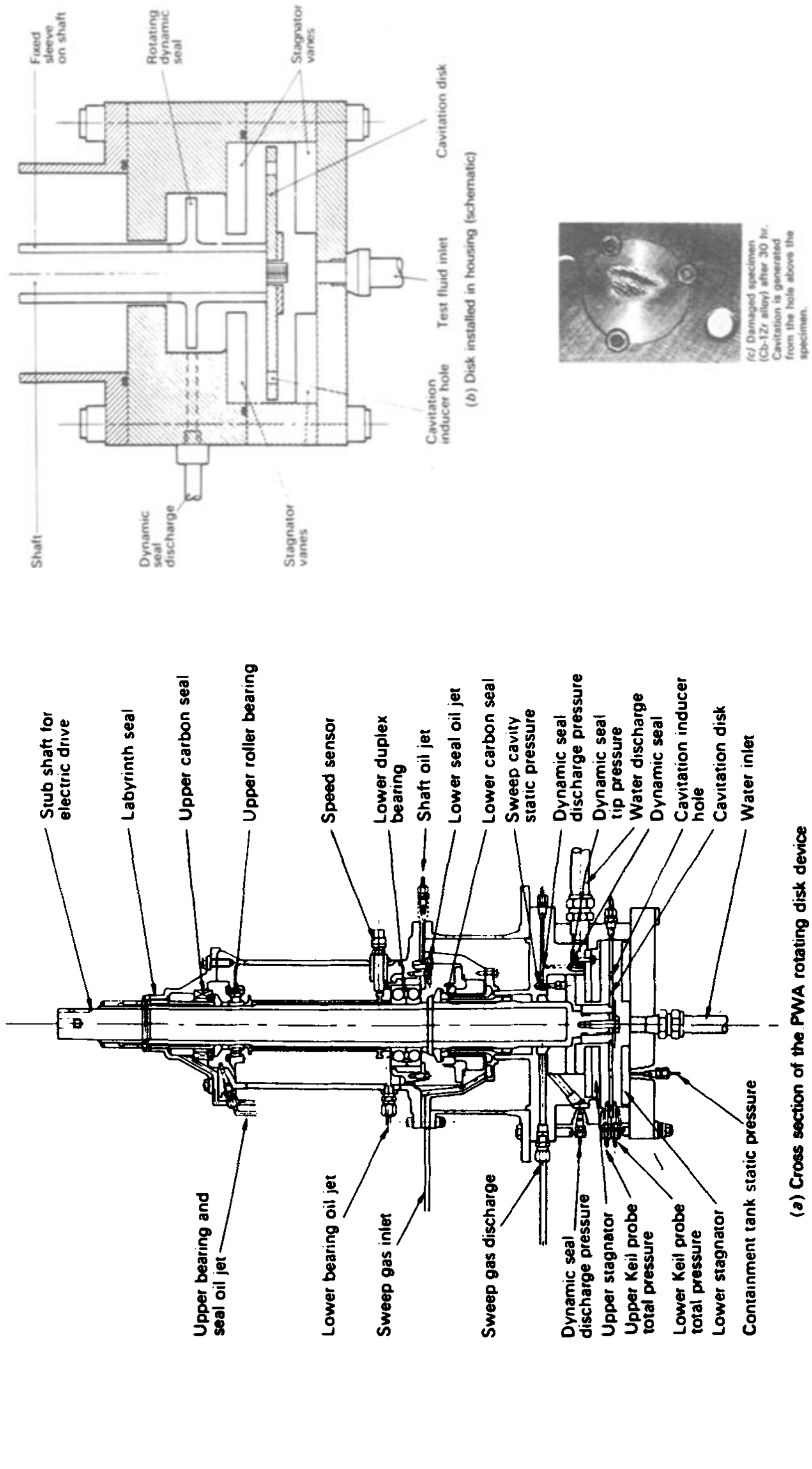


FIG. 11—*Rotating disk with drill ducts for air supply.*

However, it is certainly true that the vibratory type of damage devices, to be discussed next, are considerably more economical, certainly in first cost. Operating costs, primarily that of operator salary, are probably similar. Length of test required for a given material, that is, damage intensity (Table 2), for the vibratory device covers the same general order as the others.

Vibratory Cavitation Devices—The vibratory type of cavitation damage test, already described, is certainly the simplest, cheapest, and most common of all presently known cavitation damage test devices. It is also capable of providing erosion rates of the same general order as the flowing systems already discussed. It is also the only one for which an ASTM standard has been promulgated (ASTM Vibratory Cavitation Erosion Test (G 32-72)). Figure 13 (from Ref *6*) is the schematic of the University of Michigan device of this type which is designed for a variety of liquids, temperatures, and pressures. This unit is somewhat more complex than the standard ASTM device referred to in G 32-72 since the sealed tank is replaced by an open beaker. This type of test device is most useful for comparison of material resistances, evaluation of effects of different fluids, temperatures, and pressures, but it is not suitable for evaluation of probable cavitation erosion in the usual fluid-handling machine, since the very important flow parameter of velocity is not modeled. In the present state of the art, it is not possible to predict damage in a flowing situation from vibratory test results.

Variations of the vibratory device have been used (but not yet standardized), wherein a cavitation field is provided by the vibrating horn, but the specimen to be tested is held stationary in the cavitating



(a) Cross section of the PWA rotating disk device

(b) Disk installed in housing (schematic)

(c) Damaged specimen (Cb-1Zr alloy) after 30 hr. Cavitation is generated from the hole above the specimen.

FIG. 12—*Water rotating disk cavitation damage test device at Pratt and Whitney Aircraft, CANEL [24].*

TABLE 2—*Comparative damage intensities for different types of facilities.*[a]

Magnetostriction		Intensity[b] (watts/cm^2 x 10^7)
devices, numbers 1 to 7		0.004 to 2.5
Venturis		
number 8 to 9	Boetcher type	0.1 to 0.1 x 10^{-2}
number 10	Shal'nev type	0.1
number 11	Shal'nev type	0.03
number 12	Shal'nev type	0.1
number 13	U-M	0.3 x 10^{-4}
Rotating Disk		
number 14		4
number 15		0.34
number 16		1.0

[a] Adapted from tables appearing in Ref *25* with the kind permission of the American Society of Mechanical Engineers.

[b] "Intensity" of damage as defined in Ref *25* is calculated from the erosion produced by assuming that, to erode unit volume of a material, an energy input equal to the strain energy of the material is required. This assumption is, however, verified by other experiments.

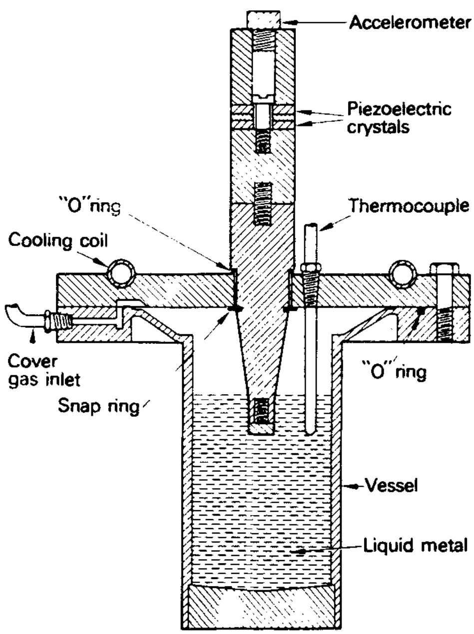


FIG. 13—*Liquid metal vibratory facility at the University of Michigan.* (By permission, McGraw-Hill, copyright 1970, from Ref *6*.)

horn; the specimen to be tested is held stationary in the cavitating field rather than attached to the end of the vibratory horn, as in the standard arrangement. This arrangement is useful for the testing of materials which cannot be vibrated by the horn without deleterious extraneous effects.

Since the stationary specimen is usually located with only a small clearance from the vibrating horn, this stationary specimen test geometry is useful for the testing of materials for bearings, since the bearing geometry is well modeled even though the effects of velocity are absent.

Conclusions

Fluid-induced erosion, both single and multiphase, has been considered according to the various phenomena from which it may be generated. These include both simple high-velocity single-phase flows, and also liquid and solid particle impact as well as cavitation. These latter phenomena are considered as multiphase in nature. It is concluded that in cases of engineering interest there is no plausible mechanism for single-phase erosion of relatively strong materials unless essentially multiphase phenomena as droplet or particle impact or cavitation contribute, or both. Finally, the various types of erosion testing devices are considered and described as to their range of utility, limitations, and relative merits.

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Low Stress Abrasive and Adhesive Wear Testing

REFERENCE: Tucker, R. C., Jr., and Miller, A. E., "**Low Stress Abrasive and Adhesive Wear Testing,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, pp. 68-90.

ABSTRACT: Laboratory testing procedures used to evaluate materials for their resistance to adhesive wear and dry abrasion under low stress conditions are presented. The abrasion test described utilizes a gravity-fed silica sand stream conveyed between the specimen and a rotating rubber wheel to produce the wear. The adhesive wear test uses a block-on-ring machine, and wear and friction under dry or boundary lubrication are evaluated. The effects of test variables on the reproducibility of the results and the determination of the wear rate are discussed.

KEY WORDS: wear tests, adhesive wear, abrasive wear, sanding, boundary lubrication, friction

The development of new materials or the selection of existing materials for a wear sensitive application in many cases requires laboratory test methods for characterizing their wear and friction behavior, since it is not practical to test a large number of potential alloys or coatings in actual service. Such tests must (*a*) duplicate the actual wear conditions as closely as possible, (*b*) utilize specimens with simple geometries which can be easily and accurately fabricated, (*c*) be of reasonably short duration, and (*d*) demonstrate a reliable ability to rank materials in a relative sense which correlates well to observed performance in field service applications and can be duplicated in different laboratories. This paper discusses two such test methods which meet these criteria and are in use to measure low-stress abrasion [*1*][4] and adhesive wear: the dry sand rubber wheel test for abrasion [*2,3*] and the Falex Model No. 1[3] test machine for adhesive wear [*4*].

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[4] The italic numbers in brackets refer to the list of references appended to this paper.

A goal of this discussion is to further stimulate interest in the establishment of standard test methods and wear reference materials, preferably under the auspices of ASTM, so that published test data can be directly compared and therefore become generally more useful. To that end, a step-by-step sequence for testing materials using each device is presented and the important variables noted. Additional information concerning wear tests methods and their evaluation can be obtained from Ref *5*.

A persistent problem in trying to compare the wear performance of various materials using data from literature sources is a lack of commonality in the method of reporting wear losses. A variety of "theoretical" wear constants or factors [*6,7*], bearing performance factors [*8*], or relative wear factors [*9–13*] are reported. These terms may be useful in some cases, but since there is no universal agreement on their definitions or the reference materials used they should always be specifically defined. A better practice, it is felt, would be to report the actual wear scar volumes, irregardless of whether or not some other indicator of wear is used.

