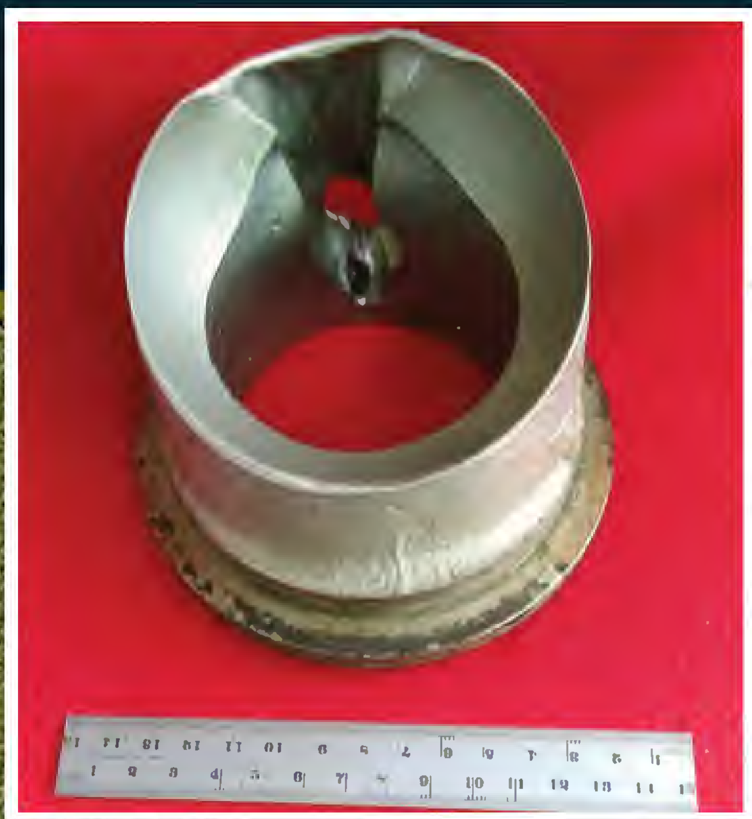
TRIBOMATERIALS

PROPERTIES AND SELECTION FOR FRICTION, WEAR, AND EROSION APPLICATIONS



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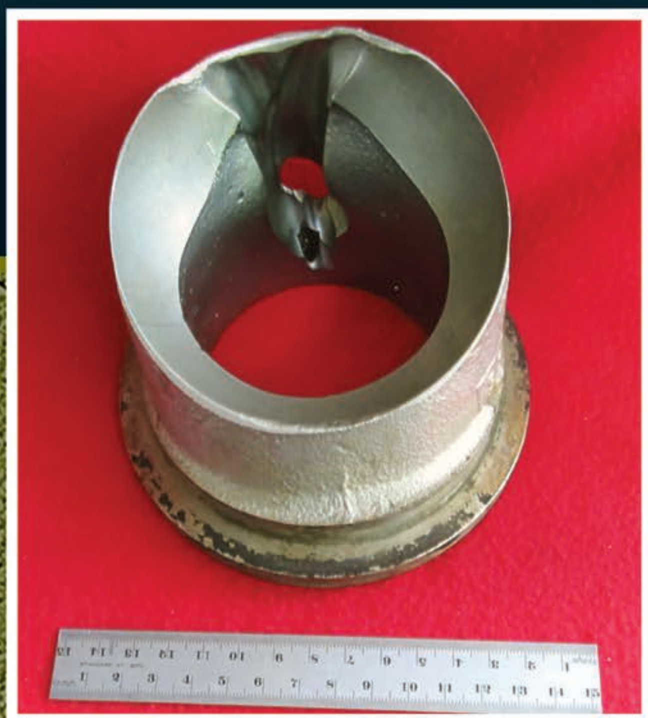

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Cover image: Slurry erosion of a stainless steel ball valve seat that did not adequately conform to the polyurethane-coated lead ball

