Engineering Design for Wear

Second Edition, Revised and Expanded

Raymond G. Bayer
Tribology Consultant
Vestal, New York, U.S.A.

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To my wife, Barbara

Preface

It has been a decade since the first edition of this book was published. During that period important changes in the field of tribology have occurred. As a consultant I have also gained additional tribological experience in a wide range of industrial applications. It was thus decided to develop a second edition with the goal of incorporating this new information and additional experience into a more useful and current book, as well as clarifying and enhancing the original material. The purpose and perspectives of the first edition were to be maintained, namely, "*to provide a general understanding . . . for the practicing engineer and designer [and an] engineering perspective . . .*". As rewriting progressed it became clear that the greatly expanded text would develop into a much larger volume than the first. We therefore decided to divide the material into two volumes, while keeping the basic format and style. Essentially the first two parts of the original edition on the fundamentals of wear and wear testing are combined into a single volume, *Mechanical Wear Fundamentals and Testing* (Marcel Dekker, 2004). The remaining two parts of the first edition, which focus on design approaches to wear and the resolution of wear problems, are the basis for this second volume, *Engineering Design for Wear*.

While a good deal of background material is the same as in the first edition, significant changes have been made. The most pervasive is the use of a new way of classifying wear mechanisms, which I have found to be useful in formulating approaches to industrial wear situations. As a result, Part A, Fundamentals, has been reorganized and rewritten to accommodate this new classification and to include additional material on wear mechanisms. Additional wear tests are described in Part B, Testing, which has been expanded to include friction tests. These first two parts are discussed in *Mechanical Wear Fundamentals and Testing. Part A, Design, of Engineering Design for Wear* has been modified by expanding several sections, as well as adding a section on a design methodology, design triage, that has been found to be useful. Among the expanded treatments is the consideration of material aspects and the treatment of rolling bearing wear and rolling wear, as well as impact wear. An additional case study has been added to the Problem Solving section, Part B, which illustrates the use of analytical modeling for resolving wear problems. Additional appendixes have been added, providing further information for use in engineering situations. These additional appendixes include tables on threshold stress for galling and sliding wear relationships for different contact situations. A glossary of wear mechanisms has also been added.

This book demonstrates the feasibility of designing for wear and using analytical approaches to describe wear in engineering situations, based on my experience over the last 40 years.

Raymond G. Bayer

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Design Perspective of Wear Behavior

1.1. INTRODUCTION

General wear behavior was treated in Part A of *Mechanical Wear Fundamentals and Testing: Second Edition, Revised and Expanded* (MWFT2E); however, the focus of that treatment was primarily on wear mechanisms and wear phenomena. While such a focus provides an overview of wear and its complexity that is generally quite valuable to the designer, it is an approach that is more in line with the perspective and concerns of the physical scientist and materials engineer rather than those of the designer. The scientist is directly concerned with the identification and understanding of the mechanisms involved. The materials engineer or scientist is concerned with the relationship of material properties to these mechanisms, so that materials can be selected and developed to resist these mechanisms. On the other hand, the designer tends to view the wear situation in terms of operational parameters and has the goal to select or develop a design that has the desired wear life. Consequently, a treatment of wear behavior in terms of operational parameters would be more directly useful to the designer. This can be developed by considering the relationships of three major operational aspects to wear behavior, namely: the nature of the contact; the type of motion associated with the contact; and the environment surrounding the contact.

In terms of the nature of the contact, it is useful to consider two broad categories. One is two-body contact, such as between gear teeth, a ball and a race in a ball bearing, a cam and a follower, a magnetic tape and a recording head, etc.; in short, this category covers the contact between two solid bodies. The other general category is a single body in contact with a fluid or stream of particles. The contact situation associated with a ship propeller and water would be an example of this category. Other examples of this type of contact are an air frame moving through a rain or dust field and the interior of pipelines involved in the transmission of fluids or slurries. It is also useful to identify and define several broad categories of motion that can be associated with these two types of contact. For the two-body contact situation, there are rolling, sliding, and impact motions. For the contact between a fluid and a single body, typical categories are cavitating or non-cavitating flow, streamline or turbulent flow, and high angle or low angle particle impingement. There are several major environmental categories, which are useful to consider for general design purposes. Among these are environments with and without hard particles (abrasive and non-abrasive environments), lubricated and non-lubricated environments, and hostile or non-hostile ambient environments. The last category would include temperature as well as gaseous elements.