The utilization of wear rates, determined from laboratory test data, to quantitatively predict life in serivce is not possible, except in rare cases where the geometry of the test is virtually identical to that in service. This is particularly true with materials that show a change in behavior during the initial period of testing, that is, exhibit a wear-in behavior. Even the definition of wear rate is not universally accepted. Some investigators use the total loss of material from the initiation of a test to the end divided by the total distance of sliding, while others use an instantaneous rate, the loss over a particular increment of testing divided by the incremental distance of sliding. The latter may be more indicative of long-term wear behavior, but the initial wear-in period may be extremely important in engineering design for service applications. Unfortunately, it is probably this period that is most sensitive to the geometry of the mating surfaces and least transferable from a laboratory test to field service. In summary, then, well defined wear rates may be useful in ranking materials, but cannot be used directly to predict service life.

Low-Stress Abrasive Wear

Apparatus

Figure 1 is a schematic drawing of the dry abrasive testing machine to be discussed here [*1,2*]. The rubber wheel consists of an 8-in.-diameter by ½-in.-thick steel hub with a ½ by ½-in. chlorobutyl rubber tire bonded to the rim and cured in a steel mold (Table 1). The wheel is driven by a 1-hp d-c motor through a 10/1 gearbox to ensure that full torque is delivered to the wheel during the test and that the rate of revolution remains

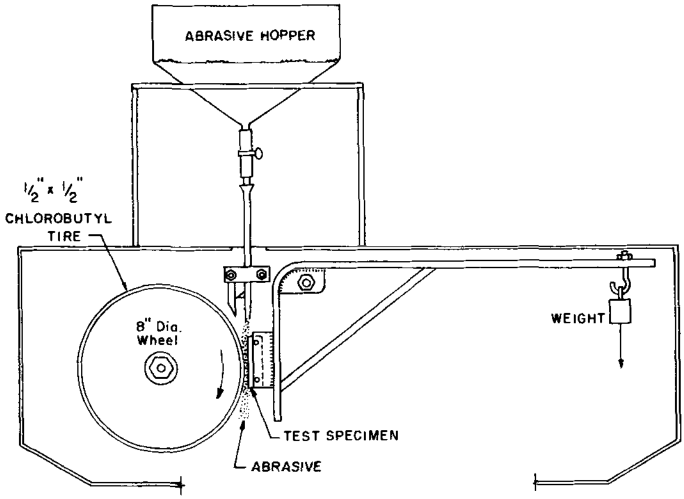

FIG. 1—*Schematic diagram of dry-sand low-stress rubber wheel abrasive wear tester.*

TABLE 1—*Formula of chlorobutyl rubber compounded for dry abrasive rubber wheel testing apparatus.*

Materials	Proportions of Compounding Materials
Chlorobutyl #HT 10-66[a]	100
Neozone A	1
HAF black	60
Circolight oil	5
Stearic acid	1
Zinc oxide	5
Ledate	2

NOTES—Specific gravity of mix: 1.15. Press cure: 20 min at 320°F.
[a] Enjay Chemical Co., Houston, Tex.

constant under loading. All the tests described here were carried out at a wheel speed of 200 rpm or a surface speed of about 470 ft/min.

The specimen is loaded against the rubber wheel through a weighted lever system. The load is applied along the horizontal diametral line of the wheel and was fixed at 30.0 ± 0.1 lb for all the tests described here.

Although the specimens can be any convenient size, the large majority of tests were made with samples having the following dimensions.

Thickness	0.50(+0, −0.1) in.
Width	1.00(+0, −0.05) in.
Length	2.5 to 3.0 in.

Care must be exercised in sample production to ensure that the test surfaces (1 by 3) are parallel, and the edges are free of burrs. The final dimension of the test surface should be produced by grinding parallel to the long dimension. The resultant surface should have a finish of about 25 to 35 μin. measured across the grinding direction to prevent channeling of the abrasive along the surface. The uniform curtain of abrasive was gravity fed at a fixed rate of 130 ± 5 g/min into the vee formed at the contact between the sample block and the wheel. The curtain is formed by dropping the abrasive through a shute with a ¹⁄₁₆ × ½-in. opening. The abrasive was a silica testing sand used by the American Foundry Society (AFS) 50-70. The sand has a uniform morphology, a somewhat rounded form, and a screen size of minus 50 plus 70 mesh (200 to 300 μm).

Procedure

To remove the flashing and the slick exposed surface from the molded rubber rim, the wheel was "run in" on a dummy block for 10 000 revolutions.

Prior to actual use, the rubber wheel was thoroughly examined to ensure that the rim was of uniform hardness and free from visual defects. The Durometer A hardness of the rubber was determined at eight equally spaced points around the perimeter of the rim according to ASTM Test for Indentation Hardness of Rubber and Plastics by Means of a Durometer (D 2240-68 (1974)). The spring-loaded indenter was held firmly in contact with the rubber for 5 s before the hardness was read. The wheel's average hardness, which should be 60 ± 1, was recorded along with the diameter and thickness measured within 0.001 in.

The actual test consisted of the following steps.

1. The specimen was demagnetized to enable the removal of small magnetic particles.
2. The specimen was degreased in trichloroethane.
3. The specimen was allowed to dry.
4. The specimen was weighed to the nearest 0.0001 g.
5. The specimen was positioned in its holder.
6. The sand flow was started, and time was allowed for the flow to equilibrate. The sand used had been dried for at least ½ h at 100°C.
7. The specimen was engaged on the wheel, trapping sand between the wheel and the specimen.
8. The test was run for the desired period.
9. The specimen was removed, and Steps 1 through 3 were repeated before reweighing.
10. The weight loss was normalized with respect to distance skid and wheel width using a reference wheel diameter of 9.000 in. and width of 0.500 in.

Specifically

$$\text{normalized weight loss} = \frac{9.000 \times 0.500 \times \text{actual weight loss (g)}}{\text{actual diameter (in.)} \times \text{actual width (in.)}}$$

It is not necessary to remeasure the wheel diameter and thickness after each run since the dimensional changes are very slow. However, some type of periodic schedule, to redetermine the wheel size, should be adopted. The chlorobutyl rubber does not tend to round up, groove, or develop slick spots during use, and it has not been found necessary to redress this type of rubber before each run as is suggested when neoprene is used [*14*]. In addition, X-ray examination of the chlorobutyl rubber surface indicates that this rubber does not load with metal debris during the test as does neoprene.

Statistical Analysis of Results

In order to quantify the reproducibility of the testing procedure and to determine the number of tests necessary to ensure a meaningful average value, it is necessary to subject the data from a number of tests to statistical analysis. A number of statistical methods are available for such analysis and have been used with varying degrees of success. However, the ASTM Recommended Practice for Choice of Sample Size to Estimate the Average Quality of a Lot or Process (E 122-72) has been found to yield the most realistic results.

In the application of ASTM Recommended Practice E 122-72, two quantities are usually not available. One indicates the variability of the test procedure and the other establishes a maximum allowable error resulting from measuring the average characteristic value from a limited sample size, n, instead of from a large sample size. The variability of the test procedure is expressed as the coefficient of variation, V_0', which is determined as the ratio of the standard deviation of the observed characteristic values determined from a series of tests to the average value of the characteristic expressed in percent. The maximum allowable sample error, e, in percent, is a judgment decision usually based upon experience.

The required sample size is given by

$$n = \left(\frac{3V_0'}{e}\right)^2$$

Table 2 gives the values of some sample sizes obtained for different values at V_0' and e.

Table 3 presents the results of applying this statistical treatment to the

TABLE 2—*Samples size dependence on coefficient of variation and allowable sampling error.*

	Coefficient of Variation (V_0')			
	5	10	15	20
Allowable sampling error (e)	...	...	...	...
5	9[a]	36	81	144
10	3	9	21	36
15	1	4	9	16
20	...	3	6	9
30	...	1	3	4
40	...	...	...	3

[a]Sample size required to assure 99.7 percent probability that measured value is within e of true average.

weight loss data generated for several different materials. It is observed that the analysis predicts with a 99.7 percent probability that the testing of one specimen of Type 316 stainless steel for 1000 revolutions from a freshly ground surface, Test A, will yield a weight loss within 10 percent of the average value that would be obtained from a larger sample size. Altering the testing procedure, Tests B through E, results in a loss of precision in the testing reflected in the increased coefficient of variation. This is probably the result of the increased handling required in increment testing and the difficulty encountered in returning the specimen to the exact location occupied during the previous test increment. A similar loss in precision could be expected for any testing procedure which requires the formation of a run-in scar prior to the actual test increment.

In Tests F and G, the lack of uniformity of material from lot to lot manifests itself as a large coefficient of variation when cross lot comparisons are made, Test F. However, within one lot the precision is very good, Test G.

The results of testing a welded overlay, Test H, shows a high coefficient of variation. Although the number of tests is limited and may not be representative of the true distribution, the apparent reduction in precision could be the result of the variability in the welded overlay microstructure [*2*].

The excellent wear resistance of sintered tungsten carbide illustrates a problem which arises when materials with a wide range of wear resistance are compared. The test increment, 1000 revolutions, produces only a small weight loss which is difficult to determine with great accuracy. This results in an increased coefficient of variation. The precision of the test can be increased by extending the test duration. However, this then makes meaningful comparison with 1000 revolution tests impossible. Correspondingly, increasing the test duration for materials with poorer wear behavior produces an extremely deep wear scar which pinches the sides of

TABLE 3—*Statistical analysis of abrasive wear data.*

Test	Material	Sample Size Tested	Testing Method 30-lb load, 200 rpm	Average Weight Loss (g)	Standard Deviation	Coefficient of Variation Percent	Calculated Sample Size
A	Type 316 stainless steel	50	0 to 1000 revolutions	0.5119	0.0066	1.3	1
B	Type 316 stainless steel	50	0 to 1000 revolutions in 100 revolution increments	0.5436	0.0328	6.1	4
C	Type 316 stainless steel	50	0 to 100 revolutions	0.0610	0.0035	5.6	3
D	Type 316 stainless steel	50	100 revolutions 400 to 500	0.0539	0.0041	7.6	6
E	Type 316 stainless steel	50	100 revolutions 900 to 1000	0.0496	0.0032	6.5	4
F	annealed HR 1020 steel (4 different lots)	100	0 to 1000 revolutions	0.6727	0.1009	15.0	21
G	HR 1020 steel same lot	20	0 to 1000 revolutions	0.6821	0.0164	2.4	1
H	stellite 1016 welded overlay	6	0 to 1000 revolutions	0.0131	0.0017	13.0	16
I	sintered tungsten carbide Kennametal K-714	6	0 to 1000 revolutions	0.0062	0.0004	6.4	4

the rubber wheel and reduces the precision. Thus, it is important to select the test duration that produces enough wear for satisfactory statistics, but not so much as to introduce a loss in precision due to mechanical effects resulting from running the rubber wheel in a deep scar.

Media

The precise details of the nature of the abrasive strongly influence the losses observed for all types of abrasion. A number of authors have examined the effect of the abrasive hardness and toughness [*2,13,15,16*], size, and angularity [*2,13,17–22*] as well as the flow rate [*23*] on the observed material loss. These observations are very illuminating and should be consulted if it is necessary to approximate a given field condition by selecting the proper test abrasive. In general, these studies indicate that two mechanisms are prominent in the removal of materials during the dry sand abrasion test. The first is produced by relatively rounded particles which plough through the surface causing material removal by repeated deformation. This type of wear is predominant when AFS 50-70 test sand is used. Secondly, highly angular particles tend to remove material in ribbons and strips by a microcutting operation. It is highly unlikely that any field condition can be solely described by either of these mechanisms alone, but situations where varying degrees of dominance exist are not uncommon. Since the resulting ranking may depend upon the mechanisms of material removal, it is important to establish the field conditions before selecting an abrasive.