For JMJ

Contents

Selected Plastic/Elastomer Acronyms

Acronym	Plastic/elastomer	Acronym	Plastic/elastomer	Acronym	Plastic/elastomer
ABS	Acrylonitrile butadiene styrene	PAE	Polyarylether	PPA	Polyphthalamide
CA	Cellulose acetate	PAEK	Polyaryletherketone	PPO	Polyphenylene oxide
CFRP	Carbon-fiber-reinforced plastic	PAI	Polyamideimide	PPS	Polyphenylene sulfide
CPVC	Chlorinated polyvinyl chloride	PAN	Polyacrylonitrile	PS	Polystyrene
CR	Polychloroprene rubber (neoprene)	PB	Polybutylene	PSU	Polysulfone
CTA	Cellulose triacetate	PBI	Polybenzimidazole	PTFE	Polytetrafluoroethylene (Teflon)
CTFE	Chlorofluoroethylene	PBT	Polybutylene phthalate	PUR	Polyurethane rubber
DAP	Diallyl phthlate	PC	Polycarbonate	PVAL	Polyvinyl alcohol
ECTFE	Polyethylene-chlorotrifluoroethylene	PDMS	Polydimethylsiloxane (silicone)	PVC	Polyvinyl chloride
EP	Epoxy	PE	Polyethylene	PVDC	Polyvinylidene chloride
EPDM	Ethylene-propylene-diene terpolymer (rubber)	PEEK	Polyether ether ketone	PVDF	Polyvinylidene fluoride
ETFE	Copolymer of ethylene and tetrafluoroethylene	PEI	Polyetherimide	SAN	Styrene acrylonitrile
EVA	Ethyl vinyl acetate	PES	Polyether sulfone	SBR	Styrene-butadiene rubber
FEP	Tetrafluoroethylene/hexafluoropropylene	PET	Polyethylene terephthalate	SI	Silicone
HDPE	High-density polyethylene	PEX	Cross-linked polyethylene	TPE	Thermoplastic elastomers
IIR	Isobutylene-isoprene rubber (butyl)	PF	Polyphenol formaldehyde	TPU	Thermoplastic urethanes
LDPE	Low-density polyethylene	PFA	Perfluoroalkoxy	UF	Urea formaldehyde
MF	Melamine formaldehyde	PI	Polyimide	UHMWPE	Ultra-high-molecular-weight polyethylene
NBR	Acrylonitrile-butadiene rubber	PMMA	Polymethylmethacrylate (acrylics)	UP	Unsaturated polyester
NR	Natural rubber	POM	Polyoxymethylene (acetals)		
PA	Polyamide (nylon)	PP	Polypropylene		

Preface

This book is about the selection of materials for applications in which interactions between rubbing surfaces or substances are a design concern. It is about the friction response of various materials under conditions that are likely in service, the wear and erosion of materials, and the testing to address friction wear and erosion (tribology) concerns. Its purpose is to review what is known about the tribology of important material systems and to show how to select appropriate materials from each family of engineering materials. The objective of the book is to learn how to design materials so that they do not fail because of tribological issues.

The terms *friction*, *wear*, *erosion*, and *lubrication* were merged into one term, *tribology*, in the 1960s when the Institution of Mechanical Engineers in the United Kingdom commissioned the Encyclopedia Britannica to create a word to describe the science of interacting surfaces. In this book, the prefix *tribo* is used. *Tribology* is a good word because any time surfaces rub, there are many possible interactions. Tribology includes the friction aspects, the lubrication aspects, and the damage aspects.

Countless studies have shown that the annual cost of friction and wear in developed countries ranges between 5 and 15% of the gross domestic product. Failures caused by using the wrong material are one aspect of the annual cost of friction and wear; short service life is another example (five years is often the life of an automobile), and energy losses due to friction are a huge contributor to global warming and to the annual cost of wear. Only one-third of the horsepower of an automobile engine is used in moving the vehicle on its intended path. The right material for a tribological application is important. Tribomaterials are important.

This book is written in traditional textbook style for use as a teaching text, but it can also serve as a reference for anyone who finds a friction, wear, or erosion concern to be a limiting factor in a design or in the operation of an existing machine or operation. The text in this book contains tribotesting data and tribology research that are the product of decades of work in the field by the authors, with the past 20 years in one of the United States' best-equipped tribotesting laboratories.

A proper tribotest does not lie.

This book contains many italicized statements similar to the preceding text. The reader should take note of these because they are intended as important points.

Laboratory tests that correlate with service and the results from these tests are presented in each chapter as selection aids.

Most of the test results used to compare the response of different materials to tribotests are historical data from papers presented by the authors at various conferences over the past 40 years or so. Some wear and friction studies were conducted at Bud Labs specifically for this book.

The book is organized with chapters on each of the important families of engineering materials that have utility in addressing tribology problems, such as copper alloys, cast irons, stainless steels, plastics, elastomers, ceramics, cermets, and coatings. A chapter is included on biotribology because it is an emerging part of engineering. There are many materials selection issues in biotribology because of corrosion and patient-reaction issues.

This book contains chapters on the types and mechanisms of friction, wear, and erosion, as well as a chapter on tribotesting. The latter illustrates how laboratory testing can supply needed selection information. The book concludes with a chapter on the tribology of lubricants and another on the materials selection process. The lubrication chapter is intended to introduce the subject to readers who are lubricant users rather than lubricant formulators. The last chapter presents methodology to quantify candidate properties by using a selection matrix.

Each chapter contains a chapter summary with a glossary, takeaway concepts, questions for discussion, references, and selected references.

The engineering units used are generally SI and English, in keeping with the style of *Friction, Lubrication, and Wear Technology*, Volume 18 of *ASM Handbook*, 2017. However, many of the historical graphs and tables are presented in the units used in the original studies; this was done to prevent possible conversion errors. In addition, small dimensions are given only in nanometers, micrometers, or millimeters, and small forces are in Newtons. This is because the authors feel these units are the most appropriate.