Before considering wear behavior in terms of these categories, it is worthwhile to consider some of the more general aspects of wear behavior in relationship to design and design practices. Design approaches to wear must recognize the following characteristics of wear:

1. Wear is a system property, not a material property.
2. Materials can wear by a variety of mechanisms and combinations of mechanisms, depending on the tribosystem in which it is used.
3. Wear behavior is frequently nonlinear.
4. Transitions can occur in wear behavior as a function of a wide variety of parameters.

As will be shown, the complexity of this situation can be reduced to a significant degree by categorizing wear situations according to operational characteristics.

1.2. SYSTEM NATURE OF WEAR

Wear is not a material property nor is it a unique physical mechanism. It is best thought of as a system response. Materials can wear by a variety of mechanisms and material properties and operational parameters jointly influence wear behavior. This general nature of wear is significant to the designer, as can be seen in the following considerations of some design practices.

A common and useful practice in design is to study the performance of an existing design and to look for correlation between various performance elements and design parameters. As will be brought out in this section on wear design and in the following one on problem solving, such an activity is a very valuable one for wear performance. However, the correlations sought and the considerations that must go along with the development of these correlations must take into account the nature of wear behavior and wear phenomena. This point can be illustrated by considering two errors frequently made in design situations. One is to attempt to use device wear performance to establish an intrinsic wear resistance or relative wear resistance for a material. The tendency in this case is to think of a material as a good or bad wearing material, in general, or as being a better or poorer wearing material than another, again in general. This violates one of the fundamental aspects of wear, namely that wear is a system property and not a material property. Consequently, rankings or assessments that can be made are relative to the conditions of that application. For different conditions, the wear performance of a material can change and different rankings can result. The second error is to use the wear behavior of a material observed in an application to infer a universal mode of wear for either that material or that situation. This second error is similar to the first in that it violates a fundamental aspect of wear behavior. Namely, materials can wear by several mechanisms, which are dependent not only on material properties but also on conditions surrounding the contact (i.e., the overall wear situation).

There is another general characteristic of wear that is significant in design. In development engineering or design, there is frequently the need to extrapolate performance characteristics of an existing mechanism from one application to another. In the case of wear, this might be the extension of a design to a higher load situation, faster speed, a different environment, or different life requirements. Particularly, with the latter, there is a tendency to assume a linear relationship for such extrapolations. However, because of the transitions in wear behavior that are possible and the complex nature of wear phenomena, such relationships are frequently nonlinear and can vary with the wear situation or system. Therefore, it is not possible to identify a universal relationship or set of relationships that can be used for all cases. To the designer, this means that without the existence of supporting data such extrapolations can be erroneous and arbitrary. However, with the proper consideration of the tribosystem and supportive data, appropriate relationships can be selected and used to provide these types of extrapolations. Approaches of this type will be presented later in the section on design.

1.3. BASIC MECHANISMS OF WEAR

Several general mechanisms for wear were discussed in Part A of MWFT2E and were grouped into seven major categories: adhesive wear, single-cycle deformation wear, repeated-cycle deformation wear, oxidative wear, tribofilm wear, thermal wear, and abrasive wear. In design, a simplistic view of these basic categories for wear mechanisms is quite often useful and can aid in the identification of significant parameters and in the selection and formulation of engineering models for wear. Fundamental to adhesive wear is bonding between the two surfaces at the points of real contact. Consequently, surface properties of materials, cleanliness of the surfaces, and other parameters related to adhesion become significant for this mode of wear. Lubrication is a prime way of inhibiting this type of wear.

