Guide to Friction, Wear, and Erosion Testing

Kenneth G. Budinski

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Guide to Friction, Wear, and Erosion Testing

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NOTE: This manual does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this manual to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

Month, Year
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Foreword

This book is the product of a career devoted to selecting materials for a multitude of sliding/rolling/eroded mechanical components. Some components were commercial products that had to compete in the world market, and others were parts in production machinery that had to produce those marketed products. The author's responsibility was to achieve useful levels of friction and component life, all at competitive prices.

Kenneth Budinski began with degrees in Metallurgy, with virtually no knowledge of the problem of sliding/rolling surfaces. He progressed through his career with no research funding, no graduate students, and no authorization to conduct academic style research. Nonetheless, he attained a uniquely broad experience in measuring friction and wear of a very wide range of metals, ceramics, and polymers, and with very many surface processes and coatings. Budinski has been a member of Committee G02 of the ASTM (on Wear and Erosion) since 1970, sometime chair of the Committee and of its various subcommittees, and recipient of the highest G02 awards. Hardly a meeting has gone by without Budinski's presentation of yet another careful study of a wear test, together with his rigorous analysis of data from his tests. It is this combination of practical experience and scholarly discussion that has prepared Budinski to write this book. It is part definitions of terms, part identification of tribological (friction, wear, lubrication) mechanisms, part description of standard test machines, and part discussion of the philosophy of testing and material evaluation. This book is one of many of Budinski's writings, including several books, chapters in handbooks, journal papers, and other presentations.

As for test devices, there are hundreds. An account is given in this book on why most of the tests were developed and what fundamental mechanisms of wear or friction are likely functioning in each test. Indeed, in the usual case, several mechanisms may function simultaneously, changing over time of sliding, or changing during start-stop cycles of test, and changing as the use of the intended product changes. Budinski missed none of these points.

This book is a very early progress report on the art of designing a given life into mechanical components. There is not, as too many designers suppose, a direct pathway to selecting that "right" material for every product. Selecting a material to hold a tensile load is simple in that tensile properties of most materials are published and mature equations are in hand to work out the safe dimensions of such parts. Wear properties are not that simple.

There are several mechanisms whereby little bits of material are made to depart from or be rearranged upon a tribological surface. Tribological wisdom begins by identifying the major applicable mechanism and the likely one or two attending mechanisms. Even then, there are no reliable lists of materials showing resistance to specific mechanisms. Neither are there any wear tests that can be linked directly to real products. Budinski sorts out all of these issues in his several chapters. Other authors would likely divide up the overall array differently but probably not better.

The final word is that good tribological design requires a broad knowledge of tribological mechanisms, a feel for what materials may fit the case, a careful resort to wear/friction/erosion testing to narrow the range of choices, and then an assessment of the chosen material in products or production machinery. Getting it right in products puts your very company at stake: getting it right in production machinery only involves more maintenance. Budinski offers several case studies to illustrate these points.

Budinski steps into another world, though, when discussing wear/friction/erosion models. He offers a very few equations without much conviction of their utility. He mentions that if models or equations were further developed there would be no need for tests of the type he describes in this book—a very distant hope. But the many available tests may instruct us on the necessary complexity of useful wear models. Based on the number of mechanisms inherent in the many developed tests, I suggest that useful wear equations may need 30 or more variables. What hope is there, then, in equations for wear that contain 2 or 3 condition variables and only one material variable? Clearly, Budinski's book will not be replaced by useful equations for many decades.

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July 1, 2007

Preface

Friction, wear, and erosion are terms that most people use in their daily lives. Most people accept the cost of sport shoes wearing out after 4 months of use; people accept wear of roadways and flooring; people accept 30,000 miles as the limiting use of an automobile before fan belts, brakes, and other components start to wear out.

On a larger scale, most industrialized countries accept about 7% of their gross domestic product as their annual cost of wear, erosion, and unwanted friction. As one example of this annual cost: 450 million auto tires were manufactured in 2006 [1]. Probably 100 million of these tires were required for new vehicles. The remaining 350 million were most likely used to replace worn tires. Assuming that one tire cost $100, this amounts to a cost of wear of 35 billion dollars. This is just one commodity. Another staggering cost is the energy (gasoline) consumed in overcoming friction losses in an automobile. Some estimates for these losses are that as much as 30% of a vehicle's engine horsepower is used in overcoming friction in the sliding components between the gasoline explosion in the cylinders and the traction force transmitted to the roadway.

The point is that friction, wear, and erosion (tribology) concerns cost each and every person, as well as the environment, dearly. However, the world does not have to regard these costs and environmental consequences as inevitable costs of technology. They can be addressed and almost always reduced by appropriate engineering action. People older than 50 years of age will probably remember when the average life of an automobile tire was only about 15,000 miles. Today tire life is typically about 40,000 miles. What happened?

Engineers and scientists worked on this tribology problem. Tires were redesigned to be stiffer, which reduced roadway slip and thus wear. Tire materials were also improved. Undoubtedly, many of these tire improvements came to happen through screening tests conducted in laboratories, bench tests, as they are called. Tire engineers certainly could never make full size tires and run them to death to assess every change that may work. Concepts were screened by bench tests and that is what this guide is about.

This guide reviews current friction, wear, erosion, and lubrication fundamentals and describes the bench tests that are most often used to study and solve tribology problems. Tests are compared and critiqued. Information is presented to help the reader select a test that he or she might use to address a tribology concern that they are responsible for solving. The overall objective of the guide is to lower the annual cost of wear, erosion, and unwanted friction through appropriate tribotesting.

The scope includes tests that are used to study engineering materials (metals, plastics, ceramics, composites, lubricants, coatings, treatments), tests used to solve tribology problems and limited product tribotesting (abrasivity of magnetic media, printer ribbons, web friction etc.). Tire tests are not included—sorry! The tests described in this guide are predominately standard tests developed by consensus through ASTM International. Many countries have standard tests in these same areas, but the tests described in this guide are probably included in country-specific test standards. For example, every country that has tribotesting standards probably has a standard on a pin-on-disk test, a reciprocating pin-on-flat test, a sled friction test, etc. These are the same tests described in this guide. This guide is applicable worldwide.

The intended readership of this guide comprises mostly people who do not normally work in the field: students, designers, maintenance personnel, researchers, and academicians. It will help these people research a particular form of wear or friction, what tests are available, the cautions with each test, and information on how the different tests compare in severity. Also, it discusses how well they simulate real life applications. Veteran tribologists will find this guide a useful reference for ASTM test numbers and test details.

In summary, this guide is about tests (mostly standards) available to address friction, wear, erosion, and lubrication problems. It will serve as a mentor for newcomers to tribology and a useful reference for practicing tribologists. There are 13 chapters. The first presents needed terms and definitions. It is followed by a chapter on the alternates to bench testing: expert systems, modeling, and simulations; then follows a chapter on testing methodology. There are several chapters on specific forms of wear: abrasion testing, adhesive wear testing, plastic/elastomer testing, lubricated wear testing, fretting testing, rolling wear testing, and erosion testing. The guide ends with chapters on friction testing; micro-, nano-, and biotribotests; and correlation of these tests with service.

This book is essentially a project of the ASTM Committee G02 on Wear and Erosion. They are acknowledged for their sponsorship and participation in the review process. This guide is the product of more than 40 years of tribotesting in industry on the part of the author and probably another hundred years of experience in government, industry and academia on the part of the six tribology professionals who reviewed this guide for correctness and completeness. I sincerely thank them for their contributions.

K. G. Budinski

Reference

[1] J. A. Melsom, "50 Years of Keeping the Rubber Industry in the Black," *ASTM Standardization News*, December 2006, p. 41.

1

Identification of Different Types of Wear

Introduction

DIAGNOSIS IS THE FIRST STEP IN SOLVING A medical problem, a car repair, or home repair problem—just about any problem. What is the nature of the problem? What does it look like? What is its severity? Some wear diagnoses are very fast and simple. For example, when the treads disappear on your automobile tires, you can be safe in assuming that abrasive wear from roadway contact removed enough material to warrant replacement. However, when an automobile engine starts to burn oil and have less power than normal, it may take some sleuthing to find out whether something has worn out. If so, what? Similarly, if a manufacturing machine is not working properly, some components that may be buried in the machine are worn. As with a medical diagnosis, the remedy can only come when the cause is identified. So too with friction, wear, and erosion. There is a need to identify the specific type of wear, friction, or erosion before proceeding to solve the problem.

It is the purpose of this chapter to introduce some of the language of friction, wear, erosion, and lubrication and define various modes or types of friction, wear, and lubrication. The objective is to establish a foundation of process understanding before proceeding to discuss ASTM and other tests. This book concentrates on ASTM standard tests that focus on attrition of solids or friction between contacting solids. It will not discuss tests that are used by lubricant formulators to measure petroleum properties—only friction and wear tests that are likely to be performed by lubricant users. There are many physical property tests performed on lubricants. These are considered outside the scope of this guide.

This book covers important friction tests and important tests in the various categories of wear, erosion, and lubricated wear. It starts with a discussion on simulations—models that can be used to make wear and friction tests unnecessary. It ends with a chapter on correlation of lab tests with service.

Terminology/Key Words

Before dealing with the details of wear processes, it is necessary to explain some of the jargon that is used in the field. For example, this book should probably be titled "Tribotesting" because it is about tribotests, but tribo-this and tribo-that terms are derived from "tribology," which is a word not frequently used. In fact, even after it has been in use for more than 30 years, there are still many engineers and scientists who are not familiar with the term. Few universities in the world offer degrees or even courses in "tribology," and many large manufacturing companies do not have "tribology" departments. All universities and large manufacturing companies have tribology activities, but they are embedded in other departments, such as mechanical engineering, physics, or materials engineering. Therefore, "tribology" is absent in the title of this guide, but the term is frequently used within the text.

"Tribology" is a useful term because it includes all aspects of friction, lubrication, and wear. It is a relatively new word, being commissioned by a U.K. government study in the 1960s. It comes from the Greek word "tribos" meaning "to rub," and it means the science and art of friction wear and lubrication. "Tribo" has become a prefix for many aspects of tribology:

Tribotest: friction, wear, and lubrication tests
Tribosystem: friction, wear, and lubrication systems
Tribometer: friction, wear, or lubricant tester

Sometimes, tribology is used as a suffix:

Nanotribology: tribology of very small devices/substances (nanometers)
Microtribology: tribology of not-that-small devices (micrometers)
Biotribology: tribology related to living bodies

In summary, tribology is the term that best describes what this book is about, but it is not in the title because of unfamiliarity with the term in many venues.

For definitions of terms that are important to tribology, the ASTM Committee G02 on Wear and Erosion has a standard on terms: G 40 Terms and Definitions Relating to Wear and Erosion, and the ASTM Committee D02 also has a standard on terms relating to friction, wear, and lubricants: D 4175 Standard Terminology Relating to Petroleum, Petroleum Products, and Lubricants. Both of these compilations contain consensus definitions from workers in the field. The following are some of the important terms from these compilations that may be needed to use this book.

Terms from ASTM G 40: Terminology Relating to Wear and Erosion

abrasive wear, *n* — wear caused by hard particles or hard protuberances forced against and moving along a solid surface.
adhesive wear, *n* — wear caused by localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface.
asperity, *n* — in tribology, a protuberance in the small-scale topographical irregularities of a surface.
cavitation, *n* — the formation and subsequent collapse, within a liquid, of cavities that contain vapor or gas or both.
cavitation erosion, *n* — progressive loss of original material from a solid surface as the result of continued exposure to cavitation.
coefficient of friction, *n* — in tribology, the dimensionless ratio of the friction force (F) between two bodies to the normal force (N) pressing the bodies together: $\mu = F/N$
erosion, *n* — in tribology, progressive loss of original material from a solid surface caused by mechanical interaction

between that surface and a fluid, multicomponent fluid, or impinging liquid or droplets.
erosion-corrosion, *n* — a synergistic process involving both erosion and corrosion, in which each of these processes is affected by simultaneous action of the other, and in many cases is thereby accelerated.
fatigue wear, *n* — wear of a solid surface caused by fracture arising from material fatigue.
fretting, *n* — small-amplitude oscillatory motion, usually tangential, between two solid surfaces in contact.
fretting corrosion, *n* — a form of fretting wear in which corrosion plays a significant part.
fretting wear, *n* — wear arising as a result of fretting.
friction force, *n* — the resisting force tangential to the interface between two bodies when, under the action of an external force, one body moves or tends to move relative to the other.
galling, *n* — a form of surface damage arising between sliding solids, distinguished by macroscopic, usually localized, roughening and creation of protrusions above the original surface; it often includes plastic flow or material transfer or both.
Hertzian contact pressure, *n* — the magnitude of the pressure at any specified location in a Hertzian contact area (produced by line or point contact) as calculated by Hertz equations of elastic deformation.
impact wear, *n* — wear caused by collisions between two solid bodies in which some component of the motion is perpendicular to the tangential plane of contact.
impingement, *n* — in tribology, a process resulting in a continuing succession of impacts between (liquid or solid) particles and a solid surface.
kinetic coefficient of friction, *n* — the coefficient of friction under conditions of macroscopic motion between two bodies.
PV product, *n* — in tribology, the product of the nominal contact pressure on a load-bearing surface and the relative surface velocity between the load-bearing member and its counterface.
rolling, *vb* — in tribology, motion in a direction parallel to the plane of a revolute body (e.g., ball, cylinder, wheel) on a surface without relative slip between the surfaces in all or part of the contact area.
rolling wear, *n* — wear caused by the relative motion between two nonconforming solid bodies whose surface velocities in the nominal contact location are identical in magnitude, direction and sense.
run-in, *vb* — in tribology, to apply a specified set of initial operating conditions to a tribological system to improve its long-term frictional or wear behavior.
scoring, *n* — in tribology, a severe form of wear characterized by the formation of extensive grooves and scratches in the direction of sliding.
solid particle impingement erosion, *n* — progressive loss of original material from a solid surface caused by continued exposure to impacts by solid particles. (Synonym: solid particle erosion)
static coefficient of friction, *n* — the coefficient of friction corresponding to the maximum force that must be overcome to initiate macroscopic motion between two bodies.
Stick-slip, *n* — in tribology, a cyclic fluctuation in the magnitude of friction force and relative velocity between two surfaces in sliding contact, usually associated with relaxation oscillation dependent on the elasticity of the tribosystem and on a decrease in the coefficient of friction with onset of sliding or with increase of sliding velocity.
stiction, *n* — in tribology, a force between two solid bodies in normal contact, acting without the need for an external force pressing them together, which can manifest itself by resistance to tangential motion as well as resistance to being pulled apart.
three-body abrasive wear, *n* — a form of abrasive wear in which wear is produced by loose particles introduced or generated between the contacting surfaces.
traction, *n* — in tribology, a physical process in which a tangential force is transmitted across an interface between two bodies through dry friction or an intervening fluid film, resulting in motion, reduction in motion, or the transmission of power.
traction coefficient, *n* — in tribology, the dimensionless ratio of the traction force transmitted between two bodies to the normal force pressing them together.
tribology, *n* — the science and technology concerned with interacting surfaces in relative motion, including friction, lubrication, wear, and erosion.
two-body abrasive wear, *n* — a form of abrasive wear in which hard particles or protuberances which produce the wear of one body are fixed on the surface of the opposing body (as in wear by sandpaper).
wear, *n* — damage to a solid surface, usually involving progressive loss or displacement of material, due to relative motion between that surface and a contacting substance or substances.
wear coefficient, *n* — in tribology, a wear parameter that relates sliding wear measurements to tribosystem parameters. Most commonly, but not invariably, it is defined as the dimensionless coefficient, k, in the equation

$$\text{Wear volume} = k\,(\text{load} \times \text{sliding distance/hardness of the softer material})$$

This term is also called "wear factor," "specific wear rate," "volumetric wear rate," "wear constant," and others.
wear map, *n* — a calculated or experimentally determined diagram that identifies regions within which the mechanism or wear rate remains substantially the same, the regions being separated by transition lines or bands that are functions of two or more parameters.
wear rate, *n* — the rate of material removal or dimensional change as the result of wear per unit exposure parameter, for example, quantity of material removed (mass, volume, thickness) in unit distance of sliding or unit time.

Terms from ASTM D 4175: Standard Terminology Relating to Petroleum, Petroleum Products, and Lubricants

acid number, *n* — the quantity of base, expressed as milligrams of potassium hydroxide per gram of sample, required to titrate a sample to a specified end point.
additive, *n* — a material added to another, usually in small amounts, to impart or enhance desirable properties or to suppress undesirable properties.
base oil, *n* — a base stock or a blend of two or more base stocks used to produce finished lubricants, usually in combination with additives.
break-in, *n* — in tribology, an initial transition process occurring in newly established wearing contacts, often accompanied by transients in coefficient of friction, or wear rate, or both, that are uncharacteristic of the given tribological system's long-term behavior (synonym: run-in, break-in).
crude oil, *n* —A naturally occurring hydrocarbon mixture, generally in a liquid state, that also may include compounds of sulfur, nitrogen, oxygen, metals, and other elements.

DIN – abbreviation for "Deutsches Institut fur Normang" (German standards body).
dropping point, *n* – a numerical value assigned to a grease composition representing the corrected temperature at which the first drop of material falls from a test cup and reaches the bottom of the test tube.
dry solid film lubricants, *n* – dry coatings consisting of lubricating powders in a solid matrix bonded to one or both surfaces to be lubricated.
flash point, *n* – in petroleum products, the lowest temperature corrected to a barometric pressure of 101.3 kPa at which application of an ignition source causes the vapors of a specimen of the sample to ignite under specified conditions of test.
friction, *n* – The resistance to sliding exhibited by two surfaces in contact with each other.
insolubles, *n* – in lubricating grease analysis, the material remaining after the acid hydrolysis, water extraction, and solvent extraction of soap-thickened greases.
kinematic viscosity, *n* — the ratio of the viscosity to the density of a liquid.
load-wear index, *n* – (or the load-carrying ability of a lubricant) an index of the ability of a lubricant to minimize wear at applied loads. Under the conditions of the test, specific loadings in kilograms-force having intervals of approximately 0.1 logarithmic unit are applied to the three stationary balls for ten test runs prior to welding. The load-wear index is the average of the sum of the corrected loads determined for the ten applied loads immediately preceding the weld pair.
lubricant, *n* – any material interposed between two surfaces that reduces friction or wear or both between them.
lubricating grease, *n* – a semi-fluid to solid product of a dispersion of a thickener in a liquid lubricant.
lubricating oil, *n* – a liquid lubricant, usually comprising several ingredients, including a major portion of base oil and minor portions of various additives.
lubricity, *n* – a qualitative term describing the ability of a lubricant to minimize friction between, and damage to, surfaces in relative motion under load.
oxidation, *n* – of engine oil, the reaction of the oil with an electron acceptor, generally oxygen, that can produce deleterious acidic or resinous materials often manifested as sludge formation, varnish formation, viscosity increase, corrosion, or combination thereof.
pour point, *n* – in petroleum products, the lowest temperature at which movement of the test specimen is observed under prescribed test conditions.
scratches, *n* – the result of mechanical removal or displacement, or both, of material from a surface by the action of abrasive particles or protuberances sliding across the surfaces.
scuff, scuffing, *n* – in lubrication, surface damage resulting from localized welding at the interface of rubbing surfaces with subsequent fracture in relative motion which does not result in immobilization of the parts.
soap, *n* – in lubricating grease, a product formed in the saponification of fats, fatty acids, esters, or organic bases.
SRV, *n* – Schwingung, Reibung, Verschleiss, German test machine (translation: oscillating friction and wear).
synthetic, *adj* – in lubricants, originating from the chemical synthesis of relatively pure organic compounds from one or more of a wide variety of raw materials.
thickener, n – in lubricating grease, a substance composed of finely divided particles dispersed in a liquid lubricant to form the product's structure.
viscosity, *n* – the ratio between the applied shear stress and rate of shear. It is sometimes called the coefficient of dynamic viscosity. This value is a measure of the resistance to flow of a liquid. The SI unit of viscosity is the pascal second (Pa.s). The centipoise (cP) is one millipascal second (mPa.s) and it is also used as a measure of viscosity.
viscosity index, *n* – an arbitrary number used to characterize the variation of the kinematic viscosity of a fluid with temperature.

Terms from Other Sources

polishing – removal of material from a solid surface by rubbing with a substance or substances in such a manner that the surface roughness is lowered as rubbing progresses.
abrasion – surface damage produced by hard particles or protuberances forced against and moving along a solid surface – also called abrasive wear.
gouging – macroscopic gouges, grooves, dents, and scratches from a single impact of a hard/abrasive material.
oxidative wear – in metals (usually hard), in rubbing contact the surfaces become covered by oxides produced from repeated rubbing of wear detritus. Also called "mild wear."
slip – relative motion between contacting solid surfaces.
slurry erosion – material removal produced by a suspension of a solid material in a liquid.
droplet erosion – material removal/damage to a solid by the mechanical action of impacting liquid droplets.
solid particle erosion – progressive loss of original material from a solid surface due to continued exposure to impacts by solid particles.
boundary lubrication – less than complete lubricant separation of surfaces; portions of the mating surfaces contact continuously or intermittently.
hydrodynamic lubrication – complete separation of rubbing surfaces by a lubricating film.
elastohydrodynamic lubrication – usually in Hertzian contacts, complete separation of rubbing surfaces with the real area of contact altered (usually increased) by elastic deformation of the contacting surfaces.
chemical mechanical polishing – lowering of surface roughness by the combined action of abrasion and chemical attack of a surface (also called "chemo – mechanical – planarizing").

Why Identify Wear Mode

Materials wear and erode by different processes and corrective measures are different for the different processes; so too are the wear tests that we use to address these wear, friction, and lubrication problems. Rivers cut gorges by the erosive force of water impingement often coupled with effects of entrained hard particles (silica, etc.); railroad tracks wear by the compressive fatigue spalling on the tops of tracks and impact wear at frogs and switch plates, metal-to-metal wear at curves, and abrasive wear in dirty areas; flooring and steps wear by the abrasive action of dirt and shoes; ash handled in piping in coal-fired boilers penetrates by solid particle erosion; copper water pipes penetrate when fluid velocity gets too high; concrete dam spillways lose tons of material as the result of erosion from cavitating water flow. The materials that resist liquid erosion are different from those that resist solid particle erosion. So too are the tests that compare materials to resist liquid erosion and those that resist solid particle erosion. Wear tests have value only if they simulate the conditions in a tribosystem of interest and correlation to field data. Spalling wear of railroad tracks needs to be simulated by rolling contact – a roller/wheel rolling on a counterface under Hertzian stresses. Liquid erosion in metal tubing is best simulated by a test rig that reproduces fluid velocities like the system of interest. Wear and friction tests need to simulate the tribosystem of interest, and this in turn means that wear mode must be identified. This is a fundamental step.

Categories of Wear

There are different opinions of the types of wear that exist, but most people working in the field agree that erosion should be dealt with differently from wear because erosion has fluid motion as a source of the mechanical action on a surface. Fundamentally, material removed from a solid surface can only occur by three processes:

1. It can be fractured.
2. It can be dissolved.
3. It can be melted/vaporized.

Basically, wear and erosion only occur by these processes, and some types of wear can involve all three. However, wear processes are not usually broken down into these three "simple" categories. The ASTM Committee G02 Wear and Erosion categorizes wear into abrasive or nonabrasive. Erosion is broken down into particle, droplet, slurry, liquid, and cavitation. This guide will use this system and then the specific wear modes in each general category. Figure 1-1 is one interpretation of categories of wear. Figure 1-2 shows categories of erosion. These specific modes will be discussed.

Figure 1-3 shows our categories in friction, and Figure 1-4 shows our lubrication categories. There is a "home" for most major friction and wear processes. Each "process" has distinguishing characteristics that eventually translate into a different friction or wear test. Wear tests differ in the mechanics of rubbing, the specimen geometry, the medium, and the rubbing conditions, that is, all sorts of parameters. Common tests will be described in subsequent chapters, but at this point, the goal is to show how to identify a wear mode.

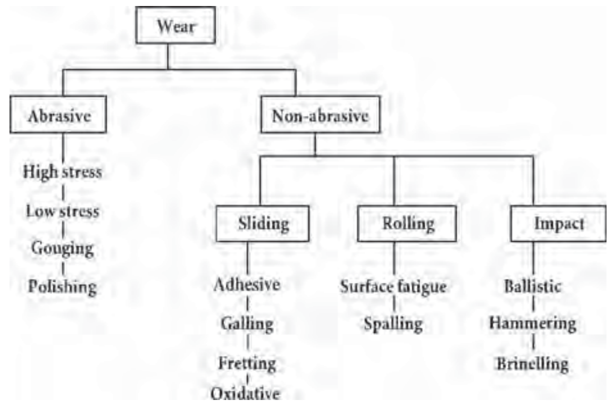

Fig. 1-1—Two major categories of wear and some specific modes in each category.

Abrasive Wear

ASTM G02 has just two categories of wear: abrasive and nonabrasive. However, it is likely that abrasive wear occurs in intentionally nonabrasive systems and vice versa. For example, wear debris generated in a nonabrasive metal-to-metal sliding system can be abrasive if it is a metal oxide. Similarly, some abrasives can remove material by a nonabrasive adhesive wear process. For example, tumbling metal parts with smooth stones can polish or wear the metal parts by the mechanism of metal adhesion to the stones. So, what tribologists term "abrasive wear" are systems that intentionally involve particles or protuberances (like file teeth) that are harder than the wearing counterface. Material removal in these systems occurs by scratching as shown in Figure 1-5.

The particle or protuberance penetrates the surface to a fraction of its diameter (maybe one-tenth) and generates a furrow as it is forced into and moves along a solid surface. This form of abrasive wear is easy to recognize. Using a 5 to 10× loupe, the surface is clearly full of scratches, as shown in Figure 1-6. This is also called "scratching abrasion."

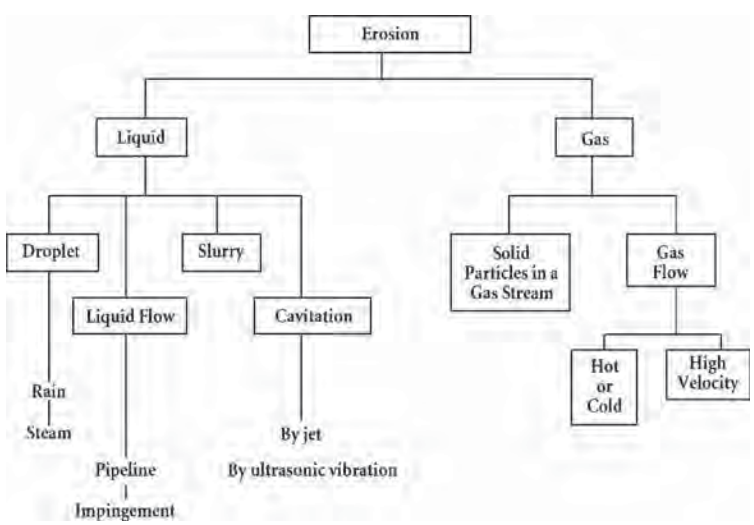

Fig. 1-2—Types of erosion.

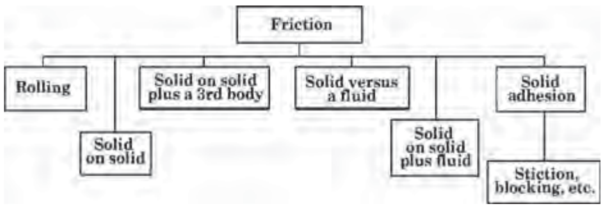

Fig. 1-3—Types of friction.

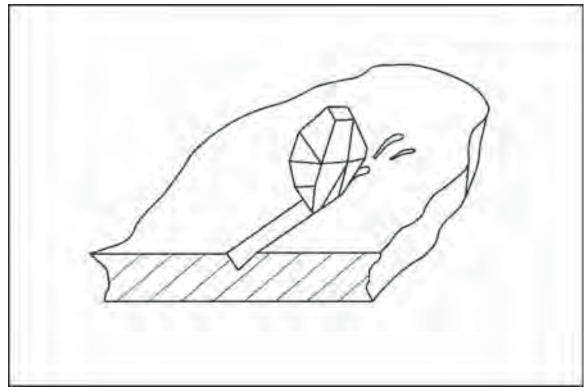

Fig. 1-5—Schematic of low-stress abrasive wear.

Figure 1-1 listed four types of abrasive wear: high-stress, low-stress, gouging, and polishing. These specific modes of abrasive wear evolved because they look different on worn parts and different tests are used to simulate them. Low-stress abrasion is the type of abrasion that occurs in earth tilling, sliding coal down a chute, and walking on a floor with dirt between your shoes and the floor. High-stress abrasion produces scratching possibly coupled with indentations because the stresses imposing the abrasive on a surface are sufficient to fracture the abrasive. This kind of abrasion might occur in a coal crusher or when dirt particles get trapped between hard steel gear teeth. Surface grinding as used in all machine shops is high-stress abrasion. The stresses are sufficient to fracture the abrasive grit. This is one of the causes of reduced efficiency in metal removal. A surface subjected to high-stress abrasion looks like the ground surface in Figure 1-7.

Gouging abrasion is surface damage produced by impacting or crushing rocks or other hard and strong materials. A classic example of this is digging buckets on excavators and power shovels. Needless to say, this type of abrasion occurs in the beds of trucks that receive dropping loads of rocks from an excavator. Most aggregate used in concrete is obtained by crushing rocks to a desired size. Rock crushers experience gouging wear (Figure 1-8). Obviously, gouging wear will be conjoint with high- and low-stress scratching abrasion because, when a rock is crushed, some of the pieces will scratch under low-stress conditions and some will probably scratch under high-stress conditions.

Polishing abrasion is not as succinct a mechanism as the previously mentioned types of abrasion. Polishing is material removed from a solid surface in such a manner that its surface roughness is reduced. A perfectly polished surface shows no scratches when viewed with ordinary optical microscopy (Figure 1-9). This example shows a few scratches and hardness indents. Polishing is performed by forcing hard, sharp particles against a surface and moving them along that surface, but the conditions are controlled such that the abrasive material does not produce visible scratches. Material may be removed by adhesion of the softer metal (the wearing surface) to the abrasive particles.

Probably the form of polishing with the most important industrial significance is polishing of silicon surfaces and layer-deposited surfaces for integrated circuits and computer chips. In this example, chemicals are added to the abradant and there is a chemical reaction between the media (corrosion) and the abrasive polisher by continually removing the corrosion product. This process is known as chemical mechanical polishing (CMP) or by the newer term "chemo-mechanical planarizing" (also CMP).

Nonabrasive Wear

"Nonabrasive wear" is not a very definitive wear category, but it became the consensus term for the ASTM wear activities that did not deliberately involve abrasion or erosion. In reality, it is the category of wear that involves sliding systems (conforming or nonconforming surfaces) that do not intentionally contain an abrasive medium. For example, gear trains, cams and followers, plain bearings, and slides do not intentionally contain abrasive particles. Thus, they are considered to be nonabrasive wear systems. Figure 1-1 also shows rolling and impact categories in nonabrasive wear. These systems do not intentionally include abrasive particles. In fact, many nonabrasive tribosystems are lubricated. "Adhesive wear" is the term that was at

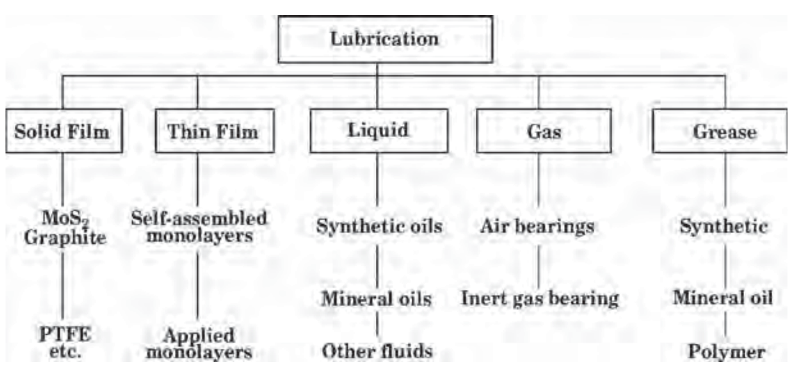

Fig. 1-4—Types of lubricants.

Fig. 1-6—Pump sleeve abraded by contaminants in packing.

Fig. 1-8—Gouging wear.

one time used in place of "nonabrasive" wear as a wear category. However, it was downgraded to a wear mode because most solid-solid sliding systems do not show distinct evidence of adhesion of surfaces. More often than not, low-wear metal-to-metal sliding systems polish as they wear whereas true adhesive wear is characterized by macroscopic plastic deformation of surfaces (Figure 1-10). Scoring and scuffing are essentially synonyms for significant adhesive wear.

Adhesive wear is material removal or transfer by adhesion between surfaces in relative motion. Often, wear in conforming sliding systems starts by adhesive wear and then polishing may occur by the abrasive action of trapped debris from the original adhesive wear.

Galling

Galling is a severe form of adhesive wear characterized by the formation of excrescences – macroscopic protuberances generated by adhesion between the rubbing surfaces (Figure 1-11). Galling is extremely common in stainless steel sanitary systems. Stainless steel fasteners commonly gall (and seize) when being torqued in stainless steel components. Excrescences result from localized solid-state welds between the rubbing surfaces. When galling occurs in sliding systems with very little running clearance, it can lead to seizure, that is, the moving parts no longer move. There are local solid-state welds preventing sliding or rotation.

Oxidative Wear

Mild wear in hard-hard unlubricated metal couples is often termed oxidative wear. When two hardened steels are rubbed together without lubrication, in most sliding conditions the rubbing surfaces will eventually take on a rusted appearance (Figure 1-12). The "rust" is iron oxide generated from metal particles rubbing together in the sliding interface. They get fractured ever smaller and the fracture surfaces react with the air to form oxides. The "rust" is iron oxide, not from aqueous corrosion, but from the reaction of fracture surfaces with ambient air. When hard-hard couples run lubricated, oxidative wear does not usually occur because the lubricating fluid helps separate the surfaces and it carries away minute particles rather than allowing comminution.

Fretting Wear

Fretting, by definition, is oscillating motion of small amplitude. When one surface "frets" against another, it can produce fretting wear, that is, material removed by oscillatory motion

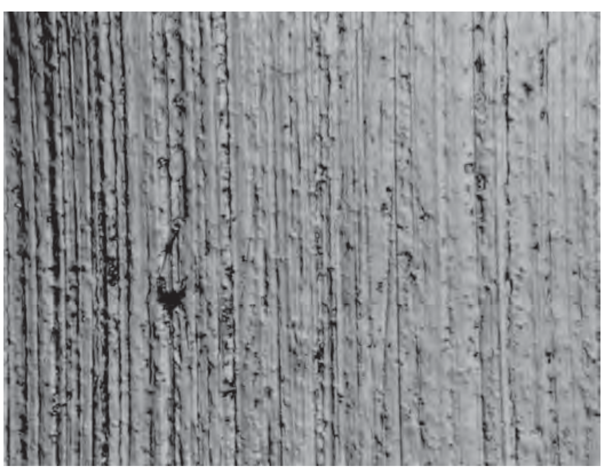

Fig. 1-7—High-stress abrasion of soft steel produced by surface grinding.

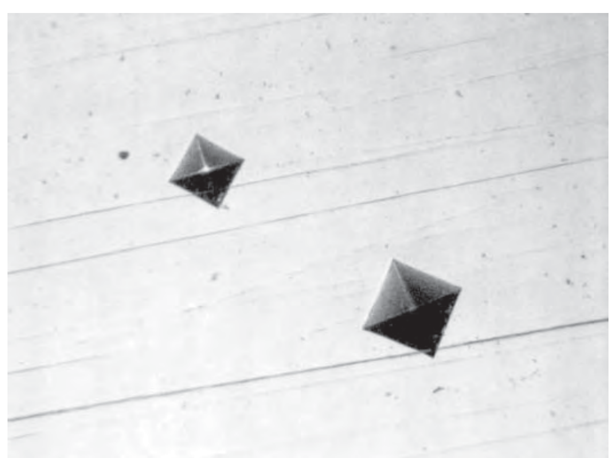

Fig. 1-9—Hardness indents and scratches in polished steel.

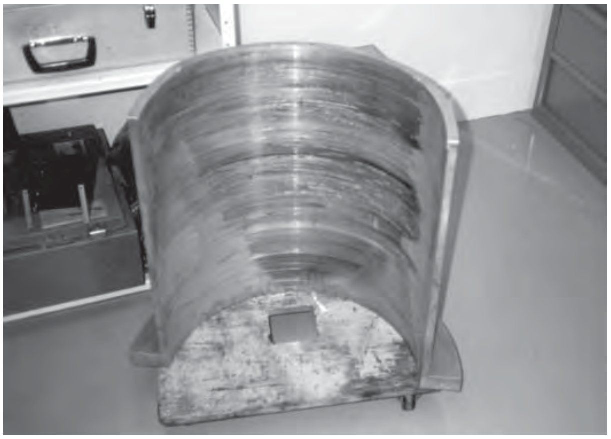

Fig. 1-10—Adhesive wear in the form of scoring on a large bushing.

between surfaces or fretting corrosion if the fretted surfaces react with the ambient environment. For steels in air, fretting corrosion looks like the rust or oxidative wear (Figure 1-13). Fretting usually occurs only with relative motions in the range of 10 to 300 μm. At rubbing amplitudes less than 10 μm, surfaces usually accommodate the relative motion by elastic deflection of contacting asperities. At rubbing amplitudes more than 300 μm, ordinary reciprocating sliding occurs. Fretting damage commonly occurs in contacting surfaces (like plastic mold seal surfaces) that are not supposed to move relative to each other, but do. It occurs in most materials, and plastics are particularly prone to it. A very common occurrence in metals is under rolling element bearings. When inner races are pressed off shafts, the contact area may look rusty. This usually means that the inner race was fretting on the shaft. Often, the damage appears slight. The "rust" deposit is removed and the shaft is put back in use. Fretted surfaces appeared "gnarled" when cleaned, but optical magnification may show that the "gnarled" surface also contains pits that can lead to fatigue failures. This is the most common reason to address fretting damage.

Rolling Wear

True rolling is difficult to achieve. It exists only where there is movement in a desired direction without relative motion or slip between a revolute surface and a counterface. A ball rolling on a flat surface is likely to have "no slip" at a small annulus in the apparent area of contact. Some relative motion between a revolute shape and a mating counterface comes from the elastic deflections of the contacting surfaces. Gross slip comes from skidding or lack of traction. A significant manifestation of rolling wear is surface fatigue (Figure 1-14).

Coated surfaces can spall under rolling contact conditions (Figure 1-15). Surface fatigue of solid surfaces comes from stress-induced initiation of subsurface cracks which grow to the surface and produce material removal. Spalling of coatings occurs from stress-induced cracks that initiate at the coating/substrate interface.

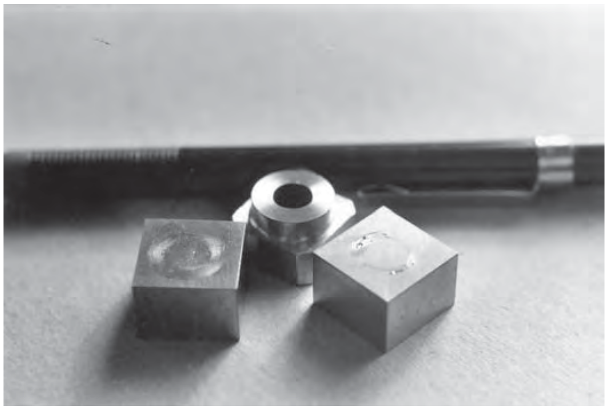

Fig. 1-11—Galling.(on right block); burnishing (on left), shape of counterface (center).

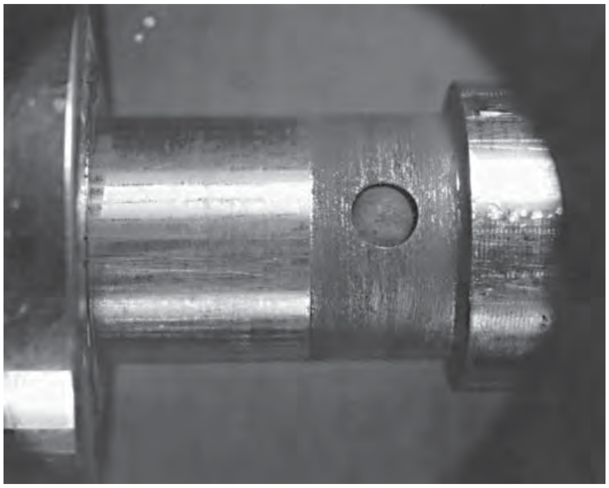

Fig. 1-12—Oxidative wear.

Impact Wear

Impact wear is material removal and damage to a solid surface produced by repeated impacts to that surface by another solid. Sometimes, the manifestation is spalling, not unlike surface fatigue caused by rolling. The impacts produce subsurface cracks that eventually propagate to the surface. Sometimes the

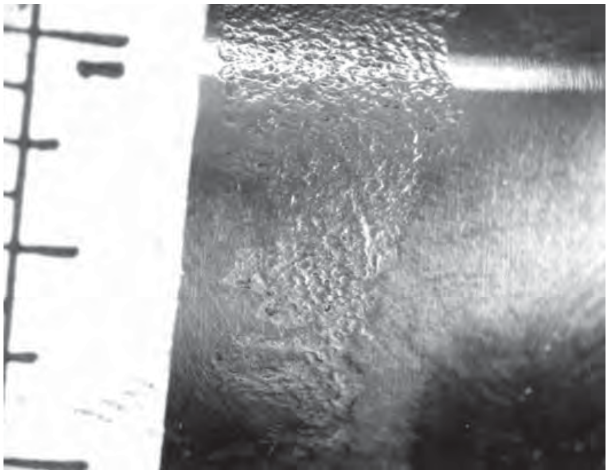

Fig. 1-13—Fretting damage with debris removed.

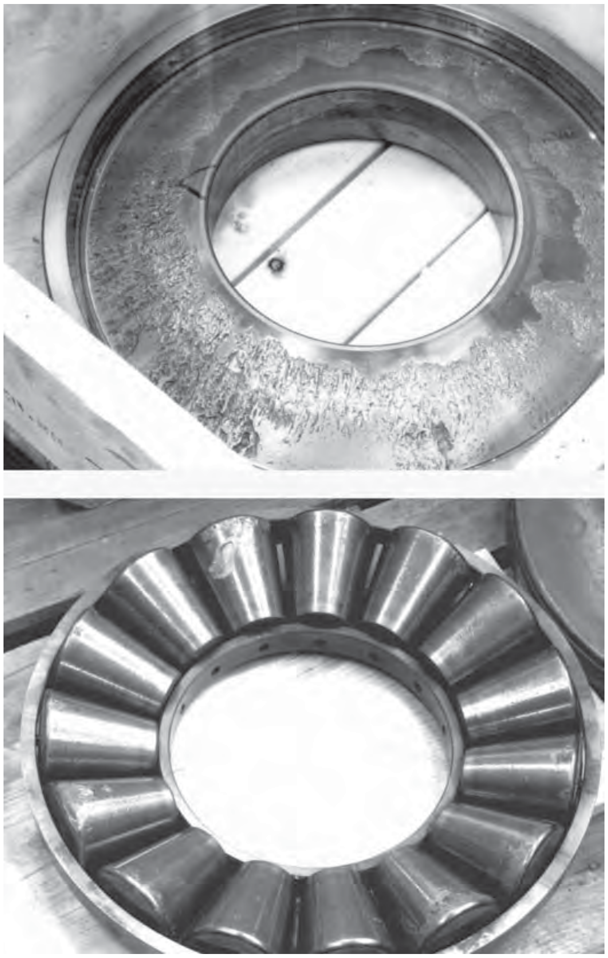

Fig. 1-14—Surface fatigue of a million-pound thrust bearing.

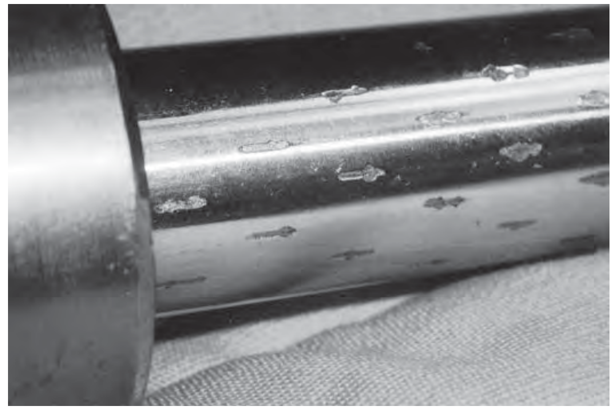

Fig. 1-15—Spalling of chromium plating from surface fatigue.

damage is the result of plastic deformation or many overlapping pits. Impact wear as in wear of jackhammer tools is usually conjoint with high-stress abrasion (Figure 1-16). A costly manifestation of impact wear is loss of sharp edges on plastic and metal punching/perforating tools. Edge rounding on punches usually occurs by microscopic fracturing of cutting edges from the repeated compressive stresses that come with punching holes and other shapes in steel sheets.

Other Forms of Wear

There are a number of types of wear that do not necessarily fit into the dozen or so modes just discussed. Most are not encountered by the average designer so they will only be mentioned and not discussed in detail as those forms of wear that are covered by standardized tests.

Machining Wear

Wear of tools used to cut other substances can be significantly different from ordinary nonabrasive wear. A lathe tool used in turning steel can produce chips that are red-hot. The tools can soften from the heat in generating chips, and in some cases atoms from the tool can diffuse into the work to produce material removal. This occurs when diamond tools are used on steels (carbon diffuses into the steel) and this is why this practice is avoided. Cutting tool materials are best tested by actually cutting a material of interest under controlled cutting conditions and evaluating tool wear with microscopic measurement of the material removal at the cutting edge such as cratering, flank wear, and rake wear (Figure 1-17).

Human Joint Deterioration

Arthritis is deterioration (wear) of the lubricating/separating cartilage and films that separate bones at joints. There has been limited progress in solving this wear problem, but medical professionals worldwide regularly replace worn and damaged human joints with prosthetic devices that also wear. In fact, wear of the prosthetic joints is a limiting factor in their use. Most of the artificial hip joints used today in the United States rub a metal or ceramic ball on a plastic socket. The plastic is usually ultrahigh molecular weight polyethylene. The mating material can be a 300 series stainless steel, a cobalt/chromium alloy, or aluminum oxide ceramic. Each actuation of these systems produces many tiny wear particles that must be accommodated by the body. If there are more particles produced than the body can deal with using its "protection-against foreign-body" mechanisms, the bones tend to loosen in the area of the implant.

There are ASTM wear tests that are used by some to screen materials for these types of applications (ASTM G 133),

Fig. 1-16—Impact wear.

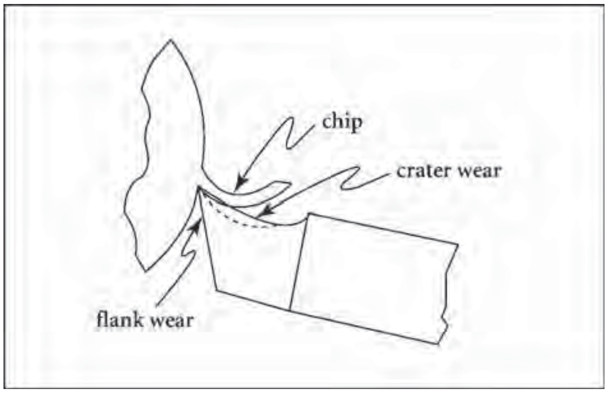

Fig. 1-17—Cutting tool wear (cratering, etc.).

but most simple wear tests do not replicate the complicated motions that actual human joints experience. Also, it is not possible to duplicate the lubricating fluids in the body. Most tests are conducted in bovine serum as an approximation. In Europe, metal-to-metal couples are common, but the metal alloys (cobalt-based Stellite types of material) are said by some to create toxicity problems. Joint replacements are offered with different service lives (10, 20, and 30 years), but at present most do not do the job as well as nature's system (Figure 1-18). Tribotests on elegant test rigs that duplicate motions and forces continue to be used to study and develop particle-free (no wear) prosthetic devices for joints.

Erosion

It could be argued that wear-causing particles or wear detritus can behave like a fluid and thus other forms of wear such as

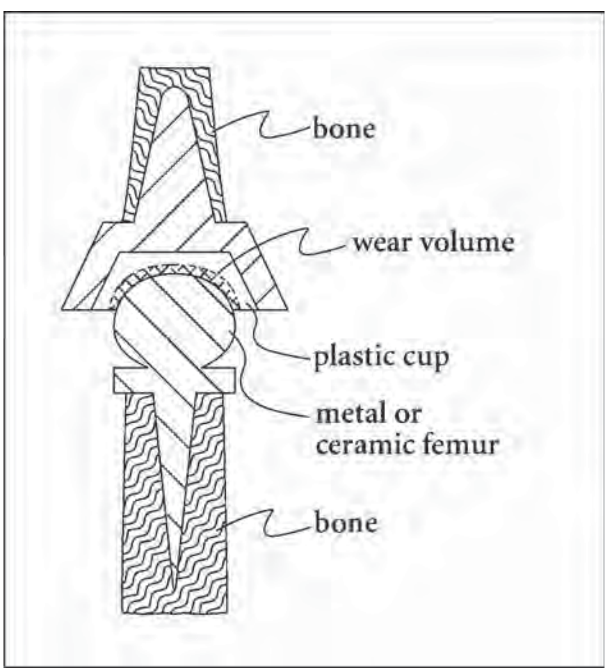

Fig. 1-18—Wear of a hip implant.

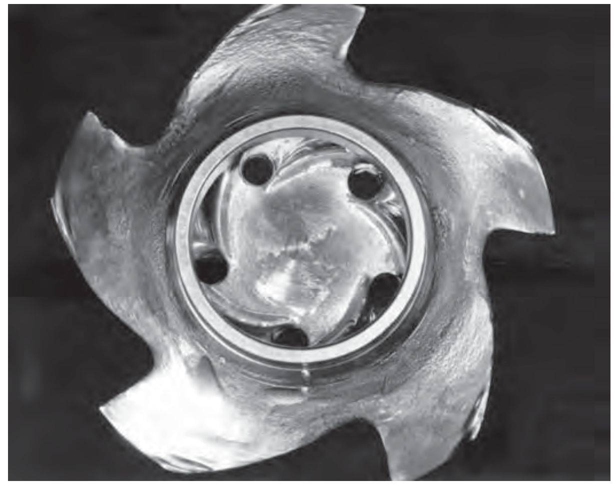

Fig. 1-19—Slurry erosion on a pump impeller.

metal-to-metal wear could be construed as "erosion." However, from the art and science standpoint, it is desirable to call progressive material removal processes that involve mechanical action from fluids as erosion processes. Many erosion processes have incubation periods not present in sliding wear processes, and as we shall see in the chapter on modeling and simulation, the equations to predict removal rates are quite different. The following are the more important erosion processes.

Slurry

A slurry is any mixture of solid particles and a liquid. The particles can be as large as centimeters in diameter and as small as nanometers. The liquid fraction can be anything that allows the slurry to be "pumpable." Concrete contains only about 10% by weight water when it is ready for pumping, but it is still a slurry. Slurry erosion is progressive loss of material from a solid surface by the action of the slurry sliding/flowing on the surface. The erosivity of the slurry is a function of the nature of the slurry components and the fluid. Slurry erosion is common in oil well fluid handling systems (Figure 1-19) and pipelines carrying coal and other minerals from mine to process sites (Figure 1-20).

Solid Particle

Sand blasting is the classic example of solid particle erosion. Material is removed by the mechanical action of hard particles

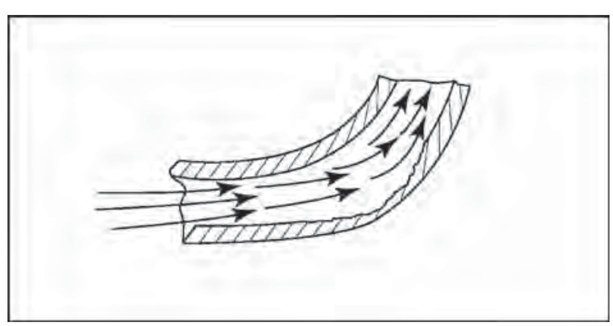

Fig. 1-20—Schematic of slurry erosion.

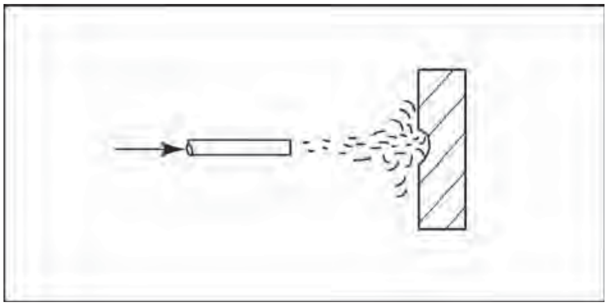

Fig. 1-21—Schematic of solid particle erosion.

impinging on a softer surface (Figure 1-21). This type of erosion is common in any system in which gas streams carry abrasive particles. Boiler ash-conveying systems erode through at bends by solid particle impingement. Fan blades in dusty atmospheres get damaged by solid particle erosion. Sand blast equipment erodes the blasting target (Figure 1-22). The damage to the target of an impinging stream of particles in a gas carrier depends on the size of the particles, the hardness, sharpness, fluence, flux, impinging angle, and particle velocity.

Cavitation

Cavitation is the collapse of entrained bubbles in a liquid. When a submerged bubble collapses, energetic jets of the liquid can be produced that can erode a surface that it impinges on (Figure 1-23). The local pressure on a solid surface from a bubble collapse jet can be as high as 100,000 psi. A cavitation field can occur in a pump, around a ship's propeller, in ultrasonic debubblers – many industrial applications. Figure 1-24 shows cavitation erosion patterns in a stainless steel tank to which ultrasonic debubblers were attached. These debubblers remove entrained bubbles from liquids prior to coating the liquids on substrates.

Droplet

When an airplane goes through a rain field at 500 miles per hour (mph), the droplets striking solid surfaces cause droplet erosion. Droplet erosion is very similar to solid particle erosion. A water droplet traveling at 500 mph has energy similar to a solid particle in damage potential (Figure 1-25). Needless

Fig. 1-22—Solid particle erosion of a sand blast fitting.

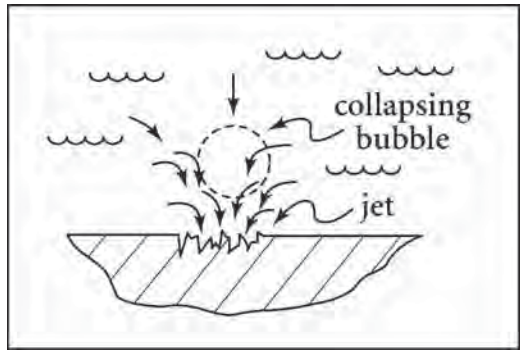

Fig. 1-23—Schematic of cavitation erosion.

to say, rain erosion is a significant factor in aircraft. It can erode windshields, radar domes, paint, even aluminum. If steam conditions are not just right in steam turbines, the steam produces condensate droplets that impinge on turbine rotors traveling at very high velocity. The steam droplets can produce droplet erosion that can render the rotors unusable.

Impingement

This form of erosion arises from the mechanical action of fluid flow on solid surfaces. It can be conjoint with corrosion. In its most drastic form, it is water jet cutting. A stream of 50,000 psi water can cut through plastics, wood, and many nonmetals. In this form, it usually cuts by inducing fractures in the solid under impingement. The more prevalent form of impingement erosion occurs in pipelines (Figure 1-26), where the impinging fluid continually removes protective films until perforation occurs. Process chemicals entering a reactor can cause impingement erosion at the point where the chemicals strike the vessel wall.

Gas

Without particles or droplets and at room temperature, most gases are benign to many materials. However, when temperatures are high enough to cause gases to react with impingement surfaces, the gases can erode surface reaction products producing

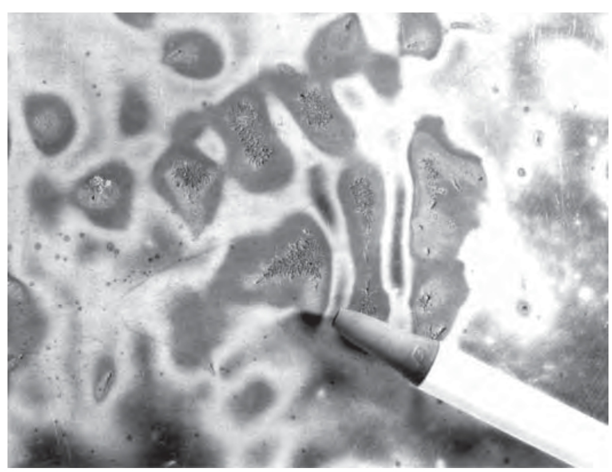

Fig. 1-24—Cavitation erosion of stainless steel from an ultrasonic debubbler.

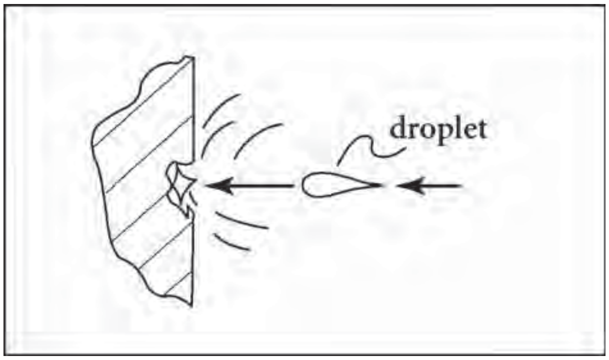

Fig. 1-25—Droplet erosion.

gas erosion of surfaces. Oxygen/fuel cutting and welding torches routinely need replacement because of hot gas erosion. As one might suspect, this is a very serious problem in rocket engines. The combustion gases can raise surface temperatures to the red heat range and the gas velocity can be sufficient to cause mechanical removal action on the hot surfaces containing the propulsion gases. Ceramic-based materials are often the only candidates for high-temperature gas erosion situations.

Atomic/Molecular

Atomic/molecular erosion is material removal atom by atom or molecule by molecule in vacuum sputtering systems. Often this type of erosion is intentional. It is used to clean surfaces atomically before application of thin-film coatings for electronic or other applications. The classic example of this type of erosion is in electronic devices that employ a filament that emits electrons as in vacuum tubes. The filament eventually "burns out" because it is thinned by atomic erosion. Ion milling is an application of atomic erosion. Ions bombard a surface and "knock out" surface atoms. This process is used to thin specimens to atomic thicknesses for transmission electron microscopy. It has industrial applications in microengraving.

Spark

Like sputtering, spark erosion is often intentional. Spark erosion removes material by localized melting conjoint with forces that eject the molten material. This kind of erosion eventually occurs on most switches carrying significant currents, but the most important application is in electrical discharge machining, where it is used to shape metals. An electrode is brought into proximity with the surface to be eroded, and capacitive discharge types of power supplies create sparking between the electrode and the substrate. The substrate melts at each spark event. Both surfaces are covered with dielectric and this fluid assists removal of the detritis generated by local melting. Sparking rates and intensity can be controlled to control the machining rate and surface finish. Electrode erosion can be equal to the work piece erosion. Use of continuously fed wire as the electrode gets around the problem of electrode erosion; the wire electrode is continuously replaced. Electrical discharge machining/machined-surfaces display consists of microscopic craters that produce a matte surface texture (Figure 1-27).

Laser Ablation

Short pulses of lasers can produce ablation of surfaces, that is, material is heated so fast and energetically that it goes from solid to gas. This process can be used to clean surfaces. Contaminating plastic films can be ablated from metal rolls. Laser ablation is used to erode materials for marking names, slogans, etc. engraved on rocks, glass, ceramics, metals, etc. In the United States, laser ablation is used to "refresh" facial skin. The outer layer of skin is ablated and the body's process for healing the "damaged" surface allegedly improves the appearance when healing is completed. Of course, laser ablation can produce undesirable erosion when lasers unintentionally hit surfaces.

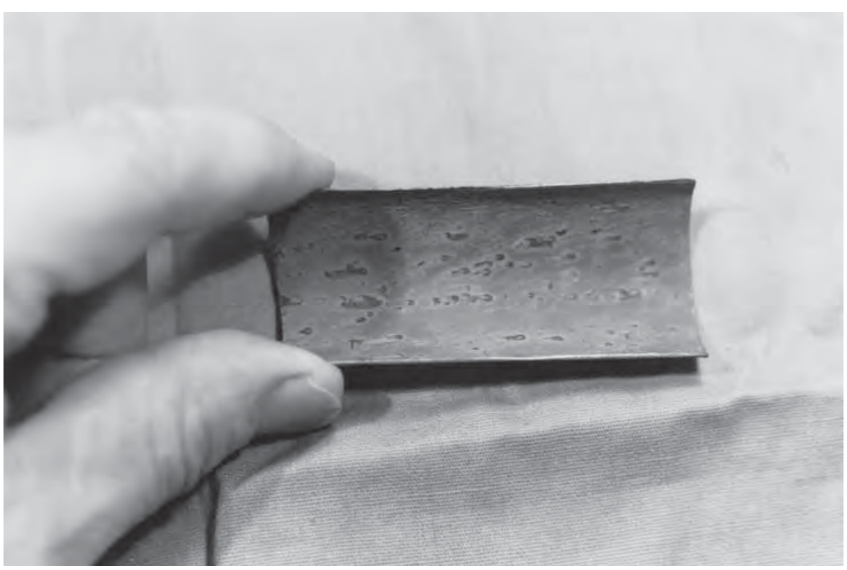

Fig. 1-26—Impingement erosion on the inside of a copper water pipe.

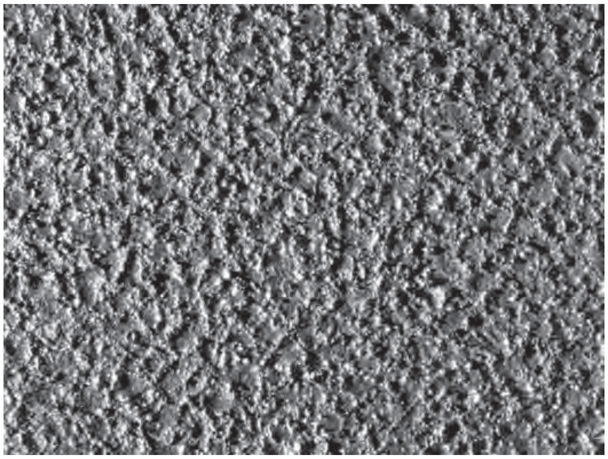

Fig. 1-27—Spark erosion from electrical discharge machining (EDM).

Types of Friction

Sliding

Friction is a force resisting motion in a direction opposing motion of a solid on another solid when movement is attempted and while relative motion continues. It can be reduced, but never fully eliminated. It is manifested in every mechanical device, every motion of a living body part on another surface, and every place that a solid slides on another solid. Static friction is the term used to describe the force required for breakaway (initiation of motion). In some electronic devices such as disk drives, the term "stiction" is used to describe the breakaway force between a magnetic sensing and recording head and the magnetic medium. "Blocking" is the term used for the sticking that can inhibit relative motion between plastics that have been sitting on each other for extended periods of time.

Breakaway forces on almost any tribosystem can be affected by environmental factors that lead to "sticking" at startup. A common cause of this sticking in sensitive systems is a moisture (water) meniscus. Breakaway requires overcoming the surface tension effects of the moisture. The more correct term for the force required to overcome "sticking" events is static friction force. The force continuously resisting (and opposite to the direction of motion) is "kinetic friction." The dimensionless ratio of the friction force to the normal force pressing the bodies together is called the coefficient of friction.

The friction between solid bodies in contact depends on the nature of the bodies. A material does not have a coefficient of friction; only a material couple in a tribosystem has a coefficient of friction. For this reason, whenever friction characteristics are tested and reported, the report must always identify the members (materials) involved in the friction tribosystem as well as the nature of the tribosystem. If there is a third body present such as water, this must also be reported. The following is the recommended way to report friction—state the couple and the conditions:

> The coefficient of friction of the 6061-T6 rider on the A2 tool steel counterface ranged from 0.3 to 0.5 under steady-state sliding in the ASTM G 99 pin-on-disk test (5N normal force, 1 m/s sliding velocity, in DI water, at 20°C).

Rolling

Rolling friction is the force on a revolute shape resisting rolling as it is attempted or during rolling. Its direction is opposite to the intended direction of rolling. As mentioned in previous discussions, there is relative motion (slip) on every rolling element, but rolling friction is the net effect. Like sliding friction, there is a rolling coefficient of friction and it is mathematically the same as sliding friction: the resisting force on the rolling member/the normal force on the rolling member. The motion of every revolute shape on another surface is resisted by rolling friction. Ball and roller bearing manufacturers have complicated empirical formulas containing many factors to estimate rolling friction in their bearings, but these are not readily available to users and rolling friction tests are a recourse. Like sliding friction, the nature of the tribosystem needs to be reported. Rolling friction strongly depends on the nature of the bodies involved, their size, stiffness, hardness, and even their surface texture. These need to be reported with test data.

Solids Contacted by a Fluid

Fluid friction ranges from the heating produced on leading surfaces of space vehicles on re-entry to attritious losses in internal combustion engines from crankshafts splashing in the oil in the crankcase. Both of these are serious results of fluid friction. Fluid friction is the energy dissipated when a fluid moves in contact with a solid surface or vice versa. In the re-entry example, the friction of gas molecules rubbing on the nose cone of a space craft expends enough energy to make the protective tile surface red hot. In the automobile engine example, the energy lost in "sloshing" oil about in the engine can equal 10 percent of the power produced by the engine. Fluid friction is a factor in flow of any fluid in a pipe. Each restriction, change in direction, protuberance in the flow is subject to fluid friction forces. The nature of the fluid (e.g., viscosity, physical properties), the nature of the solid surfaces, and the environment control fluid friction forces. There are mechanical devices such as traction drives and transmissions, in which the frictional characteristics of fluids on smooth solid surfaces need to be measured. The fluids used in these applications are called traction fluids. They are essentially oils formulated to be "less slippery" than normal lubricating oils. Lubricated tests are used to measure traction coefficients of these special oils.

Static Friction/Blocking

Blocking is a serious problem in the plastic film and sheet business and most manufacturers use coatings or interleaving with paper and the like to prevent material adhesion of plastics. Residence times of days are usually used to test for blocking. The force to move one plastic on another after sitting for 100 or 1,000 hours is measured. Plasticized vinyls are notorious for their tendency for blocking. Diffusion of plasticizers from one surface to the other is usually the root cause of this blocking.

Stiction is commonly measured by essentially instrumented disk drives. The recording head is allowed to set on the disk for 10 or 100 hours (etc.) and the force on the head at startup is called the stiction force. Humidity can cause stiction by forming a meniscus around the head/disk contact. Nanoindentors and some nano-friction testers measure the "pull-off" force, which is defined as the force needed to pull a scanning probe tip of some material (e.g., maybe silicon, maybe diamond) from a surface. This is not called "stiction," and pull-off force is a commonly used term.

Types of Lubrication

Solid Film

"Solid film" and "dry film" are terms used for solid coatings applied to a surface to reduce wear and friction between contacting solids. Solid film is the preferred term. These coatings can be any thickness, but the usual range is from approximately 2 μm to about 75 μm. They can be polymers such as fluorocarbons; they can be inorganic materials such as molybdenum disulfide; or they can be graphites or they can be chemically or electrochemically formed surface reaction products. "Teflon S™" is probably the most common fluorocarbon solid film lubricant. It is used on garden tools and all sorts of devices that are apt to get wet or dirty and are likely never to be lubricated by users. It stays in place to lubricate until worn off. Molybdenum disulfide is probably the most popular inorganic solid film lubricant. It is a fine solid powder that can be burnished into a surface to lubricate. Molybdenum disulfide and graphite are "intercalative lubricants." Crystal platelets slide on each other like playing cards slide on each other when shuffled. They have a hexagonal crystal structure, and these crystallites slide on each other by interplanar shear. The fluorocarbons lubricate by behaving like a "liquid" under high loads. They are weak and their low shear strength provides their lubricity.

Phosphate conversion coatings are the most commonly used chemically formed lubricating coatings. They are essentially corrosion products produced by immersing steel parts in phosphoric acid and proprietary ingredients. They are usually 1 to 3 μm in thickness and lubricate by forming particles to separate surfaces when used dry, and when used with oil they act as a porous surface to retain lubricants and separate surfaces. This is the primary function of any lubricant, that is, to separate surfaces that can contact and slide on each other. If the surfaces are completely separated by an unctuous material like a grease or oil, they will not touch and thus will not wear.

The fluorocarbons and intercalative solid-film lubricants are most often applied by mixing with a "paint" type binder and spraying them on a surface like spray painting. Most require baking for cure of the organic binder, and binders can range from air-dry cellulosics to high-temperature baked phenolics or other thermosets. Sometimes these coatings are applied over as-sprayed thermal spray coatings (Figure 1-28). This yields a surface of hard peaks with solid lubricant retained in the valleys. Some silicone coatings can be applied as a "varnish" and thus they too can be classified as solid-film lubricants. Finally, one of the oldest solid-film lubricants is wax.

There are countless waxes; some are generated from mineral oils, and some come from living things. Carnauba wax is an incredible gift of nature. It is obtained by scrapings from leaves of a plant and it is applied to a surface as a thin film and buffed. Waxes are weak solids that can be deposited on surfaces to separate them. They are extremely important in manufacturing web products that may stick to each other. Waxes prevent contact and that is how they lubricate and prevent sticking. They also do a nice job of protecting automobile finishes from water contact since many are hydrophobic as coatings.

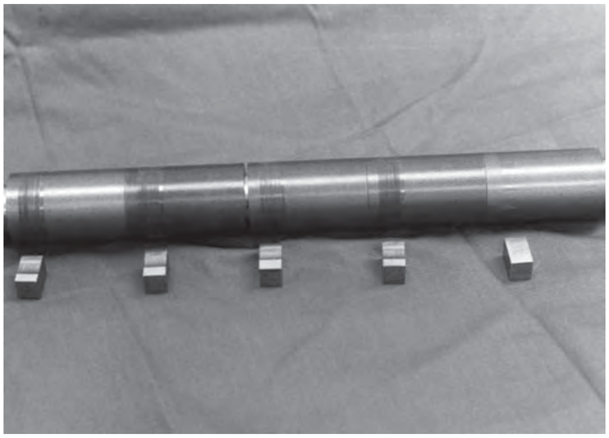

Fig. 1-28—Thermal spray/lubricant coatings after wear testing.

Thin Film

This may not be an "official" lubricant category, but it reflects a trend in the 1990s to apply lubricants at the molecular level. The claim is that a single layer of molecules is bonded to a surface to prevent contact and reduce friction against other surfaces. Self-assembled monolayers are lubricant thin films produced by reactive absorption of the lubricant species. Surfaces are treated by dipping, vacuum coating, spinning, etc., with a lubricant that contains molecules with an end group that wants to bond to the surface to be treated. These molecules assemble themselves with their reactive end to the surface and the remainder of the molecule stands proud to separate surfaces when contact is attempted. Special molecules that react with surfaces for adhesion are often contained in compounded oils, but this category refers to species that supposedly work as bonded films only one of several molecules thick. These kinds of lubricants are important on hard drives and similar electronic devices where surface separations need to be in the nanometer range.

Liquid

Liquid lubricants are the most widely used lubricants. They are everywhere. They keep vehicles running, turbines generating electricity, refrigerators and air conditioners cooling, trains running, airplanes flying. They work by separating solid surfaces so that they do not rub on each other. If full separation is achieved, hydrodynamic lubrication is said to exist; if the contacting surfaces are not completely separated, boundary lubrication is said to exist; if the surfaces deform to achieve fluid separation, this is called elastohydrodynamic lubrication (Figure 1-29).

Of course, the systems that produce complete separation are ideal. If boundary lubrication exists, the contacting surfaces will wear. A ball bearing running at only a few hundred revolutions per minute could produce boundary lubrication. The rotational speed of the balls is not high enough to "pump" the lubricant into the rolling interface with enough energy to produce surface separation. Lubricated tests are almost always velocity sensitive. Whatever the test it is probably necessary to test at the velocity of interest using triboelements that simulate geometries of interest. Similarly, loads of interest need to be simulated.

A part of liquid lubrication is hydrostatic lubrication in which a body is floated on a lubricant film that is introduced

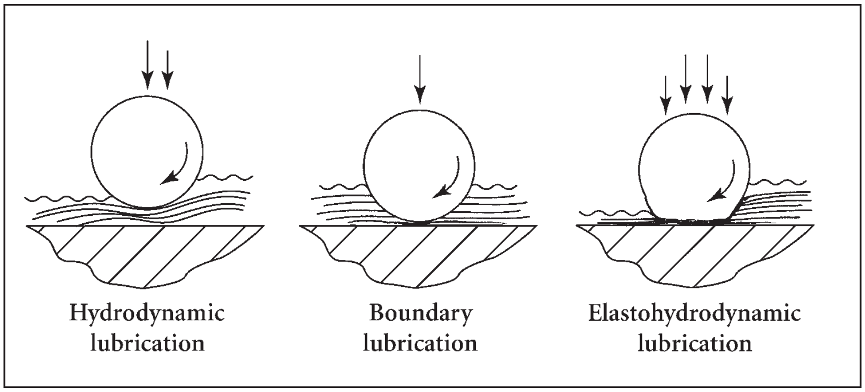

Fig. 1-29—Degrees of lubrication.

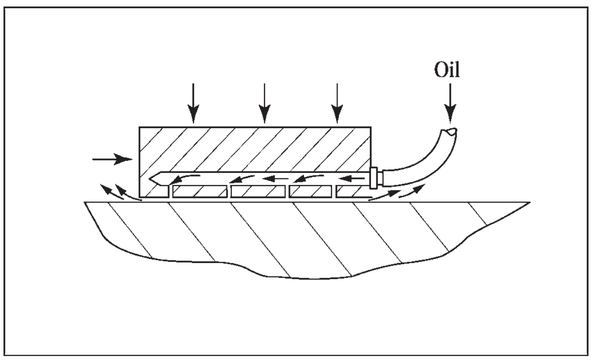

Fig. 1-30—Hydrostatic bearing.

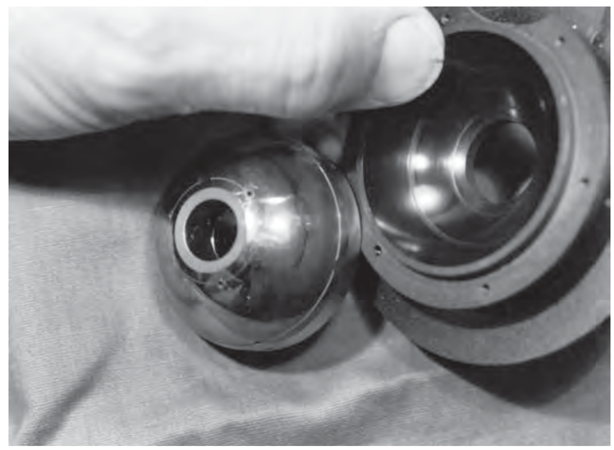

Fig. 1-31—Air-bearing components after a crash (contact at speed).

between conforming bodies at sufficient pressure to allow one body to float on the lubricant film (Figure 1-30). Even without relative motion, the bodies are separated by a fluid film.

Gas

The most common form of gas lubrication is pressurized air. Orifices are placed in strategic locations in conforming surface bearings and the sliding member is lifted and supported on an air film (Figure 1-31). Of course, the gas can be something other than air. Gas bearings usually provide friction characteristics similar to hydrodynamic lubricated systems. They can run at high velocities. These bearings are used in spindles that may rotate faster than 100,000 rpm. The limiting factor in the use of these bearings is often response to impact loads. If the bearing contacts the support surface, wear damage can destroy the bearing. Shock loads from any source need to be avoided.

Grease

A grease is an oil or other lubricating substance held in a filler that provides thixotropic behavior. There are many fillers used and their role is to act as a reservoir for a fluid or solid lubricant. The most common greases have mineral or synthetic oils as the lubricating substance and inorganic clays as the filler. In rolling element bearings, the oil comes out of the grease as the speed (and temperature) of the bearing increases. When the bearing rotation stops, the oil goes back into its clay reservoir ready for its next encounter.

There are probably more types of greases than oils. All greases are essentially proprietary since there are no standard recipes for formulating greases. However, there are property "standards" for greases, for example, marine-bearing, high-temperature, and waterproof grease formulations make options to conform to "standard" applications. A common test for efficacy of a grease is to put it in a bearing and run the bearing under load until failure or some set number of revolutions (10^{10} for example) are achieved.

Chapter Summary

Hopefully, enough terms have been defined so that newcomers to tribology can deal with the "jargon" used in describing tests. It is also important that readers at this point be familiar with the scope of this guide on wear, erosion, and friction in tribosytems. There are areas such as machining wear that will receive only token coverage. It was also pointed out that parts do not just wear. They wear or erode by different modes, and identification of the appropriate mode is an important first step in solving wear problems. At this point, readers should know the difference between wear and erosion; the latter requires mechanical action of a fluid.

A very important “cosmic truth” from this chapter should be that a material does not have a coefficient of friction. Friction requires more than one member. It is a system effect. It is manifested as the energy dissipated when one member moves on another in a particular way, in a particular device. It was shown that there are various types of lubrication as well as types of lubricants. Some lubricant tests will be described in future chapters, but at this point, it is sufficient to know the difference between an oil and grease and something about solid-film lubricants.

Important Concepts

The following concepts should be taken from this chapter:

1. Wear tests must simulate a tribosystem of interest to be of value.
2. There are many modes of wear and a valid test must simulate a particular mode.
3. Erosion differs from wear in that it involves the mechanical action of a fluid.
4. Friction is affected by the nature of the contacting materials, by third bodies, by any substances on contacting surfaces, and by the mechanics of a sliding system.
5. A material does not have a coefficient of friction; it is a system effect.
6. There are many types of lubricants, but their role is always to separate rubbing surfaces and lower friction and wear.
7. The first step in a tribological study is to identify a friction, wear, or erosion mode.