In addition, these studies indicate that the observed wear is highly sensitive to the size of the abrasive and the feed rates when either or both are small. The wear is observed to become insensitive to these parameters when both become large. The abrasive size (200 to 300 μm) and feed conditions (130 g/min) described here are in this insensitive range.

Increment

The duration of the test is a factor which must be considered seriously before embarking on a testing program. Some abrasion testing procedures currently reported in the literature [*1–3,12,14*] require a period of run-in followed by 3000, 5000, or 6000 additional revolutions which constitute the test. Does a "best" test duration exist?

Figure 2 shows the total weight lost by annealed 1020 steel specimens as a function of the total number of revolutions and the testing increment. This indicates that as the testing increment increases, the weight lost per revolution approaches a constant value for the entire range; however, total loss decreases with increasing increment. This observation is more

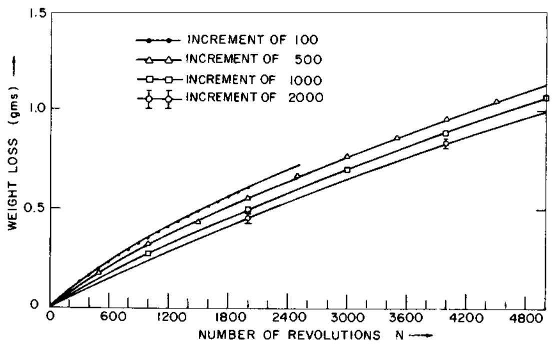

FIG. 2—*Total weight lost for annealed HR 1020 steel during abrasion testing at different increments.*

pronounced with some materials, absent in others, and actually reverses for others. In testing case hardened materials or thin coatings where low increment testing provides the only means of investigating the wear behavior, it is observed that not only does lower increment testing result in an overall increase in weight loss, but also there is a marked difference in the weight loss per revolution from region to region over the testing range. This, or course, makes it difficult to compare the performance of wrought materials with their coating counterparts. To conclude, however, that large increment testing is then the proper alternative neglects the fact that in welded overlays, for example, microstructures may not be uniform with depth due to large density differences in the microconstituents and the presence of mixing zones. Long-term tests may then penetrate the material of interest producing erroneous results. Thus, the test increment must be selected so that the proper material is being sampled and attempts to directly relate weight loss data from one test increment schedule to another should be avoided.

Low-Stress Adhesive Wear Testing

Low-stress adhesive wear testing occurs in industry predominantly under conditions of boundary lubrication [*24*]. Adhesive wear may also be significant when no intentional lubricant is present or, in more recent times, in the rather unusual environments of vacuum [*25*], liquid metals, or inert gases [*24*]. A very wide variety of test devices has been used to determine adhesive wear and friction characteristics. A recent compilation [*26*] lists over 100 friction and wear test devices, a high fraction of which can be considered adhesive wear testers. If these devices were to be classified by their geometries of contact, it would seem that virtually every combination has been tried and virtually all types of relative motion used as well. Many of these tests, however, are better suited to lubricant evaluation than to evaluating the wear resistance of the material.

To facilitate the comparison of wear test data generated in various laboratories, it would be advantageous to have a commercially available, well characterized wear test machine and a standardized test procedure. To that end, the Falex Model No. 1 (formerly the Dow Corning LFW-1) machine was chosen for preliminary studies here. It was designed by Sonntag [*4*] in the early 1950's and has been refined several times since then. For the most part, it has been used for lubricant testing [*27–31*], and an ASTM calibration standard for this purpose has been developed (ASTM Calibration and Operation of the Alpha Model LFW-1 Friction and Wear Testing Machine (D 2714-68)). It has, however, also been used for some wear testing for materials development [*8,32–36*], but little, if any, attention has been paid to the effects of various test procedures on the test results and certainly no common test methods exist so various data in the literature can be directly compared.

The Falex No. 1 machine is shown in Fig. 3. It uses either a flat or

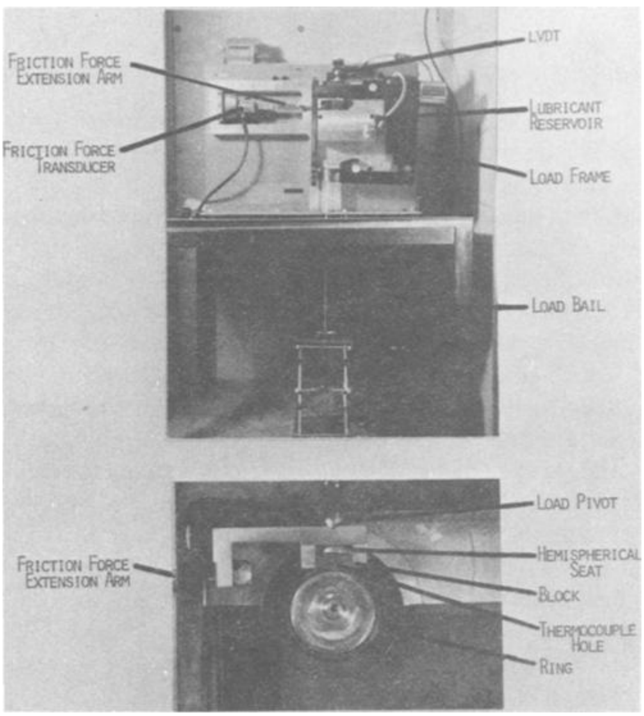

FIG. 3—*Falex Model No. 1 (LFW-1) wear test machine. Ring rotates counterclockwise for unidirectional testing.*

conforming block riding on a rotating or oscillating ring. The friction force is measured using a transducer aligned tangentially with the ring surface and perpendicular to both the line of contact with the block and the direction of loading. The load is applied using a unique compound lever arrangement through a knife edge over a hemispherical ball seat for the block. The machine can be used for dry testing, or the ring may be partially or completely submerged in a lubricant.

There have been several models of what is now the Falex Model No. 1, but those currently available provide variable unidirectional speeds from 0 to 72 or 0 to 468 ft/min. These speeds are set manually, and the rate of acceleration from 0 to the test speed is an arbitrary function of the operator's manual skill. This may present a problem in reproducibly measuring "static" friction forces, but no statistically valid experiments to determine the effect have been run by the authors. No mention of the rate of acceleration is made in ASTM Method D 2714-68. The tolerance on the test speed in the ASTM method of 72 ± 1 rpm does not seem realistic, at least on the low speed machine which has only a one-turn potentiometer control.

Test Procedures

Although ASTM Method D 2714-68 provides a method for the calibration and use of the machine, some changes are necessary when using the machine to characterize the friction and wear of various materials. Obviously, the load, rate of rotation, and lubricant are to be considered as variables and are not fixed as during calibration. In addition to the problem of setting the rate of rotation, already mentioned, the dimensional tolerances on the ring and block specimen can be broadened and the specimen and machine cleaning procedure relaxed without degrading the test. It has been found that an increase of at least 0.012 in. in the diameter of the ring can be made with no detectable effect on the friction or wear measurement. This allows the economical testing of coatings on readily available standard specimens. The use of trichloroethane rather than benzene and methyl ethyl ketone to clean the specimens and apparatus makes compliance with current government regulations much easier. Other solvents could probably be used as well without measurable effect on wear or friction measurements.

The following procedure was used for the work reported here and is suggested as a standard procedure for materials evaluation.

1. The block and ring were cleaned ultrasonically in trichloroethane. A methanol rinse was used to remove any traces of trichloroethane residue. The blocks and rings were allowed to dry completely. The blocks and rings were handled with clean, lint-free cotton gloves from this point on.

2. Profilometer traces and surface roughness measurements were made.

3. The block and ring were weighed to the nearest 0.0001 g.

4. The block width and ring diameter were measured to the nearest 0.0001 in.

5. The ring shaft and the lubricant well were cleaned with trichloroethane.

6. The hemispherical block holder was put on the block and a small amount of extreme pressure (EP) molybdenum disulfide (MoS_2) grease was put on the hemispherical surface.

7. The block was placed in position on the machine and, while holding the block in position, the ring was placed on the shaft and the ring locked in place using a torque wrench in accordance with the manufacturer's instructions.

8. The block was aligned on the ring while placing a light manual pressure on the lever arm to bring the block and ring into contact. Care was taken to be sure the edge of the block was parallel to the edge of the ring. The set screws were tightened to fix the block in position, and the pressure on the lever arm was released.

9. The required weights were placed on the load bale, and the lever arm was adjusted in accordance with the manufacturer's instructions. The load was then removed by raising the weights.

10. The thermocouple was inserted in the block and the recorders were adjusted.

11. The lubricant well was filled with the required amount of lubricant and the ring was rotated several times.

12. The revolution counter was set to zero.

13. The weights were gently lowered, applying the required load.

14. The machine was turned on and the rate of rotation was slowly increased until the ring started to rotate while recording the static friction force. The rate of rotation was increased to the desired rate.

15. The friction force, lubricant and block temperature, and displacement of the block were recorded, as required, during the test.

16. The test was stopped automatically at the preset number of revolutions.

17. The block and ring were removed, cleaned in trichloroethane, and reweighed.

18. Surface roughness measurements and profilometer traces were made. The ring diameter was measured to 0.0001 in. and the block scar width and length to at least the nearest 0.001 in. or the block scar area to 0.01 $in.^2$

As with any test method, the effects of varying each of the parameters or conditions of the test on the accuracy and precision of the data are important. The effects of variations in a few of these parameters on the data generated by the Falex Model No. 1 test will be discussed in the following sections.

Surface Roughness

The texture and surface roughness of the block and ring can have a significant effect on the friction and wear behavior of materials in the Falex Model No. 1 test. Even in long-term tests, the effect of an initially rough surface can be persistent because of gouging or material transfer early in the test. If a hard rough surface is run against a relatively soft material (and material transfer is minimal), the wear rate may be very different than with polished surfaces throughout the test.

It should be kept in mind that a center line average (CLA) of arithmetic average (AA) measurement is only a rudimentary characterization of the surface. A profilometer trace gives far more information and may be very important in interpreting the results of this test, since various textures with similar CLAs can result in significantly different wear and friction behavior.

Environment

The Falex Model No. 1, as stated earlier, is equipped to run with the ring either partially or completely submerged in a lubricant. In addition, the test can be run dry or with the ring and block enclosed in a furnace. The maximum gas temperature is either 500 or 700°F depending on the type of machine, but the maximum block and ring temperature are much lower (about 300°F for the lower temperature furnace).

It would be very useful to have several different types of lubricant specified as reference lubricants to facilitate direct comparison of reported wear data. A single reference lubricant would be even more convenient, but not realistic. It would be better to characterize wear in various classes of lubricants, for example, to have a reference representative of lightweight motor oil, hydraulic fluid, etc., recognizing, of course, that small changes in a lubricant's chemistry can result in large changes in friction and wear behavior. The reference lubricants could only be used for relative ranking of material. ASTM Method D 2714-68 requires a mineral oil that might be considered as one reference lubricant except that it is very difficult to obtain mineral oil with the specified viscosity. Mineral oils with higher or lower viscosities are readily available, and the adoption of one of these or a well characterized paraffin oil should be considered.