Single-cycle deformation wear is the result of a harder object deforming, cutting, or fracturing as a result of relative motion. A single engagement is all that is required for this type of wear. With this type of wear, the concern is with the presence of hard particles and sharp profiles. Consequently, shape, hardness, surface roughness, and number of particles are significant to wear behavior, as well as the mechanical properties of the material being worn. Lubrication has little effect on this type of wear and may increase wear under certain conditions.

Repeated-cycle deformation wear results from the accumulation of deformation as a result of repeated contact. This accumulation of deformation, caused by repeated cycles of stress and strain, lead to the formation and propagation of cracks. As discussed in Sec. 3.4 of MWFT2E, there are a number of different mechanisms of this type, for example, surface fatigue, delamination, and ratcheting. However, for engineering purposes, it is useful and generally sufficient to think of these as simply as fatigue or fatigue-like wear processes. Such processes can occur on a macro- or micro-scale in two-body contact situations, with particles in abrasive wear situations, and in one-body wear situations with particles and fluid flow. Mechanical properties of the wearing material and stress levels are primary factors in this mode. Since lubrication can reduce shear on the surface, it can reduce fatigue wear, however, it is usually more significant in terms of adhesive wear.

These three mechanisms, adhesion, single-cycle deformation, and repeated-cycle deformation (fatigue), directly result in material loss from a surface or deformation of a surface. Oxidative, tribofilm, and thermal wear processes are different. Oxidation, tribofilm formation, and thermal effects do not directly lead to material loss or damage. Oxidative, tribofilm, and thermal wear involve a combination of these effects with one of the other three mechanical wear processes, which do directly result in loss of material from a surface. A useful way of thinking about oxidative, tribofilm, and thermal wear mechanisms is as modifiers of the mechanical wear processes. It is also important to recognize that oxidation, tribofilm, and thermal processes can indirectly affect wear through their effect on friction, since wear processes can be sensitive to surface shear and traction.

With oxidative wear, the chemical reactivity of the surface is important, as well as the chemical environment and temperature of the application. Lubrication can be very significant with relationship to oxidative wear, particularly if the lubricant contains surface-active elements which result in the formation of oxide layers. There are two other ways a lubricant can influence oxidative wear; it can provide a barrier to chemical attack from the environment and it can reduce surface temperatures by reducing friction and conducting heat away from the contact. Break-in or run-in can be an important factor in terms of oxidative wear as well.

For transfer and third-body film formation such aspects as roughness, motion, geometry, and composition (chemical aspects) are factors. The use of lubricant with material pairs that rely on the formation of physical films for good wear behavior can result in increased, rather than decreased wear. This is particularly true in the case of many situations involving the use of self-lubricating plastics, where good wear behavior is frequently associated with the formation of transfer films. As with oxidative wear, break-in can be an important factor in terms of the formation of these physical films and tribofilm wear.

The thermal properties of the materials, frictional heating, conduction of heat away from the interface, and the thermal characteristics of the materials affect thermal wear processes.

While abrasion is wear caused by hard particles or protuberances, it is generally only significant in situations that involve hard particles, either loose or attached to a surface. The size, shape, hardness, and number of particles are significant parameters in this type of wear, as well as their friability. When the wearing surfaces are softer than the particles, the dominant mechanisms for wear are single-cycle deformation processes, e.g., cutting and plowing. When the surface is harder, repeated-cycle deformation processes become dominant. In either case, oxidative wear processes can be involved and be significant, particularly in situations where there are liquids or hostile gaseous environments involved.

It is important in design to recognize that the composition and make-up of wear surfaces, as well as mechanical properties, can change during the wear process because of the formation of oxide and transfer films and work or strain hardening effects. As a result, the properties of those surfaces may be unique to the wear situation and may be significantly different than those of the original materials. It is also important to recognize that in most wear situations, it is possible and likely that more than one of the mechanisms may be present. As was discussed in Part A of MWFT2E these mechanisms can interact and combine, but one will frequently predominate as the controlling factor. The dominant mechanism can vary with different tribosystems.