Resources for More Information

More Definitions/Case Histories

ASM Handbook, Vol. 18, *Friction Lubrication and Wear Prevention*, Materials Park, OH, ASM International, 1989.

Fundamentals

Kragelskii, I. V., *Friction and Wear*, London, Butterworths, 1965.

Hutchings, I. M., *Friction and Wear of Engineering Materials*, Boca Raton, FL, CRC Press, 1992.

Stachowiak, G., *Wear – Materials Mechanisms and Practices*, New York, Wiley, 2005.

Williams, J. A., *Engineering Tribology*, Oxford: Oxford University Press, 1994.

STP 474, *Characterization and Determination of Erosion Resistance*, W. Conshohocken, PA, ASTM International, 1970.

Testing

Neale, M. J. and Gee, M., *Guide to Wear Problems and Testing for Industry*, New York, Wiley, 2000.

Related ASTM Standards

G 40 – Terms and Definitions Relating to Wear and Erosion.

D 4175 – Standard Terminology Relating to Petroleum, Petroleum Products, and Lubricants.

2

Alternatives to Testing: Modeling and Simulation

Introduction

THE SCENARIO: A LUBRICANT IS NEEDED FOR A plain bearing of CDA 172 phosphor bronze sliding against nitrided steel to complete a project. Your company's "lubricant selection expert system" is called up on your CAD terminal; information is entered on shaft size, speed, torque, normal force, and desired service life; and the computer displays a trade name and type of a specific lubricant to use, how it is to be applied, and lubrication intervals.

This is what many designers would like to happen with most tribological design situations. Such an expert system does exist in which one can select a lubricant, but most engineers at the time did not have these tribological design aids on their terminals; also, many sliding interfaces do not have generic application conditions. That is the problem addressed in this chapter. There are limited usable models, computer simulations, and expert systems available to help designers deal with wear and friction problems, but this chapter will discuss what is out there. Hopefully, it will let newcomers in tribology become familiar with modeling and simulation in the various wear and friction categories. Specifically, this chapter will discuss expert systems, computer simulation, finite element (FEM) wear models, erosion models, friction models, wear maps, and lubrication models.

Expert Systems

The concept of expert systems is to write software for computers that allows the computer to analyze existing data and experience and deduce a solution to a problem. This was a popular research and development effort that started in the 1990s. It is still very much in use, but under different names. In fact, just about any computer website that queries users would use expert system concepts. For example, some airlines in 2006 introduced computer screens to replace the ticket counter attendants. They ask you your name, where you are going, flight number, number of bags, etc. The end product is seat assignments, boarding passes, and luggage tags. The computer was programmed to perform the tasks of the "expert," the ticketing agent. Ticketing agents used to look at your tickets, ask you questions, and then more questions based upon responses. All of these questions and possible answers can be put into the computer's memory. The computer becomes the expert, the ticketing agent.

Obviously, the objective of these systems is to replace the "expert" with a machine that will work 24 hours a day with no pay, no vacation, and no benefits. Bearing- and lubricant-selection systems offered by some suppliers are expert systems if they work from user queries. The lubricant-selection system mentioned in the introduction was a proprietary system used by a large chemical corporation (that no longer exists). It was developed by in-house tribologists. The company's product line was such that many additives in formulated lubricants, like all commercial oil and grease, could not be tolerated in contact with their product. Thus, any lubricant used in corporate equipment had to be screened for product compatibility. The tribology department did this screening and they arrived at a group of approved greases, oils, hydraulic fluids, traction fluids, etc. This example makes for an ideal basis for an expert system. The computer was loaded with property information on approximately 100 lubricants, not the thousands that are commercially available. Next, the computer was "taught" to ask the selection questions that the lubricant expert asked customers. They included questions such as:

1. What is to be lubricated?
   (Typical answers):
   - ball bearing — Sealed? / Open?
   - plain bearing
   - gear — Open? / Sump?
   - machine way — Dirty? / Clean?
   - slide
   - etc.
2. What is the environment?
   (Typical answers): vacuum, wet, dry, outdoors, hot, cold, etc.
3. Anticipated operating temperature
   (Typical answers): room temperature (20°C), 200–300° F, 300–400° F
4. How many units do you need to lubricate?
   (Typical answers): 1, 1 to 10, 10 to 100, thousands, millions, etc.

5. What quantity of lubricant will each unit require?
   (Typical answers): 1 to 10 mL
   10 to 100 mL
   100 mL to 1 liter
   1 to 10 liters
   etc.

The expert knows that each response points to a particular group of approved lubricants and, with enough questions, the expert will arrive at a recommendation of a single lubricant. The computer software was "taught" what the expert would do with every query response. There was a companion proprietary system to the lubricant system that selects plain and rolling element bearings. Again, only approved bearings could be used, so there were boundaries to the system, which is almost mandatory. Experts use only materials/solutions with which they have experience, and no expert is ever going to be familiar with all of the lubricants or bearings in the world. Thus, these systems are useful aids in eliminating testing, but their effectiveness depends on their author(s).

When properly executed by an appropriate expert, these aids can reduce or eliminate the need for testing. However, there are not a lot of tested, useful expert systems available to the average engineer or designer. A second problem that exists with some systems is that they are not compatible with CAD systems. Designers faced with a wear- or lubricant-selection issue would like to call up a lubricant or bearing selection system from his or her terminal, but often the CAD software does not permit it. In summary, expert systems can be great where available, but in 2006, availability was limited.

Computer Simulations

Supercomputers and PC networks are used by some tribologists to simulate surface interactions at the molecular or atomic level. These simulations have proliferated since 2000 or so and they are getting more sophisticated each year. At the present time, they are limited in the number of atoms or molecules that they use. Often, simulations are conducted with between 50 and 500 atoms/molecules. Models often take the appearance of two-dimensional "balls" (Figure 2-1), but some models are three-dimensional.

Each atom or molecule is assigned its atomic constants (lattice dimensions and nuclear potential field) and Newton's equations of motion are solved for all the atoms. Then surface "a" is slid on surface "b," and the computer simulation indicates if, for example, atoms from surface "a" transfer to surface "b," or if atoms from "a" are knocked from the system. Sometimes they mix or do other things. These simulations are most often applied to nanotribology systems such as an atomic force microscope tip sliding on an atomically smooth surface. In general, they show which triboelement is more durable (loses less atoms or molecules).

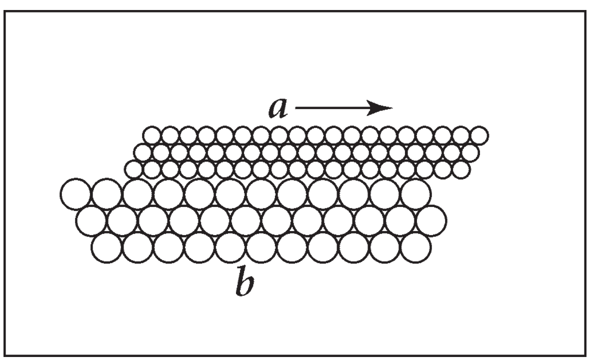

Fig. 2-1—Atomic model of atoms from metal "a" sliding on metal "b."

Needless to say, these simulations are simplified. Real surfaces are not atomically flat or in contact. Real surfaces are covered with atomic species (contaminants, oxides, etc.) that are different from the host surfaces. Nonetheless, atomic and molecular dynamic simulations tell researchers what is theoretically happening at the atomic level and this is allegedly what happens someplace on a real surface in the real areas of contact.

Like expert systems, molecular dynamics is not a standard tool available to engineers and designers faced with a real-life problem. In 2006, molecular dynamics is mostly used in universities, and are most applicable to the study of lubricant films that are applied in single layers (self-assembled monolayers). Thus, simulations involving small numbers of atoms are more applicable. As computers become more powerful, these simulations will follow suit.

Finite Element Modeling

FEM is a process for computer modeling interactions between contacting solids by superimposing a two- or three-dimensional mesh on the surfaces with elastic properties of the materials involved assigned to the ligaments of the mesh. For example, a sphere in contact with a flat plane will show the stress distribution of the contacts (Figure 2-2).

When the sphere is indented into the flat surface, the nodes in the mesh will be displaced a certain amount depending on the elastic constants of the material (modulus of elasticity and Poisson's ratio). Once the contacting members deform, the computer can calculate the stress at any node. The model output is usually an output with various colors corresponding to the stress level. The highest stress level is usually red to differentiate it from the "lesser" colors.

The model user can see a stress or deflection map of the contact. Motions can be applied and one can see how one surface slides on another. However, for surfaces sliding on one another, the analyst must tell the computer what the frictional characteristics of the rubbing surfaces are and this could require a test.

FEM models are almost a must in determining contacting stresses of shapes that are nonstandard, not spheres, flat, or revolute surfaces, for example, a contoured punch perforating plastic sheet (Figure 2-3). The shaped end of the punch will produce a stress and deflection pattern as it penetrates that would be very difficult to calculate without FEM techniques.

FEM software is widely available and there are many proficient users of this modeling technique. The analyst assigns the mesh size and shape and thus controls the fidelity of results. If an inappropriate mesh was used, the model may produce misleading results. Another problem with this modeling technique is that most systems assume elastic behavior in both members. Most wear processes involve plastic flow. Some FEM software allows plastic behavior in the members, but there are usually limits on the amount of plastic deformation that the model can handle.

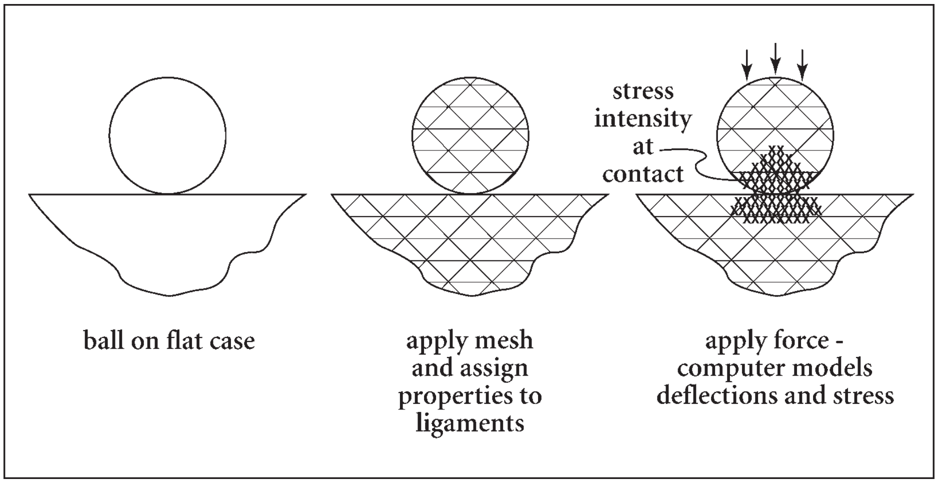

Fig. 2-2—Schematic of finite element modeling.

An important use of FEM in tribology is pinpointing areas of highest stress and relative slip. For example, dies used for perforating plastic were wearing away from the cutting edge. It was not apparent what was happening to produce this wear until finite element modeling quantified high slip in the observed wear area (Figure 2-4). Once the mechanism of die erosion was pinpointed by FEM, it was possible to use FEM to solve the problem. Shapes were empirically placed on the end of the punch to limit the lateral product slip that was producing the die erosion.

Wear is almost always highest in areas of high load and high slip, and FEM is an excellent tool to study loads and slip fields in tribosystems. Its use is recommended wherever conventional mechanics calculations cannot handle a particular contact geometry or motion.

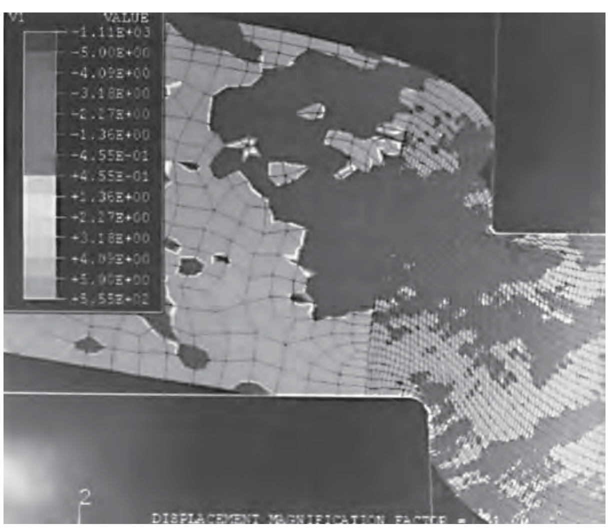

Fig. 2-3—Finite element model for plastic sliding during perforating.

Friction Models

The basic principles of friction have been known for thousands of years, but the Amonton expression for friction coefficient allows its calculation using ordinary mathematics:

$$F = \mu N$$

Where F = friction force
μ = coefficient of friction
N = normal force

This same expression works for rolling friction. Friction becomes the force to produce rolling of a revolute shape. There are many models that allow calculation of the friction coefficient of a sliding couple from surface texture parameters, but there is not universal acceptance of any such relationship in the general tribology community.

The Amonton model for friction shows that the friction force is independent of area. The usual explanation for area independence is based upon the assumption that the friction force results from bonding of asperities on contacting surfaces (Figure 2-5).

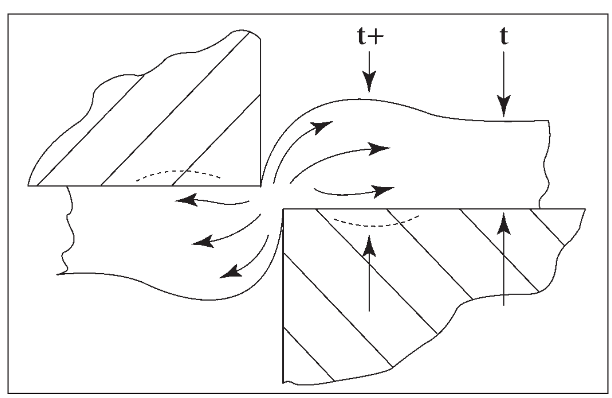

Fig. 2-4—Plastic flow that was causing tool erosion.

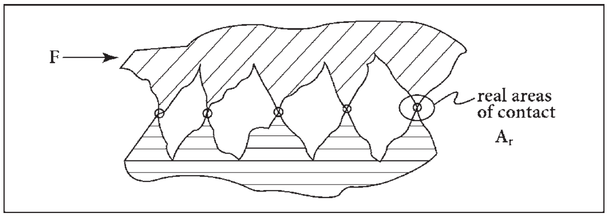

Fig. 2-5—Asperity contact when motion is attempted.

It is also assumed that the real area of contact A_r is a function of the hardness (H) and normal force (N) [2]:

$$A_r = N/H$$

Also, the friction is thought to be the product of the real area of contact (A_r) and the shear strength of the contacting junctions: $F = A_rS$.

Combining these two equations

$F = A_r S$ (where S = shear strength of junctions)
$N = A_r H$
$\mu = F/N = A_rS/A_rH = S/H$

Thus, the friction coefficient is a function of the shear strength of the material and the hardness $\mu = S/H$. This model explains the area independence and why the friction coefficient is never zero. Materials always have a shear strength and hardness; and friction coefficients are seldom greater than one. The shear strength of a material is not likely to be ten times its hardness.

A flaw in this model is that it does not accommodate surface films or both members of the sliding or rolling couple. The shear strength in the model is assumed to be the shear strength and hardness of the weaker of the two, but it would be nice to have a model like a Hertz stress equation that includes the mechanical properties (modulus and Poisson ratio) of both members.

In general, friction models are limited to the Amonton equation, but the shear stress model seems to agree with observations. Friction should be the result of adhesive bonds between surfaces times the number of bonds. Some surface texture measuring techniques can deduce real areas of contact between surfaces and the shear strength/real area of contact model could conceivably produce reasonable friction force results if good data are available on junction shear strength; this is not too likely. The cosmic truth that applies to friction is that it is an energy dissipation process. When work into a device is greater than the work out of a device, the difference is probably friction energy. Any way of calculating lost energy will yield system friction losses. The trend in friction study in 2006 is to record friction energy with time in sliding and rolling tests. Most studies show that friction does not correlate with wear, and there are no accepted models to use to calculate friction in any tribosystem.

Wear Models

Adhesive Wear

Like friction, there are countless models for various types of wear and under all sorts of conditions, but the wear model with wide acceptance is the Archard equation [Dawson].

$$\text{Wear} = KFD/H$$

Where K = a constant for the system

F = force pressing bodies together
D = sliding distance
H = the hardness of the softest member of a couple

This is not a "first principle" equation in that the "K" must be measured for the system of interest. It is really an affirmation of common sense. The equation states that wear increases with the force pushing the bodies together and with increased sliding distance. If one member is not very hard, the wear volume increases. These are common sense factors, which is why this equation is so popular. Intuitively, wear will increase with load and sliding distance, and making the sliding members hard will reduce the system wear.

It is common practice to assign wear coefficients to couples by solving for the "K" in the Archard equation. Textbooks list typical wear coefficients for various sliding couples: like metals, unlike metals, hard metals, soft metals, boundary lubricated, etc. [1]. Most often, tabulated ranges are so large (two or three orders of magnitude) that they usually cannot be used in a design situation.

The Archard equation has been modified and rearranged countless ways, but nobody has succeeded in replacing the experimentally determined "K", with material properties like those used in finite element models. The equation is useful, however, in that it demonstrates the role of load, sliding distance, and hardness, but the unknown "K" in the equation precludes its use as a first-principle model for adhesive wear. The Archard equation is also the most popular "model" for scratching abrasion. Load and sliding distance are still in the numerator, and hardness in the denominator with a term related to the conical angle of the abrasive that is doing the scratching is added [2].

$$W = KFD/H \times B$$

where $B = 2 \cot \theta/\pi$ and θ = the included angle of the indenting point of an abrasive particle. This equation is not usually applied to gouging and polishing abrasion. Like the adhesive wear situation, the wear coefficient, K, needs to be experimentally determined.

Erosion Models

Solid Particle Erosion

Solid particle erosion equations invariably include factors relating to the nature of the particle (K), the velocity of the particles (v), the mass of particles impacting a surface (M), the angle of impact (θ), the hardness of the material impacted (h), and (F), the flux (particles per unit area).

$$\text{Wear} \sim \frac{Kv^2MF}{h} f(\theta)$$

The system factor (K) is empirically determined and thus this equation is like the Archard equation only modified to include the factors that intuitively should increase or decrease erosion. The velocity (v) exponent is usually in the range of 2 to 5, making it very important; the mass of abrasive (M) makes sense in the top of the equation. The more particles that strike the target, the more the damage; the flux, F, is simply the mass of particles per unit area. Of course, it makes a difference if, for example, 100 grams of particles impinge on a square millimeter or a square meter. These models include a flux term. The function of theta (θ) is an angle term that means that targets are usually sensitive to the incidence angle of an impinging jet.

The angle effects of an impinging jet has been observed by everyone who performs these studies. Parallel flow intuitively should produce low erosion, but what is probably not intuitive is that every target material has some impingement angle that produces the most damage (material removed). Soft metals usually erode fastest at impingement angles in the range of 25 to 30 degrees; brittle materials usually exhibit the highest erosion rates at normal incidence. The explanation usually offered for this observation is that brittle materials spall at normal incidence while particles embed in soft metals.

Thus, solid particle erosion models need to include the factors in the preceding equation. The angle factor is usually dealt with by laboratory testing. A material under study should be impinged at various angles to establish maximum sensitivity. The hardness (h) is on the bottom of the equation as it is in the Archard equation. Again, this intuitively belongs there, but complex heterogeneous materials are never well characterized by only indentation hardness.

In summary, solid particle erosion models must include factors relating the nature of the impinging particles, the target material properties (hardness, elastic modulus, density, etc.) and the incidence angles. All of these can be dealt with but, in 2006, most researchers were still doing empirical studies to at least measure the wear factor in the equation. Design engineers should not rely solely on present-day models for life prediction. Testing is usually advised.*

Slurry Erosion

A slurry is a liquid containing suspended solids. This definition can mean anything from mud to tap water in some cities. The solids in U.S. tap water are usually microscopic and so few in number that it is unlikely that they would produce slurry erosion in conveying lines and related hardware. However, mud is likely to produce erosion damage. The fundamental equation for force (force = mass × acceleration) dictates that the size or mass of the entrained solids that can have an effect on erosion. Thus, quantity of entrained solids (by weight or volume fraction) can have an effect as can the size of the solids. Large particles driven by a fluid striking a target will produce more force (to cause damage) then small particles. Similar to the solid particle erosion systems, the fluid velocity will have an effect on erosion.

However, in solid particle erosion there is usually not a fluid-related material loss component in models using room temperature gases, unless the gas is something that can cause attack of the target and material loss without the particle impacts. More often than not, slurry erosion involves a material loss component because of the attack of the target by the fluid that makes up the slurry.

In metal systems, the abrasive tends to remove passive films on the metals allowing corrosion to take place and assist the particles in removing material. At this point, the model for slurry erosion could look something like the following:

$$W \sim C_1\left[\left(\frac{MV^a dD}{E}\right)f\theta\right] + C_2$$

where W = erosion rate
M = mass of particles per unit of fluid (loading)
D = density (or other particle parameter such as hardness, shape)
V = fluid velocity
d = particle diameter (mean)
θ = impingement angle
E = target material property (modulus, hardness, etc.)
C_1 = constant for the tribosystem
C_2 = corrosion rate of fluid under system conditions
a = velocity exponent

Thus, the model looks like the solid particle model except that particle size and corrosion factors are added. Similar to solid particle erosion, there is not an exact equation that works for all systems. The originator of the Miller number for slurry abrasivity, John Miller (ASTM G 75), suggests the following order of importance for factors that affect slurry abrasivity:

particle hardness
particle size
particle shape
particle size distribution
friability
concentration

All these are conjoint with the mechanical action of the fluid and the corrosivity of the fluid.

In summary, models for slurry erosion are probably even less developed than most other wear/erosion models. Finite element/fluid flow computer models are absolutely helpful, but how abrasive a slurry is really depends on Miller's list and the work has yet to be done to put all of these factors into a model. Testing is the common way to predict erosion at present.

Liquid Erosion

Beach accretion is a classic example of liquid erosion. In this instance, the liquid is forced against the solid surface (the beach) by wave action and there may or may not be chemical effects conjoint with the mechanical action from waves. An example of chemical effects of wave action would be waves acting on a clay bluff. The water from the waves softens the clay. In industry, liquid erosion occurs in piping systems, especially where there are high velocities or changes in direction of a stream. In infrastructures, liquid erosion causes material removed from rock and concrete structures in dams, sluice ways, and power-generating machinery.

In every household, liquid erosion will very quickly destroy the valve seat on any faucet. A tiny opening left when the faucet was not shut off firmly will create a tiny stream of water at high velocity that easily erodes brass valve seats. The homeowner only observed dripping, but the seat is seeing a very high-velocity stream. This is often termed "wire-drawing" in the United States. The seat appears to erode in deep channels that are a width comparable with a fine wire.

*Note: The preceding relationship is not a usable equation, but rather the author's estimation of the role of the factors that control a particular wear or erosion process. The same is true for the others that follow in this chapter.

Thus, liquid erosion is material removal from a solid surface initiated by the mechanical action of flowing liquid. The process has an incubation period with metals that derive their corrosion resistance from passive surface films. The material removal is low while the film is being removed and accelerates after the film is removed. Corrosion specialists have even developed empirical critical fluid velocities that certain metals can withstand. For example, copper plumbing has negligible erosion if fluid velocity is kept below 5 feet per second. The critical velocity for 300 series stainless steel may be 25 feet per second.

Models for liquid erosion usually contain factors for fluid velocity (V), the nature of the fluid (viscosity, density, etc.) (e), temperature (T), mass flow of fluid (M), impingement angle (θ), and a factor for chemical effects, C. The velocity effect can be exponential (b).

$$\text{Liquid erosion} \sim \left(MV^{b}eT\right)f\theta + C$$

As in the case with most wear and erosion processes, there is no nice equation that designers can use to calculate erosion rates. However, fluid modeling software is good enough to predict fluid velocities, and these data can be used with critical velocity factors to mitigate or prevent erosion in piping and the like. Preventing shoreline erosion on the other hand requires a higher form of intervention.

Cavitation

This form or erosion may be the least "popular" one based upon research interest. There are few researchers worldwide who devote significant time to this phenomenon. This is probably attributable to the fact that it is a costly problem only in selected applications. For example, cavitation erosion probably seldom occurs in automobiles, aircraft, or electromechanical equipment. It is a costly problem in pumps, ship propellers, ultrasonic agitation devices, and hydraulic systems, particularly water turbines. The mechanism of material damage is material removal produced by microscopic jets created when liquid bubbles at a solid surface implode. The liquid rushes to fill the void and creates a jet that can produce pressures on the target surface that may be 100 ksi, which is enough to damage many materials. It is not unlike water-jet cutting action. It can damage most materials and chemical effects (corrosion) may or may not be conjoint. The metals that have reasonable resistance to cavitation erosion are those with high tensile strength and tenacious oxides on their surface (titaniums, Stellite-type materials, and chromium plating).

Models need to include temperature (t), the nature of the liquid (viscosity, thermal conductivity, etc.), the stability of bubbles, their size, concentration as well as the target material's tensile strength, passivity, and possibly hardness. This yields a rather "messy" relationship:

$$W\begin{pmatrix}\text{cavitation}\\ \text{erosion}\end{pmatrix} \sim \frac{\partial kdsn}{TS\ HpPt}$$

where:

∂ = liquid viscosity
k = liquid conductivity
d = bubble diameter
s = bubble spacing
n = number of bubbles
t = temperature
TS = tensile strength of target
H = target hardness
p = target passivity
P = pressure above the liquid

In other words, there are no universally accepted models that allow the calculation of cavitation damage. The most pronounced factor that controls cavitation is temperature. It is known that cavitation does not occur in boiling water and it is also known that bubbles need nuclei to initiate and that nuclei appear to be associated to the degree of dissolved gas in a liquid. For example, cavitation is suppressed in deionized or distilled water. Hot water (>150°F) is less prone to cavitation. Bubbles seem to be stimulated by dissolved gases and this makes sense since a bubble is filled with vapor/gas. These gases probably come from the liquid.

In summary, cavitation may be farther from other forms of erosion in the quest for a usable predictive model. Some factors that control the process have been identified. Materials have been identified that resist cavitation damage and FEM and other computer models are useful in controlling the fluid dynamics that can lead to cavitation in many propulsion and fluid flow systems.

Fretting Models

Fretting is like cavitation in "popularity." It is a serious problem in many mechanisms and it is a potential problem in all mechanical and electronic devices. The latter is often the limiting factor in plug-in type electrical connections. Reciprocating motion at electrical contacts invariably produces fretting damage if measures are not taken to reduce the relative motion or separate the surfaces with an unctuous material. There are models that relate tensile and elastic properties of materials to fretting fatigue tendencies, but there are no universally accepted models for prediction of fretting damage. One fretting researcher [3] listed the following as factors that control tendencies for damage in a contacting couple:

Amplitude of relative motion [a] (higher produces more damage; <10 μm produces no damage)
Real contact pressure [p] (greater pressure produces more damage)
Number of oscillatory cycles [n] (more produces more damage)
Material couple [k] (as in Archard equation)
Oscillation frequency [f] (not as significant as the other factors; can occur after three rubs or after 30,000 rubs)
Temperature [t] (effect not as significant as a, p, n, or k)
Atmosphere [A] (determines if you will get fretting wear or fretting corrosion; reactive atmospheres increase damage)
Couple hardness [P] hard/hard couples are sometimes less prone.

A model that includes all of these parameters may look like

$$W \sim \left[\frac{kapn(fx10^{-4})t}{P}\right]A$$

The palliative practice adopted in many engineering communities is to calculate or measure relative motion of "contacting couples" and reduce the relative motion. FEM and conventional calculations and measurements can be used for this. The electronic engineers have adapted a gold/gold couple as a "fretting-resistant" couple. Gold does not react with the atmosphere, thus reducing the A in the model to a low number. Unfortunately, this is a costly solution. So, models that work are welcome.

Surface Fatigue Models

Surface fatigue is a significant mode of deterioration in rolling tribosystems and in gears that experience a combination of sliding and rolling as teeth contact each other. Impact wear is also part of surface fatigue. The common factor in these examples is Hertzian loading of contacting surfaces. Ball bearings start out with point contact at rest and then go to line contact. Rollers contact in a line; wheels on crowned tracks have various elliptical contacts that may have other shapes but, in all cases, it is quite possible that the compressive stresses in these real areas of contact can approach elastic limits. When this happens, the surfaces can pit, spall, and crack from subsurface fatigue. A subsurface crack starts and propagates to the surface producing a "wear" particle.

Surface fatigue is addressed by rolling element bearing manufacturers by empirically determining the load capacity of a bearing and publishing these data for users. The load capacity is usually the load that most bearings of a particular size and type can survive one million revolutions. The equation for the rated life of a ball or roller bearing is:

$$L_{10} = \left(C/P\right)^k \times 10^6 \text{ (revolutions)}$$

or

$$L_{10} = \frac{16700}{N}\left(C/P\right)^k \text{ (hours)}$$

where:

L_{10} = bearing life
C = dynamic load capacity of a bearing from the manufacturer (the load in N at which the life of a bearing is 10^6 revolutions and the failure rate of a large number of bearings is 10%)
P = the applied radial load (N)
k = constant: (3 for ball bearings, 10/3 for roller bearings)
N = rpm

Unfortunately, this is not a first principle model. It involves test information, C, as do most wear models.

The key to survival in surface fatigue situations is to keep the subsurface stress low. This can be done by calculating Hertz stresses, and for complicated shapes FEM models can be used. Rolling element bearing manufacturers know that these stress calculations should include stress concentration factors for inclusions and second/third phase microconstituents. Clean steels produce the best bearing/gear life. There are models for fatigue life of rolling element bearings that include parameters for mean microconstituent size, mean-free path between microconstituents, and even the relative hardness of these microconstituents and the matrix.

In summary, surface fatigue models mostly require empirically measured system data. FEM and other stress determination systems are tools that designers can use to determine state of stress in their tribosystem and then keep that stress in the elastic regimen.

What to Do About Modeling: Summary

Needless to say, computers and programming are continuously improving so it may very well be possible to use computer simulations and modeling to eliminate testing. This situation is claimed to be present by the many investigators who compare their models with actual testing data and show near-perfect correlation. However, as of 2006, this situation only exists for specific tribosystems, for example, magnetic media rubbing on a ferrite head material, not for any abrasive wear system. The modelers have refined their model, usually in an iterative way, so that it correlates with testing. For those who want to use models rather than testing, one can refer to the wear models compiled by Professor Ken Ludema and coworkers at the University of Michigan. One of these may be applicable to a system of interest. A thesis by one of his doctorial students contains 125 different equations [Meng]:

This chapter has probably demonstrated that, for most wear and erosion systems, an Archard-type model exists, but these models all involve some constant that must be empirically determined. The models all show wear/erosion increases with load and sliding distance, and say wear modes decrease as the hardness of one or both members increases. So, the situation is that there are some specific models in the literature that are good enough to eliminate testing, but their use is not recommended unless your tribosystem is absolutely identical to the tribosystem used to develop the model. Bench and field tests have a long history of success in predicting wear and erosion tendencies if they are properly executed. So review available models and tests, and then decide if one or the other is more appropriate.

Important Concepts

The following concepts should be taken from this chapter:

1. Some models (empirical) are based upon specific test results and thus apply only to systems like the one used to develop the model.
2. Some models are based upon concepts (conceptual) and assumptions that support the concepts. Users must decide if the concepts are pertinent to their tribosystems. (The models in this chapter are conceptual.)
3. Models based upon first principles do not include experimentally determined quantities in the model. Unfortunately, many may not correlate with real tribosystems.
4. Useful first-principle models (like force = mass × acceleration) are scarce in tribology.
5. A useful wear model must consider contact stresses and respect elastic limits of materials.

Resources for More Information

Fundamentals

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[2] Rabinowicz, E., *Friction and Wear of Materials*, New York, Wiley, 1965.

[3] Waterhouse, R.B., *Fretting Corrosion*, New York, Pergamon Press, 1972.

3

Methodology/Test Selection

General Methodology

Establish the Purpose

HOW DOES A PERSON START IN ADDRESSING THE task of conducting a wear test? The same way that any engineering or research effort is started: decide upon the purpose and objective of the proposed test. This is not a trivial task. These elements should be well thought out as they can affect the entire test program. Some of the common reasons for conducting a wear tests include the following:

1. Purpose: to solve a current wear problem
   Objective: to get a machine back in operation
2. Purpose: to prevent a perceived wear problem in a new system
   Objective: to ensure desired serviceability of a machine
3. Purpose: to rank a class of materials or treatments for wear resistance
   Objective: to provide guidelines on application of materials and treatments to provide optimum serviceability
4. Purpose: to research a wear mechanism
   Objective: to design materials that will resist a type of wear
5. Purpose: to develop wear resistant materials or treatments
   Objective: to make profits for your company who will market the material or treatment

The approach to take in establishing a wear test program will depend on the purpose and objective. For example, if a material user wants to know which type of plastic bushing will run against a soft carbon steel shaft in a particular machine, the boundary conditions for the test program have been established. The goal is to test plastics against a common counterface, and the operating conditions of the elements of the wear system are known. The next step is apparent: select a test machine, candidate materials, establish a test procedure, and proceed to rank the candidate plastics for relative merit.

On the other hand, if the purpose is to develop a wear-resistant diffusion coating so that a heat treating shop can market the process, the test program will be quite different. The treatment developed by your company may be used in a myriad of ways and you must consider the many types of wear that a coating-for-sale might see. A coating that provides excellent metal-to-metal wear may fail miserably when subjected to solid particle erosion. Thus, the very first step to be taken in wear testing is to establish firmly the purpose and objective of the test so that boundary conditions may be established on the test program.

Establish the Objective

As we have shown in these examples, the second step in wear testing is to put some limits on the test, the boundary conditions. One place to start in doing this is to ask the question: how might this system wear? Parts do not just wear, they wear in different ways. Consider the modes of wear and decide which mode or modes are most likely to occur in your system. Figure 3-1 is one classification of wear processes. There are others, but the wear modes listed are the ones that most people feel differ in mechanism. If the wear problem to be addressed is sand flowing in a chute, it is easy to see that this problem could be addressed by an abrasion test. Sometimes it is not all that evident as to the predominating mechanism of wear. Figure 3-2 lists the modes of wear and the types of systems that are likely to be subject to this mode of wear.

Define the Wear System

One of the problems that exists in studying wear or friction is that neither is a property of a material. Both wear and friction are products of relative motion between materials. A wear system is composed of the materials that experience relative movement. Czichos has suggested a systematic technique for looking at wear systems (Figure 3-3). His "wear system" consists of the members that will experience relative motion, the ambient environment, the lubricant, and the interactions that occur between the system members. In the case of conforming solids, it is clear that the wear system is the contacting members and their sliding circumstances. A wear system can also be a metal surface that is subject to cavitation damage from a liquid.

The input to the wear system is work in the form of mechanical action and the materials that are interacting. The input work can be measured by parameters such as relative sliding velocity, normal force, sliding distance, and the like. The output of the system is the desired work. This output work may be motion of a cam follower mechanism; it may be conveyance of a slurry or rolling of a train wheel. The wear system can have disturbances acting upon it such as elevated temperature, vibration, contaminants in the form of dirt, or there may be

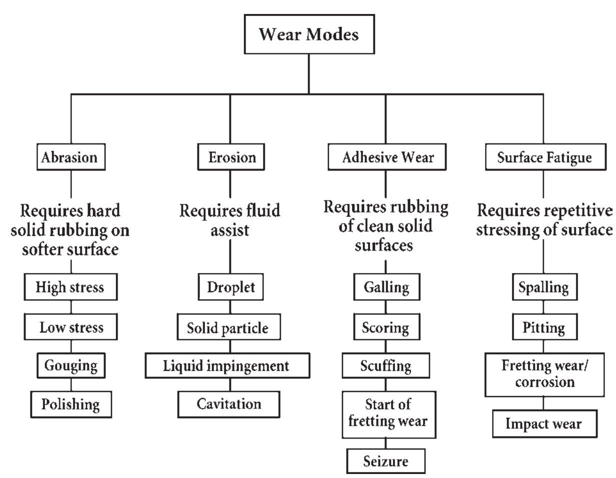


Fig. 3-1—Wear modes.

unanticipated motions such as run-out in a rotating member. These factors can influence the wear system, the work output, or the wear output. The outputs of a wear system are the products of the wear processes that are occurring in the system: heat, friction, material removal, wear debris, noise, and the like. It is the damage that is done to the system by wear processes.

This guide is not suggesting that a potential user of wear testing subscribe to the systems approach suggested in this illustration, but it is presented as a guideline or checklist of the factors that are to be observed in designing a wear test. It also serves to emphasize the point that wear is not a property of a material or a material couple. Wear is the product of a system; this system embraces many factors. From the practical standpoint, because wear is a product of a particular sliding system, a test that models one system cannot necessarily provide applicable data for a system that is different. This is an important point to keep in mind in conducting wear tests. The test results obtained in an abrasion test will not apply to a wear system that involves rolling element bearings. A reciprocating mechanism cannot be simulated with a continuous motion test, like a pin-on-disk. A valid wear test should simulate the system of interest.

Reporting the Data

Various wear tests will be discussed in a subsequent section, but a part of wear testing methodology is reporting and treatment of the data that are taken in a wear test. Whatever the test rig, the elements that should be monitored are essentially the factors that are shown in the illustration of a wear system (Figure 3-3). There is an ASTM standard on reporting wear (ASTM G 118) that proposes fields for wear databases, and another (ASTM G 115) shows the important data to record in a friction test, and then there is the ultimate wear data compilation standard, ASTM C 805. It is probably the most complete checklist for a tribotest. Figure 3-4 illustrates a data sheet for a wear system that contains two members in the wear couple. The major elements of this data sheet are:

1. Test variables
2. Structure of the tribosystem
   a. complete description of the test materials
   b. description of the test surfaces
   c. description of the test environments (lubrication, etc.)
3. Tribological characteristics: the test results

Wear mode	Can occur in
Abrasion	
Low Stress	Agriculture equipment, handling minerals
High Stress	Comminution equipment
Gouging	Earth moving, mineral benefication
Polishing	Handling solids containing mineral fillers
Erosion:	
Solid Particle	Sandblast equipment
Fluid Impingement	Pipe elbow, rain on aircraft
Cavitation	Pumps, mixing impellers, ultrasonic devices
Slurry Erosion	Oil drilling, pumping, mineral benefication
Adhesion:	
Fretting	Bolted-together machine components
Adhesive Wear	Gears, cams, slides, bushings
Seizure	Dry sliding systems
Galling	Valves, sliding surfaces, bushings
Oxidation Wear	Hard-metal sliding systems
Surface Fatigue:	
Pitting	Gear teeth, rolling element bearings
Spalling	Surface-treated parts
Impact	Riveting tools, hammers
Brinelling	Static overload on rolling element bearings

Fig. 3-2—Wear modes and applications where these modes may occur.

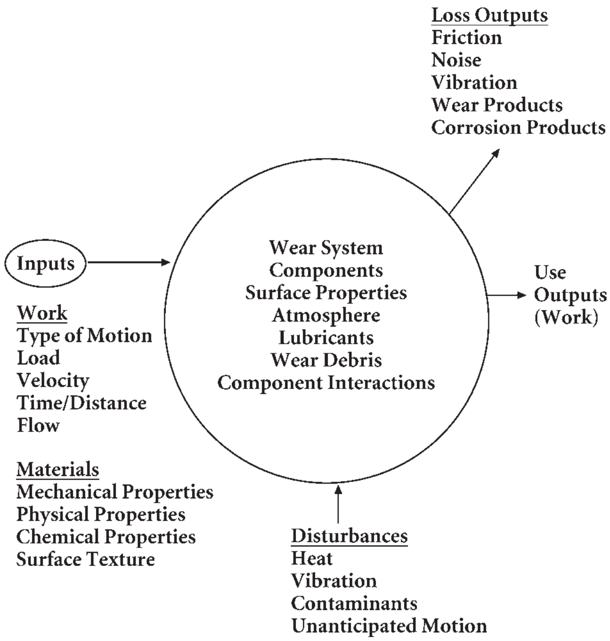


Fig. 3-3—The wear system per Czichos.

This data sheet can serve as a checklist for some types of tests, but it may not be suitable for an erosion test or some of the other forms of wear that involve chemical reactions. The important point is that when a wear test is conducted, the data should include all of the things that can have an effect on the wear system. Far too often in the literature, wear data are reported in such a sketchy manner that it is difficult to believe. Useful wear test data should be accompanied by a description that is detailed enough to allow the reader to understand how the data were obtained.

Elements of a Valid Wear Test

In addition to following the general methodology suggested in the previous discussion, there are some additional guidelines to keep in mind in order to produce meaningful results from a wear test. The following list is proposed:

1. Material documentation
2. Statistical significance
3. Surface conditions
4. Role of time/distance
5. Test environment
6. Wear/friction measurement
7. Reporting system losses

Material Documentation

It is obvious that when metals are tested it is important to document the exact alloy, its heat treatment, its microstructure, and its hardness, but there are subtleties of materials that can affect wear test results that are often ignored: grain orientation, decarburization, manufacturing process (cast vs wrought), segregation, carbide morphology, grinding burn, method of machining, etc. These sorts of things can affect wear test results, and they should be recorded and addressed.

Polymeric materials are particularly sensitive to method of manufacture. An injection-molded material may behave differently than the same material made by another process. Another consideration that exists with testing any polymeric material is surface cleaning. Just about any organic solvent can affect the surface of a polymer by absorption or chemical reaction. The best surface preparation is to have the test materials completely untouched and uncontaminated from the time of manufacture to the time of testing. If this is impractical, a freshly machined test surface will prevent test complications from solvent cleaning. Because plastics absorb moisture, it is also advisable to incubate test samples in the lab atmosphere for 24 hours before testing.

Composites often have a resin-rich surface that may have flatwise properties that are entirely different from that of edgewise samples. It cannot be assumed that ceramic and cermet coatings applied to surfaces with thermal spray and other techniques will have the same properties of the same materials in bulk form. The same thing is true of powdered metals. There is some evidence that suggests that the wear properties of cast alloys are different from the same alloy in wrought form. The point to be made is that in wear testing, minor differences in the composition or treatment of test materials can be an effect on wear test results. The thermal and mechanical processing that the materials experienced in manufacture should be well documented.

Statistical Significance

A dream of many wear researchers is to conduct the number of replicate tests for each material calculated from sample-size statistics. Tests of statistical significance require adequate replicate tests. Unfortunately, most wear tests require rather expensive specimens and rather detailed measurements to assess the wear damage; sometimes even 10 test replicates is more than a project budget can endure. More troublesome than sample cost in achieving statistical significance in a test is the time that it takes to conduct wear tests. Most wear tests take from several hours to hundreds of hours to run. A laboratory test to screen 6 plastics for a particular application would probably take a minimum of 500 hours of test time if 40 replicates were run on just one set of test parameters. Time and cost constraints make it difficult to conduct as many wear tests as one would like, but statistical analysis of data should not be ignored. ASTM E 122 is a standard to help in estimating the right number of test replicates. Factorial design of experiments can be used to decrease the number of tests needed and to determine significant interactions between test variables. One widely used wear test, the ASTM G 65 dry sand/rubber wheel wear test, suggests the use of coefficient of variation to determine if a test is under control from the statistical standpoint.

For example, if the coefficient of variation is over 10% for six or so replicate tests, the G 65 test is out of control. A simple way to determine if there is a statistical difference between test results is the use of error bars corresponding to plus and minus three standard deviations from the mean. If the error bars on a data plot of results between samples do not overlap, one can be reasonably sure that the differences observed are statistically significant (Figure 3-5). There are many other ways to apply statistical significance. Some wear tests are not very repeatable by nature, but the tests that have been standardized

TRIBOSYSTEM DATA SHEET

TEST PURPOSE: ______

TEST DESCRIPTION/METHOD: ______

TEST VARIABLES:

Load	______	Sliding distance	______
Velocity	______	Lubricant	______
Type of motion	______	Contact area	______
Frequency	______	Abrasive size	______
Temperature	______	Stroke amplitude	______
Humidity	______	Stroke frequency	______
Pressure	______	Total test time	______

FRICTION DATA:

μ_s ______ μ_k ______

How measured (interval) ______

TEST MATERIALS:

Material type	Member A	Member B
Geometry	______	______
Dimensions	______	______
Chemistry	______	______
Designation	______	______
Surface finish	______	______
Hardness	______	______
Coatings	______	______
Density	______	______

TEST RESULTS:

	A	B
Mass change	______	______
Wear volume	______	______
Specific wear rate	______	______
Wear coefficient	______	______
Wear ratio	______	______
PV limit	______	______
Wear debris	______	______

Date | Tested by:

Fig. 3-4—Wear data sheet.

by ASTM contain data on repeatability and users can ask ASTM for the interlaboratory test results (research report) that were obtained when the test was under development. This type of data can be used to determine whether test results are reasonable. The newcomer to wear testing should not be discouraged by high coefficients of variation; they may be typical of that wear process, but it is advisable to perform as many replicates as your budget will allow and apply statistics to the data. Three replicate tests is normally the smallest number of tests that statistics can be applied to.

Surface Condition

It was mentioned that surface films need to be dealt with on polymeric materials; confounding films also can be present on metal and other materials that are unlikely to be affected by organic solvents. Test materials can be solvent cleaned, but this does not mean a wipe with a solvent-wetted rag. Such techniques merely dilute surface films and make the layer thinner. The venerable technique for cleaning oils and greases from a surface is vapor degreasing. Hanging the samples over a boiling solvent such as benzene so that only distillation-cleaned solvent touches the sample is an effective cleaning technique. The use of volatile solvents is discouraged in some organizations because of health and environmental concerns. Current cleaning alternatives include everything from cryogenic fluids to laser ablation. The effectiveness of these processes needs to be established before they are accepted as suitable for use on wear test specimens.

Intuitively, surface texture can affect the results of a wear test. Test surfaces should be controlled with as many surface texture parameters as is practical. The minimum surface control should include specification of roughness average, Ra, and lay. Additional surface parameters that may need to be monitored are maximum peak height, the average of the ten highest peaks and the peak count. The ASTM test for solid film lubricants, D 2981, specifies a surface roughness of 16 to 24 microinches RMS for conforming metal surfaces and a test for plastic-to-metal couples specifies a roughness of 4 to 8 RMS on the metal samples and 24 to 30 RMS on the polymer sample. These types of roughnesses are suitable for many other tests.

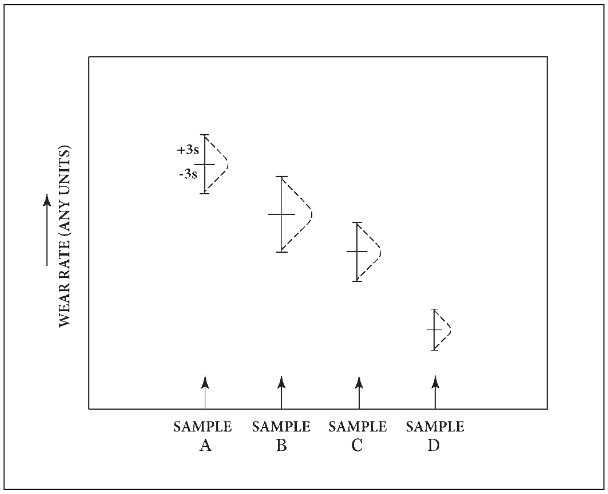


Fig. 3-5—Use of error bars based on ±3 standard deviations as a test of differences.

Unfortunately, surface lay often is ignored in surface specifications, and it should not be. A lathe-cut surface is quite likely to wear differently than a ground surface. Thus, surface lay that is a product of machining techniques should be specified and kept constant for a test.

Role of Time and Distance

Most wear processes are not linear in rate. The ideal test will monitor wear and friction for a sufficient time to ensure that break-in effects are passed and the equilibrium wear rate is monitored. If the goal of a test is a quick screening of several materials, the complete wear spectrum can be monitored on several samples. If an equilibrium wear rate is established after, for example, 1 hour, this time may be used for the larger number of tests.

Test Environment

We mentioned that humidity can affect the results of polymer tests because they absorb moisture and change properties; moisture also can affect wear tests on materials that are immune to moisture absorption. Many tribology studies have shown that the relative humidity in the test environment can have a significant effect on the abrasion resistance of metals as measured by two and three body abrasion tests. Other studies have shown that vacuum can affect wear processes that involve oxidation of surfaces during the wear process. Needless to say, if a wear system under study involves wear under any environment other than room temperature air, then the minimum environment control should be maintenance of temperature and humidity conditions that are similar to the system of interest.

Wear and Friction Measurements

Decisions and conclusions from wear tests are usually based upon measurements of wear and friction. The validity of the test is a function of the precision of test measurements. Measurement of friction and wear damage is probably the hardest part of running a wear test. Usually, wear tests are run for a relatively short period of time compared with the anticipated service life of a wear system. The amount of material removed or the wear damage is likely to be very small in comparison to the mass and size of the test samples. Many modes of wear cannot even be assessed by normal mass loss measurements. Figure 3-6 is a tabulation of the common ways that various forms of wear are measured. Mass loss by weighing samples before and after testing is the most common way to measure wear, but this is easier said than done. If an abrasion test uses an aggressive abrasive and a long test time, reasonable measurement precision can be obtained with an analytical balance, but polishing wear and gouging wear can cause complications. For example, in a gouging test the samples may simply be deformed. There is severe surface damage, but no material removal.

In polishing wear, the abrasive may be submicron in size and running the test long enough to get enough wear to measure reliably on an analytical balance may be impractical. As another example, in measuring the wear of tape heads from magnetic media, some researchers have had to rely on electrical resistivity measurements and sophisticated analytical techniques to detect material removal. Solid particle and slurry erosion tests usually can be assessed by gravimetric mass loss measurements, but droplet and sometimes cavitation damage often must be measured by physical damage assessment. These types of measurements can be difficult to quantify. For example, droplet erosion tests on materials for hypersonic aircraft often show that a material will be "torn to shreds," but the material is still there and no mass loss occurs. Cavitation often produces pitting with material removal that is too small to measure by gravimetric techniques. In this instance, qualitative measures of pitting severity may have to be resorted to.

Fretting damage is another form of wear that is difficult to quantify. Increase of electrical contact resistance can be used to assess damage, but gravimetric methods are difficult to use because the damage is usually pitting and oxidation. Galling measurements are somewhat subjective. The tester must make a decision on when galling in the form of surface excrescences occurs. Some researchers use surface finish changes, but this technique is not agreed upon by everyone who does these types of tests. Surface fatigue is most often applied to rolling element bearings, and surface fatigue tendencies are often rated by life testing the rolling element bearings. The pitting and spalling that occur in this mode of wear are difficult to measure by mass loss techniques. Damage may be severe with hard to detect mass loss.

The techniques listed in Figure 3-6 can serve as a guide to what people are doing to measure wear in various types of wear systems, but the suggestion that applies to all wear tests is, wherever possible, report wear in volume loss per unit time of sliding distance; for example, cubic millimeters per meter of sliding. Report losses for all elements in the test system and whenever possible show a wear versus sliding distance curve.

Many wear test devices provide concurrent measurement of friction force. What does one do with this information? Friction information can be an indicator of important wear events in some wear processes such as galling and the early stages of adhesive wear, but a very important point to keep in mind in measuring friction of sliding couples is that the friction force observed in a system is not necessarily related to the system wear. For example, a wear couple of two grades of cemented carbide shows negligible wear under severe sliding conditions, but extremely high friction ($\mu > 1$). In systems that produce wear debris that is trapped between faying surfaces, the

WEAR MODE	COMMON WEAR MEASURMENT TECHNIQUE
Abrasion	
Low Stress	Mass loss (gravimetric)
High Stress	Mass loss (gravimetric)
Gouging	Mass loss (gravimetric)
Polishing	Volume loss calculated from scar size
Erosion:	
Solid Particle	Mass loss (gravimetric)
Fluid Impingement	Mass loss/physical damage
Cavitation	Mass loss/physical damage
Slurry Erosion	Mass loss (gravimetric)
Adhesion:	
Fretting	Electrical measurements, fatigue resistance, physical damage
Adhesive Wear	Volume loss calculated from scar size
Galling	Physical damage, surface texture change
Oxidative Wear	Volume mass loss calculated from scar size
Suface Fatigue	Physical damage, component life

Fig. 3-6—Common methods for measuring wear.

friction force is not the adhesion tendencies of the mating couple, but rather it is the friction response of the conforming surfaces sliding over a third member, the wear debris.

Friction measurements are most worthwhile where the force required to produce sliding has an effect on system operation. For example, the torque to rotate a large thrust bearing may be 1000 foot-pounds if lubricated bronze versus hard steel is used for the bearing couple. If the roller thrust bearing was used for this application, it may be possible to rotate the same system with a torque of maybe 200 foot-pounds. A smaller drive motor could be used.

Another factor that is important in measuring friction is that the friction measuring system has a spring constant and part of the friction force is simply the force to strain the mechanical components that are used to measure the friction. Static or breakaway friction may simply be inertial effects of the measuring system or the friction couple. Like wear, friction is also a function of time or sliding distance. It may not be constant and the proper presentation of friction data should be a friction profile as test parameters are varied and as sliding distance increases.

Friction force and coefficients of friction can be useful data derived from wear tests, but friction data should be presented with detailed documentation of the test conditions, the measuring system, and the mating materials. More importantly, friction coefficients should not be used as predictors of wear behavior unless extensive testing has shown that this is the case. In most systems, it is not.

Reporting Wear Losses

Wherever possible, wear should be reported as a volume loss. Wear modes such as fretting and galling that may not produce a mass loss require judgment, but the ASTM galling standard, G 98, uses threshold galling stress as the test metric. One of the most important factors to keep in mind in systems that involve conforming solids is to report wear of all members. It is very common to use wear factors to report the wear properties of polymers, but in more cases than not, the wear on the mating surface (usually a metal) is not documented nor is the nature of the mating material. A valid wear test will furnish wear information on all members in the wear system.

A product of many wear modes is wear debris. Ferrography is a technique that allows separation and classification of wear debris from lubricants. Analysis of wear debris can often be an important part of a wear test. Flake-type particles from metal systems are believed by some to be indicators of delamination wear. The presence of metal particles in debris that is mostly oxide can indicate information on the initiation of the wear process. In this case, adhesion between the surfaces may have been a step in the wear process. If the wear debris is identified as a hard oxide, this would suggest that this debris plays a role in system wear by acting as an abrasive. The presence of microchips in wear debris from polishing wear tests has been used to suggest that the mechanism of this wear process is scratching or low stress abrasion. Other wear losses that should be reported (if they seem significant) are: system noise, friction, heating of the system, transfer of surfaces, cracking, the nature of the wear debris, surface discolorations, surface scuffing, and changes in surface texture.

In summary, a valid wear test requires attention to many of the details that we have discussed in this section. Wherever possible, use a standard wear test. If none of the standard tests matches your wear system, survey the literature and find one that appears to be applicable.

Test Selection

In 2007, the the ASTM G02 Committee on Wear and Erosion approved a standard (G 190) on how to select wear tests. It presents additional details on how to simulate an application, techniques used to accelerate wear and erosion, apparatus considerations, specimen preparation, test protocol, damage measurement, documentation, and correlation. This document repeats some of our suggestions to achieve a valid test and provides additional insights into methodology and selection.

The selection of a wear, erosion, or friction test is no different than selecting a mechanical property test to solve a problem. If a lifting device fails in service, chances are the failure investigator will perform a tensile test on what remains of the failed device. This test simulates the action that caused the failure. If a stainless steel vessel stress cracks in service, the investigator will conduct tests to determine if the liquid in the vessel causes stress cracking or did the cracking come from some other source. The failure investigator will simulate the application in the lab. That is the recommendation of this guide. The remaining sections of this guide will discuss the tests that are available for a particular wear mode. If a project includes erosion of guides for a belt conveying abrasive solids in a solution, it is advisable to review available slurry erosion tests and pick one. If a project is limited by seal wear, like an O ring versus a rotating shaft, it may not be possible to find a standard seal wear test, but there are standard wear tests that can be used to rub a rubber specimen on shaft material under process conditions.

The standard tests started this way. Enough people repeated tests in the literature and test rigs were similar enough to allow interlaboratory tests and eventually the development of a standard. The following are some points on test selection not addressed in our methodology discussion.

Procedure

View wear as a system property, not a material property. The group of elements that affect wear behavior should be referred to as the tribosystems of interest.

1. Select a test that simulates your tribosystems and that provides acceptable repeatability of test results.
2. Be thorough in documentation of test results.

Simulation

1. Using exact service conditions is not usually possible because the test may take too long to be practical. Literature searches can be helpful in deciding which parameters can be accelerated.
2. Comparison of the worn surfaces on test specimens with the surfaces of parts worn in service can be an indication if the test is producing the same type of wear as the service conditions. The two wear manifestations should look alike.
3. A decision must be made on the geometry of the mating couple. The options are usually point contact, line contact, or conformal contact. Point contact solves alignment problems; line contact presents alignment problems that can easily be addressed if the test specimens can be realigned after a brief rub until they are aligned. Area conformance is only possible on specimens (like the ends of pins) that are worn into conformance before the wear test starts or by the use of "floating" sample holders that prompt conformance. The point and line contact geometrics are well suited to assessing break-in, but the stress changes throughout the test while stress remains constant on conforming pin specimens and other conforming shapes. Most tribologists opt for the point or line contact option since real life machines do not have rubbing members that are allowed to wear-in before the machine runs. Point or line contact simulates many real-life machines since most machined surfaces contain errors of form that produce mismatches between contacting parts. Hence, point or line contact always exists in real life at start of life.

Test Protocol

1. A standard reference material for a particular test can be tested periodically to see whether a test is in control. This testing is advisable.
2. ASTM tests provide sufficient details and cautions to ensure good repeatability and minimum data scatter.
3. Three replicates are considered to be a minimum, but ASTM publishes guides (ASTM E 122) to assist in calculation of test sample sizes.
4. Many wear mechanisms are nonlinear. Wear volume versus time measurements is the preferred way to rank materials rather than only to observe wear volume at an end point.

Chapter Summary

The picture painted in this chapter is one of attention to detail in performing a valid test as well as in selection of an appropriate test. The selection process essentially involves the same steps used in any major project or capital purchase. The test purpose and objective are established and then the test specification. A list of "musts" and "wants" can then be reviewed and candidate tests can be compared on the number of "musts" and "wants" listed for each candidate.

As an example, a design engineer needs to select a new a plastic plain bearing for a movable machine guard. The present oil-impregnated bronze bushing requires oil and it exudes oil in use. The machine is used in a medical environment and oil use is creating customer complaints. Several different plastics have been suggested as candidates. How does one make sure that the one selected will wear less than the bronze bushing with the oil. It must also have low friction and no stick-slip behavior (noise). The objective is a sanitary hinge with 10-year life and cost similar to the bronze bearing.

Step one in a test selection is defining if it is a wear, friction, erosion, or lubrication problem − selecting a "tribocategory." It is wear. Is it lubricated or not? Not. What is the exact wear mode. Referring to Figure 3-1, the tribosystems fit into the adhesive category, specifically plastic versus metal. Figure 3-1 does not list ASTM test candidates, but subsequent chapters will provide a significant list of candidate tests for most wear modes.

Now it is time to establish a test specification. At this point, it has been established that the test must use unlubricated reciprocating/oscillating wear of plastic versus hard W1 steel (60 HRC) and the plastic/metal couple must have better tribological properties than W1 steel versus oil-impregnated powdered metal bronze. A suggestion on establishing a test specification is to go through a checklist of these features and list musts and wants. Table 3-1 is a strawman checklist with musts for this project checked off.

One item on the "must" list significantly reduces the number of candidate tests; #5, 110° oscillating motion. This means an oscillating rig or a reciprocating rig. Oscillating is the most simulative type of motion using 110° of oscillation. The block-on-ring test configuration can be run in oscillating motion, but there is no standard oscillating test for plastics. The G 133 reciprocating test can rub a 3/8″ diameter hard steel ball on plastic or bronze counterfaces. It also fulfills all of the other musts and wants. Thus, this was the test selected. Three replicates will be tested from four different plastics and system wear will be compared with a hard steel ball (52100 at 60 HRC) versus oil-impregnated bronze flat stock of the same composition as the problem bushing (three replicates).

The suggested approach to test selection is as follows. Establish testing "musts" and "wants" (Table 3-1), put these into a test specification, and then compare the test specification to the features available in different tests (Table 3-2). It is not unlike shopping for an automobile. Select the one that best fits a list of wants.

Important Concepts

The following concepts should be taken from this chapter:

1. Start a study by analyzing a tribosystem of interest for key operating parameters (key issues, type of contact, load, speed, mode of wear, etc.).

TABLE 3-1—Wear/friction test checklist.

	Desired Characteristics	Must	Want
1.	Lubrication		
2.	No lubrication	✓	
3.	Record friction force	✓	
4.	Constant specimen contact		
5.	Test conforms to consensus standard		✓
6.	Low-cost specimens		✓
7.	Quick test <3 h		✓
8.	Controlled environment		
9.	Elevated temperature		
10.	Below room temperature		
11.	Specimen immersed in a fluid		
12.	More than one test per specimen		
13.	Continual recording of wear		
14.	Computer control of test		
15.	Test data available on reference materials		
16.	Organic solvents not required		
17.	Fixed speed and force		
18.	Test does not require special safety precautions		
19.	Setup samples not required		
20.	Test uses mass loss as a test metric		
21.	Test uses profilometry to assess wear		
22.	Wear can be optically measured		
23.	Test can be conducted on the shop floor		
24.	Test requires an operator present for test duration		
25.	Test can be conducted by anybody with minimal training		
26.	Test simulates a specific wear/friction mechanism	✓	
27.	Test assesses conjoint corrosion		
28.	Test consumables readily available		
29.	Test produces continuous indication of friction force	✓	
30.	Test produces wear versus time result (or friction versus time) (or both)		
31.	Test rig is commercially available		
32.	Test must be available in a contract testing firm	✓	
33.	Specimen alignment is not a test concern		
34.	Test provides continuous motion		
35.	Test provides interrupted, oscillating, or reciprocating motion	✓	

TABLE 3-2—Features of some common wear tests.

Test	Features	Concerns
Pin-on-disk	• Continuous motion • Simple test specimens • No specimen alignment problems	• Testing at different disk radii may produce different results • Does not simulate real tribosystems
Reciprocating ball-on-plane	• Reciprocating motion • Multiple tests possible on small specimen • No specimen alignment problems (w/ball)	• Only simulates reciprocating tribosystems • May be frequency limitations (usually <10 Hertz)
Block-on-ring	• Simulates a bushing/shaft tribosystem • Blocks are easy to make • Can test at high forces	• Specimen alignment can be a problem • Rings can be costly from special materials
Crossed-cylinder	• No specimen alignment problems (w/ball) • Fast test	• High contact stress • Noisy • Wear measurement can be difficult
Thrust-washer	• Known contact area • Simulates a thrust bearing	• Wear measurement can be difficult • Test times are very long

2. Tests usually need to accelerate some system factor. Increase those that are likely to increase (anticipated or not) in service.
3. Wear in a bench test must look like wear in the application under study.
4. Test selection requires matching a wear system to a test system.
5. Whenever possible, simulate an application.

Resources for More Information

Sketches of Test Rigs

Benzing, R. J. Goldblatt, I. Hopkins, V. Jamison, W. Mecklingberg, K. and Peterson, M. B., *Friction and Wear Devices*, 2nd Edition, Park Ridge, IL, American Society of Tribologists and Lubrication Engineers, 1976.

Materials for Wear Applications

Rigney, D. A. and Glaeser, W. A., Ed., *Source Book on Wear Control Technology*, Materials Park, OH, ASM International, 1978.

Fundamental Tests

Dawson, D., *History of Tribology*, 2nd Edition, London, Institution of Mechanical Engineers, 1998.

General Testing Information

Bayer, R. G., *Mechanical Wear Fundamentals and Testing*, 2nd Edition, Boca Raton, FL, Taylor and Francis, 2004.

Ruff, A. W. and Bayer, R. G., Ed., *Tribology: Wear Test Selection for Design and Application*, STP 1199, ASTM International, W. Conshohocken, PA,1993.

Neale, M. J. and Gee, M., *Guide to Wear Problems and Testing for Industry*, New York, Wiley, 2000.

Czichos, H., *Tribology, a Systems Approach to the Sciences of Friction, Lubrication and Wear*, Amsterdam, Elsevier, 1978.

A Catalog of Friction and Wear Devices, Park Ridge, IL, American Society of Tribologists and Lubrication Engineers, 1973.

Hasemoto, K., *Studies on the Abrasive and Erosive Wear of Materials in Japan*, Nagoya, Sintokogyo, 1983.

Blau, P. J., Ed., *A Compilation of International Standards for Friction and Wear Testing of Materials, VAMAS Report No. 14*, Oak Ridge, TN, Oak Ridge National Laboratory, 1993.

Bayer, R. G., Ed., *Selection on Use of Wear Tests for Materials*, STP 615, ASTM International, W. Conshohocken, PA, 1977.

Yust, C. S. and Bayer, R. G., Eds., *Selection and Use of Wear Test Systems for Ceramics*, STP 1010, ASTM International, W. Conshohocken, PA, 1991.

Bayer, R. G., Ed., *Selection and Use of Wear Tests for Coatings*, STP 769, ASTM International, W. Conshohocken, PA, 1982.

Bayer, R. G., Ed., *Effects of Mechanical Stiffness and Vibration of Wear Test Devices*, STP 1278, ASTM International, W. Conshohocken, PA, 1996.

Related ASTM Standards

C 808 - Guideline for Reporting Friction and Wear Test Results of Manufactured Carbon and Graphite Bearing and Seal Materials *(This standard is a tabulation of the material property and test parameters that should be considered in performing friction and wear tests.)*

D 2981 - Test Method for Wear Life of Solid Film Lubricant in Oscillating Motion *(This is a test of a stationary block in line contact with a coated oscillating ring. The arc is 90°; the speed is 87.5 cycles/min; the force is 630 lb. The test is terminated when the COF exceeds 0.1).*

E 122 - Practice for Calculating Sample Size to Estimate, with a Specified Tolerable Error, the Average for a Characteristic Lot or Process *(This standard presents the details on how to calculate the number of samples required to have statistical significance in results from a friction or wear test.)*

G 65 - Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus *(There are five procedures using different forces and durations; in the test a flat test specimen is forced against a rotating (200 rpm, 9" dia) rubber-tired wheel and 50/70 mesh test sand is metered into the rubbing interface; test force can vary from 45 to 130 N, lineal abrasion varies from 71.8 to 4309 feet, wear volume on the specimen is the test metric.)*

G 98 - Test Method for Galling Resistance of Materials *(The end of a half-inch diameter pin is rotated 360 degrees on a flat block with increasing load until galling occurs.)*

G 115 - Guide for Measuring and Reporting Friction Coefficients *(A methodology is described for conducting friction tests and interpreting the data; schematics are presented on many ASTM friction testing standards.)*

G 118 - Guide for Recommended Format of Wear Test Data Suitable for Databases *(This guide recommends necessary fields for keeping friction and wear test results in a computerized database.)*

G 190 - Guide for Developing and Selecting Wear Tests *(This guide presents important factors to consider when designing a wear testing program.)*

4

Abrasive Wear Testing

Introduction

ABRASION TAKES PLACE ON CRUSHER JAWS WHEN rocks are crushed to make pea-size stones for pavement. This type of abrasion is termed gouging abrasion because handling big rocks gouges truck bodies and all of the equipment that is used to mine and process the rock to a finished product. However, once big rocks are converted to neat pea-size stones, they produce low-stress abrasion when they are conveyed or slide down chutes. If the same stone were milled to a one-micrometer powder, it might produce polishing wear on the comminution equipment. The mechanism of gouging abrasion is macroscopic plastic deformation of surfaces coupled with high-stress scratching abrasion. The pushing of the rock against and across the working surfaces is sufficient to cause the rock to crush; thus, it is high-stress abrasion. When the pea stone is sliding on a metal or plastic chute, it produces low-stress or scratching abrasion because the stone's sharp edges produce scratches on the contacting surfaces. Finally, the scratches are no longer macroscopic when one-millimeter stone particles rub on surfaces. It removes material probably by a mechanism of microscopic scratches and adhesive transfer of material from the rubbed surface to the harder rock. For these reasons, there are basically four categories of abrasion tests, and one should be selected to simulate a particular application.

The purpose of this chapter is to describe ASTM tests and others that are commonly reported in tribology literature. Some opinions on applicability and precautions in use also will be presented. The objective of this chapter is an understanding of the differences between the tests and how to apply them to problems. This chapter will cover the major categories of abrasive wear: gouging, low stress, high stress, and polishing.

Gouging Abrasion

The ASTM G 81 gouging abrasion test was developed by a task group with strong earth-moving/mining interests. They wanted a test that would enable them to screen materials for applications such as power shovel buckets, off-road dump truck bodies, and rock comminution equipment. The test rig is a commercially available laboratory jaw crusher. The crushers are not large, maybe two feet by two feet by four feet, but each test requires crushing two tons of mineral rock from football size to pea size with plates covered with test samples (Figure 4-1).

Wear is assessed by mass loss on the test plates. Each jaw contains a test plate, and a reference plate and wear of the test material is compared with the reference material to produce a wear factor. The wear factor is the test metric of the candidate. Numerically, this number indicates whether the candidate material was not as, or more, wear resistant than the reference.

Test samples have nominal dimensions of one-half inch by four inches by four inches and they are usually bulk materials, but coatings could be applied. The ASTM standard uses a T1 steel reference material with a hardness of about 300 HB. A typical tester is shown in Figure 4-2. An obvious precaution in using this test is that different rocks will produce different results. The use of reference material can normalize this. If a supplier of digging equipment wants to use this test to compare abrasion-resistant materials for an excavator bucket, it may be well to test with morainial gravel, as well as quartz-like or magma rock.

This test is the only ASTM abrasion test that involves the huge forces required to crush rocks. It is the most appropriate test for evaluation of materials for truck bodies and hoppers that receive quarried rocks, or for coal crushers, or for all mills, or any type of machine that may contact football and larger size rocks with sufficient force to crush them. The primary impacts of corners of rocks create the "gouging" component of the damage and the crushed rock may produce high or low stress abrasion. Thus, this is a conjoint mechanism for material removal, scratching abrasion from rock fragments, and fracture from overlapping gouges. Normally, this test is not used on very hard material (>480 HB). It may not be appropriate for pneumatic drills and tools used to deconstruct masonry structures (jackhammer, drills, etc.). Figure 4-3 illustrates an application where gouging is the primary mode of material removed.

Low-Stress Abrasion

ASTM G 65

The ASTM G 65 dry-sand, rubber, wheel abrasion test is probably the most widely used abrasion test. As shown in Figure 4-4, the concept of the test is to rub relatively coarse sand (50 to 70 mesh) against the test material using a rubber wheel. It produces scratching abrasion. The edges of the sand dig into the test surface and produce furrows in the surface, and chips of material are removed from the scratch furrows. The force of the specimen against the wheel is 200 N. Mass loss of the test specimen converted to a wear volume is the test metric. Figure 4-5 is a photo of a commercial tester which can also perform the ASTM G 105 wet-sand abrasion test that will be discussed in the chapter on erosion testing. Figure 4-6 shows a set of typical wear scars.

This test simulates digging in sandy soil, hard particles sliding on surfaces, conveying abrasive substances in particulate forms. This is the test to use for an application where it is unlikely that the abrasive substance will be pushed against a surface with sufficient force to crush the abrasive. Glass fibers in a filled plastic can scratch a contacting counterface, but the abrasive (the glass fibers) will not be crushed. They are bedded in plastic with a low modulus of elasticity (>1 ksi). However, they can produce low-stress abrasion.

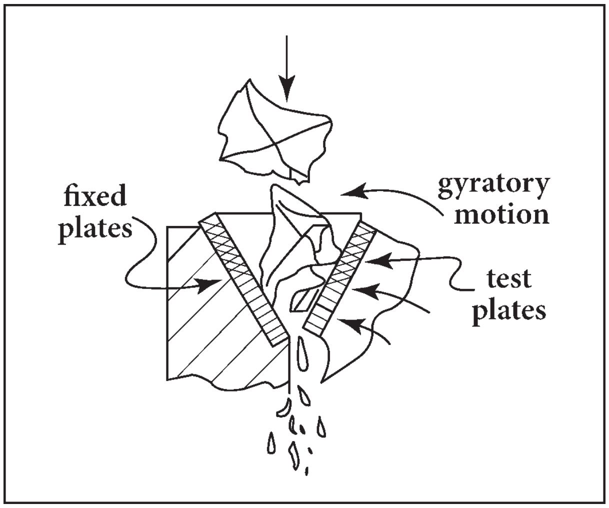


Fig. 4-1—Schematic of gouging abrasion test.

Fig. 4-3—Application that may require gouging resistance.

Some concerns in using this test are:

- Obtaining the proper sand flow rate;
- The change of wheel hardness and diameter over time;
- That the test specimen can be harder than the test sand; and
- Refinishing of the rubber wheel is periodically needed

Getting the proper sand flow rate every time was one of the most troublesome factors in the development of this test. In fact, for interlaboratory tests, all sand nozzles were made by the same shop at the same time. The nozzle must conform to the standard and the sand flow rate should be frequently monitored. Early tests with dry-sand rigs indicated that wheel hardness was a significant variable. As wheels age, they get harder and may not conform to the standard; they should not be used. Similarly, only the specified rubber (chlorobutyl) should be used. Other rubbers will yield different results.

Some test specimens such as cemented carbides are hardly scratched by 50 to 70 mesh sand using the prescribed test load, sand flow, rubber wheel, and test duration. This is a limiting factor and the reason for the development of the loop abrasion test, which will be described later. The test sand has a hardness of about 700 kg/mm^2 and many wear-resistant materials are harder than this. In addition, the test loads can be too high for many coatings, and the mass loss measurement is not accurate enough to reliably detect mass losses resulting from removal of two-micrometers-thick coatings. The loop abrasion test may be considered in this case as well. Finally, the rubber wheel wears during testing and this must be

Fig. 4-2—Gouging tester.

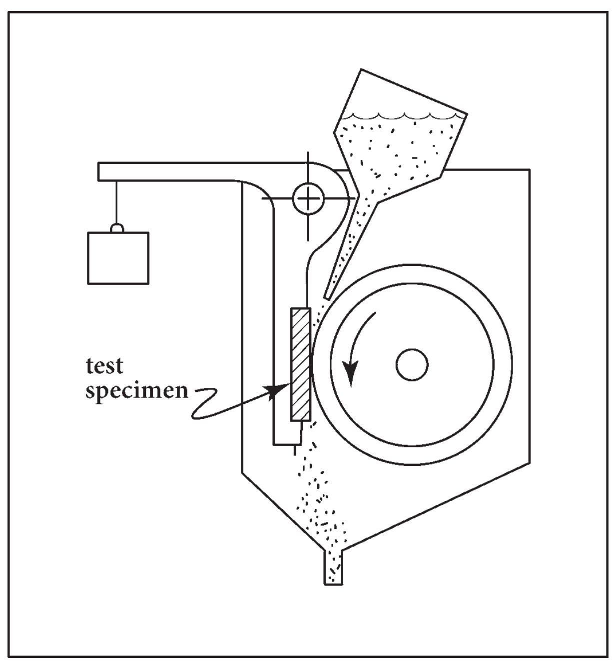


Fig. 4-4—Schematic of dry-sand rubber wheel test.

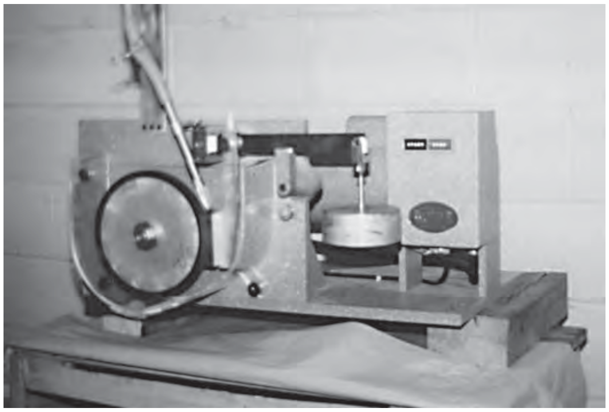


Fig. 4-5—Dry sand test rig.

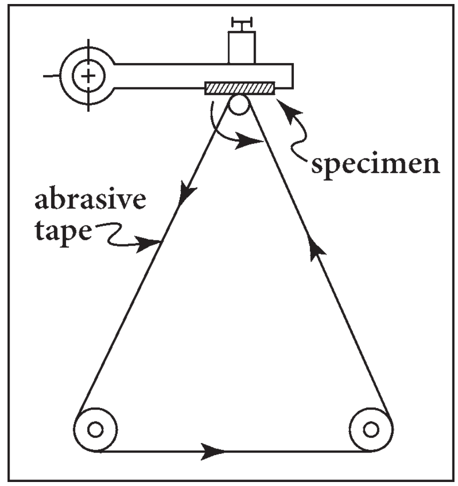


Fig. 4-7—Schematic of ASTM G 174 loop abrasion test.

accommodated by normalizing the diameter of the wheel at the time of testing to the new-wheel diameter of nine inches. It is also important for the wheel to have a perfectly uniform surface. If there is nonuniform wear or rubber damage, the wheel must be resurfaced. The standard presents details on how to do this, but it is not a trivial matter to get a perfect surface on rubber by turning it on a lathe.