There seems to be little advantage in trying to run the test with the lubricant preheated as specified in ASTM Method D 2714-68. If it were desired to run the test as isothermally as possible, either a higher preheat temperature may have to be chosen or a cooling system used, since much higher temperatures than that specified in the standard occur when testing many materials due to the frictional energy alone.

Although the surface temperature of the block is undoubtedly higher than the temperature measured by the thermocouple embedded a short distance below the surface, the recorded temperature is often indicative of wear rate [32] and can be useful in comparing materials with similar thermal properties. Since the temperature can be recorded continuously, abrupt changes in temperature during the test may indicate the point at which the mechanism of wear changed.

Load

With most materials wear loss in tests on the Falex Model No. 1 increases in approximately a linear manner with load as predicted by most wear models [37] (within the range of loads possible with the Model 1). As illustrated in Fig. 4, however, the rate may either increase or decrease with increasing load. Both types of behavior have been reported in many other

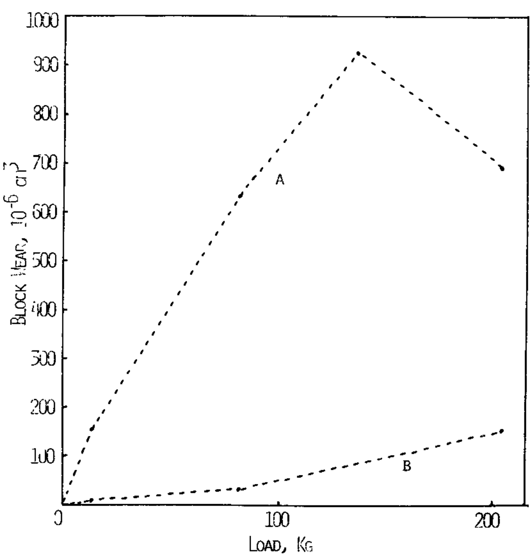

FIG. 4—*Block scar volume as a function of load after testing in Falex Model 1 at 180 rpm for 5400 revolutions in Mil H5606A hydraulic fluid of* (A) *plasma-deposited aluminum rings and* (B) *modified plasma-deposited aluminum bronze blocks against SAE 4620,* R_c*60, steel rings.*

systems and attributed to the formation or breakdown of oxide films [37]. Structural collapse of the material may also occur, particularly if porous materials are being tested. It is, therefore, hazardous to try to extrapolate wear rates or, in some cases perhaps, even to assume that relative ranking will remain constant, beyond the range tested.

Rate of Rotation

The effect of the rate of rotation may vary from one combination of materials to another [*38*]. To obtain some idea of the sensitivity of the wear measurement to the accuracy of setting the rate of rotation, a series of experiments was run similar to the calibration standard ASTM Method D 2714-68, except for the cleaning procedure and a substitution of paraffin oil with a viscosity of 125 to 135 cSt. As in the standard, the load was 150 lb; temperature, 110°F; duration, 5000 revolutions at 72 rpm; block, SAE 01 steel, R_c 28 to 33 (4 to 8 rms); and the rings SAE 4620, R_c 58 to 63 (5 to 15 rms). Single tests were made at 10, 50, 100, and 200 rpm, and six tests at 72 rpm. The results, shown in Table 4, indicate that any effect due to changes in the rate of rotation within the range tested are masked by the scatter in the data. Obviously, this situation may not be true for other materials.

TABLE 4—*Effect of rate of rotation on block scar volume.*

Rate of rotation, rpm	10	50	72	100	200
Scar volume, 10^{-5} cm^3	9.43	3.41	8.32	6.21	11.1
			14.1		
			23.2		
			23.5		
			20.5		
			20.1		

Measurement of Wear

The amount of wear resulting from a Falex Model No. 1 test has been determined in a number of ways based on measurement of the average block scar width, projected area of the block scar, profilometer traces of the block and ring scar, and weight change of the block and ring. The most common method of measuring wear of the block is based on the average width measurement as specified in ASTM Method D 2714-68. This can be precise and accurate if the wear scar is nearly rectangular (Fig. 5*A*), and there is no debris build-up (Fig. 5*B*) or excessive plastic deformation (Fig. 5*C*) that obscures the edge of the scar.

Block scars with very jagged edges, such as in Fig. 5*D*, also make interpretation extremely difficult. There might be some justification in simply excluding such results as being outside the range of test capability of the device. The most common method used in such cases, when utilization of the data seems warranted (with less jagged edges, than shown in Fig. 5*D*), is to visually estimate a center line through each edge of the scar. A somewhat more accurate method is to take an enlarged photo of the surface and measure the projected area with a planimeter.

Both the width and area measurements are converted to a volume loss

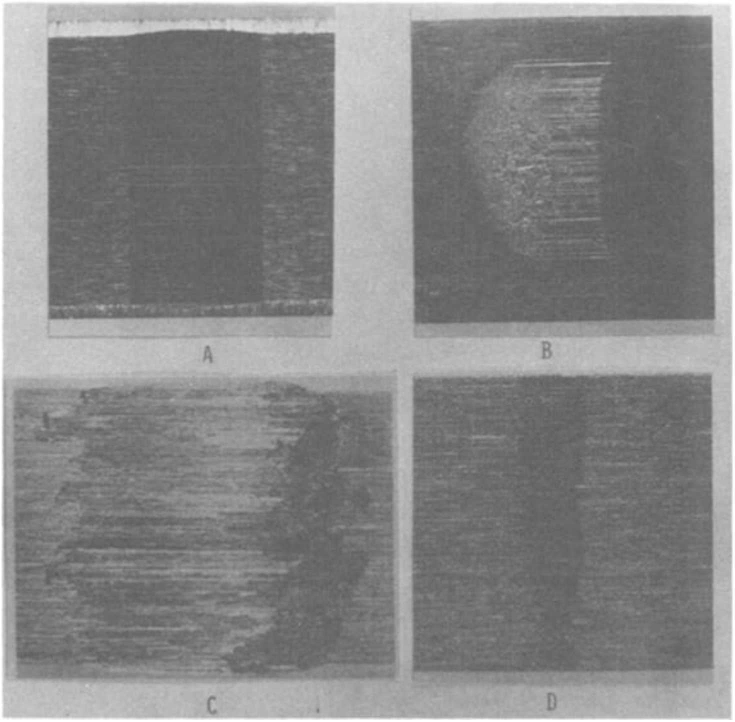

FIG. 5—*Block scars after Falex Model 1 testing showing* (A) *a clean straight-edged scar,* (B) *a scar with a build-up of granular debris,* (C) *a scar with extensive plastic deformation, and* (D) *a scar with a jagged edge (approximately X6).*

by assuming that the cross section of the scar is circular and of the same diameter as the ring. In a few instances with very hard coatings on the blocks, it has been found that this was not true. Therefore, it is advisable to check the cross-section configuration with a profilometer trace. The profilometer trace itself could be used to measure the scar cross section, but the accuracy and efficiency of this method has not yet been investigated.

The use of a weight change to measure adhesive wear can be inaccurate because of material transfer to either the block or ring or because of debris accumulation at either end of the wear scar on the block. Contamination, oxidation, or the incomplete removal of lubricants from porous materials may also contribute to errors in weighing. The inaccuracy becomes more acute, of course, with smaller scars.

An estimate of the relative merits of using scar width compared to weight change to calculate volume loss can be made assuming reasonable limits of accuracy for each type of measurement and assuming "ideal" straight-edged, clean scars in fully dense material. A "good" balance is accurate to ±0.0001 g, thus an accuracy of no better than ±0.0002 g is expected when determining a change in weight. This is equivalent to a scar volume of about 2.5×10^{-5} cm^3 (1.5×10^{-6} $in.^3$) (for iron), which, in turn, is equivalent to change in scar width of about 0.002 in. when the scar is 0.10 in. wide. Since it should be possible to measure the width and length of an ideal straight block scar to ±0.001 in., it seems reasonable to assume that the weight change method should be more accurate for scars greater than about 0.10 in. wide and the width measurement method more accurate for narrower scars. Because of the problems with contamination or debris, however, the width method is most commonly used for all block scars. On a ring, the volume equivalent to the minimum expected error in weighing corresponds to a change in diameter of only 1.4×10^{-7} in. Thus, a weight change measurement is usually more accurate than a diameter measurement and is the most commonly used method.

The continuous measurement of the combined wear of the block and ring using the linear variable differential transformer (LVDT) mounted above the block on the Model No. 1 is useful for following the general process of wear during the test and occasionally detecting changes in mechanism. It is difficult, however, to separate thermal expansion effects from wear effects to quantitatively use the results to measure wear.

Several sets of experiments were run to partially evaluate the precision of the width and area methods of determining the block scar volumes. In a simple check of the precision of measuring the block scar by the width method, five individuals measured the same clean, straight-edged scar using a 0.005-mm (0.0002 in.) filar eyepiece on a microhardness tester. The maximum deviation from the average of 10 measurements of the width near one edge of the block was 0.15 percent, 0.29 percent in the center, and 1.3 percent near the opposite edge, indicating a deviation from the overall average well under 1 percent (0.001 in. for a 0.10-in. scar).

In a comparison of the scar width, scar area, and weight change methods of determining block scar volumes, four tests were run as specified in ASTM Method D 2714-68 except that paraffin oil with a viscosity of 125 to 135 cSt was used, and the parts were cleaned with trichloroethane. The detailed procedure previously outlined was followed. Clean, straight-edged scars were obtained. Each width measurement used in the calculation of scar volume was the average of the scar width measured three times in the center and 1 mm from each end of the scar (that is, a total of nine measurements). A machinist's microscope with an accuracy of 0.0001 in. was used. The scar area used in the calculation was the average of four measurements made to the nearest 0.01 in. on enlarged photographs (approximately ×10) of the scars with a planimeter. The magnification of each individual photograph was calculated from a measurement of the block width on the photo and the actual block. These basic methods of measurements were used in the rest of the experiments described in this paper.

The results are shown in Table 5. There is reasonably good correlation

TABLE 5—*Comparison of block scar volume measurement by the scar width, scar area, and weight change methods.*

Specimen Number	Scar Area Method	Block Scar Volume, 10^{-4} cm,^{3} Scar Width Method	Weight Change Method
2984-94	5.848	7.599	6.633
2935-97	6.867	6.262	8.035
2951- 1	4.933	5.640	5.612
2951- 4	7.917	10.116	8.418
Average	6.39	7.40	7.18
Coefficient of variation, %	20.	27.	18.
n (number of specimens required for 99.7% probability and 50% assumed error	2.	3.	2.

between average values of the scar volumes for the four tests as measured by the three methods. The coefficients of variation for the three methods are also comparable. The close correlation between the weight change and width methods would be expected in view of the earlier discussion, since the width of these scars is about 0.1 in. The coefficient of variation is slightly better for the planimeter method than the width method in this case. The procedure in ASTM Recommended Practice E 122-72 to estimate the required sample size was just described. If a 99.7 probability is again desired, the results, assuming an error of 50 percent, are shown in Table 5. This error (that is, difference between the measured average of the sample and the average of the total population) is more than adequate for most materials selection or development work.