Tribology is a unique field. The interactions between rubbing surfaces can be very complicated and unpredictable. However, laboratory testing and industrial experiences have shown that most engineering materials have niches in which they perform well. This book is an attempt to share this accumulated knowledge and, in doing so, to help readers produce designs without tribological issues.

Kenneth G. Budinski
Steven T. Budinski

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This book would not have happened without incredible help from others. Ann Marie and Lynne Buonomani were the facilitators. They took care of logistics, computer-related issues, cover art and translation of unreadable script into typed manuscript. Content reviews were done by Steve Shaffer from Bruker Corp., by Michael Budinski from the National Transportation Safety Board (NTSB), and from Mark Kohler from Arnprior Corp. Mark also conducted most of the tribotests reported in this book over the past three decades or so. His contributions were beyond significant.

We also acknowledge the work of Steve Lampman, Amy Nolan, Dave Vargas, Madrid Tramble and the ASM Staff for their efforts in publication.

About the Authors

Kenneth G. Budinski graduated from General Motors Institute in Flint, Michigan, with a degree in mechanical engineering. After five years at the Rochester Products Division of General Motors, he attended graduate school at Michigan Technological University in Houghton, Michigan, and graduated with an M.S. in metallurgical engineering. He started his professional career as a development engineer in the Materials Engineering Laboratory of the Eastman Kodak Company in Rochester, New York. After 38 years of tribology research and testing at Kodak, he joined Bud Labs in 2002 as Technical Director and remains in that position in 2020.

During Ken's 38-year tenure at Kodak, he specialized in tribology problems. Kodak had many unique problems in this area because of photoactivity concerns; lubricants could not be used in many pieces of production equipment and in many manufacturing areas. Ken developed countless materials solutions for sanitary and unlubricated sliding systems. His laboratory became the corporate resource for tribology problems and tribotesting. He authored more than 50 papers in refereed journals and presented more than 100 papers at conferences worldwide.

Ken is a Fellow of ASTM International, ASM International, Rochester Engineering Society, and is currently Chair of the ASTM International G02.5 Subcommittee on Friction. He has won many awards for his technical contributions and is the author of the materials textbook *Engineering Materials: Properties and Selection* (Pearson Education), which is now in its ninth edition. He has authored four other technical books.

Steven T. Budinski graduated with a Bachelor's degree in mechanical engineering from the University of Dayton, Dayton, Ohio. He has worked as an engineer at C. J. Winter Machine Works, Rochester Steel Treating Works, and Eastman Kodak Company. He started Bud Labs in 1998 and is currently the Operations Manager, with responsibility for tribotesting, test machine development, specimen machining, fabrication shop, scheduling, and sales. Bud Labs performs proprietary research projects but also maintains continuing research programs in tribotesting and in the mechanisms of material damage from various forms of wear and erosion.

CHAPTER 1

Tribology, Tribosystems, and Related Terminology

1.1 Wear of Materials

The inspiration for this book is from the biennial International Wear of Materials Conference (WOM) that originated in 1977. This conference is run by an international steering committee of wear researchers, and the focus of the conference is on the engineering materials aspects of wear such as:

- What is rubbing on what?
- What are the relative wear volumes?
- What is the mechanism of material removal as opposed to papers on the lubricants?
- What treatments and coatings are used to prevent wear?

Everybody understands what wear is because it is something that everyone deals with. Our tires, vehicle engines, work gloves—most things that see frequent use and wear. *Wear* in these instances means *loss of function or diminished function* because material has been removed by rubbing. The layperson's definition of wear may be *the progressive removal or alteration of material from a solid surface caused by rubbing contact*. There are many other versions of a wear definition, but this one suffices. In some countries, the word *irreversible* is used to modify the term *removal*, but it is probably best left out because there are many researchers working on self-healing materials. If one of these concepts works, then wear may become reversible; also, in biotribology, such things as skin abrasions heal—the skin removal is reversible. Wear definitions sometimes include *surface alteration*.

The subjects covered in the WOM conferences and in this book are predominately the materials that are used to make the tools and things that we use in our daily lives.

Engineering materials (n): the materials that are used to make durable goods, machines, tools, structures, and devices.

Essentially, this book is about the metals, ceramics, plastics, and composites that are used to make just about everything. This book will define and describe many forms of wear and many processes that are commingled with wear.

Wear has been studied since prehistoric times. Early humans learned that foot coverings made from saber-tooth tiger skin lasted longer than those made from the hide of a tyrannosaurus rex. These same people learned that it is better to grind grain on a granite rock than on a sandstone rock; they learned that flint rocks were harder than other rocks and could be used as tools. However, in the 1940s to 1960s, wear as an accepted field for university study received needed publicity from the early work of two researchers from Cambridge University in the United Kingdom, David Tabor and William Bowden. They wrote some classic books about wear and friction, and that increased the number of universities around the world with a research effort in wear and related subjects.