ASTM G 174

The ASTM G 174 loop abrasion test addresses some of the concerns of the dry-sand test. This test, illustrated in Figure 4-7, abrades a flat sample with aluminum oxide finishing tape, and test options have been developed for screening very hard materials and coatings such as cemented carbide bulk materials and thin hard coatings like titanium nitride. Wear is calculated from scar width and these measurements work on micrometer-level coatings. Different abrasives can be used and G 174 test options include two abrasive sizes; 30 μm and 3 μm. The latter is used for thin coatings. A typical tester is shown in Figures 4-8 and 4-9; a typical wear scar is shown in Figure 4-10.

A precaution in using this test is not to allow slippage of the abrasive loop on the drive spindle. The standard specifies a test time and if the loop slips on the drive spindle (because of insufficient belt tension) the test specimen may receive less than the specified 897 m of abrasion in the 1-hour test time. This potential issue is solved by counting the loop passes with a photocell. This ensures proper loop speed and total abrasion distance. This test has replaced the G 65 test for low-stress scratching abrasion in some laboratories, and it provides a repeatable scratching abrasion test for hard metals and coatings that are difficult to evaluate on the G 65 test. The G 65 test produces higher rates (up to 33×), but material ranking correlates (Figure 4-11).

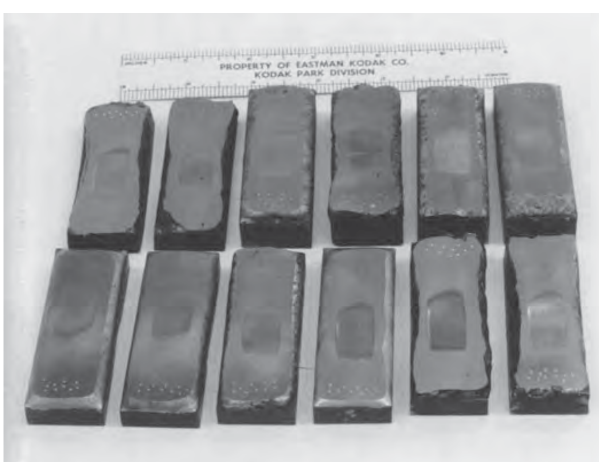


Fig. 4-6—ASTM G 65 test specimen.

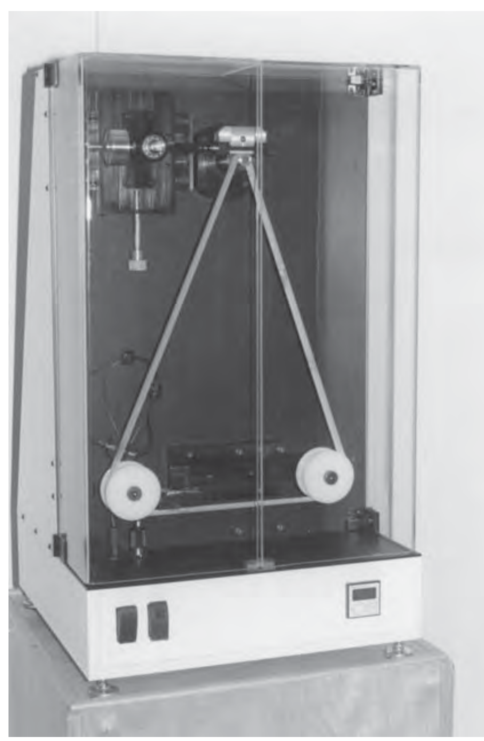


Fig. 4-8—Loop abrasion tester.

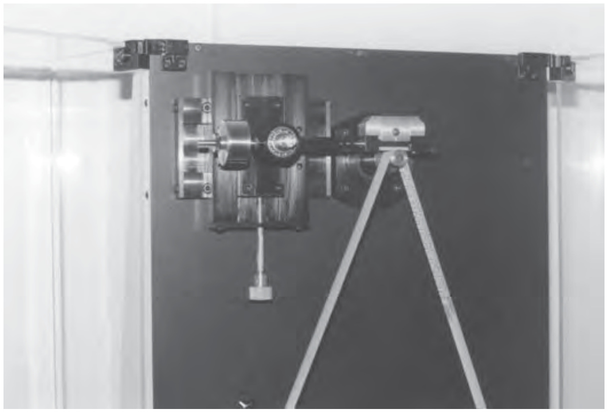


Fig. 4-9—Loop abrasion specimen loading system.

ASTM G 132

The G 132 drum abrasion test is like the G 174 test in that the test material is rubbed against a fixed abrasive medium (sandpaper). However, this standard uses garnet rather than aluminum oxide or sand as the abrasive. This was done because it was felt that garnet with a hardness of about 800 kg/mm^2 is more indicative of mineral hardnesses encountered in mineral benefication and mining. The test specimen is a one-quarter-inch-diameter pin that rubs on end on a large rotating drum (12-inch diameter × 40-inch face) that is covered with 200 grit garnet abrasive paper. The test pin follows a spiral path down the drum such that it always encounters fresh abrasive. A reference specimen is tested on the path between the first spiral, and wear is expressed as a wear factor based upon the mass lost of the test material to the reference material (1080 steel; 250 HB). The pin is rotated as it spirals down the abrasive drum and it is also conditioned to mate the drum before testing. The test rig is shown schematically in Figure 4-12.

This test was designed for bulk materials, and the required pin configuration for the test specimen and its run-in precludes its use on many coatings and makes it difficult for some hardfacings. The use of garnet as the test abrasive makes the screening of hard metals and ceramics less applicable. On the plus side, this test uses fresh abrasive at all times.

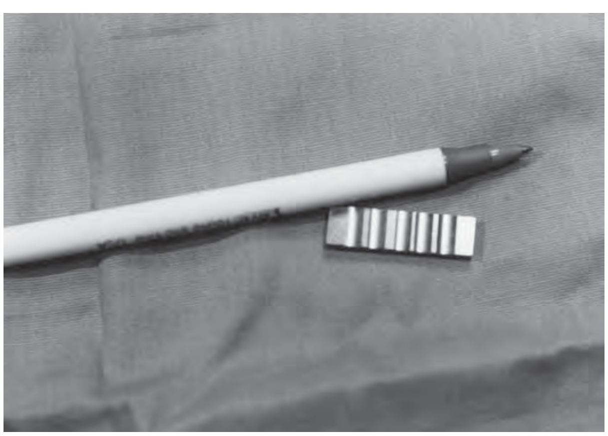


Fig. 4-10—Multiple scars on a G 174 test specimen.

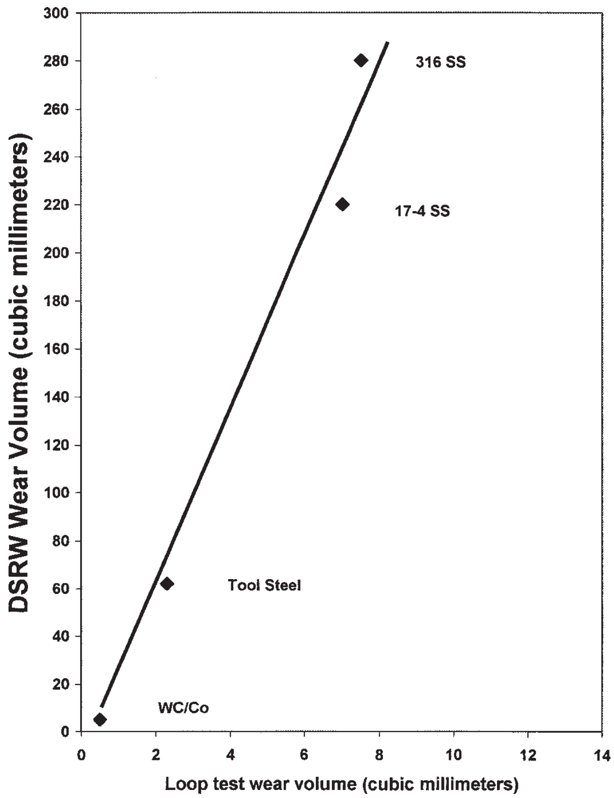


Fig. 4-11—Correlation of abrasion results (wear volume) between the ASTM G 65 dry-sand/rubber wheel abrasion test and the ASTM G 174 loop abrasion test (Adapted from: Ives, L.K. Budinski, K.G., Measuring Abrasion Resistance with a Fixed Abrasive Loop, Wear of Materials VII, Amsterdam: Elsevier, 1998.).

The G 174 test requires multiple passes on abrasive which was a concern to some in the standardization of the test.

ASTM G 171

Low-stress abrasion is characterized by scratching of a surface by hard particles or protuberances. The G 171 scratch test can be used to assess scratch resistance as it applies to scratching abrasion. Sometimes it is difficult to get samples of a coating

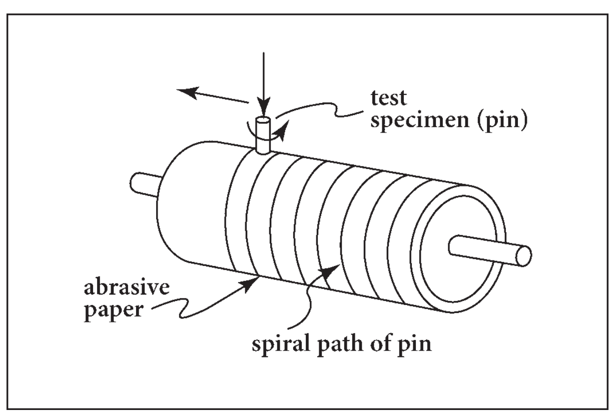


Fig. 4-12—Schematic of the ASTM G 132 abrasion test.

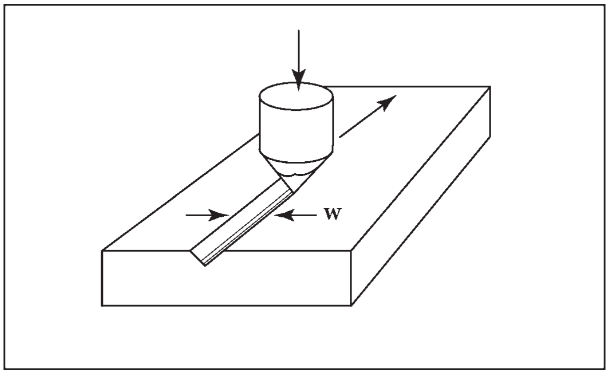


Fig. 4-13—Schematic of the ASTM G 171 scratch test.

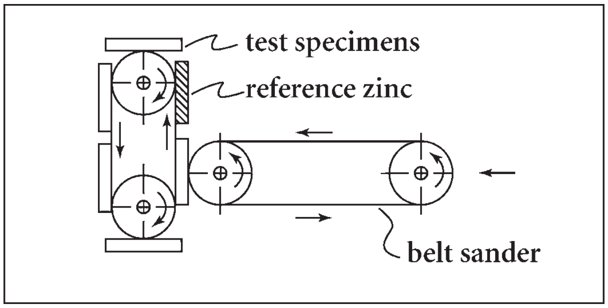


Fig. 4-15—Schematic of plastic abrasion test.

or material in a shape conducive to one of the previous low-stress abrasion tests. A single point scratch test can sometimes serve as a predictor of low-stress abrasion resistance. The G 171 test employs a Rockwell C type diamond indenter as the scratching stylus, and it is loaded and dragged across a test surface to produce a 10-mm-long scratch. The scratch width is measured and the scratch load divided by the scratch area (based upon scratch width) yields a scratch hardness with units of kilograms per square millimeter. The test standard gives specifics on the loading, speed, and scratch measurement. Figure 4-13 is a test schematic. Figure 4-14 shows a typical scratch.

Scratch testing often is used on paints and plastics that may be difficult to test with the other low-stress abrasion tests. Sometimes it is necessary on surfaces that are too hard to test with aluminum oxide or silicon carbide which are usually the hardest abradants that are readily available. A precaution in using scratch testing is ensuring freedom from contaminants on the diamond and test counterface. It can sometimes be difficult to measure scratch width because of the deformed materials that make up the sidewalls of the scratch. The ASTM standard presents guidelines on scar measurements.

ASTM D 1242

This standard has been withdrawn, but it was a two-body abrasion test for plastics that essentially uses a belt sander to abrade plastic test specimens and their wear (mass loss) is compared with a zinc reference. This test, which is illustrated in Figure 4-15, can be used to compare a number of different materials in the same test. The abrasive is 60 grit silicon carbide and samples are subjected to 72 passes against the abrasive belt. The dry-sand rubber wheel and the loop abrasion test have been used on plastics with modified procedures. However, abrasion resistance data on plastics is not readily available. The G 65 test with reduced load and test time produced abrasion resistance rankings that correlate with field testing. In addition, the G 174 test has been used. Like the old plastic test, it is a two-body abrasion by abrasive media. The standard procedure for metals may be too aggressive for many plastics. The standard specimen is only 3 mm thick and may wear through. Test option C with only 20 (rather than 80) loop passes has been successfully used to screen plastics for abrasion resistance.

ASTM D 4060 (Taber)

A device known as the Taber Abraser (Figure 4-16) has been used for several decades to study the scratching abrasion resistance of floor coverings. Some laboratories also use it on plastics, rubbers, paper, and other nonmetallic materials. Sometimes it is used on metallic electroplated coatings and thermal spray coatings (F 1978). This test uses a four-inch by four-inch test specimen, for a prescribed time, and under a prescribed load (Figure 4-17). The test metric is mass change on the specimen. Sometimes, percent haze in the rubbed area is the test metric on transparent plastics. Different types of abrasive wheels are available and, of course, you must use the same abrasive wheel for a test series. The tester is also available with an abrasive particle feeder that distributes abrasive particles in front of a rubber wheel which rubs them on the surface. "Rubbed particles" are vacuumed from the test

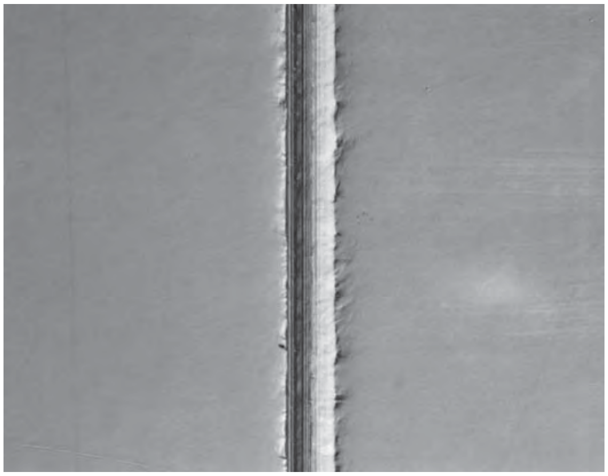


Fig. 4-14—Typical scratch.

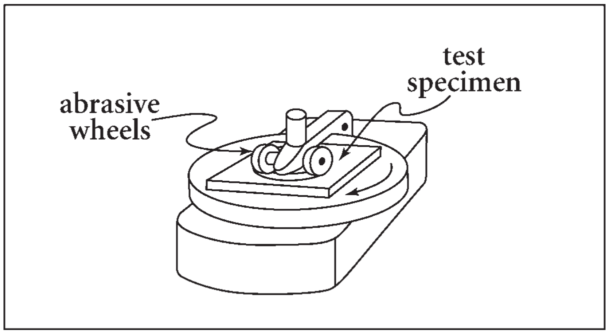


Fig. 4-16—Schematic of the Taber Abrader.

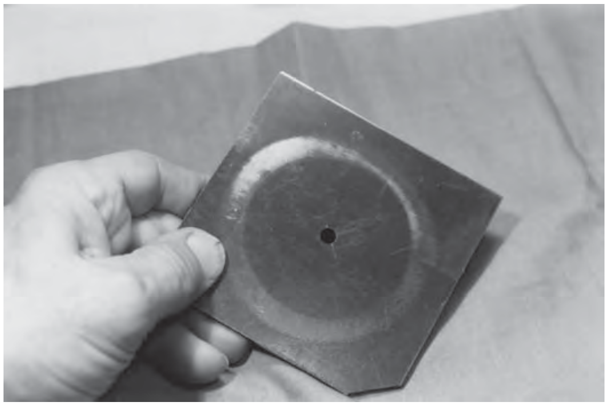


Fig. 4-17—Taber test specimen (after testing).

surface. Another modification is a reciprocating tester using the Taber wheels in a form that looks like a pencil eraser. This test was not standardized at the time of writing this guide, but it is intended for use on nonuniform shapes that cannot easily be made into normal four-inch by four-inch coupons.

The Taber tester does two-body (rubber + abrasive vs sample) and three-body abrasion (loose abrasive vs sample is performed in ASTM F 510 with an ancillary grit feeder). Users need to decide which system simulates the tribosystems in which they are interested. A significant consideration in using the Taber test is measuring small mass changes on relatively large test specimens when the test is used for platings and hard materials. Floor tiles will lose significant mass during the test, but chromium-plated steel will not. Thus, this is a concern in using this test on anything other than the flooring materials and polymer coatings for which it was intended. Profilometry sometimes can be used to measure shallow wear scars. The G 65 dry-sand/rubber wheel test is more widely used for three-body abrasion studies on materials and the G 132 and 174 tests are more widely used on two-body abrasion tests for metals. The Taber test is widely used on coatings and films. Sometimes the relatively large specimen size can be a consideration in its use.

Nonstandard Tests

Figure 4-18 shows the spectrum of low-stress abrasion tests that are reported in the literature. Of course, there are literally hundreds of tests, but they seem to fit into these categories. The right one to use is the one that best simulates your tribosystem. All of the types in Figure 4-18 have been discussed except the loose particle tests. Test specimens are simply rubbed against particles by submerging the test specimens in the loose particles. It is a two-body test without significant

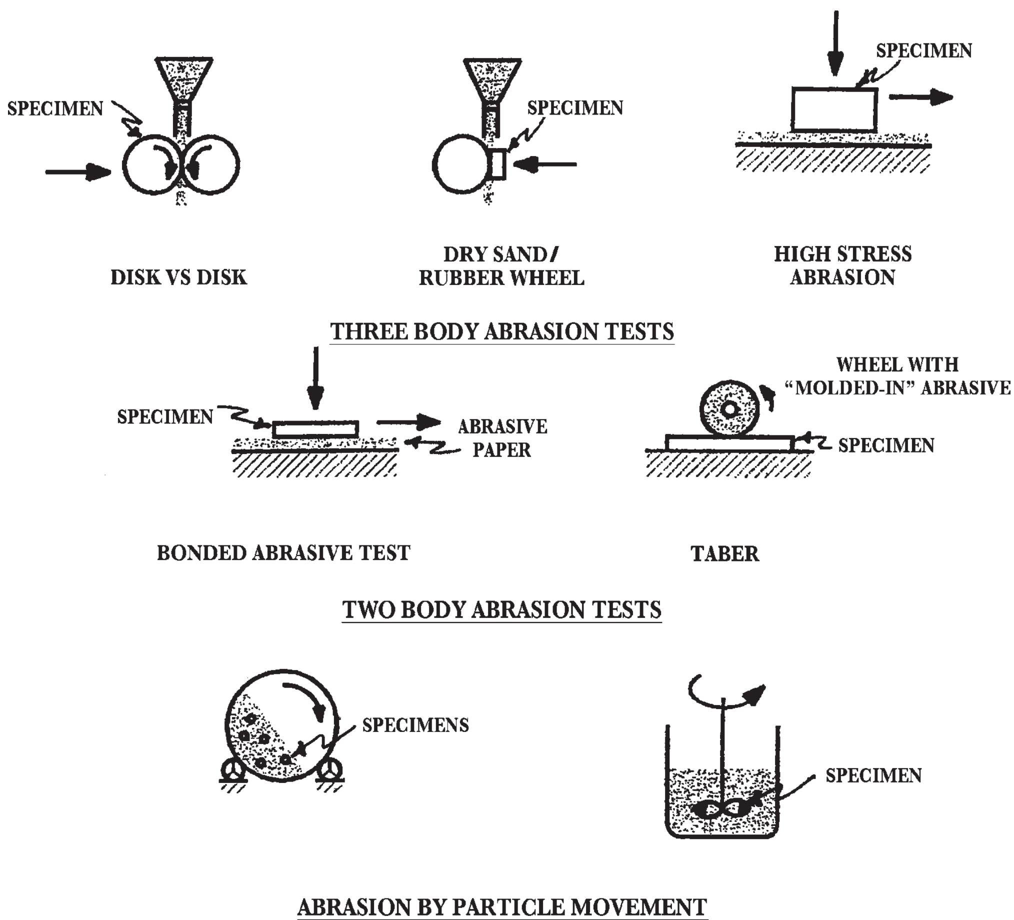


Fig. 4-18—Common abrasion tests.

normal force pressing the particles against the test material. An example is rotating a propeller with test coupons attached to the blades, and the propeller is immersed in a container of sand or sludge, etc. These kinds of tests are usually used to assess the abrasion resistance of materials against media that are so different from abrasives in standard tests that they must be used. For example, this type of test has been used to assess the abrasivity of dried sewage sludge. The sludge was a fluffy, lightweight "dirt." It was abrasive, but these kinds of tests are usually slow and often they produce polishing abrasion rather than scratching abrasion.

Summary

Low-stress abrasion is probably the most prevalent form of abrasive wear, and we have no shortage of tests to rank materials for their resistance to this form of abrasion. Each test has its application niche. The types of materials to be evaluated often have a significant effect on which test to use. For example, the G 65, G 132, and G 174 tests are well suited for bulk materials. G 174 may be the test of choice for hard metals, hard coatings, and ceramics, whereas the Taber test is best for flooring and paints. The best test for plastics is still a controversy, but the Taber Abraser is popular. ASTM G 65 works very well on fusion hardfacings, whereas G 174 may work better on thermal spray coatings. The G 132 test is probably preferred for materials that see use in tillage and mining. The scratch test works on most materials, but correlation to field results may need to be done for each case. It is advisable to avoid particle movement tests unless there is no alternative. They often take too long to screen a group of candidate materials.

High-Stress Abrasion

The upper left schematic in Figure 4-18 could depict a high-stress abrasion test if the mating rollers were steel and if they were pressed together with sufficient force to crush the abrasive dropped between the rolls. The classic three-body high-stress abrasion test is illustrated in Figure 4-19.

A test sled specimen is rubbed on a copper annulus submerged in abrasive particles. The load on the specimen is sufficient to cause crushing and embedding of the abrasive in the copper lap. Mass loss on the sled is the test metric. The abrasive can be any particle of interest. It is the copper counterface and metal test specimens that make this a high-stress test. If

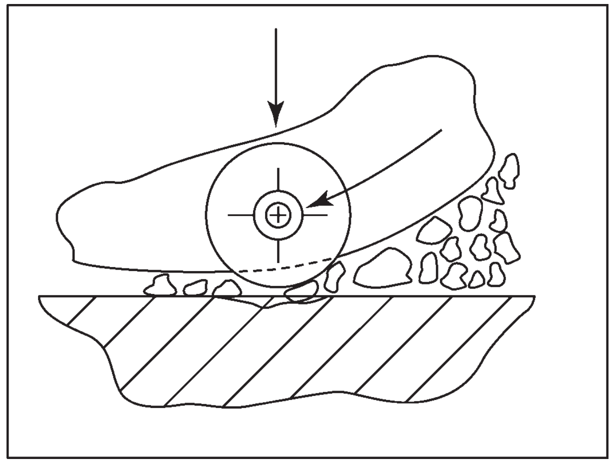


Fig. 4-20—Schematic of another type of high-stress abrasion test.

the lap were rubber, it would probably produce low-stress abrasion. This is not an ASTM standard test, but there are simpler tests that could easily be made a testing standard. Figure 4-20 is a schematic of a test that used the copper lap principle, but is faster and easier to use. Copper washers affixed to a rotating wheel "drive" the abrasive particles into the test coupon (Figure 4-21). A scar is produced that can be measured by profilometry to yield material removal. The test takes only thirty minutes and can be used on a wide variety of counterface shapes.

ASTM B 611 is a wet high-stress abrasion test. It is like the G 65 in configuration, but the abrading wheel is steel; the abrasive is 30 grit aluminum oxide and the test specimen and wheel are immersed in a grit/water slurry. This test will be described in more detail in the erosion chapter.

A coal crusher is a perfect example of high-stress abrasion. Heavy hardfaced steel or other hard-surface rolls rotate on a horizontal platen and large coal chunks are introduced in front of the roll. The coal lumps are crushed to powder as they repeatedly pass through the roll/platen nip. The abrasive medium, the coal, is imposed on the surface with sufficient force that it fractures. These devices are used on power plant boilers that accept fluidized powdered coal as the fuel.

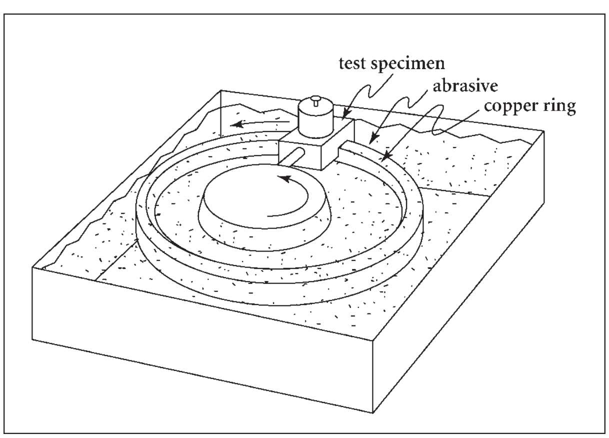


Fig. 4-19—Schematic of high-stress abrasion test.

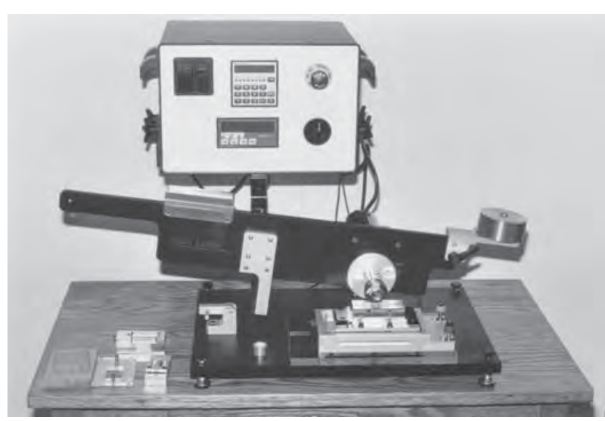


Fig. 4-21—Test rig used for the test illustrated in Figure 4-20.

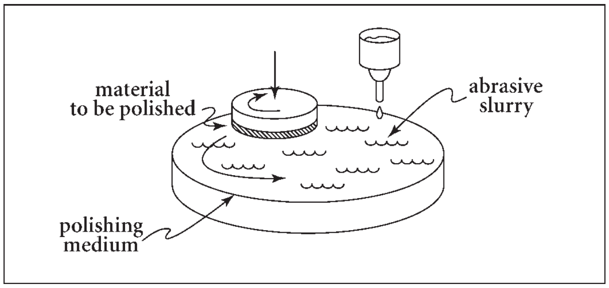


Fig. 4-22—Schematic of chemical mechanical polishing (CMP).

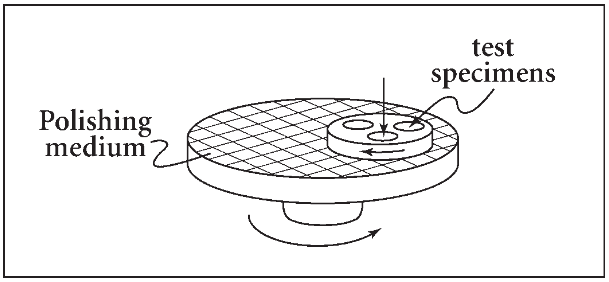


Fig. 4-24—Typical setup for metallographic polishing.

Tests that simulate high-stress abrasion are not plentiful. The reason for limited research and testing in this area is not clear, because this type of abrasion is present in most earth moving, road construction, and digging activities. Power shovels, excavators, and masonry demolition are happening everywhere in the world. In any case, when this type of abrasion is a limiting factor in an application, high-stress abrasion tests like those mentioned can be useful for screening materials to make equipment and tools last longer.

Polishing

This guide's definition of polishing abrasion (Chapter 1) is wear that is characterized by leveling and lowering of surface features without visible scratching, making surfaces shiny. Polishing is not widely studied as a form of abrasive wear, but as chemo-mechanical planarizing (CMP). It is probably the most important wear process on the planet. CMP allows computers to be as we currently know them. Computer "chips" are made on CMP-treated silicon wafers and we all know that these chips are the computer's "engine." Some of these chips have ten or more coatings that are individually applied and "planarized" or made flat and polished to a mirror finish. Of course, the silicon wafer that is the substrate for these coatings must also be planarized. Just the consumables for planarizing is a two-billion-dollar-a-year industry in the United States. Thus, there is a lot of testing in evaluating consumables and CMP processes to make planarizing better and lower cost.

Planarizing machines that are similar in principle are most commonly used for "wear testing" of surfaces and evaluation of the effectiveness of polishing abrasives. They are illustrated in Figure 4-22. CMP material removal rates are determined mostly by measuring changes in chip features (like a cone or angled surface) with time. Wear volumes are calculated from geometry changes. There is no standard ASTM test for CMP in 2006, but a task group has been formed to work on one.

Before CMP, metallographic polishing techniques have been used to study polishing. Most metallographic polishing systems finish with loose abrasive embedded into a cloth or compliant surface (Figure 4-23). Some of the particles rub on the metal surface and this contact removes material. Some researchers [1] believe that material is removed by scratching abrasion and the scratches are too small to be seen with conventional microscopy. Polishing is usually accomplished with abrasive particles that are less than 1 μm diameter. Since only about 10% of a particle's shape digs in three-body abrasion, the scratch depth would be less than 0.1 μm or as small as 0.01 μm for 0.1 μm polishing compound, which is very difficult to detect optically.

The traditional bench test for polishing abrasion is a metallographic polishing station. Most polishers hold multiple specimens in a ring that rotates about an axis offset from the axes of a wheel or platen which contains the polishing medium (Figure 4-24). The polishing medium can be anything that can be applied or embedded on the rotating platen. If the effectiveness of polishing cloths is being assessed, the abrasive size and type will be fixed (for example, 1 μm Al_2O_3) and the specimen wear rate will be the test metric. The polishing time and normal force are held constant. Specimens can be any material. They are usually one inch or one and one-quarter-inch-diameter disks in the United States, and volume loss in a polishing cycle can be determined by mass change or by measuring fiduciary markers. Mass change is difficult to do because the mass loss is likely to be in the range that is difficult to detect with conventional weighing techniques. Vickers or Knoop hardness indents can be used. They can be put on the surface to be polished and periodically checked with optical microscopy for change in apex width.

Polishing abrasion by loose particles can be assessed by putting test specimens on a propeller that is rotated in the abradant of interest (Figure 4-25). These kinds of tests are slow

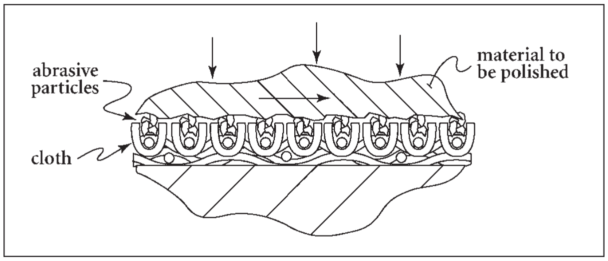


Fig. 4-23—Abrasion (polishing from loose particles embedded in a flexible medium).

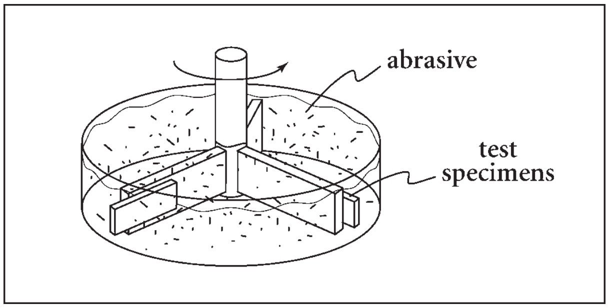


Fig. 4-25—Abrasion by particle motion.

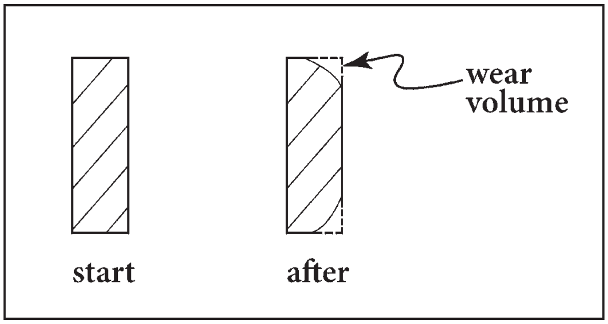


Fig. 4-26—Measuring corner radii to assess wear volume.

and the same problem with measurement of wear volume exists. One technique that works well is to use profilometry of the leading edge of specimens that have a sharp 90° edge profile at the start of the test (Figure 4-26).

In summary, polishing abrasion is more difficult to quantify than many other abrasion processes because of the small volume (mass) of material removed. What makes polishing different from the previous forms of abrasion is that material removal is not conjoint with scratches, plowing, gouges, and other macroscopic manifestations of abrasion damage. Polishing wear produces mirror-like surfaces in most materials. Sometimes, measuring this type of material removal requires some "laboratory ingenuity."

The mechanism of material removal is still subject to debate, but there is significant evidence for help from chemical effects in many planarizing operations. In the absence of any possible chemical effects, polishing wear probably is produced by adhesive bonding of minute particles or even atoms of the abraded material on the abrasive material. Scratching is also possible, but the abrasion and removal of chemical reaction products is probably the most commonly accepted removal mechanism. As of this writing, there was no ASTM, CMP, or ordinary polishing wear test standard. It is recommended that that metallographic or CMP equipment be used for testing until test standards are in place.

Product Abrasivity

A company manufactures magnetic media-recording tape. The product is deemed too abrasive by customers; it could wear out expensive tape recording heads. How do you determine whether your product is more or less abrasive than the competition's? How abrasive is your company's product? These questions arise with countless products, especially products that are conveyed as webs through manufacturing operations. Conveying webs means guiding and steering the web and wherever there is contact, there could be lots of rubbing. For example, steel mills convey sheets and strips at speeds of hundreds of feet per minute. Any place where relative slip occurs is a potential place for abrasive wear and sometimes adhesive wear. Product abrasivity is the subject of this discussion.

Some of the tests that are used will be described and recommendations will be made on measuring abrasivity. Some industrial examples in which abrasivity is a factor are shown in Table 4-1.

There are many more, but the idea is that many products contain materials that may be abrasive to surfaces that they have to contact in manufacture or in use. How do you assess relative abrasivity?

TABLE 4-1—Industrial examples in which abrasivity is a factor.

Product	Concern
Paper products	Wear of rollers and guides
Photographic film	Wear of rollers, guides, and cameras
Sheet and strip metals	Wear of rollers, guides, tools
Magnetic media	Wear of manufacturing equipment and wear interfaces (heads, guides etc.)
Thread/yarn/fabrics	Wear of conveying equipment
Printer ribbons	Wear of type characters
Wood products	Wear of tools
Filled plastics/composites	Wear of tools

Standard Tests

Of the preceding list, two are covered by current ASTM Standards: Printer ribbons and yarn. The printer ribbon test was designed to simulate wear of character hammers hitting the ribbon many times. The characters wear and require replacement. The ribbons on these devices are fabric impregnated with ink. The inks or fabrics can contain fine particulates that could be abrasive. The test uses a ball rubbing against a four-foot-diameter drum covered with the ribbon material (Figures 4-27 and 4-28). The ball is fixed in a holder that traverses over the width of the drum as it rotates and ball wear is the test metric. The more ball wear, the more abrasive the ribbon. If the ribbon is kept constant, different materials (as hemispherical riders) can be assessed. This test has the designation of ASTM G 56. The yarn test (D 3108) rubs the yarn against a stationary pin at relatively high speeds and the friction is measured (Figure 4-29). The friction coefficient is the test metric, but the volume wear on the pin can be used as a measure of the abrasivity of the yarn.

Magnetic Media

Magnetic tapes use iron oxide as the material that is magnetized. There are two types of iron oxide: hematite and magnetite. It is the latter that is used in magnetic tapes. It has a hardness of about 1000 HV which makes it abrasive to most metals. When iron oxide rubs on tape heads and other surfaces, it tends to form a "varnish" on the substrate that diminishes magnetic response; so to make abrasivity worse, most

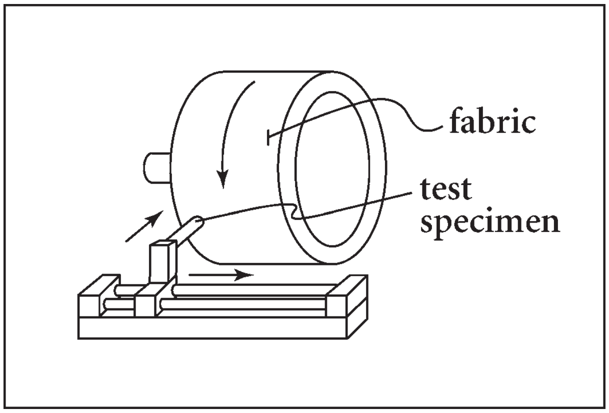


Fig. 4-27—Schematic of the G 56 ribbon wear test.

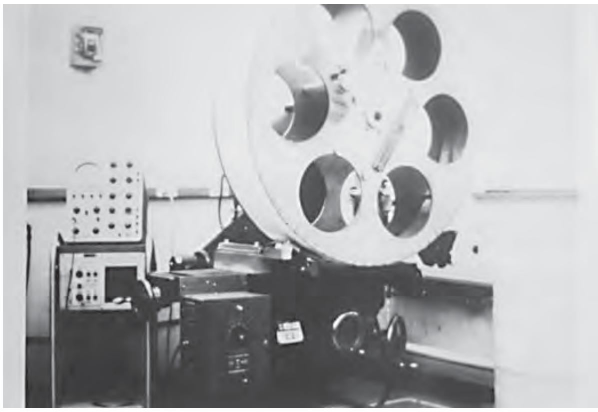


Fig. 4-28—ASTM G 56 test rig.

magnetic tape manufactures also add some aluminum oxide particles to the magnetic coating to perform the task of head cleaning (abrasion). Of course, if too much aluminum oxide is added, the tape can become destructive to most surfaces it contacts. Abrasivity of magnetic media is usually assessed by running a reel-to-reel tape drive with a "wear station" in between the reels (Figure 4-30). A ball or hemispherical rider of the material of interest is pressed against the moving tape and there is an anvil to back the tape up in the area of contact. Pin-on-disk types of test rigs have also been used to do product abrasivity assessments.

Photographic Paper/Film, Plastics, Paints

Silica overcoats commonly are used to strengthen emulsions on photographic film. Abrasivity of these films is a concern. They wear out tooling used to slit, chop, and perforate. The abrasivity of various formulations has been assessed by a pin-on-product test that reciprocates a hemispherical rider on a slowly rotating flat platen (Figure 4-31).

The slow rotation of the platen increases the time to wear through surface coatings. In fact, the test usually is conducted such that the coating does not wear through. In this instance, the test metric is the volume of material worn from the rider. This test also can be used to assess durability of surface coatings by recording the time to failure of coatings using cemented carbide or other pin rider which experiences negligible wear. This test also is used to assess abrasivity of papers and packaging materials; it has even been used on sheet metals, wood products, and filled plastics. It can be run such that

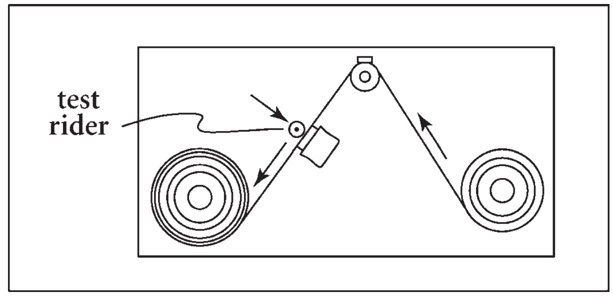


Fig. 4-30—Schematic of magnetic tape abrasivity testing.

the rider always "sees" fresh surface or for longer periods of time that may involve sliding of the rider on previously tracked surface. The advantage of this test over reel-to-reel tests and other tests that provide virgin surface for rolling is the amount of test material needed. For example, in a magnetic medium, reel-to-reel testing may require 1000 feet of product to produce measurable rider wear. Of course, more than one replicate of each material will be needed. Thus, at least 3000 feet of tape are needed for each material tested. The rotating/reciprocating abrasivity test only needs an eight-inch by eight-inch square of material for each test.

This test has not been standardized, but it has been used for more than 20 years in photographic films and papers. Its results correlate with production tooling observation. If the combo-tester (combination of reciprocating and rubbing motion) shows a material to be abrasive, it will show up in production tool wear.

Ball Cratering Test

The last test to be described in this chapter on abrasion, the ball-cratering test, rightly belongs in the chapter on erosion because it uses a particle-laden slurry to produce specimen damage. It could have a corrosion component due to chemical reaction with the slurry, and this makes the process more erosion than abrasion. However, this test is widely used as an "abrasion test" for coatings and surface treatments, so it will be covered here rather than in the erosion chapter. This test seemed to arise in Europe and it is being promoted by the European Union through the European joint research organization (VAMAS). The test presses a rotating hard steel sphere (about one inch in diameter) against a flat test specimen and a slurry of water and abrasive particles is fed through the contact region (Figure 4-32).

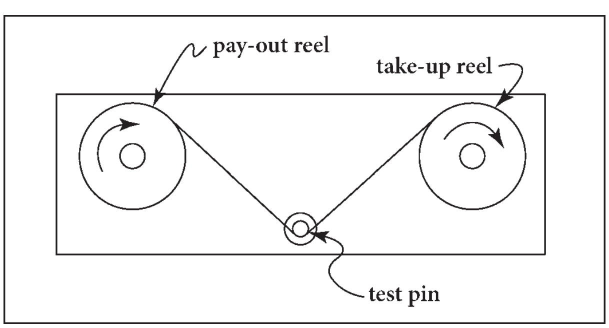


Fig. 4-29—Schematic of yarn wear test.

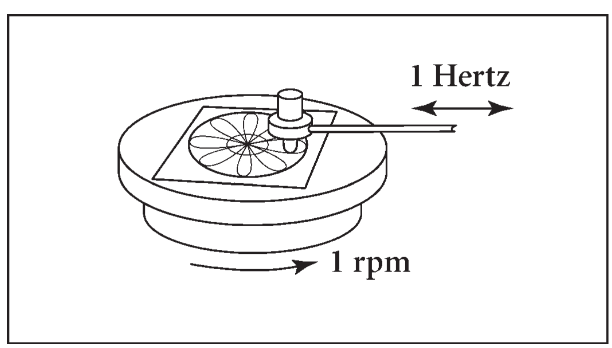


Fig. 4-31—Film/paper abrasivity tester.

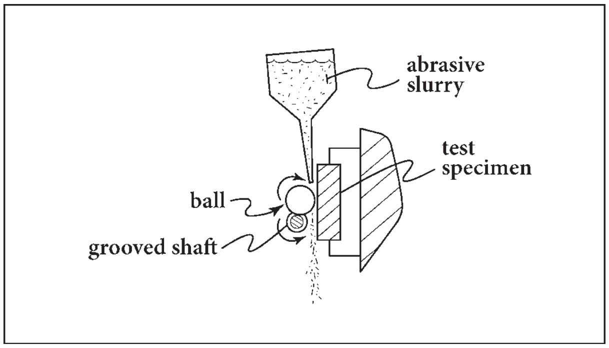
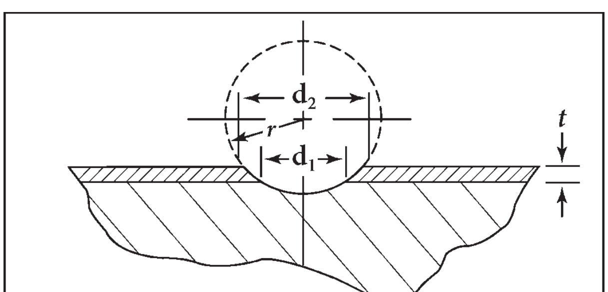


Fig. 4-32—Schematic of the ball-cratering test.

This test arrangement produces a spherical wear spot on the test specimen that can easily be converted to a wear volume if one knows the radius of the ball and the diameter of the wear scar. The ball is usually driven by a notched shaft and the normal force is usually just the weight of the ball, but some testers have a positive drive on the ball and various normal forces can be applied. There are mathematical formulas available to measure coating thickness from the "rings" that show up in wear scars on coated specimens. There are commercial versions of this tester available as well as modifications that eliminate the slurry. Some commercial versions of this test use an abrasive-impregnated wheel to produce a wear crater for coating thickness measurement. There are also test versions where the ball is clamped and driven with a shaft. It is not free to slip in the drive mechanism.

A major concern in using this test is obtaining uniform slurry feeding into the contact region. One proposed standard uses 3- to 5-μm particles of silicon carbide as the abrasive and techniques such as bubbling air in the slurry are used to keep the particles in suspension. Ball wear is another concern. The ball rotates with a single rubbing path. Worn balls preclude the use of spherical volume equations in calculating counterface wear.

As of the preparation of this guide, an ISO standard was reported to be under development. It is widely used in the thermal spray and PVD coating industry as a quality control tool to measure coating thickness. In this application, it is not necessary to worry about test repeatability. All that is required for a successful coating thickness measurement is to wear through the coating and measurement of the resulting rings (Figure 4-33).



$$t = \sqrt{r^2 - (d_1/2)^2} - \sqrt{r^2 - (d_2/2)^2}$$

Fig. 4-33—Measuring coating thickness from a ball-cratering scar.

Chapter Summary

There are many tests (including ASTM tests) not described in this chapter, but the ten or so that were described are probably the most popular. Some of these tests produce two-body abrasion; some produce three-body abrasion. Some are low-stress; some are high-stress. Some are polishing. It is always recommended to select a test that simulates the application of interest. If a system of interest is two-body abrasion, then select from two-body tests. If the system of interest produces polishing abrasion, then select from the polishing tests.

In solving a specific wear problem, one can examine the wear failure with optical microscopy and deduce the type of abrasion; low-stress exhibits just scratches; high-stress exhibits scratches as well as grit embedding and comminution of the abrasive medium; gouging exhibits gouges and so on. The wear in the bench test should look like the wear on the part of interest. The abrasive should be the same type and size as that found in the system of interest. Finally, the motions and wear contact should be like those anticipated in service.

Important Concepts

The following concepts should be taken from this chapter:

1. The mechanism of material removal in most abrasive wear systems is scratching/plowing by hard, sharp protuberances.
2. The hardness of the abrader and counterface plays a major role in material removal; hard particles on a soft counterface remove the most material.
3. "Wet abrasion" is really erosion and there is likely a chemical component (dissolution) to the material removal mechanism.
4. Selecting a two-body or three-body test is a key decision that must be made.

Resources for More Information

Coatings

Bhushan, B. and Gupta, B. K., *Handbook of Tribology: Materials, Coatings, and Surface Treatments*, New York, McGraw Hill, 1991.

High-Stress Abrasion

Kruschov, M. M. and Babeckev, M. A., *Friction and Wear in Machinery*, Vol. 12, New York, American Society of Mechanical Engineers, 1958.

Totten, G. E., *Mechanical Tribology: Materials, Characterization, and Applications*, Boca Raton, FL, CRC Press, 2004.

CMP

Liang, H., *Tribology in Chemical-Mechanical Planarization*, Boca Raton, FL, CRC Press, 2005.

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Marinescu, I. D., Rowe, W. B., Dimitrov, B., and Inasaki, I., *Tribology of Abrasive Machining Process*, Norwich, NY, William Andrew Publishing, 2004.

Related ASTM Standards

B 611 – Test Method for Abrasive Wear Resistance of Cemented Carbides *(Line contact of a test specimen vs a 1020 steel wheel submerged in #30 grit aluminum oxide slurry, 20-kg normal force, 1000 revolutions against a 6.5-inch-diameter steel wheel, 100 rpm.)*

D 3108 – Test Method for Coefficient of Friction, Yarn to Metal *(100 m/minute, 0.1gf/denier tension, 180-degree wrap on pin.)*

D 4060 – Test Method for the Abrasion Resistance of Organic Coatings by the Taber Abrader *(Abrasive-filled rubber wheels slip on a rotating flat specimen–many test options are available for different materials.)*

G 56 – Test Method for the Abrasiveness of Ink-Impregnated Fabric Printer Ribbons *(0.25-inch-diameter balls rub on a large drum covered with fabric with a force of 100 g, for 14,700 m.)*

G 65 – Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus *(There are five procedures using different forces and test durations; the test forces a flat specimen horizontally against a 9-inch-diameter rotating rubber wheel (at 200 rpm) while 50/70 mesh silica sand is metered into the rubbing interface, test force can vary from 45 to 130 N, test duration can vary from 71.8 to 4309 lineal feet of abrasion; specimen wear volume is the test metric.)*

G 81 – Test Method for Jaw Crusher Gouging Abrasion Test *(2000 pounds of rock are crushed by test plates and reference plates in the crusher jaws; wear ratio, specimen/reference material, is the test metric.)*

G 105 – Test Method for Conducting Wet Sand/Rubber Wheel Abrasion Test *(Flat specimen in line contact with rubber wheel in 50-70 mesh sand slurry, 50 lb normal force, 449 ft/min., 1000 revolutions on three 7-inch-diameter wheels of different Durometers, report volume loss at 60 Durometer.)*

G 132 – Test Method for Pin Abrasion Testing *(6.35-mm-diameter pins are rubbed on end in a variety of machines on fixed abrasive, 1 to 2.5 MPa contact pressure, 1 to 10 cm/s speed, optional sliding distance.)*

G 171 – Test Method for Scratch Hardness Using a Diamond Stylus *(Cone stylus with 120 μm tip radius, 120 degree angle, optional test load, 5 mm minimum scratch length, speed of 0.2 to 5 mm/s, measure scratch width, calculate hardness from load and scratch width.)*

G 174 – Test Method for Measuring Abrasion Resistance of Materials by Abrasive Loop Contact *(This test uses line contact of a flat specimen on an abrasive loop for a given sliding distance; scar width is measured to calculate wear volume; there are four different procedures with loads from 100 to 200 g, speeds from 5 to 15 m/min, test durations from 20 to 680 loop passes, loop length = 132 cm.)*

Reference

[1] Samuels, L. E., *Metallographic Polishing by Mechanical Methods*, Materials Park, OH, ASM International, 1982.

5

Adhesive Wear Testing

Introduction

AS WAS PREVIOUSLY MENTIONED, THE TERM "adhesive" essentially defines a wear mechanism, and mechanisms are seldom universally agreed upon. In addition, the term "adhesive wear" is not popular, but for this guide, it is preferred over the "nonabrasive" alternate term. Many times, the "adhesive" component may be minor, but "nonabrasive" may have no meaning to newcomers in tribology. In any case, the ASTM G 40 definition is: "wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or loss from either surface."

There are several major types of wear in this category:

- Sliding wear: any solid sliding on any other solid
- Galling: severe form of adhesive wear
- Scoring/scuffing wear: grooves and scratches in the sliding direction
- Oxidative wear: mild wear in hard/hard unlubricated ferrous systems

In addition, there are four types of relative sliding to consider

- Unidirectional continuous
- Reciprocating
- Complex (slide, roll, etc.)
- Intermittent

Discussion will be limited to tests that are unidirectional, continuous, or reciprocating because most of the standard tests fall into these two types of sliding. Complex sliding is used, for example, in tests that simulate human joints in which motions are reciprocating combined with articulation. Intermittent motion tests are mostly employed in special tests to simulate an application. For example, photographic lenses in satellites are programmed to be translated by ball screws with a sequence that may consist of 70 clockwise rotations followed by 10 counterclockwise, then a dwell and then 30 rotations back, etc. The four types of adhesive wear will be addressed with standard and non-standard tests. The chapter will conclude with test selection remarks.

Galling: ASTM G 98

Probably the most "fundamental" adhesive wear test is the galling test ASTM G 98. This test involves the 360° rotation of a 0.5-inch-diameter flat-ended pin end-wise on a flat counterface. The load on the couple is constant for each rotation and is increased for subsequent rotations until galling occurs. The test metric is the threshold galling stress. This stress is equal to the highest load that the couple can withstand without galling divided by the apparent area of contact of the end of the pin.

This test almost needs a mentor, that is, someone who knows how to identify galling. The definition of galling is a severe form of adhesive wear characterized by localized roughening or protrusions from a surface. Figure 5-1 shows the test schematic, and Figure 5-2 shows a galled gear tooth. A key part of galling is the formation of excrescences — material flowed up from the surface. This is really the most significant damage from galling. It can cause seizure in plain bearings and many tribosystems. These excrescences use up running clearance. Galling can occur in a very small amount of sliding. In fact, it often occurs in systems that are not supposed to see relative motion, like a drill chuck. If a drill rotates in the chuck, it is likely to gall. Most shanks are lower in hardness than the drill point, and these are very prone to galling.

Before galling starts, conforming rubbing surfaces often "burnish." This burnishing is plastic deformation of the real area of contact between the rubbing surfaces. At very light loads, the deformation may be confined to interacting asperities on the highest wave forms. As load increases, the burnished area grows larger. More surface is plastically deformed. If galling does not occur, the plastic deformation will continue on one or both surfaces and eventually wear particles may form from one or both surfaces. After continued sliding, the deformation of both surfaces will slow down and the sliding surfaces will become separated by a layer of "third bodies," mostly wear detritus. This is what happens most of the time with unlubricated metal-to-metal couples that do not gall. Plastic-to-metal and other mixed system couples may react differently.

The identification of galling is probably the only precaution in using the test standard. The sketches in Figure 5-3 show what can happen in the test: Only the damage in the last sketch is called "galling." The tendency to gall is very dependent on hardness, and very hard materials like high-speed steels at 64 HRC seldom gall; similarly cemented carbides resist galling.

There are commercially available testers for the G 98 galling test, but suitable test rigs have been made from Brinell hardness testers and from tensile testers. Care must be taken to ensure proper specimen alignment and avoidance of edge effects. Some investigators put a hole in the center of the cylindrical specimen to eliminate zero velocity in the center. Some investigators use linear rather than rotating motion, but the original G 98 test has been shown to correlate with service results and its use is recommended to identify sliding couples that are gall resistant. A new test method is under development using annular specimens (mating donuts), but it may be several years before the standard is published.

Pin-on-Disk: ASTM G 99

The pin-on-disk test (Figure 5-4) is popular because it is easy to conduct, fast, and the equipment is readily available. The ASTM test standard allows a wide range of balls or hemispherical riders (from 2 to 10 mm) and disks can be from 30 to 100 mm in diameter and 2 to 10 mm thick. Many users try to use the specimen sizes indicated in the standard's interlaboratory tests so that these tests can be repeated to check the viability of a test

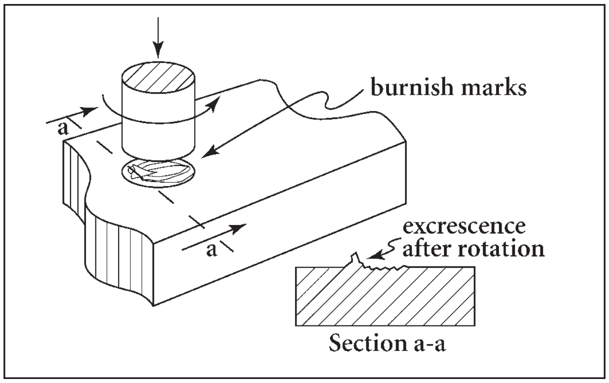

Fig. 5-1—Schematic of a galling test.

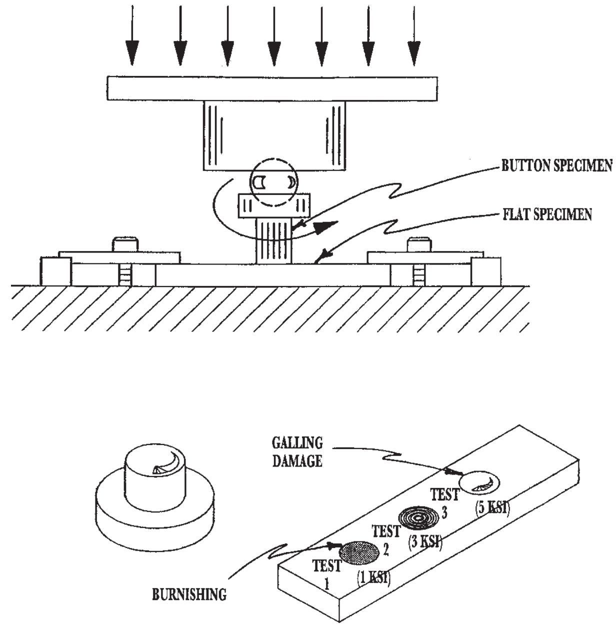

Fig. 5-3—How to recognize galling.

rig. The interlaboratory tests used 10-mm balls, 40-mm-diameter disks, 10 N force, a velocity of 0.1 m/s, and a sliding distance of 1 km. However, the standard allows any normal force, speed, and distance. The standard specifies what data to collect and report.

A precaution necessary in this test is calculating wear volume on the ball and disk. Mass change is allowed, but the standard tends to promote calculation of ball wear from the ball scar diameter and disk wear from the scar radius and depth profile. Of course, some formulas only work when only one member, the ball or the disk, wears. In real life, most times the ball wears flat so the equation can be used, but the counterface develops a "furrow" that is flat, not radiused on the bottom (Figure 5-5). The counterface wear in this instance can be obtained from the scar depth "d," the scar width "W," and the scar radius "R." The counterface wear volume is essentially an annulus that can be calculated using simple geometry formulas: scar area (cross-section) times mean scar diameter. Ball-on-plane wear measurement "options" are discussed in the ASTM G 133 standard. This can serve as a reference on what to do when both the ball and counterface wear.

A concern with this test is that hardly any machines use components that look like a ball-on-flat. Thus, this tribosystem is atypical of metal-to-metal or other solid/solid sliding system geometries. This is not a real problem. If the test is used for screening materials, it will rank them and as long as stresses and test velocities are selected that approximate the system under study. Probably the major limitation of this test is the availability of balls or hemispherical riders made from different materials. Balls are abundant and low cost in hard steel (SAE 52100), hard stainless steel (440C), glass, austenitic stainless steel, carbon steel, and nylon. Of course, there are companies who will make balls for any materials for a price, but this can add significant elapsed time (for delivery) to a project. Overall, the pin-on-disk test is a good screening test for materials that will be subjected to continuous sliding under light loads with or without lubrication.

Reciprocating Ball-on-Plane: ASTM G 133

The ball availability problem is still present with this test, but hemispherical riders can be fabricated at reasonable prices

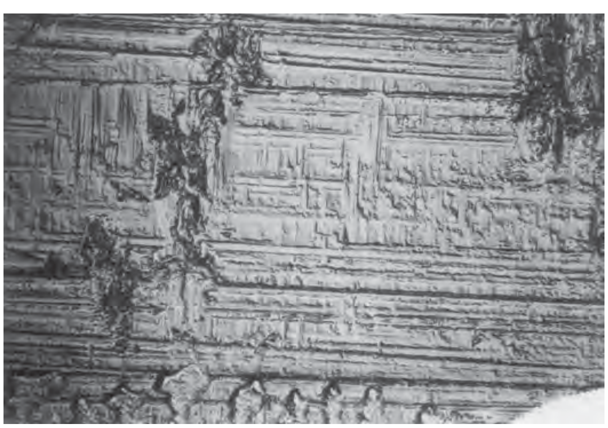

Fig. 5-2—Incipient galling on a gear tooth (transverse to grind lines).

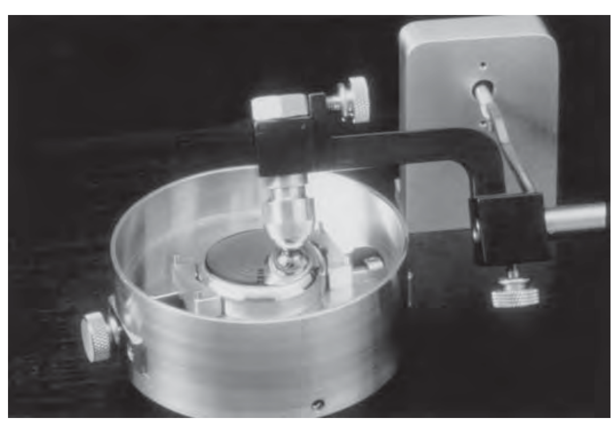

Fig. 5-4—Pin-on-disk tester (Courtesy of Implant Sciences Corp.).

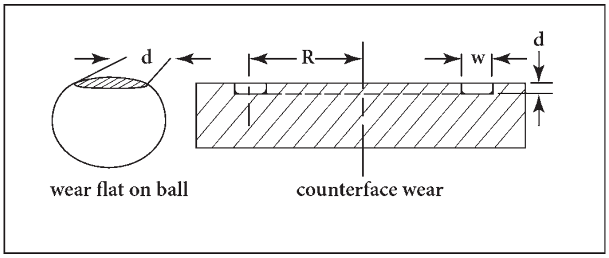

Fig. 5-5—Rider and counterface wear in a pin-on-disk test.

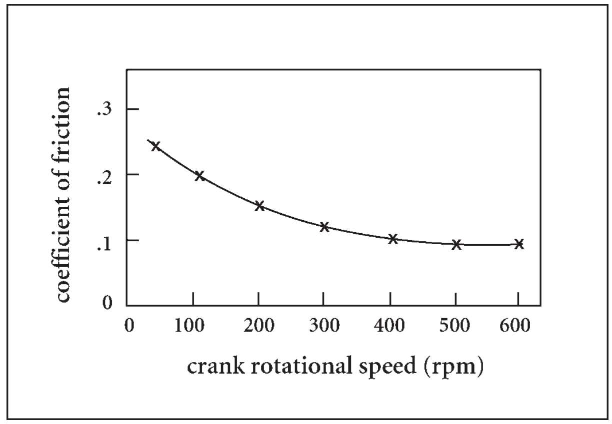

Fig. 5-6—Effect of speed on a lubricated reciprocating couple.

from most materials. The standard test uses linear reciprocation with a crank type velocity profile (some commercial machines use a scotch yoke). The ball and scar measurement concerns are the same as in the pin-on-disk. However, the standard does a good job of guiding users on appropriate wear volume measures for different balls, and counterface wear results.

There are two procedures in the ASTM G 133 standard; one is for dry or unlubricated couples:

A: 20 N normal force, 3/8 diameter ball, 10-mm stroke, 5 Hertz, 1-km sliding distance

The other test is for lubricated systems:

B: 200 N normal force, 3/8 inch diameter ball, 10-mm stroke, 10 Hertz.

At 600 cycles per minute (10 Hertz), the lubricated systems can exhibit hydrodynamic lubrication so friction force readings are not for the material couple, but the lubricant/test sample couple. In fact, wear probably only occurs when there may be momentary specimen contact at direction reversal. If the speed is varied in the lubricated test, it may be possible to develop a better feeling for the couple friction as shown in Figure 5-6.

This test is recommended for screening material, coatings, or lubricants for use in reciprocating systems. However, it is so fast and easy to use that it is often used to screen couples that may see continuous motion. The test takes less than 20 min, and the 10-mm stroke length means that small samples can be used. Thus, it is often used because it can be done on small specimens with a wide variety of shapes. Procedure A is often the screening test of choice for many studies. Experience with this test suggests that rankings from this test apply to other than reciprocating sliding systems. It is a first-line screening test.

Block-on-Ring: ASTM G 77

There are many ways to rub two solids together. One of the most common tests is the block-on-ring. The test schematic is shown in the upper left of Figure 5-7. The plethora of specimen configurations for studying sliding wear can be attributed to at least two factors:

Factor 1: The desire to simulate a particular tribosystem

Factor 2: The desire to facilitate the measurement of wear on both members

The test shown in Figure 5-7 is intended to simulate bushing/shaft tribosystems (lower left). It fulfills factor 1. However, if reasonable materials, speeds, and loads are used, you may have to run this test continuously for months to get enough wear on the members to measure accurately the wear that occurred. If you want to compare ten different bush materials for an application, you could end up with a test program that could span years; that is too long for most wear problems. The block-on-ring test is believed to be an accurate simulation of the bushing test because all bushings have a running clearance such that at startup there is line contact between the bush and shaft, just like the contact that occurs in the block-on-ring test (Figure 5-8).

The ASTM G 77 block-on-ring test uses a small block ($0.25 \times 0.4 \times 0.7$ inches) in line contact with a 1.317-inch-diameter ring. The block rubs on the ring for a given time (distance) under a given load and the wear volume on both members is the test metric. The difficult part of the test is to get the block aligned with the ring so that the block scar is not tapered (Figure 5-9).

Most users use a hardened steel ring and run candidate materials/coatings against the "standard ring." These rings can be purchased at moderate cost. The test can be used for lubricated couples and there is an ASTM (D 2714) test that can be used to calibrate a tester. The test runs a steel couple in a specified lubricant and checks to see if the wear volumes of the members fit the calibration limits. Unfortunately, the "official" calibrating fluid has limited availability (and thus high cost) and some users use "light" mineral oil from the drugstore as the calibrating fluid.

For quite a number of years, the G 77 test was used for plastics as well as metals and other materials. However, studies showed that the relatively short G 77 test (1 hour) produced different rankings than a longer time test (20 hours). After a number of interlaboratory tests, a new block-on-ring test was standardized for plastics using a larger diameter ring (6 inches), a different size block and shorter test times (ASTM G 137). More recently, the G 77 test was rewritten for plastics as a separate standard, G 176. It uses a test time similar to the G 137 test. One significant difference between these tests is that the G 137 test requires intermediate wear scar measurements on the block, but ring wear is not measured. This can be a concern particularly with glass and carbon fiber fillers where counterface wear can become measurable.

In summary, the block-on-ring test is popular for evaluation of lubricated and unlubricated couples. Its foremost advantage is that the line contact at startup accelerates the block wear such that very short test times are possible. Test times are in hours, not hundreds of hours. Test times can be short (10 minutes) when evaluating coatings. Of course, one must consider if this accelerated test can predict long-term behavior. The metal-to-metal tests have proven to correlate with service conditions that involve tool materials, copper alloy-bearing materials, and hardfacings. This test has been the "gold standard" for some types of

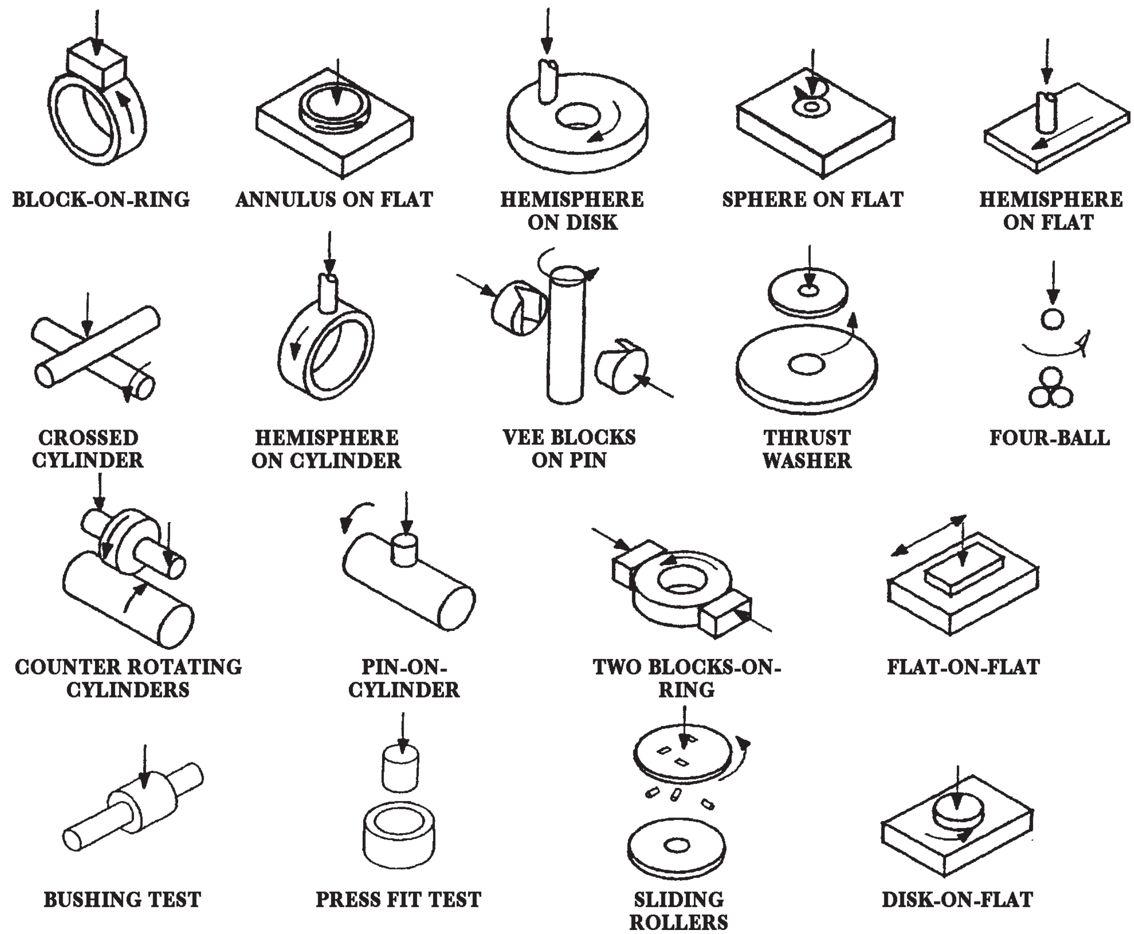

Fig. 5-7—Common metal-to-metal wear test specimen configurations.

solid lubricants. As mentioned previously, the longer test time block-on-ring variations are preferred for plastics. Overall, this test is a reasonable simulator for continuous motion applications for bushings and the like. We recommend its consideration for these types of applications, but be certain that Hertz stress and sliding conditions are reasonable for the mechanical properties (yield strength) and physical properties (heat dissipation, modulus, etc.) of the test materials. In other words, do not select a starting load that produces a Hertz stress above either material's compressive yield strength.

Scuffing/Scoring

Scoring and scuffing are forms of sliding wear characterized by localized macroscopic "scratches" or "furrows" in the direction of motion (Figure 5-10). The term "scoring" will be used because it is in more common use. A cross-section of a score mark is shown schematically in Figure 5-11.

Its form is essentially a furrow not unlike those produced by scratching abrasion. What causes them? They are caused by localized adhesion between a rider and a counterface. The adhered metal/material is an "up-feature" on the surface of the rider and this feature which is raised above the prevailing surface finish acts like an "abrasive" grain to plow a furrow. Why does localized adhesion occur? Statistically, circumstances for adhesions are present on all conforming surfaces, but on a micro or nanoscale someplace there will be a spot in the contact region where all of the factors that make materials adhere to each are just right. Scoring is really galling. It usually occurs in boundary-lubricated systems where there are lapses in full fluid separation of the sliding members. Also, scoring most often occurs in soft metals/materials. In steels, for example, scoring has been observed at hardnesses less than 60 HRC.

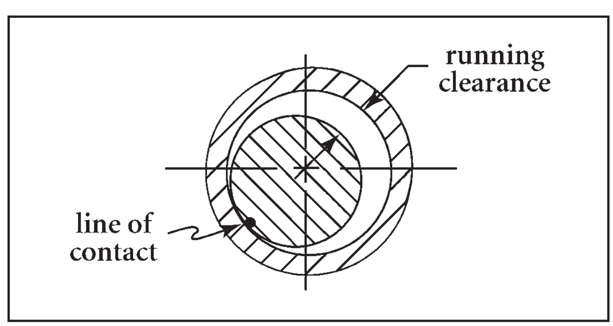

Fig. 5-8—Line contact in a bushing/shaft wear system.

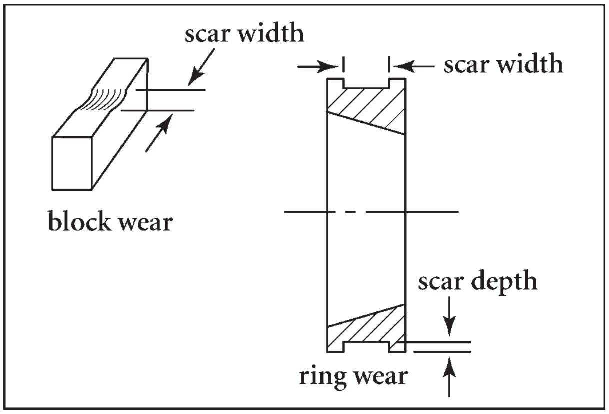

Fig. 5-9—Typical block and ring scars.

Gear studies seemed to suggest this as a "threshold" hardness. Automotive cylinders are made from cast irons that are not even on the Rockwell C scale so they are very prone to scoring during poor lubrication events. Plain bearings made from soft bronzes are similarly prone to scoring. Any conforming surfaces in relative sliding are candidates for scoring.

How does one measure the scoring tendency of couples? The ASTM G 98 galling test can and has been used, but it does not simulate pistons in cylinders or other scoring prone systems. Gears are very susceptible to scoring on teeth where there is a combination of rolling and sliding. A traditional gear test is the FZG test. This test runs a set of gears with a special shape on essentially a dynamometer, a device that progressively increases speeds and loads until excessive gear wear or scoring occurs. Of course, the G 133 reciprocating test can be used as well as the block-on-ring test. The metric in these tests can be the stress, speed, or other condition that first produces scoring. The reciprocating test has been modified to use a counterface made from a diesel engine cast iron cylinder liner and a rider of a piston ring (ASTM G 181).

In summary, scoring on conforming sliding surfaces is the result of localized adhesion of one surface on the other. The adhered material plastically deforms a furrow in the softer member and possibly in the harder member. There are many reasons for the initiation of the original transfer. It could initiate at a microstructural inhomogeneity, a material defect, a spot with no fluid separation, a surface nonuniformity, or any of a hundred other reasons. Wear is statistical in nature. Different events occur in every rub. Scoring is most likely to occur in hard/soft, soft/soft couples and is less likely in hard/hard couples. As always, the use of test geometries that simulate an application of interest is recommended. The G 133 reciprocating test is a prime candidate to simulate reciprocating motion and a block-on-ring configuration would be a good choice for scoring tendencies in continuous motion. The following are some characteristics of scoring.

1. Scoring is plastic deformation of the surface; the yield strength was locally exceeded
2. Scoring usually occurs when separating films are locally disrupted
3. Testing for scoring resistance of candidate couples/lubricants should simulate the application

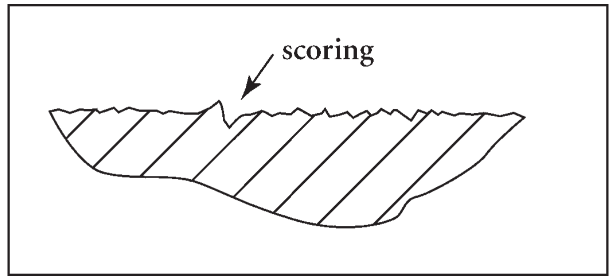

Fig. 5-11—Schematic of score marks (travel is into the page).

Oxidative Wear

Oxidative wear is a form of metal-to-metal wear characterized by reaction of one or both surfaces with the ambient environment to produce a reaction product on one or both rubbing surfaces. This is also call "mild wear." It happens most in unlubricated systems and steels are the most prone. If contact rubbing steel surfaces look "rusty," this is probably oxidative wear (Figure 5-12). New microscopic asperity fractures occur spontaneously between rubbing surfaces and these fracture surfaces oxidize. When a wear particle is produced, if it stays between the faying surfaces, it will react with the environment (oxidizes in air) and

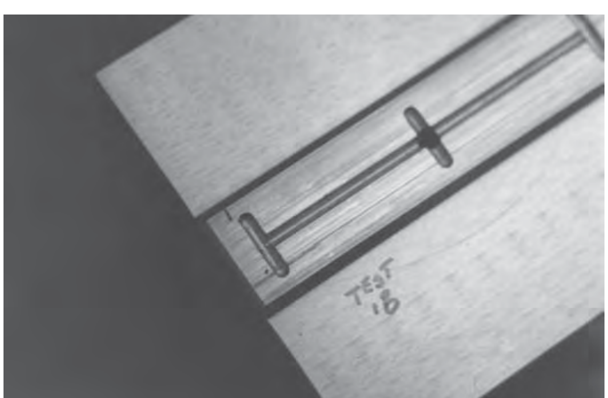

Fig. 5-10—Example of scoring (Babbitt flat pad versus hard steel).

Fig. 5-12—Example of oxidative wear (near threads).

these particles look like rust in steel sliding systems. Most homeowners in the United States never oil their door hinges (until they squeak), but if you ever remove a hinge pin after a year of use, you would find the pin rusty. This is not from atmosphere corrosion; the pin is covered with a wear reaction product from a year (or years) of unlubricated rubbing. It is mild wear because the number of rubbing cycles is really quite low. Even a bathroom door sees mild wear. If it is used 10 times a day, this is still less than 4000 ninety-degree rotations per year. If the pin is 0.25 inch in diameter, this is less than 25 meters of sliding per year, which is not much as wear systems go.

In machinery, oxidative wear frequently occurs in unlubricated hard/hard systems. Many rubbing faces on injection molding dies are not lubricated because of product contamination. These hard steel couples are candidates for oxidative wear. Any kind of surface separation by oil, grease, solid lube, plating, etc. will minimize or eliminate oxidative wear. Any wear test that simulates the sliding conditions can be used to compare various couples for their oxidative wear behavior. Pin-on-disk and reciprocating ball-on-plane tests are frequently used. However, the standard block-on-ring (ASTM G 77) test may be too severe. If the rubbing surfaces are metallic and oxide free, it may be that your test conditions are too severe.

Some final thoughts on oxidative wear are as follows:

1. Oxidative wear suggests poor lubrication
2. The goal of testing should be identification of couples/lubricants that prevent oxidative wear
3. Oxidative wear is never desirable
4. Metal/plastic couples often resist "dry" wear better than any metal/metal couple.