A further evaluation of the precision of the scar width and area methods of measurements was made using four tests in accordance with ASTM Method D 2714-68 (including the specified mineral oil with a viscosity of 63 to 65 cSt) except for cleaning the parts in trichloroethane. Again, clean straight-edged scars were obtained. The measurement methods described here were used, but each complete measurement procedure was repeated five times (for example, the width measurements for each block consisted of five individual measurements in five sets of nine). Each of the five averages was used to calculate a scar volume. The results are shown in Table 6. The precision of the width measurements was slightly better than that of the planimeter method. The correlation between volume loss calculated by the width measurement and calculated from weight loss was reasonably close when the scar width was greater than 0.1 in., but poor when the scar width was about 0.05 in. This supports the previous comments on the relative merits of the methods as a function of scar width. The distinct difference between Specimens A and B compared to C and D has not yet been explained, but is being investigated.

TABLE 6—*Block scar volume calculated from scar width, area, and weight change.*

Specimen	Scar Volume, 10^{-5} cm^3 A	B	C	D
Scar width method				
average	74.2	61.7	7.60	8.06
coefficient of variation, %	0.51	0.83	0.23	1.06
Scar area method				
average	69.7	58.7	7.33	7.48
coefficient of variation, %	1.98	2.72	7.16	1.82
Weight change method (single measurement)	74.0	62.5	2.04	1.53

The effects of the scar profile on the precision of measuring the volume loss by both the width area techniques was explored by using a clean block scar (similar to Fig. 5*A*), a scar with a large pile-up of granular debris (shown in Fig 5*B*), and a scar with a jagged edge (shown in Fig. 5*D*). Two individuals made six separate sets of measurements of each type on each scar. Again each set of measurements was done using this procedure and a separate scar volume was calculated. The results are shown in Table 7.

The coefficients of variation for the scars with obscured edges were very much larger than those for the clean scar. Nonetheless, the average scar volumes measured by the two individuals using the width measurement are reasonably close for each scar. This is probably because the position of each measurement was rather precisely defined and therefore reproducible. It does not indicate that the measurements were particularly accurate for the scars with obscured edges.

TABLE 7—*Block scar volumes calculated from scar width, area, and weight change.*

	Clean Scar	Scar Volume, 10^{-5} cm^3 Granular Debris	Jagged Edge
Width method			
1st Individual Average	62.49	17.48	3.71
Coefficient of Variation, %	0.59	5.00	1.19
2nd Individual Average	67.70	19.95	3.59
Coefficient of Variation, %	0.71	24.9	4.54
Area Method			
1st Individual Average	62.53	12.03	6.81
Coefficient of Variation, %	1.68	31.0	9.18
2nd Individual Average	62.87	7.66	9.01
Coefficient of Variation, %	3.21	1.23	5.66
Weight change method	66.33	(−13.35)	4.80

The average scar volumes measured by the two individuals using the area method for the clean scar were very close and comparable to the values measured by the width method. The wide difference in average values for the scars with obscured edges reflects a difference in the interpretation of the edge of the scar. (Neither individual was instructed as to where the actual edge was and their judgments obviously differed.) The hazard of using weight change to determine scar volume when wear debris is retained on the block is evident in Table 7—an obviously erroneous increase in block volume being implied for the block with granular debris! Several techniques of cleaning the surfaces of blocks to eliminate debris or deformed material have been considered, but a satisfactory method has not been developed. Thus, the relative accuracy of the two methods for determining the volume of scars with obscured edges cannot be determined on the basis of this set of experiments, but some of the pitfalls have been shown.

Reporting Wear Loss or Rates

The most common method of comparing the wear behavior of materials is to run the test continuously for a constant number of revolutions (or constant sliding distance) and report the total wear. Occasionally, a wear rate is calculated by simply dividing the total volume lost by the total distance of sliding. This can obviously be misleading because of changing configuration of the scar in a flat block-on-ring test. If the test is run incrementally, a wear rate at a given distance of sliding can be calculated. A potential advantage in this method is the ability to compare the wear rates of different materials at the same pressure or value of load per apparent unit area [*35*]. But again this may be misleading since for different materials similar rates at a given pressure may be reached after very different total distances of sliding.

The effect of running a test in several increments compared to running it continuously for the same total number of revolutions or sliding distance is shown in Table 8. In this series of tests, SAE 01 tool steel blocks, 60 R_C, were run against 4620 steel rings, 60 R_c, in 30 weight motor oil under a 450-lb load. Apparently, any incremental effects are less than the scatter in the data for this material combination and under these particular test conditions. Different materials or different test conditions may show a difference between incremental and continuous testing. (This data provides another comparison between the scar area and width measurement techniques and indicates that the prescision of the two techniques is comparable in this case.) It should be noted that a great deal of care was necessary to realign the block on the ring for each increment of testing. If this method of testing were to be used, it is suggested that a mechanical stop be installed on the block fixture to facilitate realignment.

TABLE 8—*Comparison of incremental and continuous wear testing.*

	Revolutions			
	1 000	3 000	5 600	10 000
	Block Scar Volume, 10^{-5} cm^3, by Scar Area Method			
Incremental test				
A	2.3	2.8	3.7	4.4
B	3.2	4.5	5.5	8.2
C	2.9	4.2	5.2	7.7
average	2.8	3.8	4.8	6.7
coefficient of variation, %	16	24	20	31
Continuous test				
E	0.88	1.2	1.4	1.0
F	...	5.8	5.6	3.1
G	...	3.0	4.4	4.5
average		3.3	3.8	2.9
coefficient of variation, %		70	57	61
	Block Scar Volume, 10^{-5} cm^3, by Scar Width Method			
Incremental Test				
A	2.1	2.7	3.3	5.1
B	4.5	4.7	5.6	9.2
C	3.0	3.9	5.6	8.1
average	3.2	3.8	4.8	7.5
coefficient of variation, %	38	27	27	28

Friction Force

A strain gage load cell on the Falex Model No. 1 allows the continuous recording of the friction force. With a recorder having a fast response time, a variety of friction force traces are observed depending, of course, on the materials and the lubricant. If normal smooth wear is occurring, a narrow trace of friction force results. A wide band, indicating a rapidly fluctuating friction force, may be representative of stick-slip behavior. In any event, the friction force may change during a test, either increasing or decreasing; to fully characterize the behavior of a material, these changes should be reported as a function of the distance of sliding. If a fluctuating force is observed, the maximum and minimum defining the band width should be reported, not just the average value.

Conclusions

A laboratory test for abrasive wear testing and one for adhesive wear testing have been discussed. A procedure has been developed for using each to characterize the friction and wear behavior of materials in a manner suitable for materials development and materials selection for service. These procedures or similar procedures should be considered for standardization to facilitate the comparison of wear and friction data reported in the literature. In addition, a reference abrasive media and several lubricants, as well as reference abrasive wear blocks and adhesive wear rings, should be adopted to assist in the relative ranking of material on common scales. It should be kept in mind, however, that without specific comparison to materials with known field service performance, a prediction of friction or wear behavior in service is not possible based on the laboratory tests themselves. Even with direct comparison, only relative ranking is possible. Extrapolation of the data generated in these tests, or any other wear test, to loads, speeds, or environments outside the range tested is hazardous.

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Wear Testing for Office and Data Processing Equipment

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ABSTRACT: The metallic wear situations frequently encountered in office and data processing equipment are reviewed. Motions producing the wear and the nature of the interfaces are discussed. The reasons for wear testing for these applications are identified and a test methodology is discussed. The more frequently encountered wear tests (for example, ball-plane, pin-on-disk, and block-ring tests) are evaluated in terms of this background. An overview is established based on these considerations.

KEY WORDS: wear tests, data processing equipment, office equipment, metals

A survey of the wear literature will reveal that wear testing is done for office and data processing equipment; however, it also indicates that there is no single, universal test used for these applications, nor is there an identifiable, unique wear technology for this type of equipment. An extensive spectra of wear test apparatus, and techniques, typical of the entire field of wear, are used for these applications. The aim of the paper is to present a general wear test methodology and relate it to the problems of wear testing for office and data processing equipment. In the course of doing this, the more common tests, as well as some more unique tests, will be identified and reviewed in terms of this methodology.

Methodology

Establishing a purpose for the wear test is an appropriate initial step in providing a wear test methodology. In the case of office and data processing equipment, the purpose of wear testing is most often to rank

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candidate materials for a particular application so that the ranking truly reflects their potential performance in an application. This test should not only rank the materials in the correct order but should also make sure that the relative wear in the test is the same as that in the intended application. Such a ranking then enables the design engineer not only to identify the material with the best wear resistance for that application but also to optimize the material selection, reflecting the best trade-off between cost-performance, manufacturing consideration, and life goals. Ideally, it would also be desireable if such a test could provide the basis for lifetime predictions prior to the testing of prototype or actual hardware.

This goal gives the wear test an "application" orientation. The key to the test is the selection of the proper test apparatus and test parameters so that the wear conditions of the test simulate the intended application in all essential aspects. At present, that selection process lies somewhere between an art and a science, involving a blend of scientific knowledge and experience.

There are four areas to consider in this selection process: loading (load and geometry), motion, environment (including lubrication), and wearing media. In considering the equivalence of test and application conditions in terms of these four aspects, the complex nature of wear phenomena must be kept in mind [*1*].[2] This should not be done only from the point of view as to what *should* occur. It should also be done in terms of the potential differences in wear behavior that can result from the dissimilarities between test and application. In considering the equivalence of the loading condition, both the applied force and resulting stress should be considered, since it has been shown that wear can be a function of both stress and load. A test which employs a 50-lb normal load is not a good simulation for an application which uses a fraction of a pound load, nor is a test which introduces plastic deformation suitable for an application in which only elastic deformations are produced. In either case, different wear phenomenon could be introduced as a result of the different loading conditions. The dependency on load and stress implies a dependency on geometry as well. As a result, the test geometry should also be appropriate for the application. However, if stress and load are appropriate, the geometry usually is too.

Similarly, the concern with motion should not only extend to the speeds involved, but also to the type of motion as well as to which member experiences the greater amount of wearing action. A test in which Material A rubs against B is not a good simulation of an application in which Material B rubs against Material A. Also, a sliding test is not a good simulation of an application in which the primary interaction is rolling

[2] The italic numbers in brackets refer to the list of references appended to this paper.

or impact, nor is a test employing gross sliding an ideal simulation of a fretting situation.

In considering the equivalency of the environmental conditions, many factors must be taken into account; these include such things as the ambient temperature, humidity, corrosiveness of the atmosphere, amount of dirt or other contamination, and the amount of lubrication. A test that does not use a lubricant is not a good simulation for an application that does.

Finally, the wearing media of the test should be similar to that occurring in the application. If the application involves a V2[3] surface which produces the wear, a V40 roughness should not be used in the test. Also, if the wear is produced by the abrasive action of paper in a machine, a metal-to-metal wear test should not be used to rank materials for that application.

These four aspects of a wear test must not only be considered in a singular manner, but they must also be considered in a joint manner. For example, since the temperature at the interface of the two surfaces can often influence wear, there must be concern with all aspects that can influence that temperature (for example, loading, motion, and environment, as well as the method of heat loss in the test as compared to the application). Consider another example regarding lubrication. Since a fluid lubricant can provide boundary quasihydrodynamic or hydrodynamic lubrication depending on the load, speed, and geometry involved, all these factors must be considered in judging the similarity between test and application.

