CHAPTER 34

WEAR

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There is no shorthand method of designing machinery for a specified wear life. Thus a step-by-step method is given for designers to follow. The method begins with an examination of worn parts of the type to be improved. The next step is an estimate of stresses, temperatures, and likely conditions of operation of the redesigned machinery. Material testing for wear resistance is discussed, and finally, a procedure is given for selecting materials for wear resistance.

34.1 GENERAL PRINCIPLES IN DESIGN FOR WEAR RESISTANCE

The wear life of mechanical components is affected by nearly as many variables as human life. Wearing surfaces are composed of substrate material, oxide, absorbed gas, and dirt. They respond to their environment, method of manufacture, and conditions of operation. They suffer acute and/or progressive degeneration, and they can often be partially rehabilitated by either a change in operating conditions or some intrusive action.

The range of wearing components and devices is endless, including animal teeth and joints, cams, piston rings, tires, roads, brakes, dirt seals, liquid seals, gas seals, belts, floors, shoes, fabrics, electrical contacts, disks and tapes, tape heads, printer heads, tractor tracks, cannon barrels, rolling mills, dies, sheet products, forgings, ore crushers, conveyors, nuclear machinery, home appliances, sleeve bearings, rolling-element bearings, door hinges, zippers, drills, saws, razor blades, pump impellers, valve seats, pipe bends, stirring paddles, plastic molding screws and dies, and erasers. There is not a single universal approach to designing all these components for an acceptable wear life, but there are some rational design steps for some. There are no equations, handbooks, or material lists of broad use, but there are guidelines for some cases. Several will be given in this section.

34.1.1 Types, Appearances, and Mechanisms of Wear

Wear is a loss or redistribution of surface material from its intended location by definition of the ASTM. Using this definition, we could develop a simple explanation for wear as occurring either by chemical reaction (that is, corrosion), by melting, or by mechanical straining. Thus to resist wear, a material should be selected to resist the preceding individual causes of wear or else the environment should be changed to reduce surface stress, temperature, or corrosiveness.

The preceding three natural processes are too broad to be useful for material selection in light of the known properties of materials. A more detailed list of material properties appropriate to the topic of wear is given in Table 34.1.

The preceding methods of material removal are usually not classified among the "mechanisms" of wear. Usually a *mechanism* is defined as a fundamental cause. Thus a fundamental argument might be that wear would not occur if there were no contact. If this were so, then mere contact could be called a mechanism of wear. However, if we define a *mechanism* as that which is capable of explanation by the laws of physics, chemistry, and derivative sciences, then mere contact becomes a statement of the condition in which surfaces exist and not a mechanism. But if stresses, lattice order, hydrogen-ion concentration, fugacity, or index of refraction were known, *and if* the effect of these variables on the wear rate were known, then a mechanism of wear has been given. Most terms used to describe wear therefore do not suggest a mechanism. Rather, most terms describe the condition under which wearing occurs or they describe the appearance of a worn surface. Terms of the former type include dry wear, metal-to-metal wear, hot wear, frictional wear, mechanical wear, and impact wear. Closer observation may elicit descriptions such as erosion, smooth

TABLE 34.1 Material Properties Involved in Wear

Chemical action
1. Chemical dissolution
2. Oxidation (corrosion, etc.)
Mechanical straining
3. Brittle fracture (as in spalling; see below)
4. Ductile deformation: a. To less than fracture strain (as in indentation) b. To fracture (as in cutting, galling, transfer, etc.)
5. High-cycle fatigue (as occurs in rolling contacts)
6. Low-cycle fatigue (as in scuffing, dry wear, etc.)
7. Melting

SOURCE: From Ludema [34.2].

wear, polishing wear, cavitation, corrosive wear, false brinelling, friction oxidation, chafing fatigue, fretting, and chemical wear. Still closer observation may reveal spalling, fatigue wear, pitting corrosion, delamination, cutting wear, deformation wear, gouging wear, galling, milling wear, plowing wear, scratching, scouring, and abrasion. The latter is often subdivided into two-body or three-body abrasion and low-stress or high-stress abrasion. Finally, some of the terms that come from the literature on "lubricated" wear include scuffing, scoring, and seizure. Most of these terms have specific meanings in particular products and in particular industries, but few find wide use.