Chapter Summary

Abrasion (see Chapter 4) usually is presented as the costliest form of wear. It is more prevalent that all of the other forms, probably because we live in a world in which dirt is everywhere and most dirt is chemically composed of hard inorganic substances. It is abrasive to most materials. Adhesion wear is not as apparent as abrasion, but it is usually considered to be the second most costly form of wear. Abrasion wears out the tires on vehicles − at great annual cost. Adhesive wear and other wear processes that start as adhesive wear are probably responsible for engine, suspension, and other vehicle systems wearing out.

Forms of adhesive wear are very prevalent in metal-to-metal sliding systems and the reason why these kinds of sliding systems are prone to wear is that they are often composed of material couples that are very prone to severe wear when not separated by a lubricant. Usually soft metals are used in mechanical devices (like an automobile engine) for at least one member in a sliding couple because fabrication costs are much lower on soft metals than hardened and ground metals. So the goal of many adhesive wear tests is to find the lowest cost couple that will survive for a particular design life.

Reciprocating tests are used to screen couples for piston/cylinder combinations; pin-on-disk tests are used to screen materials for cams and other continuous-motion mechanisms. Galling tests are used to screen valve couples. Block-on-ring tests screen bushing-shaft combinations. The tests that we described in this chapter are important in dealing with the second most costly form of wear.

Important Concepts

The following concepts should be taken from this chapter:

1. Adhesive wear starts by microscopic adhesion between surfaces in rubbing contact.
2. If solid-on-solid tests are performed lubricated, there is usually a sliding speed at which the lubricant will fully separate the sliding members. It is not advisable to test at these speeds if mating couple wear properties are the test goal.
3. Flat-ended riders do not usually conform to the counterface for the apparent area of contact. They tend to ride only on the trailing edge. This is why spheres or hemispherical riders are preferred for these tests.
4. Surface texture and lay of specimens are important in adhesive wear tests. They must duplicate the intended service.

Resources for More Information

Wear Tests

Bayer, R. G., *Selection and Use of Wear Tests for Metals*, STP 615, ASTM International, W. Conshohocken, PA, 1976.

Bayer, R. G., *Selection and Use of Wear Tests for Coatings*, STP 769, ASTM International, W. Conshohocken, PA, 1982.

Fundamentals

Rigney, D. A., Ed., *Fundamentals of Friction and Wear of Materials*, Materials Park, OH, ASM International, 1987.

"Surface Texture (Surface Roughness, Waviness and Lay)" ANSI/ASME B46.1, New York, American Society of Mechanical Engineers, 1985.

Other Views on Adhesive Wear

Suh, N. *The Delamination Theory of Wear*, Amsterdam, Elsevier, 1977.

Merchant, H. D. and Bhansali, K. J., *Metal Transfer and Galling in Metallic Systems*, Warrendale, PA, The Metallurgical Society, 1987.

Related ASTM Standards

G 40 – Terminology Relating to Wear and Erosion

G 77 – Test Method for Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test *(Line contact of a stationary block on a rotating ring; test load, velocity, and duration are the user's option.)*

G 98 – Test Method for Galling Resistance of Materials *(The end of a 1/2 inch diameter pin is rotated 360 degrees on a flat block with increasing load (fresh surfaces) until galling occurs.)*

G 99 – Test Method for Wear Testing with a Pin-on-Disk Apparatus *(Pins or spheres from 2 to 10 mm in diameter slide on disks from 30 to 300 mm in diameter; speed, load, temperature, duration, and lubrication is the user's option.)*

G 133 – Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear *(The unlubricated procedure uses a 3/8-inch-diameter ball, 25 N, 10 mm stroke, 5 Hz, 100 m sliding distance; lubricated the force is 200 N, 10-mm stroke, 10 Hz, 400 m sliding distance.)*

G 137 – Test Method for Ranking Resistance of Plastic Materials to Sliding Wear Using the Block-on-Ring Configuration *(This test uses a larger block and ring than the G 77, test force is from 20 to 40 N, velocity from 0.5 to 1 m/s, test duration is variable until steady state is obtained.)*

G 181 – Practice for Conducting Friction Tests on Piston Ring and Cylinder Liner Materials Under Lubricated Conditions *(This test is like the G 133 test except the rider is a segment of a piston ring against a flat or curved liner; the user selects the test parameters.)*

6

Plastic/Elastomer Wear

Introduction

PLASTICS ARE POLYMERIC MATERIALS THAT CAN be molded into shape by flow at some elevated temperature. Elastomers are polymeric materials that have high elongation (more than 100% in a tensile test) and forcibly return from elongation/deformation; they have high restitution. It is current practice to combine moldable plastics with elastomers to make thermoplastic elastomers; essentially, these are injection-moldable rubbers. There is a plastic phase and a rubber phase in the microstructure.

To make this subject a bit more complicated, plastics are often filled with substances that run the gamut from extremely hard aluminum oxide to unctuous polytetrafluoroethylene (PTFE,* or Teflon). In addition, some plastics are commonly reinforced with continuous (woven) or nonwoven materials such as cotton, canvas, glass, plastic filaments, carbon fiber, boron fiber, ceramic whiskers, and nanoparticles. In other words, they can be very heterogeneous, and many formulations, probably more than 20,000, are commercially available.

How do these materials wear? The short answer is that they wear differently than metals, ceramics, and other traditional engineering materials. And that is the reason why there is a chapter dedicated to them. Their differences compared with metals and ceramics often lead to problems in diagnosing wear type and in simulating service conditions in laboratory testing.

This chapter will discuss plastic and elastomer wear testing and include thermoplastic and thermosetting plastics in the "plastic" category and all rubbers in the elastomer category. All important "rubbers" are really elastomers, polymers with high elongation, and the only true "rubber" is natural rubber and it is used mostly in adhesives. Thus, "rubber" is technically an elastomer because even natural rubber can be made in a chemical plant from polyisoprene.

Therefore, this chapter will cover plastic and elastomer wear and these categories will include all of the materials that are termed plastics, rubbers, and elastomers, probably a more correct term is "polymer wear." All of these materials are composed of repeating molecules or "mers." Table 6-1 lists some of the idiosyncrasies of polymers that present a tribological challenge. There are probably other idiosyncrasies of polymeric materials that may be a factor in tribotesting, but many of the common concerns have been noted. Plastics wear differently from competitive engineering materials, and this difference needs to be addressed in wear testing. What modes of wear apply to polymeric materials? Figure 6-1 is an attempt at including the important ways that plastics wear and erode.

In addition to wearing and eroding, plastics also can cause wear of contacting surfaces. They can be abrasive; counterfaces can adhere to plastics and they can then wear counterfaces because the counterface is locally sliding self-mated. Plastic-to-plastic wear often results in severe wear by the tendency of plastics to self-weld (Figure 6-2). Hard fillers and reinforcements in plastics are one of the most insidious issues to deal with in wear testing. There are scores of particulate fillers that are added to plastics as well as a significant number of chopped or continuous reinforcements:

Then, to further complicate matters, plastics very often contain friction modifiers:

- Rubbers
- MoS_2
- WS_2
- SbO_3
- Graphite
- PTFE
- Silicones
- Waxes
- Oils

Plasticizers increase viscoelastic behavior, as do rubbers. The rubbers usually are present as a second microscopic phase and the plasticizers work by making inline slip of molecular chains among themselves easier. Both usually, but not always, increase friction between the plastic and a counterface from another material system.

Molybdenum disulfide (MoS_2), tungsten disulfide, and graphite are intercalative lubricants that tend to transfer from the plastic to a mating counterface and "slipperiness" is produced by the basal planes of the intercalative compounds sliding on each other.

Polytetrafluoroethylene (PTFE) (or Teflon and the like) lubricates by easy shear. Fluorocarbon lubricants have very low shear strength. Like graphite and the inorganic lubricants, they tend to transfer to counterfaces and, when PTFE slides on itself, it behaves as if "fluid lubricated."

Silicone oils are the friction modifiers that most often are put in injection-molded plastics. If plastic parts need to rub together in a mechanism or in assembly and they do not rub as desired, silicone is added (by barrel injection or other technique) until the desired friction behavior is achieved. There are even proprietary processes for filling and injection-molded plastic with "bubbles" filled with petroleum oils. The "bubbles" burst when wear occurs and the oil minimizes additional wear.

Some plastics are externally lubricated with friction modifying substances, and whenever plastics are externally lubricated, one must always determine if the applied chemical can cause some immediate or delayed degradation of the polymer. Natural waxes such as carnauba wax are frequently applied on plastics as a topical friction modifier. Waxes coat the surface with microscopic wax platelets preventing the plastic from

*This chapter uses standard acronyms for some plastics. A comprehensive listing can be found in the Budinski/Budinski reference at the end of the chapter.

TABLE 6-1—"Tribological idiosyncrasies" of plastics.

Polymer Property	Tribological "Challenge"
Low stiffness ($E > 10^3$ ksi)	"Hertzian" contacts are usually not Hertzian but conformal
Low strength (YS < most metals)	Most keep test loads low to prevent plastic deformation instead of wear
Many polymeric materials have viscoelastic properties	Elastic contact mechanics do not rigidly apply
Low melting points compared to most other engineering materials	Must monitor testing speeds for melting
Poor heat conductors compared to most metals	Must monitor testing speeds to prevent melting
Anisotropy (from directed mold flow and reinforcement lay)	Be aware that surface properties can vary significantly on a given specimen
Fabrication process	Triboproperties can be much different between molded surfaces and machined surfaces on the same parts
Crystallinity	The degree of molecular alignment (crystallinity) can be different in plastics that are chemically the same molecule. Crystallinity affects wear.
Tendency for adhesive transfer	In certain tribosystems (like a pin-on-disk) the test plastic may transfer to the counterface so an apparent plastic-to-metal test can be a plastic-to-plastic test.
Tendency for plastic deformation	Sometimes a plastic will deform significantly in a wear test without losing mass – there is damage, but no mass loss.
Plastics can have "skins" that are different from the bulk	May need longer test times
Many polymers degrade from UV radiation	Must make this a concern of tribosystems used outdoors
Plastics' properties degrade with time	Triboproperties in year one of service may be very different from year five.
Fillers/reinforcements	Some can be abrasive to counterfaces
Chemical sensitivity	Some plastics can be significantly degraded by petroleum or other lubricants

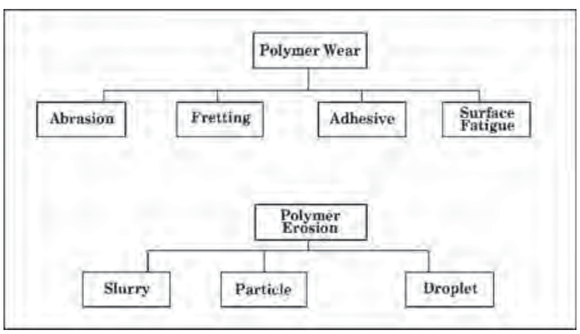

Fig. 6-1—Polymer wear and erosion.

touching counterfaces. Only the wax platelets touch (until they are eroded).

What all this means from the wear testing standpoint is that all of these things need to be considered when planning and executing a wear test. You must know what is in or on the plastic that you are testing and you must know the potential effects of these additives on wear tests. Finally, one must even be aware that cleaning procedures can have a profound effect on wear testing results. Ultra-high molecular weight polyethylene is a popular plastic used in hip and knee prosthetics. After too many early revisions (a medical euphemism for surgical removal of a worn joint implant), it was learned that the gamma and x-radiation that was used to sterilize the plastic parts caused chain scission (breaking of

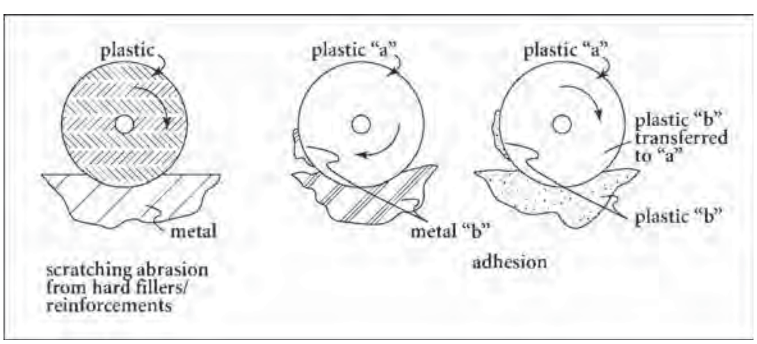

Fig. 6-2—Some plastic wear mechanisms.

molecular chains) that greatly reduced the plastic's wear resistance.

Plastics and elastomers are chemicals and, as such, there is always the potential for them to react in a negative way with other chemicals that contact them. This is an important testing concern that we will address in our discussion of specific wear tests.

Abrasion Tests

The ASTM B 1242 test was shown schematically in Figure 4-14 in Chapter 4. The test plastic is made into coupons (1/4 × 4 × 4 inches) that are affixed to a sort of sample conveyor that rotates perpendicular to a belt sander with a particular size (220 mesh $A1_2O_3$) abrasive on the belt. The belt sander is spring forced against the plastic plaques as they index in front of the sander. A reference specimen of pure zinc is also abraded with the plastic specimens and the test metric is the relative mass loss on the plastic compared with the metal.

Needless to say, this is an aggressive test and all plastics will be abraded. Some concerns are as follows:

1. Does this test simulate any application?
2. Can you get plaques with the same surface (molded, etc.) required of the application?

Of course, these concerns exist in all plastic wear tests. However, contact with a belt sander may be more abrasion then any plastic will ever be subjected to. The aluminum oxide is so hard and sharp that it may scratch all plastics equally.

Our concern about surface finish being the same as the application applies to the relatively large plaques of test material required by the test. Getting test samples this large with a molded surface may require a mold just to make test plaques. This becomes a very costly expense, but one that must be incurred if you need to assess the abrasion resistance of a molded surface. In summary, this ASTM test requires a special piece of equipment and relatively large test specimens. These factors probably resulted in the withdrawing of the test standard in 2003.

It is included in this discussion since it is likely that people may want to try this kind of abrasion test.

Taber Abraser

Table 6-2 lists some of the ASTM standards that use the Taber Abraser. The basic tester is illustrated in Figure 4-16. A flat test sample (usually 4 × 4 inches square) is affixed to a rotating platen. Rubber wheels filled with abrasive are dead weight-loaded on the rotating test specimen and they are rotated by the rotating test coupon in such a way that they produce a crosshatched scratching in a 3 inch diameter (mean) test track on the specimen. The wear test usually lasts for a fixed number of platen rotations and wear is assessed in different ways. With opaque plastics, mass change is usually used. With transparent or translucent plastics haze, reflected light, or transmission of light are used as test metrics.

Different wheels are available; some are knurled metal; some contain fine and some contain coarse abrasive. An option with this test is to use a grit feeder in front of the rubber wheel. This allows the use of abrasive particles that may not be available molded into the rubber wheels.

This test was originally intended for plastic floor tiles and sheet coverings to simulate dirt particles scrubbing on the flooring as third bodies between the flooring and shoe soles. However, the original rubber wheel test produces two-body abrasion; only the grit feed option produces three-body abrasion.

Users of the Taber test must be cautious about:

- Wheel wear/shape (repeatability)
- Wheel hardness (repeatability)
- Accurate damage/wear assessment
- Debris removal (repeatability)
- Specimen contact (repeatability)

If wheels are rounded or angled, there will not be full contact, which can affect repeatability. The abrasive-filled rubber wheels age with time and get harder. This in turn makes them more "abrasive." There are expiration dates on wheels, but they are often ignored. Newer Taber Abrasers are equipped with a vacuum head that removes debris so that a plastic/coating can be continually abraded. Some type of debris removal is needed to make sure that the abrasive wheel contacts the test specimen during each pass. Accumulated wear detritus "protects" the surface and must be removed. The test specimen cannot be warped or bent for uniform wheel contact.

All of these cautions are relatively easy to meet. However, assessing specimen wear in this test can sometimes be challenging. For example, 10 mm-thick plastic plaques may only receive surface dullness in the 100 rotation test. Mass change may be too small to accurately measure. This problem is addressed with transparent plastics by measuring the increased haze in the wear tract by optical techniques (ASTM D 1003).

In summary, the Taber Abraser is a popular device for abrading plastics, but its large test sample is sometimes a problem in assessing wear by gravimetric techniques. The haze method is also not without problems. This assessing wear may be the most significant test concern.

Falling Sand

This test is illustrated in Figure 6-3. It allows a given amount of 80 mesh silicon carbide abrasive to gravity-fall on a flat test specimen inclined at 45° to the falling particle stream. This test is often used on transparent plastics and paints. The change in light transmission can be the test metric on transparent plastics. Mass change can be used on paints and solid plastics. This test is not considered in this guide as an erosion test because there is not a significant contribution in mechanical action from the fluid (air). The force on the abrading particles is gravity, not an energetic fluid like an air blast.

This test does not simulate a specific tribosystems, but it provides a ranking of a material's resistance to low-velocity particle erosion. Users need to establish for themselves if this test correlates with a service condition. For example, a more aggressive version of this test that uses pea-sized stones and a slinger is used to test the resistance of plastics and paints for automobile wheel wells and rocker panels that are stone impacted from tires. This test could also qualify as an erosion test.

Dry-Sand Rubber Wheel: ASTM G 65

Of course, people have used the dry-sand rubber wheel abrasion test on plastics, but the standard 6000-wheel revolution test will wear through most plastic specimens made to the standard thickness of 3.2 to 12.7 mm. Figure 6-4 shows test results on a variety of plastics using the G 65 test standard test with a test duration of only 400 revolutions (2 min) instead of one of the standard test durations.

The results showing a 90 Shore A Durometer polyurethane elastomer as the winner followed by ultra-high molecular weight polyethylene concur with industrial experience. These

TABLE 6-2—ASTM standards that use the Taber Abrader, courtesy of Taber® industries.

	Ref.	CS-10F*	CS-10	CS-17	H-38†	H-10	H-18	H-22	Load (g) Per Wheel	Vacuum Nozzle Gap
Carpet, Automotive	D 3884		x						1000	7 ± 1 mm
Carpet, Broadloom	D 3884				x		x	x	500 or 1000	7 ± 1 mm
Ceramic, Unglazed Tile	C 501							x	1000	1/16 – 1/8″
Ceramic, Whitewares & Related	C 501							x	1000	1/16 – 1/8″
Coatings, High Gloss	D 6037		x*						500	Not specified
Coatings, High Perf. Interior Architectural Wall (ref. D 4060)	D 3730		x	x					1000	6.5 mm (1/4″)
Coatings, Industrial Water-Reducible (ref. D 4069)	D 4712		x	x					1000	6.5 mm (1/4″)
Coatings, Metallic Thermal Spray	F 1978							x	250	Not specified
Coatings, Organic	D 4060		x	x					1000	6.5 mm (1/4″)
Coatings, Powder (ref. D 4060)	D 3451		x	x					1000	6.5 mm (1/4″)
Coatings, Protective (ref. D 4060)	D 5144		x	x					1000	6.5 mm (1/4″)
Coatings, Solvent-Borne Architectural (ref. D 4060)	D 5146		x	x					1000	6.5 mm (1/4″)
Coating, Waterborne Architectural (ref. D 4060)	D 5324		x	x					1000	6.5 mm (1/4″)
Dimension Stone	C 1353							x	1000	1/16 – 1/8″
Inked Ribbons, Erasibility of	F 362	x							500	Not specified
Leather, Dyed	D 3884		x	x					500 or 1000	7 ± 1 mm
Leather, Durable	D 3884								1000	7 ± 1 mm
Leather, Upholstery	D 7255						x	x	*1000	7 ± 1 mm
Nonwovens	D 3884		x	x			x		250	7 ± 1 mm
Plastic, Transparent	D 1044					x			500	1/32 – 1/16″
Printing, Images Produced by Copiers and Printers	F 1478	x							250	Not specified
Resilient Floor Coverings (w/Grit Feeder Attachment)	F 510	x							1000	≤ 1/4″
Rubber Floor Tile (ref. D 3389)	F 1344						x		500	*1/4″
Textile Fabrics	D 3884						x	x	1000	7 ± 1 mm
Textile Fabrics, Coated	D 3889						x*		*1000	*1/4″

*C-wheels are abrasive-filled rubber. 10F is least abrasive, CS-17 is most abrasive.
†H-wheels are vitrified clay/abrasive of different abrasive size.

two materials are the most widely used plastics for abrasion resistance. The data also suggest that friction played a role in the results. PTFE was more resistant to abrasion than most of the engineering plastics. It is well known that PTFE is so mechanically weak that it is seldom used for any load-bearing member unless it is reinforced or kept from deformation in some other fashion. The data also show that the more rigid plastics are poor performers in a three-body abrasion test.

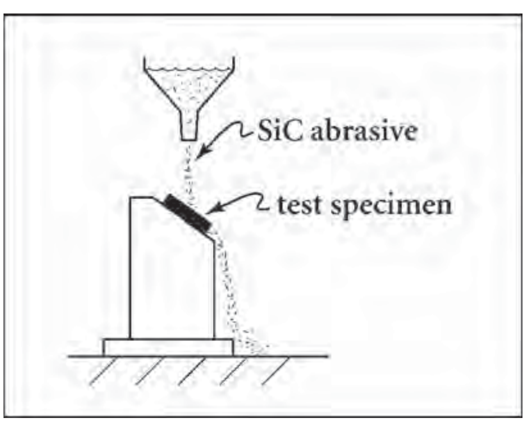

Fig. 6-3—Schematic of the falling abrasive abrasion test.

Loop Abrasion Test: ASTM G 174

This test was described Chapter 4, "Abrasive Wear Testing," and it was originally intended for metals but has been expanded to coatings, ceramics, hard metals, and cermets. This test also works well on plastics with reduced rubbing against the 30-μm aluminum oxide finishing tape. Figure 6-5 shows the ranking of a variety of plastics using a test option of one-loop pass. The test specimens always are subject to fresh abrasive. This test is a bit abrupt, and therefore a 10-pass test was performed on some of the same plastics. The results are shown in Figure 6-6.

The latter test only takes minutes and it appears to produce better discrimination. Test results are similar to those of the dry-sand rubber wheel test. In general, the hard, brittle plastics abrade easier than the slippery/rubbery plastics. It is thought that this occurs because the plastic deflects rather than penetrates when acted on by the sharp points on abrasive grains. Also the abrasive grains slide rather than scratch with slippery plastics. The G 174 test also can be performed on one-quarter-inch square flexural strength specimens, which often

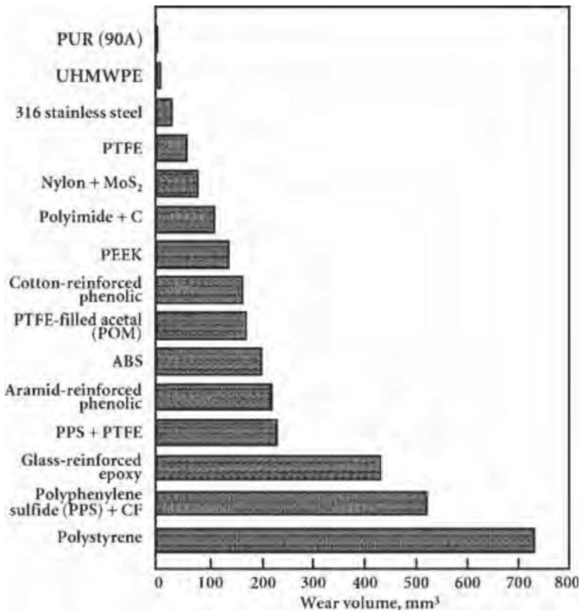

Fig. 6-4—Wear volumes of various plastics when abraded by 50 to 70 mesh silica (ASTM G 65 with shortened test time). Lower is better.

are available in molded form in many types of plastics. Of course, this would be a nonstandard procedure. The loading mass could be reduced so that the line-contact loading is the same as the standard width specimen.

Scratch Test: ASTM G 171

This test is very useful in assessing how easily different plastics scratch. There are many applications, such as auto reflectors, wind screens, paints, solid-surface countertops, floor finishes, etc., for which scratch resistance is desirable and candidates need to be ranked for scratch resistance. This is an abrasion test with a single asperity (a diamond) as the abrader. This test uses a Rockwell C diamond and the scratch length and force can be selected by the user.

The test metric is the scratch hardness and this number is essentially the force on the diamond divided by one-half of the projected area of the indenter (all of the scratching is performed by the leading half of the penetrator (Figure 6-7). A significant concern with this test is accurate measurement of scratch width. A scratch is a furrow with material plastically displaced to the sides (Figure 6-8). Optically, one may measure "W" as the width. Profilometer measurement of scratch width may indicate W_1 as the width. The test standard addresses this issue and gives suggestions on measurement technique.

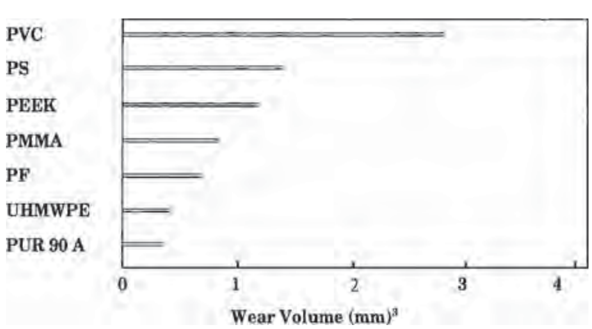

Fig. 6-5—Abrasive wear of selected plastics after 1.3 m of abrasion by 30-μm finishing tape (200 g loading mass, 100 rpm spindle speed, 0.625-inch spindle diameter, half-inch-wide specimen).

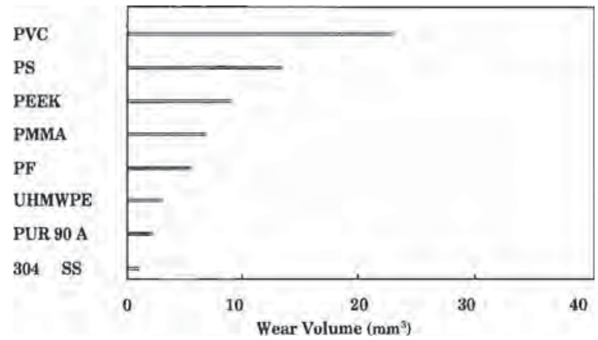

Fig. 6-6—Wear volumes produced by G 174 loop abrasion tests on one-quarter inch × one-quarter inch × one-inch flex bars (10 passes, 30 μm Al_2O_3, 100 rpm, 100 g).

Some commercially available scratching devices increase the load on the penetrator as it moves on the test surface. The load at the onset of scratching can be measured and used as a test metric. This technique is most often used to measure the load at which hard coatings spall. The simple G 171 scratch test is a very useful tool for assessing scratch resistance, but the correlation between scratch hardness and abrasion resistance remains to be established. The standard does not purport that the correlation exists.

Rubber Abrasion

Needless to say, abrasion is one of the most important forms of degradation of rubber. In fact, it is probably the biggest form of wear attrition on the planet, if one considers the annual wear volume from vehicle tires. There are probably a billion vehicles in operation daily losing rubber to rubbing on pavement, stones, or whatever roads are made from. Wear of tires depends on the amount of slip that occurs in the footprint of the tire. Of course, we mean under normal rolling conditions. A skid is abnormal and produces abnormal wear. If tires experience pure rolling, they would not wear. The definition of rolling is no relative motion between the revolute shape and counterface as the revolute shape moves under a force and in a particular direction. Pure rolling only occurs in a portion of the tire contact. There is also slip which makes the tires wear.

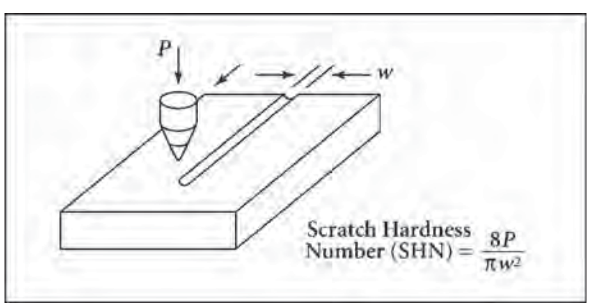

Fig. 6-7—Scratch hardness number.

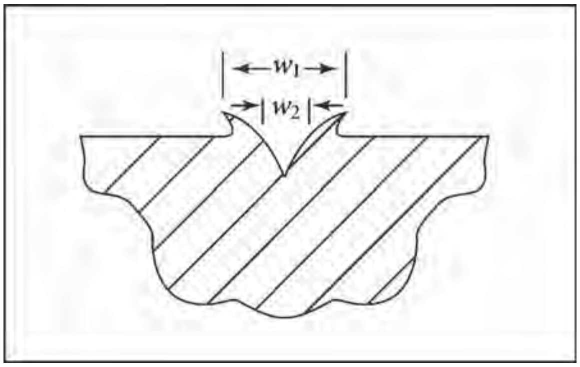

Fig. 6-8—Measuring scratch width.

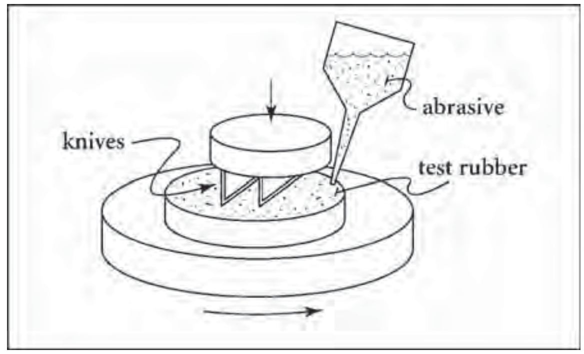

Fig. 6-10—Schematic of PICO Abrader.

Steel belting more than doubled the life of tires compared to polyester belted tires. The steel reinforcement reduced the "slip" portion of the rolling contact. There are ASTM vehicle tests for tire rubber abrasion resistance, but there is no reason why ASTM G 65 or G 174 could not be used. Most vehicle tires are made from SBR rubber (styrene butadiene) and any departures would require an incredible amount of friction (traction) testing. Thus, there may not be a market for new tire rubbers because of friction issues.

There are a number of ASTM test standards for rubber and rubber goods:

D 3389: coated fabric abrasion resistance
D 1630: rubber property − abrasion resistance (Footwear Abrader)
D 2228: abrasion resistance by Pico Abrader Method
D 5963: abrasion resistance (rotary drum abrader)

The footwear test uses a line contact rubber specimen pressed (five pounds of force) against a drum covered with 40 grit garnet (Figure 6-9). The coated fabric test uses the Taber Abrader in the usual fashion. The Pico Abrader uses razor blade-like carbide knives to cut the rubber (Figure 6-10) and concurrently, a "dust" of aluminum oxide and diatomaceous earth is fed on the specimen. The D 5963 rotary drum abrader spirals a rubber disk down a sandpaper (60 grit Al_2O_3) drum under a dead weight. The specimen can be rotated if desired. All three of the rubber tests have a test metric of an abrasion index based upon how candidates lose mass compared to reference rubbers. A concern with these tests is availability of reference rubbers and all three tests use rather complicated procedures. The G 174 loop abrasion test is much easier to perform and it is essentially the same concept as the D 1630 and D 5953 tests, that is, two-body abrasion. Polyurethane is a widely used elastomer for abrasion applications. It is a standard material for die springs and forming punches where it must withstand millions of rubs and impacts. Its abrasion resistance is a function of its Durometer hardness, and hardness may also be a concern with other rubbers (Figure 6-11).

In summary, there are a variety of abrasion tests for rubber, but the fillers/reinforcements and Durometer readings are likely to affect results and thus they need to be made a testing consideration. Reference materials are also a concern because all rubbers age or change with time as well as with environmental exposure conditions. High-Durometer (A-scale) polyurethanes traditionally are very resistant to abrasion compared with other rubbers. A castable 90 A polyurethane could be used as a reference and thus a new sheet could be cast whenever a fresh reference is needed. Compare candidate rubbers to 90 A PUR since its abrasion resistance in field conditions is well documented. This is just a suggestion for consideration. The current ASTM standards use traditional volcanates as references.

Sliding Wear of Plastics/Elastomers

Plastic-to-Metal

The ASTM G 77 block-on-ring test (Figure 6-12) has been used for many years to rank plastics for plastic bushing applications. The block is made from plastic, and standard hard steel rings are used as the counterface. After many years of use, it was learned that longer-term tests produce a different ranking. A special block-on-ring test, G 137, evolved as a "better" plastic

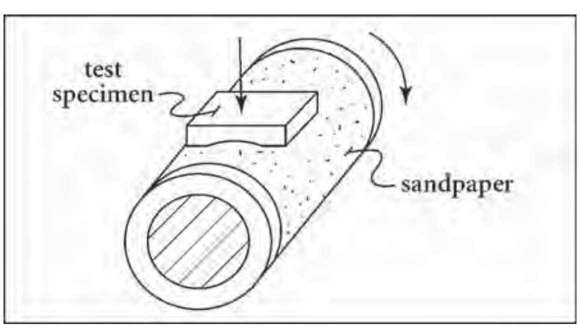

Fig. 6-9—Rubber versus sandpaper test.

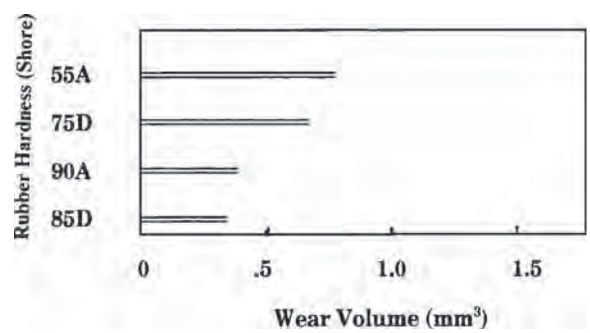

Fig. 6-11—Wear of various Durometer polyurethanes in the G 174 loop abrasion test (10 passes, 30 μm Al_2O_3, 100 rpm, 100 g).

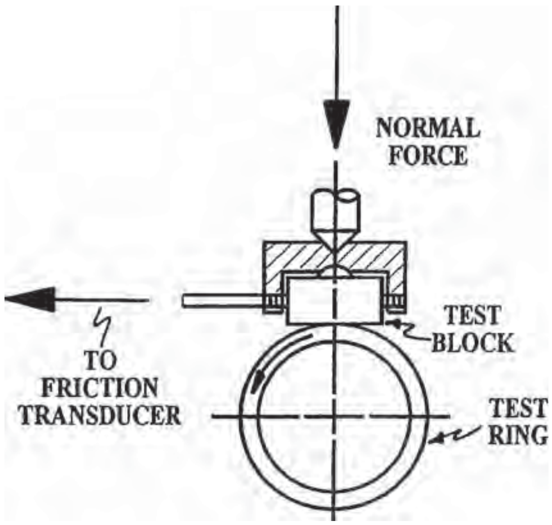

Fig. 6-12—Schematic of ASTM G 77 block-on-ring test.

test. The G 77 test lasts only one hour; the G 137 test is 25 hours with intermittent wear measurements. It also uses a bigger diameter ring (6″ vs. 1.3″). A newer version of the G 77 test has been formulated to provide a longer test, like G 137, but with the less expensive specimens of the G 77 test. The new plastic block-on-ring test is ASTM G 176.

Another test that was widely used in the early days of engineering plastics is the ASTM D 3702 thrust washer test (Figure 6-13). The test metric of the block-on-ring tests is mass change usually measured from a wear scar width calculation (wear volume calculated from scar width). The thrust washer test uses mass change and the test can be misleading if the plastic washer wears by displacement. It may be severely reduced in height, but there may be no mass loss. Many plastics are prone to deformation wear which is more readily measured in the block-on-ring tests.

Another important test in the early days of plastics for bearings is the bushing test. The plastic test specimens were bushings made from plastics of interest. The bushings were run against a standard shaft at a certain speed and load. These tests often required hundreds of hours to get significant mass loss measurement. Block-on-ring tests have largely replaced the bushing and thrust washer tests.

However, a major concern in ASTM as well as other plastic-to-metal tests is the wear that the plastic produces on the metal counterface. Glass and carbon fiber-reinforced plastics often produce significant counterface wear. The G 137 test does not require measurement of counterface wear, only plastic wear. Even hardened steels wear rubbing against filled plastics and thus counterface wear should always be measured. It is just as important as the plastic wear. It is recommended to present wear data in bar graphs that show plastic and counterface wear and together they are the system wear and this should be the test metric (Figure 6-14).

Pin-on-Rotating Disk

Pin-on-disk (ASTM G 99) and reciprocating pin-on-flat tests (G 133) can be used to assess sliding wear properties of plastics. Again, counterface wear should be measured. The pin-on-rotating disk test should be used to simulate continuous sliding; of course the reciprocating test simulates reciprocating motion applications. This test should be used only for reciprocating systems because the transfer of plastic to the counterface can be significantly different in reciprocating motion than continuous.

Both of these tests may require a plastic ball rider. These are easily made with a ball mold. Many development labs add this capability to molds that make flexural strength bars. If a ball mold is not available, hemispherical riders can be machined but be aware that a machined surface may wear much differently than a molded surface. Of the tests mentioned, the block-on-ring is probably the most widely used, followed by the thrust washer (D 3702). The G 133 test is a fast screening test for reciprocating systems.

Plastic-to-Plastic

These are many tribosystems that involve plastic-plastic mating couples, and as one might expect, such systems are prone to friction welding. Plastic/plastic couples should be avoided if possible, but they never will be completely eliminated, so in testing these systems, we recommend exact duplication of motions, speeds, forces, molded surfaces, and state of lubrication. For example, most electric saws, drills, and the like have housings made from plastic and the actuation switch is also plastic. Eventually, these wear and stick. Initial lubrication may make this plastic-plastic tribosystem last until the motor or other part of the system fails.

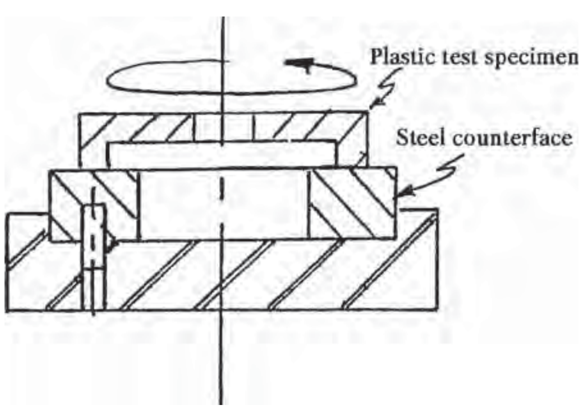

Fig. 6-13—Schematic of ASTM G 3702 thrust washer test (upper "washer" is the test plastic).

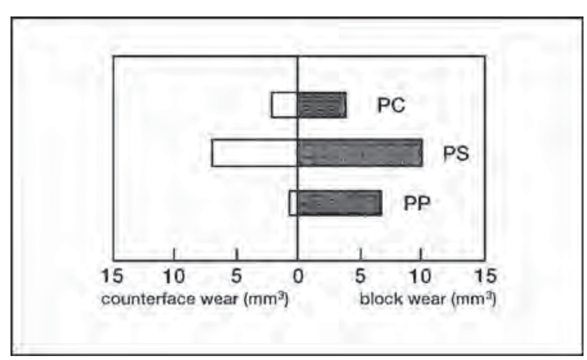

Fig. 6-14—Presentation of block and counterface wear data in block-on-ring wear tests.

Plastic-to-Ceramic/Cermet

The potential for plastic counterface wear can be ameliorated by using a ceramic, cemented carbide or cermet counterface. However, compatibility of these kinds of materials with various plastics is not well documented, and the use of compatibility tests often is a wise decision. For example, PTFE-filled acetate experiences low wear coupled with most hard steels. How it responds to a WC/Co counterface is not generally known and bench tests may be required.

Counterface roughness is always a consideration in any plastic/other material wear test. Too smooth or too rough counterfaces can cause greater-than-normal wear rates. The ideal counterface roughness is approximately 0.25 μm Ra. A ground or lapped surface usually produces the lowest wear rate against many plastics. In addition, care must be taken to remove as-molded surfaces on hard metal counterfaces (unless this is the anticipated service situation). Molded ceramics/cermets often contain errors of form that can act as files on the plastic or they may contain mold release or heat treat scale that can affect results.

Break-In

As mentioned previously, some standard wear tests are too short in duration. Molded surfaces usually are rich in resin, and they may behave differently than the bulk. There may be wear transitions caused by surface inhomogeneities that are missed in short tests (Figure 6-15). We suggest using long-term tests that were developed to include possible break-in effects and early wear transitions. Break-in and steady-state wear rate are determined by plotting wear versus sliding distance (time) for a long enough test duration to produce low, monotonous slope on the wear versus time curve.

Specific Wear Rate

It is common in Europe to express wear of plastics by specific wear rate. This term allows one to run a wear test, get a specific wear rate, then calculate dimensional loss in service knowing the sliding distance and normal force. Specific wear rate is based upon the Archard equation which states that the volume of wear in a wear test (or application) is a function of the sliding distance and normal force:

$$W = k\,DP$$

where W = wear volume (mm^3),
D = sliding distance (m),
P = force of one member on the other (N),
k = a constant = specific wear rate.

thus,

$$\text{specific wear rate} = \frac{W}{DP} \quad \frac{mm^3}{mN}$$

If a wear test is conducted at 10 N normal force with a sliding distance of 1 km, these data and the wear volume are used to solve for specific wear rate. If it is 50×10^{-9} mm^3/mN, it is possible to go to a production system and put in sliding velocity and time to arrive at a sliding distance. If the normal force is known—say that it is 3 N—it is now possible to solve for dimension loss per unit time (ex. 0.1 mm/year). If the material has a significant break-in rate as well as a steady-state rate, then caution should be exercised in using specific wear rate. A single value will not show this effect.

PV Limit

Another unique aspect of conforming surface wear tests on plastics is the concept of "PV limit." PV is an acronym for pressure (P) multiplied by velocity (V). The concept proposed is that for every plastic couple there is a PV limit; if this limit is exceeded, the sliding couple will experience rapid wear/deterioration. PV limit is experimentally determined using any conforming surface wear test if tests are conducted in a way that develops a PV limit curve. One test option is to hold velocity fixed and vary normal force until rapid degradation occurs (Figure 6-16). This series of tests yields one point for a PV limit curve. The test is repeated at a different velocity and another point is obtained and so on until a curve is developed that shows the safe operating range for a particular couple (Figure 6-17). Temperature, friction, melting, or other factors can be the test metric if they show a transition from desirable behavior to undesirable behavior. The way that PV is supposed to be used by designers is that they calculate the PV (in pounds per square inch × feet per minute or Pascals × meters per second) for their application, then find the PV limit curve for the couple that they wish to use and make sure that their PV is in the "safe" region.

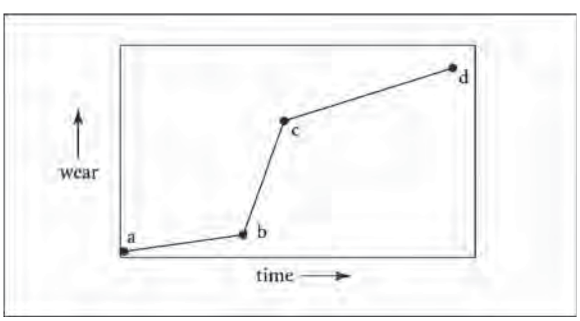

Fig. 6-15—Wear of plastic with time. A test terminated in area "ab" will produce different results than those allowed to run for longer times. "cd" is the steady-state wear rate.

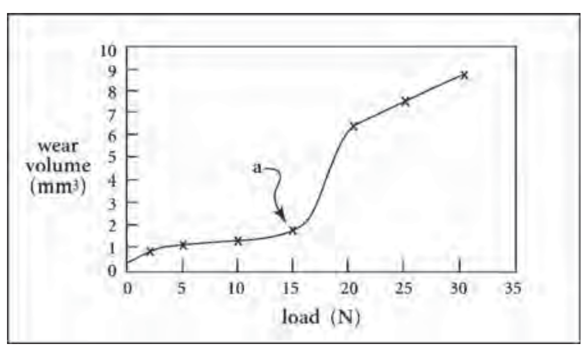

Fig. 6-16—Load (pressure) is increased until inflection occurs at a particular test velocity.

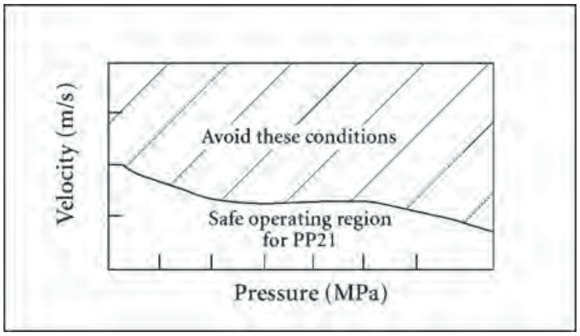

Fig. 6-17—Use of PV information to show safe operating regions for a specific plastic (PP21).

A concern with this concept is that the PV data apply only within the range of the conditions used in developing the data. As an example, nylon has a stated PV limit in English units of just under 10,000 versus hard steel. Theoretically, a designer who only has an apparent contact pressure of 1 psi on an application could run the couple with a sliding speed of 10,000 feet per minute. Of course, melting would occur. The PV limit tests never used sliding speeds that high so the data are not applicable. If developing a PV limit for a sliding couple is a testing objective, the developed PV limit data should clearly state the testing range in pressure and velocity that was used in developing the data. Potential users should be made aware that the data apply only to pressures under XX Pa and velocities below XX m/s.

Erosion of Plastics

Fortunately, plastics are not corroded by most aqueous and air fluids, so erosion in a fluid usually does not have a corrosion component. For example, a plastic basement sump pump may be pumping a sand water slurry, but material attrition can be attributed mostly to mechanical action of entrained hard particles (stones, sand, dirt, etc.). A significant exception to this statement is: plastics used outdoors may not be eroded by rain by itself, but coupled with UV or IR radiation degradation plastics may erode from rain water (Figure 6-18).

In any case, erosion of plastics due to contact with fluids in motion requires consideration of whether the fluid is corroding (degrading) the plastic as well as attrition due to the mechanical action of the fluid and other phases/particles in the fluid.

ASTM Tests

All of the erosion tests previously described can be used on plastics. The G 76 solid particle erosion test will produce severe damage to most plastics. The concern with this test is that measurement of mass loss may not take into consideration material that is damaged, but not removed. For example, abrasive blasting a plastic like polyethylene may shred the plastic producing attached fibrils. It is displaced, not lost material and weight change measurements may not accurately depict the damage. The length of the test may need to be altered until a definite wear crater is produced. A similar problem occurs with the G 32 and G 134 cavitation tests. Cavitating jets tend to shred plastics and more creative damage assessment techniques may be required.

Fig. 6-18—Matrix erosion on a composite light post used outdoors.

The ASTM G 73 rain erosion test uses samples affixed to the tip of a propeller that may have a supersonic tip velocity. Rain droplets tend to shred, even explode, plastics at these velocities. This test simulates aircraft entering a rain field and, of course, the concern is erosion of plastics, adhesives, coatings, and metals on the aircraft. Most windscreens on aircraft are polycarbonate and they must resist erosion. Radomes on the nose of aircraft are usually plastics and they must resist rain erosion. Thus, more creative damage assessment techniques often are required in these types of tests as applied to plastics. Often photos of test samples are all that is needed to document complete failure.

The Miller slurry test (ASTM G 75; Figure 6-19) can be used on plastics and elastomers. The original Miller number test ranks the abrasivity of various slurries (with a Miller number) using a hard chromium alloy iron rider. If the white iron rider is replaced with another rider, a "SAR number" or slurry abrasion resistance number is generated by measuring the attrition of the rider after a 16-hour test in a slurry of 50% water and 50% silica sand (50–70 mesh). The rider can be plastic. The Miller test can be used on elastomers by making the rider the rubber to be evaluated and replacing the rubber lap (Neoprene) that the rider rubs on with a glass plate. The SAR type of test is a useful test for plastics and rubbers that may see reciprocating wear in a particular slurry.

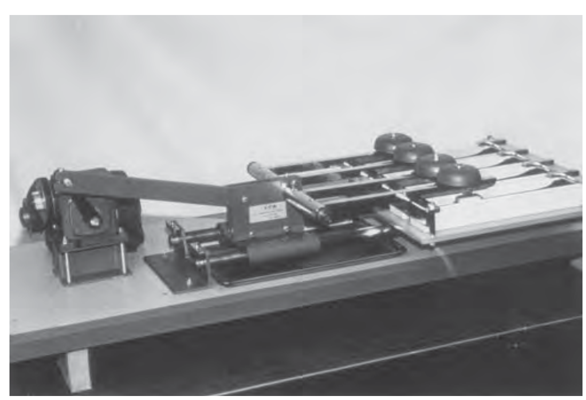

Fig. 6-19—Miller slurry test rig.

Nonstandard Tests

The ball cratering test that was previously described can be used on plastics. It is normally only used for fine abrasive/slurries (<10-μm particle size). If a use situation involves erosion of plastics by fine particulate in water, the ball cratering test could be used. A unidirectional slurry erosion test that can be used with any material couple and slurry is shown schematically in Figure 6-20. This test simulates plastics rubbing against a counterface immersed in a liquid. The liquid can contain particles. The test can also be run dry with the slurry pot filled with dry material such as sand or some particulate product. The test specimen is the rider and attrition can be determined by mass change.

Chapter Summary

Plastic wear and erosion testing is different from most other wear tests in that one must be very concerned with surface films and heterogeneity. Surface films such as mold release agents can be present; often they are silicones and these are very difficult to remove without altering the plastic surface. It is best to test as-molded surfaces made under controlled molding conditions.

Most molded plastic surfaces are resin rich compared to the bulk and thus there is likely to be a wear rate transition once this layer is penetrated. Tests need to be long enough for steady-state wear to dominate. Also, in conforming-surface tests, the roughness of the test counterface can affect results. Most metals and ceramics will abrade any plastic if they have a rough surface like between 1 and 2 μm Ra. The preferred roughness is from 0.1 to 0.25 μm Ra. In any instance, counterface roughness must be measured and considered in testing. Specimen cleaning must be done with a material/technique that does not chemically attack the plastic.

Erosion tests and some conforming-surface wear tests have the problem of displaced material as the manifestation of damage. Mass change measurements can miss this damage. Most plastic wear and erosion tests require additional care and even ingenuity in obtaining quantitative damage assessment.

Important Concepts

The following concepts should be taken from this chapter:

1. Plastics are poor heat conductors and, thus, sliding speeds must be kept moderate to prevent local melting.
2. Molded surfaces can have different properties than bulk material.
3. Longer tests are preferred.
4. Counterface wear should always be a test metric.

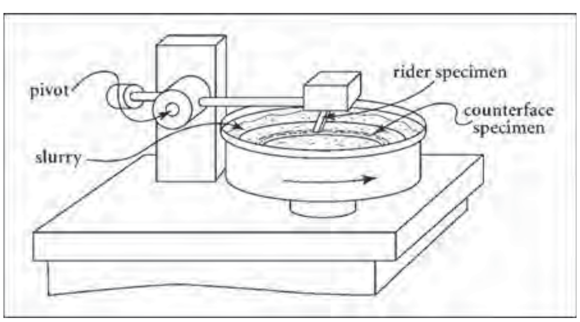

Fig. 6-20—Schematic of 30-day wet erosion test.

5. Molded plastics are anisotropic. Properties may vary by part location.
6. Plastics usually need lubrication (external, second phase, etc.) to be suitable for sliding wear applications.
7. Plastics can be abrasive (to rollers, etc.).
8. "Standard" abrasion tests can be used on plastics, but some require reduced severity (loads, time, speed).

Resources for More Information

Plastic Wear Tests

Bayer, R. G., *Wear Tests for Plastics: Selection and Use*, STP 701, ASTM International, W. Conshohocken, PA, 1979.

Bartenev. G. M. and Lavrentev, V. V., *Friction and Wear of Polymers*, Amsterdam, Elsevier, 1981.

Moore, D. F., *The Friction and Lubrication of Elastomers*, Oxford, Pergamon Press, 1972.

Lee, L. H., Ed., *Advances in Polymer Friction and Wear*, Bul. 5A, New York, Plenum Press, 1974.

Denton, R. and Keshavan, M. K., *Wear and Friction of Elastomers*, STP 1195, ASTM International, W. Conshohocken, PA, 1992.

Composite Wear

Friedrich, K., *Friction and Wear of Polymer Composites*, Dusseldorf, Verlag, 1984.

Wear Fundamentals

Yamaguchi, Y., *Tribology of Plastic Materials*, Amsterdam, Elsevier, 1990.

Keshavan, K., *Wear and Friction of Elastomers*, STP 1145, W. Conshohocken, PA, ASTM International, 1992.

Bayer, R., *Wear Testing Advanced Materials*, STP 1161, ASTM International, W. Conshohocken, PA, 1992.

Plastic Acronyms

Budinski, K. G., and Budinski, M. K., *Engineering Materials: Properties and Selection*, Upper Saddle River, NJ, Prentice Hall, 2003.

Related ASTM Standards

C 501 – Standard Test Method for Relative Resistance to Wear of Unglazed Ceramic by Taber Abrader *(H-22 coarse wheel, 9.8 N force, 1000 revolutions.)*

D 968 – Standard Test Methods for Abrasion Resistance of Organic Coatings by Falling Abrasive *(Sand or silicon carbide falls by gravity on a coated metal or glass specimen until the coating is penetrated; abrasion resistance is the mass of abrasive required to remove one mil (0.001 inch) of coating.)*

D 1044 – Standard Test Method for Resistance of Transparent Plastic to Surface Abrasion *(72 rpm, CS-10F Taber Abraser wheel; user selects load and duration; change in light transmission is the test metric.)*

D 1630 – Standard Test Method for Rubber Property – Abrasion Resistance (Footwear Abrader) *(A rubber is abraded by 40 grit garnet paper on a drum; the wear depth in the rubber is compared with that of a reference rubber tested before and after the test rubber.)*

D 2228 – Standard Test Method for Rubber Property – Relative Abrasion Resistance by Pico Abrader Method *(A pair of cemented carbide knives are loaded against the rotating test rubber; mass loss is measured.)*

D 3702 – Standard Test Method for Wear Rate and Coefficient of Friction of Materials in Self-lubricated Rubbing Contact Using a Thrust Washer Testing Machine *(40-hour break-in followed, by test with user- determined speed, load, and test duration.)*

D 4060 – Standard Test Method for Abrasion Resistance of Organic Coatings by the Taber Abrader *(CS-10 or 17 wheels, 1000 g/wheel, duration is user's option, mass change is measured.)*

D 5963 – Standard Test Method for Rubber Property – Abrasion Resistance (Rotary Drum Abrader) *(A rubber specimen is loaded against [10N] and spirals down a sanding drum covered with 60 grit aluminum oxide abrasive, mass change is measured.)*

D 6037 – Standard Test Method for Dry Abrasion Mar Resistance of High-Gloss Coatings *(Taber Abrader with CS-10 wheel, 500 g, 10 revolutions suggested, measure gloss change.)*

F 510 – Standard Test Method for Resistance to Abrasion of Resilient Floor Covering Using an Abrader with a Grit Feed Method *(240 grit aluminum oxide, leather wheels, 1000 g, 2000 revolutions.)*

F 735 – Standard Test Method for Abrasion Resistance of Transparent Plastics and Coatings Using the Oscillating Sand Method *(The test specimen is covered with a layer of 8/10 silica sand in a cradle that reciprocates at 5 Hz; change in light transmission is measured.)*

G 65 – Standard Test Method for Measuring Abrasion Using the Dry-Sand/Rubber Wheel Apparatus *(Specimens are forced against a rubber-tired wheel and 50/70 mesh silica is fed between the rotating wheel and stationary specimen, mass change is the test metric.)*

G 137 – Standard Test Method for Ranking Resistance of Plastic Materials to Sliding Wear Using a Block-on-Ring Configuration *(A plastic block is forced vertically against a rotating disk, test speed and load are the user's options, but the specimen is removed from the rig at least 6 times to measure the progression of wear; specific wear rate is calculated.)*

G 171 – Standard Test Method for Scratch Hardness of Materials Using a Diamond Stylus *(A conical diamond penetrator is scratched on a surface and the scratch width is measured.)*

G 174 – Standard Test Method for Measuring the Abrasion Resistance of Materials by Abrasive Loop Contact *(For plastics, a 30-μm aluminum oxide abrasive tape is rubbed tangentially for 20 loop passes [27 m] against a specimen forced against the loop with a 100-g mass, wear volume is calculated from the scar size.)*

G 176 – Standard Test Method for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method *(Falex 1 test machine, 200 rpm, 10 lbf, 20-hour test time, block wear volume is measured.)*

7

Lubricated Wear Tests

Introduction

THE PURPOSE OF MOST WEAR TESTS IS TO SIMU-late a specific situation, a type of motion, frequency, speed, etc. Of course, some tribosystems involve the use of lubricants. Thus, representative bench tests also use lubrication–a lubricated wear test, which is the primary subject of this chapter. The objective of a lubricated wear test is often to determine the efficacy of a particular material couple when lubricated in a specific way. There are also tests, called lubricant tests, that keep the material couple constant and test the friction or wear reduction characteristics of lubricants, although these tests are not included in the chapter scope. The evaluation of lubricants is such a large subject that it could not be properly addressed in one short chapter.

In addition, there are a plethora of lubricant tests that address characteristics other then their friction and wear reduction capabilities. For example, oil tests include biodegradability, viscosity, foaming, acidity, and contaminants. Grease tests include tests to assess stiffness (cone penetration), corrosivity, evaporation characteristics, and separation characteristics. Solid film lubricant tests include corrosivity, adhesion, and shock resistance. Screening lubricants requires more than wear tests. The chapter objective is knowledge of wear tests that can be used to screen material couples in the lubricated condition.

This chapter will describe important lubricant families and then discuss some of the more commonly used ASTM and nonstandard tests. Many important lubricant terms were defined in Chapter 1. Additional terms will be defined as needed. We will discuss ASTM standard tests and then some nonstandard tests.

Many wear tests are performed in a way that allows measurement of the system friction. In lubricated tests, it is imperative to keep in mind that system friction usually depends on the speed of the relative motion between the test surfaces (Figure 7-1). In other words, the friction and wear at 10 rpm may be completely different than the wear that occurs at 1000 rpm. The latter may be orders of magnitude lower because at some speed the lubricant will fully separate the conforming surfaces. Because they do not touch, they do not wear. The well-known Stribeck curve applies to oils and greases (Figure 7-2) and it shows that a lubricant will lubricate differently depending on speed and viscosity.

In summary, many of the wear tests described for adhesive wear can be used under lubricated conditions, but the utmost care must be taken to make sure that sliding speed, viscosity, and temperature effects on the lubricant are considered.

Types of Lubricants That Can Be Encountered

Lubricating Oils

As defined in Chapter 1, a lubricant is any material imposed between two sliding surfaces that reduce the friction and wear between them. In fact, most anything that separates surfaces usually lubricates them. This can include wear debris, dirt, and corrosion–lots of things. However, none of these unintentional separating materials is as effective as oil. Oil is a fluid derived from petroleum or other hydrocarbon starting materials with sufficient viscosity and shear characteristics to allow it to separate rubbing surfaces under appropriate conditions and reduce friction and wear between them. "Under appropriate conditions" means that it is likely that one drop of oil will not separate a bushing on a 50-mm diameter shaft; a light mineral oil will not work (for long) in a race engine, and a crankshaft immersed in oil will not have complete separation between bearings and journal surfaces at a rotational speed of one revolution per minute.

It takes the right conditions to have oils completely separate surfaces. As one might expect, many lubricated wear tests are purposely designed to stress a lubricant's ability to completely separate surfaces. In fact, two popular lubricated wear/lubricant tests, the four-ball and the pin-on-vee block, test at ever increasing loads until the test specimens seize. The load at seizure becomes the test metric. These types of tests can be termed "load-carrying ability" tests.

Getting back to oils, there are more types of oil commercially available than anyone can probably become familiar with. However, there are commonalities in all. All oils start as a base oil. Base oil is a petroleum product distilled from crude oil. It is the product of a refinery. Crude oils are the naturally occurring liquids (or solids like tar sands) that are extracted from the earth's crust. They differ in composition based upon where they are located, and they contain compounds of sulfur, nitrogen, oxygen, metals, and a variety of elements. They are refined to different purities and are sold to oil formulators or compounders, in different grades that reflect impurity levels. Regulatory agencies generally recognize four grades of base oil. The greater grades have higher quality (and cost).

Grade IV oils are synthetic oils. Unlike base oils made from crude oil, synthetic oils are engineered from starting material other than petroleum from the earth's crust. For example, they could be made from hydrocarbon gases. The significant difference is that the long-chain hydrocarbon molecules that make up the oil have greater consistency than hydrocarbon molecules in base oils that started life in the ground. These oils may have a varied molecular weight. Chains may be from 225 to 700 molecules in length (molecular weight) whereas synthetic oils may have chain lengths that may vary (molecular weight) by only 10%. Crude oils can contain 600 to 800 different compounds and the hydrocarbon molecules can be mixtures of paraffinic, naphthenic, or aromatic structures. Synthetic oils are theoretically a single chemical entity such as poly-alpha-olefin (PAO). The alleged benefits to the user from synthetic oils can be improved life and properties at elevated temperatures. These better properties are said to be the result of their more uniform structure.

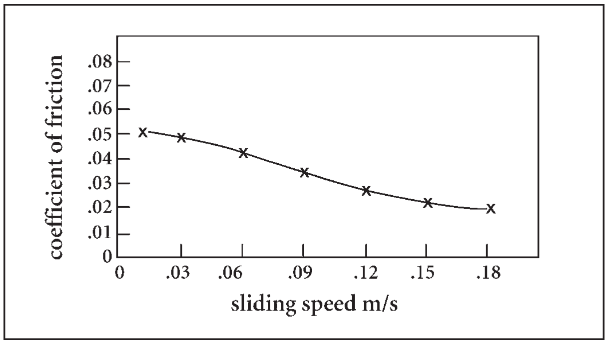

Fig. 7-1—Effect of test velocity on coefficient of friction of a test couple in a test oil.

Getting back to differences in oils, base oil, be it a grade I, II, III, or IV, is not a lubricating oil until it is compounded. Compounded oil is what people buy—it is base oil with an additive package. Additives are materials mixed with base oils to impart or enhance desirable properties or to suppress undesirable properties. Additives for oils used in automobiles usually include antiwear additive, additives to reduce oxidation of oil at elevated temperatures, additives to control viscosity, additives to prevent foaming, additives to control sludge, additives to control varnish formation, and the like. Additive packages may make up only a few percent of the volume of formulated oil, but they are the key to performance in service. The additive package is what discriminates one oil from another one and, as one might expect, formulations usually are proprietary. Table 7-1 tabulates standard property tests that are performed on oils. This summary is updated in ASTM D 6074. Oils are tested for these many physical properties before they are tested for efficacy in wear and friction tests. An oil will not be suitable for use in an automobile if it turns to a semisolid at the freezing temperature. Similarly, it will not make good automotive oil if it foams and flows out of the engine breather tube at 2000 rpm.

In summary, oils are commonly included in wear and friction studies. Commercial oils are compounded. They are base oils with an additive package, and tribological, physical, and rheological properties depend on the nature of the base oil and additive package. Often lubricated wear and friction tests are conducted under severe load and velocity conditions to stress the oil and separate additive packages.

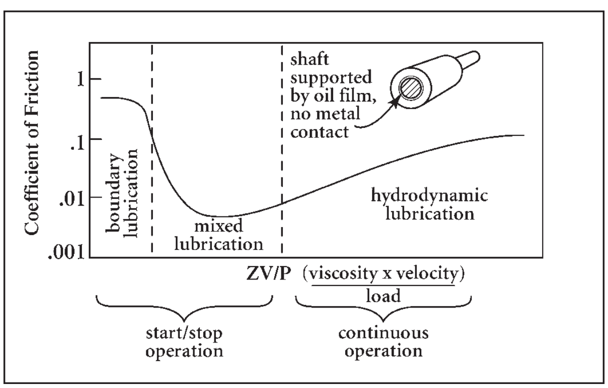

Fig. 7-2—The "Stribeck" curve for friction of lubricated systems.

Lubricating Greases

The ASTM definition of grease recommends that the term "grease" always be preceded by "lubricating" to differentiate the grease used in machinery for lubrication from the grease used in French fry cookers. The ASTM Committee D02 definition for a lubricating grease is "a semi fluid to solid product of a dispersion of a thickener in a liquid lubricant." Greases are formulated like lubricating oils from a base oil and an additive package. Thickeners are often inorganic materials such as clays that have an "open structure" that serves as an oil receptor. The concept of oil in a thickener is similar to water in a sponge. The liquid is held in the interstices of the thickener until called for in service. Most lubricating greases have a peanut butter consistency at room temperature but, in a bearing, frictional heat causes the oil to come out of the thickener in liquid form to separate the balls, races, and separator. When the machine is shut down the oil goes back into the thickener structure waiting for its next call to service.

Thickeners are mostly present in the form of microscopic fibers with dimensions of a few micrometers in diameter and a fiber length of about 100 μm. They can be soaps such as calcium or lithium or natural clay. The thickener and the additive package for the base oil are usually proprietary. They are the features that discriminate one lubricating grease from another. The additive packages can contain many of the same additives used in lubricating oils.

Lubricating greases have their own set of property tests that may need to be considered when screening greases in wear and friction tests (Table 7-2). Some of the tests listed are for determining tribological properties as opposed to physical properties (D 2596, D 2266, D 4170, D 3704, D 5707). An important property of lubricating greases is stiffness. This is an indicator of the ability of lubricating grease to stay in place (where it is needed). There are penetration tests that rate lubricating greases for their stiffness, but in wear testing, it is often necessary to develop techniques to quantify migration from the sliding interface. Of course, low-temperature properties are also a consideration, as are rust prevention and corrosion.

In summary, using oils and greases in friction and wear tests requires attention to anticipated use conditions. If materials are being evaluated for use in automobile engines, the bench tests need to at least simulate the operating temperature. Sometimes things such as soot or Arizona dust need to be added to a lubricant to better simulate use conditions. It is these kinds of factors that complicate bench tests involving greases and oils. However, there are bench tests that have been developed for lubricants and lubricate material couples that reportedly simulate engine tests costing ten to fifteen times as much.

Solid Film Lubricants

Solid film lubricants are simply coatings on solid surfaces that improve tribological performance. They can be burnished in lubricating solid such as graphite; they can be polymer coatings filled with a lubricating material; they can be mixtures of materials applied by vacuum, deposition techniques such as sputtering; they can be thermal sprayed coatings. Polymer coatings filled with lubricating materials are probably more commonly used, but the binderless coatings such as the vacuum and thermal sprayed coatings are becoming more popular.

Solid film lubricant coatings can be applied in thicknesses from a fraction of a micrometer (for sputtered coatings) to as

TABLE 7-1—Joint ASTM/IP lubricant test methods.

ASTM Test Number	IP Test Number	Method Description
D 92-01	36	Flash and Fire Points by Cleveland Open Cup
D 93-00	34	Flash Point by Pensky-Martens Closed Cup Tester
D 97-96a	15	Pour Point of Petroleum Products
D 189-01		Conradson Carbon Residue
D 297-92		API Gravity
D 445-97	71	Kinematic Viscosity and Cal'c of Dynamic Viscosity
D 482-00		Ash in Petroleum Products
D 524-00		Ramsbottom Carbon Residue
D 611-82	2	Aniline Point Determination
D 892-01	146	Lubricant Foaming
D 943-99	157	Oxidation of Inhibited Oils
D 1492-96		Bromine Index
D 1500-98		ASTM Color
D 2007-01		Aromatics, Saturates, Polars in Base Oil
D 2008-91		UV Absorbance of Petroleum Products
D 2270-93	226	Cal'c of Viscosity Index from Kinematic Viscosity
D 2272-98		Oxidation Stability—Rotating Vessel
D 2500-99	219	Cloud Point of Petroleum Oils
D 2549-91		Aromatic/Nonaromatic Separation
D 2622-98		Sulfur by X-Ray Fluorescence
D 2710-99		Bromine Index by Electrometric Titration
D 2786-91		Hydrocarbon Types of Saturates
D 2887-01		Simulated Distillation (Volatility)
D 2983-01		Low-Temperature Brookfield Viscosity
D 3228-96		Kjeldahl Nitrogen
D 3239-91		Aromatics Molecular Types in Base Oil
D 3339-95		Acid Number
D 3829-93		Borderline Pumping Temperature
D 4289-97		Elastomer Compatibility
D 4530-00		Carbon Residue—Micro Method
D 4624-93		High-Temp/High-Shear Viscosity by Capillary Viscometry
D 4629-96	379	Organically Bound Nitrogen
D 4636-99		Corrosiveness of Hydraulic Oils
D 4683-96		High-Temp/High-Shear Viscosity by TBS
D 4741 -00		High-Temp/High-Shear Viscosity by Tapered Plug
D 4742-96		Oxidation by Thin Film Uptake
D 4871-00		Guide for Universal Oxidation Test
D 4927-96		Elemental Analysis
D 5293-99		Cold Cranking Viscosity of Engine Oils at −5 to −35°C
D 5480-95		Volatility by Gas Chromatography
D 5481-96		High Temp/High Shear Viscosity by Capillary Viscometry
D 5483-95		Oxidation of Grease by DSC
D 5776-99		Bromine Index
D 5800-00		Noack Volatility
D 5864-00		Aquatic Aerobic Biodegradation
D 5949-96		Pour Point by Automatic Pressure Pulse
D 5950-96		Pour Point by Automatic Tilt
D 5985-96		Pour Point by Rotation
D 6006-97		Biodegradability of Hydraulic Fluids
D 6074-99		Guide to Characterizing Hydrocarbon Base Oils
D 6082-00		High-Temperature Foaming
D 6366-99		Trace Nitrogen
D 6616-01		High-Temp/High-Shear Viscosity by TBS at 100°C
E 1687-98		Carcinogenic Potential of Metalworking Fluids

TABLE 7-2—ASTM/IP Standards for Evaluating Lubricating Grease Properties and Performance

ASTM	IP	Test Method Title
D 217	50	Test Methods for Cone Penetration of Lubricating Grease
D 566	132	Test Method for Dropping Point of Lubricating Grease
D 942	142	Test Method for Oxidation Stability of Lubricating Greases by the Oxygen Bomb Method
D 972	183	Test Method for Evaporation Loss of Lubricating Greases and Oils
D 1092		Test Method for Apparent Viscosity of Lubricating Greases
D 1263		Test Method for Leakage Tendencies of Automotive Wheel Bearing Greases
D 1264	215	Test Method for Water Washout Characteristics of Lubricating Greases
D 1403	310	Test Methods for Cone Penetration of Lubricating Grease Using One-Quarter and One-Half Scale Cone Equipment
D 1404		Test Method for Estimation of Deleterious Particles in Lubricating Grease
D 1478		Test Method for Low-Temperature Torque of Ball Bearing Greases
D 1742		Test Method for Oil Separation from Lubricating Grease During Storage
D 1743		Test Method for Corrosion Preventive Properties of Lubricating Greases
D 1831		Test Method for Roll Stability of Lubricating Grease
D 2265		Test Method for Dropping Point of Lubricating Grease over Wide Temperature Range
D 2266	239	Test Method for Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method)
D 2509	326	Test Method for Measurement of Extreme Pressure Properties of Lubricating Grease (Timken Method)
D 2595		Test Method for Evaporation Loss of Lubricating Greases over Wide Temperature Range
D 2596	239	Test Method for Measurement of Extreme-Pressure Properties of Lubricating Greases (Four-Ball Method)
D 3336		Test Method for Performance Characteristics of Lubricating Greases in Ball Bearings at Elevated Temperatures
D 3337		Test Method for Evaluation of Greases in Small Bearings
D 3527		Test Method for Life Performance of Automotive Wheel Bearing Grease
D 3704		Test Method for Wear-Preventive Properties of Lubricating Grease Using the (Falex) Block-on-Ring Test Machine in Oscillating Motion
D 4048		Test Method for Detection of Copper Corrosion from Lubricating Grease by the Copper Strip Tarnish Test
D 4049		Test Method for the Resistance of Lubricating Grease to Water Spray
D 4170		Test Method for Fretting Wear Protection by Lubricating Greases
D 4289		Test Method for Compatibility of Lubricating Grease with Elastomers
D 4290		Test Method for Determining the Leakage Tendencies of Automotive Wheel Bearing Grease Under Accelerated Conditions
D 4425		Test Method for Oil Separation from Lubricating Grease by Centrifuging (Koppers Method)
D 4693		Test Method for Low-Temperature Torque of Grease-Lubricated Wheel Bearings
D 4950		Classification and Specification for Automotive Service Greases
D 5438		Practice for Collection of Floor Dust for Chemical Analysis
D 5706		Test Method for Determining Extreme Pressure Properties of Lubricating Greases Using a High-Frequency, Linear-Oscillation (SRC) Test Machine.
D 5707		Test Method for Measuring Friction and Wear Properties of Lubricating Greases Using a High-Frequency, Linear-Oscillation (SRV) Test Machine.
D 5969		Test Method for Corrosion-Preventive Properties of Lubricating Greases in the Presence of Dilute Synthetic Sea Water Environments
D 6138		Test Method for Determination of Corrosion Prevention Properties of Lubricating Greases Under Dynamic Wet Conditions (EMCOR Test)
D 6184		D6184-98 Standard Test Method for Oil Separation from Lubricating Grease (Conical Sieve Method)
D 6185		Standard Practice for Evaluating Compatibility of Binary Mixtures of Lubricating Greases

thick as 100 μm for thermal spray. The lubricating materials are usually powder particles ranging in size from a nanometer to 10 μm. Probably the oldest solid film coating is graphite, and the most popular solid film lubricant is molybdenum disulfide. Other materials that can be used are polytetrafluoroethylene and other fluorocarbons, boron nitride, tungsten disulfide, antimony oxide, and soft metals such as silver and indium.

The solid film lubricants that require an organic binder can have binders from any of the polymeric materials that are used for paints. For example, molybdenum disulfide can be added to an air-dry lacquer or to an epoxy or phenolic that must be baked to cure. These coatings are applied with painting techniques and the pretreatment of the substrate is a critical part of their use. They may not adhere properly without proper pretreatment of the substrate.

The lubricating properties of these solid film coatings depend on their composition. The painting variants have a wide variety of properties depending on the binder to active lubricant ratio. Sputtered molybdenum disulfide is all molybdenum disulfide, and the properties mostly depend on the coating thickness and the bond achieved in the coating process. The same thing is true about the pure lubricant paint type coatings such as Teflon S and the thermal spray coatings. Adhesion is the name of the game.

For decades, laboratory bench tests have been used for screening types of solid film lubricant coatings for their ability to reduce friction and wear as well as for their ability to adhere to a surface. Some tests assess the wear characteristics of the coatings, some tests assess the load-carrying capability, some tests assess cycles to failure, and some assess friction characteristics.

The block-on-ring test that is used for metal-to-metal and oil-lubricated metal-to-metal tests is a commonly used bench test for this class of materials. These tests are complicated by thickness difference and the age-old question of whether to coat one member or both members. Often the answer to the latter question is deferred to the coating supplier. They usually run their own test to answer this question. One way to deal with thickness difference in comparing coatings with different thickness is to stop the test at wear-through and compare wear rates rather than wear volume for a given test time. The tests that are run to determine load-carrying capability usually ignore thickness differences and it is simply a matter of which coating can carry to most load whatever its thickness. A cycle-to-failure test can be conducted neglecting thickness differences.

ASTM Lubricated Wear Tests

Block-on-Ring: ASTM G 77

The ASTM G 77 block-on-ring test that was described in Chapter 4 can be used lubricated and there are several ASTM specifications for evaluating lubricants with this rig.

D 2714 – Calibration and operation of the Falex flock-on-ring friction and wear-testing machine

D 2981 – Wear life of solid film lubricants in oscillating motion

D 3704 – Wear preventative properties of lubricating greases using the block-on-ring test machine in oscillating motion

The D 2714 standard is intended to calibrate the machine. A specific test is conducted in relatively low viscosity mineral oil, the type available in drug stores in the United States, and a certain scar size is to be obtained on a 30-HRC 01 tool steel test block sliding against a 60-HRC steel ring. The calibration standard also specifies a friction force range after a specified sliding distance. The test ring is half immersed in the oil. This procedure could be used to evaluate material couples in a particular lubricant. The G 77 standard does not specify a ring or block material since the objective of the test is to evaluate unlubricated material couples.

When the D 2714 test was developed, all participating laboratories were sent the calibrating fluid from the same 55-gallon batch of mineral oil. This "master batch" of calibrating fluid is now depleted and a potential concern is obtaining a comparable mineral oil. One way for a laboratory to deal with the situation is to buy a large quantity of a lot that produces the desired calibration results and keep this on hand for calibration.

In using the block-on-ring tester to screen material couples in a desired lubricant, it is advisable to simulate service conditions with speed and load, if possible. If you are evaluating lubricants, it may be well to test with a hard/hard couple (ring and block at 60 HRC) and perform a speed series to determine where hydrodynamic lubrication starts. Essentially, develop a Stribeck curve. Then, test the lubricants in the boundary and the hydrodynamic range.

The ASTM D 2981 oscillating test for solid film lubricants uses the same machine as the G 77 and D 2714 tests with an adjustable crank arm substituted for drive pulleys. The ring oscillates through an adjustable arc and the block is stationary (the same size rings and blocks as the other tests and both at 60 HRC). The normal load is 630 lb (283 kgf), and the test is run until the solid lube coating fails based upon friction force increase. The test is terminated at a coefficient of friction of 0.1.

A concern with this test is breaking the machine or stalling the motor when the coating fails. Some coatings could be removed quickly yielding a friction coefficient of 1 and a friction force of 630 lb, far above what most transducers can tolerate. On the other extreme, some coatings may last indefinitely; screening solid film lubricants can be less risky on the G 133 reciprocating test. The oscillating test for grease, D 3704, does not set operating parameters for the block-on-ring tester. Load, speed, test couple, and test duration are the options. The standard deals with application of the grease and how to assess the wear.