When the Wear of Materials conferences started in 1977, the *wear community* was sort of divided into two interest groups—namely the "lubricant people" and the "materials people." The lubricant community primarily consisted of chemists (oil, grease, and additive formulators), chemical engineers (they made the oil and grease), petroleum engineers (they found the oil), physicists (they modeled the lubricants), and the mechanical engineers who dealt with bearings, gears and mechanism design, and the fluid mechanics of lubrication. The engineering material community consisted of metallurgists, materials engineers, ceramics engineers, polymer engineers, and mechanical engineers who delved into the stress and strains involved in rubbing contacts. In fact, for the first 40 years of the Wear of Materials conferences, papers on lubricants and lubrication were banned by the conference organizers. The technical societies for the lubricants community in the United States were the American Society of Lubrication Engineers (ASLE) and the American Society of Mechanical Engineers.

The materials aspects of wear (materials durability) were somewhat separated from the lubricant aspects of wear—preventing solid versus solid contact with lubricant films.

By 2019, the separation between the materials and lubricant communities was reduced. The WOM conferences have held steady in size and they started to allow some lubrication/lubricant papers.

The ASLE is now the Society of Tribologists and Lubrication Engineers (STLE). Their annual conferences are now about five times the size of the WOM conferences, drawing delegates from more than 40 countries. They accept papers and cover subjects on all aspects of friction, wear, lubrication, and erosion. The separation between the lubricant communities and the materials community no longer exists. However, this book is mostly about materials, but there are chapters on tribotesting and lubricants.

1.2 Tribology

A probable reason for the present unity between the *lubricant people* and the *materials people* is the establishment in the United Kingdom in the 1960s of a word to unite all the different people working on things that rub. They came up with the word *tribology* from the Greek word *tribos*, which means "I rub."

There are various definitions for the word *tribology*, but the one offered by the Encyclopedia of Tribology Terms (Ref 1) is: *(n) tribology is the art and science of interacting surfaces and related technologies.*

This word was needed because of the economic significance of the degradation of engineering materials that can be attributed to wear, or more correctly, tribological losses. All things on planet Earth that eventually fail to perform their intended function do so by one of three failure mechanisms:

1. Things can wear out.
2. Things can break (fracture).
3. Things can dissolve (corrosion).

Personal experiences in everyday life can attest to the cost of these three modes of failure. The highest monthly costs for average families in the United States are for housing, food, and vehicles (usually). Driving a new car in the United States costs about $5,000/year; the average cost of a new car is about $35,000 in 2019. People usually buy new cars because some major system on their car failed and needed to be replaced. These failures are often caused by wear.

The government of the United Kingdom commissioned a study to further spotlight and estimate the annual cost of wear in their country. The culmination of the study was the Jost Report in 1966 (Ref 2), authored by Dr. Peter Jost. His report presented the details of the annual costs, and overall, the report suggested that from five to ten percent of a country's gross national product (GNP) was the annual price of wear. The report also used the word *tribology* to describe the friction, wear, erosion, and lubricant study. This type of study has been repeated in many countries, and that is why all industrialized countries on the planet have significant technical efforts in the field of tribology. The United Kingdom may have been the first to establish tribology graduate (Ph.D.) programs at universities. In 1966, the United States achieved its first documented tribologist. This was the first time that a Ph.D. graduate in the United States called himself or herself a "Tribologist."

The STLE name change was made in 1972, and around 1990 (with the involvement of Peter Jost), World Tribology Conferences were initiated. These worldwide tribology events are conducted about every five years, in different countries—the last was in Beijing, 2017. China has readily espoused the field of tribology with many technical societies, a journal on *friction*, and many universities with Ph.D. programs in tribology. Tsinghua University had more than 100 Ph.D. students at the time of the last World Tribology Conference. Thus, the word *tribology* has united the many facets of friction wear, erosion, and lubrication—and it is a good word because it is so inclusive. It is the reason this book is entitled *Tribomaterials* instead of *Wear of Materials* (plus, *Wear of Materials* is copyrighted by WOM, Inc.).

1.3 Tribomaterials

The *tribo* part of the word *tribology* has become a prefix for many aspects of tribology:

- Tribologists—People who earn their living by working in friction, wear, erosion, and lubrication
- Tribotesters—Equipment used to study friction, wear, erosion, and lubrication
- Tribocouple—Two members in a tribotest

There is not an official definition of *tribomaterials* in most lists of terms and definitions (ASTM G40, ASTM D4175, and OECD), but in simple terms, it means any of the materials that are used in tribology. This book's definition of *tribomaterials* (n) is *the solids and other substances that are used to address friction, wear, erosion, and lubrication issues.*

Needless to say, this book cannot cover all of the materials that are used for all the aspects of tribology. This book mostly deals with the materials that are used in industry in making durable goods. There is a chapter in this book on biotribolgy, but this book deals with the device aspects as opposed to the anatomical issues. For example, implants and the like are really durable goods; they are usually solids and made in factories like other durable goods. This book also has a chapter on lubrication that deals with lubrication fundamentals and the materials that go into the most widely used lubricants.