The degree to which the test parameters and conditions should match the application is a function of the materials involved and the wear phenomenon occurring in the application. For example, in the testing of polymer material, much more concern has to be given to temperature and speed conditions than for metals. Judgements frequently have to be made in this area, but they should be based on a knowledge of wear behavior, experience, and the application.

In addition to the simulation aspects of a wear test, there is one other aspect that is important. The wear test and associated evaluation of wear characteristics should be sensitive to the same range of wear to which the application is sensitive. For example, in an application in which 1-mil coatings are used, the appropriate wear test should allow the evaluation of wear within 1 mil. This methodology for wear testing is quite general and, to a large extent, is reflected in the other papers of this symposium. They also illustrate that the implementation of such a methodology will result in significantly different test apparatus and techniques depending on application. In the following section, the application of this methodol-

[3] Center line average of two as measured by profilmeter such as a Tallysurf machine.

ogy to the wear testing of metals for data and office product equipment will be considered.

Wear Tests

Since the methodology emphasizes the simulation aspects of wear testing, it is appropriate to begin this section by considering the wide variety of wear situations encountered in office and data processing equipment. Some examples of the wear situation are: noble metal electrical contacts, type elements, guide surfaces for paper, cam followers systems, latches, bearings (ball, roller and journal), magnetic heads and recording surfaces, punches, pawl-detents, clutches, and brakes. While all of these situations have unique aspects, they also tend to have some general characteristics, which are given in Table 1.

A review of Table 1 indicates that a typical wear situation for this type

TABLE 1—*Characteristics of wear contacts in office and data processing equipment.*

Sizes—small; maximum component dimensions typically less than a few inches at most, with dimensions less than an inch common; thin sections common, <0.25 in; contact areas ranging from a maximum of the order of 0.1 in.^{2} to the order of 10^{-5} in.^{2} typical; size and shape frequently selected to provide low inertia and fast response; contacts often nonconforming.

Motions—contact may involve sliding, impact, or rolling, either pure (mainly for sliding) or mixed, for example, combined impact-sliding or rolling-sliding action; surface speeds can range up to several hundred inches per second; fretting motions common; unidirection and reciprocating motion common; amplitude of motion typically less than 1 in. but with short cycle times, for example, order of milliseconds or tens of milliseconds; both continuous and intermittent motion common.

Loads—loads typically in the range of 1 to 5 lb, with lighter and higher loads possible; dynamic loading frequent; because of small size of contacts and peak dynamic loads, stress levels frequently are high or moderate, for example, 10 000 to 100 000 lb/in.^{2}

Tolerances—small; typically ranging from 0.1 to 2 mils.

Lubrication—most contacts are lubricated; thin, wipe film of lubricant, obtained from contact with wicks, frequently used; impregnated porous materials used; oils, greases, and solid lubricants used; minimum use of relubrication; lubrication for life desireable; lubricant usually confined to immediate contact areas.

Environments—mild and relatively clean, typical of an office environment; air conditioned environments common, sometimes required; internal machine temperature 20 to 30°F above room ambient temperature.

Lifetimes—several years typical; number of operations without wear out typically range from millions to hundreds of millions.

Wear Levels—maximum wear acceptable frequently in the less than several mils.

of equipment would have the following characteristics: light load, small precision components, relatively clean and moderate environments, and light lubrication. However, a wide variety of motions may occur: one-way or reciprocating sliding, impact, rolling, fretting, and various combinations. Recognize that while the loads are light, the components are also small, so that stress levels are not necessarily low. For metal-to-metal contacts, stress levels from a few hundred psi to about 10^5 psi are encountered; however, stresses are generally in the elastic range.

For ferrous metals, the small size and precision of the components also influence the type of heat treatment that is done. For example, case depths in steel components are normally in the range of 0.1 to 10 mils, not 100 to 200 mils encountered in other applications. The precision of the components reflects the sensitivity of the mechanisms to dimensional change. In many applications, wear of a few mils can significantly influence performance. In certain cases, wear of less than a tenth of a mil can be significant (for example, in high-density magnetic storage system).

For the purposes of this paper, the metal wear situation occurring in these machines may be categorized in the following manner: (*a*) roller, ball, and journal bearings, (*b*) miscellaneous metal-to-metal contacts, and (*c*) miscellaneous metal-to-nonmetal contacts. The wear testing of bearings represents a specialized field in itself and is treated in earlier papers of this conference [*2,3*]. While this category will not be considered here, the general concepts discussed in the preceding section should be applied to bearing testing, namely, the test should simulate the intended application.

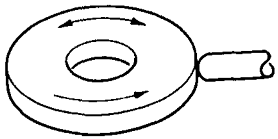
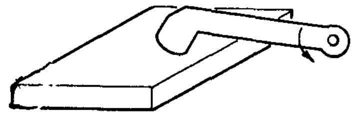
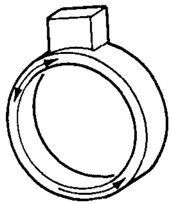
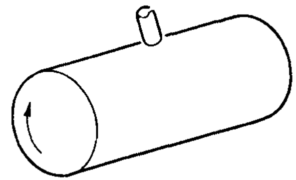
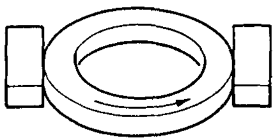
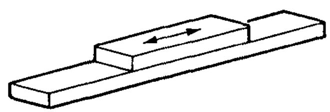
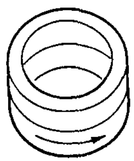
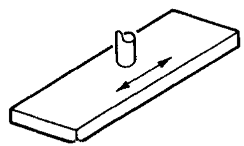
There is no specific wear test or even an identifiable technology for the second area, that is, metal-to-metal contacts in office and data processing equipment. Rather the type of wear test apparatus and test methods that are used for general metal-to-metal wear situations are used here. Such techniques are discussed by the other authors in this conference [*4*];[4,5,6] however, in this paper their relevance to office and data processing equipment is considered.

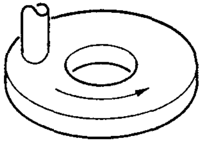
In Table 2, a summary of some of the more commonly used wear testers is given; a more extensive listing may be found in Ref *4*. Many of these test configurations are one-of-a-kind machines developed and used in one lab, while others are available in commercial units.

The applicability of any test apparatus to office and data processing equipment must be considered in terms of the concepts expressed in the prior section. Basically, this means having the test simulate the intended application in key aspects. Since office and data processing equipment involve a wide variety of wear situations, and since there are so many individual test apparatus and techniques, it is not feasible to comment on each individual apparatus and technique in terms of its applicability to these wear situations. Rather some general observations will be made in terms of the four parameters considered previously: motion, loading, environment, and wear media.

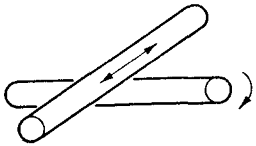
[4] See p. 12.
[5] See p. 30.
[6] See p. 68.

TABLE 2—*Wear test apparatus.*

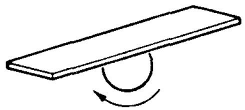
Geometry	Motion	Geometry	Motion
	unidirectional Sliding		reciprocating sliding
	unidirectional or oscillatory sliding		unidirectional sliding
	unidirectional sliding		pure rolling and rolling plus sliding
	unidirectional sliding		small amplitude oscillatory sliding (fretting motion)



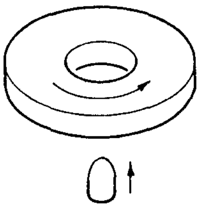
unidirectional sliding



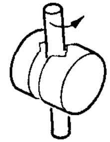
unidirectional sliding or unidirectional sliding plus oscillatory motion



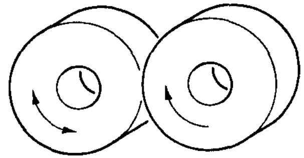
unidirectional sliding



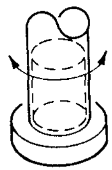
reciprocating sliding



small amplitude oscillating sliding (fretting motion)



normal impact and normal impact plus sliding



normal impact

NOTES—
Specimen Size
Typical dimensions of pins and blocks are less than an inch.
Typical dimensions of rings and disks are approximately a few inches.
Loads
Wide range of loads covered by these tester (fraction of a pound to thousands of pounds).
Some apparatus provide adjustable loading features, while others provide a single load.
Some apparatus automatically increase load in preset increments.
Speeds
Vary with apparatus, but a wide range available (0.1 in./s to 10^2 in./s).

A review of Table 2 shows that for the majority of cases, the common feature of the apparatus is sliding motion. Frequently, this is unidirectional or large amplitude reciprocating motion. For wear situations in which gross sliding is the primary motion, these tests are appropriate. However, for situations in which the primary motion is normal impact or in which the motion is small amplitude oscillating sliding (such as in a fretting situation), they are not appropriate. For such situations, apparatus which provide such motions are required.

While there are some apparatus described in the literature [5–9] which provide such motions, they are not common nor as readily available as sliding wear apparatus. However, for fretting (or fretting corrosion, or both) situations, which are frequently found in office and data processing equipment, more universal sliding wear testers may be used, provided they have a reciprocating motion whose amplitude can be adjusted low enough. For example, in our own laboratory, a reciprocating ball-plane apparatus whose amplitude can be adjusted to several mils has been used to successfully rank material for use in a fretting situation.

The loading conditions in many of the test apparatus and techniques are also another area of concern; test loads in the range of 50 lb or more are frequently encountered. While large contact areas are frequently used so that the resulting stress levels are appropriate to office and data processing equipment, such loads are not; hence, there is poor simulation. Both stress levels and load should be similar to that of the application, since both may influence wear behavior.

In addition, when tests use heavy loads and large specimens, the measurement of wear utilized is often coarser than the level of wear acceptable in the application. In such a case, the wear data may not be relevant to the application. The influence of the coarseness of the test is particularly evident when evaluations involve the thin coatings or layers, that is, a few mils in thickness, which are commonly used in these applications. Such tests may not be sensitive enough to rank such material.

Some test equipment and procedures are designed to rank materials in terms of the maximum load that can be applied, for example, the load at which catastrophic wear or seizes occur. While such an approach may be appropriate for situations in which severe conditions occur, they are not appropriate for the application considered here, since in office and data processing equipment such extreme conditions are not encountered. Such a test mode is not a reasonable simulation for these cases, where the concern is the ranking of materials performance under light or moderate conditions.

For metal-to-metal contact in office and data processing applications, normal laboratory conditions frequently offer a good simulation of environmental conditions. Consequently, since most test apparatus are used under normal lab conditions, environmental conditions are usually not an area of major concern.

Since many of the metal wear situations involve lubrication, many of the wear tests should also use lubrication, since this is a key parameter in wear behavior. However, in such cases, the difference between a test evaluating the wear characteristics of a metal in the presence of a lubricant and the evaluation of a lubricant must be recognized. In many cases the same wear apparatus and similar techniques can be used for both purposes [4]. For the wear testing of metals, the lubricant and method of lubrication should be the same as or equivalent to that used in the application. Wear test conditions should not be used which stress or degrade the lubricant beyond the levels experienced in the application.