The mildest forms of wear tend to be associated with repeated-cycle deformation mechanisms, either by themselves or in conjunction with tribofilm and oxidative wear mechanisms. (See Figure 4.14 in MWFT2E.) Repeated-cycle deformation mechanisms are generally the dominant wear mechanism associated with long-term behavior. Adhesion and single-cycle deformation mechanisms tend to be significant in initial wear behavior and can be much more severe than repeated-cycle deformation mechanisms. Abrasive wear can be the dominant form of wear, when there are sufficient particles present, and can be more severe than adhesive wear. The effect of single-cycle deformation wear can be eliminated and reduced in most cases by using smooth surfaces, appropriate shapes (e.g. well-rounded corners and edges), and keeping abrasive particles out of the wear zone. Similarly, the effects of adhesive wear can be minimized principally by the use of lubrication and also by the appropriate choice of materials. In general, it is desirable to select design parameters, which reduce the tendency toward the potentially more severe forms of wear, that is, adhesive, single-cycle deformation, thermal, and adhesive mechanisms, as well as the more severe forms of repeated-cycle deformation mechanisms.

1.4. MILD AND SEVERE WEAR BEHAVIOR

Among the many types of transitions that can occur in wear behavior, the transition from mild to severe wear is of singular importance in design. In order to achieve the lifetimes or reliability desired for most devices or machines, wear behavior must be in the mild regime. Wear rates associated with severe wear behavior generally are too high to provide long component life and low maintenance. In certain applications, severe wear behavior cannot be avoided, such as in ore processing or earth moving equipment. In these cases, routine maintenance is high.

Generally speaking, all materials can and do undergo transitions from mild to severe wear. Such transitions can occur for a variety of reasons. For example, many plastics undergo a transition from mild to severe wear as a function of sliding speed or the combination of sliding speed and pressure (1). This is associated with temperature increases at the interface that occurs with higher speeds and pressures. A metal in an abrasive wear situation might experience a transition as a function of the size and hardness of the abrasives encountered. If the abrasives are fine and are softer than the metal, polishing will occur; if coarser and harder than the metal, then a coarse, rough wear scar with many grooves will result (2,3). Changes in the angle of impingement of a fluid or slurry stream can also result in a transition from mild to severe wear, as can the introduction of slip in a rolling situation or sliding in an impact situation. An example of the latter is that of wear behavior of elastomers under nominal impact conditions. If there is little or no sliding associated with the impact, wear behavior can be mild. However, with the introduction of sliding or slip, wear rates increase dramatically and severe wear occurs (4). Also in impact situations, an over-stressed condition can occur for elastomers. At impact conditions below a critical stress, wear behavior is mild; while above the critical level (over-stressed), it is severe (5). From these examples it can be seen that the transition from mild to severe behavior for materials can involve any or all of the elements involved in a tribosystem, involving not only the chemical and physical elements, but also the mechanical elements as well.

During the development and the evaluation of a design, it is important to recognize the possibility of such transitions. From a design standpoint, it is obvious that it is desirable to select designs and design parameters that foster mild wear behavior and avoid those elements which tend to result in severe wear behavior. Consequently, an awareness of those elements, which control mild–severe wear transitions in an application, is important. These elements are addressed further in the sections on operational categories of tribosystems (1.5–1.7) and materials (1.8). Also, it should be kept in mind that while severe wear behavior is generally unacceptable, there is generally a considerable range for wear rates in the mild wear regime. As a result, simply insuring that mild wear behavior occurs is generally not adequate to insure adequate life. Because of the desirability to have long life with low maintenance, the designer is generally more concerned with the characteristics of mild wear behavior than severe wear behavior.

1.5. OPERATIONAL CATEGORIES OF TRIBOSYSTEMS

Since the designer can usually describe the tribosystem in terms of operational parameters, it would be useful to correlate wear mechanisms with these operational parameters. In this way the designer can understand the relationship of physical and material parameters with his design parameters and their influences on performance. Unfortunately, a general correlation to specific mechanisms cannot be done at the present time; however, some general trends can be developed that relate broad categories of tribosystems and generic wear mechanisms. While there can be exceptions to such trends, they do provide useful information and guidance in design. One useful way of relating general trends of wear behavior to operational characteristics of tribosystems is shown in Table 1.1. This scheme is based on three major attributes of the tribosystem, which were identified previously, namely the nature of the wear interface, the type of motion at that interface, and environment of that interface.