The overarching objective of this book is for readers to develop a repertoire of materials that can help in common design situations where friction, wear, erosion, or lubrication are limiting factors.

The book has chapters on the most widely used *tribomaterials*. For example, there is a chapter on copper alloys. Every machine designer knows very well that powder metal (P/M) bronze bushings are almost always a first choice for designs that require the rotation of a shaft in a bushing. They are cheap, very available, and they work very well in most simple bushings versus shaft applications. Most fractional horsepower motors come equipped with these types of plain bearings. Cast irons have been used from the start for internal combustion engines because they work successfully in this application. Austenitic stainless steel is avoided for many wear applications because they are notorious for wear problems when they are self-mated. These kinds of situations exist for all the major types of engineering materials.

This book discusses the pros and cons of the candidates in each material category and makes recommendations for a repertoire of materials from each material group. These suggestions for consideration are based upon many years of laboratory testing of various candidates from each materials group. Modeling and artificial intelligence in tribology are not currently at the point where designers can ask a computer search engine to pick a material for a wear application, as will be pointed out in the book. Testing is often the best way to find the right material for a particular application.

Tribosystems

Tribomaterials are used in tribosystems, yet another new word is minted. *Tribosystems* (n) definition is *an entity that involves interacting surfaces in relative motion.*

This is a useful term in tribology since it points out that tribological processes like friction wear, erosion, and lubrication are system effects. A tire is not a tribosystem, but it becomes part of a tribosystem when it is rolling on pavement.

- The tire and pavement constitute a tribosystem.
- A bushing and a shaft is a tribosystem.
- A large machine, like an automobile, is a combination of many tribosystems.
- A piston in a cylinder is a tribosystem.
- The window lift is a tribosystem.
- The windshield wipers and the motors and arms that actuate them is a tribosystem.

Tribology problems are addressed one tribosystem at a time. For example, the internal combustion engine contains many rubbing (and some rolling) parts. Engines are studied on dynamometers for final outcome, but an engine consists of many tribosystems and each one must be designed and evaluated separately. There are accepted tests for the piston ring versus cylinder wall tribosystems; there are tests to evaluate connecting rod bearings versus crankshafts; there are tests to evaluate material couples for camshafts and followers. The point is that tribological processes involve members, and they are studied in that manner. The only test that is meaningful in evaluating piston ring wear is to rub candidate piston ring materials against candidate cylinder wall materials—this is how wear problems are addressed.

Erosion differs from wear in that it involves the mechanical action of a fluid.

> ***Erosion, in tribology: progressive loss of material from a solid surface due to mechanical interaction between that surface and a fluid (Fig. 1.1).***

The key concept is that a fluid is producing the mechanical action that produces the progressive loss of the material. There are various forms of erosion, and this book will go into details on each, but undoubtedly the

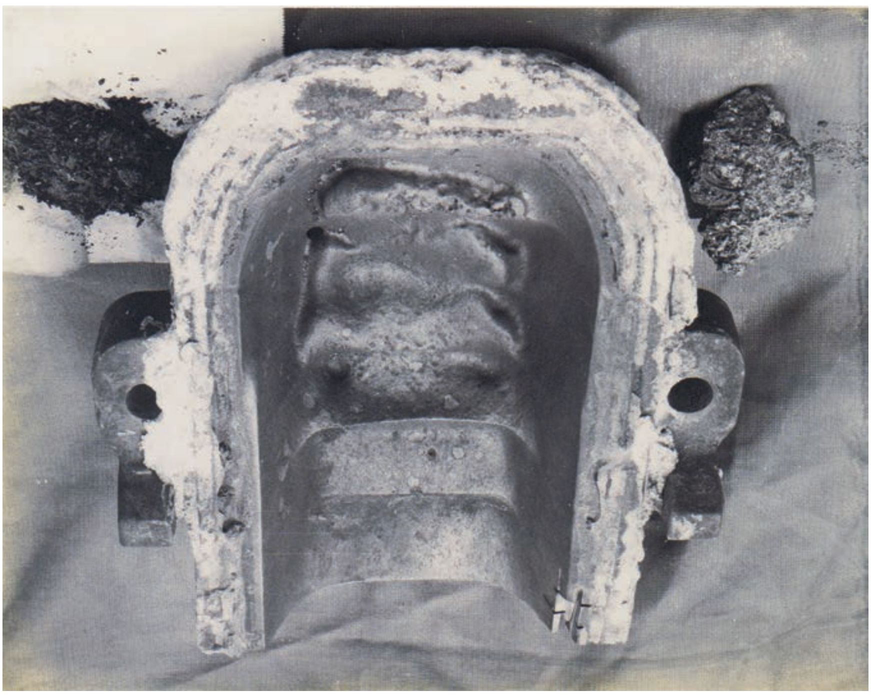

Fig. 1.1 Solid particle erosion of a pipeline wear-back (replacable impingement target at elbows) by boiler flyash