In general, the block-on-ring test is a suitable simulator of common tribosystems such as plain bearings (bushings) with a shaft in a cylindrical hole with a running clearance. Its significant advantage over the real thing (like a bushing on a shaft) is that the block and ring scars obtained allow more accurate quantification of wear of both members compared with gravimetric techniques.

Aside from the obvious problems of specimen alignment, a significant concern in using this test is: there is a tendency to increase the line contact stress to levels above the yield strength of one or both members of the sliding couple. Another concern is the severe vibration that can occur in high load tests. Some test procedures tend to produce failures of machine components. Some machines have advertised load capabilities of approximately 500 kg with the standard size specimens. This kind of load will result in a Hertz stress greater than the compressive yield strength of any metal or cemented carbide. The message here is to use this test under reasonable test conditions. Do not accelerate speed and load to conditions that are outside of the realm of the real tribosystems that the test is simulating.

Reciprocating Test: ASTM G 133

Procedure b of the ASTM G 133 ball-on-flat reciprocating test is intended to be run lubricated. The dry test load is 25 N; the lubricated load is 200 N. The sliding distance is increased to 400 m, and the frequency is increased from 5 to 10 Hertz. The test couple is completely immersed in a lubricant of the user's choice. The stroke is maintained at 10 mm.

A concern with this test is the single sliding speed. The friction and wear in lubricated systems are influenced by sliding speed, and procedures can be in the hydrodynamic region for some lubricants and test surfaces. Under hydrodynamic conditions, the sliding members are separated and wear will be nil. If the test is conducted to screen material couples, testing under hydrodynamic lubrication conditions may make material differentiation difficult. . A solution is to test at several speeds. A friction versus velocity plot will provide information on the lubricant separation. The friction coefficient will plateau at its lowest level when hydrodynamic lubrication is achieved. Wear screening tests may be more effective when conducted in the boundary lubrication regimen.

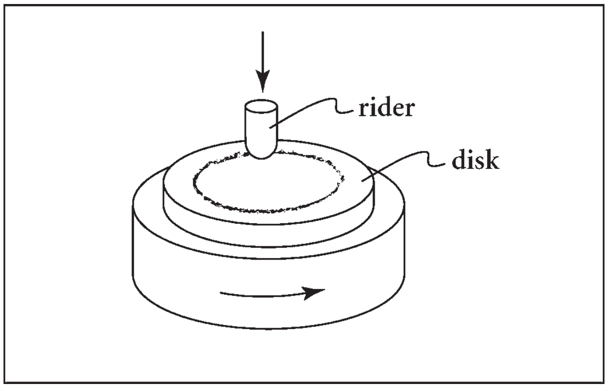

Fig. 7-3—Schematic of the pin-on-disk test.

Pin-on-Disk: ASTM G 99

The pin-on-disk test is popular for all sorts of wear tests (Figure 7-3). It is easy to perform, and unlubricated most materials will readily wear at relatively light normal forces and sliding velocities. Lubricated tests require higher normal forces. The G 99 standard allows the use of any speed and normal force, but the frictional velocity concern exists. Several test velocities are suggested. Another concern is retaining lubricant at high sliding velocities. Centrifugal force wants to fling the lubricant off of the disk and out of the container. There is a limiting speed for most machine designs.

This test is most often restricted to light loads (<20 N) and low velocities (<1 m/s). With a hemispherical rider, it does not simulate many real-life tribosystems. For this reason, it is mostly used for researching mechanisms and the like.

Four-Ball Test: ASTM D 4172

This is not a lubricated wear test; it is a lubricant test. It was stated that lubricant evaluation is not within the scope of this guide, but the four-ball test with modifications is quite widely used as a wear test. The D 4172 test is illustrated in Figure 7-4.

The three lower balls are fixed, and the upper ball rotates on the three fixed balls. The test metric is the average size of the scars on the three lower balls after 60 min of rubbing at 1200 rpm and at a normal force of 147 or 392 N. The test oil completely covers the balls and it is heated to 75°C. The balls are made from 52100 steel (12.7-mm diameter) and they are made with "extra polish."

Because the standard fixes the ball material, this test evaluates different lubricants rather than materials. In fact, a significant concern in using this test to perform lubricated wear tests is obtaining polished balls from the various materials that one might want to evaluate. Various techniques have been developed to put flats on the lower balls or modify this test.

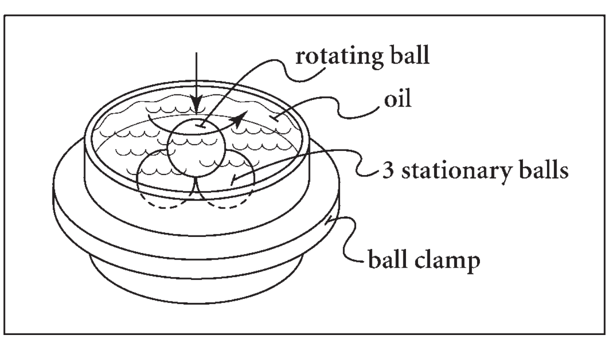

Fig. 7-4—Schematic of the four-ball test.

Conceptually, this test allows hard metals to rub on each other at very high stresses and this taxes a lubricant; it provides a good screening tool. Another concern with the test is that when lubricants cannot provide enough surface separation, the balls can weld and damage the machine unless it has a shear pin or similar protection.

Friction and Wear of Greases with the SRV Tester: ASTM D 5707

This test is like the G 133 reciprocating ball-on-plane but with higher reciprocating frequency (50 Hz vs 5 or 10 Hz), longer time (2 h vs <20 min), and lower amplitude (1 mm vs 10 mm). The normal force is the same, 200 N, as is the test rider (52100 steel at 60 HRC and ×10 mm in diameter). The counterface is a 52100 steel disk at 60 HRC, 9.85 mm thick, 24 mm in diameter. Grease is applied to the contact area as a pea-sized dollop. The test metric is the diameter of the wear scar on the ball and the depth of the groove in the counterface.

The SRV machine is also used for evaluating extreme-pressure lubricants. ASTM D 6425 is a standard test method using the same size and material for test specimens, the same stroke (1 mm), and the same test time (2 h) and frequency (50 Hz), but with a higher normal force (300 N vs 200 N). The test metric is the same ball wear scar and groove depth except the friction coefficient is reported at 15-min time increments throughout the test.

A significant feature of the SRV machine is its high oscillating frequency and normal force capability. It can have an oscillating frequency of 500 Hz and a normal force of 2000 N. The specimen stage can be heated to 900°C. The stroke can be adjusted from 0.1 to 4 mm. It can be used for fretting tests since the normal fretting test amplitude is in the range of 10 to 300 μm.

This relatively small amplitude range can be a test selection concern. The standard tests with a 1-mm stroke do not simulate many tribosystems. Reciprocating mechanism amplitudes are usually much larger. It may be appropriate to use this test rig to simulate fretting tribosystems.

BOCLE: Ball-on-Cylinder: ASTM D 5001

A significant problem with many block-on-ring tests is getting the block perfectly parallel with the cylindrical surface of the ring. Tapered wear scars are the result of misalignment between the two. The ball-on-cylinder test solves this alignment problem. The test uses a ring that is similar to the ring used in the ASTM G 77 block-on-ring machines, but larger in diameter. A ball is loaded against the ring with an initial point contact (Figure 7-5).

The test parameters are as follows:

Ring	8720 steel case hardened to 60 HRC
Ball	52100 steel at 60 HRC (12.7-mm disk)
Force	1 kgf
Cylinder speed	240 rpm (on 50 mm diameter ring)
Test duration	30 min

Specimens immersed in flowing test fluid
10% RH in test chamber

The point contact can create a high contact stress, but the normal force is relatively low so the stress level with a steel couple will be well below the compressive yield strength of the

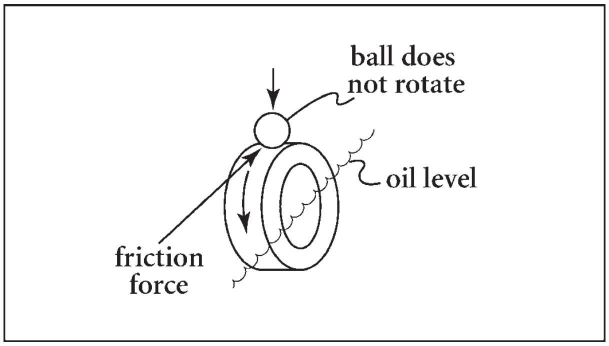

Fig. 7-5—Schematic of the "BOCLE" test.

steel couple. Another significant part of this test is the requirement for the test to be conducted in 10% RH. The test is written to evaluate the lubricity of aviation fuel, and apparently fuel is at low humidity at flying altitudes and the developers wanted the test to simulate flight conditions.

The test metric is the ball wear scar diameter. If this test is used to evaluate different materials rather than fuels, the test specimens would be made from candidate test couples. It may be costly to get polished balls and bearing raceways made from candidates so specimen costs may be a consideration in using this test.

Load-Carrying Capability Tests

Pin and Vee Block: ASTM D 2670

The "Pin and Vee Block" test has been used for more than 40 years to assess the properties of lubricants under extreme pressure conditions. A metal pin rotates between two vee blocks that are incrementally forced with a mechanism against the lubricated rotating pin until seizure occurs. ASTM D 2670 is a test using this machine for wear properties of fluid lubricants and D 3233 applies this device to extreme pressure lubricants. The device is shown schematically in Figure 7-6.

The test metric in D 3233 method A is the force to produce seizure as the load is continuously increased by a machine ratchet mechanism. Method B step loads the specimens in 1112 N increments and holds each load for one minute, but the test metric is still the pin force at failure (seizure).

This test was popular for lubricants in the 1960s and was expanded to use in screening metal couples in the 1980s. The mechanism is fairly complicated and there are many details to be addressed in calibration and use.

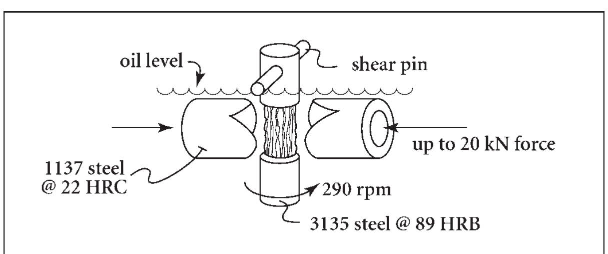

Fig. 7-6—Schematic of the pin and vee block test.

A concern with this test for screening wear couples (with the fluid held constant) is exceeding the compressive yield strength of the candidate materials. With line contact between a pin and vee blocks, it is quite possible that "failure" will simply be plastic deformation of the contacting surfaces. The lubricant is supposed to separate the surfaces to prevent wear, but with a force of 20,000 N available, the vee blocks could conceivably form a conforming bearing that is resistant to seizure, but the surfaces are damaged or "worn" from plastic deformation rather than material removal. It may be advisable not to use this test for wear testing, only lubricant/seizure testing.

ASTM D 5183 Four-Ball Friction Test

The formal title of this test is "Determination of the Coefficient of Friction of Lubricants Using a Four-Ball Wear Test Machine." The test rig can be the same as that used in the ASTM D 4172 four-ball test, only in this test the lubricated balls are incrementally loaded until seizure is imminent. The friction coefficient is calculated for the test members at the various load increments. But the failure load is probably the test result given the most importance. Oils are rated by their load to failure.

ASTM D 2981 Block-on-Ring Test for Solid Lubricants

This test uses the Falex block-on-ring wear test as a coating durability test by running until the coated surfaces fail. Coefficient of friction is used as the criterion for failure. If the coefficient increases greater than 0.1 the test is terminated. The test metric is cycles to failure. This is an oscillating test. The standard size blocks and rings are used and the solid film lubricant is applied to the ring. The ring is hard (60-HRC 4620 steel; the block is hard O1 tool steel (60 HRC). The oscillating speed is 87.5 cycles per minute with a 90° arc as the degree of oscillation. After a one-minute wear in at a test load of 30 lb, the load is increased to 630 lb and the oscillation is continued until the coating fails

A caution with this test is that if the coating fails abruptly, the friction force can increase rapidly and destroy a force measuring transducer or other machine parts. It is not unusual for a hard/hard steel couple to have a coefficient of friction of 0.6 in dry sliding in a block on ring configuration. Therefore, if the coating gets completely removed fast, the friction coefficient can go from 0.05 to 0.6 abruptly. The force transducer can see a force increase from around 30 lb to almost 400 lb. Most friction transducers do not have that range and it could result in the loss of a $700 transducer.

Thus, there are machine damage risks in conducting load capability types of tests on lubricants. Many contract test labs deal with these risks by not quoting on tests that use high test loads and seizure or failures as the test metric.

A Lubricated Fretting Test

A chapter will be dedicated to fretting, but there is a standard test that is written for lubricating greases that fits into this discussion of lubricated wear tests. The test is ASTM D 4170 "Standard Test Method for Fretting Wear Protection by Lubricating Greases." The test oscillates the races of two thrust bearings under a thrust load (Figure 7-7).

This test was originally called the "Fafnir Test," and it has been used for more than 30 years to compare the ability of

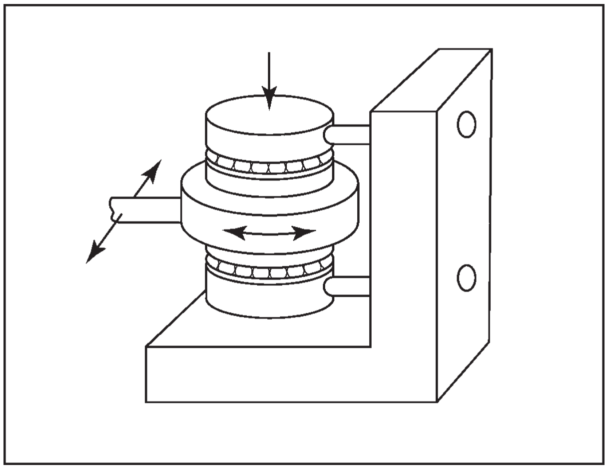

Fig. 7-7—Schematic of the thrust bearing "fretting" test.

various greases to have a palliative effect on wear from small oscillatory motion. The oscillatory motion in this test is a 12° arc of one raceway of each thrust bearing. The circumference translation of the raceway with respect to the fixed raceway is more than one millimeter, which is out of the amplitude range normally considered to be "fretting." Thus, this test is really an oscillatory wear test rather than a fretting test, but it still is useful for comparing materials and lubricants for applications involving this type of motion. The load on the ball thrust bearings is about 2450 N; the frequency is 30 Hz; the test is 22 hours in length. The test metric is the mass loss on the bearing races. A concern in using this test for material studies is obtaining test couples as thrust bearings. Special balls and races can be costly.

Testing Gears with the FZG RIG

Gears are a special tribocomponent. They are used in countless mechanical systems and wear almost always compromises the system. ASTM D 4998 describes using a gear wear test to evaluate hydraulic fluids, but the machine described in the testing standard is also the most used device for assessing gear materials. This machine allows a set of gears to be run together carrying a significant load (torque) and a lubricant (heated; Figure 7-8). The gears are run together for 20 hours under a torque of 373 N.m at 100 rpm. The gears for the ASTM test standard are case-hardened alloy steel at 60 HRC and the test metric is mass change on both gears.

Gear couples can be evaluated in a particular lubricant, but they must be made to the FZG specification. The test gears are both 20 mm wide. The pinion has a pitch diameter of 75 mm and the mating gear has a pitch diameter of 100 mm. This test can also be used to assess gear coatings and treatments for wear and friction effects. Considerations in using this test include:

1. Cost of test gears
2. Test rig availability

Both of these concerns are essentially economic factors and can be easily addressed.

Rolling Element Tests

Ball and roller bearings constitute a significant fraction of lubricated tribosystems and there are many commercial bearing testers on the market. Many "homemade" tests also exist. Rolling element bearings are tribosystems in themselves and thus they are tested as a tribosystem. A simple test that has been used for many years on lightly loaded bearings (less than 100 N) is to simply rotate the bearing with a motor and load the outer raceway with a weight (Figure 7-9).

There are many ways to achieve this same effect, but a hanging weight is probably the simplest method. Some rigs heat the bearings. There are various ways to test bearings. Some investigators simply run the bearings until they fail (the bearing may seize; it may make noise; it may get too hot as sensed by a thermocouple). Other investigators run the test for a fixed time and measure component mass loss or they cut the bearings apart and rate raceway and ball wear.

An obvious limitation of these tests is the length of testing. If you want to compare 12 bearings and/or 12 lubricants, it could take months of 1000-plus hours per test. The usual solution to this problem is to use many motors. The test rig can be low cost and a dozen motors also can be reasonable in cost.

For those interested in frictional characteristics during wear, there are tests that measure friction (torque) in rolling element bearings under load. One type of commercial tester vertically step loads the bearing at various speeds and holds one raceway with a torque sensor (Figure 7-10). The test metric is bearing friction force with a given bearing and lubricant at various speeds and loads.

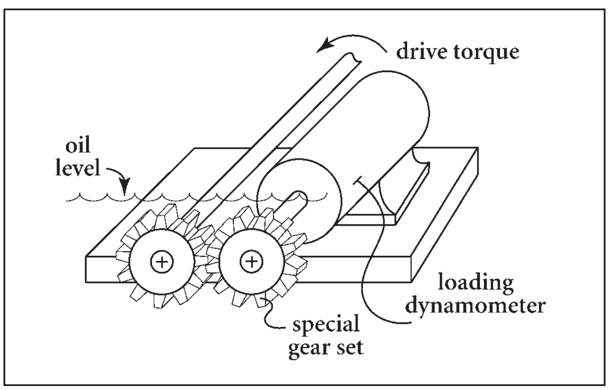

Fig. 7-8—Schematic of the FZG gear tester.

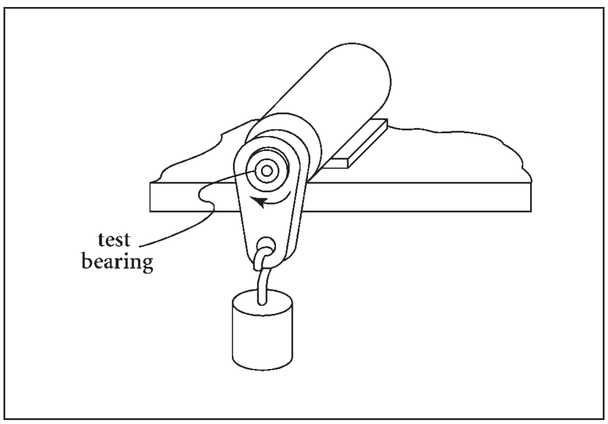

Fig. 7-9—Schematic of a bearing test.

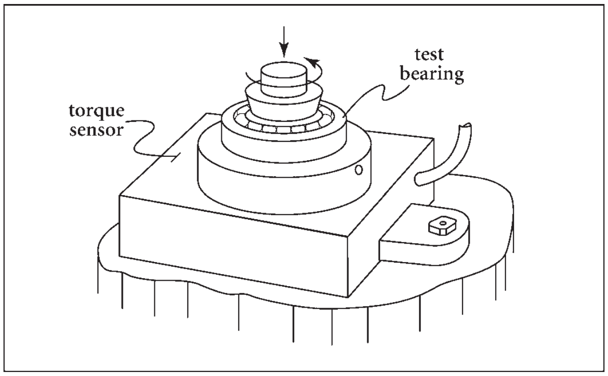

Fig. 7-10—Bearing friction tester.

An obvious concern in using this test on rolling element bearings is that loading is axial. The majority of rolling element bearings used are designed for radial loading. A more appropriate test would be the same concept only with radial loading. Wear is assessed by sectioning bearings and rating raceway damage.

Chapter Summary

ASTM lubricated wear tests are mostly under the purview of the "D02" Committee on fuels and lubricants. The most used lubricant tests were discussed but most of the D02 Committee tests on fuels were not covered because fuel lubricity is a very specialized field. Of the tests described, the block-on-ring is probably the most popular for evaluating wear in a fluid lubricant. The pin-on-vee-block test is probably the most popular test for evaluating the effectiveness of lubricant additives intended to lessen wear under high loads. The FZG tester is the most appropriate for gear materials and gear lubricants. The block-on-ring is popular for assessing solid film lubricant (coated rings). As in all tribosystems, an appropriate test should simulate an application. Thus, the best test is one that does this.

Important Concepts

The following concepts should be taken from this chapter:

1. Sliding or rolling speed has a profound effect on the performance of lubricated tribosystems; design tests to investigate these effects.
2. There is a tendency to use ever-increasing forces in lubricated tests. The stresses on contacting members should be calculated and test stress should be maintained well below yield strengths.
3. Short-term screening tests usually need confirmation with longer term (simulation tests).
4. Perfect lubrication (hydrodynamic) prevents contact between test specimens; so wear test should also be conducted at conditions that produce boundary lubrication (as would occur at startup and shutdown).

Resources for More Information

Lubrication Fundamentals

Booser, E. R., Ed., *CRC Handbook of Lubrication, Vol. 1, Application and Maintenance*, Boca Raton, FL, CRC Press, 1983.

Booser, E. R., Ed., *CRC Handbook of Lubrication, Vol. 2, Theory and Design*, Boca Raton, FL, CRC Press, 1984.

Kragelsky, I. V., Alisin, V. V., and Blagonravov, A. A., *Tribology–Lubrication, Friction, and Wear*, New York, Wiley, 2001.

Booser, E. R., *Tribology Data Handbook: An Excellent Friction, Lubrication, and Wear Resource*, Boca Raton, FL, CRC Press, 1997.

Wear Testing

Ludema, K. C., *Friction, Wear, Lubrication: A Textbook in Tribology*, Boca Raton, FL, CRC Press, 1996.

Seireg, S., *Friction and Lubrication in Mechanical Design*, Boca Raton, FL, CRC Press, 1998.

Sethuramish, A., *Lubricated Wear*, Amsterdam, Elsevier, 2003.

Related ASTM Standards

D 2625 – Test Method for Endurance (Wear) Life and Load-Carrying Capacity of Solid Film Lubricants (Falex Pin and Vee Method) *(For solid film lubricants, line contact of opposing vee blocks on a continuous rotating pin, rotation, 20°C, 290 rpm, loads up to 4450 N, record wear life in minutes (a), or load capacity (b).)*

D 2670 – Test Method for Measuring Wear Properties of Fluid Lubricants (Falex Pin and Vee Block Method *(Line contact of two opposing vees on a continually rotating pin, 20°C, 290 pin rpm, 700 lbf, 15 minutes, load to failure or pin wear measured.)*

D 2714 – Test Method for Calibration and Operation of the Falex Block-on-Ring Friction and Wear Test Mxachine *(Line contact of O1 steel block (30 HRC) vs a 4620 steel ring (60 HRC), continuous rotation, at 43.3°C, 72 rpm, 150 lb, 549-m sliding distance, measure block wear and friction.)*

D 2981 – Test Method for Wear Life of Solid Film Lubricants in Oscillating Motion *(Line contact of a stationary block on an oscillating ring, 90° arc, for solid film lubricants, 87.5 cycles per minute, 283 kg, measure wear life in minutes; failure is high friction [>0.1].)*

D 3233 – Test Method for Measurement of Extreme Pressure Properties of Fluid Lubricants (Falex Pin and Vee Block Method) *(Line contact, for extreme pressure fluids, continuous rotation at 290 rpm, loads to 20,000 N, record load at failure.)*

D 3704 – Test Method for Wear Preventative Properties of Lubricating Greases Using the (Falex) Block on Ring Test Machine in Oscillating Motion *(20°C, optional speed, oscillating motion, 4620 steel ring (60 HRC), vs O1 steel block at 30 or 60 HRC, loads to 2860 N, record block wear.)*

D 4170 – Test Method for Fretting Wear Protection of Greases *(Ball thrust bearing test for greases, 12° arc oscillation, 52100 balls and races, at 20°C, 30 Hz, 2450 N, 22 hours, record bearing mass loss.)*

D 4172 – Test Method for Wear Preventative Characteristics of Lubricating Fluid (Four-Ball Method) *(For oils, 3 point contacts on continuously rotating ball vs stationary three-ball cluster, 52100 steel balls, 20°C, 1200 rpm, 392 or 147 N, 60 minute, record ball scar diameter.)*

D 4998 – Test Method for Evaluating Wear Characteristics of Tractor Hydraulic Fluids *(FZG test rig using spur gears to rate oils, case hardened gears at 121C, 100 rpm, up to 199 Pa, 20 h, record gear mass change.)*

D 5001 – Test Method for Measuring the Lubricity of Aviation Turbine Fluids by the Ball-on-Cylinder Lubricity Evaluator (BOCLE) *(Ball on cylinder test rig, 52100 steel ball stationary against a continuously rotating 8620 ring [60 HRC] to measure fuel lubricity, at 25°C, 10% RH, 240 rpm, 10 N, 30 min, record ball scar diameter.)*

D 5183 – Test Method for Determining the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine *(Friction of oils, point contact, continuous rotation at 800 rpm, 75°C, 52100 balls , 392 N, 60 min, record ball wear, seizure load, coefficient of friction.)*

D 5707 – Test Method for Measuring Friction and Wear Properties of Lubricating Grease Using A High-Frequency, Linear Oscillation (SRV) Test Machine *(Reciprocating motion of a hard steel [52100] ball on a hard steel flat (52100 at 60 HRC), 200 N, 1-mm stroke, 50 Hz, 2 hours, record ball and flat wear, coefficient of friction.*

D 6425 – Test Method for Measuring the Friction and Wear Properties of Extreme Pressure (EP) Lubricating Oils Using SRV Machine *(Reciprocating motion on the SRV test rig to evaluate EP oils, 52100 ball vs 52100 steel flat [60 HRC], optional temperature, 50 Hz, 300 N, 2 hours, record ball and disk wear, coefficient of friction.)*

8

Fretting Tests

Introduction

FRETTING DAMAGE OCCURS IN COUNTLESS applications where it is not recognized or where it is ignored. It is also relatively ignored in testing practices, and that is why an entire chapter is dedicated to this form of "nonabrasive wear." Hopefully, this attention will counteract the relative neglect that it receives from the technical community. One significant reason for fretting damage neglect is that the damage is frequently "visually negligible." A classic example is fretting damage on wires in rope and other metal-strand cables. Repeated use involves elastic elongations of individual wires. Because of the braiding, the wires do not elongate the same under load, and some wires are stretching more than others, which means microscopic relative slip. Eventually, the wires that are subject to the most fretting motion start to fail because the fretting damage produced a deep pit that acted as a stress concentration. However, the wire rope user may never see any visual external damage until enough wires have failed to produce dangerous damage. Often, the damage is never detected until a load is dropped when the entire wire rope or cable breaks. Fretting corrosion is a limiting factor in the use of wire ropes and similar cables subjected to alternating loads.

Fretting corrosion similarly is a limiting factor in turbine vanes. Jet engines and many turbine devices work by forces on a wheel of "vanes" that transmit combustion or fluid forces to rotary motion. The vanes are held in close-fitting dovetails and varying elastic deflections result in microscopic oscillating slip (fretting motion) between the vane's root and its mount. Fretting damage in this instance can lead to fracture and vane failure, which usually causes complete failure of the engine or device.

Fretting corrosion is the limiting factor in the life of many plastic injection molding molds. Micrometer-deep vents are ground in the mold surfaces to allow air to escape from the mold as the plastic fills the mold. Each time that the mold is closed, the contacting surfaces "adjust" or slip to accommodate machinery errors of form, and this rubbing produces fretting corrosion or wear. The vents eventually disappear (in 1 million cycles or so), and regrinding is necessary. Eventually, the mold dimension ends up out of specification, and the mold must be scrapped.

Finally, fretting damage is a limiting factor in packaging and package decoration. If six beverage cans are allowed to touch in shipping a six-pack, customers tend not to buy packages received with advertising images worn off from fretting damage. Appliances and the like that are shipped from long distances will have fretting damage on product surfaces whenever the packing or parts are allowed to travel in rubbing contact. Fretting damage will make many products unsaleable. The oscillatory motion to produce the damage comes from small movements in transit.

The point is that fretting damage is an important but insidious factor to be dealt with. It has limiting importance in many applications but receives less than its share of research, testing, and technical attention. The purpose of this chapter is to bring awareness to fretting damage and to show how to recognize it and test material couples for their propensity for fretting damage. The chapter objective is more "fretting-aware" technologists. This chapter will start with a review of the factors that affect fretting damage and then describe identification of fretting damage, standard tests, and nonstandard tests.

Mechanisms of Fretting Corrosion and Wear

In Chapters 2 and 3, fretting was defined as small-amplitude oscillatory motion (less than 300 μm); fretting wear is surface damage/material loss as a result of this motion, and fretting corrosion occurs when there is a reaction of the rubbing surfaces with the ambient environment coupled with the mechanical damage produced by the rubbing of contacting surfaces. Fretting corrosion is the usual manifestation of fretting in metals; most metals oxidize under repeated dry rubbing in air. However, fretting damage is very common in plastic/plastic couples and, in this instance, the reaction with the environment is thought not to be a significant factor. Therefore, fretting of plastics produces fretting wear. There is no oxidation in some metal/metal, metal/ceramic, and other systems, so it is important to microscopically observe fretting damage and decide if there is fretting wear or fretting corrosion. Did reaction with the environment play a role? The mechanism of fretting wear is illustrated in Figure 8-1.

Contact "x" is one "real area of contact" between surfaces "a" and "b." Surface "a" is oscillating with respect to surface "b." If the oscillations are small enough, the mating asperities on a and b elastically deflect to accommodate a's oscillation. Usually amplitudes less than 10 μm produce elastic accommodation of relative motion.

However, if the amplitude increases to approximately 50 μm, asperity "a" will rub on asperity "b" and several things can happen. If the loads are light enough, "a" will not damage asperity "b." If the loads are larger both asperities could plastically deform and adhesion can occur. If adhesion occurs, repeated oscillation could fracture the "a"/"b" junction and particulate debris can be generated. Another junction can be formed and the process is repeated and repeated. Eventually a significant damage area will result, usually combined with fretting and oxidation of debris that is continually rubbed. The freshly rubbed surfaces react with ambient air to oxidize. After time, microscopic damage can be observed (Figure 8-2).

The tendency for significant fretting damage depends upon the usual wear factors specific to the couple: load, velocity, and sliding distance (number of rubs). Increased load,

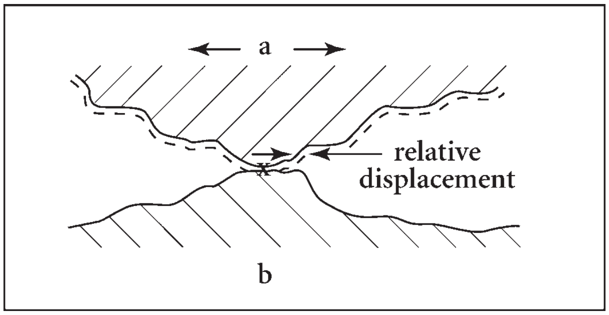

Fig. 8-1—The origin of fretting damage is local adhesion (at real areas of contact).

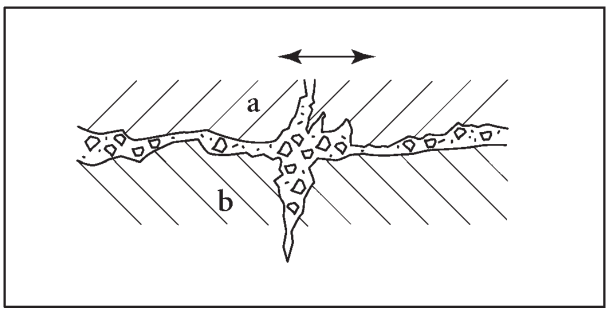

Fig. 8-2—Typical pitting in fretting corrosion.

frequency, and number of rubs increase the potential for and degree of fretting damage. However, damage can occur at frequencies of once a minute, or after a few rubs, or with a very light load. Fretting damage also can occur with most material couples. The best preventative measure is to eliminate the relative motion. If this is not possible, separate the surfaces with a lubricant. If complete surface separation is unlikely, you can test for a couple or surface treatment that mitigates fretting damage under your conditions. Fretting screening tests can be performed.

Fretting Tests

Figure 8-3 illustrates a range of test rigs that have been used to perform fretting tests. The essential elements of every test are a mechanism for producing small-amplitude relative motion and a way to load two surfaces together. Loading is usually done with a mass, but a newer option is a servo motor controlled loading device with a feedback system to maintain the desired force of member "a" pressing on member "b." Researchers use lots of imagination in producing the fretting motion, but there are three basic systems that are used: 1) mechanically moving one member with respect to the other; 2) using elastic deformation of one member with respect to the other; and 3) using thermal expansion of one member with respect to the other. Four of the rigs illustrated in Figure 8-3 use elastic deflection to produce the fretting motion. The fretting bridge is the oldest and most widely used technique to assess the effect of fretting damage on the fatigue strength of a material. Figure 8-4 is a schematic of how the system works.

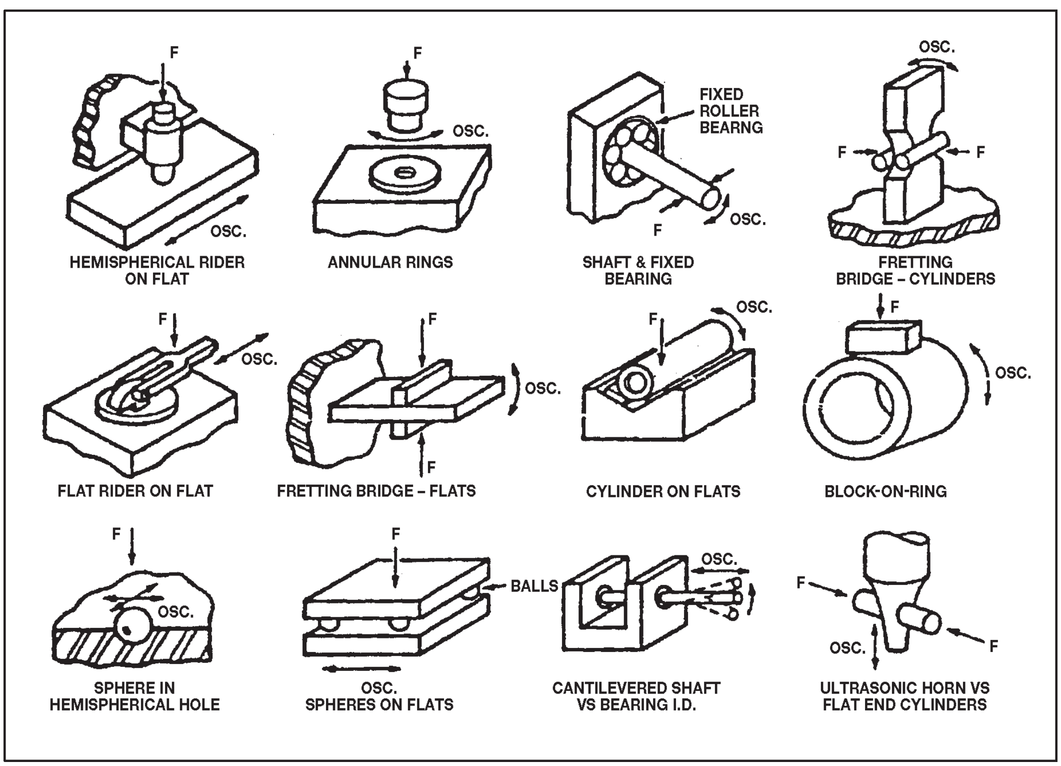

Fig. 8-3—Types of fretting tests.

When bar dd is flexed, surface bb gets longer and cc gets smaller at the line contact through a. Relative motion is produced by Hookian elastic deflection. The metric in these kinds of tests is usually fatigue life at a particular stress (deflection; Figure 8-5). Fatigue life reduces because the fretting damage creates pitting, which is a stress concentration for crack formation.

One of the most frequent occurrences of fretting damage is under ball bearings. The bearings move slightly in their housing. Maintenance people often interpret this as rust from the environment, but it is really fretting damage from the bearing moving slightly in its seat. A simple way to generate fretting damage between a shaft and bearing is to fix the outer race with adhesive and rotate a shaft with a significant cantilever from the fixed bearing (Figure 8-6).

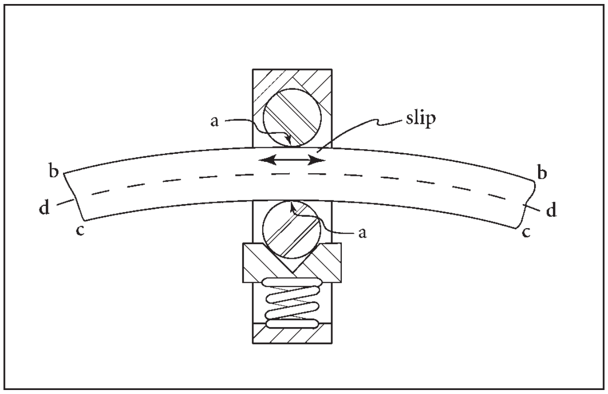

Fig. 8-4—Use of elastic deflection to produce fretting motion.

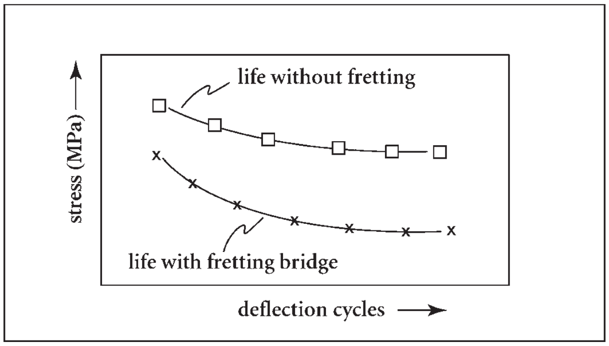

Fig. 8-5—Effect of fretting corrosion on fatigue life.

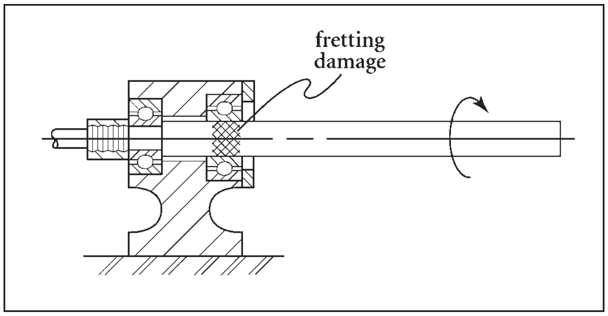

Fig. 8-6—Shaft deflection fretting tester.

This technique duplicates the frequent occurrence of fretting under rolling element bearings. Unfortunately, it is difficult to quantify the damage until it is severe enough to result in a dramatic change on the deflecting shaft. It is a useful test for coatings and lubricants to prevent fretting damage. If an uncoated shaft in uncoated bearings shows severe fretting damage after a 50-hour test, and a lubricated shaft shows no damage for the same 50-hour cycle, the test becomes a useful screening tool.

Ball-on-Plane

Many fretting researchers use a ball-on-a-flat type of specimen geometry because it eliminates problems with rider alignment; the ball produces point contact at the start. If the fretting amplitudes are low (a few micrometers) this type of specimen configuration creates a damage annulus (Figure 8-7). There is no slip in the center of the contact and the damage occurs in an annulus. The size of the annulus increases with fretting amplitude and when the slip gets above 10 μm the test produces a wear spot rather than ring. Figure 8-8 presents the appearance of a ball and its counterface (Figure 8-9) after a 100-hour fretting test with a slip amplitude of 50 μm. Damage is quantified by profilometry measurements of the counterface and ball (Figures 8-10 and 8-11). Typical test data are illustrated in Figure 8-12. This is a typical technique for assessing the fretting characteristics of candidate material/treatment couples.

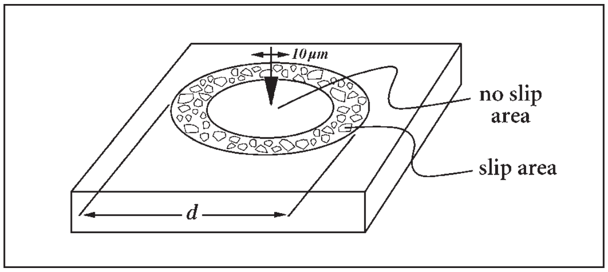

Fig. 8-7—Typical damage in low-amplitude fretting test; d is the diameter of the ball contact area

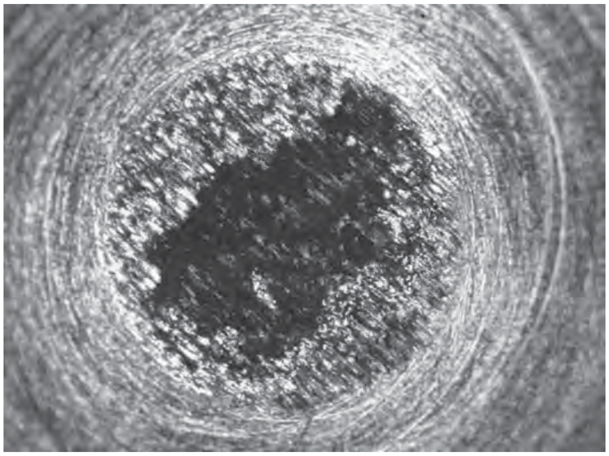

Fig. 8-8—Appearance (at X80) of a D2 rider and SiC counterface after a 100-hour fretting test (50-μm amplitude).

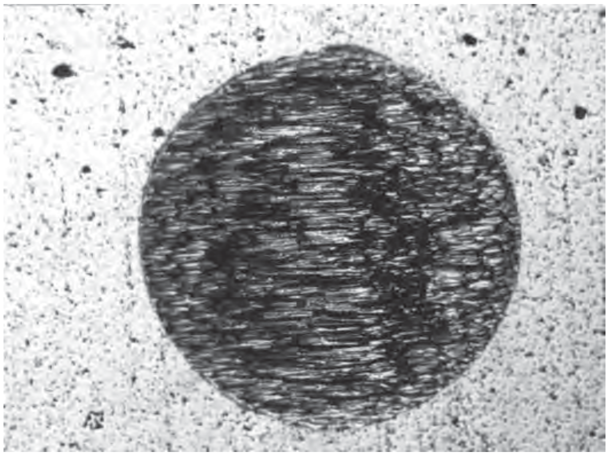

Fig. 8-9—Silicon carbide wear after 100-hour fretting test versus D2 steel hemispherical rider (50-μm amplitude).

Standard Tests: Fretting Fatigue

ASTM made a concerted effort in 1989 to standardize fretting fatigue testing by calling experts together for a symposium on standardizing fretting fatigue test methods and equipment (ASTM STP 1159). Their recommendation was to standardize the fretting bridge, specimens, and techniques and add them to the ASTM axial-load tensile fatigue test. It has not been accomplished at the writing of this guide, but the STP summarizes the variety of equipment and techniques that were used at the time for producing fatigue failures accelerated by fretting damage. The STP also recommends a slip amplitude of 10 to 30 μm as the amplitude region that produces the most fretting damage.

There are many nuances associated with use of elastic deflection to produce fretting slip and these are discussed in the STP. This document is recommended reading for studies on the role of fretting damage in fatigue.

Electrical Contact Tests

ASTM B 896 describes a crossed-wire fretting test intended to screen coatings and other palliatives used to reduce fretting damage in electrical conductors. Fretting motion in electrical connections can lead to debris/oxide generation that can interrupt current flow and produce an unintentional open circuit. The test rubs one 12-gauge wire on another 12-gauge wire with a slip amplitude of 20 μm (Figure 8-13). Specimen contact load, current, and contact potential are monitored as the load increases. The test is continued until the contact resistance becomes unstable. The test metric is essentially the time to electrical failure.

Needless to say, all environmental factors that can affect reaction of the conductors with the environment and contact mechanics need to be controlled. The test rig schematic in the standard is a "thermal motor," which means that cyclic thermal expansion of a material with a heat source is the specimen driver; thus, the slow cyclic speed (1 cycle/minute). This can be a very long test for some wire couples.

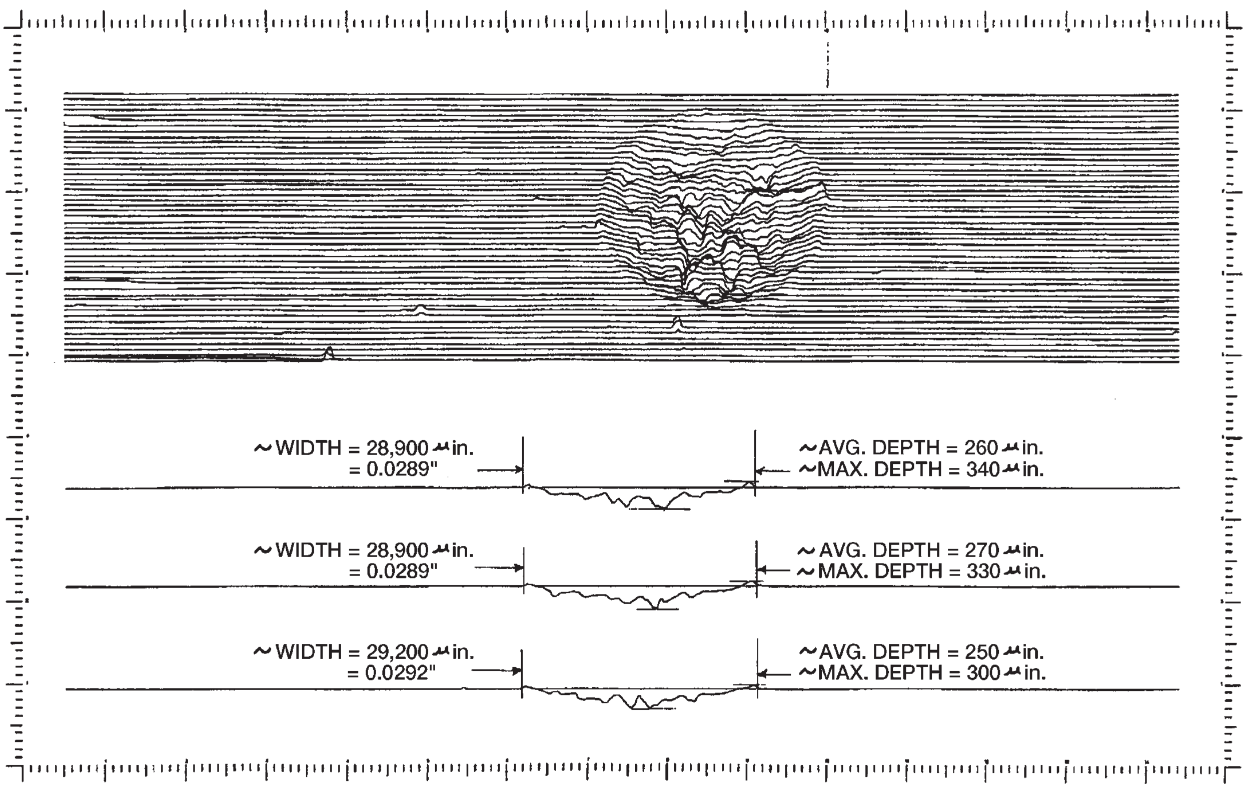

Fig. 8-10—PSZ zirconia wear crater after 100-hour fretting test versus D2 steel (50-μm amplitude, 10 lbf).

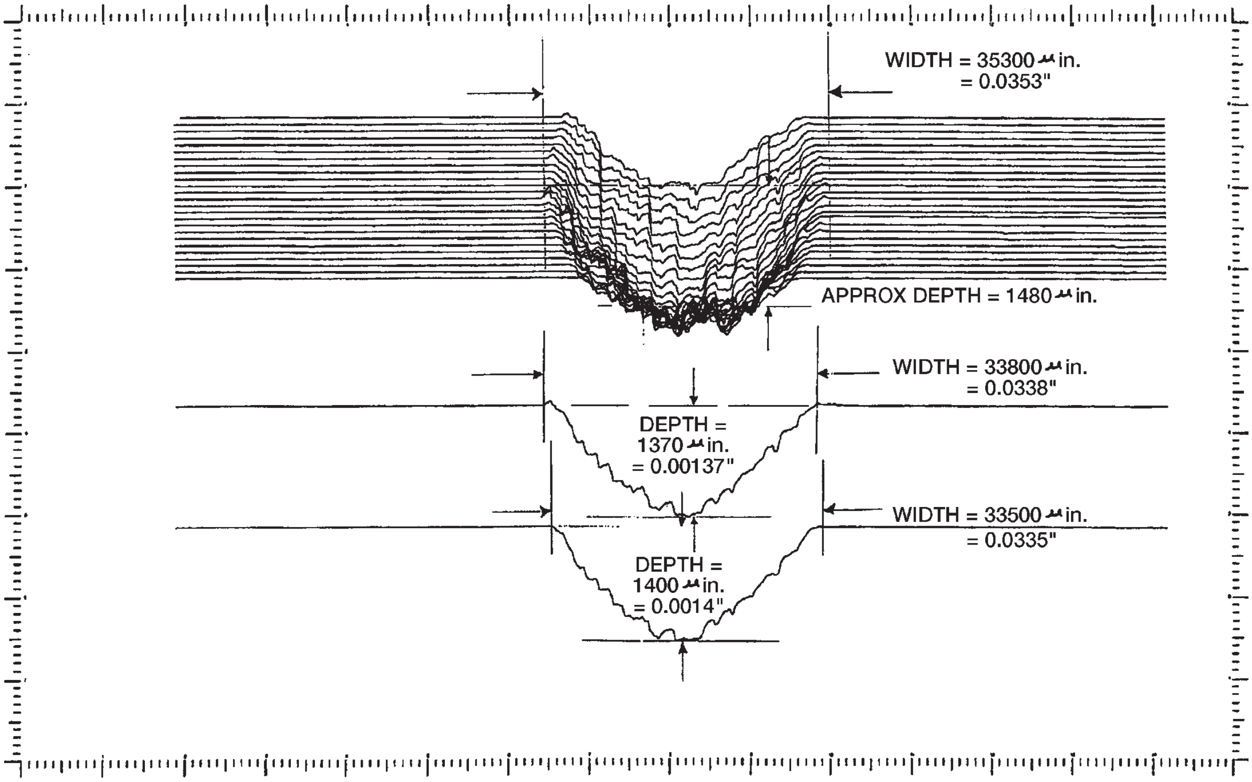

Fig. 8-11—Silicon carbide counterface wear crater after 100-hour fretting test versus D2 steel (50-μm amplitude, 10 lbf).

Hip Implant Couples

ASTM F 1875 is a departure from machine-type applications of tribology; it is a test for implants for the human body. The test specimens are candidate hip implant devices and the purpose of the test is to determine the fretting corrosion propensity of a particular couple/shape/surface/coating to fretting damage under cyclic loading that simulates loading of a hip joint in walking and running. There are elastic deflections at the cone/head interface in use and these deflections can lead to microscopic slip and fretting corrosion. A schematic of the test is shown in Figure 8-14. The test specimens are submerged in

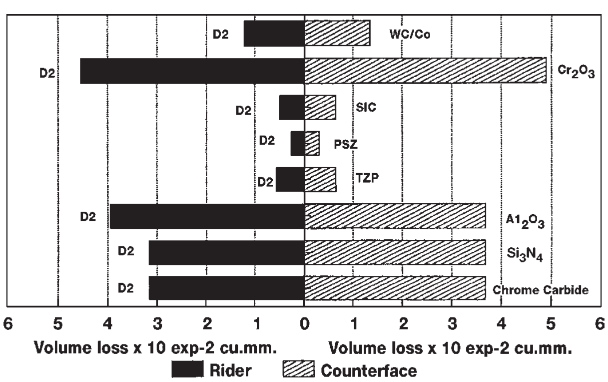

Fig. 8-12—Fretting wear volumes for various couples (10 lb, 1.7 Hz, 100 hr, 50 μm).

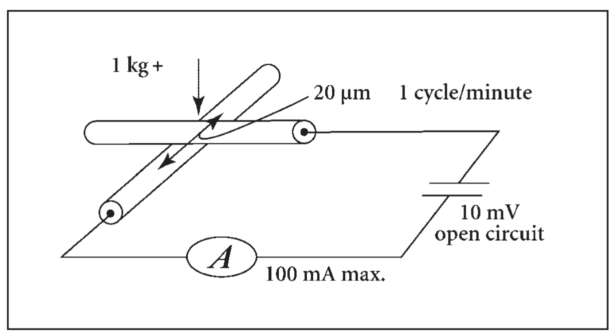

Fig. 8-13—Schematic of electrical contact fretting test.

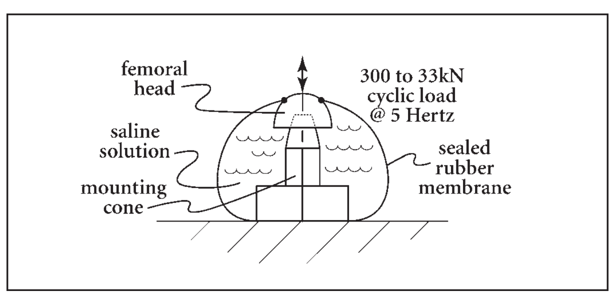

Fig. 8-14—Schematic of fretting test for femoral head/cone couples.

a fluid to simulate body fluids and the rubbing interfaces are open to the solution. The test metrics are the elemental increase in the solution of elements contained in the rubbing specimens as well as characterization of surface damage on the faying surfaces of the femoral head and cone. There are also fretting tests for prosthetic plates and screws (ASTM F 897 and ASTM F 1814). These are not tests for the average tribologist. There are many nuances pertaining to handling and cleaning the specimens and to use of these test fluids. Their use and preparation are not trivial.

Grease

The ASTM D 4170 test was already described in lubricated wear tests and it is mentioned again here because it has "fretting wear" in the title and it is a "fretting standard" by D Committee definition, but not necessarily by all fretting researchers–the slip amplitude may be too high. The balls can roll about 2.5 mm along the raceway, but they are not driven. Raceway "a" is rotated with respect to raceway "b" (Figure 8-15). If the balls follow raceway "a," the slip is some fraction of the rolling. The test standard does not state the relative ball/raceway slip amplitude. In any case, this test had been used for many years to simulate conditions that can produce false brinelling in bearings in shipment and the like. It is an accepted test for the efficacy of greases in preventing fretting damage.

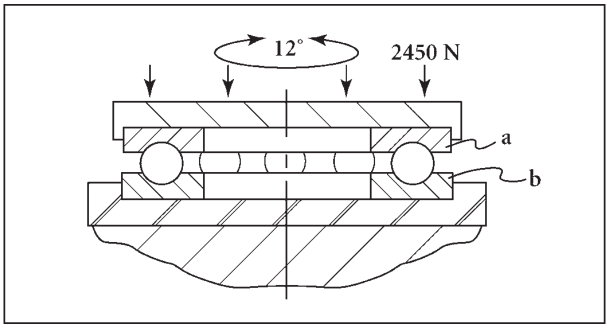

Fig. 8-15—Fretting thrust bearing.

Fig. 8-16—Typical "gnarled" surface from fretting (420 stainless-steel injection mold part; hole is 35 mm in diameter).

Chapter Summary

Fretting tests are often fatigue tests with "fretting bridges" applied to determine the reduction in fatigue strength produced by fretting damage on a particular material. A ball-on-flat configuration is the other widely used specimen configuration. These tests are not covered by ASTM standards and that can be a problem. These tests are not as simple to run as they sound. There is a significant amount of technology required to make a fretting bridge work as intended and a reciprocating ball rider produces damage assessment problems. The ASTM standard fretting tests cover crossed wires and prosthetic implant components These are really "component" tests. General testing may be done with the ball-on-flat configuration.

Fretting damage often is ignored, and this practice can often lead to disastrous failures. Engineers need to always consider the possibility for and the effects of fretting on structures and mechanisms that could be subjected to oscillatory slip of small amplitude. Packaging engineers should be the most concerned. Cans and bottles rubbing each other in truck or rail transport can produce unsaleable products. Fretting produces an insidious form of wear that must not be ignored. It should be addressed in the design stage and fretting test can identify couples that survive anticipated slip conditions.

Important Concepts

The following concepts should be taken from this chapter:

1. "Fretting" means small-amplitude reciprocating motion.
2. Fretting corrosion is damage produced on contacting surfaces by reaction of the rubbing surfaces with their environment.
3. Fretting wear is fretting damage in the form of material removal and deformation without assistance from environmental effects.
4. Fretting amplitude (relative sliding) is in the range of 10 to 300 μm.
5. Fretting occurs at high and low normal force, speed, surface, and with most material couples that are subjected to fretting type contacts.
6. Fretting damage can be reduced by couple choice, by coatings that separate surface, and by other surface treatments.
7. Fretting fatigue is failure by fracture of a structural member from cyclic stress initiated by fretting damage to the surface of the structural member.
8. Fretting damage can be diagnosed by a "gnarled" (Figure 8-16) surface texture with a red or black powder deposit if fretting corrosion is coupled with fretting wear.
9. Fretting damage is usually small in dimensional loss, but may result in pits that may be orders of magnitude deeper than the macroscopic dimensional loss.

Resources for More Information

Machine Effects

Bayer, R. G., Ed., *Effects of Mechanical Stiffness and Vibration on Wear, STP 1247*, ASTM International, W. Conshohocken, PA, 1991.

Testing

Attia, H. M., and Waterhouse, R. B., Ed., *Standardization of Fretting Fatigue Test Methods and Equipment, STP 1159*, ASTM International, W. Conshohocken, PA, 1992.

Brown, S. R., Ed., *Materials Evaluation Under Fretting Conditions, STP 780*, ASTM International, W. Conshohocken, PA, 1982.

Fundamentals

Waterhouse, R. B., *Fretting Corrosion*, Oxford, Pergamon Press, 1972.

Waterhouse, R. B., and Hiku-Lori, A., Eds., *Metal Treatments Against Wear, Corrosion, Fretting and Fatigue*, Oxford, Pergamon Press, 1988.

Related ASTM Standards

B 896 – Test Methods for Evaluating Connectability Characteristics of Electrical Conductor Materials *(12-gauge wires are fretting in crossed-wire mode at an amplitude of 20 μm until electrical failure occurs; time to failure is the test metric.)*

D 4170 – Standard Test Method for Fretting Wear Protection by Lubricating Greases *(Ball thrust bearings are oscillated through a 12° arc , 30 Hz, 2450 N, for 22 hours, mass loss is the test metric.)*

F 897 – Test Method for Measuring Fretting Corrosion of Osteosynthesis Plates and Screws *(Bone screws and a plate are fastened to plastic rods and a reciprocating mechanism that flexes the plate and creates plate/screw movement (in a saline solution); the test metric is mass change, appearance, and metals in the solution.).*

F 1814 – Standard Guide for Evaluating Hip and Knee Joint Components *(Recommends fretting tests on taper junctions, and mating, non-articulating surfaces.)*

F 1875 – Standard Practice for Fretting Corrosion Testing of Modular Implant Interfaces: Hip Femoral Head-Bore and Cone Taper Interface *(Contains two methods and two procedures, but in all cases the specimens are articulated femoral stem and head components in solution. Fretting wear is assessed by chemical analysis of the solutions or by potentiodynamic polarization techniques that indicate corrosion currents during articulation.)*

9

Rolling Wear, Impact Wear, and Surface Fatigue Testing

Introduction

HOW DOES ROLLING ON A SURFACE WEAR IT? As mentioned in the discussion of rolling wear in Chapter 2, pure rolling only occurs in a fraction of the total footprint of a revolute shape (ball, roller, wheel, etc.) that rolls on another surface (Figure 9-1). Rolling means that both surfaces are at the same velocity; there is no relative slip. When there is slip, there is wear (and friction). It is really the same as sliding wear except that the relative slip can be very small. Therefore, rolling wear occurs by the nonuniform slip that accompanies a Hertzian contact.

Impact wear is somewhat related. It is material loss/damage produced by a solid surface repeatedly impacting another solid surface. Hookean mechanics dictates that elastic deformation of surfaces occurs under impact. Plastic deformation can also occur. Both produce relative slip of one surface on another—the requirement for sliding wear (Figure 9-2). Both surfaces deflect and both can wear. Even if the force (P) is insufficient to produce plastic deformation of either surface, there is relative motion between them because by Hooke's law, for every applied force there is deformation.

$$E = \sigma/\varepsilon$$

$$\text{Modulus of elasticity} = \quad E = \frac{\sigma \text{ stress (force)}}{\varepsilon \text{ strain (movement)}}$$

Impact and rolling often lead to surface fatigue. Surface fatigue is the localized fracture of material from a solid surface caused by the action of repeated compressive stressing of a surface. There are various ways to analyze the state of stress between conforming bodies, but for rolling, the maximum stress under a ball or cylinder is located below the surface (Figure 9-3). This phenomenon is what leads to surface fatigue. Repeated rolling over a surface or repeated impact can cause counterface material or counterface coatings to spall from subsurface cracking leaving pits or craters (Figure 9-4).

In summary, the problem addressed in this chapter is surface spalling and other surface fatigue damage produced by rolling, rolling/sliding, or impact. This type of damage is termed surface fatigue; in gears it is commonly referred to as pitting; on rails it is called spalling; on rolling element bearings the damage can be pitting, line of travel, spalling, or cracking. Some tribology professionals term this type of wear "surface fracture" wear rather than surface fatigue.

Some tribology professionals may claim that most forms of wear involve surface fatigue. When one solid slides on another, wear seldom occurs in the first pass of one surface on the other. Measurable wear may not occur until the millionth pass, but each pass did a minute amount of damage and the cumulative effect of measurable wear was the result of surface fatigue, repeated stressing of the contacting surfaces. Both schools of thought are not in conflict with this guide. Most wear processes involve surface fatigue and fracture. However, rolling and impact produce wear manifestations that are different in appearance and mechanism from sliding wear or erosion processes that repeatedly stress a surface. The wear processes that receive attention in this chapter are differentiated from the other processes that may involve surface fatigue in that they are produced by repeated compressive stressing of surfaces as opposed to shear stresses and stresses that are more tangential in nature.

The purpose of this chapter is to describe common manifestations of surface fatigue and tests that are used to simulate this condition in the laboratory. The chapter objective is to supply the reader with sufficient information to allow a user with a problem to select an appropriate test for this phenomenon. The chapter will begin with additional descriptions of manifestations of surface fatigue and proceed to descriptions of standard and nonstandard surface fatigue and impact tests for screening materials.

Surface Fatigue of Coatings and Surface Treatments

Hard coatings and surface treatments commonly are used to make surfaces more wear or erosion resistant. However, if they are not engineered to accommodate application stresses they can fail by surface fatigue. Freezing rain can deposit a hard, brittle coating on everything exposed to it. If a significant amount of wind accompanies the freezing rain, the ice-covered trees can produce a dangerous example of surface fatigue. As the trees sway with the wind, the adhered brittle ice coating starts to crack. Ice can crack when it is subjected to strains of 0.01 or so. The swaying trees develop crack patterns coinciding with the highest strains on limbs and trunks. Surface fatigue produced spalling of a hard, brittle coating on an elastic substrate, the wood of the tree.

Figures 9-5 and 9-6 show a tool that suffered a similar type of surface fatigue of a hard brittle coating on an industrial tool. This notching punch reciprocated with a stroke of 2 mm in a ball bushing. It was used to put a notch in a plastic container. It cycled every two seconds and may have run for as much as 16 hours a day. It saw a lot of cycles and failed after about two months in service because of surface fatigue of the

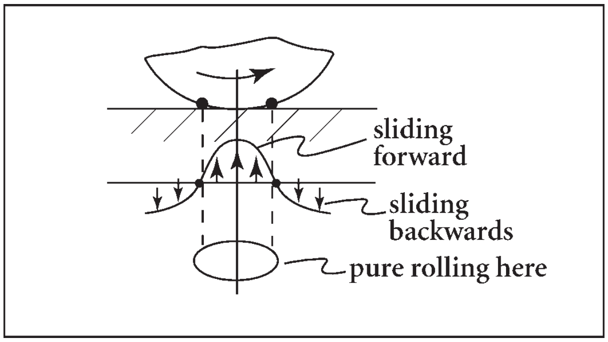

Fig. 9-1—The rolling portion of a ball-on-plane contact.

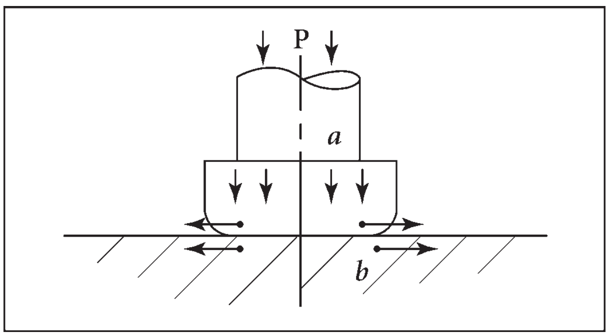

Fig. 9-2—Motion produced on impact. Surface elements from "a" and "b" move normally to accommodate the impact energy.

coating on the shaft that reciprocated in a ball bushing to provide the stroke of the punch. The shaft was made from type S7 tool steel with a hardness of 55 HRC. This material was selected to provide toughness so that the end of the notcher would not break at its unavoidable stress concentrations. A 50-μm hard chromium plate (70 HRC) was applied on the S7 shaft to provide the necessary wear resistance for rubbing against the hardened 52100 balls (60 HRC) in the ball bushing. The chromium plate eventually spalled in the areas where the shaft contacted the balls in the ball bushing. What went wrong? The chromium was applied to a relatively hard substrate. Why did it spall?

The plating spalled because the Hertzian stresses from the contacting balls were not adequately accommodated. In addition, this hard chromium always contained a myriad of microscopic cracks that were characteristic of the plating process that was used. These through-thickness cracks created stress concentrations that exacerbated the Hertz stress effects on the plating adhesion (Figure 9-7). Accommodation of stress through the thickness of wear coatings is the key factor in using coatings for wear applications and it is even more important for rolling and impact applications. It took ball bearing manufacturers almost a decade to develop a coating for balls in ball bearings that would not spall.

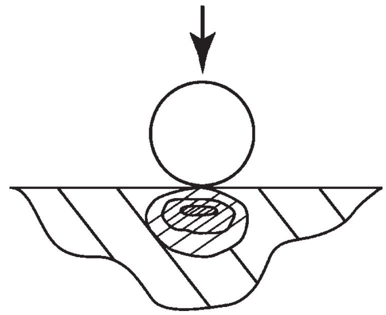

Fig. 9-3—Subsurface stress distribution under a sphere.

This spalling failure could have been avoided by engineering the surface to better accommodate the ball stresses and by not using a coating that was fraught with stress concentrations (microcracks). Finite element modeling techniques can be used to quantify contact stress fields and some programs allow inclusion of coatings. Gradient coatings could be designed that distribute the Hertz stresses over a larger area and reduce the tendency for surface fatigue. Physical vapor deposition coatings can be varied in thickness and composition to even allow a gradient of elastic moduli for stress accommodation. Finite element modeling and gradient coatings can be used to prevent an "ice on wood" or "ice on snow" type of situation when using hard coatings or surface treatments to address surface fatigue wear.

Surface Fatigue in Rolling Element Bearings

One of the classic "problems" that can occur in ball or roller bearings is "false brinelling." The manifestation is elliptical dents or marks in the raceways that correspond to at-rest ball or roller locations (Figure 9-8). As mentioned in the chapter on fretting, this damage is not rolling surface fatigue, but fretting damage produced by vibrational motion between balls and raceways when the rolling elements are not rotating, as in transport. Fretting corrosion can also occur on the OD of the outer raceways when the outer raceway is loose in its housing.

Tight fits on the OD or ID of raceways can lead to surface fatigue of the raceways. Rolling element bearings are intended

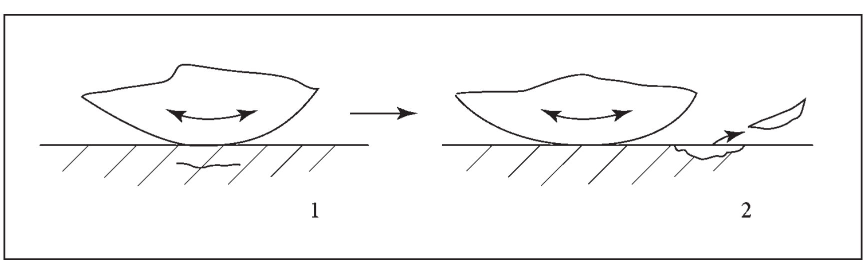

Fig. 9-4—Spalling from a subsurface crack.

Fig. 9-5—Notching punch.

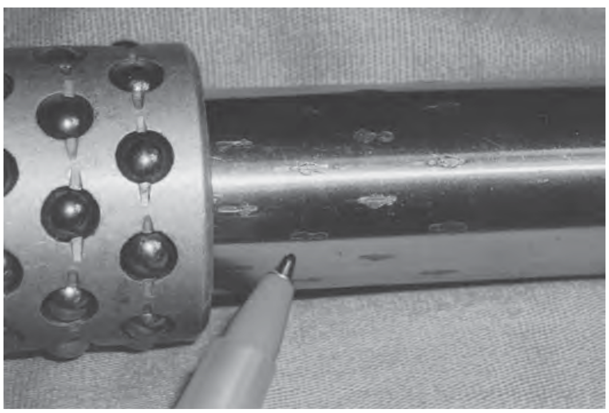

Fig. 9-6—Spalled chromium plate on punch shaft.

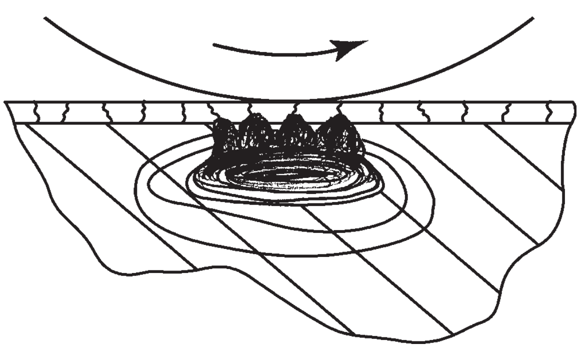

Fig. 9-7— Stress concentrations from cracks in chromium lead to a complex stress pattern with large subsurface stresses that lead to bond failure of the chromium.

Fig. 9-8—False brinelling (from microscopic oscillatory motion of the bearing balls).

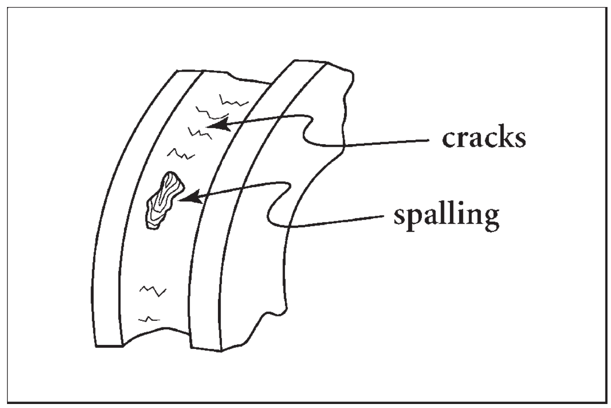

Fig. 9-9—Spalling from a bearing raceway from excessive interference (cracking then spalling).

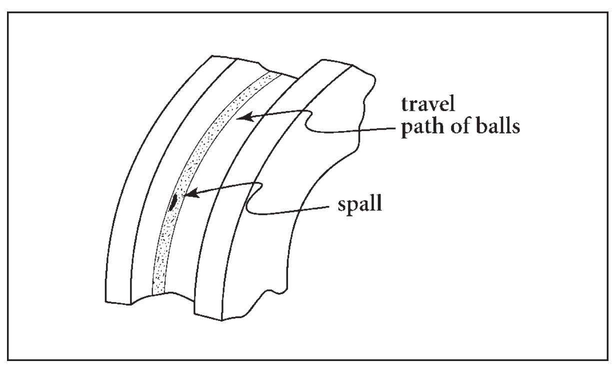

Fig. 9-10—"Normal" fatigue failure of a rolling element.

to operate with a particular running clearance between the assembled balls (or rollers) and races. If a bearing is put on a shaft with excessive interference, the inner raceway expands using up this clearance. The Hertz stress between the balls and race can exceed even the compressive strength of the material and in use, the bearings will fail by surface fatigue. Cracks will start in the raceway and spalling will happen (Figure 9-9).

Excessive interference on the OD will produce the same effect. The inner stressed raceway may spall first and once spalling occurs, usually the spalled material rapidly causes complete bearing failure.

If all of the fits are correct, a rolling element bearing will probably still fail by surface fatigue, however, after orders of magnitude of revolutions compared with a bearing subjected to improper fits. The surface fatigue could initiate either in raceways or in the balls or rollers and it will look like Figure 9-10. It will occur in the travel path of the balls. Surface fatigue of a rolling element bearing an also be the result of insufficient lubrication, overload, or simply the end of life of the bearing.

Balls or rollers under a particular type of loading will develop a "travel path," and visible change in surface texture produced by microscopic wear of the "up features" on the surface. The travel path is the result of the slip that occurs in a ball or roller contact. As mentioned in this chapter's introduction, pure rolling only occurs in a fraction of the Hertz contact.

Since the 1950s, the bearing industry has used a technique to rate the normal fatigue life of a bearing called the "L_{10} life."

$$L_{10} = \left(\frac{C}{P}\right)^{\chi} \times 10^6$$

Where:

C = basic dynamic load rating (determined by the manufacturer)
P = dynamic bearing load
χ = 3 for ball bearings and 10/3 for roller bearings

C usually is determined by the life testing of bearings using millions of revolutions to failure as the test metric. "Failure" is often measured by vibration sensors and excess vibration usually results from surface fatigue in the form of travel path cracks or spalls. Weibull statistics are often used to analyze the failure data and a published L_{10} life means that 90% of the manufacturer's bearings will survive 10 million revolutions at the designated load rating. For example, if the bearing has a load rating of 50,000 N from the manufacturer's tables and it will operate at a constant radial load of 6,000 N, the L_{10} life will be:

$$\left(\frac{50{,}000}{6{,}000}\right)^3 \times 10^6 = 578.7 \times 10^6 \text{ revolutions}$$

At 3,600 rpm, the predicted life is 2670 h.

It is now common to "adjust" the L_{10} life with multiplication factors related to cleanliness and other related operating factors. The pertinent point with regard to tribotesting is that surface fatigue resistance is a key factor in rolling element bearings and life ratings of bearings are usually determined by laboratory testing actual bearings to failure. Manufacturers of steels for rolling element bearings go to great lengths to produce clean steels and fine microconstituents. Surface fatigue failures are prone to initiate at microstructural impurities and microconstituents.

Surface Fatigue of Rails, Tracks, and Wheels

Railroad tracks commonly have localized areas of surface fatigue in high-use switching areas (Figure 9-11). Surface compressive stress is sufficient to initiate a subsurface crack, and repeated rolling on the cracked area produces macroscopic spalling. In fact, spalling of hot rolling mill scale on tracks can occur in the first use. There is a relatively brittle coating on the surface and a hard brittle coating on a ductile substrate is always an opportunity for spalling.

From the economic standpoint, spalling of railroad tracks may be more important than surface fatigue failures of wheels or rails used for industrial applications such as cranes and trolleys. There are a number of ways that surface fatigue is mitigated on railroad tracks, but most involve increasing their hardness and compressive strength. Switch frogs, the track that is impacted when the wheel jumps the rail gap at a switch, are often hardfaced with manganese steels. These steels rapidly work harden and get harder as you impact them. Flame hardening is also used to increase surface hardness and strength.

Fig. 9-11—Surface fatigue of railroad track.

The size of railroad and crane rails creates a problem in reducing surface fatigue. The root cause of surface fatigue is stresses high enough to exceed the fatigue strength of the track material. The obvious solution to this problem is to use higher hardness and higher strength materials. In other words, use hardened steels. Hardening twenty-foot-long sections of track is not a trivial matter. In fact, it is a very difficult and costly venture. So it is really not a viable option.

However, hard rails, tracks, balls, and rollers are the way that surface fatigue is addressed in ball and roller slides that are used in many machine applications. Surface fatigue of balls, rollers, and raceways is a common cause of failure. Many manufacturers offer replaceable ways and replacement rolling elements. Raceways are either through hardened to 60 HRC and balls and rollers are of similar hardness. Surface fatigue can occur in slides used in production machines simply because of the large number of stress cycles. A punch press operating at 1,000 strokes per minute can accumulate over a million stress cycles in a single day. If surface fatigue does not occur, wear due to sliding will eventually be the mode of failure.

Railroad wheels are available in different heat treatment conditions and hardnesses to deal with surface fatigue. Most are carbon steels with carbon contents in the range of 0.5 to 0.9. Some are quench-hardened and tempered. Some have no heat treatment. Hardnesses can range from 220 to 360 HB. A switch yard locomotive may use the 220 HB wheels whereas the 360-HB wheels may be intended for a passenger locomotive that may see the highest speeds in service. Surface fatigue of wheels usually occurs by propagation of subsurface cracks not unlike the mode of failure that occurs in rolling element raceways. Hertzian stressing of the wheel and tracks is the root cause of the surface fatigue. Steels are heat treated to increase their fatigue strength and this is how surface fatigue is dealt with.

Surface Fatigue of Gears

When the involute shapes of spur gears mesh and transmit power, the teeth experience both sliding and rolling. Rolling

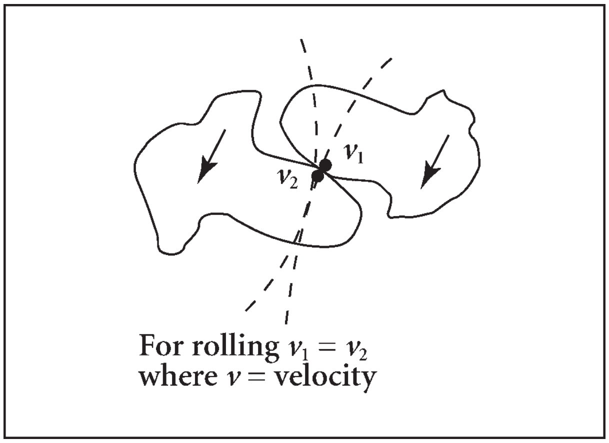

Fig. 9-12—"Rolling" in gear teeth.

occurs where the velocity of a point on a tooth of one gear has the same velocity as a tooth on the other gear (Figure 9-12). Scoring occurs where the teeth rub on each other and pitting occurs by surface fatigue. Pitting starts as subsurface cracks and spalling produces the depressions on the teeth that are referred to as "pits." They often are located near the pitch diameter. Repeated compressive stressing is their origin.