Two general types of wear interfaces are considered in this approach; one is an interface involving two solid surfaces, two-body, and the second involves a single solid surface interacting with a fluid or particle stream, one-body. For the two-body contact, three major types of relative motion are identified, rolling, impact, and sliding, along with some significant sub-categories. In the case of one-body contact, two major categories, impingement and flow, along with some sub-categories, replace these. The environment is broken down into lubricated or not, with and without particles, and normal and hostile ambient conditions. These operational characteristics are then related to the generic wear categories of abrasion and adhesive, single-cycle deformation, repeated-cycle deformation (fatigue), oxidative, tribofilm, and thermal wear mechanisms.

There are some general aspects that need to be considered in relationship to Table 1.1. One of these is associated with the fact that different areas of or locations on a component may have different operational parameters associated with their wear. For example, at the pitch line of a gear tooth the motion may be pure rolling, while at the tip, it is mostly sliding. Similarly in a pump, different regions might be characterized as wearing by impingement and others by flow across the surface. Consequently, Table 1.1. should be interpreted in terms of individual wear points or sites rather than in terms of a part or device. A second aspect is that the mechanisms identified are the most common ones not necessarily the only ones than may occur in these situations. For example, cutting tool wear, which can be considered sliding wear situation, can involve atomic wear processes (diffusion) in addition to those indicated in the table. Finally, chemically and physically formed layers may occur and frequently do when a lubricant is used. Such effects are considered as part of the lubrication processes, not as oxidative or tribofilm wear.

1.6. TWO-BODY TRIBOSYSTEMS

While all major categories of wear mechanisms can occur with two-body tribosystems, the nature of the relative motion between the surfaces, as well as the presence or absence of particles at the interface, is important in terms of their relative significance to long-term wear behavior. (See Chapter 3 of MWFT2E). In the case of pure rolling and impact, repeated-cycle deformation, or more specifically, fatigue is the predominant mechanism. While with sliding, repeated-cycle deformation mechanisms, like fatigue and other fatigue-like mechanisms, and adhesive wear mechanisms are likely. Single-cycle deformation can also be significant and even dominate the wear behavior in these situations. However, their significance in typical engineering situations is typically limited to initial wear behavior and can be minimized and eliminated by the selection of appropriate shapes and roughness conditions. Under mild sliding conditions in such situations, repeated-cycle deformation tends to predominate; under severe conditions, adhesion predominates. With sliding or rolling, the presence of hard particles at the interface can introduce abrasive

Table 1.1 Operational Classification of Wear Situations

Contact Type: Two-Body

Motion		Environment[a] Lubrication	Particulates	Ambient	Significant mechanisms[b]
Rolling	Without slip	None	None	Normal	SCD (if beyond elastic limit) RCD TH (with plastics)
				Hostile	SCD (if beyond elastic limit) RCD OX TH
			Hard particles	Normal	SCD (if beyond elastic limit) RCD TH (with plastics) AB
				Hostile	SCD (if beyond elastic limit) RCD OX TH AB
		Lubricated	None	Normal	SCD (if beyond elastic limit) RCD
				Hostile	SCD (if beyond elastic limit) RCD
			Hard particles	Normal	SCD (if beyond elastic limit) RCD AB
				Hostile	SCD (if beyond elastic limit) RCD AB
	With slip	None	None	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with plastics) TF (with plastics, composites and ceramics)
				Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with plastics) TF (with plastics, composites and ceramics)
			Hard particles	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with plastics)

(continued)

Table 1 (*Continued*)