most costly form of erosion is liquid erosion of coast and shorelines. Each year hurricanes and cyclones erode strike areas, often forever changing the shape of shorelines. Islands can be created where there were none before or islands can be totally eroded out of existence. The building and structure damage from associated high winds are typically in billions of dollars in costs, but the erosion damage to shorelines often cannot be repaired—coastline losses can be priceless.

This book will not discuss the tribomaterials that can be used to address this type of erosion, but there are technologies that exist to deal with erosion produced by natural phenomena. Gabions (steel cages filled with football-sized rock) called surge, work well for riverbank erosion. Water dams (large reinforced rubber bladders from two to several meters in diameter—and sometimes hundreds of meters long, filled with water) help break waves threatening coastal structures. There are technical entities that study and deal with these types of erosion, like the ASTM International Committee D18 on Soil and Rock. They have standards dealing with erosion control materials like armor stone, the durability of rocks, and the use of all sorts of erosion control devices.

This book will address, for example, liquid erosion in plastics and metal piping; solid particle erosion as would occur in fans carrying particle-laden air; rain season is dealt with as is the type of erosion that can be produced when cavitation fields occur in liquids. However, shoreline erosion is part of the annual cost of wear that is a burden to every economy on the planet Earth.

1.4 Terminology

The *tribo* prefix from tribology had been applied to many subsets in the field of tribology, and many *triboterms* are used in this book. It may seem a bit overused, but health industry people do the same with their *bio* prefix.

There are probably more triboterms than are needed, but the use of the inclusive aspect of the term tribology is important; an engineering material cannot wear out by itself—it must be acted on by a force of some nature. If it is another solid or substance, then a tribosystem is established. The whole field of tribology is rife with terms and definitions that are useful and necessary for dealing with and solving wear problems.

The glossary at the end of this chapter is intended to familiarize readers with some of the fundamental tribology terms that will be repeated throughout this book. These definitions are not as rigorous as those in *official* sources of tribology terms such as:

- ASTM G40 Standard Terminology Relating to Wear and Erosion. The G40 definitions were developed by the ASTM G2 Committee on Wear and Erosion.

- ASTM D4175 Standard Terminology Relating to Petroleum, Petroleum Products, and Lubricants. The D4175 definitions are the product of the ASTM D2 Committee on Fuels and Lubricants.
- Organization for Economic Cooperation and Development (OECD) Tribology Terms and Definitions. The OECD definitions come from tribologists in the European Union.

They may have somewhat different definitions for the same term, and the definitions in this book are often *abstracts* of the definitions of all these august bodies.

Main Points

The definitions in the glossary of this chapter mostly concur with definitions from the end of chapter references. There will be many more, but the 40 or so listed apply to all the engineering material discussions that will follow. *ASM Handbook,* Volume 18, *Friction, Lubrication, and Wear Technology* (Ref 3) contains additional details on a variety of subjects related to this book. Pertinent sections of *ASM Handbook*, Volume 18 will be listed at the end of each chapter in the *Selected References.* The Glossary of Terms in *ASM Handbook*, Volume 18 contains hundreds of tribology definitions. Another useful source of tribology definitions and related tribology subjects is the *ASME Wear Control Handbook* (Ref 4). The ASTM definitions are consensus definitions, and this should make them more accepted, but they are often more complicated. The definitions in the Glossary section at the end of each chapter in this book are often condensations of longer ASTM definitions.

Each of the remaining chapters will deal with a specific tribological process or specific engineering material, and each chapter includes a list of important terms from the chapter. Each chapter has a list of main ideas, concepts, and questions that pertain to the information provided.

Hopefully, it was clearly explained earlier that the book title "Tribomaterials" is a better title than "Wear of Materials" because it is more inclusive. Also, hopefully, it has become apparent that tribology is really an important part of engineering, a country's economy, and the environment. A 2019 advertisement for a tribology course at the Massachusetts Institute of Technology (MIT), a prestigious university in the United States, cited that friction, wear, and erosion is costing the United States six percent of its gross national product. A simple calculation on the cost of tire wear validates this kind of cost—in 2018 there were 2.5 billion tires and 70 million new cars manufactured worldwide. This suggests that well over 2 billion tires wore out at an average cost (in the United States) of $150 each. Thus, the cost of wear for this one commodity was over $300 billion in one year—and tire wear has greatly improved in the past seven decades. In 1950, it was common to only get 10,000 miles of life from a tire; a life of 40,000 miles for a tire is now typical in the United States. Thus, tribology improvements save lots of money and, in the case of tires, this increased wear life really helps the environment since disposing of worn tires has always been a problem.