Hertz stresses in gear teeth are determined from Hertz stress equations for contacting cylinders. There are math models that can be used to arrive at tooth hardnesses that can accommodate a particular operating Hertz stress. For example, one model uses 360 times the average Brinell hardness number of the gear teeth as the maximum Hertz stress that can be tolerated by that particular material couple. As is the case with other surface fatigue situations, high contact stresses are dealt with by increasing the hardness and strength of the gear materials. Increasing residual compressive stress on a surface is also known to help reduce surface fatigue. Peening and case hardening are typical techniques for producing helpful surface compressive stresses. These compressive stresses tend to inhibit crack opening and propagation and thus eventual spalling.

Impact Wear and Surface Fatigue

Solid particle and droplet impacts can damage a surface, but we are categorizing these events as erosion. Impact wear by our definition is unintentional loss of material from a solid surface caused by repeatedly striking another solid surface. This tribosystem is important in many industrial applications and, of course, it is a key tool in the construction business in the form of pneumatic hammers. There are also rock-drilling tools that use impact. Rock and concrete drilling with repeated impacts of a pneumatic drill produces wear of the tool bits. Percussion rock drilling tools often use cemented carbide tools that lose material by matrix erosion. The primary mechanism of material removal is from abrasion from the concrete or rock. Abrasion wear tests are probably the most applicable tests for these applications.

In this section, we are addressing wear of tools such as high-speed riveting hammers that are used to swage materials, to fasten levers to shafts, to emboss, to mechanically print. Most of these applications involve a tool material striking a work surface. A metal-to-metal impact involves a variety of deformation possibilities (Figure 9-13).

In addition to these deformations, there is lateral slip of both members caused by the sideways deformations that must occur because of Hookean behavior. The compressive stresses are Hertzian in nature with possible vibration contributors. In addition, the shear stress condition is different from rolling and sliding because of the forced lateral deformation (Figure 9-14). All of these situations result in a form of wear often characterized by surface smoothing, then deformation, then fretting damage, and finally spalling of material by surface fatigue (Figure 9-15).

Impact wear on tools is dealt with by screening candidates with impact wear testers. The material solutions used for other forms of surface fatigue, hard, high strength materials are also used to address impact wear. Hardened tool steels are the usual candidates. Some impact situations like a hammer against a chisel are characterized by plastic deformation. The battering ends of cold chisels have a hardness of about 200 HB, whereas a typical carpenter's hammer head has a hardness usually about 450 HB. When the same hammer is used on a softer nail, the situation is repeated. Deformation occurs on the soft nail head and the hammer head is subjected to lateral rubbing of the deforming nail against the head.

In the event of a hard/hard impact wear situation, the lateral motion of the contacting surfaces is much smaller and the mode of wear may switch from significant metal rubbing on the battering tool to a fretting type of wear. Each surface moves a very small amount (micrometers) laterally on the other, a fretting motion. Thus material removal in hard/hard

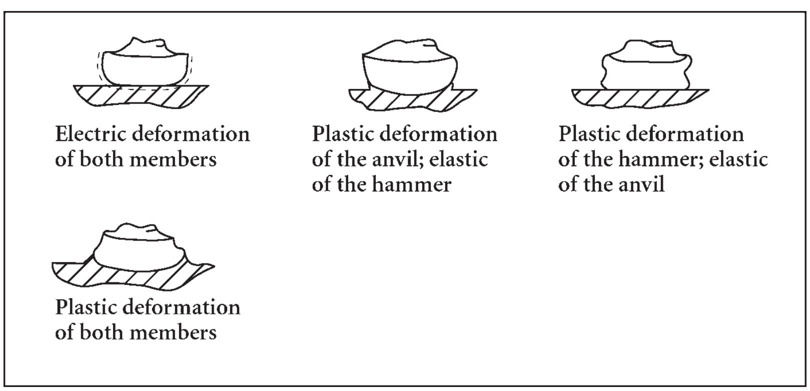

Fig. 9-13—Possible tribological events in solid/solid impact.

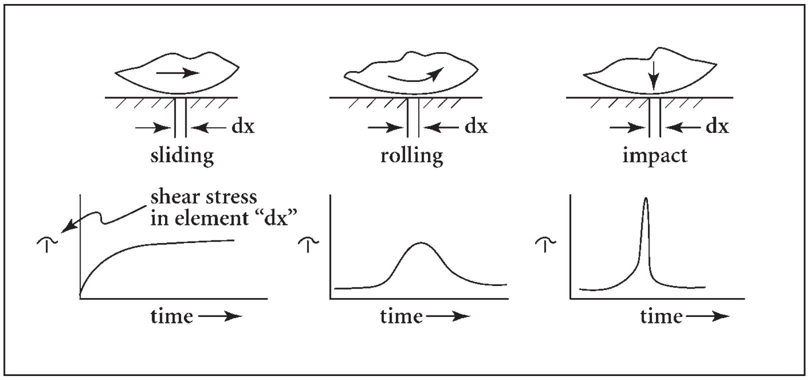

Fig. 9-14—Shear stress in rolling and impact contacts.

impact can be material loss due to fretting coupled with spalling of localized areas due to surface fatigue.

Rolling Element Wear Tests

The common way that ball and roller bearing users assess life capability is to run life tests using a designated lubricant. For example, a company may have a grease that they standardized

Fig. 9-15—Surface fatigue on a hammer head (as the result of repetitive impact).

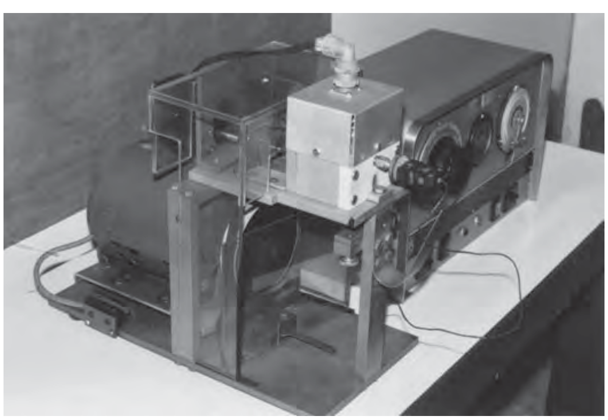

Fig. 9-16—Bearing tester (temperature is controlled).

or for certain types of bearings. They will degrease candidate bearings, lubricate them with their standard grease, and life-test them. They will have a criterion for failure such as vibration, temperature rise, or rolling friction. Life tests can be conducted on a battery of ordinary electric motors (Figure 9-16) or in more sophisticated rigs that monitor vibration and the like (Figure 9-17). Testing to failure requires Weibull statistics or similar analysis to analyze the data, but life tests usually yield a life graph like Figure 9-18.

Bearing manufacturers and lubricant formulators, of course, perform these kinds of tests. Users perform these tests where failures in service cannot be permitted. Statistics are used to determine probable life and the bearings are changed out well before the estimated life is achieved. Aircraft engines are an example where this kind of serviceability is needed.

The concerns with these kinds of tests are the elapsed time required to perform them and the fact that all life tests require replicates and statistical analysis. It is the nature of tests to failure that some bearings will fail at 2 million revolutions and some will fail at 20 million. Weibull statistics can

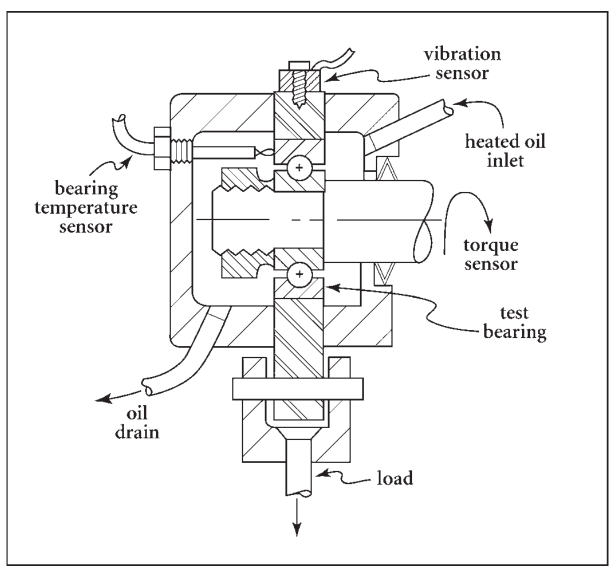

Fig. 9-17—Ball/roller bearing life test setup.

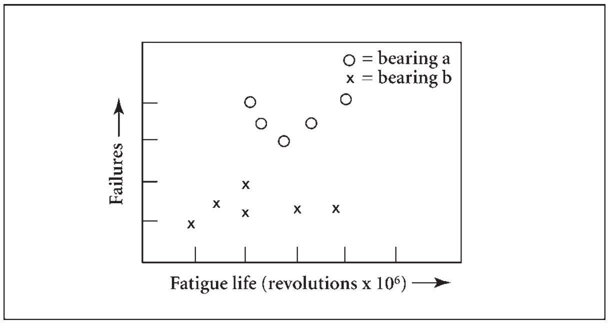

Fig. 9-18—Typical bearing life data.

make sense of these data and provide an estimate of the number of test replicates needed. Surface fatigue is the usual failure mode and this is what one must do if you need the utmost confidence in the serviceability of ball and rolling bearings. In fact, the very concerned users change the grease and use acoustic emission or other nondestructive tests to check all bearings before they are put into service. There are many machines in which a bearing failure could cost lives or equipment losses in the millions.

Gear Fatigue Tests

The FZG tester that was described in Chapter 6 is an accepted testing technique for the fatigue life of gears. As is the case with rolling element bearings, some gear failures can be just as catastrophic as bearing failures. FZG gears are relatively inexpensive to make and to check the surface fatigue characteristics of a particular gear couple FZG gears are made from candidate couples and life test them at test loads to failure. Gears are probably more prone to scoring, Figure 9-19 (scuffing to some), and scoring could occur before surface fatigue. However, this is not bad since a user also needs to know if a particular gear couple is prone to scoring.

Plastic gears are very common in business machines and many other essential devices and they also can fail by surface fatigue, but tooth wear is more likely. They are life tested on dynamometer types of testers not unlike the FZG machine.

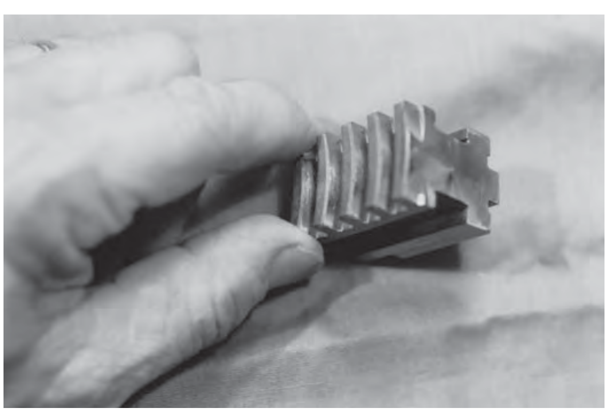

Fig. 9-19—Tooth scoring.

Fig. 9-20—Pitted and spalled worm wheel.

Increase in gear backlash is often the test metric and surface fatigue will be determined in post-test examination.

There is an ASTM test standard on "surface fatigue" (ASTM D 6121). It is written for testing hypoid gear oils for automobile axles. The test is run on actual axle assemblies and the ring gear, pinion, and pinion bearings are inspected for pitting, spalling, and other indicators of surface fatigue. The test cycles the axle at two torque levels: one for conditioning, one for testing. The actual test is 24 hours at 80 rpm wheel speed with a torque of each wheel of 2359 Nm.

Obviously, this is not a test for the average tribology-testing lab. It requires an axle dynamometer and lots of monitoring equipment. Tests like this are needed on gears that are not simulated adequately on the FZG machine. The FZG machine normally uses spur gears and it is most used for spur gear testing. Similarly, worms and worm wheels (which also fail by surface fatigue (Figure 9-20) should not be studied on the FZG using spur gears. A valid test must simulate the application (worms and worm wheels).

Rolling Surface Fatigue Tests

A rail fatigue testing technique that has been used in clean rooms and sanitary manufacturing facilities with overhead cranes and lifting devices on rails is to equip each wheel with a vacuum and analyze the debris emitted from each wheel/track interface (Figure 9-21).

Cycling crane wheels and tracks can be performed on a universal testing machine or other suitable source of reciprocating motion (Figure 9-22). The driving force for these studies was to eliminate spalling of surface scale, which fell from

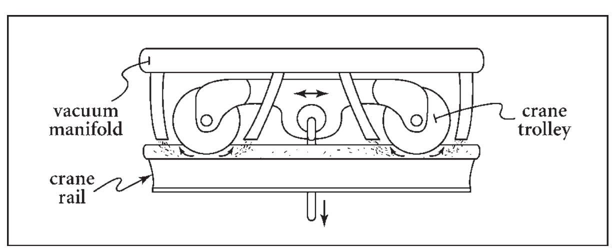

Fig. 9-21—Use of vacuum systems to address surface fatigue of crane sails.

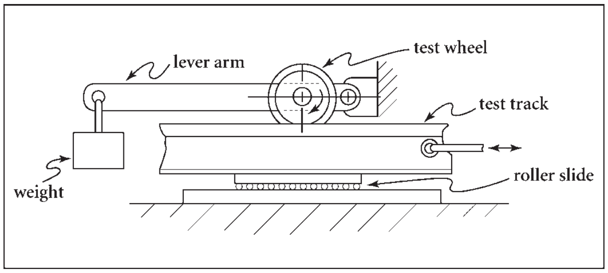

Fig. 9-22—Test setup for testing wheel/track couples for surface fatigue characteristics.

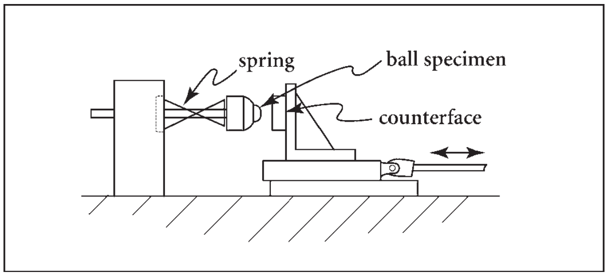

Fig. 9-24—Use of a reciprocating wear tester to produce impact wear.

rails and contaminated product. Rails are commercially available only in carbon steels and austenitic stainless steel in the United States, so most research evolves around heat treating the crane rails or conditioning them to remove mill scale and the like that can spall.

A common laboratory tester that has been used for railway tracks and wheel studies is a disk-on-disk device (Figure 9-23). Because there is slip in any rolling application, the disks in the disk-on-disk tester can have different velocities. Tests are conducted with various degrees of slip. Slip is usually presented as a percent. Mass loss on the disks provides wear data, and the surfaces can be examined to rate surface fatigue in the form of pitting and spalling.

There are testers for full-size railway wheels. The wheels essentially run on dynamometers similar to those used for automobiles. These tests also investigate the structural integrity of the wheels. Needless to say, if a full-size wheel loaded with 50 kN fractures at a running speed of 100 km/h, there is great risk from fractured pieces. Thus, full-size wheel tests are conducted with appropriate safety equipment. The most widely used test for studying surface fatigue of wheels versus rail track is the disk-on-disk test.

Impact Wear Tests

Impact wear tests can be conducted on a standard reciprocating pin-on-flat wear tester. The normal flat plate specimen is replaced with a spring-loaded ball or rod (Figure 9-24). Mass change can be measured on both members or profilometry can be used to measure scar profiles and mass changes can be calculated from these profiles. If an application requires high-frequency impacting and ultrasonic sealing, horn can be altered with a spring device or other technique to impact materials thousands of times a second. Impact damage on a ball often looks like fretting corrosion damage and accurate measurement of damage can be a significant part of a study. High-speed impacts as in ballistics are outside the scope of this book; they apply to military equipment.

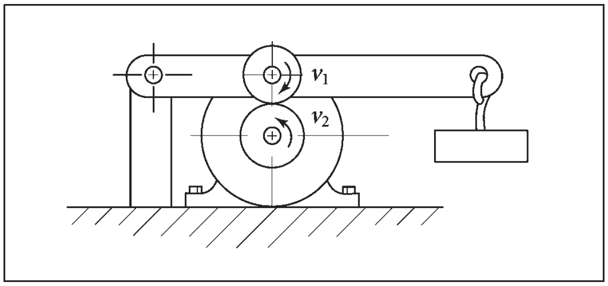

Fig. 9-23—Disk-on-disk tester for surface fatigue testing.

Chapter Summary

Rolling and impact often produce surface fatigue as a failure mode and a variety of tests are used to simulate these applications. Because spalling usually is localized, it may need visual or microscopic examination of surfaces to detect its presence. Also, tests need to simulate the Hertzian stress anticipated in an application.

Important Concepts

The following concepts should be taken from this chapter:

1. Rolling is always accompanied by some slip (so wear will be conjoint).
2. Spalling is a common failure mode in rolling and impact systems.
3. Impact can produce fretting motion (and fretting damage).
4. Hertzian stress levels need to be calculated and Hertz stress kept below the compressive yield strength in testing.
5. Coatings can be prone to spalling under rolling and impact conditions. They should be engineered to accommodate stresses.

Resources for More Information

Rolling

Zarilsky, F. V., *Life Factors for Rolling Element Bearings*, Park Ridge, IL, Society of Tribologists and Lubrication Engineers, 1992.

Harris, T. A., *Rolling Bearing Analysis*, 3rd Ed., New York, Wiley, 1991.

Stolarski, T. A., and Tobe, S., *Rolling Contacts*, New York, Wiley, 2000.

Tallian, T. E., *Failure Atlas for Hertz Contact Machine Elements*, New York, ASME Press, 1992.

Impact

Engel, P. A., *Impact Wear of Materials*, Amsterdam, Elsevier, 1976.

Related ASTM Standards

D 4998 – Evaluating Wear Characteristics of Tractor Hydraulic Fluids *(FZG test rig, case-hardened spur gears self mated at 121°C, 100 rpm, 166 to 194 Pa, 20-hour test, record gear mass change.)*

D 6121 – Test Method for Evaluation of Load-Carrying Capacity of Lubricants Under Conditions of Low Speed and High Torque Used for Final Hypoid Drive Axles *(Full-size gears and axles are tested in a special test rig.)*

G 133 – Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear *(Procedure a: 3/8-inch-diameter ball, 25 N, 10-mm stroke, 5 Hz, 100 m of sliding at 22°C.)*

10

Erosion Testing

Introduction

EROSION IS DIFFERENT FROM WEAR IN THAT there is a fluid contribution to the mechanical action that is producing wear. If the fluid is corrosive to the material being eroded, it will increase material removal. Water is often corrosive in erosion on metal base systems so there will be a contribution. On the other hand, air in solid particle and droplet erosion is not corrosive to most materials so there will not be a "dissolution component." When a fast-moving stream erodes a canyon through solid rock there may or may not be a corrosion component depending on the type of rock. Water in copper plumbing can certainly have a chemical component. In fact, any of the metals that rely on passive films for corrosion resistance are likely to be corroded when the mechanical action of the fluid or particles in the fluid disrupts the film formation kinetics.

This chapter will describe some of the tests that are commonly used to research erosion processes and rank engineering materials for use in erosive applications. Retrieving oil from hundreds/thousands of meters below ground always produces erosion of the drilling tools. Handling coal in mining and again in coal-fired boilers produces erosion. Venting sand/dirt-laden air erodes fans and impellors. Droplets impacting aircraft erode affected surfaces. And, of course, working soil as in farming erodes tillage tools. Thus, erosion is very widespread and of great economic importance. Hopefully, this chapter will provide people who are confronted with solving erosion problems a path forward. This chapter will discuss tests for the major forms of erosion, solid particle, slurry, droplet, impingement, cavitation, and erosion corrosion. Standard tests will be described where they are available.

Solid Particle Erosion Tests

As a repeat of the definition in Chapter 2, solid particle erosion is material removal/damage to a solid surface produced by repeated impacts of solid particles. Sand blasting is the most common example. Holding a sandblast nozzle a short distance from a steel surface and impinging it on the surface will erode a hole through the steel plate if allowed to impinge for a length of time. It is erosion by our definition because it involves the mechanical action of a fluid. The gas propellant imparts kinetic energy to the particles and that energy is expended in deformation and fracture on impact.

Some of the tests used for solid particle impingement are shown in Figure 10-1. Most involve high-velocity particles, but the falling sand test only uses earth's gravitational pull on the sand as the source of particle velocity. At increased velocities, solid particles become tiny projectiles, each capable of damaging a solid surface if the velocity is sufficient. Sand sliding down a chute will wear the chute, but the rate will be very low. In addition, the "impingement" is parallel with the surface which greatly reduces the force at which the particles contact the solid surface. Before 1950, coal was a popular fuel for heating homes in the United States. "Coalmen" delivered coal regularly to individual houses, and it was delivered from the truck using a wheel barrow by a soft steel chute through a window into a coal bin. The wheel barrows and coal chutes shined up, but almost never wore through. The same situation existed on the shovels and tubs used to deal with the ash after the coal was burned.

On the other end of the velocity scale, shutters for sandblast nozzles burn through in minutes. Wearbacks on cyclone separator elbows 10 mm thick can penetrate in a month. Damage is a function of the velocity to a power from 2 to 5. In addition, it has been shown in single particle tests that irregularly shaped particles can tumble in the transport stream and act like rotating cutting tools on impact (Figure 10-2). Sometimes, especially at normal impact on ductile metals, the particles can imbed and then reduce subsequent damage.

In summary, solid particle erosion is very dependent on the nature of the particles (hard, sharp, irregular, smooth, etc.), the impact angle, the fluence (a few or many particles) and the velocity. If air or a nonreactive gas is the propellant, there may be no chemical effects. It is the mechanical action of the particles that produce the damage. The differences between available tests mostly revolve around particle velocity. Particles in a liquid are considered in our section on slurry erosion.

Falling Sand Test

The falling sand test in Figure 10-1 is mostly used on coatings and transparent plastics. It is covered by ASTM D 673. Abrasive particles are allowed to strike a test specimen at 45° to the sand stream for a fixed length of time. The test metric for transparent plastic is loss of light transmission as measured by a photonic device that senses loss of light transmission. The metric for paints and organic coatings is mass loss.

The concern with this test is that it does not simulate a particular application. If a study is concerned with ranking protective coatings on acrylic eyeglass lens, it may not simulate any condition that the eyeglasses will ever be exposed to. Tests involving rubbing with a tissue immersed in lens cleaning solution or testing with a variety of cleaning materials (paper towels, handkerchief, lens cleaning cloths, etc.) may better simulate eyewear service.

Gas Jet Erosion Test

ASTM G 76 is a standard test procedure that impinges 50-μm aluminum oxide at a target 10 mm away from a WC/Co nozzle with a bore of 1.5 mm at a velocity of 0.1 m/s and at normal incidence. The particle mass flow rate is 2 g/min, and the test lasts for 10 min. Volume loss is the test metric and it is obtained from mass change measurements or from

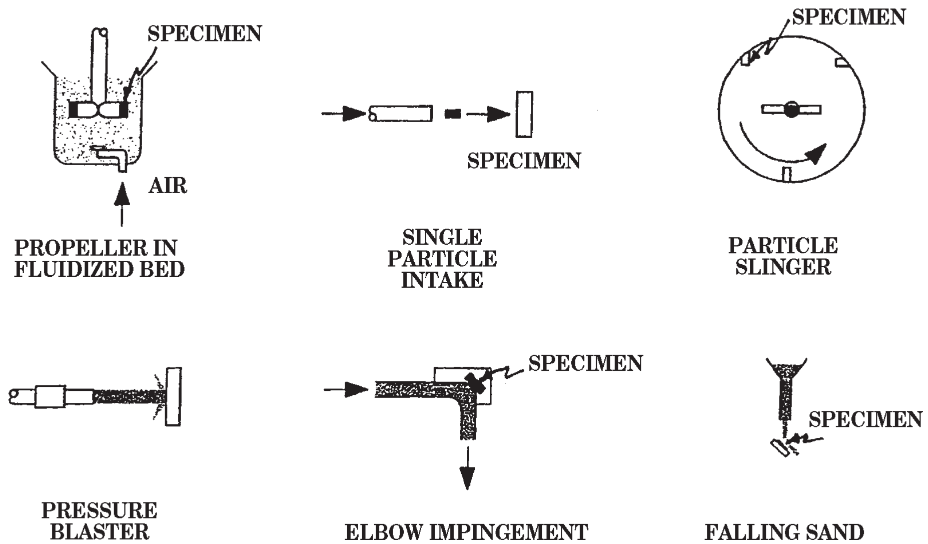

Fig. 10-1—Types of solid particle impingement tests.

profilometry measurement of scar depth and area. There are a number of "challenges" in performing this test. The test rig is shown schematically in Figure 10-3. A sample holder is shown in Figure 10-4.

Challenge number one is obtaining the required 2 g/minute of aluminum oxide in the gas stream. Feeding abrasive into a gas stream at a precisely controlled rate is not a trivial matter. A simple valve as shown in the schematic usually does not work. Sometimes putting a vibrator on the hopper works, but the best results are obtained by using a motor-driven device like a screw that will precisely meter out the proper amount of grit.

The next challenge is measuring the mass flow that exits the nozzle. This is often done by directing the nozzle into, essentially, a vacuum cleaner bag for a time and weighing the bag. The more elegant approach is to use a laser velocimeter that measures the obscurity of the laser beam produced by particles. These devices are often very expensive.

The other significant challenge is measuring the velocity of the particles. The laser velocimeter will do the job. The "poor person's" technique is to direct the nozzle into rotating parallel plates (Figure 10-5). There is a slot in the first plate (about 1 mm wide) and no slot in the second plate. Knowing the angular distance from the slot to the impact mark in the second plate, the distance between the plates and the rotational velocity of the plates, it is possible to calculate the velocity of the particles. The hard part is getting a crisp impingement mark on the second plate. Using shiny aluminum foil on this plate helps. It is also necessary to use a high-speed motor to rotate the plates; 3,600 rpm is usually adequate.

In summary, this is a difficult to run test because of the challenges mentioned, but it does a very good job of simulating particle impingement in cyclone separators, comminution devices, even dust and particles striking aircraft propellers and helicopter rotors. It is probably the most widely used solid particle erosion test.

Slurry Erosion Tests

The definition of a slurry from Chapter 1 is any liquid/solid mixture that is pumpable. Big chunks of coal in water qualify if they can be pumped. On the other end of the scale, toothpaste can also be called a slurry. It is calcium carbonate particles in a thixotropic liquid. It is pumped into the tubes that consumers buy. Concrete is a slurry and it is pumpable (with some effort). The mining, petroleum, and chemical process industries depend on conveying feedstocks in slurry form. Slurries erode by the action of abrasive particles in the liquid contacting pump housings and piping. If the fluid is corrosive to the pump or piping material, it will be conjoint with

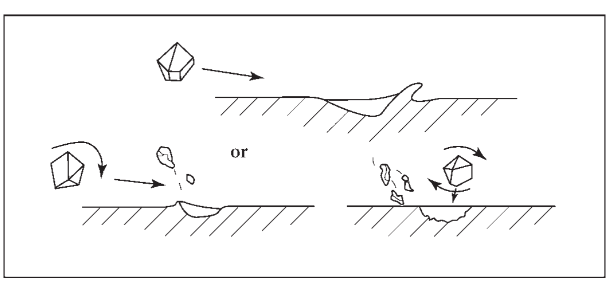

Fig. 10-2—Cutting action of particles.

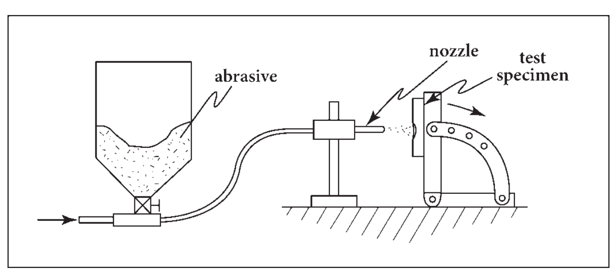

Fig. 10-3—Schematic of the ASTM G 76 jet erosion test.

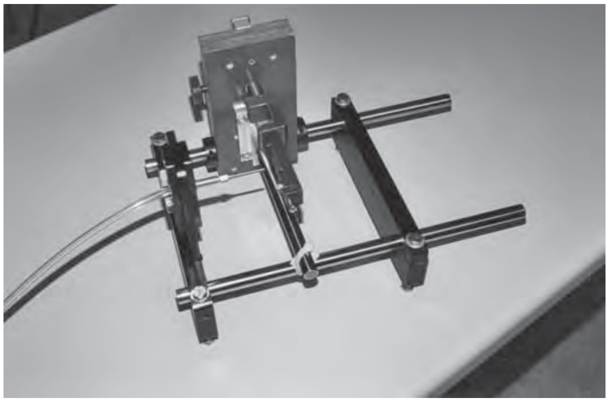

Fig. 10-4—Specimen holder for jet erosion tests.

erosion. Some tests identify the "corrosion" and "abrasion" components of the erosion.

A variety of slurry erosion tests are illustrated in Figure 10-6. The Miller number test is widely used to assess the abrasivity of slurries and to rank materials for their ability to survive pumping various slurries. A flat test specimen reciprocates on a rubber lap immersed in a slurry of interest. When a standard rider of high-carbon, high-chromium white iron is used, a Miller number is developed by the test. The higher the Miller number; the more abrasive the slurry. When the rider is made from candidate materials, the test will rank metals in a particular slurry. The latter test yields a slurring abrasion resistance number. The Miller test can be run with original slurry and then a buffered slurry to determine the corrosion component of the erosion. A concern in using this test is that it was intended to simulate reciprocating pumps. Continuous pumps may not be properly simulated by a reciprocating test.

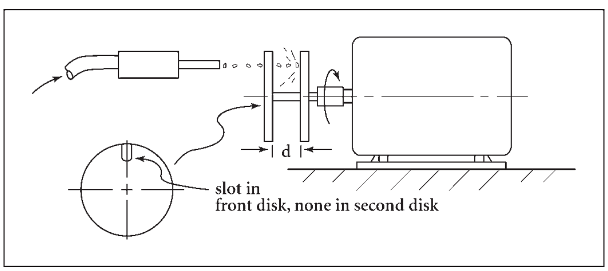

Fig. 10-5—Schematic of double-disk test for particle velocity.

Wet-Sand/Rubber Wheel and the Carbide Abrasion Test

The ASTM G 105 (Figure 10-7) wet-sand abrasion test was previously described in the chapter on abrasion testing; it is mentioned again because being wet, it is really an erosion test. A concern with this test as an erosion test is that with a 1-hour test time, it does not really allow sufficient time for corrosion to remove a measurable amount of material if corrosion can occur. A second concern is that the large abrasive (50–70 mesh silica) does not really disperse well even with agitation. Of course, dispersion and suspension of particles is a concern in all slurry erosion tests.

The ASTM B 611 wet abrasion test for cemented carbides is very similar to the rubber wheel test in concept (Figure 10-8). It is designed to screen cemented carbides for their abrasion resistance. It uses a steel wheel instead of rubber; the abrasive is 30 grit aluminum oxide. Again, the test time (10 min) may be too short to allow corrosion to be a factor, but it is a very effective test for screening carbides for applications where abrasion is the primary concern and it is known that the fluid does not affect cemented carbides. The cobalt binder in conventional cemented carbides can be susceptible to corrosion in aqueous environments, so any wet test raises the question as to whether this is an accurate predictor of dry abrasion. Ceramics can be screened in this test if they can be made into the required specimen configuration. This is a high-stress abrasion test because the stresses are sufficient to fracture the abrasive (carbide test specimen, steel wheel, 200 N normal force).

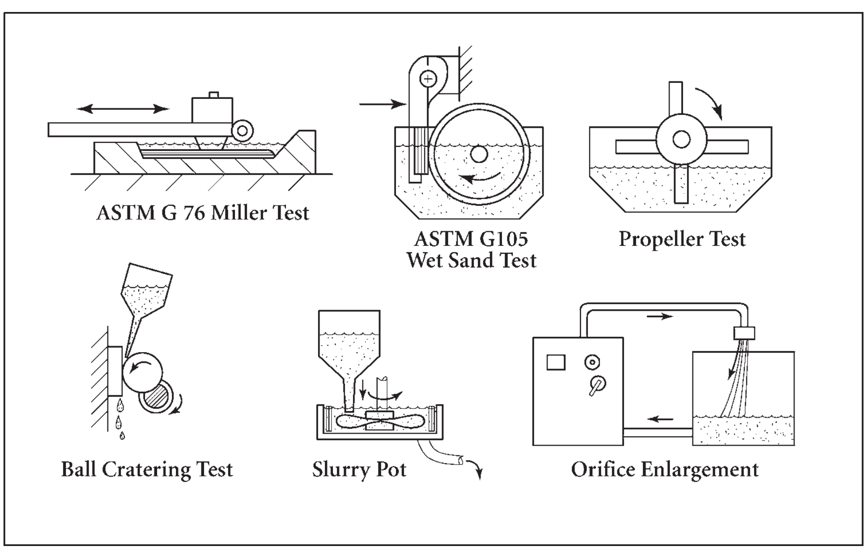

Fig. 10-6—Various slurry erosion tests.

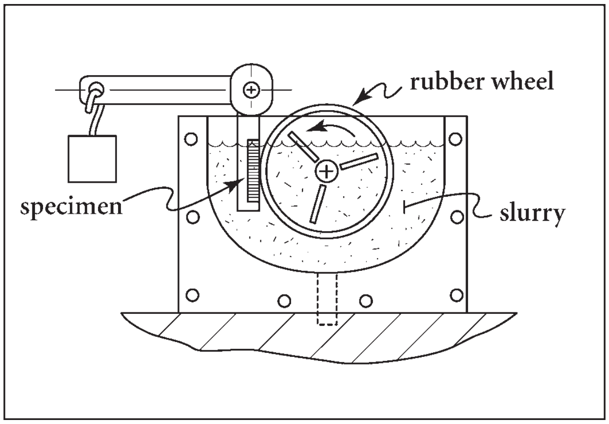

Fig. 10-7—ASTM G 105 wet-sand abrasion test.

Propeller Tests

This is not the correct name for these tests, but it describes the basic concept of the test: affix specimens to the tip of a propeller and rotate it immersed in a slurry. The basis of the concept is that it simulates erosion that would occur on an impeller in a rotary pump. It would also simulate the slurry action on a pump casing. Of course, there is great economic interest in slurry pumps; they are widely used in construction (mud pumps), in mining, in making potable water, even in household sump pumps.

The propeller test in Figure 10-9 presents one with eight blades that are the test specimens, totally immersed in the slurry. Some investigators use a horizontal propeller partially immersed. The concept is the same. The tips of the propeller are exposed to the highest velocity slurry and there is a gradient in velocity going towards the centerline. This allows investigation of the microscopic nature of particle strikes at different angles and velocities.

Calculating the effect of corrosion during wear has been standardized as ASTM G 119 entitled: Determining Synergism Between Wear and Corrosion. However, this test may a bit complicated to perform for many labs because it uses potentiodynamic polarization techniques. It does determine the corrosion component of slurry erosion. A concern with impeller tests is providing enough impact energy for the abrasive to be an effective erodent. For example, rotating a propeller in a large tub of sand (Figure 10-9) would take a very long time to erode specimens. An impeller in close proximity to the vessel wall will increase particle “action” on the impeller tip. Particles will be forced against the tip with higher forces than if the impeller operated in a much larger vessel.

Fig. 10-8—ASTM B 611 high-stress abrasion test for cemented carbides.

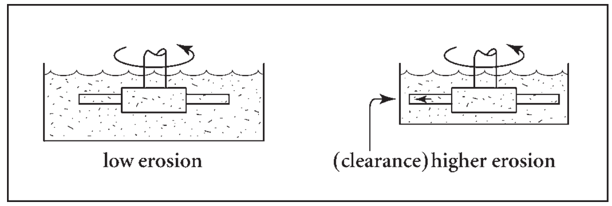

Fig. 10-9—Propeller erosion tester.

Ball Cratering Test

Like the wet-sand test, we described this test in the chapter on abrasion. It probably belongs as an abrasion test if test times are short. However, it is a slurry test as well as a wet abrasion test. It uses a fluid that could interact with the test specimen. There are some concerns that users should keep in mind when using this test, the foremost of which is getting a consistent slurry. How does one keep the abrasive suspended? An air bubbler helps, but this test needs a foolproof mechanism for keeping the slurry particles in suspension and delivering them to the ball specimen interface (Figure 10-10). Any process/device can be used, but the issues need to be addressed.

The test results also depend on the sphericity and surface texture of the ball, the abrasive size, motion, and mass flow of slurry particles. In other words, this test needs to be conducted with a testing standard. An ISO standard was in preparation at the time of this writing.

Slurry Pot

The ASTM G 119 wear/corrosion synergy test is a slurry pot test. The common elements of a slurry pot test are a horizontal propeller and complete immersion of the impeller. The U.S. National Association of Corrosion Engineers (NACE) has for many years had a test standard on a test to increase fluid velocity and assess effects on corrosion rate. The test is illustrated in Figure 10-11.

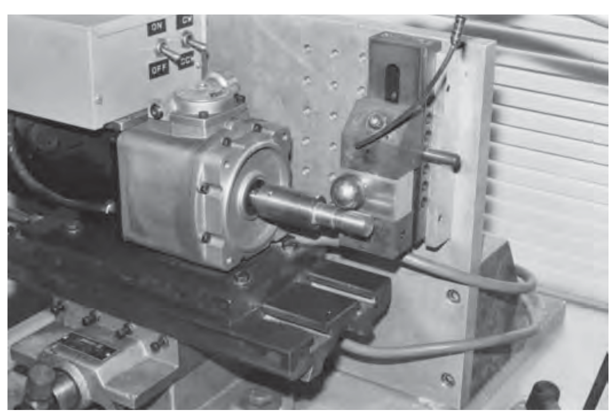

Fig. 10-10—Ball cratering tester.

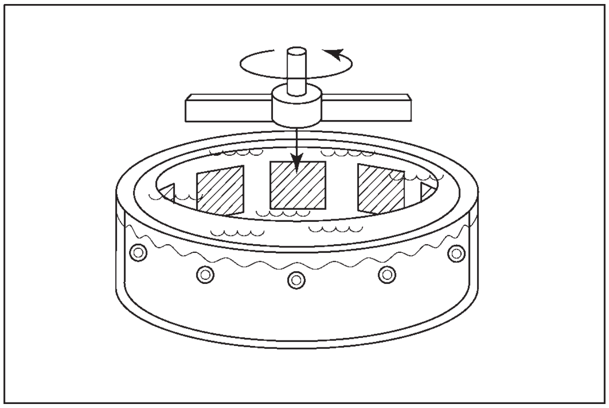

Fig. 10-11—Schematic of NACE liquid erosion test.

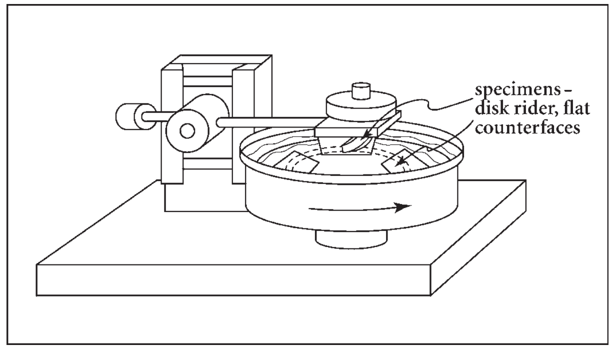

Fig. 10-12—Schematic of an erosion/corrosion test rig.

The impeller can create a particular fluid velocity, and the effect of this can be determined by mass change measurements on the test specimens that are electrically isolated from each other by embedding in a nonconducting plastic (i.e., PTFE) ring. This specimen holder has been incorporated in slurry pot tests and a slurry rather than liquid is introduced into the pot. A concern with this slurry test is that the abrasivity of the particles can change with time. A way to avoid this concern is to have a large supply of slurry and have it only make one pass through the pot and then be discarded. This is probably the best way to run a slurry test if the equipment is available. Who can argue with once through when this is what happens in pipelines and most slurry handling devices?

Orifice Enlargement

The final schematic in Figure 10-6 may be the simplest test for evaluating the resistance of materials to a particular slurry. One simply buys a commercial slurry pump, supplies it with the slurry of interest, and pumps it through an orifice made from the candidate materials under study. The test metric is the variation of orifice size (diameter) with time, which yields a mass change and wear volume when the test is completed.

This test is not widely used; a probable cause is the cost of the slurry pump. Another concern is obtaining orifices out of all of the materials of interest. For example, if thermal spray coatings are candidates for a particular slurry application, they cannot be evaluated by this test since they cannot be sprayed inside a one-millimeter diameter hole.

Erosion/Corrosion

Most of the tests described to this point are short-term tests, often less than a hour in duration. Corrosion requires time and thus a longer term test. A longer term erosion/corrosion test is illustrated in Figure 10-12. Test specimens are mounted horizontally in a plastic disk. The specimens are immersed in the test liquid or slurry and rotated while a dead weighted rider rubs on a portion of each test specimen. Several specimens can be evaluated at once and the rider can be whatever might rub against a material in service. For example, if a project calls for evaluating shaft materials that will be exposed to rubbing by a seal or "O" ring, the rider can be made from the "O" ring or seal rubber. An erosion/corrosion scar will develop in the rub area if the rubbing activates the surface more in the rubbed area than not. The test also can be run with a single disk counterface rubbing against a rider of interest. Corrosion without rubbing can be compared with results under erosion/corrosion conditions. This test is commonly run for 30 days, which usually is long enough to ascertain if rubbing is rendering a material corrosive in a liquid that it normally would resist. Typical erosion/corrosion scars are shown in Figure 10-13.

Droplet/Impingement Erosion

Probably the most common form of impingement erosion in industry is erosion in introducing chemicals into vessels and in bends in pipelines carrying fluids at high velocity (Figure 10-14). Chemicals, water, or steam entering a vessel and impinging on something in the vessel can create impingement erosion. There are no particles in the incoming stream, but the energetics of impingement removes protective films, corrosion occurs, and reformed films are repeatedly removed. Impingement situations like that illustrated in Figure 10-14 are often dealt with using a sacrificial plate as the impingement target. If the plate is mechanically fastened, different materials can be tested and compared for serviceability. It is not common to perform impingement bench tests, but there is probably a need for such tests. The advent of low-cost, high-pressure water cleaning rigs at home supply centers has meant indiscriminate

Fig. 10-13—Erosion of corrosion resistance materials after 30-day rub test versus rubber belting.

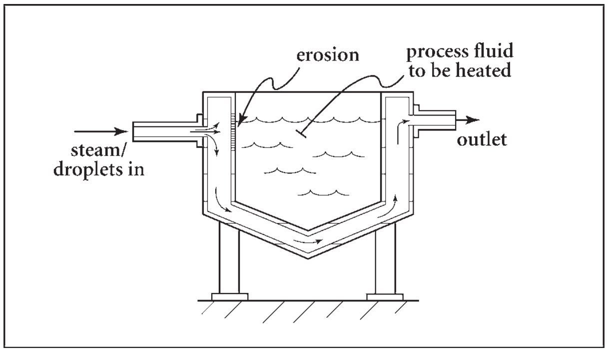

Fig. 10-14—Impingement erosion of a heat exchanger opposite a vessel inlet.

use of these devices to erode many surfaces like building brick or stone. The "cleaning" is often causing harmful erosion. Tests are needed to bring awareness of erosivity of liquid impingement.

Liquid impingement by droplets can produce significant erosion damage when the droplet velocity is similar to the action of a jet plane traveling through a rain field. In fact, the ASTM G 73 droplet erosion test uses test specimens attached to the tips of aircraft propeller blades several meters in diameter powered by a 200 HP motor. Water nozzles create an artificial rain field with known droplet sizes. Test specimens are subjected to the "rain field" for a known time and a cumulative erosion rate curve is developed for a test material and compared to a reference material (Figure 10-15).

The test standard allows various specimens (droplets), velocities, and droplet sizes. The standard addresses specimen preparation, establishing erosion curves and interpreting the test results. The test is applicable to metal, composite, plastics, and other materials that may see rain field erosion on aircraft. Figure 10-16 shows a propeller type test rig.

In summary, the erosivity of a rain field on impacting surfaces of an aircraft at mach 1 can never be simply simulated. Hence, this test is not something that the average tribology lab may want to tackle. However, that is not necessary. There are contract testing labs that will perform these tests. Therefore, if a new aircraft paint and windshield plastic are offered as superior to those currently used, there are rain-erosion tests that can be used to quantify their erosion resistance and ascertain if they really are superior.

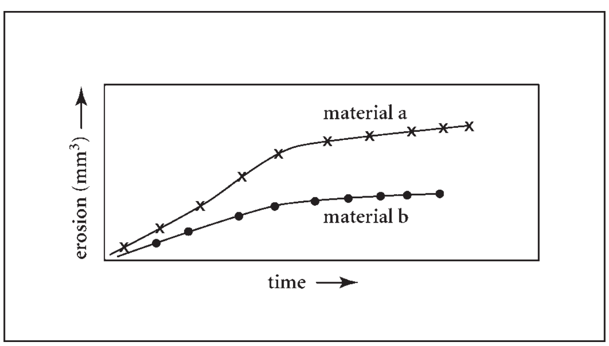

Fig. 10-15—Typical cumulative erosion curves.

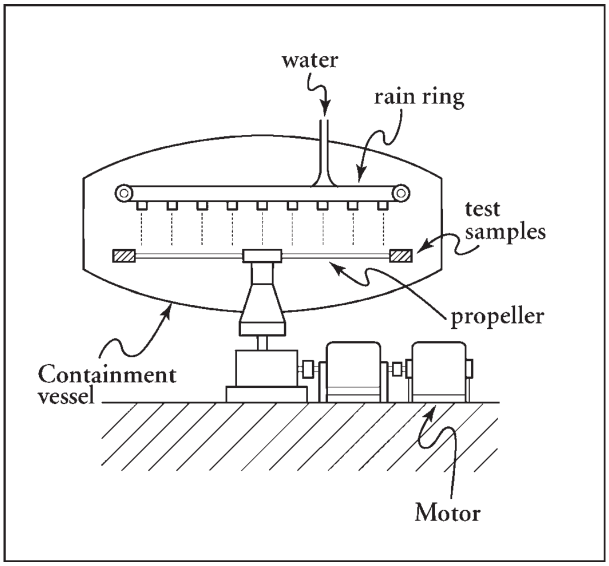

Fig. 10-16—Rain erosion tester.

Cavitation

The ASTM G 40 definition of cavitation is: "the formation and subsequent collapse, within a liquid, of cavities or bubbles that contain vapor or gas or both." As mentioned in Chapter 2, cavitation occurs in many industrial applications, and it is a problem to be addressed. On the other hand, it is widely used for cleaning everything from fine jewelry to automobile valve covers. In all cases, it can cause significant unwanted damage. In the chemical process industry, ultrasonic debubblers are widely used to degas liquids. Cavitation damage to the plate that couples these devices to vessels is a limiting factor in the application of this technology. Similarly, cavitation damage is often a limiting factor in the amount of flow that can be passed through hydroelectric generating dams. Concrete spillways erode from cavitation damage.

Figure 10-17 shows some of the ways that cavitation fields are produced for the purpose of evaluating the cavitation resistance of materials. There are ASTM test standards on the ultrasonic horn and water jet techniques.

Cavitation Testing with an Ultrasonic Horn

In ASTM G 32, the test specimen is a small "button" that is attached to the end of an ultrasonic horn (Figure 10-18). The button is threaded on the tip of an ultrasonic horn that is capable of vibrating at a frequency of 20 kHz. The type of test liquid is optional, but distilled water is often used and the liquid is cooled to maintain a constant temperature (Figure 10-19). The frequency and amplitude of the horn vibrations are measured and are controlled (20 kHz, 150 μm). Like the droplet erosion test, the test metrics include the cumulative mass loss of the specimen and the erosion rate characteristics (Figure 10-20). The test is usually run until the erosion rate curve shows a declining erosion rate. The reference material for the test is a pure nickel and the time to reach a declining erosion rate on this material is about 4 hours in water. Figure 10-21 compares cavitation damage on machine parts with the damage on an ASTM G 32 test specimen. They look the same; this

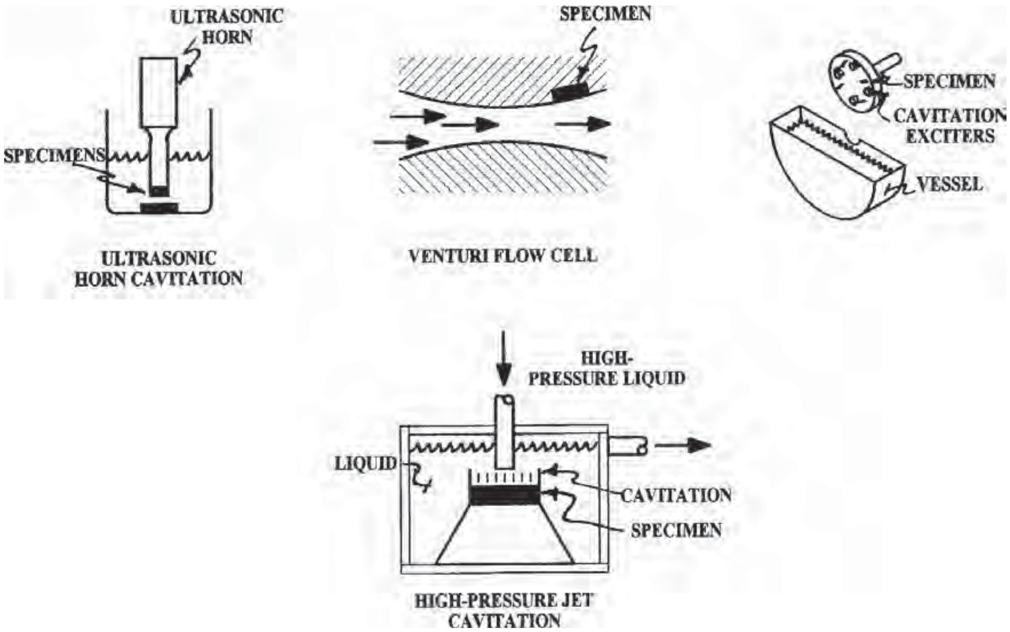

Fig. 10-17—Cavitation test rigs.

suggests that the test does a good job of simulating this type of service.

Some users of ultrasonic horn cavitation tests place the test specimens in the liquid vessel a specific distance from the horn tip and still measure the erosion rates as in G 32. This is called the stationary specimen test and this technique solves the problem of having to make tiny buttons with a fine thread out of difficult to machine materials.

Overall, the G 32 test has become the "gold standard" for comparing the cavitation erosion resistance of materials. The major concern with this test is making a tip from materials of interest. It is not a trivial task.

Submerged Water Jet Cavitation Test

The concern about machining wear-resistant materials into buttons for the vibratory horn test is also addressed with the ASTM G 134 test on Erosion of Solid Materials by Cavitating Liquid Jet. The test specimen is a small button like the one used in the vibratory horn test, but it does not have to be threaded on the end of an ultrasonic horn (Figure 10-22).

Various liquids can be used in the test. However, the standard test uses water at 35°C. According to equations in the test method, the cavitation field produced by the submerged nozzle is a function of the upstream and downstream pressures at the nozzle. The cavitation field is rated with a dimensionless number, σ, that is essentially the ratio of the downstream pressure (Pd) and upstream pressure (Pu): σ = Pd/Pu. It is a measure of the tendency to create cavitation. Upstream pressures can vary to 25 MPa and downstream pressures can vary to 0.6 MPa. The standard test specifies testing the test rig at two cavitation numbers: 0.09 and 0.025. It is also suggested that a standard reference material, UNS N02200 nickel, be used to check the test setup for severity of cavitation. Mass loss of the test specimen is the test metric.

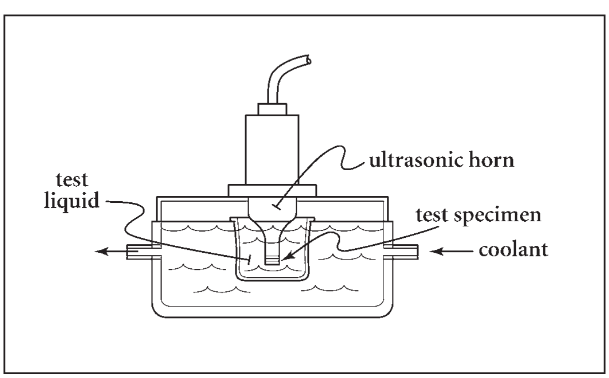

Fig. 10-18—Schematic of ASTM G 32 tester.

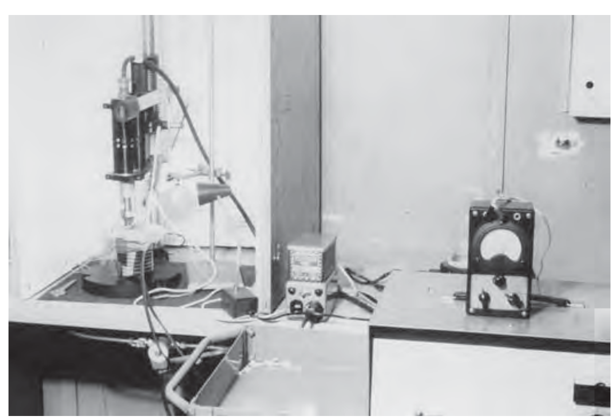

Fig. 10-19—ASTM G 32 test rig.

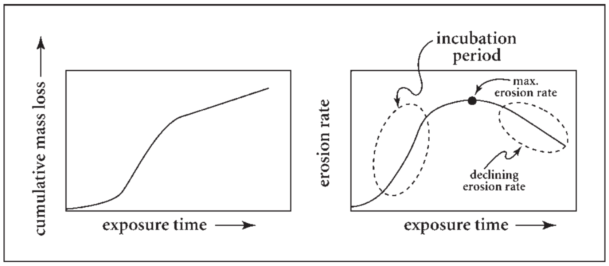

Fig. 10-20—ASTM G 32 test metrics.

Tests on candidate materials are conducted at a single cavitation number with a nozzle-to-specimen standoff distance at which the maximum cavitation rate exists. The exact standoff distance is determined experimentally. Thus, it is necessary to develop cumulative and instantaneous erosion rate curves like those generated in the ASTM G 32 test. The test report contains cumulative test time, cumulative mass loss, cumulative volume loss, maximum instantaneous erosion rate, incubation time, and a table showing the normalized erosion and incubation resistance of each material.

In summary, this (and ASTM G 32) are not as simple as some of the other erosion tests that have been discussed. The erosion rig is essentially a water jet cutting nozzle immersed in a liquid, but there are many details that need to be addressed to make the test rig suitable for studies that comply with the test method. Fortunately, drawings and details are available for users. This test is much more aggressive than the G 32 test and it does not require that the test material be threaded. A concern in using this test is the relative complexity of the rig and test. There are contract testing laboratories available to address this issue.

Chapter Summary

The ASTM erosion tests were emphasized, but there are countless versions of each test. The solid particle erosion test simulates erosion from air-born particles at room temperature and for jet engine and coal-fired boiler simulations this same kind of test is conducted hot. Some rigs can go to 1200°C. These tests are the accepted way to study solid particle erosion.

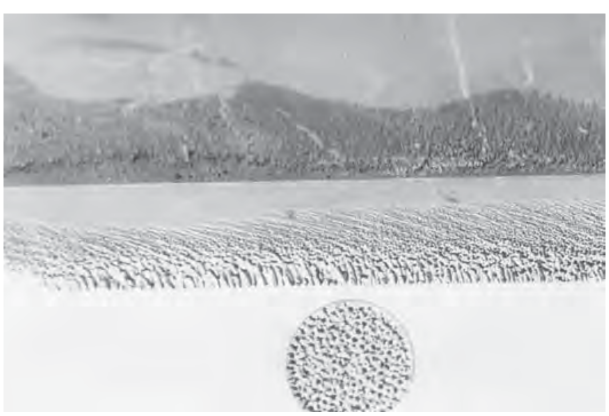

Fig. 10-21—ASTM G 32 test specimen (lower) has the same appearance as service cavitation damage (upper).

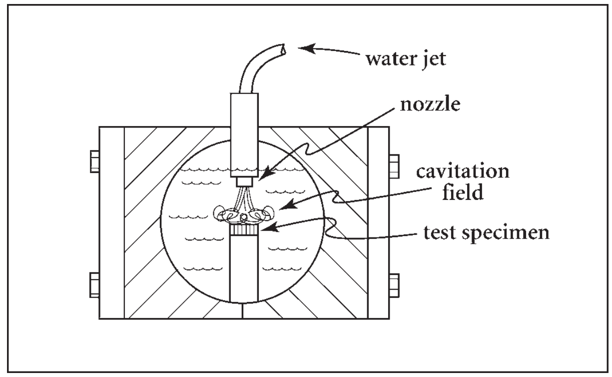

Fig. 10-22—Schematic of ASTM G 134 test rig.

Droplet erosion tests using the ASTM G 73 test method requires extensive equipment, but these studies can be outsourced to labs that have the required facilities.

There are many slurry erosion tests; the Miller test and wet-sand rubber wheel test are standardized. The Miller test accommodates any type of slurry; the wet-sand test only uses a silica/water slurry. Slurry pot tests usually include techniques to measure the corrosion component of the test and there is an ASTM standard on determining the synergy between wear and corrosion (ASTM G 119). The ASTM B 611 is the "gold standard" for screening cemented carbides. There are two ASTM standard cavitation tests: one uses a vibratory horn, the other uses a submerged water jet to create a cavitation field. The latter is considered more aggressive.

Important Concepts

The following concepts should be taken from this chapter:

1. Erosion differs from wear in that the mechanical action of a fluid in motion contributes to material damage or loss.
2. Short-term (i.e., a few hours or only minutes) erosion tests may not be long enough to properly address corrosion. This should be considered in selecting an erosion test.
3. Solid particle erosion tests require careful control of fluence, flux, velocity, and particle size, or particle shape, nozzle diameter, nozzle-to-target distance and test duration.
4. Liquid/droplet impingement and cavitation erosion tests should reflect that this type of erosion is typified by various stages (incubation, accelerated attack, steady-state) and material removal should be monitored with time.
5. Cavitation field intensity needs to be controlled in cavitation erosion studies.
6. The erosivity of a slurry depends on the volume fraction of particles, the nature of the fluid and the size and shape of the particles.
7. Fluid velocity is a key factor in erosion testing and needs to be measured and controlled.

Resources for More Information

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Solid Particle Erosion

Levy, A. V., *Solid Particle Erosion and Erosion Control of Materials*, Materials Park, OH, ASM International, 1995.

Hutchings, I. M., *The Erosion of Materials by Solid Particle Impact*, Columbus, OH, The Materials Technology Institute of the Chemical Process Industries, 1983.

Related ASTM Standards

B 611 – Standard Test Method for Abrasive Wear Resistance of Cemented Carbides *(A test specimen is pressed against a soft steel wheel (6.65 inches diameter) immersed in a slurry of 30 grit aluminum oxide; the wheel rotates at 100 rpm; a 20 kg force presses the specimen against the wheel for 1,000 revolutions and mass change is measured on the specimen.)*

G 32 – Standard Test Method for Cavitation Erosion Using Vibratory Apparatus *(The test specimen is attached to the tip of an ultrasonic horn immersed in a liquid and the erosion rate is measured with time.)*

G 73 – Standard Practice for Liquid Impingement Erosion Testing *(This is a practice, and this standard does not recommend a specific test, but rather presents a guide on how to establish cumulative erosion curves and use them with reference materials to evaluate candidate materials.)*

G 75 – Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (Slurring Abrasion Resistance Number) *(Mass loss is measured on a hard iron block that reciprocates on a rubber lap immersed in a slurry of interest; the test conditions are 48 rpm, 5-lb load, 20-mm stroke, 6 hours of rubbing.)*

G 76 – Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets *(Users can select test parameters, but the standard conditions are 1.5-mm nozzle distance, 50-mm nozzle diameter, 50-μm aluminum oxide, particle velocity of 30 m/s, 90° impingement, test duration 10 minutes at 2 g/min.; measure wear volume.)*

G 105 – Standard Test Method for Conducting Wet-Sand/Rubber Wheel Abrasion Tests *(Test specimens are forced against a 7-inch diameter rubber wheel, with a force of 50 lb for 1,000 revolutions in a slurry of 50/70 mesh silica and water; three rubber wheels of different Durometer hardnesses are used and the test metric is a plot of wear volume versus wheel hardness.)*

G 119 – Standard Guide for Determining Synergism Between Wear and Corrosion *(An erosion test of the user's option is conducted with and without corrosion and the synergism is assessed; the erosion test without corrosion is is made possible by repeating the erosion test with cathodic protection applied to the test specimen.)*

G 134 – Standard Test Method for Erosion of Solid Materials by Cavitating Liquid Jet *(A high-pressure liquid jet is directed at a submerged test specimen placed a set distance from the nozzle. Users can select test conditions or use standard test conditions. The erosion rate of the material in a given liquid under a specified cavitation condition is the test metric.)*

11

Types of Friction and Friction Testing

Origin of Friction

MANY CLEVER PEOPLE HAVE BUILT PERPETUAL motion machines and no one has succeeded in making one that works. The machines eventually stop because of friction. Friction is an energy dissipation process that accompanies a body or substance in relative motion in contact with another body or substance. When a solid body slides on another solid, it takes energy to put the body in motion and keep it moving. This energy is dissipated at the rubbing surfaces, usually in the form of heat or deformation. When a solid body is moved through a fluid, the energy required to produce motion is dissipated by movement of the fluid as in waves or even results in heating. Re-entry of the U.S. space shuttle is an example of friction between a solid (the shuttle) and a fluid (air) and the energy of the collision and rubbing of air molecules on the shuttle surfaces is heating. A fluid in a pipe dissipates energy at the fluid/pipe interface. Rolling a revolute shape like a tire on a solid surface requires energy and this energy is dissipated by tire and roadway heating. There is no zero friction mechanism because there is always rubbing when a body or substance is set in motion and rubbing of solid surfaces or substances dissipates energy. A first principle of physics is "for any force there is an equal and opposite reaction force." The friction force is often the reaction force dictated by physics. The mathematical definition of friction force, per ASTM G 40, is: F − the resisting force tangential to the interface between two bodies when, under the action of an external force, one body moves or tends to move relative to the other.

Amonton in the 18th century produced the formula for a unitless quantity to quantify the friction force, the coefficient of friction (μ). The ASTM G 40 definition is: In tribology, the dimensionless ratio of the friction force (F) between two bodies to the normal force (N) pressing the bodies together: $\mu = F/N$.

In contacting solids, it is universally agreed that the force to initiate motion of a body can be different from the force required to sustain relative motion of one body on another, so two coefficients of friction have evolved; the static and kinetic coefficients of friction. The static coefficient of friction is the coefficient of friction corresponding to the maximum friction force that must be overcome to initiate macroscopic motion between two bodies (per ASTM G 40). The kinetic coefficient of friction is the coefficient of friction corresponding to the friction force needed to sustain relative motion between two bodies in contact at any point in time.

These are the basic definitions that pertain to friction between contacting solids. Note that these definitions all refer to contacting bodies, not a material. A problem in dealing with friction is that people often say that a material is low friction. A material cannot have a coefficient of friction. It is a system effect. This coefficient is unique to a system. It takes into consideration factors such as

- Surface texture
- Sliding speed
- Contact geometry
- Type of motion (reciprocity, continuous, etc.)
- Environment
- Mating materials
- Mechanical properties of mating materials
- Separating films/particles and
- Contaminants

It was stated that friction is an energy dissipation process. A material sitting on a table is not dissipating energy and thus it cannot have a coefficient of friction. Thus, after Amontons' law, there should be a law stating that

> "A material cannot have a coefficient of friction. It is a property of a specific tribosystem."

Frequently, material suppliers advertise that this is a "low-friction" material. Such statements are meaningless. Whatever the material, a counterface can be identified that will produce very high friction with the "low-friction" material. For example, Teflon is commonly referred to as a low-friction material, but at low normal forces; Teflon has high friction against many metal and plastic counterfaces. Its friction coefficient against steel, for example, lowers by a factor of about 5 when loads produce compressive stresses near its compressive yield strength.

Whenever coefficient of friction data are presented, they should include the mating couple and the test conditions.

> For example: The coefficient of friction of PTFE in continuous sliding at 5 cm/s against 30 HRC 1020 steel (12 μm Ra) in the ASTM G 77 block-on-ring test is 0.1 to 0.2.

Another point that may have utility in dealing with coefficient of friction (μ) is that this system property is independent of area:

$$\mu = F/N$$

The explanation of this is based upon the fact that energy dissipation only occurs at the real areas of contact not the apparent area of contact. All surfaces have errors of form. They are not perfectly smooth and flat. When surface "a" is placed on surface "b" (Figure 11-1), contact only occurs in selective spots, that is, the real area of contact.

Friction is the result of "accommodations" that occur in the real area of contact when motion or pulling-off is attempted. In the case of simple sliding of surface "a" on surface "b," the

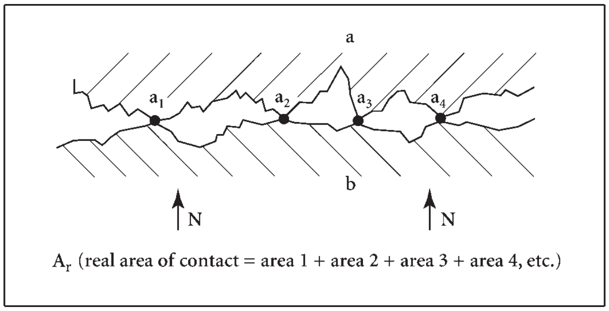

Fig. 11-1—Real area of contact between "conforming" surfaces.

friction force can be mostly a function of the shear strength of a/b junctions (T) and the material hardness (H):

$$T/H$$

Teflon has a low shear strength; thus, if Teflon is one member in the sliding couple, the coefficient of friction will tend to be low in most sliding systems. High shear strength and hardness in a couple (like hard steel self-mated) will tend to have high friction on many systems. However, a lubricated hard/hard couple in continuous sliding system can have a very low coefficient of friction. A coefficient of friction can never exist exclusive of its tribosystem.

Importance of Friction

Friction as a force has great practical significance. It is what makes automobile transmissions operate (friction of clutch plates). Tire/roadway friction produces motion in a direction on an automobile. Hand/wheel friction is needed for steering and, of course, friction of brake pads/rotor couples stops the automobile. Belt/pulley friction is also needed to drive accessories like power steering and brakes as well as the water pump and air conditioner. Some designer had to arrive at a number for coefficient of friction for each of these systems in the design stage.

In industry, friction in clutches cycle punch presses; rolling mill friction drives steel through rolls to make shapes; product/roller friction make conveyors work; assembly lines often have friction drives on part nests; friction of bulk materials on conveyor belts is necessary to move feedstocks to processing equipment. A successful morning shower depends on suitable friction between your feet and the shower floor; then friction between your shoes and flooring keeps you from slipping while walking in the house, street, or office. Copiers and printers are full of rollers that transport paper by friction forces.

In summary, there are countless mechanisms that rely on friction forces for function. So it is important. And friction coefficients cannot be calculated from material properties. This is the dilemma addressed in this chapter. Because friction is a system effect, it must be measured in a system. Bench tests are commonly used to develop useful friction data. There are countless empirical equations using surface texture and material properties for calculating the coefficient of friction of a system, but these equations are not widely accepted. Simulations are the norm.

Types of Friction and Important Facts

There are different modes of wear and erosion and friction likewise has different modes as shown in Figure 11-2. Rolling friction is usually lower than sliding friction. That is why the wheel was invented. However, it still takes force to initiate and sustain rolling. Like the coefficient of friction for sliding, there is a coefficient of rolling friction (μ_r). It is the ratio of the force required to produce rolling F_r and the normal force on the revolute body N_r:

$$\mu_r = F_r/N_r$$

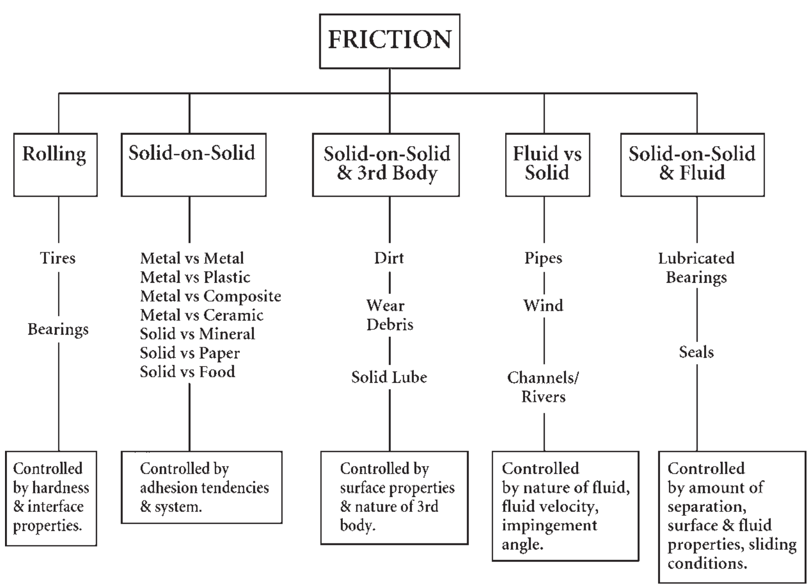

Fig. 11-2—Types of friction.

Rolling resistance is very important in many applications, but from the economic standpoint, tires versus pavement probably is the most important; the harder the tires, the lower the rolling resistance. Nearly everybody has tried to ride or push a bicycle with a flat tire or poorly inflated tires. When the tires are inflated to the proper pressure, there is a significant difference. Besides hardness, modulus of elasticity of a wheel or other revolute shape controls the rolling resistance. The greater the elastic modulus of the revolute shape and what it rolls on, the lower the rolling resistance. There are empirical equations for the rolling coefficient of friction and most include factors such as hardness, modulus, and radius of the revolute shape in the denominator. One may resemble the following:

$$\mu_r \sim \frac{F}{N} K\left(\frac{1}{hER}\right)$$

where K is a constant for the system, h = hardness, E = modulus of elasticity, and R = radius of the revolute shape. This makes sense because friction is an energy dissipation process. Soft, low modulus materials will deform more on rolling than hard high stiffness materials, and deformation dissipates energy. It is easier to roll a cart with 10-cm-diameter wheels than one with 10-mm-diameter wheels.

On the other extreme, third bodies interspersed between the rolling element and the rolling surface will increase rolling resistance. It is a lot easier to roller skate on a clean roller rink track than it is to roller skate on the same surface covered with sand particles. It takes additional energy for rollers to rise up over the particles.

Rolling element bearings are taken for granted. We depend on them for most machines, all modes of transportation, and countless indispensable products that affect our quality of life. They reduce friction compared with plain bearings because the coefficient of rolling friction is lower than sliding. They make it low by using hard and high-modulus balls and rollers and when they are lubricated and running at sufficient speed, the ball or rollers do not touch the raceways. They are supported by a microscopically thin lubricant film and this reduces the wear that occurs when they contact. There are allegedly (per ball bearings manufacturers) about 25 factors that control the rolling coefficient of friction of a ball bearing, but most of the friction losses come from the stiffness of the grease and ball retainer rubbing. Only about 5% of the friction results from hysteresis or repeated elastic deformation of the rolling elements and the raceway. There are tests that apply to the rolling coefficient of friction and these will be described later.

Solid-on-solid is the second type of friction described in Figure 11-2. This is the conventional sliding friction that was discussed in the definition of coefficient of friction. When friction started to be the subject of scientific studies in the 15th century, it was thought that the coefficient of friction for all sliding systems and materials was approximately one-third and that friction was caused by surface "rugosities," the hills and valleys that make up surface texture. It was thought that when an imperfect surface slides on another imperfect surface, the upper body must rise up over the hills and this takes additional energy (friction; Figure 11-3) This concept was thought to have been laid to rest when experiments slid atomically smooth cleaved crystals on each other and obtained very high friction coefficients. There were essentially no "rugosities" on either surface, yet the friction coefficient for the couple was high. However, equations relating the coefficient of friction of solids-on-solids to surface texture parameters regularly appear in current scientific journals.

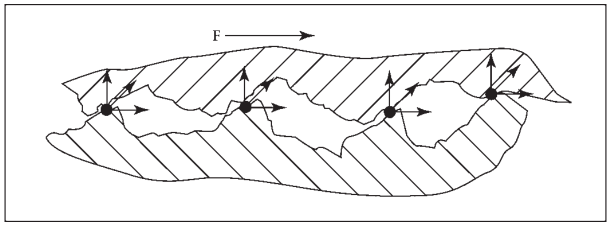

Fig. 11-3—Surface "rugosities" as a force in sliding friction.

The accepted mechanism for this kind of friction is that it is the result of adhesion between the surfaces, deformation that occurs on the surfaces during sliding, as well as a contribution from films on the surfaces that may attract, repel, or interact in some way.

$$F_F = F_d + F_a + F_{af}$$

where F_F = friction force, F_d = force required to deform conforming surfaces (includes surface texture), F_a = adhesion (molecular or atomic) between surfaces, and F_{af} = force to accommodate surface films.

Therefore, the rugosities on a surface play a role as do the nature of the contacting materials (atomic, etc.) and the films that exist on each real surface. As an example of the latter, laboratory tests indicated that small plastic parts would slide best down ultrahigh molecular weight polyethylene tracks; therefore, the production line was built with this material. However, nothing slid properly on Monday mornings. After hours of pushing stuck parts, the tracks worked fine all week. It was discovered that the 50% humidity in the building formed a high-friction water film on the tracks when they were unused over the weekend. This was the F_{af} in the above equation. The tracks had to be replaced with a material that was not as affected by humidity films. In any case, this is the type of friction that most designers must deal with and we will describe the tests that are commonly applied.

"Solid-on-solid with a third body" was discussed as it applies to rolling friction; it increases it. However, third bodies can often reduce sliding friction between conforming bodies. For example, sliding a heavy box across a smooth tile floor can be made easier by sprinkling fine sand on the floor. The particles "roll" to lower friction.

Some tribologists have made this concept practical for industrial use. They developed solid particle "lubricants" for various tribosystems. A very traditional third body for friction modification is solid film lubricants. It has been known for probably centuries that certain compounds like graphite "lubricate" a wide variety of tribosystems. These lubricants are termed intercalative, and they lubricate by shearing and sliding on certain crystallographic planes such as the basal plane of hexagonal materials. The graphite crystallites slide on each other to reduce friction. Molybdenum disulfide and tungsten disulfide are traditional intercalative materials that when coated on sliding surfaces serve to modify system friction. The important point is that when third bodies are between the sliding surfaces, a new tribosystems is created and the friction will not be steel-on-steel (or whatever substrates are involved), but steel-on-particles–on steel. Friction is frequently monitored in wear tests. If any wear occurs, debris will separate the sliding surfaces and the tribosystems will be different from the sliding couple. Friction data from wear tests only apply to systems that include third bodies like those produced in the wear tests.

Fluid versus solid type of friction in Figure 11-2 is governed by laws of fluid mechanics. This type of friction usually has importance in sizing devices to move fluids through pipes and other types of structures that contain fluids. Sometimes, it is necessary to measure and control this type of friction. For example, to field test low-friction coatings for the hulls of ice breakers used in U.S. territorial waters, they tied full-size ships (with instrumented hausers) to shore bollards and directed the ship out to sea at various throttle settings. Hauser tension was measured and the water-to-hull friction was determined from these data. Racing boat hulls get similar water/hull friction testing in large tanks.

Pipe friction is important in sizing pipes carrying water and all sorts of process fluids. Heating systems use air/pipe and air/fitting friction data to size furnace blowers. This kind of friction testing is outside the scope of this book, but there are tests that apply.

Solid-on-solid with a fluid between is the last type of friction in Figure 11-2, and it may be the most important. It is estimated (by one auto manufacturer) that at least 30% of the horsepower of an automobile is lost to friction. These are solid-on-solid tribosystems with a fluid between the faying surfaces. Since the year 2000 or so, some auto manufacturers have lowered the viscosity recommendations to use lighter oil to reduce not only the solid-on-solid friction but "attritious" losses, that is, power lost to just "sloshing" oil about in the crank case. The lower the viscosity, the lower the attritious losses.

Friction laws change with this type of tribosystem. Sliding friction is no longer a function of the forces for deforming the surfaces, for overcoming rugosities, for atomic bonding, etc.; when lubricating films separate sliding (or rolling) surfaces, the system friction becomes a function of the lubricant. The famous "Stribeck curve" in Figure 7-2 of Chapter 7 explains it best.

The coefficient of friction of the tribosystems changes as the speed increases and the viscosity/load relationship changes. Essentially, this curve states that friction is high at low speed because there is solid-to-solid contact. As the speed increases, the surfaces become partially separated and the friction goes down. Then, as the speed increases, the coefficient of friction starts to increase. As load and speed become more severe, the fluid becomes "more solid" to transmit forces between the contacting bodies. In fact, there is a pressure at which every oil will take on "solid properties." The oil is carrying and transmitting forces as high as those on the conforming solids in the system. In fact, traction fluids are special oils made with aromatic molecules and the like that are higher friction "solids" under usage stresses. They are designed to be "high-friction" oils.