Our fourth concern is the wear media used. Since it is known that the wear of a material is not simply associated with that material but also with the mating surface (material), test techniques that use only one wearing media may not provide valid ranking that is applicable to all cases. The wear media should be at least similar in composite and roughness to that used in the application for which the test is being done; ideally, it should be the same.

In many of the testers, a conforming area or line contact is used. In such cases, initial wear behavior is ignored because of alignment problems and wear data are obtained during the more stable period of wear, after seating has taken place. For office and data processing equipment application in which small amounts of wear are of interest, initial wear behavior is frequently of importance. Hence, such techniques are not very appropriate for such cases. Rather the use of techniques that enable the initial wear period to be studied (such as the use of point contact, for example, sphere-place contact) are desired frequently.

The third type of wear situation which occurs for metals in office and data processing equipment is their contact with nonmetals. Two subcategories are convenient here. One subcategory is the contact with nonmetals which are used in a structural manner as load bearing surfaces. Examples of this are metal gear mating with polymer gears and an all metal cam follower against a nonmetallic cam. The second subcategory is the contact with a flexible nonmetallic member, such as paper, ribbons, or tapes.

For the former category, the same type of wear apparatus and techniques that are used for metal-to-metal contact are frequently appropriate here. The same concerns apply in terms of loading, environment, motion, and wear media. However, in this case the range of testing conditions which provide a good simulation to the application may be governed by the nonmetal. This is frequently the case when the nonmetal is a polymer, since the wear behavioral of polymers is far more sensitive to load, speed, temperature, and humidity than many metals.

For the second category, metal wear by ribbons and paper, different techniques are required, since exposure to large surface areas of the ribbon or paper, or both, are required to produce significant wear on hard metals. This area has received very little attention to date. However, some general evaluation techniques are proposed in the literature [*10,11*]. While the wear mode in such cases is often thought to be abrasion [*12,13*], such tests as the Taber Abraser[7] does not provide good simulation because of the differences between the abrasive media normally used with that apparatus and paper or ribbon.

Conclusion

The discussions of wear test methodology and wear tests indicate that there is no one universal test method that is applicable to all metal wear situations in office and data processing equipment. In fact the emphasis on the complexity of wear phenomenon and the need to simulate the application in the test tend to create an overly pessimistic picture, namely, that there is very little virtue or possibility in testing wear behavior outside of prototypes for each case. However, this is not the situation. While it is true that one wear tester may not be able to provide all the answers for all the situations encountered, a few, fairly general types of testers used appropriately can provide accurate and useful information. For example, in our own laboratory, a reciprocating ball-plane apparatus[8] has been found quite valuable in selecting and evaluating materials. This tester provides the flexibility in load, material, and motion so that a large variety of sliding situations can be simulated for our applications.[9]

The wear test methodology stresses the need to have similarity between key parameters of the test and application. For data processing and office product application, many of the wear tests and testers available do not provide the needed similarity. While these tests might provide gross ranking of the materials, they frequently do not provide the necessary accuracy or definition in this ranking for engineering purposes, particularly where the achievement of a particular lifetime is required. In these cases, the primary lack of similarity is in the area of loading, type of motion, and sensitivity. For office and data processing equipment, testers that use small contacts and loads, and provide the proper motion and sensitivity are appropriate.

[7] Manufactured by Taber Instrument Inc.; used in ASTM Test for Relative Resistance to Wear of Unglazed Ceramic Tile by the Taber Abraser (C 501-66(1971)) and ASTM Test for Resistance of Transparent Plastics to Surface Abrasion (D 1044-73).

[8] A modified Bowden-Laben apparatus as described in Ref *14*.

[9] For example, in an application involving a pulley and shaft combination, equivalency of performance of hand chrome plating and baked electroless nickel plating was successfully established. This approach is further discussed in Ref *15*.

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K. C. Ludema[1]

Wear Debris as an Indicator of Valid Simulation in Wear Tests

REFERENCE: Ludema, K. C., "**Wear Debris as an Indicator of Valid Simulation in Wear Tests,**" *Selection and Use of Wear Tests for Metals, ASTM STP 615,* R. G. Bayer, Ed., American Society for Testing and Materials, 1976, 102–109.

ABSTRACT: Wear testing is often unreliable because wear is a complex process. There are several wear modes for each material, and often a small change in operating condition produces a drastic change in wear rate. Uncertainty in developing wear tests may be reduced by examination of wear debris from both the wear tester and the full scale machine being simulated. If the debris from both are similar, the wear test is worthy of further use.

KEY WORDS: wear tests, wastes, simulation, wear

Wear testing may be a successful and useful exercise, but it is often necessary for the wear test and the developer thereof to mature together. In the face of the great range of available materials and the multitude of wearing environments, it is surprising when a good wear test is found. Engineers who have developed successful wear tests surely should be commended, even though the tests usually are limited in scope. On the other hand, those with little experience in wear characterization or wear testing often give up before they should.

Wear tests are developed and used, apart from research, for four situations. Each of the four situations is sketched here together with the difficulty encountered in each.

1. If a machine of interest is very complex or expensive, a "simulator" may be designed to test certain components for wear life. For sliding elements, the simulation is usually effected by duplicating the contact pressure, the sliding velocity, type of lubricant, thermal conditions, and other such obvious quantities. In systems with rolling-element bearings and

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gears, the actual element may be loaded artificially and run in a bench test. The difficulty with a wear simulator is that its value is unknown until some comparison is made between the performance of the simulator and the full scale machine. One major uncertainity is that the full scale machine has many elements in it that provide a different environment than is found in a simulator. It is not usually possible to discount the interaction between elements out of hand, and thus complete confidence in a wear simulator is often delayed until after development of the full scale device.

2. "Accelerated" tests are very attractive and are done usually to arrive at early conclusions at low cost. The chief difficulty with accelerated tests arises from the fact that they are usually done by simply increasing the severity of one contact condition, such as contact stress or sliding speed. Unfortunately, this change may shift the wear mechanism to an entirely different mode than in the machine of interest, and the test data become useless. Frequently this is not discovered until late in the testing.

3. Wear testing is often done for "quality control" purposes in the manufacturing process. Such tests are usually developed to operate independent of an operator. The difficulty in these tests is that the test conditions may shift or change in character slightly, or the material being tested may be changed during production and the operator is not fully trained to be aware of these changes. Then the test may become a liability in that it will reject too many good parts or accept too many bad ones. Either alternative is costly, particularly if the validity of the wear test must be detected by a drift in scrap rate, customer complaint, or recall rate.

4. In product development candidate materials are "screened," often by a single standard wear test. Apparently, it is implied in such tests that all materials tested respond in the same way to differences between the test conditions and real service. Development programs often progress a long way before an erroneous procedure is discovered.

Tests for each of these four situations have their own peculiar limitations, and if unsuccessful, constitute a waste of time and money. In view of the present technology and discoveries in wear, a new procedure could be instituted which could give an early indication of the validity of a wear test. That procedure is to examine wear debris from the wearing parts of both the test device *and* the full scale machine. If the debris in both cases are different, the wear test in almost all cases is not valid, or at best any correlation would be fortuitous. If the debris from each are similar, the wear test is probably worthy of further development.

The motivation to study wear debris arises from the fact that there are several distinct types of wear debris, just as there are several modes of wear. A firm connection between the modes of wear and the types of wear debris is still lacking, but there is some progress reported in the literature.

Examples of Wear Mode and Debris Appearance

In the study of wear debris, a wide range of observations is made. Many conclusions may be reached by simple visual observation, with and without optical aid. However, a very useful tool is the scanning electron microscope (SEM) with associated analytical attachments [*1*].[2] Because of the great depth of focus capability of the SEM, it is possible to view rough surfaces at high magnification. On the other hand, the SEM can be set to a conveniently low magnification, about ×20. One can scan quickly a large surface, and locate and provide elemental analysis of debris of all sizes and texture without special handling of parts or debris. In recent studies, these instruments have resulted in verification of several previously postulated wear modes.

The various wear modes, the conditions for achieving various wear modes, and the appearance of the worn surface are described in a great number of published papers. The appearance and composition of wear debris, however, are reported in few papers, and there are some conflicting reports. A summary of some of the papers is given here and divided in terms of "adequacy" of lubrication.

Dry Sliding Wear

Perhaps the most definitive work in separating modes of dry wear in steel is that of Welsh [*2*]. He showed that great changes in wear rate could result from small changes in applied load when sliding a pin against a ring, as shown in Fig. 1. He and several previous investigators [*3–5*] separated wear modes in terms of mild and severe wear. Regions a and c are mild wear regimes where the surface of the ring, that is, the large body, is covered with a dull brown coating of finely divided oxide. In Region b the surface is bright and rough, and the debris is "metallic." Other workers [*6*] found that the progression of wear in the mild regime began with the gradual transfer of all the loss from the pin to form a film on the counter surface. This was followed by oxidation of the film with subsequent loss of the oxidized particles from the system as wear debris. In the severe wear regime, transfer takes place as just shown, but the transferred layer is broken off without severe oxidation. Further, it was found that the "mild" wear process is limited by the rate of oxidation of the transferred film whereas the severe wear process is limited by the rate of transfer of material from the pin to the countersurface. A major finding also is that wear rate is very dependent on atmosphere. In a gas pressure of 10^{-3} torr (133 μm Pa) wear rate is reduced to one tenth that for atmospheric pressure in the mild regime, presumably by limiting the rate of oxidation of the

[2] The italic numbers in brackets refer to the list of references appended to this paper.

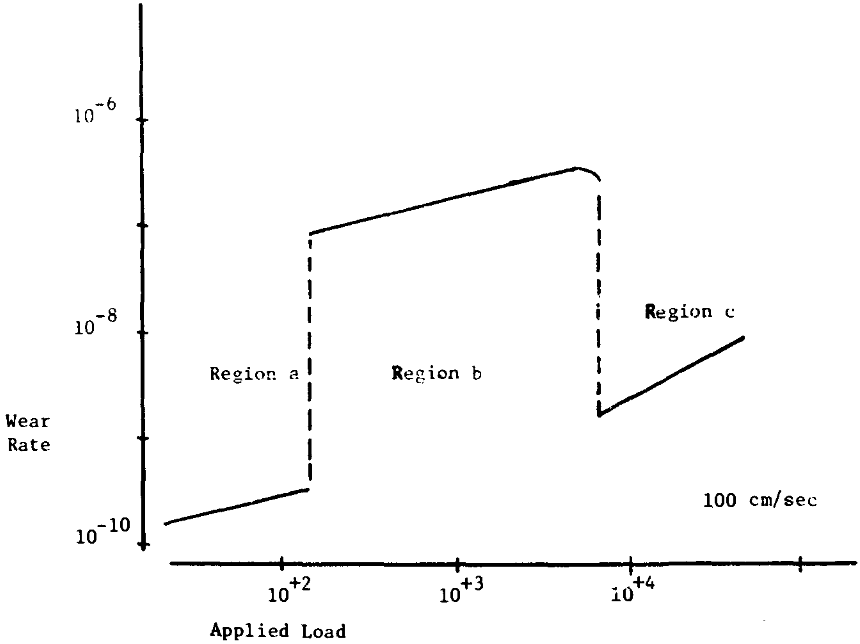

FIG. 1—*Wear rate of 1052 steel pin at various applied loads from a pin-on-ring apparatus* [2].

transferred film. A still lower pressure, that is, 10^{-7} torr (13.3 μmPa), mild wear is never established because of seizure between the pin and the counter surface. Incidentally, it is the position of several authors that accumulated oxide debris is *not* a cause of wear.