This book is intended to help reduce the worldwide costs of friction, wear, and erosion by proposing the use of a repertoire of materials that experience and lab testing have shown to work better than others. There can be significant cost savings in using the right materials for tribological applications.

Summary

Glossary

abrasion. The process of removing material from a surface by the action of hard and sharp protuberances or particles acting on that surface (Fig. 1.2).

Fig. 1.2 Abrasion of a stainless steel pump sleeve by glass-filled packing

adhesion. In tribology, the tendency for transfer and cold-welding effects between mating surfaces (Fig. 1.3).

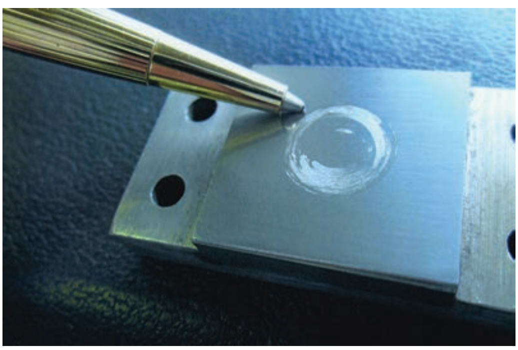

Fig. 1.3 Adhesive transfer of stainless steel to cemented carbide after one revolution of contact by a stainless steel annulus

alloy. In engineering materials, a material produced by adding different elements or substances to a base material or substance.

asperity. A concept whereby surfaces are thought to be comprised of microscopic peak-like features. Each peak is an asperity.

bearing. A support for a moving element designed to reduce friction and contact wear.

coefficient of friction (COF). A mathematical expression relating the friction force (F_f), to the normal force pressing the bodies together (F_n): COF = F_f/F_n.

composition. In engineering materials, the volume or weight percentage of elements that constitute a substance.

counterface. In tribology, one member of a rubbing system; for example, if a ball is rubbing on a flat, the flat is called the counterface and the ball is called the rider.

crystal structure. A systematic and repeated arrangement of atoms in a material (usually three-dimensional).

couple. In tribology, two members in rubbing contact.

equilibrium. In engineering materials, a state of existence where enough time is allowed for everything that wants to occur, to occur.

fretting. Relative motion of small amplitude (usually less than 300 micrometers).

friction. In tribology, the resisting force to start motion of a body or bodies at rest and the retarding force that bodies or substances in motion experience due to contact with other surfaces or substances.

galling. A form of adhesive wear characterized by formation of macroscopic excrescences material flowing up from a surface (Fig. 1.4).

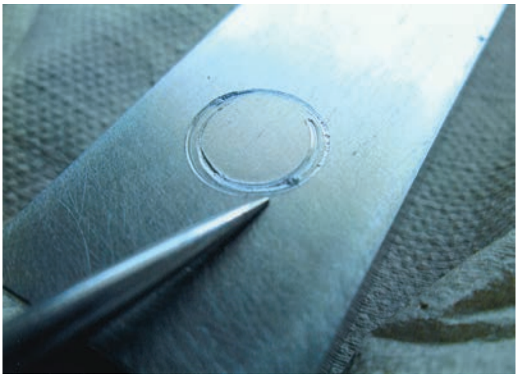

Fig. 1.4 Galling formation of excrescences from rubbing contact with another metal

hardfacing. Applying with welding techniques materials with properties perceived to be superior to that of the substrate.

hardness. In materials engineering, a material's resistance to penetration determined by indentation.

heat treatment. In engineering materials, applying a prescribed thermal processing to a material to change the properties of the material.

Hertzian contact. In tribology, point or line contact between bodies.

***in vivo*.** In biotribology, use of a material within the human body.

lubricant. Any substance that wets or attaches to a surface and reduces system friction.

lubrication. The application of a substance between mating surfaces to reduce friction and wear.

microstructure. In engineering materials, the internal features of a material that need significant magnification to be observed, usually greater than seven times, and studied (Fig. 1.5).

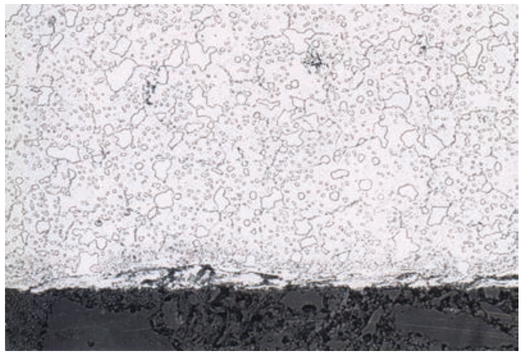

Fig. 1.5 Microstructure of 440C stainless steel etched with Vilella's etch showing grain boundaries and carbide phases (white areas) at 500×

mechanical properties. Attributes of a material that require destruction (alteration) of the material to measure.

phase. A homogeneous component of a material (the carbides in Fig. 1.5 are a phase).

physical properties. Attributes of a material that can be measured without destruction or alteration of a material.