Figure 11-4 shows the kinds of lubricants that are available. We already discussed solid-film lubricants, but as shown in the figure, the principle types of oils that are available are mineral and synthetic. Mineral oils are formulated from a base oil that is refined from petroleum taken from the ground plus property additives. Synthetic oils are manufactured from chemical feedstocks. They are engineered to have chain lengths that are in a certain range while mineral oil contains

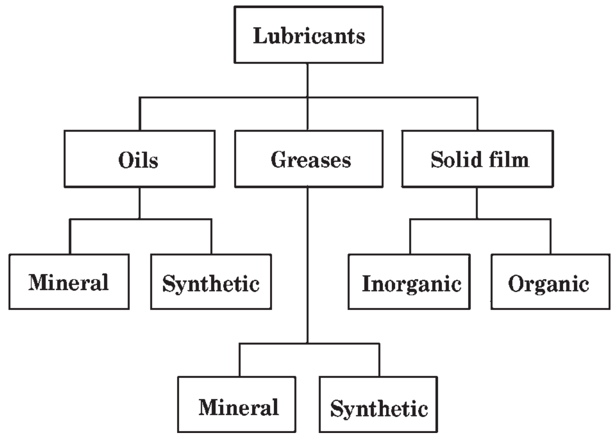

Fig. 11-4—Types of lubricants.

organic chain lengths that can vary significantly in length and impurities. Synthetic oils are more resistant to property changes at elevated temperatures.

The friction coefficient of lubricated systems can be less than 0.1 whereas unlubricated solid-to-solid couples can have friction coefficients of 0.1 to more than 1. Hydrodynamic lubrication means complete solid separation and the friction coefficients can be as low as 0.001 in hydrostatic bearings. Air or other gas bearings can have friction coefficients that are also in this range.

In summary, there are at least five types of friction and they have different origins, and they have different tests. All are energy dissipation processes; all can be affected by surface texture, surface films, and deformation of conforming surfaces, and all are affected by atomic and molecular interactions that depend on the chemical makeup of the sliding surfaces and the sliding environment. Friction is a byproduct of every tribosystem, but it can be measured and dealt with.

Friction Databases

Every machinery and engineering handbook will have some (usually very old) data on the coefficient of friction of selected sliding couples (like Table 11-1). However, if the data are not accompanied by details on test conditions, it is not advisable to use them. In fact, handbook data on friction coefficients should not be used unless the data were developed in a tribosystem equivalent to the tribosystem of interest. As mentioned a number of times, friction is a system effect. All of the components and factors that constitute a tribosystem can affect friction, and it is very unlikely that sufficient details are presented with friction databases to allow a designer or engineer to match a system of interest to data generated by this. Testing is recommended.

Factors That Affect Friction

Figure 11-5 summarizes the factors that can affect system friction. Just about everything is the short answer to: what affects friction? The factors that intuitively affect friction, the nature of the material couple, the loading conditions, the sliding conditions, and the environment do affect friction to different degrees. Figure 11-6 shows the range of friction coefficients

TABLE 11-1—Coefficient of friction for selected plastic/plastic couples.

Couple			μ_k
Polycarbonate + 12% PTFE	vs	Polycarbonate (PC)	0.19
Polycarbonate + 12% PTFE	vs	Polycarbonate + polyester (PET)	0.19
Polycarbonate + 12% PTFE	vs	PC + 10% aramid fiber	0.09
Polycarbonate + 12% PTFE	vs	Liquid crystal polymer	0.10
Polycarbonate + 20% glass fiber	vs	PC	0.24
Polycarbonate + 20% glass fiber	vs	PC + 10% aramid fiber	0.29
Polycarbonate	vs	PC + 10% aramid fiber	0.47
Polycarbonate	vs	Polyamide (PA) 20% aramid	0.08
Polycarbonate	vs	PC + 50% aramid	0.43
Polycarbonate	vs	Acetal copolymer	0.22
Polycarbonate + 15% PTFE	vs	Ultrahigh MW polyethylene	0.1
Polycarbonate + 15% PTFE	vs	Polyamide/imide	0.41
Polycarbonate + 15% PTFE	vs	Phenolic (Grade CE)	0.22
Polycarbonate + 15% PTFE	vs	Polyphenylene sulfide	0.16
Polycarbonate + 15% PTFE	vs	Diallyl phthalate	0.30
Polycarbonate + 15% PTFE	vs	Acetal	0.31
Polycarbonate + 15% PTFE	vs	Acetal + 15% PTFE	0.11

Testing in an ASTM G 133 test modified with 2N force, 1.7 Hz, average for 10^5 cycles, 2.5-cm stroke.

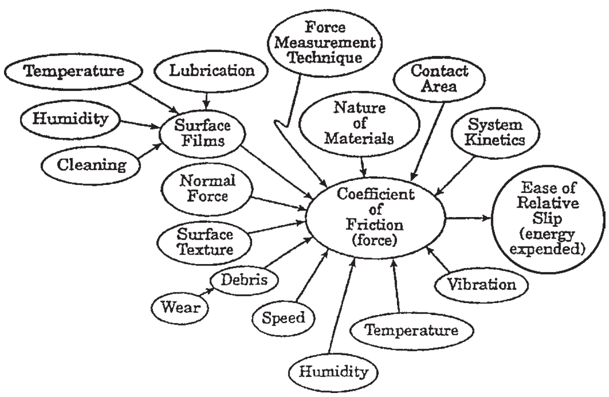

Fig. 11-5—Factors that affect friction.

that can be obtained by sliding various materials on a common counterface—a hardcoated aluminum roll. These data confirm the point about friction as a system effect: A material does not have low or high friction. It takes at least two materials to have a sliding (or rolling) system. Figure 11-7 shows the effect of surface roughness and sliding velocity on a particular couple. Both have an effect. Figure 11-8 shows the effect of normal force on the coefficient of friction of metal couples. When the forces pushing metals together get high enough to deform one or both surfaces during sliding, the friction force tends to decline because both surfaces are deforming and the force required for deformation is relatively constant even though the normal force is being increased. Thus the coefficient of friction decreases. Of course seizure can occur and then the friction coefficient becomes meaningless because the sliding couple has bonded.

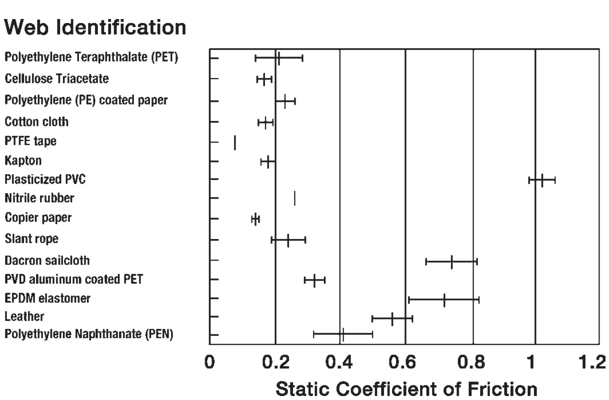

Fig. 11-6—Coefficient of friction of various web materials sliding on a hard coated aluminum roller using ASTM G 143 friction test.

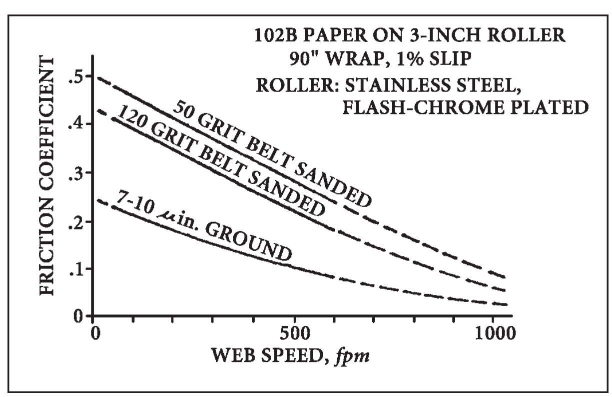

Fig. 11-7—Effect of surface roughness and velocity on the friction of paper sliding on a roller.

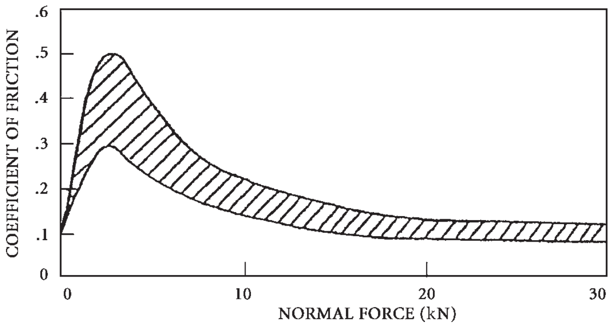

Fig. 11-8—Effect of load on the coefficient of friction of metal/metal couples in galling tests.

Figure 11-9 is a friction map showing how load affects the friction of a variety of materials rubbing on a 300 series stainless-steel counterface. Load had a significant effect on some systems, not on others. This is what happens in testing; most factors can have an effect and need to be noted and controlled.

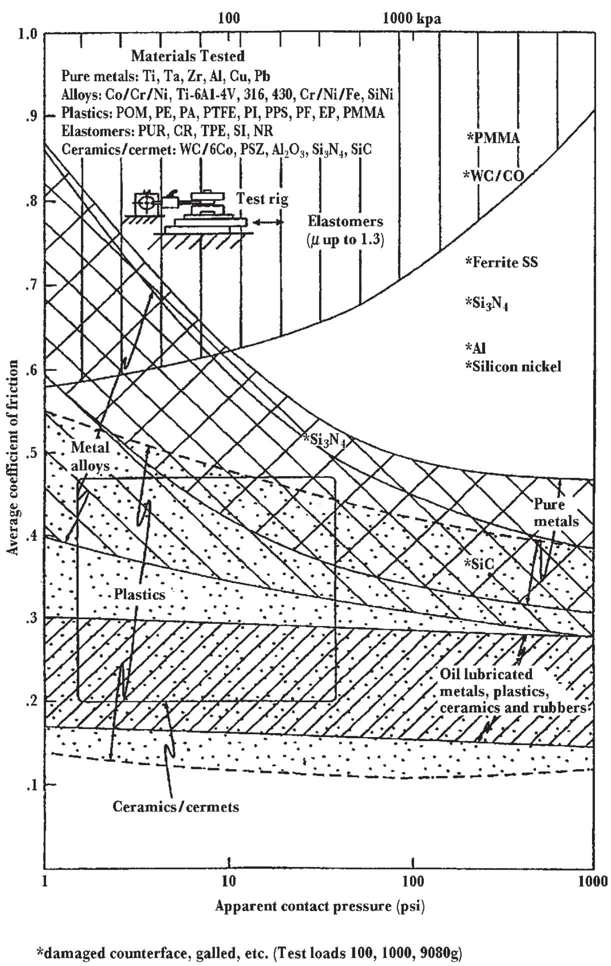

Fig. 11-9—Friction map of various materials mated with type 316 stainless steel in reciprocating motion.

Sliding Friction Tests

ASTM G 115 is a standard on conducting any friction test and recording test data. It is like a testing protocol. Figure 11-10 shows the equations that are commonly used to calculate coefficient of friction. The inclined plane formula is based upon Amonton's formula, $\mu = F/N$, but it has been simplified by trigonometry. The capstan formula is based upon summing forces on an increment of material contacting a cylinder. Friction coefficients are also measured in wear tests and specimen configurations can resemble the tribosystems illustrated in Figure 11-11. Amonton's formula is used for all of these systems except the web wrapped around a cylinder. The capstan formula applies to this system. We remind you, however, that if these tribosystems are wearing, the friction coefficient is not for the apparent sliding couple, but for the sliding couple and wear debris that depends on the amount of wear particles produced.

Another important point in the G 115 specification is the type of friction force recordings that are possible. It was stated many times that a material does not have a coefficient of friction, then it is a product of a system. Also, there are two coefficients of friction for a tribosystems, the initial or static friction coefficient and the kinetic friction coefficient. As shown in

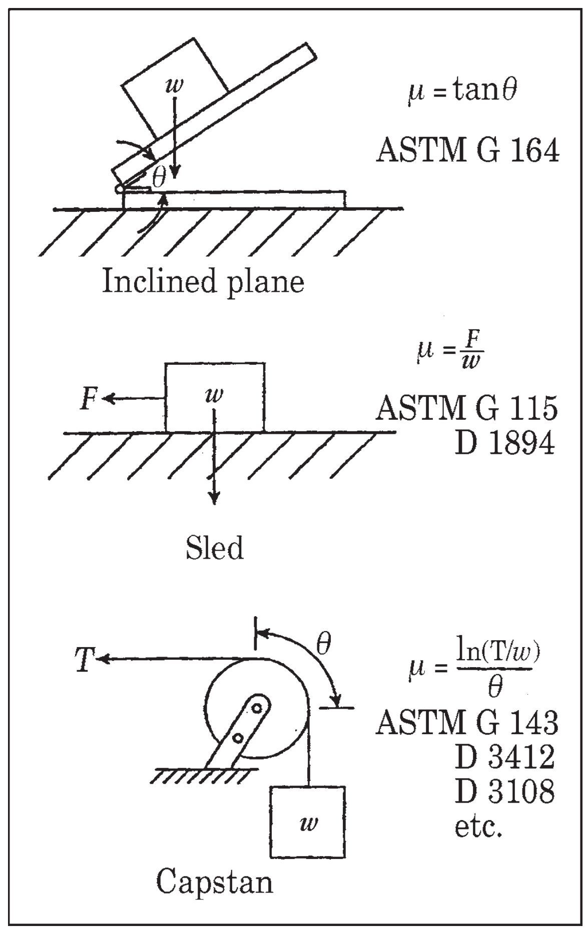

Fig. 11-10—Equations for coefficient of friction.

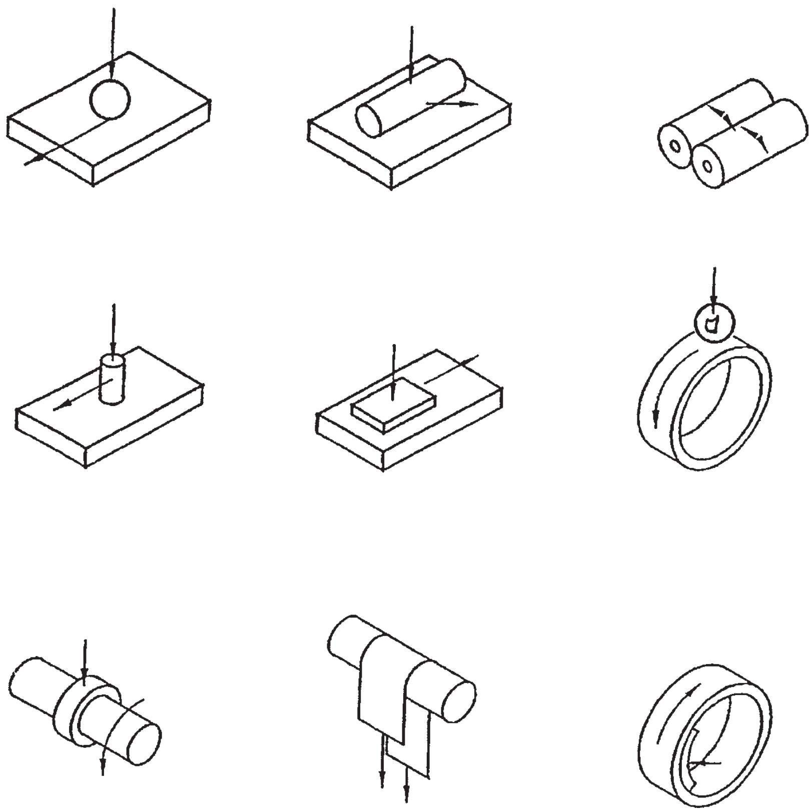

Fig. 11-11—Typical specimen configurations for friction testing.

Figure 11-12, friction force recordings can vary over the course of time.

What force do you use for the static coefficient, the kinetic coefficient? Case I shows a sliding system where the force required to start moving is larger than the force required to sustain motion. So the force corresponding to point “a” would be used to calculate the static coefficient of friction and the “b” force would be used to calculate the kinetic coefficient of friction. Many couples do not have a pronounced breakaway force spike and the friction force recording may resemble Case III. The “c” force would be used to calculate the static coefficient and the “b” force would be used to calculate the kinetic coefficient. Sometimes, the sliding friction force goes up or down with time. This suggests an unstable system and the way that this is dealt with in many wear tests is to report the friction coefficient at prescribed time (sliding) intervals such as at 10 revolutions, 100 revolutions, 1,000, 10,000, and 100,000, etc.

Case II in Figure 11-12 is what the force recording looks like with time when stick-slip occurs. Stick-slip is defined in ASTM G 40 as:

> A cyclic fluctuation of the magnitude of the friction force and relative velocity between two elements in sliding contact, usually associated with a relaxation oscillation dependent on the elasticity in the tribosystems and on a decrease of coefficient of friction with the onset of sliding or with increase of sliding velocity.

The definition has a footnote that cautions users not to interpret any increase or decrease in friction force as stick-slip. Stick-slip produces a harmonic vibration like Case II. In fact, it often is accompanied with noise. The classic example of stick-slip is a squeaky door hinge. The squeak is the harmonic vibration and if the force pushing the door were recorded on closure, it would resemble Case II. Stick-slip can usually be eliminated by changing the tribosystem’s stiffness, load, or velocity. For example, opening a squeaky door very fast can sometimes stop the stick-slip (as could a few drops of oil). When stick-slip occurs in a system undergoing a friction test, it is common to not report a coefficient of friction. Report “stick-slip behavior” as the result. If five tribosystems are to be tested and they all exhibit stick-slip behavior, the degree of stick-slip can be quantified by reporting the standard deviation or range of the harmonic force fluctuations.

“Stiction” is a term often used in describing friction characteristics of read/write heads on computer drives in contact with recording media. The ASTM G 40 definition of stiction is:

> A force between two solid bodies in nominal contact acting without the need for an external normal force pressing them together, which can manifest itself by resistance to tangential motion as well as to being pulled apart.

Read/write heads are designed to “fly” at some height over the media due to air being pumped into the interface by the rotating media disk or in magnetic tape by the speed of the

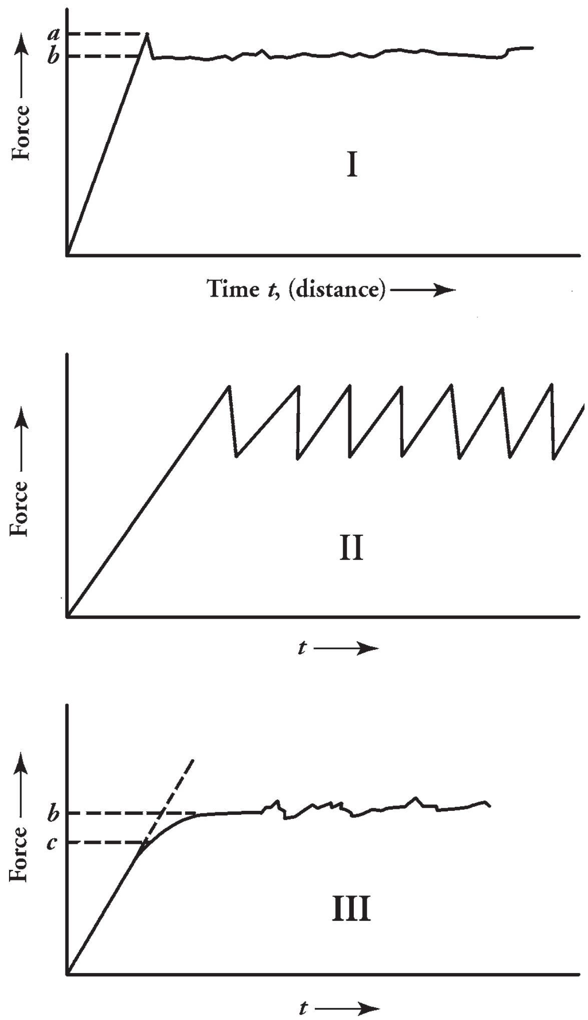

Fig. 11-12—Examples of friction force recordings.

tape transport. Stiction occurs when the device is at rest and the head can touch the media. There can be an attraction of the head on media due to some chemical, molecular, or atomic attraction or absorbed films such water vapor can be the cause. A water vapor meniscus is a common source of stiction (Figure 11-13). A significant force may be required to simply pull the head off the media as well as a tangential force to move the head laterally. Stiction is undesirable in most head/media systems and coatings and the like are used to minimize it. Stiction pull-off forces are measured with sensitive force transducers.

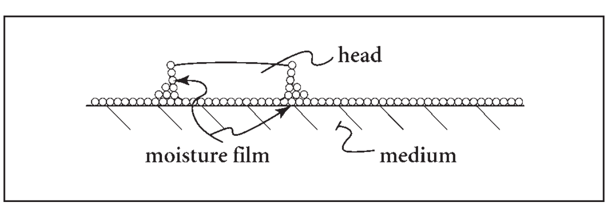

Fig. 11-13—Meniscus effect from adhered water vapor.

Another definition that needs to be established before discussing individual friction tests is the term "traction." What is the difference between traction and friction? The ASTM G 40 definition of traction is:

> A physical process in which a tangential force is transmitted across the interface between two bodies through dry friction or an intervening fluid film, resulting in motion, reduction in motion, or the transmission of power.

The short answer to the question is that they are the same. Friction is transmitting a force across an interface. When a box is pulled on a floor, there is a tangential force on the floor produced by the pull. A portion of the pulling force was transmitted to the floor. Tires, footwear, paving, and flooring studies often report "traction" data, but what they are usually measuring are friction coefficients. The term "traction" is used when the friction at an interface is used to propel another body (Figure 11-14).

Needless to say, there are countless indispensable tribosystems that rely on traction to work (trains, motor vehicles, footwear, etc.) When two bodies are separated by a fluid, traction can be produced by the separating fluid. It can transmit force. An automobile transmission is an example of a device that relies on transmission of a force (the engine) to the drive train through plates separated by a thin layer of transmission fluid. Certain oils are formulated with "more rigid" molecular structures and the like so that they behave more like a solid than a liquid under shear stress and transmit force. These special oils are called traction fluids and they are intentionally less "slippery" than lubricating oils.

In summary, traction (T) is force used to propel a body whereas "friction" usually has the connotation of a force impeding motion. Mathematically, they are both force ratios.

$$\text{Friction coefficient: } \mu = F/N$$

where F = friction force and N = normal force.

$$\text{Traction coefficient: } \mu = T/N$$

Friction Measurement and Recording Protocol

It was mentioned that friction often varies as sliding or rolling proceeds. So what should be recorded? How are friction forces recorded? ASTM G 163 is a standard guide for "Digital Data Acquisition in Wear and Friction Measurement." It is common

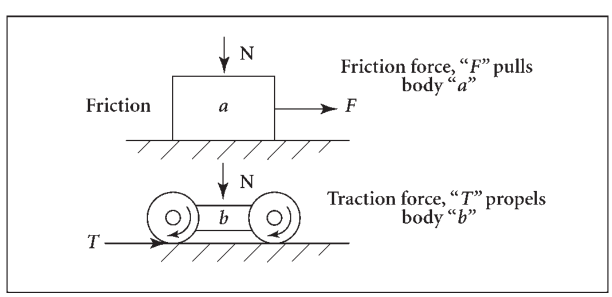

Fig. 11-14—The difference between "friction" and "traction."

practice to use force transducers, either strain gage or piezoelectric devices, to sense friction forces. These devices have limitations. For example, strain gages can be easily overloaded and ruined. Although piezo crystals are usually very resistant to overloading, they have the problem of electronic drift when used in unidirectional loading. Thus, strain gages are preferred for unidirectional applications and piezo crystals excel in reciprocating devices with alternating loading directions.

Outputs from force transducers usually are sent to computerized data acquisition system and the data are then analyzed by computer software. ASTM G 163 presents recommendations on suitable hardware, analog-to-digital conversion, software, sampling rate, calibration, data storage, and data reduction. Computers produce processed data, but are the data correct? Adherence to this standard can help ensure accurate data recording and reduction.

Analog recorders have been used for decades with great success. They do not have many of the problems associated with telling computers what you want them to do. A major limitation of analog recorders is dealing with too much data in the form of strip charts or other printouts. Of course, analog recorders with pens present the continual ink-drying-out problem and the cost and time involved in pen replacement. Computers can be taught to put the friction data for any length test on a single screen or piece of paper. The problem with computerized data acquisition is that it is necessary to engineer signal acquisition, analog to digital conversion, amplification, filtering, noise protection, timing of data collection, compilation of data, and conversion to useable friction information. These are not trivial tasks.

One of the fundamental problems is that most computers cannot recognize the tiny millivolt outputs of many force transducers. The signal must be amplified and sometimes shielded and filtered. This must be done without distorting the true force characteristics. The computer must be told when to sample. In a reciprocating test, some of the force readings can be zero, that is, when the motion stops at the end of a stroke. The computer must be told what to do with the plus, minus, and zero readings. When data are compiled, it is likely that it will be necessary to see how the friction force varies with time and convert the force recordings to friction coefficients. Data are transferred to a spreadsheet to do the calculations and produce a graphical output. The next problem is that most spreadsheets have data point limitations. If sampling is too frequent, it can overwhelm the spreadsheet software. Finally, some data-acquisition software programs upgrade annually so you must continually change your system and the new system may not accommodate old data.

In summary, friction force measurements and recording with computers require consideration of a myriad of details. This guide recommends including a check to make sure that the final data from the computer is accurate and not filtered to the point of yielding wrong answers.

Reporting Friction Data

ASTM G 118 is a guide for "Recommending Format of Wear Test Data Suitable for Databases." This guide essentially suggests fields for databases that are used to log friction and wear test results. There is a similar friction and wear "Report Form," in the ASTM C 808 standard on reporting friction and wear testing results of carbon/graphite materials. The point of both of these documents is that there are many specimen and test details that need to be recorded if the data generated are going to be suitable for future use by others. If a key detail like sliding speed is omitted, the data cannot be used by others. In fact, it may be necessary to repeat a test years later, but this is not possible if the test speed or other key parameter was not documented.

The G 118 standard is setup for computer use and required data fields are suggested in seven areas:

1. Test identification
   - Number
   - Date
2. Type of test
   - ASTM or other number
   - Other description
   - Lubricant or other defining features
3. Test conditions
   - Loading
   - Velocity
   - Total sliding distance
   - Temperature
   - Ambient environment
   - Other significant features (type of motion, lubrication, etc.)
4. Test specimens

   Material A
   Material type
   Specification/designation
   Shape/dimension
   Grade
   Processing
   Heat treatment
   Composition
   Surface texture
   Hardness
   Cleaning
   Weight before test
5. Specimen identification

   Material A
   Sample number
   Material B
   Material type
   Specification/designation
   Shape/dimension
   Grade
   Processing
   Heat treatment
   Composition
   Surface texture
   Hardness
   Cleaning
   Weight before test
   Material C
   Sample number
   Third Body/Lubricant
   Material type
   Specification/designation
   Identifying features
   Grade
   Processing
   Special treatments
   Composition
   Viscosity
   Properties
   Additives

Others
Sample number
6. Test results (for each tribocomponent A, B, C, etc.)
   - Wear volume
   - Mass loss
   - Static friction coefficient
   - Friction coefficient at 1,000 cycles, mid-test, end, etc.
   - Comments on test
7. Documentation
   - Literature citation
   - Company file number
   - Other locator of data

A computerized database requires enough fields to ensure that someone else is able to repeat the test in the future. If all necessary details are supplied, the database will have utility to others, to possibly save repeating a test, to eliminating the need to perform a test. Information from databases should not be used unless the test used in developing the data simulates your design conditions. However, these kinds of test details are required on the test before a decision can be made on the applicability of the data. Most friction databases do not have many of the test details suggested by G 118 and C 808.

Solid-on-Solid Friction Tests

ASTM G 115 "Standard Guide for Measuring and Reporting Friction Coefficients" is intended to guide users in selecting an ASTM friction test as well as to guide users in performing a valid test. Some of the figures presented in this chapter came from this standard. Schematics are presented on many of the ASTM friction tests that are available. Many ASTM friction tests use one of the basic test concepts shown in Figure 11-11. Table 11-2 lists some ASTM tests that use the inclined plane, sled, or capstan test concept.

Footwear Tests

There are four ASTM standards using the "James Machine," which simulates shoe/walkway interaction in walking. However, the James Machine specification F 489 was withdrawn in 2005. ASTM F 489, F 609, F 695, D 2047, and D 5859 use a variable incidence tester, a proprietary device for assessing traction of footwear versus painted surfaces. ASTM F 2157 uses a pendulum device to assess the "skid resistance" of footwear on synthetic surface running tracks.

Frictionometer

A device called a frictionometer is covered by ASTM D 3028, and it measures the friction of plastics and other materials against other plastics, metals, or other materials at higher sliding speeds than the inclined plane, sled, and capstan type tests. A disk is rotated and it is tangentially contacted by a spring-loaded rider. The rider is attached to a pendulum that rotates in the direction of sliding. The degree of rotation is a measure of the sliding friction (Figures 11-15 and 11-16).

The friction metric in this test is usually different in ascending velocity than descending velocity and a test metric is the ascending and descending friction forces. The rider disk is about 25 mm in diameter with a width of about 1 mm. This test simulates lightly loaded Hertzian contacts at sliding velocities from 1 to 3 m/s.

Pavement/Tire Tests

Needless to say, it is difficult to simulate a tire/highway tribosystem in the laboratory, so there are friction tests that use actual tires and roadways. ASTM E 670 is a test that uses a three-wheeled trailer towed behind a car as the test apparatus. Two of the wheels are skewed and water can be directed between the tire and pavement. The test metric is a number related to the amount of skidding at a certain velocity.

Another test, ASTM E 707, uses a small tire (go-kart) on a pendulum glancing on a pavement specimen to rate the friction between a test tire and various pavement textures. Finally, ASTM E 510 uses two tires on a vertical spindle skidding on a pavement specimen to develop friction data on pavement surfaces versus tire rubber. Torque measurements are the test metric and they correlate with the ease of the tires sliding on the pavement specimen.

ASTM G 143: Capstan Friction

This standard uses the fundamental capstan test rig to measure the friction coefficient of a flexible web material draped over a cylinder (Figure 11-17). This test simulates paper, plastic, or other materials manufactured in web or strand form sliding on a roller as in conveyance. There are two ASTM standards on this type of test on yarn: ASTM D 3108 and D 3412. A typical capstan test machine is shown in Figure 11-18.

The coefficient of friction is a function of the wrap angle on the cylinder. The angle is in radians and it can be for multiple revolutions. A boat winch typically uses two wraps and thus the friction is very high; the force on the loose end (to keep the rope cinched to the winch drum) is low.

The G 143 standard allows testing any flexible material that can conform to the 100-mm-diameter cylinder. The user also can select the pulling speed, distance, and loading mass and angle of wrap. The test yields the static and kinetic coefficient of friction as well as friction observations such as stick-slip. A caution with this test is to pull the test material over the cylinder in a straight line. If the flexible material has a width

TABLE 11-2—ASTM friction tests that use common test methodologies.

Inclined Plane	Sled	Capstan
D 3248 for cardboard	D 4917 for paper	D 3108 for yarn
D 3334 for woven fabric	D 1894 for plastics sheet	D 3412 for yarn
G 164 for surface lubes	D 4521 for wood flooring	G 143 for plastic sheet
D 4918 for paper	D 4521 for fiberboard	
D 4521 for fiberboard	D 3247 for cardboard	
G 164 for lubricated surfaces	D 2394 for flooring	
	D 2534 for waxed floors	

over a few millimeters, it is probably necessary to use a bridle as described in the standard. Another significant concern is cleaning the cylinder between tests. Some test specimens, for example, may transfer wax to the cylinder surface. This must be removed before the next test.

Solid-on-Solid Plus Third Body Tests

Thrust Washer Test

ASTM D 3702 is a wear test that is popular for plastics. The test specifies measuring friction as well. Of course, there will be third-body wear particles present in the test so this is a solid-on-solid plus third bodies test. A factor that makes this test popular is that the apparent area of contact is thought to be unchanging during the test. This is not the case with Hertzian contact configuration test specimens like a sphere. The apparent area of contact changes as the flat on the sphere gets larger in diameter. The specimen configuration for this test is shown in Figure 11-19.

The apparent area of contact is the annulus of the thrust washer. It rotates on the counterface annulus which is fixed to a torque-measuring device (Figure 11-20). This device

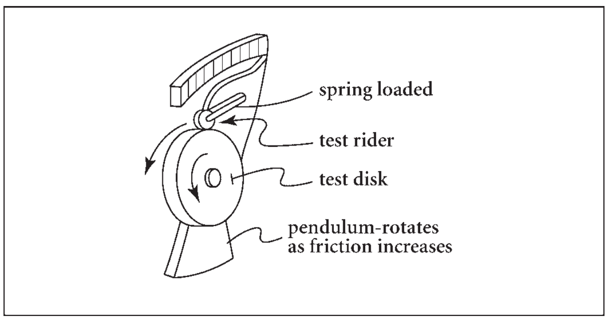

Fig. 11-15—Schematic of pendulum friction tester.

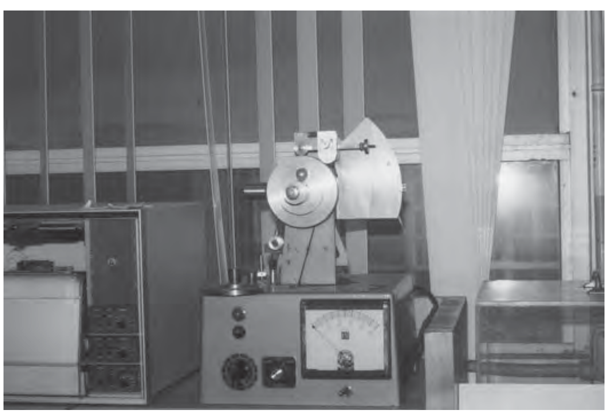

Fig. 11-16—Frictionometer.

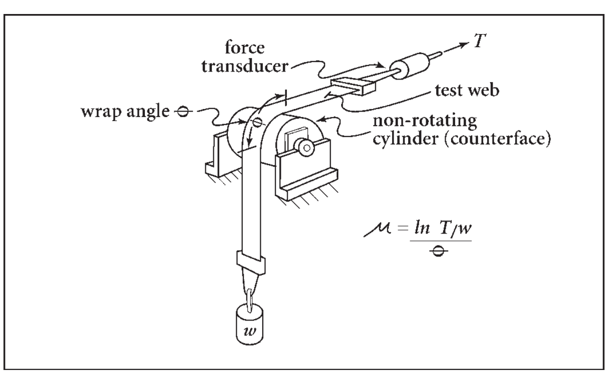

Fig. 11-17—Schematic of ASTM G 143 capstan friction test.

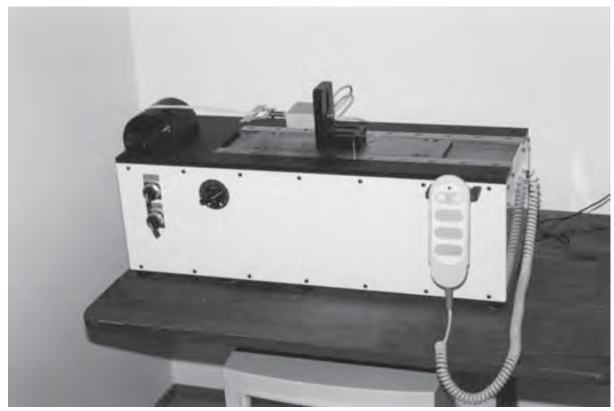

Fig. 11-18—Capstan test rig.

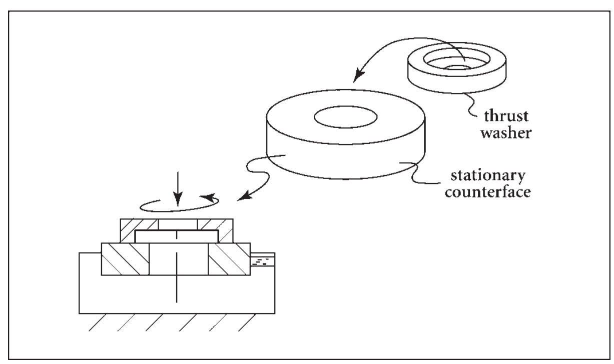

Fig. 11-19—Schematic of thrust washer test.

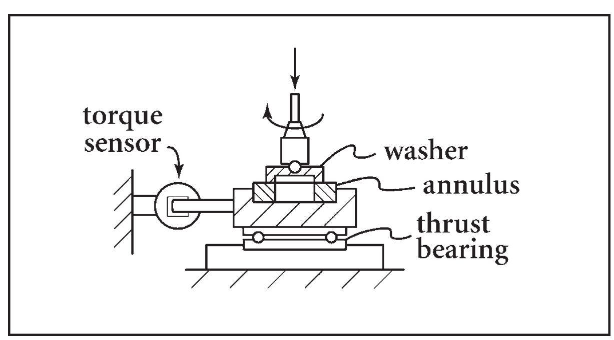

Fig. 11-20—Thrust washer test rig.

produces the data that are used to calculate the friction coefficient for the test couple. The thrust washer is usually made from plastic and counterface is steel, but the test couple could be any material.

The D 3702 test is quite lengthy. It specifies a 40-hour break-in before starting the wear test. Round Robin tests were 100 hours long after the 40-hour break-in. This is a factor to consider in using this test. The normal test machine only runs one couple at a time. The standard is not specific on how to record friction force. It requires recording the coefficient of friction, but does not specify when to take readings during the long test. This test is suitable for PV testing since the pressure can always be deduced because the apparent area of contact is always known.

Block-on-Ring Test

There are three ASTM wear test standards that use this specimen configuration:

ASTM G 77
ASTM G 137
ASTM G 176

G 77 and G 176 use the same size specimens (Figure 11-21). A worn block is shown in Figure 11-22, a worn ring in Figure 11-23. G 137 uses the identical concept, but the block has dimensions of 6 × 6.35 × 12.7 mm. The ring is 100 mm in outside diameter and 15.88 mm wide. The suggested ring material is a hardened steel (60 HRC) that "does not wear." The 6 × 6.35 mm end of the block is forced vertically against the ring. The test force and speed can be selected by the user, but the interlaboratory tests lasted 48 hours with seven mass change measurements during the test to establish a wear versus time curve. The test metrics are specific wear rate and the average friction coefficient is for the steady-state portion of the wear/time curve.

A caution in using this test is removing the block periodically for weighing. If the equipment does not locate the block exactly, there will be a new break-in after each weighing cycle which can be variable. It is extremely difficult to remove wear test samples and get them back perfectly. Of course, this test yields the friction for a solid-on-solid plus third body wear debris. It does not yield the friction coefficient of material "a" on material "b."

The G 77 block-on-ring is popular with metals and coatings and the G 176 is intended for testing plastics. It competes with the G 137 and D 3702 thrust washer test. In both tests, the friction force is obtained by holding the block with a force transducer (Figure 11-24). The G 77 test is short in duration: 5,400 revolutions at 197 rpm (27 min). The G 176 test is 240,000 revolutions at 200 rpm or 20 h. The normal force is 10 lb. This test is really designed for lubricated plastics, plastics with PTFE, and other lubricative fillers. An unlubricated plastic like nylon or phenolic may not last the required 20 hours.

Pin-on-Disk

The G 99 pin-on-disk test (Figure 11-25) can be used for friction testing and it can have significant utility in light-load testing. The block-on-ring test can use normal forces in excess of

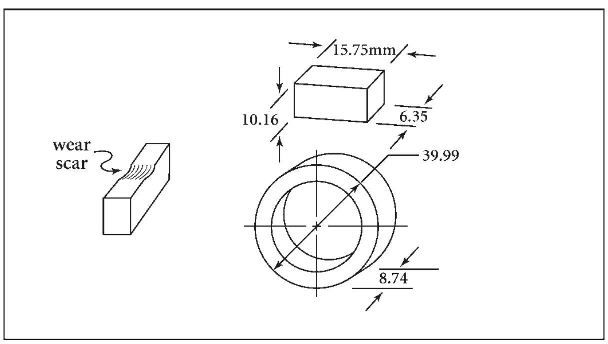

Fig. 11-21—ASTM G 77 and G 176 test specimens.

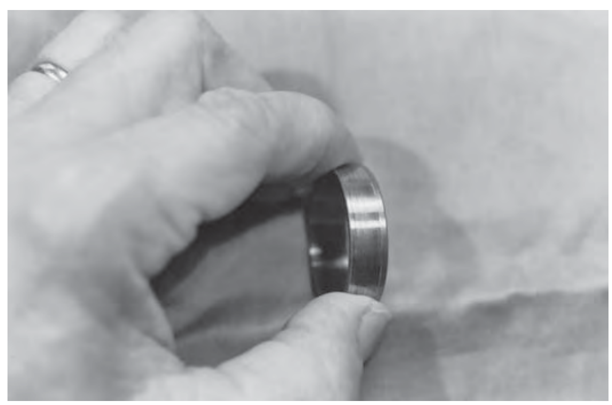

Fig. 11-23—Worn G 77 test ring.

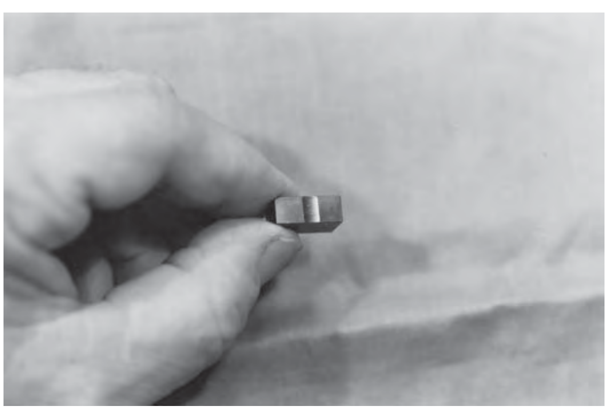

Fig. 11-22—Worn G 77 test block.

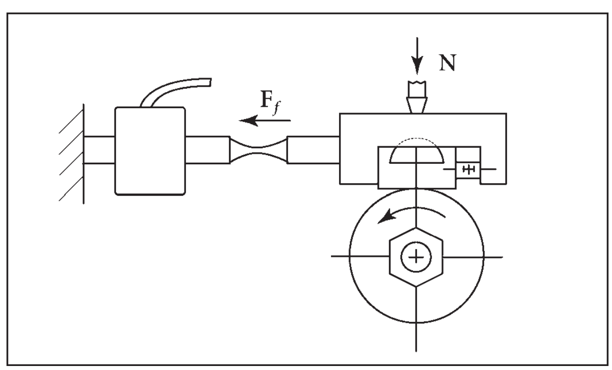

Fig. 11-24—Friction force measurement in the G 77 test.

600 lb. The pin-on-disk test can be used with loads less than 1 N. It is a good choice for evaluation of the friction modification characteristics of thin wax and lubricant films. The friction can be continuously monitored and the friction force recording can indicate when coatings are penetrated. It is also a good test to be used to measure the friction effects of a coating as well as its durability (by penetration testing).

Reciprocating Block-on-Plane

The ASTM G 133 (procedure "a") test is useful for examining the friction characteristics of various couples in reciprocating mode (Figure 11-26). The G 133 "a" load is 20 N, which is suitable for self-lubricating plastics, but this same test can be conducted at lower normal forces for couples that may be very sensitive to the normal force used in a test. The force recording on a reciprocating test includes the "push and pull" stroke and the friction force can be different. If it is, it should be recorded as "push or pull." This test works on all materials and it is a very good simulation of a reciprocating mechanism such as guidepost/bushing couples on a punch press die.

Rolling Friction

Rolling friction can be measured just like sliding friction. It is possible to push or pull an object on wheels, balls, or rollers and measure the force to start the object moving and the force required to sustain motion. That force divided by the normal force on the rolling element provides the breakaway coefficient of rolling friction and the latter the kinetic coefficient of rolling friction. It is also possible to use an inclined plane and the angle at initiation of rolling is a measure of the breakaway friction force. A commercial tester assesses the friction characteristics of rolling element bearings by holding the one race fixed with a transducer and rotating the other. Figure 11-27 shows a schematic of a testing technique that can be used to measure the force to initiate rolling of an overhead crane wheel on its track. Figure 11-28 is a photo of the setup. Force was sensed on a universal test machine. The steel cable to the slide is pulled with crosshead motion (upward).

Bearing Friction Tester

Figure 11-29 is a schematic of a commercial bearing friction tester. This tester axially loads a test bearing between a torque sensor and a motor spindle that rotates the inner race. The loads and speeds can be varied and the torque sensor converts the torque reading to a continuous recording of "bearing friction," the rolling coefficient of friction.

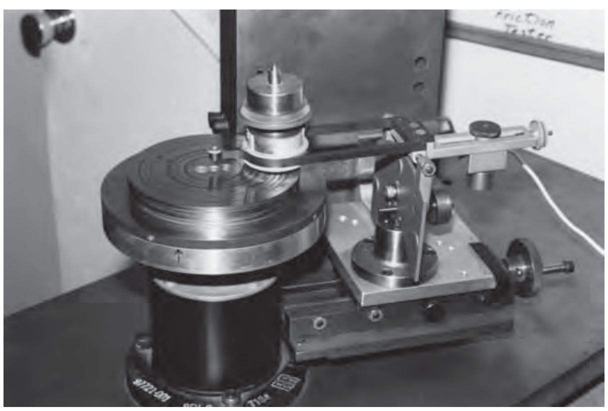

Fig. 11-25—Pin-on-disk tester.

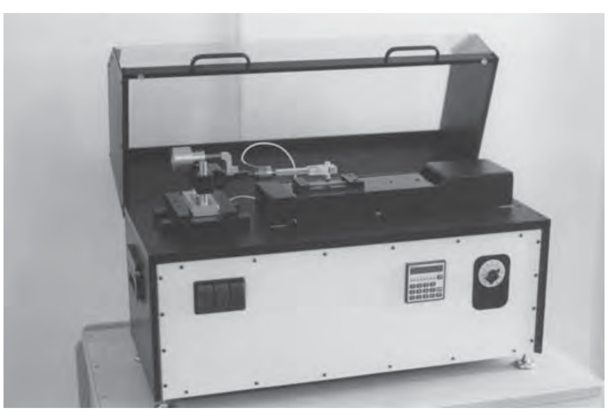

Fig. 11-26—Reciprocating pin-on-flat tester.

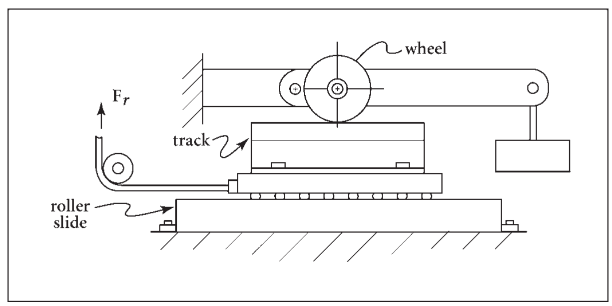

Fig. 11-27—Measuring the friction of a wheel on a track.

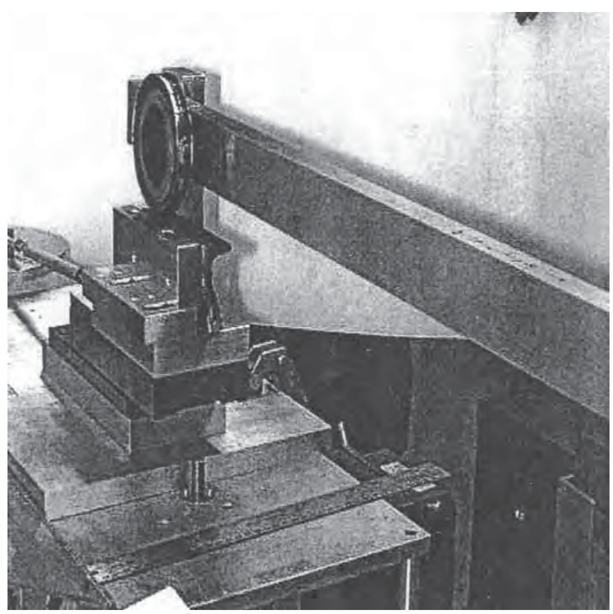

Fig. 11-28—Wheel friction tester.

There was not an ASTM standard on this device as of 2006, so users probably perform the test differently. A significant feature of this test is that the torque sensor responds to the net friction effects of all of the bearing components as well as the grease. A concern with this test, however, is the axial loading of roller bearings. This is not normal. Most rolling element bearings are designed for radial load. So to be true to simulations, this test should only be used for thrust bearings.

Spin-Down Friction Testing

An application where rolling element bearing friction is very important is in conveyor rollers. Many web products drive conveyor rollers by light tangential contact. If bearings have high friction, the web product can slip on the rollers and be damaged. A test that evolved to assess the friction of rolling element bearings on conveyor rollers is shown in Figure 11-30. A drive motor with a quick disconnect contacts a conveyor roller and brings it to the speed that it will see in service. The roll is maintained at the specified rpm for 10 min and the drive wheel is removed. The time that the roller takes to stop rotating is a measure of bearing friction. Of course, different bearings or greases must be compared with the same roller and starting speed.

Friction of Ball Bearings at Low Temperature

ASTM D 1478 uses a torque measuring system to determine the starting rolling friction of various ball bearing greases. The test is illustrated in Figure 11-31. The cold box is maintained at −20°C. The drive shaft rotates the inner raceway of the bearing at one rpm while a force sensor holds the outer race. The test metric is the starting and running torque.

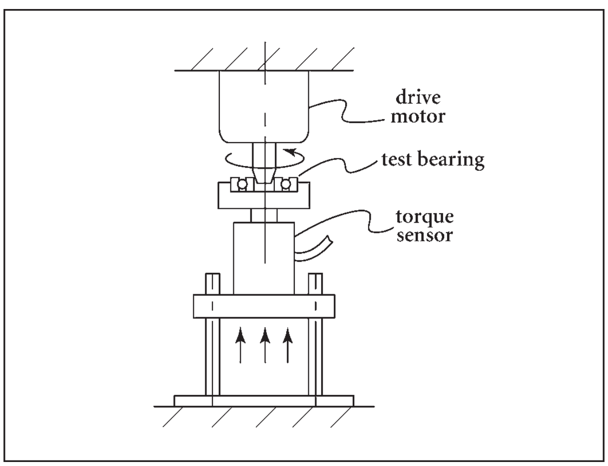

Fig. 11-29—Bearing friction tester.

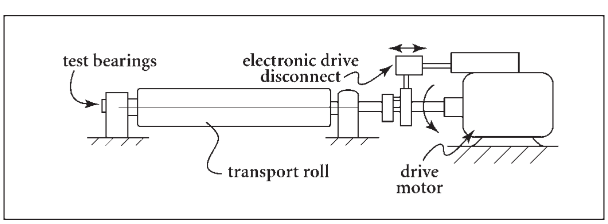

Fig. 11-30—Roller spin-down friction test.

This test is intended to simulate situations where ball bearings are used as pivots and the like in instruments that may see cold temperatures in service as in aircraft. These pivots need low breakaway friction to work properly and this test can rank candidate bearings for their ability to work as a "low-friction" pivot.

Ball Bearing Friction at Room Temperature

The inclined plane test that is used in several ASTM standards for sliding friction (G 164, D 4918) can be used to measure the breakaway rolling friction of ball and roller bearings. The inclined plane is raised until an object on the plane starts to slide and that angle is the test metric. In this test, a ball bearing is balanced on the inclined plane with a balance arm which also serves as the mass for a normal force. The plane is raised until rolling of the outer race occurs (Figure 11-32). This angle is a measure of the friction required to make the inner race start to rotate with respect to the outer race.

An important concern with this test is to ensure that the bearing's outer raceway rolls on the inclined plane rather than slides. Rolling is achieved in the test by covering the inclined plane with soft flexible plasticized tape (black electrical tape, non-stick side up). Of course, all inclined plane friction tests require care in raising the plane. There can be no jerky or halting motions and the speed should be controlled. If done properly, this simple test rig does the same job as the more complicated D 1478 (a commercial) test rig. An ASTM standard on this test was approved in 2005: ASTM G 182.

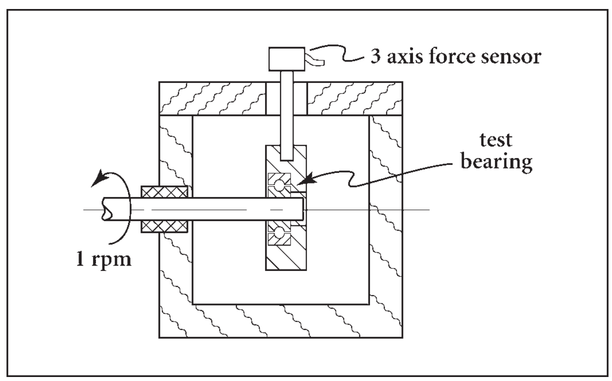

Fig. 11-31—Low-temperature bearing friction tester.

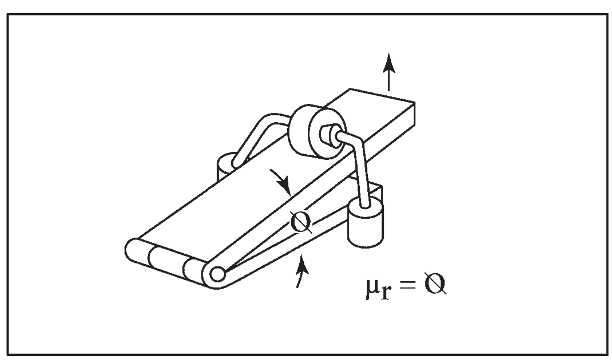

Fig. 11-32—Inclined plane test for rolling element bearing friction.

Solid-on-Solid Plus a Fluid/Lube Friction

ASTM G 164 test for presence of surface lubrication uses the same inclined plane as the bearing friction tester shown in Figure 11-32. This test is intended to determine if there is a lubricious coating on a surface. The element that slides down the inclined plane as it is raised is an ordinary paper clip affixed to a balancing rider like the one used to hold a bearing in the rolling friction test (Figure 11-33). The balance arm supplies the normal force for the sliding rider. The test surface is affixed to the inclined plane. The inclined plane is raised until the rider moves. The tangent of that angle is the static coefficient of friction for that couple.

This test was developed as an ISO standard in the silver halide photographic industry. It was used as a quality control tool to determine whether a film surface contained wax or not. It was not intended to put an absolute coefficient number on every film surface, but the friction differences between a film with and without wax would be dramatic (for example, 0.1 with wax and 0.4 without). The ASTM standard is also intended for this kind of differentiation testing. It works well on plastic webs and often pinpoints winding/spooling problems. It can also be used on coated steel to determine if scratch reduction coatings are in place.

The cautions with this test are the same as with any inclined plane test; the inclined plane must be raised slowly and smoothly. Paper clips can wear with frequent use and they can be replaced with any noncorrugated or embossed metal paper clip. The paper clip can be reused for many tests, but cleaning is required after every trip down a specimen.

ASTM D 5183: Four-Ball Friction Test

The official title of this standard is "Determination of the Coefficient of Friction of Lubricants using the Four-Ball Wear Test Machine." As brought out in the title, this test determines friction in a solid-on-solid tribosystem with a lubricant separating the surfaces. It does not measure the friction of a lubricant as alleged in the title, but a tribosystem containing contacting hard steel solids separated by a lubricant film. The test uses four 12.5-mm-diameter balls with a bottom cluster of three held stationary while the fourth ball is rotated on the nested balls (Figure 11-34).

The lower balls are held stationary by a torque or force measuring device so that friction forces can be measured. The upper ball rotates at 600 rpm; the lower balls are covered by the test oil at 75°C; the balls are allowed to wear in for 60 min with a normal force of 40 kgf on the rotating ball. The oil is drained from the wear-in procedure, the balls are cleaned still clamped and fresh test oil is added and the central ball is loaded in 10-kgf increments until the torque sensor indicates incipient seizure. The coefficient of friction is measured at the end of each 10-min test interval.

There are other modifications of this test, but basically it makes an oil "fail" and measures the friction coefficient when that happens. The cautions that apply to this test include ensuring cleanliness of the balls and their condition before testing. Also, this test does not simulate a real tribosystem. The Hertzian loads can overwhelm any metal.

ASTM D 3233: Falex Pin-and-Vee Block Test

This test is like the four-ball test in that the test couples a small-diameter (6-mm) pin and small vee blocks which clamp against the pin like a nutcracker until seizure is imminent. Figure 7-6 in Chapter 7 is a schematic of the test.

The pin-and-vee blocks can be made from any material and they are immersed in the test fluid. Early Falex machines had a clever mechanical system for incrementally increasing the clamp force on the vee blocks. Modern machines can do it in a number of ways (stepper motors, etc.). The test reports the load at seizure when the friction force is high enough to break a shear pin or weld the tribocomponents together. This test is like the preceding in that it does not simulate a real tribosystems and it does not produce a quantitative friction coefficient, only a friction failure point. This test is also used to assess solid-film lubricants (ASTM D 2625).

ASTM D 6425: Reciprocating Lubricated Friction and Wear (SRV Machine)

This test evaluates the efficacy of lubricants under reciprocating motion of rather small amplitude (1 mm). A 12.5-mm-diameter ball is oscillated on a flat disk (Figure 11-35). The forces on the ball rider can be as high as 300 N; the test duration is 2 hours at 50 Hertz and the test contact is lubricated with a small amount of the test fluid (0.3 mL) applied to the couple. The friction force is monitored throughout the test and the test yields a recording of the coefficient of friction for the tribosystems for the 2-hour test run. The test couple can be heated. It is intended to assess the effect of extreme pressure additives in engine oils and the like. This test uses a small amplitude that may not simulate systems that are subject to more macroscopic sliding.

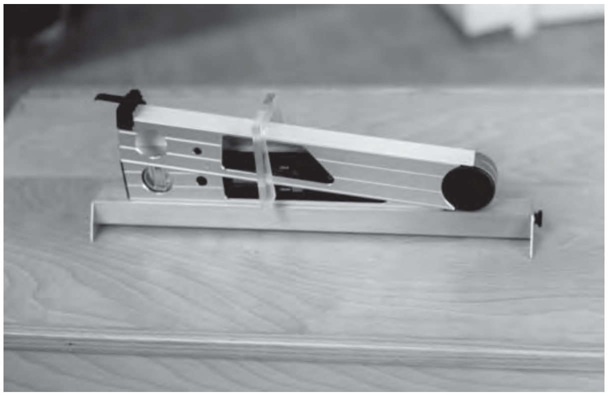

Fig. 11-33—ASTM G 164 paper-clip friction tester.

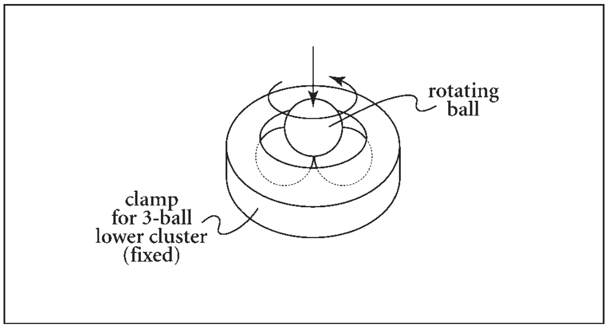

Fig. 11-34—Schematic of the four-ball test that is used for "friction" of lubricants.

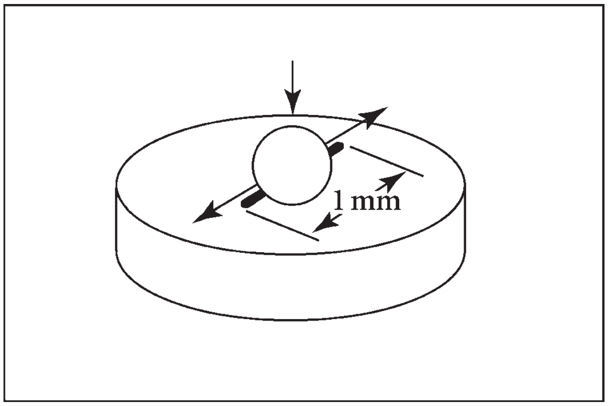

Fig. 11-35—Schematic of SRV reciprocating test.

ASTM G 133: Procedure B Reciprocating Ball-on-Plane and Lube Test

This test is like the SRV in that it uses a hemispherical shape reciprocating on a flat, but the stroke is 10 mm instead of 1 mm. There are other differences, but the test concept is the same. Test conditions are:

Rider radius	4.76 mm
Normal force	200 N
Frequency	10 Hz
Sliding distance	400 m (33 min)
Temperature	150°C
Full immersion in oil	–
Stroke	10 mm

Ball and counterface wear is measured and the friction coefficient is optional, but most test rigs produce force data throughout the test. One caution with this test is that it is relatively short in duration, probably too short to obtain wear trend data.

Chapter Summary

There are different types of friction and many different test rigs for assessing friction characteristics, but most use the force measurement concepts and test schemes that have been used for many years. It is very important to remember that friction is a system effect and that a material, a grease, an oil does not have a coefficient of friction. System friction in the presence of third bodies and fluids can be measured, but this is a measurement for a tribosystem, not one member of a tribosystem.

Testing should be done using tests that have been established for a particular friction system (type of friction). Since friction in a sliding or rolling system depends on so many factors, tests in a simulated system are probably in order whenever it is important to have an accurate assessment of system friction. Handbook data seldom apply because of system differences.

Important Concepts

The following concepts should be taken from this chapter:

1. Friction is a systems effect.
2. Friction is an energy dissipation process.
3. Friction exists in all sliding and rolling systems
4. There are different types of friction systems:
   Solid-on-solid
   Solid-on-solid with third bodies
   Solid-on-solid with a separating fluid
   Rolling
   Solid versus fluid
5. Friction tests must simulate a system of interest to be applicable to that system.
6. Handbook friction information only applies to systems like those used to develop the data.
7. Friction measurement techniques need to consider friction variations in a system.
8. Friction from wear tests almost always involves a third body (wear debris).
9. Lubricated friction can depend on lubricant viscosity and sliding speed as well as the couple.
10. System wear may not correlate with system friction.
11. System friction can be significantly affected by environmental circumstances (humidity, temperature, surrounding atmosphere).

Resources for More Information

Fundamentals

Singer, I. L., Pollock, H. M., Eds., *Fundamentals of Friction: Macroscopic and Microscopic Processes*, Dordrecht, the Netherlands, Kluwer, 1992.

Pusson, B. N. J. and Tosatti, E., *Physics of Sliding Friction*, Dordrecht, the Netherlands, Kluwer, 1996.

Bowden, F. P. and Tabor, D., *Friction and Lubrication of Solids*, Oxford, Clarendon Press, 1950.

Buckley, D. H., *Surface Effects in Adhesion, Friction, Wear and Lubrication*, Amsterdam, Elsevier, 1981.

Rabinowicz, E., *Friction and Wear of Materials*, 2nd Edition, New York, Wiley, 1995.

Applications

Blau, P. J., *Friction Science and Technology*, New York, Marcel Dekker, 1996.

Armstrong-Helouvey, B., *Control of Machines with Friction,* Dordrecht, the Netherlands, Kluwer, 1991.

Stolarski, T. A., *Tribology in Machine Design*, Oxford, Heinemann Newnes, 1990.

Related ASTM Standards

C 1026 – Standard Test Method for Determining the Static Coefficient of Friction of Ceramic Tile and other Like Surfaces by the Horizontal Dynamometer Pull-Meter Method *(A standard heel elastomer is affixed to a 50-lb weight and pulled on a horizontal ceramic flooring surface with a spring-type force gage.)*

D 1894 – Standard Test Method for Static and Kinetic Coefficients of Friction of Plastic Film and Sheeting *(A sled with the material of interest on the rubbing face is pulled with a force-measuring system on a flat plane covered with the counterface of interest; the force readings yield the static and kinetic coefficients of friction for the test couple.)*

D 2534 – Standard Test Method for Coefficient of Kinetic Friction for Wax Coatings *(A 180-g mass (1/2 × 1 × 3") is coated with the wax of interest and pulled horizontally with a force gage on a glass counterface also coated with the test wax.)*

D 3028 – Standard Test Method for Kinetic Coefficient of Friction of Plastic Solids *(A small plastic disk is tangentially spring loaded against a larger plastic disk in a Frictionometer test rig; a pendulum action of the small disk on the larger rotating disk produces a friction coefficient.)*

D 3702 – Standard Test Method for Wear Rate and Coefficient of Friction of Materials in Self-Lubricated Rubbing Using a Thrust Washer Testing Machine *(An annular ring rubs flatwise on a stationary flat*

counterface for a 40-hour break-in followed by a wear and friction test lasting more than 100 hours, conditions are the user's option.)

D 4103 – Standard Practice for Preparation of Substrate Surfaces for Coefficient of Friction Testing *(Describes the cleaning of vinyl and wood panels for application of polish for subsequent friction testing.)*

D 4521 – Standard Test Method for Coefficient of Friction of Corrugated and Solid Fiberboard *(This standard covers the sled and inclined plane methods for measuring self-mated static and kinetic friction coefficients.)*

D 4918 – Standard Test Method for Coefficient of Static Friction of Uncoated Writing and Printing Paper by Use of the Inclined Plane Method *(The static friction coefficient is measured for a rubber rider sliding on paper on an inclined plane.)*

D 5183 – Standard Test Method for the Determination of the Coefficient of Friction of Lubricants Using the Four-Ball Wear Test Machine *(A four-ball test is run for 60 min to establish wear flats on the balls; the break-in lube is discarded and the balls are retested with increasing normal force in a test lubricant; the friction characteristics of the tribosystem is the test metric.)*

D 5859 – Standard Test Method for Determining the Traction of Footwear on Painted Surfaces Using the Variable Incidence Tester *(A special device rubs a rubber specimen against a counterface with increasing vertical and tangential force; rider breakaway is measured.)*

D 6425 – Standard Test Method for Measuring Friction and Wear Properties of Extreme Pressure (EP) Lubrication Oils Using SRV Test Machine *(A hardened steel ball is reciprocated on a hardened steel counterface immersed in a test lubricant under specified test conditions : 50 N, 1-mm stroke, 50 Hz , 2 hours; friction force is recorded continuously to yield friction coefficients.)*

F 695 – Standard Practice for Ranking Test Data Obtained for Measurement of Slip Resistance of Footwear, Sole, Heel and Related Materials *(Presents details on how to rank footwear candidate materials for friction characteristics on walkways.)*

G 77 – Standard Test Method for Ranking Resistance of Materials to Sliding Wear Using the Block-on-Ring Wear Test *(A stationary block rubs against a rotating ring under test conditions determined by the user; friction force is recorded throughout the test for determination of the friction coefficients.)*

G 115 – Standard Guide for Measuring and Reporting Friction Coefficients *(Contains general testing methodology and schematics of many ASTM tests: B 460, B 461, B 526, D 2047, D 2394, D 2714, D 3028, D 3108, D 3247, D 3248, D 3334, D 34 12, E, 303, E 510, E 670, E 707, F 489, F 609, F 732, G 143.)*

G 137 – Standard Test Method for Ranking Resistance of Plastic Materials to Sliding Wear Using a Block-on-Ring Configuration *(A plastic block is forced vertically against a rotating hard steel disk with speed and force determined by the user; the test specimen is removed from the rig at least six times to measure the progression of wear and friction.)*

G 143 – Standard Test Method for Measurement of Web/Roller Friction Characteristics *(A web of paper, fabric, plastic, etc. is draped over a cylinder with a weight attached to the free end; the web is pulled by a force-measuring device and the force for breakaway and continuous sliding are measured and converted to friction coefficients.)*

G 164 – Standard Test Method for Determination of Surface Lubrication on Flexible Webs *(A web of interest is affixed to an inclined plane; a rider balanced on the end of a paper clip is placed on the web; the inclined plane is raised until the rider moves; the tangent of the inclined plane angle at breakaway is the static coefficient of friction for the tribosystem.)*

G 176 – Standard Test Method for Ranking Resistance of Plastics to Sliding Wear Using Block-on-Ring Wear Test – Cumulative Wear Method *(This is the same specimen configuration as used in the ASTM G 77 test; the test conditions are 10 pounds force, 200 rpm, 20 hours; friction force is continuously recorded and used to calculate friction coefficients.)*

G 182 – Standard Test Method for Determination of the Breakaway Friction Characteristics of Rolling Element Bearings *(A small diameter ball or roller bearing is made the axle of a balanced rider that is placed on an inclined plane; the plane is covered with a high friction material [PVC] and the plane is raised until the inner race of the bearing rotates with respect to the outer race; this angle is the test metric.)*

12

Micro-, Nano-, and Biotribotests

Introduction

MOST OF THE TESTS DESCRIBED TO THIS POINT simulate tribosystems in machinery. Damage and wear effects usually are macroscopic, that is, it is possible to see what happened with the unaided eye. However, the advent of computers and advances in medicine have brought about a variety of tribotests that are quite different. Microtribotests deal with sliding systems involving motions and wear events with sizes in the range of 1 to 100 μm. Nanotribology deals with wear effects that are in the range of 1 to 100 nm. Biotribology is the science of interactions occurring in human joints and internal body mechanisms. These subjects are quite diverse, but they have commonality in their specificity. Each deals with a specialty in tribology that is limited in participation, but not importance.

For example, microtribology mostly started by wear and friction studies in computer storage media. Disk drive head wear is measured in micrometers. Many micro electronic mechanisms can only tolerate wear in nanometers. Joint replacement is a significant part of biotribology and a life-changing incident for hundreds of thousands of people in the United States each year. The research and development undertaken in these areas does not occur in the average tribology lab, nor does the average machine designer use their tests, but they are part of tribotesting, and it is the purpose of this chapter to describe these fields and the tests that are use. The objective of this chapter is to provide a reference for additional tools that may apply to any tribological study.

The specific subjects that will be addressed are surface analysis tools, scanning probe microscopy, scratch testing (ASTM G 171), nanoindentation testing, biotribology tests, and ASTM standards in these areas. The tools used for micro-, nano-, and biotribology studies often can also be applied to more common friction and wear problems.

Surface Analysis Tools

Solving friction and wear problems requires understanding of each tribosystem, each surface, each substrate, their motions, speeds, and loads. Wear, friction, and lubrication are surface processes. For example, a thin coating of ice on a rough concrete surface determines wheher a person will slip when walking on it. It makes no difference that the concrete was scarified to prevent slipping. The rough concrete never comes into play. Lubrication is the ultimate example of the role of surface films. A new automobile engine would only run minutes without oil. The metal-to-metal rubbing pairs will experience severe wear and seizure will occur in one or more of the many sliding systems, thus shutting down your new engine. An oil film only of the order of the surface roughness of the parts makes the difference between imminent seizure and 200,000 miles wear life. The "components" of a surface are illustrated in Figure 12-1).

Needless to say, biosurfaces like joints in animals are even more complex, but the same layer effect is often present. The rubbing surfaces of human joints have bone as a substrate and various body-generated molecules and substances like collagen and water as films to prevent bone-on-bone rubbing (arthritis).

In summary, when one material or substance slides on another under moderate forces, the substrate is almost never directly rubbed. The nature of the separating films determines the net reaction (friction and wear). So solving many friction and wear problems depends on understanding the rubbing surface. What is on it? What is the layer thickness? What is the topography of the surface? Table 12-1 shows the more important parameters that control surface topography and Table 12-2 lists the various analytical tools that can be used to probe film thickness and surface chemistry.

The lists in Tables 12-1 and 12-2 are far from complete, but they include the "most popular" techniques. Surface finish is extremely important in most tribosystems, but it is often not given appropriate attention. Many tribologists model solid-to-solid surface contacts with asperities interacting with each other (Figure 12-2). The molecular and atomic dynamics people model solid-to-solid surfaces with equations of motion of atoms in contact (Figure 12-3).

These techniques help to understand surface interactions, but the real life situation is quite different. The molecular and asperity surfaces are really separated by all of the surface films and contaminants illustrated in Figure 12-1 and the real area of contact is controlled by a factor that unfortunately is completely ignored by almost all tribological researchers: surface waviness. Manufactured surfaces are not flat. They have a waviness and a roughness. The waviness determines the regions of contact, and the roughness determines the stress on the microscopic contact, the asperities (Figure 12-4). The main reason for ignoring surface waviness is that it is not easily measured and it is almost impossible to model because the waviness of each surface is probably unique–like a fingerprint; no two surfaces have identical waviness.

The important point from the standpoint of tribotesting is that a study on the effect of surface finish on a wear or friction process may produce meaningless results without including waviness as a key surface texture parameter. Conformance between surfaces does not start until mismatching surface wave forms are accommodated. This is why many conforming surface wear tests include a run-in; a short time rubbing at reduced velocity or load to get surfaces to conform. It is like break-in of an automobile engine–parts need to wear into each other; waviness must be accommodated.

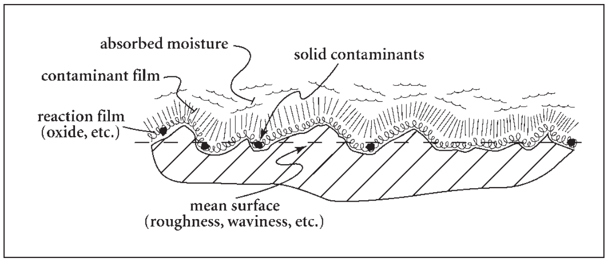

Fig. 12-1—Cross-section of a "real" surface on most engineering materials.

A final caution regarding surface texture: There are at least 20 surface texture parameters dealing with the "nonwaviness" surface features. Usually, arithmetic average roughness (Ra) is the rate-controlling parameter and the most important to measure and control. Computers have made it too easy to produce surface texture parameters such as maximum peak height, 10-point height, kurtosis, skew, etc. Countless correlation studies in industry have verified that surface roughness (Ra) waviness and lay are usually the most important to control to produce predictable tribological behavior. However, each tribosystem is different and in some systems, bearing area ratio may be a key surface parameter. It may correlate best with tribological properties, but it may not be economical to manufacture part surfaces to bearing area ratio.

Optical Microscopy

Only some of the surface analysis tools in Table 12-2, those perceived to have the widest applicability in general wear and friction testing, will be discussed. The most important tool in understanding a triboprocess is optical microscopy; surfaces need to be looked at under a microscope before and after testing. Many times, "looking" can be done with a hand-held loupe. It is possible to see the surface roughness, the surface lay, the direction of machining (manufacturing marks), porosity, large inclusions, even some films (like a fingerprint). Of great importance in doing wear tests is establishing if the specimen surfaces have the desired geometry. Are they flat? Are the edges burred or chamfered too much? Is the lay the way that you wanted it? A simple scan before testing with a bench-top zoom microscope will provide these answers.

After testing, it is recommended to scan wear or friction surfaces with a 20 to 30× zoom optical microscope to see what happened. Did mild wear occur? Polishing? Galling? Are scars uniform? Were the surfaces conforming? Are both surfaces worn?

After these low-magnification observations, you may want to observe surfaces at magnifications up to the optical limit of about 1000 times. Often, metallographic or microtome cross-sections will shed light on the nature of what happened in the rubbing. Optical microscopy is the oldest of all of the analytical tools that we have available to us in 2006 and it is still the most important to use. Optical inspection of tribosystems is a must.

Profilometry

It is always recommended that one document the surface texture of tribotest specimens, at least the Ra. The modern instruments for surface texture measurement use either contact on noncontact probes. Some instruments provide both modes. Traditional contact profilometry uses a conical diamond stylus with a 2-μm 90° radius tip. Tip forces are typically 3 to 30 mg, but there is risk of scratching surfaces which can produce measurement errors. Standard profilometry as described in ASME Y14-36M is usually safe to use on bulk metals and ceramics. Plastics and composites with compressive strengths significantly lower than metals and ceramics need to be examined after testing to determine scratching tendencies. Essentially, most polymer-based materials are scratched by stylus-contact measurements (even scanning probe microscopes with normal forces of a few nanonewtons).

The noncontact profilometers use focused lasers to measure feature peaks and valleys. Some use interferometer principles–superimposing an interference fringe on a surface and optically analyzing the light bands produced. Some instruments use laser triangulation techniques, which are similar to those used to measure feature geological heights from satellites. The concern with noncontact optical techniques is that the laser light cannot reach the bottom of narrow deep valleys. Computer algorithms are used to produce data for specimens with these kinds of features, but they are really only estimates.

Waviness width as described by the ASME Y14-36M standard is the accepted term used for features with a spacing greater than 0.030 inch. Up and down features with spacing less than 0.030 inch are termed "roughness." The waviness dilemma arises from the inability of many profilometer instruments to scan large areas. Scanning probe microscopes may use stylus strokes as small as 10 nm. They never see surface waviness because of the limited sampling length.

TABLE 12-1—The most significant topographic measures for most applications (see ASME Y14-36M for details).

Parameter	Description	Importance
Roughness (Ra) Usual range = nm to μm	Ra Average peak-to-valley height in a standard sampling distance (cutoff)	These peaks carry the load when contacted by another surface
Waviness Height = nm to mm Width = mm to cm	Width height	These features determine conformance between contacting surfaces

TABLE 12-2—Techniques that can be used to analyze surfaces.