A second effect of environment is due to moisture content in the air around the test. Figure 2 schematically shows the total wear with time of testing for steel for two relative humidities, 60 and 5 percent [*8*]. At 60-percent humidity, the wear rate is very high at first and then virtually ceases, whereas at 5-percent humidity, the wear continues at a moderate rate to become the greater of the two. Other more complex differences were seen at intermediate humidities, but the point is clear that humidity strongly influences wear rate.

In the dry wear of polyvinyl chloride (PVC) it has been found [*9*] that there is mild wear of both the polymer and the steel below 60°C, and small strings of polymer are formed with iron oxide mixed in. The debris strings lie in the direction of rubbing. On the other hand, above 60°C the wear rate of the polymer becomes severe and wear particles lie perpendicular to the direction of sliding. These particles later agglomerate to form wear bundles. There is very little iron oxide in the latter debris.

In other work with polymers such as thermal setting resins, polyethylene

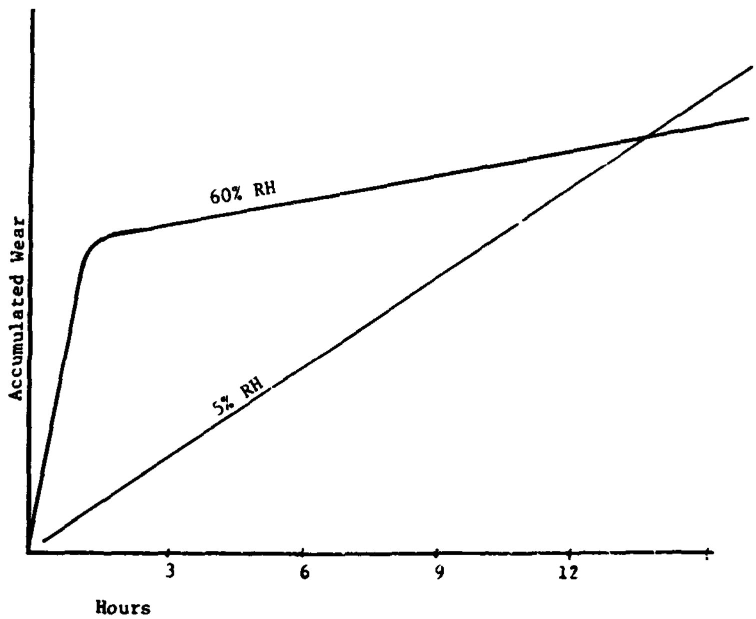

FIG. 2—*Accumulated wear after various times of sliding of 1.5Mn steel using a cross-cylinder apparatus* [8].

polytetra-fluroethylene, (PTFE), polyoxymethylene (Delrin) and polyhexamethylene adipamide (Nylon 6-6), the mild wear regime is characterized by transfer of film to the metal counterface, and wear is due to local instabilities and loss of small regions from the film. Severe wear occurs when the surface temperature increases to a particular level for each. In PTFE, the change takes place by increased thickness and instability in the transfer film. In low density polyethylene, the surface melts and the transfer film loses adhesion, resulting in loss of strings and droplets of polymer. In HDPE, Delrin, Nylon 6-6, and thermosetting resins, severe wear coincides with thermal decomposition of the polymer resulting in carbonaceous residue and large volumes of gas.

Wear of Poorly Lubricated Surfaces

Reda et al [*10*] have rubbed a number of steels together at various "severities of rubbing," achieved by varying speeds, loads, and amounts of lubricant. They found six regimes rather than the three found by Welsh. Their data are reproduced in Table 1. A progressive change from one mode to another by progressive load change, for example, is not seen.

Regimes 4 and 5 are not seen in well lubricated systems in the opinion of Reda. On the other hand, the type of debris described for Regimes 4

TABLE 1—*Wear regimes and characterizations.*

Regime	Particle Description	Surface Description	Wear Rate
1	free metal particles less than 5 μm across	variable, but shiny	negligible
2	free metal particles less than 15 μm across, ~1 μm thick	some grooving, Beilby like	low, normal lubricated rate
3	free metal particles less than 150 μm across (red)	plowing and surface cracking	moderately high
4	α Fe_2O_3 in clusters up to 150 μm diameter	some oxide coating	high
5	γFe_2O_3, Fe_3FeO (black) in clusters up to 150 μm	some oxide coating	high
6	free metal particles up to 1-mm size	severe plastic deformation	severe

and 5 is also described in papers on the testing of the efficacy of "boundary" additives in lubricants with the pin on disk machine [*11*]. These descriptions of wear debris cannot be regarded as thorough, however.

Lubricated Wear

Regimes 1 and 2 are often seen in lubricated systems. These regimes probably occur mostly during starting and stopping of machinery. The largest change in surface appearance and nature of wear debris in continuously operating machinery occurs during the first few hours of running, and this period is often referred to as the "running in" or the "break-in" stage. For reasons not yet clear, the rate of wear often decreases with time after run in, and this change is most difficult to predict from accelerated wear tests. It may be that the details of surface manufacture control the running-in stage, or perhaps the manner in which wear debris recirculates through the contact region is important.

Some interesting work on the characterization of wear debris from well lubricated jet engines, turbines, and gear boxes is reported by Scott [*12*], Westcott et al [*13*], and Ruff [*14*]. Wear debris from a number of machines was separated by a magnetic method and observed by SEM, dual light source microscopy, and other methods. Three major and important types of debris are found. One type is stranded and wire like, composed of the metal of worn parts. This debris is thought to result from abrasive processes, caused by dirt and wear debris from various parts of the system. A second type of debris is flat-platelike debris of the scale described by Reda. This is thought to come from gear teeth or other rubbing parts. The third is curved-plate shape debris, thought to come from surface fatigue of rolling element bearings. One interesting feature of the latter type of debris is that apparently the curved plates occasionally agglomerate to form spheres. Elemental analysis usually shows the spheres to be composed of bearing metal with little oxide or other foreign matter.

In the latter study, some bench tests of gears and bearings were done. The same debris was seen for the same type of component wear as in operating engine and gear box.

Configuration of Rubbing Surface

Wear testing of full scale bearings and gears seems to involve little compromise in simulation of surface conditions. On the other hand, the simulation of other sliding surfaces by simple geometries may produce erroneous results. This may be seen in comparing the results of different test devices. For example, the pin on disk machines often produce different results than the cross cylinder machine or the two-disk machine [3]. The difference in some wear modes is apparently one of the time available to cover a damaged surface by oxide. Few papers report the results of different machines for the same nominal wearing conditions.

Debris Analysis

This paper emphasizes the analysis of wear debris. Other authors emphasize the study of worn surfaces over the study of wear debris [15]. Doubtless both should be examined, but debris analysis seems a more profitable exercise where surface analysis requires stopping and possibly dismantling the apparatus. In the full scale machine, this could become expensive, and there is increasing evidence that disassembly and reassembly itself may initiate premature failure. Wear debris is always present but special procedures may be required to collect and store this debris. Debris analysis would probably also necessitate the assignment of one individual to be the in-house wear expert to take his place along side of experts in material testing, statistical methods, etc. Incidentally, the resident wear expert would be valuable for another reason as well. Since wear is so very complex, it can be expected, and it is found that each industry or subsection thereof experiences a limited range of wear problems. The resident specialist has a knowledge with which to design new products for wear prevention that is not discussed in the open literature nor is it available from a consultant.

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Summary

The papers in this book reflect one central point, namely, there are many different mechanisms for wear, and their occurrence in any given situation depends on many different factors. It is also obvious from the title of this publication that different tests are required for different types of materials. Several consequences of this complex nature of wear are clearly demonstrated.

One of these consequences is that there is not one universal wear test applicable to all situations. Instead, there are distinctly different tests for erosion, abrasive, and adhesive of types of wear, and within these categories there are more specialized tests to simulate specific conditions. This is demonstrated in the papers by Borik and Hammitt, where several types of abrasion and erosion wear tests are discussed.

A further consequence is the necessity that care must be taken to ensure that the wear test used stimulates the wear mechanism one wishes to study or that it simulates, in terms of the nature of the wear process involved, the application for which the testing is done. This is a point made in the articles by Bayer and Trivedi and by Peterson. In the paper by Ludema, a promising technique currently being developed to establish such simulation is discussed, namely, debris analysis.

The papers further suggest a general lack of standardization in wear testing. However, as Peterson indicated in his paper, such standardization would be beneficial from several standpoints—it would enable the generation of standardized reference data and enhance further work in tribology and its application to industry.

Generally, the papers indicate that there is sufficient experience in many of the areas of wear testing for the work of standardization to begin. The degree to which this is the case varies with the nature of the test. For example, Hammit points out in the field of erosion that some standard wear tests now exist, for example, ASTM Vibratory Cavitation Erosion Test (G 32-72). Also there is activity in ASTM to develop the dry-sand rubber wheel abrasion test into a standard test and to develop a test for printer ribbon abrasiveness.

In general, it might be said that in terms of the fields of wear testing discussed in this book, the areas of erosion and abrasive testing are prepared more for standardization than the area of adhesive or general sliding wear. However, even in this latter area, it is appropriate that the work of standardization begin. In this respect a worthwhile starting point, in which considerable experience in sliding wear has been developed, may be the friction and wear test machine (Falex Model No. 1 tester (formerly LFW-1)) as indicated in the article by Tucker and Miller. Also, the article by Mecklenberg and Benzig indicates that considerable information is available regarding testing for adhesive wear, which could form a basis for standardization in this area.

One aspect of importance with regards to a standardized test is the relationship between the test results and field experience. This appears to be one of the weaker aspects of wear testing, but the authors generally indicate that correlation can be and has been achieved, at least for limited ranges. But correlation generally is not known, *a priori*; it frequently has to be established in each case. Again the degree to which this is the case, both in terms of demonstrated correlation and extent of applicability, varies with the type of wear. Erosive and abrasive wear are more mature in this respect than sliding wear. In his article, Peterson comments on this aspect and the need to concentrate on and explore the correlation or lack of correlation of test results in field experience, a position which most tribologists would support.

While standardization work is appropriate and needed at the present time, it is not likely that such efforts, if based only on current knowledge, will greatly reduce the inherent problems associated with wear testing. If major advances in these aspects are to occur, it is likely that these will only follow after a better understanding of the nature and interaction of the wear processes involved.

The specific theme of this publication is the wear testing of metals. However, it is worthwhile to note that many of the more general points made by the authors, such as the need to recognize the complex nature of wear and the need to establish correlation with field performances, may be applied to wear testing of other materials. Specific parameters and techniques might differ with polymers or ceramics, for example, but the basic problems or difficulties are the same. It is intended that these will be covered in future symposia and publications.

The overall conclusion which can be reached from the papers presented is that relevant and useful wear testing can be done but not in a casual or uncontrolled manner. It must be recognized that wear is a complex, multimechanism phenomenon and care must be taken to establish the relevance of the test to the application. Further, while there is not a unique, universal wear test, there are several tests or test techniques available which have sufficient history so that guidelines concerning their use are available, both in the present publication and in the wear literature. However, much more work leading to the standardization of wear tests is desirable and needed.

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