Motion		Environment[a]			Significant mechanisms[b]
		Lubrication	Particulates	Ambient	
					TF (with plastics, composites and ceramics) AB
				Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with plastics) TF (with plastics, composites and ceramics) AB
		Lubricated	None	Normal	SCD (if beyond elastic limit) RCD
				Hostile	SCD (if beyond elastic limit) RCD
			Hard particles	Normal	SCD (if beyond elastic limit) RCD AB
				Hostile	SCD (if beyond elastic limit) RCD AB
Trends: wear increases with slip and presence of hard particles. RCD mechanisms tend to be the dominant and limiting mechanisms; abrasion can dominate; generally, mildest wear situation.					
Impact	With stationary body, without slip	None	None	Normal	SCD (if beyond elastic limit) RCD TH (with polymers)
				Hostile	SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH
			Hard particles	Normal	SCD (if beyond elastic limit) RCD TH (with polymers) AB
				Hostile	SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH AB
		Lubricated	None	Normal	SCD (if beyond elastic limit) RCD

(continued)

Table 1 (*Continued*)

Motion	Environment[a]			Significant mechanisms[b]
	Lubrication	Particulates	Ambient	
			Hostile	SCD (if beyond elastic limit) RCD
		Hard particles	Normal	SCD (if beyond elastic limit) RCD AB
			Hostile	SCD (if beyond elastic limit) RCD AB
With stationary body, with slip	None	None	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with polymers) TF (with plastics, composites and ceramics)
			Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with polymers) TF (with plastics, composites and ceramics)
		Hard particles	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with polymers) TF (with plastics, composites and ceramics) AB
			Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with polymers) TF (with plastics, composites and ceramics) AB
	Lubricated	None	Normal	SCD (if beyond elastic limit) RCD
			Hostile	SCD (if beyond elastic limit) RCD

(continued)

Table 1 (*Continued*)

Motion		Environment[a]			Significant mechanisms[b]
		Lubrication	Particulates	Ambient	
			Hard particles	Normal	SCD (if beyond elastic limit) RCD AB
				Hostile	SCD (if beyond elastic limit) RCD AB
	With moving body	None	None	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH (with polymers) TF (with plastics, composites and ceramics)
				Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH TF (with plastics, composites and ceramics)
			Hard particles	Normal	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH TF (with plastics, composites and ceramics) AB
				Hostile	AD SCD (if beyond elastic limit) RCD OX (with metals and ceramics) TH TF (with plastics, composites and ceramics) AB
		Lubricated	None	Normal	SCD (if beyond elastic limit) RCD
				Hostile	SCD (if beyond elastic limit) RCD
			Hard particles	Normal	SCD (if beyond elastic limit) RCD AB
				Hostile	SCD (if beyond elastic limit) RCD AB

(continued)

Table 1 (*Continued*)

Motion		Environment[a]			Significant mechanisms[b]
		Lubrication	Particulates	Ambient	
Trends: RCD mechanisms tend to be the dominant and limiting mechanisms; wear tends to increase with particles and abrasion can dominate; with stationary body, induced vibrations a misalignment can cause slip and fretting, which tends to result in increased wear; acceptable w generally requires stresses be in the elastic range; with moving objects, wear increases with the amount of sliding and sliding effect can dominate wear behavior; fluid lubrication can be very significant in reducing wear.					
Sliding	Unidirectional	None	None	Normal	AD SCD (if beyond elastic lim RCD OX (with metals and cerai TH (with polymers; high speeds) TF (with plastics, compos and ceramics)
				Hostile	AD SCD (if beyond elastic lin RCD OX (with metals and cerai TH TF (with plastics, compos and ceramics)
			Hard particles	Normal	AD SCD (if beyond elastic lin RCD OX (with metals and cerai TH (with polymers; high speeds) TF (with plastics, compo and ceramics) AB
				Hostile	AD SCD (if beyond elastic lin RCD OX (with metals and cera TH TF (with plastics, compos and ceramics) AB
		Lubricated	None	Normal	SCD (if beyond elastic lin RCD
				Hostile	SCD (if beyond elastic lin RCD
			Hard particles	Normal	SCD (if beyond elastic lin RCD AB