Surface Analysis Tool	Description	Usual Analysis Depth	Use
Scanning electron microscopy (SEM)	Focused electron beam is used to stimulate emissions from surface *Operates in vacuum*	1 μm	To image surfaces at magnifications of 50,000x or above and chemical analysis of microconstituents (EDS)
Transmission electron microscopy (TEM)	A focused electron beam passes through a thinned specimen *Operates in vacuum*	Goes through surface thinned from the backside	Can show crystallographic features, deformation nm-sized inclusions
Auger electron spectroscopy (AES)	Electrons bombard a surface and Auger electrons are emitted and analyzed	<0.1 μm	Sputters films from a surface for chemical analysis layer-by-layer
X-ray photoelectron spectroscopy (XPS)	X-rays bombard the surface and photons are emitted and analyzed	<0.1 μm	Identification of surface films and their thickness
Secondary ion mass spectroscopy (SIMS)	Surfaces are bombarded with ions and surface emissions are analyzed	<0.1 μm	Identification of surface films
Mass spectroscopy (MS)	Material can be evaporated from a surface and the elements present can be identified by separating them by their atomic mass	(no limit) Must remove surface layer and import into MS instrument	Identification of absorbed gases
Fourier Transform Infrared Spectroscopy (FTIF)	Infrared light is shown through an organic material and the species is identified by the amount of IR absorption	Only for organic deposits on a surface (micrometers)	Identification of organic substance
Scanning tunneling microscope (STM)	An electron-emitting probe scans the surface	>0.1 μm	Atomic/molecular images of a surface
Atomic force microscope (AFM) or more generically Scanning probe microscope (SPM)	A contact probe scans the surface to show the relative height of surface features	Images the surface by probe contact ±1 nm heights	Topographical (heights) images of a surface
X-ray diffraction (XRD)	X-rays directed at are different by atomic planes	10 μm	Can give information on crystal structure
Raman spectroscopy (Raman)	Monochromatic laser light is directed at a surface-scattering is interpreted	1 μm	Can discriminate diamond from DLC
Optical microscopy	Surface is optically magnified and viewed with visible light	Surface only	Determine the physical nature of a surface

What to do about waviness? Many applications warrant investigation of this surface parameter and whenever wear or friction tests are performed, investigators should decide if this is a parameter of concern. If the answer is "yes," quantify waviness width and height. A simple technique for checking surface waviness of flats is to simply rub the surface on a tool inspection surface plate that is flat within 0.2 μm in 10 cm. The supporting waves will be identified by rub marks from the granite surface. Round surfaces are not so easy, but a spring-loaded hone often works on an inside diameter and sensitive coordinate measuring machines can work on other shapes.

In summary, surface shape/geometry is a critical factor that needs to be addressed in all tribological studies. Also, the most useful surface texture parameters are Ra and waviness. RMS roughness, skewness, kurtosis, 10-point height, maximum peak height, peak-to-valley heights, and bearing ratios are provided by many surface instruments. However, studies to correlate these parameters with undesirable factors are usually necessary. Ra and waviness are key properties of all surfaces.

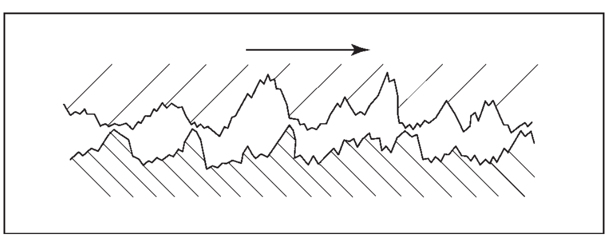

Fig. 12-2—Asperity model of solid-to-solid contact where the wear and friction behavior is controlled by the adhesion and deformation of asperities.

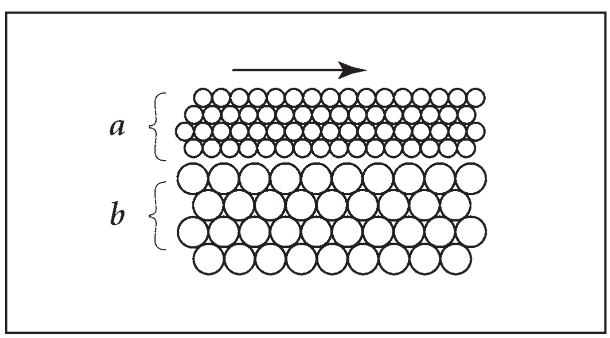

Fig. 12-3—Molecular/atomic model of surface contact.

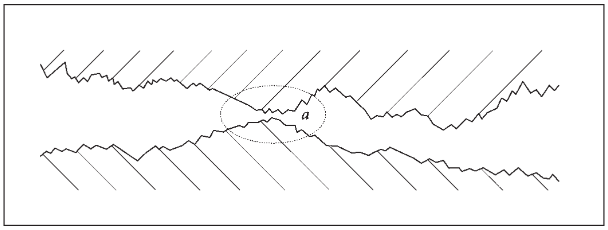

Fig. 12-4—Role of waviness in determining real area of contact.

Indentation Testing

In discussions on types of wear and factors that affect wear, it was emphasized that hardness plays a significant role in a number of wear modes such as abrasion and metal-to-metal wear. Surface hardness can be measured by indentation testing to provide insight into the performance of new tribosystems and in solving tribological problems. Indentation testing is the accepted method for determining hardness of surfaces and it can be used on bulk materials as well as on coatings that are only nanometers thick. Figure 12-5 illustrates the depth range for various hardness tests.

Rockwell C and Vickers hardness tests usually are used on bulk materials because of the depth of the penetration's indentation. Microhardness testers can be used on platings and thermal spray coatings by testing cross-sections, but the lower coating thickness limit is usually about 3 µm. These hardness-measuring techniques are normally not recommended for work on organic films like paints.

This applicability problem has been solved by the introduction of nanoindentors in the 1990s. These devices still use the basic principles of indentation hardness testing except the indentors and indentation forces are much smaller. The metric in nanoindentation testing is a force/deflection curve that looks like Figure 12-6.

The software on nanoindentors analyzes the load and unload curves to yield a hardness value in units of pressure (MPa, GPa) and some instruments produce an elastic modulus from the unload portion of the curve. The depth of indentation and the indenting force can be selected by the person conducting the test. Nanoindentation can be used to measure the hardness of thin organic coatings, plastic films, inorganic coatings, metal coatings, or any coating or bulk material in which hardness/modulus information is desired in the outermost 100 nanometers of a surface. In addition, the indentation depth should be no deeper than one third of the film/material thickness to be valid. This number is one tenth for microhardness testing. A concern with using nanoindentation in tribology studies is that precise indentation and measurement of less than 100 nm depth requires a comparably smooth surface. A

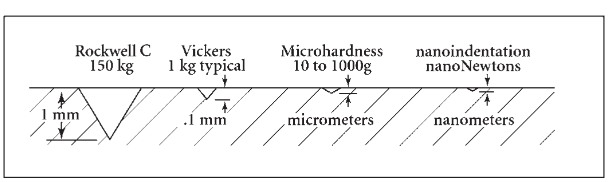

Fig. 12-5—Comparative penetration of various hardness tests.

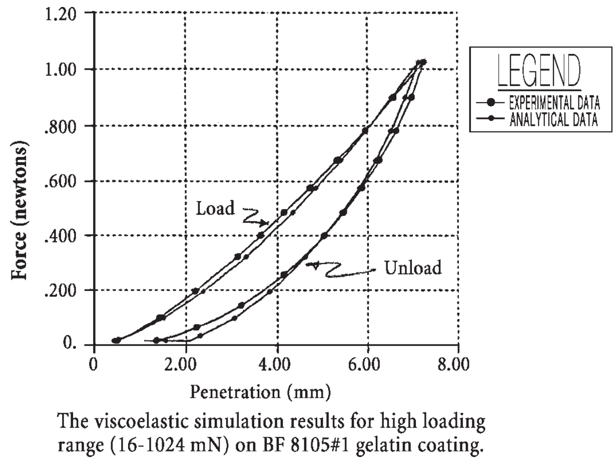

Fig. 12-6—Typical nanoindentation test.

50-nm indent on a surface with a roughness of 1,000 nm may not produce usable information. Polished surfaces are usually necessary for micro and nano indentation studies of solid surfaces.

In summary, indentation testing has been an invaluable tool in tribotesting for decades. The advent of thin coatings (<20 µm) has led to the development of nanoindentation testers that can be used on thin coatings and near-surface studies. There are ASTM procedures for Rockwell and microhardness testing (ASTM E 18), but standards have not been developed for nanoindentation as of 2006. The procedures used are mostly those that were supplied by the instrument manufacturer. In this respect, nanoindentation needs additional attention.

Scanning Electron Microscopy

Scanning electron microscopy (SEM) is almost as important as optical microscopy in studying tribological surfaces. Its distinct advantage over optical microscopy is its ability to image surfaces at different heights, that is, three-dimensional images (Figure 12-7). Optical microscopes typically have flat field

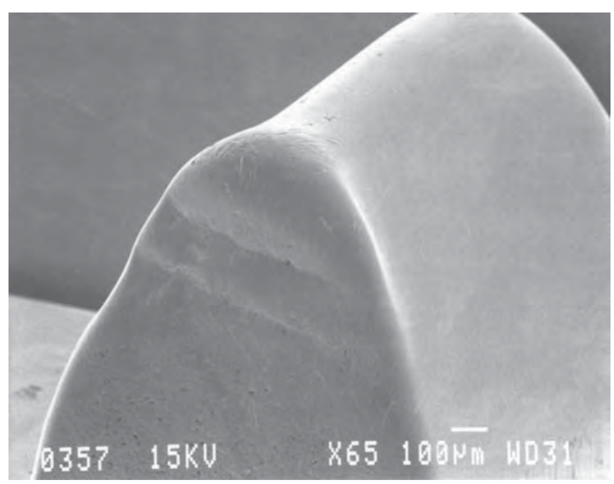

Fig. 12-7—Scanning electron micrograph of a worn sprocket tooth.

optics where surface features higher than a few micrometers cannot be fully in focus. Scanning electron microscopes can image whole gear teeth, wear scars on piston skirts, all types of tribocomponents that will fit into the SEM vacuum chamber. The vacuum requirement of most SEMs precludes study of worn components containing oils or greases; vacuum systems cannot accommodate them. In addition, most vacuum chambers have limited size. Many cannot tolerate tribocomponents or pieces of tribocomponents larger than a walnut. Most tribologists have learned to work around these limitations. Typically cellulosic or silicone replicas are used for test specimens and parts that are too large to fit into the SEM.

Many SEMs are equipped with X-ray analysis capability (EDS) that allows elemental mapping of surfaces. Surface chemical compositions can be determined, alloy designations deduced, and the composition of individual surface constituents can be determined. One additional concern with using SEMs is that the item to be imaged must be electrically conductive or made so by metal coating. In 2006, instruments were introduced that even work in nonvacuum conditions. Thus, this indispensable micro and nano analysis tool will have even more capability.

Scanning Probe Microscopy

Scanning probe microscopy (SPM) was developed to analyze surface textures at finer levels than profilometers. Its principle of operation is illustrated in Figure 12-8. A laser is focused on the probe. Its up-and-down motion is sensed by a detector and with raster scans at some distance apart a surface height map is generated (Figure 12-9), which also serves as an image of the surface.

"Scanning probe microscope" (SPM) is the generic term for instruments that scan a surface with a small radius tip (5- to 10-nm radius) with a small force (from a few nanonewtons to micronewtons) to produce an image of a surface. The commonly used term for these devices is "atomic force microscope," or AFM. The standard tip is made from silicon nitride (Si_3N_4) or silicon, but tips can be made from other materials including diamond (for scratch testing). Figure 12-10 shows the general shape of a Berkovitch probe that is widely used for nanoindentation hardness measurements. Some users adhere carbon nanotubes with lengths of about 10 μm and diameters of a few nanometers to scan into surfaces with sharp valleys and some users adhere spheres to the tip to do contact adhesion (pull off and measure the force).

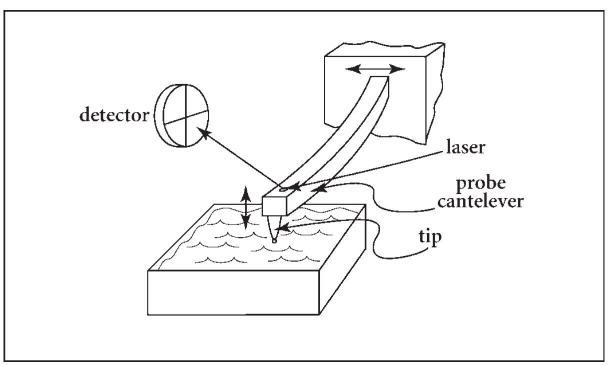

Fig. 12-8—Schematic of a scanning probe microscope (AFM).

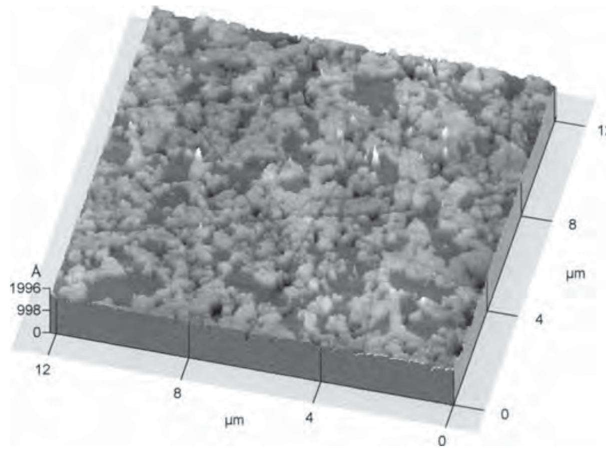

Fig. 12-9—AFM image.

Standard SPMs can scan an area defined by the user from 150 μm × 150 μm to a few nm × a few nm. They can retrace a single scan for a wear test or they can repeat an area scan to perform a wear test. The scanning velocity is usually less than 200 μm/s. A popular application of SPMs is to perform scratch tests on a surface with a fixed force or increasing force and then image the scratch as soon as the scratch test is over. This allows ranking of damage on various coatings or substrates. Diamond tips are usually used for scratch testing. Nanoindentors are preferred for heavier coatings/films, but they do not provide the imaging capability of an AFM.

Another significant application for which SPM can be used is to measure the lateral force (twisting of the cantilever) as it rubs on a surface. Some instruments have "lateral force" capability and when lateral force instruments are calibrated properly, one can obtain a map of the coefficient of friction of the tip on the scanned surface. If the surface contains microconstituents or partial coatings, the effect of these can be discerned on tip/surface friction coefficient (Figure 12-11).

A major concern with using SPMs for friction (and wear) studies is that the results obtained depend on the instrument and how it is used. Many people who publish data from these instruments do not state their test conditions or how the device is calibrated for force measurement. For example, any friction data should show

- Tip material and shape
- Cantilever spring constant
- Tip radius

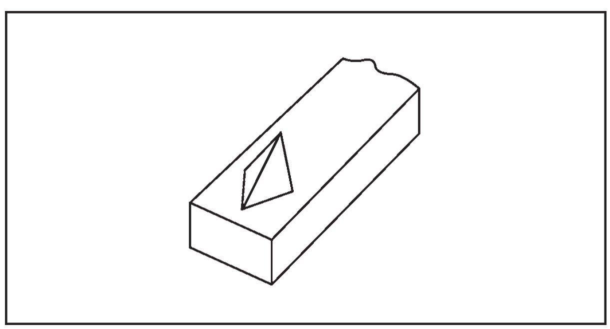

Fig. 12-10—Berkovitch tip.

- Scan speed
- Tip force
- Environment
- Scan direction (forward and backward)
- Calibration method

Calibration for normal force is straightforward: just press the tip on a documented spring and calculate the spring constant. There were at least five manufacturers of SPMs in 2006; none appeared to address a standard way to calibrate these devices for friction measurement. It is not a trivial matter and this is an opportunity for standardization.

In summary, scanning probe microscopes are without a doubt the primary testing tool used by researchers working with micro- and nano-sized mechanisms and materials. These instruments can be used to perform wear tests of the probe versus substrates and coatings. They are used for scratch testing to assess abrasion characteristics and they use the twisting of the probe as it slides over a surface to yield frictional information on the probe/surface tribosystems. A major concern with the use of these devices for tribological studies is that the results apply only to the probe tip/surface couple and probe tips are currently made from only a few materials: silicon, silicon nitride, diamond, and carbon nanotubes. The friction and wear test results depend on the probe tip materials and the test data only apply to tribosystems where one member of the couple is the same as the tip material.

SPM data should be used with reservation on real-life mechanisms unless the mechanism material couple is the same as the SPM probe tip/surface couple. Caution should be exercised in using friction data because there is not an agreed-to calibration method. SPM tests need standardization that addresses these concerns.

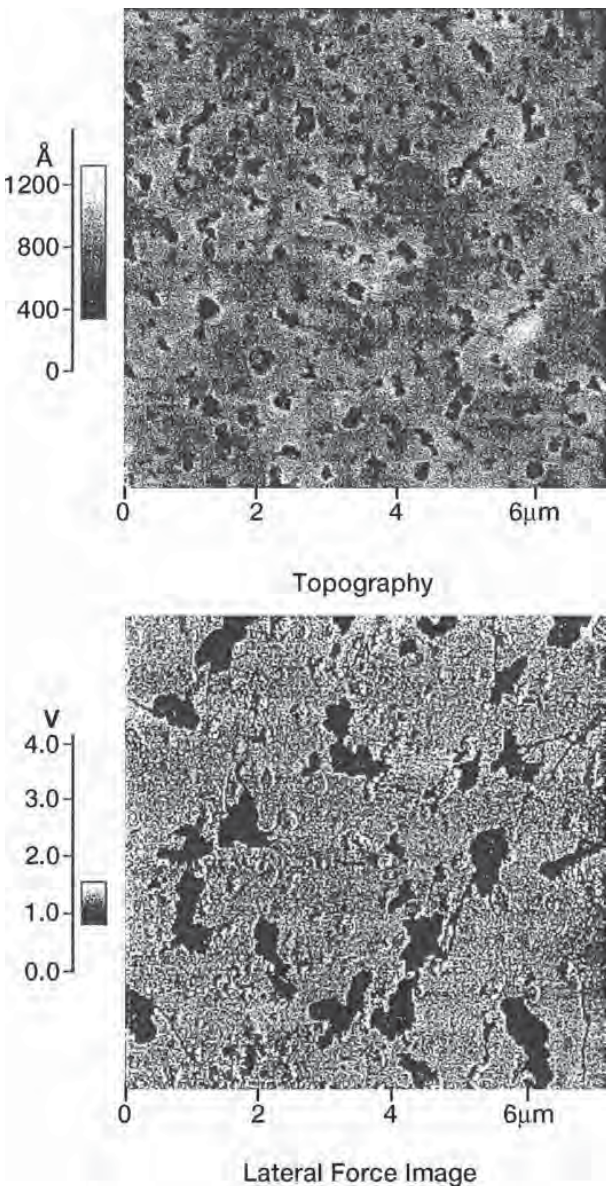

Fig. 12-11—Comparison of a topography image and lateral force image of a surface.

Scratch Testing

The earliest hardness test was "Moh's hardness," a test of what scratches what (Table 12-3). Continuing this concept, various tests have been developed to vary the surface and scratch test surfaces with a diamond as a predictor of surface durability. The rational is that a scratch from a sharp penetrator will simulate scratching abrasion. The grooves or scratches produced in abrasion tests come from penetration of sharp edges of grit penetrating and plowing material (Figure 12-12). The simplest scratch test is to load a penetrator on a surface and move the penetrator on the surface with sufficient force to produce a scratch. Candidate materials can be scratched with the same setup and the damage to different surfaces can be assessed by scratch size, length, etc.

ASTM G 171 is such a test. However, the degree of scratching is assessed by a number that quantifies the scratch damage: the scratch hardness. The test uses a Rockwell C diamond as the scratch indentor; the load is selected by the user, but interlaboratory tests were conducted with a loading mass of 300 g on the penetrator. The test metric is scratch hardness. The scratch hardness is obtained with this equation:

$$SHN = \frac{8P}{\pi W^2}$$

TABLE 12-3—Mohs hardness.

Mineral	Hardness	Mohs Number
Talc	Barely scratched by fingernail	1
Gypsum	Scratched by fingernail	2
Calcite	Scratches copper and is scratched by it	3
Fluorite	Not scratched by copper, does not scratch glass	4
Apatite	Just scratches glass, just scratched by knife	5
Orthoclase	Just scratched by a file, easily scratches glass	6
Quartz	Not scratched by a file	7
Topaz	Scratches quartz	8
Corundum	Scratches topaz	9
Diamond	Scratches corundum	10

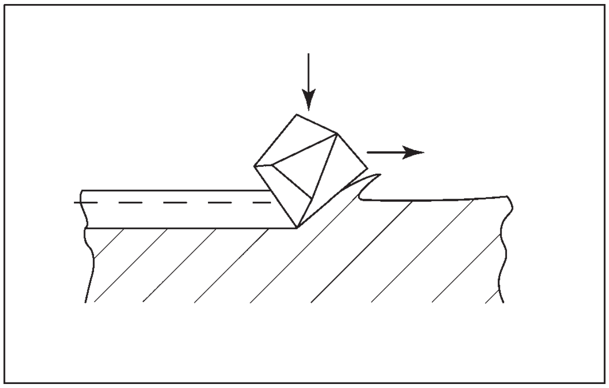

Fig. 12-12—Scratching by a hard particle.

where SHN = scratch hardness number,
P = test force, and
W = scratch width.

The units for scratch hardness are those of pressure (psi or MPa). As mentioned previously, scratch testing can be performed on SPM's or nanoindentors. The G 171 test is intended for bulk materials and the SPM and nanoindentor scratch tests can be used on films and coatings that can be as thin as a few nanometers. Some scratch testing instruments program a force increase during scratching so that the scratch length for coating failure can be used as the test metric. Some devices use acoustic emission as the measure of coating failure. A brittle coating will make a detectible (by acoustic emission) sound at spalling. Commercially available scratch testers are available with load ranges from 1 to 200 N (macro), 0.05 to 30 N (micro) and 10 μN to 1 N. In summary, scratch testing is often a low-cost effective test for screening coatings as well as substrates for potential abrasion resistance. It is easy to use; it can be quantitative and often it can be performed on a wide range of materials from paints to ceramics in hardness.

Biotribology Tests

From an economic standpoint, human joint replacement is a big business. Each year in the United States, about 300,000 of these operations are performed at a cost that may be as much as $200,000. There are a number of manufacturers of knee, hip, and other joints and they are all doing research on the best couples for replacement joints. The options for hip joints are:

Femur		Socket
300 series stainless steel	vs	ultrahigh molecular weight polyethylene (UHMWPE)
Titanium	vs	UHMWPE
Al_2O_3	vs	UHMWPE
CoCr alloy	vs	UHMWPE

In Europe, options include metal-to-metal (CoCr self-mated). There is a similar potential couple for knee joints. There are a number of ASTM tests aimed at evaluating materials to be used in prosthetic devices, such as ASTM F 1815 (fretting of hip joint components) and ASTM F 897 (fretting of plates and screws).

A number of test machine manufacturers sell sophisticated machines to cycle full-size joints submerged in bovine solution (to simulate body fluids). The machines are quite complicated in motion since it has been learned that simple sliding does not simulate the wear behavior of true joint motion. There is a rolling as well as sliding motion and advanced test machines produce human body motion and forces. In addition to joints, tribotesting is done on heart pumps and other devices that must take over for human parts. Often, full-size devices are tested rather than using bench tests.

Chapter Summary

Many surface analysis tools are available to use to dissect and identify wear/friction mechanisms and causes. Optical microscopy is the most available tool and should always be used first. Use of the other tools depends on the situation and their availability. If it is necessary to identify mechanisms some of the more sophisticated (and expensive) tools may be required. If these expensive tools are not available, consider using contract labs that do have them. SEM is probably the second most important tool for studying wear surfaces at the micro or nano levels.

Surface texture is an important property in any tribo-process and there are contact and noncontact instruments that can be used to determine micro and nano surface texture parameters. Surface roughness and waviness are usually key surface texture parameters. Profilometers are suitable for most tribosystems, and SPMs are appropriate for micro and nano tribosystems. These devices can be used as wear testers, as contact force testers, and as scratch testers.

Nanoindentors compliment SPMs by providing information of surface and thin film hardness, stiffness, and scratch hardness/durability. Biotribology tests are very specialized and not to be ventured into without collaboration with medical professionals. It is very difficult to simulate (if impossible) true in vivo conditions in a laboratory bench test. The ASTM tests have been voted on and agreed to by a diverse committee and they are suitable candidates for general studies. Microelectronic mechanisms almost always have tribological problems that will need to be addressed by micro- and nanotribotesting techniques.

Important Concepts

The following concepts should be taken from this chapter:

1. Nano- and microtribology processes are the same concept as the macro processes, but you may need to understand how to deal with tribological scale issues.
2. Microscopic examination of tribosurfaces is necessary in all wear processes.
3. Nanoindentation can yield hardness and stiffness information on films and surfaces.
4. SPMs can image surfaces at the nano level, but probe contact is necessary, which can damage some surfaces.
5. Friction coefficients measured on SPMs apply only to the material couple (tip versus test surface) used in the SPM tests
6. Surface films can be studied by wear testing and chemical analysis tools; surface and bulk mechanical properties can be studied with micro and nano tools.
7. Biotribology studies usually need to be performed in bovine serum and the like to simulate in vivo conditions.

Resources for More Information

Fundamentals

Bhushan, B., *Handbook of Micro/Nanotribology*, 2nd Ed., Boca Raton, FL, CRC Press, 1999.

Bhushan, B., *Nanotribology and Nanomechanics*, New York, Springer, 2005.

Testing

Yust, C. S. and Bayer, R. G., *Selection and Use of Wear Tests for Ceramics*, STP 1010, ASTM International, W. Conshohocken, PA, 1988.

Biotribology

Davis, J. R., Ed., *Handbook of Materials for Medical Devices*, Materials Park, OH, ASM International, 2003.

Hutchings, I. M., *Friction, Lubrication and Wear of Artificial Joints*, New York, Wiley, 2002.

Related ASTM Standards

E 18 – Test Method for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials *(This standard covers the details of the familiar Rockwell C, Knoop, and Vickers types of indention tests.)*

F 732 – Standard Test Method for Wear Testing of Polymeric Materials Used in Total Joint Prostheses *(This standard covers pin-on-disk, reciprocating pin-on-flat, and joint articulation options for rapid screening materials for possible inclusion in more expensive simulator or in vivo tests.)*

F 897 – Standard Test Method for Measuring Fretting Corrosion of Osteosynthesis Plates and Screws *(Bone screws are used to attach plates to plastic arms that are flexed to produce fretting motion. Screw and plate damage is assessed.)*

F 1875 – Standard Practice for Fretting Corrosion Testing of Modular Implant Interfaces: Hip Femoral Head—Bore and Cone Taper Interfaces *(Joint couples are loaded and cycled immersed in a suitable solution. The solution is analyzed for metallic elements after rubbing or potentiodynamic polarization techniques are used to determine the corrosion component of the rubbing damage.)*

F 1877 – Standard Practice for Characterization of Particles *(This practice is used to characterize wear particles from prostheses used in vivo or in animal studies. This practice can be used to determine if wear particles generated in bench tests are similar to those produced in in vivo studies.)*

G 171 – Test Method for Scratch Hardness Testing of Materials Using a Diamond Stylus *(A conical diamond indenter scratches a surface using optional scratching force and scratch length; the scratch width is measured and a scratch hardness number is calculated from the width and force information.)*

13

Test Confidence and Correlation with Service

Introduction

THIS GUIDE DISCUSSED THE MOST WIDELY USED wear tests and, to end this book, industrial case histories will be presented to try to convince readers to use these tests to solve problems and to perform research studies. The chapter goal is readers who recognize that bench tests are a fast, cost-effective approach to solving tribological problems.

These case histories illustrate how tribotests were successfully used to solve industrial wear and friction problems. Some of the factors that pertain to test validity will be reviewed. Then, the details of specific projects will be presented. It will be shown how some of the standard tests described in this guide were successfully applied. Finally, this guide will present some general "suggestions" in highlighted boxes on approaching friction, wear, erosion, and lubrication issues.

Test Confidence

Chapter 1 addressed modes of wear, and Chapter 3 addressed how to select a wear test. Some of the admonitions in these previous chapters will probably be repeated to help readers have confidence in their bench tests.

Test Selection

Selection of appropriate wear mode has probably been preached ad nauseum. However, it is going to be stated again since it is of utmost importance.

Identify the mode of wear that you want to address in a test.

Figure 13-1 shows the tests under the jurisdiction of the ASTM Committee G02 and the wear modes covered by their tests.

Sometimes more than one mode exists. In those cases, it usually is best to test with the mode that predominates or arises first. If a project goal is to solve an existing wear problem, the test selected should produce wear results that look like the problem at the micro and macro level.

A proper test will produce wear results that look like the problem—always check for this.

There are many geometries and many different motions that can occur in tribosystems. Valid results will probably not be obtained in a bench test unless the bench test matches the type of motion and approach angle in the application of interest. Test motions can include the following:

Types of Motion	Suitable Test Configuration
Rotation	Block-on-ring
Continuous sliding	Pin-on-disk
Reciprocating sliding	Reciprocating pin-on-disk
Impact	Hammering
Rolling	Balls/rollers
Complex motion	Hip simulator, etc.

In addition, contact geometry in tests can vary significantly (Figure 13-2).

A valid test should have the type of contact that exists in an application. The stress level and velocity should be similar.

A valid test simulates the type of contact, stress, and motion of the intended application.

A risk in following this suggestion is to make a bench test identical to an application. This is usually not advisable because if a reasonable material couple is selected for testing, a bench test could take years. Some test parameter usually needs to be accelerated to speed up screening, but caution should be taken not to create an entirely different tribosytem than the one originally intended for study. This guide's recommendation is to accelerate what may accelerate in service. For example, higher than calculated loads usually result from errors of form in machinery (runout, waviness, etc.); thus it is reasonable to test at higher than perceived loads. If velocities may be higher than normal for some reason, the test could be run at higher velocities.

Accelerate speed or load in simulations, but not enough to alter the basic tribosystems.

The classic example of accelerating tests is wear tests on plastics. Plastics are widely used for plain bearings. In the early days of plastics, various types of plastics were ranked for suitability as bushings by making bushings of candidates and running them for thousands of hours and measuring mass change. Needless to say, this kind of testing does not lend itself to statistical analysis and few products today have a 5-year lead time to do these kinds of tests. Plastics are now widely evaluated for bushing applications with a block-on-ring test which usually takes less than 24 hours to run. It simulates a bushing because bushings run with a clearance and the shaft starts out in line contact the same as a block-on-ring. The test is accelerated by concentrating the wear in a localized spot that can be easily and accurately measured even though the mass change is very small.

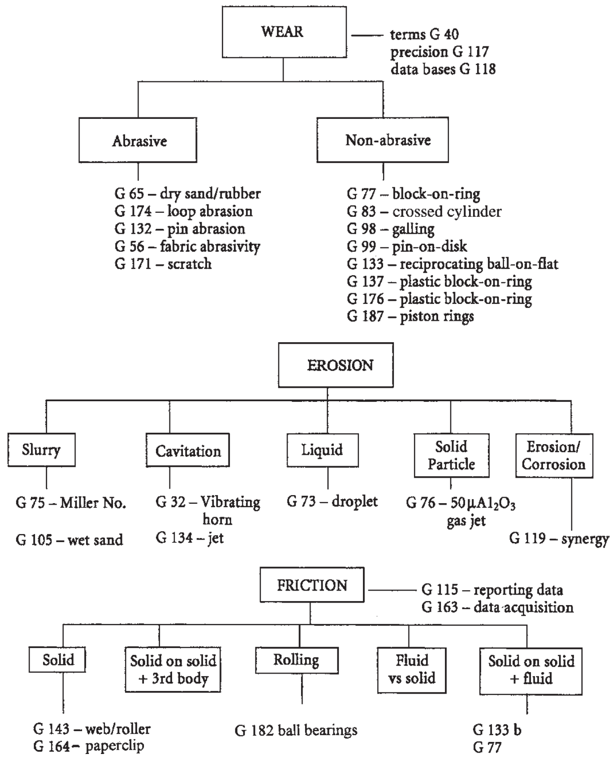

Fig. 13-1—Modes of wear and friction and some ASTM tests that apply.

The test procedure selected for a tribotest should include details on

1. Material designation/fabrication process/treatments
2. Sample identification
3. Control of surface texture
4. Control of cleaning
5. Test conditions
   a. load
   b. velocity
   c. debris/third bodies
   d. total sliding distance
   e. counterface
   f. special instructions (progressive measurements)
6. Result measurement
7. Interpretation of data/statistics
8. Report

Essentially, the aforementioned examples are typical elements in almost any ASTM test method. Material designation seems intuitive, but often people neglect the subtle test material details, that is, the surface lay that can have a profound effect on test results. Each material system has details that need to be addressed and documented (Table 13-1). Specimen entries may be much more detailed, but the message is to specify everything that could affect results.

Identify test specimens uniquely and document all properties and treatments that could affect test results.

Design test experiments to meet your testing objective. If you want to determine whether one plastic is better than another for an application, you need to establish how the current plastic fails. It may be that there are two forms of wear prevailing in the tribosystems, abrasion from process particles and wear from sliding on a hard steel. A project may use the ASTM G 174 loop abrasion test to compare the abrasion characteristics and a G 99 pin-on-disk for the sliding wear. It is also usually desirable to include a reference material with known tribological properties. For example, if the application under study uses polystyrene (PS) and it is not lasting to expectations. A decision has been made to compare it (PS) to a 5% polytetrafluoroethylene (PTFE) polycarbonate (PC), but it is also known that polypropylene (PP) works satisfactorily in a similar application; PP should also be included as a check material. Thus there will be three materials to test in the study: two checks (PS and PP) and a replacement candidate (PC+PTFE).

Know how to design tests to provide statistical significance. There are ASTM standards on statistical sampling, but no less than three replicates of each material should be tested. One test can be erroneous for a reason and there is no way to know. If only two tests are conducted, they will likely produce different numerical results and it will not be known which one is "more correct." Statistics can start to be used with three replicates. Tests for differences can be applied. In the three-plastic test example, there is a need for statistics to determine if there is a statistically significant difference between the results. There are statistical software programs to test data for difference. A graphical test is illustrated in Figure 13-3.

If the test data are plotted showing the test average plus or minus two standard deviations, a test of statistical difference is simply overlap of the error bars. If the error bars do not overlap, there is a statistically significant difference. In Figure 13-3, PS is not different from PP, but both are different from the PC candidate. Another statistical test to employ is to use coefficient of variation to determine if the test is in control. If

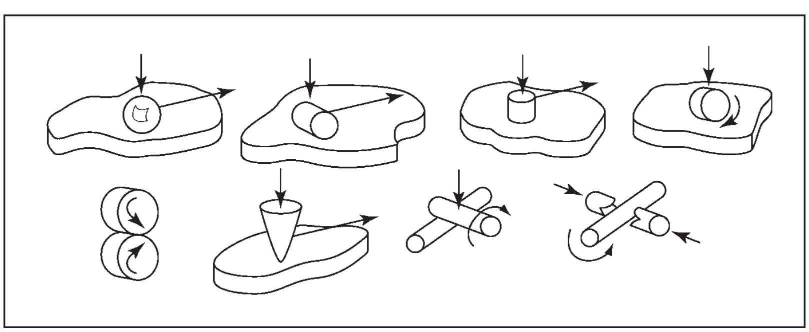

Fig. 13-2—Some types of test contacts.

TABLE 13-1—Information needed on test specimens.

Consideration	Metals	Plastics	Ceramics	Composites	Bio	Coatings
Designation	SAE 1010 Steel	PPO (AB26)	Kors 2 Al_2O_3	PF + glass AB-23	PF (atlas 12)	Chromium EL 20
Manufacture	Hot rolled	Injection molded	Sinter/hipped	Compression molded	Compression molded	Electroplated
Treatments	Anneal	Stress relieved	500°C-3 hours	None	100°C-1 hour	600°F-1 hour
Hardness	280 HB	40 shore D	1900kg/mm^2	60 shore D	30 shore D	70 HRC
Surface lay	⊥ ground	Molded	Lapped	Molded	Machined	‖ ground
Surface texture						
Ra	0.1 μm	0.1 μm	0.05 μm	0.2 μm	0.5 μm	0.5 μm
Waviness width	0.01 μm	0.01 μm	0.002 μm	0.01 μm	0.5 μm	0.5 μm
Waviness height	200 μm	200 μm	200 μm	200 mm	200 mm	200 mm
Sample dimensions	½ x 1 x 3 in.	¼ x .4 x .75 in.	½ x 1 x 3 in.	¼ x 2 x 3 in.	¼ x 2 x 3 in.	¼ x 2 x 3 in.
Test surface	1 x 3 in.	¼ x .75 in.	1 x 3 in.	2 x 3 in.	2 x 3 in.	2 x 3 in.
Cleaning	Acetone	TSP	1% NaOH +DI	TSP	400 RADS	Acetone
Test orientation	Slide ‖ grind	‖ to inject	‖ to long axis	‖ long axis	⊥ long axis	‖ to grind
Specimen I.D.	M1	P21	C33	Co42	Bi2273	Pl207

a test is in statistical control, the coefficient of variation should be less than 0.1.

$$\text{Coefficient of variation} = \frac{\text{test standard deviation}}{\text{test mean}}$$

Some wear processes, like adhesive wear of metals, produce coefficient of variations as high as 0.5, but statistics should always be used to design tests and analyze results.

Use statistics in test design and interpretation.

It is recommended that at least one specimen be used to debug a test before testing replicates of several materials. Loose connections, specimen misalignment, or other unanticipated problems may be discovered. In addition, this is an opportunity to determine if specimen surfaces are wearing as intended.

Examine a debug specimen to make sure that the wear scar looks like the anticipated mode of wear.

Abrasion tests should show scratching from the abrasive grains, for instance, hard metals rubbing produce oxidative wear, fretting tests produce a gnarled surface, and so on; make sure that the anticipated mode of wear is occurring in the bench test. One of the most important steps in any wear or friction test is to personally observe the worn test specimens. Many times testing is delegated to somebody other than the principal investigator and the principal investigator may not be shown the test results until all of the tests are complete. The net result may be no usable data; the agreed-to test may have produced strange or unexplainable results or no results at all. The test technician may have had terrible repeatability in the test such that there would be no statistical difference between materials. The test was out of control, but was still carried out as originally planned. The technician did what was asked, but there are no usable results. If the results and test specimens were personally reviewed after each test this testing disaster would not have happened. Once it appeared that the test was out of control, a different testing protocol could have been tried. The test could have been debugged to bring it under control so that usable data are produced.

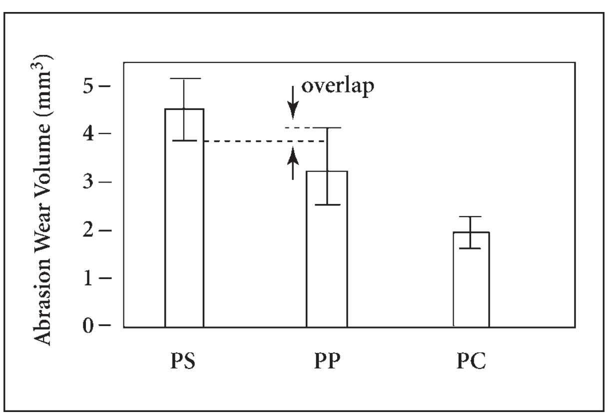

Fig. 13-3—Test data plotted with error bars.

Personally inspect worn specimens for proper scars and wear mode.

Finally, test results should be compared with the literature or benchmark tests to make sure that your results are reasonable. For example, if a test is showing that AISI 1010 steel self-mated is wearing better than A2 tool steel at 60 HRC self-mated, there may be something wrong with the test. Countless service applications of A2 tool steel show low wear rates. This is in the literature and it is widely known to be the case in service.

In summary, a valid wear test requires paying attention to a lot of details; designing tests using accepted test standards if possible, use statistics or data and observe the test results very early to make sure that the test is performing as anticipated. Use statistics to check for significant differences and check for believable results. Bench tests are better than production tests because production feedback is usually nonexistent, but bench tests need to be done right.

Correlation Case Histories

Some naysayers state that the best wear test is to make a part from the test material and try it. This seldom works because of lack of control when a part is in service. When a test material is checked on after two months in service, a likely reply from the production supervisor is: "It did not work; we put the old material back in." Or, "I'm not sure where the test material is; it may have been removed on the second shift." In addition, this kind of testing may take "forever." The remainder of this chapter will present case histories of how various bench tests were used to solve problems and the tests correlated with service results. They will cover a wide range of wear modes.

Friction

Diamond-like carbon (DLC) has been touted in the literature and by suppliers as "low friction." A laboratory study was conducted to determine whether DLC would produce a low friction against the support ride of a problem photographic film.

It has been determined that the ASTM G 143 capstan friction test correlates with production results on various photographic films. If the G 143 test shows that a particular film surface will have high or low friction against the standard roller material, hard-coated 6061T6 aluminum, these results will also occur in production.

In this study, the backside of a particular film was tested for friction coefficient against 4-inch-diameter cylinders coated with DLC, hard coat, nickel electroplate, and stainless steel. All surfaces were essentially production rolls with the exception of the DLC. The measured static and kinetic coefficients of friction are shown in Figures 13-4 and 13-5, respectively. These results indicate that DLC has high friction in this tribosystem. It is not low friction when used as a roll that slides against the backside of a particular photographic film.

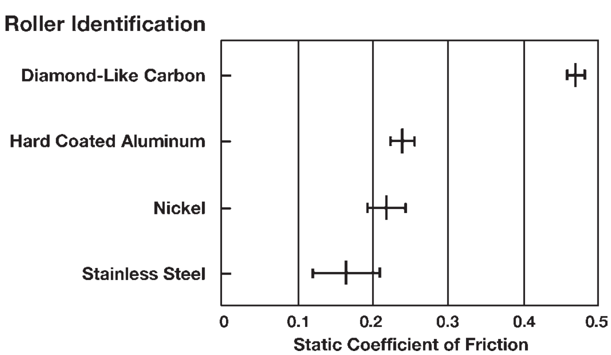

Fig. 13-4—Average static coefficients of friction of K1 film backside versus various roller materials.

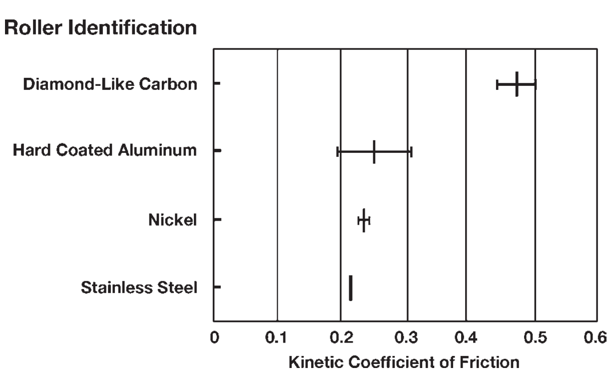

Fig. 13-5—Average kinetic coefficients of friction of K1 film backside versus various roller materials.

Thus, a bench test saved building a very expensive roll and performing a very costly production test to determine if a new coating offered some service advantages. These results also show how a tribosystems affects friction. There are countless papers in the literature stating that DLC is low friction (<0.005) self-mated in a pin-on-disk test. These data apply only to those tribosystems, not to the subject roll/film tribosystem.

Abrasion

Dies used to perforate photographic film were usually made from a 30 HRC 416 stainless steel so that they could be "sheared in" to perfectly fit gangs of hardened stainless-steel punches (58 HRC). This material couple provided adequate service life until a film was introduced with a magnetic overcoat for data recording on the backside. The 416 stainless-steel die lasted only days compared with months before the magnetic overcoat. The problem was addressed by making new dies from a cermet made from a 12% chromium tool steel and 25% titanium carbide. This material solved the die wear problem. However, after about a year of successful use, the cermet manufacturer stopped making this grade. They offered about 20 other grades, but it was too risky and costly to simply try another grade in production. Thus, a laboratory bench test (ASTM G 174 loop abrasion test) was used to compare the abrasion resistance of candidate materials with the current production material (control). The candidates had hardened and annealed matrixes, various matrix compositions, and various TiC volume fractions. The test results, which are shown in Figure 13-6, identified grades that were as abrasion resistant as the control with a soft matrix (annealed) that would still allow dies to shear in.

Grade (440-25) was put into service, it produced significantly better service life than the control that was no longer available, and it has similar shearing-in characteristics. The

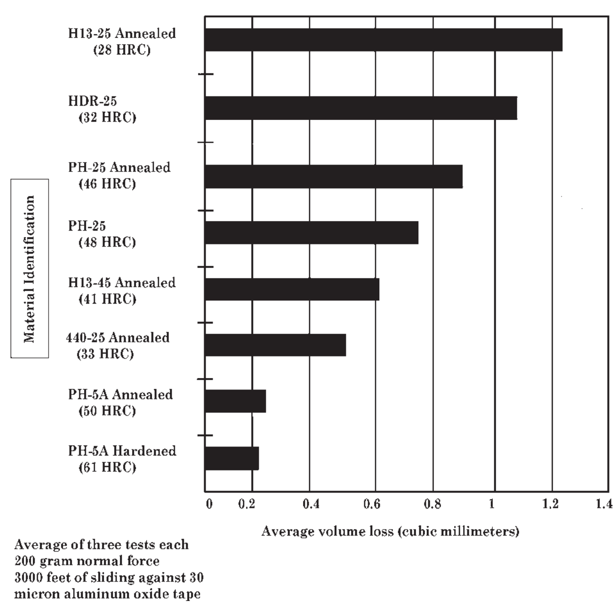

Fig. 13-6—Average volume loss of candidate materials tested using ASTM G 174.

most abrasion-resistant grade PH-5A did not shear well. The test effectively compared abrasion resistance that correlated with production abrasion from magnetic overcoats. And a typical production problem was successfully addressed.

Nonabrasive Wear

Gears used to prevent backlash in a gear train were scoring in service and it was decided to investigate chromium plating as a way of reducing the scoring tendencies. The gears were made from type 440C stainless steel at 57 HRC, and they were subjected to an oscillatory motion to control backlash. They did not rotate, only oscillate. It was too expensive and risky to evaluate the chromium plate suggestion on a production machine. It was decided to test the concept in a laboratory bench test.

The test decided on was an oscillatory block-on-ring test using the ASTM D 3704 oscillatory grease test procedure without the grease. This application used no lubrication because of sanitary conditions. The block load was designed to produce an apparent contact stress similar to service, 12° arc, 0.1/m/s, 3600 cycles (1 hour). Profilometry was used to measure wear volumes on the block and rings. The test couples included the control 440C at 57 HRC self-mated, the Cr plate (5 μm thick) self-mated and mated against 440C stainless.

The test results which are shown in Figure 13-7 show the repeatability of the three tests on each couple as well as the system wear for the three couples. The test results show no significant improvement in system wear by plating both gears and the system wear would degrade further if only one gear were plated.

This bench test prevented a significant wear problem (plating one gear) and prevented unnecessary expense and risk in plating both gears. The plating would not improve the system. Similar testing showed that a newer grade of stainless steel containing a vanadium carbide phase would improve system wear. This was implemented and scoring ceased. The lab test correlated with service.

Wear of Plastics

A seal on a pill-making machine (pelletizer) made from ultra-high molecular weight polyethylene (UHMWPE) was wearing

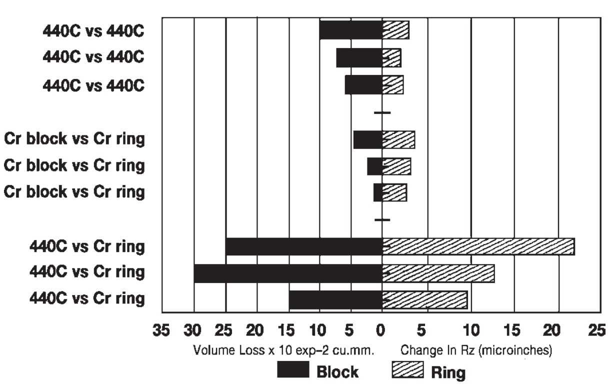

Fig. 13-7—Volume loss of test blocks and change in counterface peak height for bare and chromium-coated 440C stainless steel tested in a reciprocating block-on-ring test configuration (12° arc, 20 SFM, 25 ksi, 3, 600 cycles, 1 hour).

at a "higher-than-can-be-tolerated" rate. The seal rubbed against type 316 stainless steel unlubricated at room temperature. The sliding speed was only 50 feet per minute, and the contact pressure was only enough to keep 50-μm-diameter particulate (inorganic crystals) from migrating past the seal. As is the case with most production machines, it was too costly to screen new seal materials on the production machine. Bench wear testing of other plastic candidates was decided upon.

Selection of candidate plastics to replace UHMWPE was based upon previous favorable applications against a "soft" metal. Usually only plastics that contain a lubricant will run against a "soft" metal without severe wear. The test candidates were:

UHMWPE + lube	A grade of UHMWPE that contains microscopic voids containing a lubricant
Acetal + PTFE	A PTFE-filled polyoxymethylene
PI + PTFE	A blend of polyimide and PTFE
PPS + PTFE	PTFE-filled polyphenylene sulfide
PI + C	Graphite-filled polyimide
UHMWPE	The reference material that needed to be improved

It was decided to compare these materials using the ASTM G 77 block-on-ring test with test parameters that simulated the pelletizer conditions:

316 stainless-steel rings
Plastic blocks
10 lb of normal force
70 ft/min sliding speed
17,000 feet sliding distance (4 hours)

Friction force was monitored throughout the test and wear volume was measured on the blocks from wear scar width (using tables in the G 77 standard). Ring wear was assessed by profilometry, but was determined to be not measurable. Figures 13-8a and 13-8b show the coefficient of friction and wear volume.

These bench test results identified a material (acetal + PTFE) that should provide almost a 10× improvement in wear life. In addition, this material should reduce machine power consumption because of lower system friction. It should also be noted that the friction coefficients do not correlate with wear results. They seldom do.

In summary, a laboratory bench test identified a plastic material to replace another plastic that did not meet service life expectations. This solution was implemented and the anticipated improvement was realized. The test correlated with service.

Slurry Abrasivity

There was a proposal to add tin oxide as a suspension in photographic emulsions to address static discharge problems. This material has shown to be effective for this purpose. However, there was a concern about the material's abrasivity. If tin oxide were added to photographic emulsions, would it produce accelerated abrasion of tool used to slit cut and perforate tin oxide-containing film overcoats? Rather than coat experimental films and finish them, it was decided to try to assess the abrasivity of it in slurry form (the way it is added to emulsions).

Slurries of 30% (by weight) tin oxide, a 32.5 mesh silica, and nanometer-sized silica were prepared for abrasivity comparison in the ASTM G 75 Miller Number type of test. A quarter-inch-diameter type 6061 aluminum hemispherical rider was used instead of the white iron rider, but the G 75 neoprene

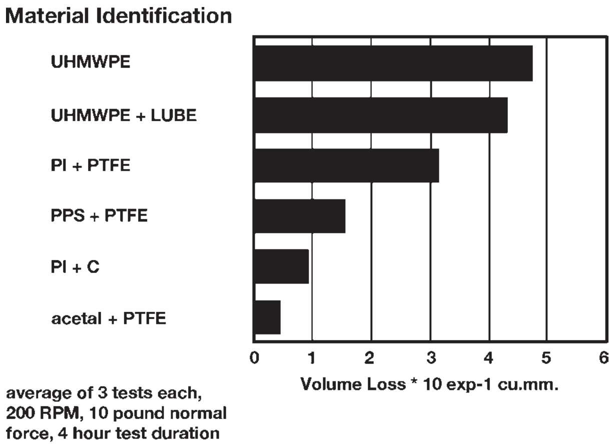

Fig. 13-8(a)—Average candidate volume loss versus 316 stainless steel (200 rpm, 10 lb, 4 hours).

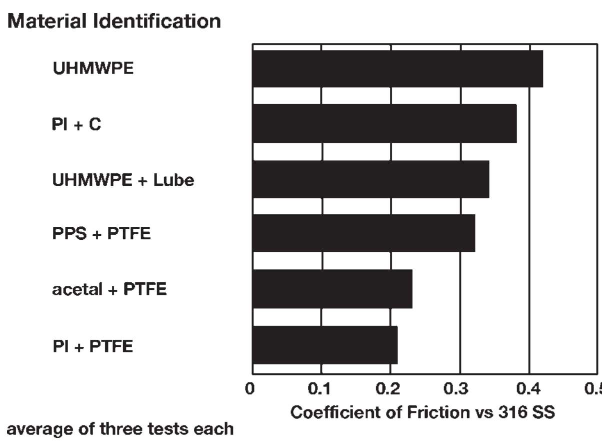

Fig. 13-8(b)—Average coefficient of friction for couples tested in (a).

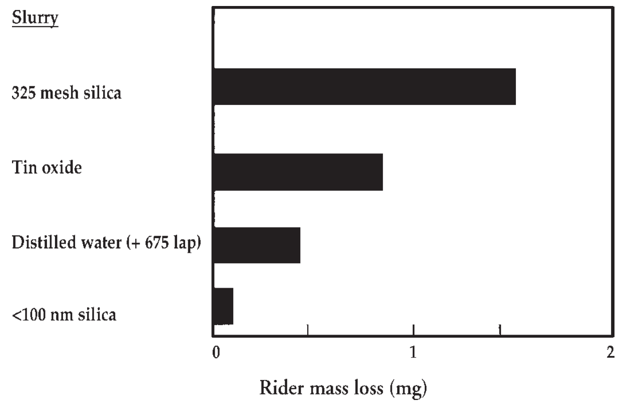

Fig. 13-9—Wear of aluminum rider rubbing on a neoprene lap in various slurries for 4 hours.

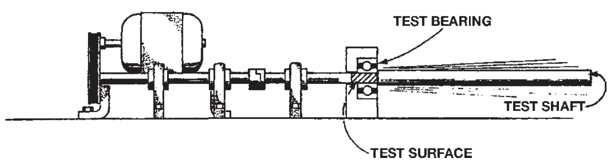

Fig. 13-10—Fretting test rig.

lap and stroke was used. The rider was reciprocated immersed in the different slurries for 4 hours with a one pound mass producing the normal force. The test specimen was reciprocated at 48 cycles per minute and the specimen was lifted at the end of each stroke to allow solution to fill in the "track." Mass change in the 4-hour test was the test metric. Three replicates were tested in each slurry, and several tests were conducted on the rubber lap immersed in water to determine if the rubber lap was wearing the rider in the absence of slurry particles.

The results (see Figure 13-9) show that the tin oxide was abrasive; the rider wore more in the tin oxide slurry than the rider wore on the rubber lap. The tin oxide was not as abrasive as the 325 mesh silica, but it may have been smaller in particle size. The tin oxide particle size was not supplied to the testing organization. The test also indicated that very fine silica (<100 nm) was not abrasive under these test conditions. In fact, it reduced rubber lap wear on the aluminum rider. It was known that the nanometer-sized silica particles could be tolerated (at a certain level) in film overcoats.

The overall conclusion of the tests was that, yes, tin oxide is abrasive. This conclusion was born out by additional tests in finishing tin oxide-coated film. The G 75-type slurry abrasivity test correlated with service life results.

Fretting Corrosion

A problem of copier machine vibration was traced to a loose fit between several half-inch-diameter roller shafts and their respective rolling element bearings. Further investigation identified fretting corrosion on the type 303 stainless-steel shaft as the root cause. The shafts were intentionally a "slip fit" in the bearings to allow for easy removal in the field. However, these "slip fits" allowed fretting motion between the shaft and inner raceway of the rolling element bearings supporting the shaft.

A project was initiated to identify a shaft treatment/material/processing that would prevent fretting corrosion yet still allow slip fitting the shafts in their bearings. The laboratory fretting corrosion test employed in the study is illustrated in Figure 13-10. Fretting motion was produced by elastic-deflection of the shaft as the unsupported end flexed. A rotational speed and shaft size was selected to produce about 30 μm relative motion between the bearing race and shaft. Various treatments were applied to the shaft and fretting damage was quantified after a 100-hour test. The test metric was the percent of the apparent area of contact covered with fretting damage after the test cycle (apparent area of contact = shaft circumference times bearing width).

Figure 13-11 shows the effect of using a rough surface on the shaft. The production shaft roughness was 0.25 μm, and this finish resulted in 96% fretting corrosion. Increasing shaft roughness had a palliative effect.

Figure 13-12 shows the effect of fixing the shaft to the bearing with anaerobic adhesive as well as different shaft surfaces. Hardfacing with a cobalt-based alloy was also effective. Electroplating was another obvious treatment to try. Figure 13-13 shows the effect using various electrodeposited

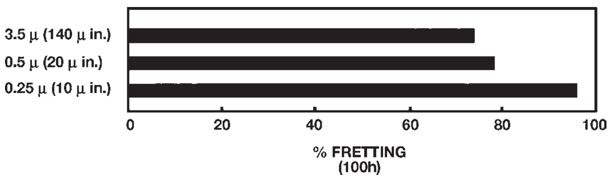

Fig. 13-11—Effect of surface roughness on fretting damage.

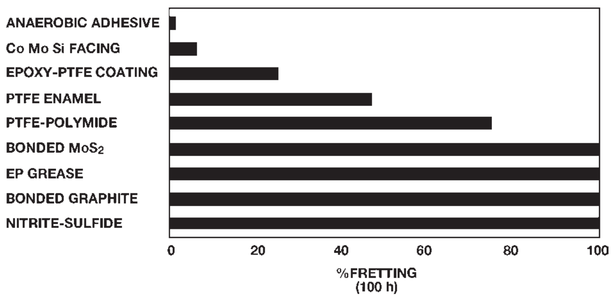

Fig. 13-12—Effectiveness of surface treatments on fretting damage.

metals on the shaft and ground to the normal production roughness and bearing clearance. Silver plating was the most effective treatment.

The anaerobic adhesive was the most cost-effective solution and this was adopted in service after additional testing to identify a grade that could be easily disbonded by impact or heat for field disassembly.

In summary, the laboratory tests correlated with service. The anaerobic adhesive worked. These tests also point out how a test that simulates an application usually produces results that correlate with an application. Another not-so-obvious point from this study is that a test rig had to be developed for the fretting problem. As of 2006, there was not a standard ASTM fretting wear or fretting corrosion test for general use. There are several ASTM standards dealing with fretting of biomedical devices, but these standards do not use a "standard" test. This is a concern that needs to be addressed by the "fretting community."

Polishing Wear

When particulate abrasives are smaller than about one micrometer, they tend to remove material by polishing; materials get smoother without scratching abrasion. Some polishing is done wet; some is done dry. As an example of a polishing wear test, a study was conducted to rank the abrasivity metal/haloid functional coatings on plastic films. Pilot rolls of four films were submitted for studies to rank their abrasivity to type 316 stainless steel, which is used in handling and conveying these films. Film formulators were developing a new product and they wanted to minimize abrasivity.

The polishing test used to rank the abrasivity of different photographic films is shown in Figure 13-14. The test films were supplied in 20-foot-long rolls, 6 inches wide. Six-inch-diameter disks were cut from each sample and they were bonded to the rotating horizontal platen of the tester. The test plan was to reciprocate a type 316 stainless steel ball on each film under prescribed conditions (0.25-inch-diameter ball, 1-kg normal load, 2.5-inch stroke, 1 Hertz, platen speed 0.8 rpm, 8-hour test time with a film change every hour, three replicates

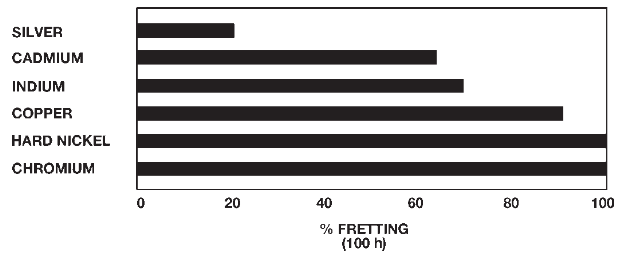

Fig. 13-13—Effectiveness of electrodeposited metals in reducing fretting corrosion.

per film). The rubbing produced polished flats on the stainless-steel balls, and the diameter of these flats was measured and wear volume was calculated from the ball scars.

The test results which are shown in Figure 13-15 indicate that some films are more abrasive than others, and this ranking was used to select a particle dispersion for the new film. As was the case with fretting, there is no ASTM standard polishing test. There are test machines commercially available that are used to rate or rank polishing consumables, but the work has not yet been done to standardize them. The test rig described in this case history was developed to assess the abrasivity of various magnetic media. The slow specimen platen rotation allows significant rubbing on fine particulate coatings without wearing through the coating. The ball rider does not always rub on an untouched surface, but rubbing is well distributed over the test area.

The wear mode is polishing and this test has been determined to correlate with service conditions. When it was used to assess magnetic media abrasivity, the rankings were identical to service results. This test correlates with dry polishing and it is easy to perform.

Solid Particle Erosion

A new coating was developed for aluminum that replaces the familiar electrochemical conversion coating: hardcoat. The new coating is thicker and much harder than the amorphous aluminum oxide that constitutes hardcoat. However, it was not known if this thicker, harder coating had tribological properties that are superior to hardcoat.

An obvious place to use an improved hardcoat is on aircraft that are subject to solid particle erosion. Helicopter

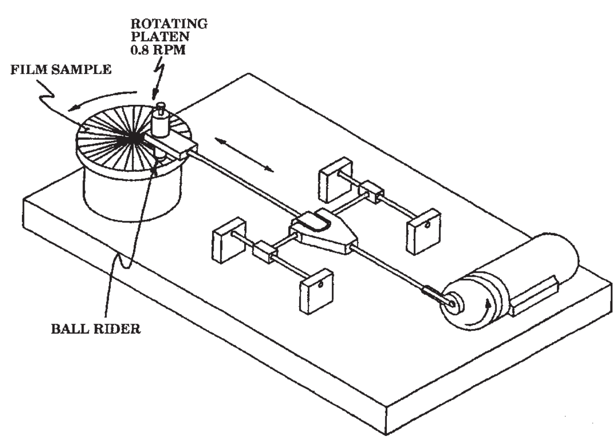

Fig. 13-14—Schematic of "abrasivity" tester.

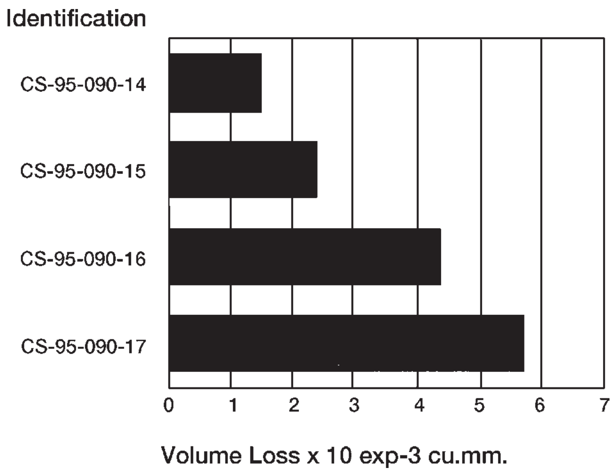

Fig. 13-15—Average volume loss of 316 stainless-steel rider versus CS-95-090-14, 15, 16, and 17.

rotors and other aircraft parts used in desert conditions are frequently subjected to erosion from sand and dirt particles. Therefore, one tribological test that was felt necessary for this coating is solid particle erosion. It was decided to compare the new plasma-generated electrochemical conversion coating (CIC) with chromium electroplate, anodized and hardcoat on aluminum, thermal spray WC/Co, and a hardened tool steel.

ASTM G 76 was selected as an appropriate test to rank these surfaces for their resistance to erosion from impacting hard particles. The test uses a small-diameter sandblast nozzle with a standoff distance of 10 mm, an aluminum oxide abrasive (50 μm), a mass flow of 2 g/min, and a 10-min erosion time. Mass loss is the test metric. When the standard G 76 test procedure was used, some of the coatings penetrated in the 10-min test time. Some did not. The test was modified to stop the test (with a shutter) when the coating is penetrated and the wear volume was measured by profilometry of the wear crater. The test results, which are shown in Figure 13-16, indicated that the new coating (CIC) had much better particle erosion resistance than conventional hardcoat.

In summary, this test is extremely useful for simulating the erosive effects of airborne particulate. We did not do a correlation study in this instance, but this test had been shown to have excellent correlation with sand blast targets. It is common practice to measure mass flow in abrasive blasting experiments with a device that slips on a blast nozzle when it

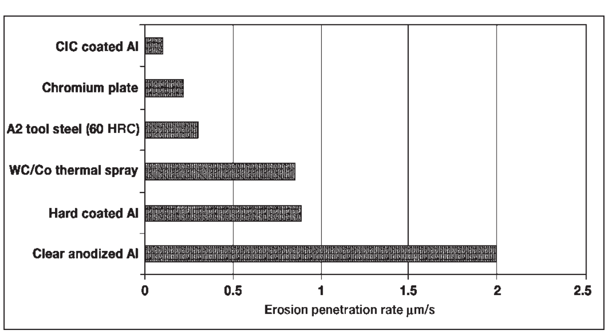

Fig. 13-16—ASTM G 76 jet erosion tests on various coatings.

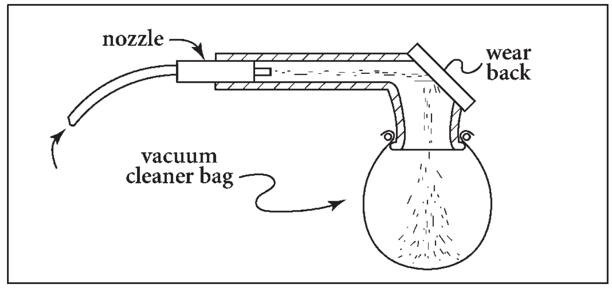

Fig. 13-17—Device for measuring mass flow of abrasive in abrasive blasting erosion studies.

is at a steady-state blasting status (Figure 13-17). Many materials were tested as wear backs and the results correlated perfectly with the ASTM G 76 bench test. It is our recommended test for simulating gas-borne particle erosion.

Lubricated Wear Testing

A problem with unsatisfactory service life of a staking device prompted a lubricated wear study using a reciprocating pin-on-flat test. The stakers in question are actuated by a ball forced against angled ramps on fingers. The ball pushed the fingers outward to stake a metal cap on a metal can. These devices were frequently greased, but still wore to the point of replacement in only about one month's use. The decision was made to screen candidate lubricants and identify one that was significantly better (less metal wear) than the present. The ball in the stakers was made from 52100 steel at 60 HRC; the staker fingers were made from cast D2 tool steel at 60 HRC.

These materials were used in the ASTM G 133 ball-on-plane reciprocating test with the loads and stroke modified to simulate the application (5/16 inch-diameter ball, 4-mm stroke, normal force 20 N, sliding speed 3.8 cm/s, duration 3 hours). The test metric was wear loss on each member. The test results, which are shown in Figure 13-18, identified two greases that performed superior to the control grease.

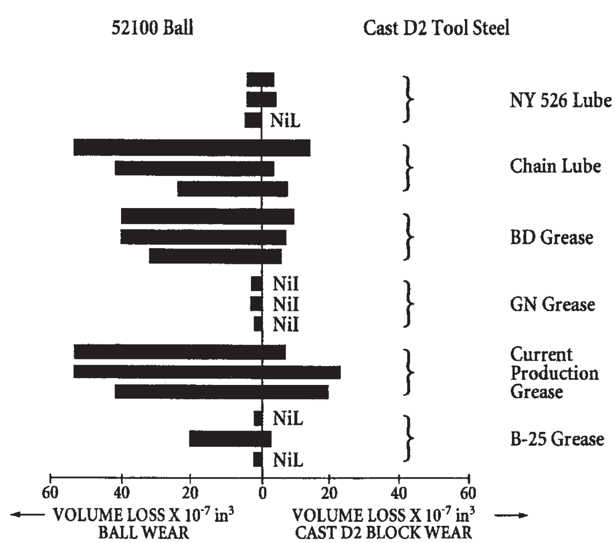

Fig. 13-18—Reciprocating wear test results on various greases.

In summary, the GN paste was selected as the winner of the screening tests. It was put in several production stakers and in all cases, life was improved to over the course of 6 months. In fact, these stakers ceased to be a maintenance problem and staker life typically was a year. The lab test results correlated with the application. Service conditions (stroke, material pair, loads, etc.) were used in the bench test and this sort of simulation usually produces correlatable results. The ASTM G 133 test is very adaptable to a wide variety of reciprocating service conditions.

Erosion/Corrosion

A service life problem with erosion of casing and impeller "wear rings" in large water pumps prompted a study on material couples for improved service life. The pumps have wear rings on both sides of the impeller and case to resist axial thrust during pumping. The problem material couples were 316 stainless-steel versus bronze and bronze self-mated.

This tribosystem was simulated in the lab with an ASTM G 77 block-on-ring test with the specimens immersed in water. Most block-on-ring test machines have the capability of running a test couple immersed in a fluid. The only limitation is the corrosivity of the fluid and its reactivity with the seals on the spindle holding the test ring. Seven material couples were compared in this study. The test conditions were 10-lb loading mass, 600 rpm, 72,000 cycles. The volume loss on both members was the test metric. The test results, which are shown in Figure 13-19, indicate that a chromium oxide thermal spray coating applied to one of the wear rings would significantly reduce system wear. This was implemented and the service life ceased to be a concern. The laboratory test correlated with service life.

Chapter Summary

This chapter has presented some suggestions on how to achieve a bench test that correlates with service and then some case histories of tests that produced practical results that solved problems, that is, that correlated with production. This chapter and this book close with some general comments. In every tribosystem, there is probably a "most important concern." It is of course, an opinion, but this guide is mostly opinion based upon 40+ years of laboratory wear and friction testing. Table 13-2 presents some "important" concerns with each type of wear and friction that was mentioned.

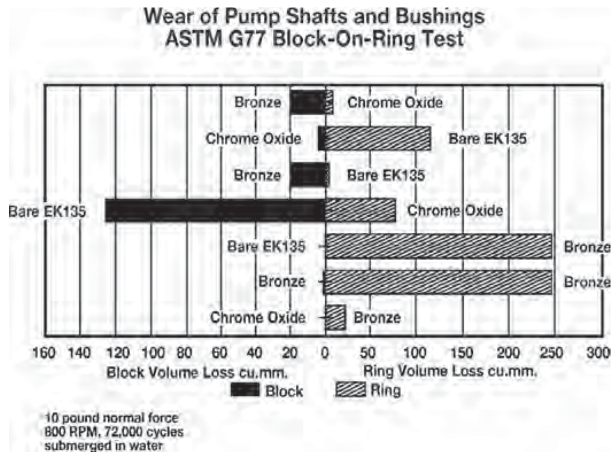

Fig. 13-19—System wear for various wear ring couples in water.

Important Concepts

The following concepts should be taken from this chapter:

1. Tests must simulate real-life conditions if they are to produce useful data.
2. Statistics must be used in testing for differences.
3. Meaningful laboratory tests duplicate materials and treatments that simulate service.
4. The worn surfaces from a valid wear test look like the wear surfaces from service.

In conclusion, laboratory testing can be the best way to solve a wear or friction problem if the person performing the test is vigilant in making the bench test simulate an application. It must be the same type of motion, the same environment, the same material couple, and test methods that have been shown to correlate with service. Sometimes it is necessary to use other property tests to support friction and wear tests. A coating may be identified that is very abrasion resistant, but with terrible bond strength. Impact tests added to the wear tests would have identified this weakness. Think about the operating environment and ask: Do these studies include all of the factors that are likely to be limiting factors in the intended service environment? If there is confidence that this has been done in the lab, there is likelihood that the results will correlate with service. Problems can be solved in the lab and

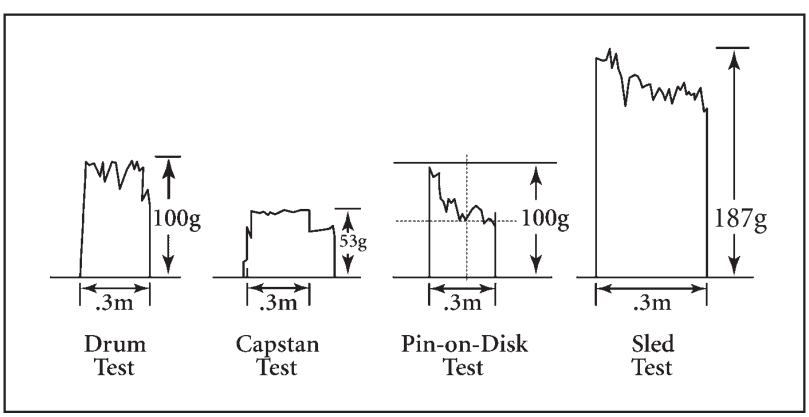

Fig. 13-20—Variations of friction force for the same sliding couple on four different test rigs; μ varied from 0.2 to 0.4.

TABLE 13-2—Important concerns in various types of tribotesting.

Subject	Most Important Testing Concern
Friction	Friction is a system effect and the friction coefficient of a given couple may be different in every test rig (Figure 13-20). Thus, one cannot say that a material has low friction (or high); only a tribosystem can yield a friction coefficient.
Abrasion	There are various types of abrasion (low stress, gouging, high stress, 2-body, 3-body, polishing) and you must simulate a specific type to perform a valid test.
Erosion (solid particle)	Particle velocity is very important and difficult to measure; however, it must be done.
Erosion (droplet)	Evaluating damage to plastics and composite can be challenging; they may shred.
Erosion (cavitation)	You must decide whether the stationary ultrasonic-horn or water-jet test best simulates your tribosystem.
Erosion/corrosion	Duplicating velocity and measuring surface damage can be challenging.
Lubricated wear	Sometimes test loads produce stress (Hertzian or other) that exceeds the compressive strength of one of the members. Tests that do this may be meaningless.
Nonabrasive wear	If the test couple squeals and vibrates during the test, the test conditions are probably unrealistic. Real tribosystems do not produce 130-dB noise levels.
Rolling	Decide if you have true rolling or a combination of rolling/sliding and then simulate the service situation.
Fretting tests	You must decide on an amplitude that simulates an application of interest. Results vary significantly with amplitude.
Slurry abrasion	One must always question if there is a uniform flow of particles between the specimens and the corrosive effect of the liquid. How much material removal is from abrasive scratching and how much is from dissolution of the active metal surface.
Galling	One must decide when galling starts. Excrescences are the normal criterion.
Scoring	One must decide if and when this occurs. It is not a well-defined wear metric.
Impact wear	Fretting damage is often a part of impact wear. One must decide if fretting contributes a significant component.
Surface fatigue (rolling)	This is difficult to simulate in bench tests. It may take a long time to initiate.
Lubricant screening	Short-term tests neglect degradation due to aging and environmental changes.

disastrous consequences can be prevented that can occur when tribological behavior is neglected or not correctly tested.

This guide is the tribology advice based upon a lifetime of work in the field and testing pitfalls were shared so that they are not repeated by others. This guide presents the tests that have shown to "work" and suggestions were made on how to select the appropriate ones for an application. Good luck in tribology, and always keep the intended application in mind when testing.

Resources for More Information

Examples of Wear Failures

Neale, M. J., Ed., *Tribology Handbook*, U.K., Newnes-Butterworth, 1973.
Summers-Smith, J. D., *A Tribology Casebook*, New York, Wiley, 1996.

A Comprehensive Guide to Different Types of Wear

Peterson, M. G. and Winer, W. G., Eds, *Wear Control Handbook*, New York, American Society of Mechanical Engineers, 1980.

Materials for Wear Applications

Glaeser, W. A., *Materials for Tribology*, Amsterdam, Elsevier, 1992.
Budinski, K. G., *Surface Engineering for Wear Resistance*, Upper Saddle River, NJ, Prentice Hall, 1979.
Budinski, K. G. and Budinski, M. K., *Engineering Materials Properties and Selection*, 2nd Ed., Reston, VA, Reston Publishing Co., 1983.

Early Work in Wear Testing

Evaluation of Wear Testing, STP 446, ASTM International, W. Conshohocken, PA, 1969.

Subject Index

NOTE: Entries followed by *f* indicate figures; *t* indicates tables.

KEN BUDINSKI is the technical director of Bud Labs, a ten-year old company that designs and builds friction and wear testers and conducts tribological (friction, wear, erosion, and lubrication) studies for clients. He is Chairman of the ASTM Subcommittee G02.50 on Friction and he previously served as Chair of the G02 Committee on Wear and Erosion. He is a member of the ASTM Committee B08 on Metallic and Inorganic Coatings and a member of the steering committee for the Biannual International Wear of Materials Conference. His duties at Bud labs include test and machine design, and analysis/interpretation of client test results.

Mr. Budinski has a BS in Mechanical Engineering from General Motors Institute (1961) and an MS in Metallurgical Engineering from Michigan Technological University (1963). He worked at Rochester Products Division of GM from 1957 to 1962, starting as a cooperative engineering student and ending as a manufacturing development engineer specializing in die casting. Upon completing graduate studies at Michigan Tech he joined the Materials Engineering Laboratory of the Kodak Park Division of Eastman Kodak Company as a metallurgist. Wear problems at this plant started his interest in wear testing and wear research. This plant made photographic films and the sensitive nature of the products meant that production machines had to run at high speed with no lubricants that could contaminate the film. The films sliding on themselves and other surfaces also required many tribological advances to control friction and prevent scratching. The net result of Kodak's unusual wear and friction requirements led Mr. Budinski to learn as much as possible about tribology and he established one of the most comprehensive tribology labs in the US. His tribology studies were key to many products and to many manufacturing operations. He retired from Kodak in 2002 as Technical Associate and immediately joined Bud Labs as Technical Director.

He became a member of ASTM (G02) in 1972 and participated in most of the interlaboratory studies for developing the G02 Wear and Friction test methods. He has lectured on wear and friction in countless courses. He taught Engineering Materials at Rochester Institute of Technology and Monroe Community College. He participated in a National Science Foundation technology transfer mission to China in 1983 and another to Belarus and Poland in 1996. He shared his materials engineering experience by authoring and coauthoring eight editions of a textbook titled *Engineering Materials: Properties and Selection* (Prentice Hall). He authored the very first book on Surface Engineering (*Surface Engineering for Wear Resistance,* Prentice Hall); he also authored teaching texts on technical writing (*Engineer's Guide to Technical Writing,* ASM) and technical presentations (*Guide to Preparing and Delivering Technical Presentations,* ASTM International). He has presented more than 100 papers at technical conferences and has authored more than 50 papers in refereed journals.

Mr. Budinski is a Fellow in ASTM International, ASM International, and the Rochester Engineering Society. He has won many awards for his technical achievements including "Rochester Engineer of the Year" (2000). His most significant contribution to engineering and science has been sharing his research and learning in tribology and engineering materials. This book is a continuation of this sharing.

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