P/M. In engineering materials, material made by compaction and consolidating of metal powders,

polishing. A form of abrasion that results in reducing the prevailing roughness of a surface and related surface parameters.

polymer. An organic material comprised of a macromolecule or many joined molecules.

rolling. Moving in a direction by rotation of a shape with a diameter that rotates about an axis.

scoring. Local plastic deformation in the form of grooves of a rubbing surface in the direction of motion (Fig. 1.6).

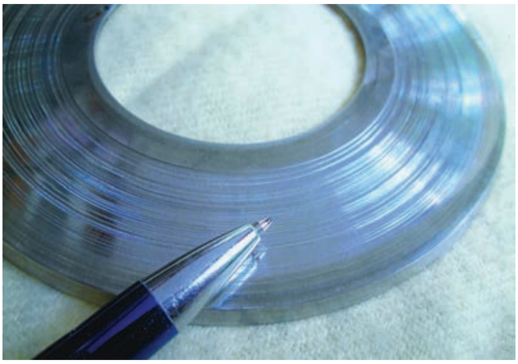

Fig. 1.6 Scoring of a stainless steel from rubbing contact with another steel part

scuffing. A localized wear transition characterized by a change in surface appearance from *polished* (mild wear) to more severe adhesive wear (significant surface disruption and plastic deformation). This type of wear damage usually occurs in inadequately lubricated tribosystems (Fig. 1.7).

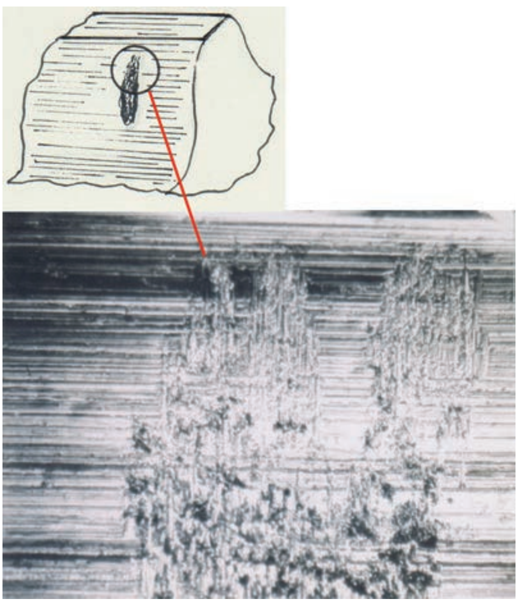

Fig. 1.7 Scuffing of a gear tooth

seizure. The unintentional stoppage of relative motion of members in a tribosystem by a tribological event (like galling).

sliding. Relative motion between contacting solid surfaces.

spalling. Surface fracture that results in the removal of a large piece of a surface (similar to roadway potholes).

surface texture. The combined waviness and heights of surface features.

transfer. In tribology, in sliding systems the tendency of materials to become coated on mating surfaces by surface interaction (Fig. 1.3).

traction. The friction force that acts to drive a rolling element (like a tire).

tribofilm. A surface layer that forms on one or more rubbing surfaces as a product of the rubbing reactions.

tribotesting. Studies conducted on laboratory simulators or on actual machines to rank or otherwise study candidate materials for a tribosystem.

wear. Progressive loss or alteration of a solid surface by the action of rubbing, sliding, or rolling in contact with another material or substance/substances (Fig. 1.8).

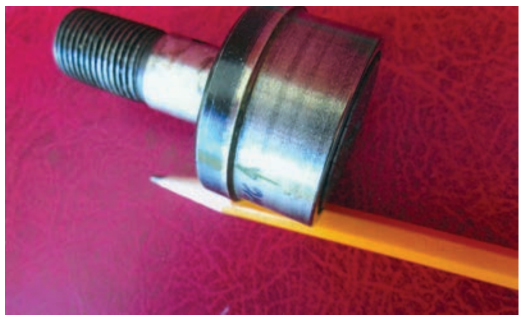

Fig. 1.8 Wear of a cam follower. There was no step in the outside diameter when it was new.

Major Concepts and Ideas in Tribology, Tribosystems, and Related Terminology

- Tribology is a useful term because it includes all aspects of rubbing surfaces.
- Wear is a significant percentage of every country's gross domestic product (GDP).
- Friction may account for 30% of the energy used worldwide.
- Friction and wear have many forms and each form has its specific *treatments*.
- Friction and wear can be controlled by design and proper selection of materials.

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