Valiant attempts are continuously being made to define wear terms in the professional societies, but progress is slow. Researchers have attempted to classify most of the terms as either abrasive or adhesive mechanisms primarily, with a few terms classified as a fatigue mechanism. It is interesting that adhesiveness or abrasiveness is not often proven in real problems. Rather, a given wear process is simply modeled as abrasive *or* adhesive and often considered as exclusively so. Some authors attempt to escape such categories by separating wear into the mild and severe categories, which introduces value judgments on wear rates not inherently found in the other terms. Mechanisms of wear will be discussed at greater length below.

34.1.2 Design Philosophy

Most wearing surfaces are redesigned rather than designed for the first time. Thus designers will usually have access to people who have experience with previous products. Designing a product for the first time requires very mature skills, not only in materials and manufacturing methods, but also in design philosophy for a particular product.

The philosophy by which wear resistance or wear life of a product is chosen may differ strongly within and between various segments of industry. Such considerations as acceptable modes of failure, product repair, controllability of environment, product cost, nature of product users, and the interaction between these factors receive different treatment for different products. For example, since automobile tires are easier to change than is an engine crankshaft, the wear life of tires is not a factor in discussions of vehicle life. The opposite philosophy must apply to drilling bits used in the oil-well industry. The cone teeth and the bearing upon which the cone rotates must be designed for equal life, since both are equally inaccessible while wearing.

In some products or machines, function is far more important than manufacturing costs. One example is the sliding elements in nuclear reactors. The temperature environment of the nuclear reactor is moderate, lubricants are not permitted, and the result of wear is exceedingly detrimental to the function of the system. Thus expensive metal-ceramic coatings are frequently used. This is an example of a highly specified combination of materials and wearing conditions. Perhaps a more complex example is that of artificial teeth. The surrounding system is very adaptable, a high cost is relatively acceptable, but durability may be strongly influenced by body chemistry and choice of food, all beyond the range of influence by the designers.

Thus there is no general rule whereby designers can quickly proceed to select a wear-resisting material for a product. One often heard but misleading simple method of reducing wear is to increase the hardness of the material. There are, unfortunately, too many exceptions to this rule to have high confidence in it except for some narrowly defined wearing systems. One obvious exception is the case of bronzes, which are more successful as a gear material against a hardened-steel pinion than is a hardened-steel gear. The reason usually given for the success of bronze is that dirt particles are readily embedded into the bronze and therefore do not cut or wear the steel away, but this is more of an intuitive argument than fact. Another exception to the hardness rule is the cams in automotive engines. They are hardened in the range of 50 Rockwell C instead of to the maximum available, which may be as high as 67 R_C. A final example is that of buckets and chutes for handling some ores. Rubber is sometimes found to be superior to very hard white cast iron in these applications.

We see in the preceding examples the possibility of special circumstances requiring special materials. The rubber offers resilience, and the cam material resists fatigue failure if it is not fully hardened. It is often argued that special circumstances are rare or can be dealt with on a case-by-case basis. This attitude seems to imply that most wearing systems are "standard," thus giving impetus to specifying a basic wear resistance of a material as one of its intrinsic properties. Little real progress has been made in this effort, and very little is likely to be made in the near future. Wear resistance is achieved by a balance of several very separate properties, not all of them intrinsic, that are different for each machine component or wear surface. Selecting material for wear resistance is therefore a complex task, and guidelines are needed in design. Such guidelines will be more useful as our technology becomes more complex, but some guidelines are given in the next section.

34.2 STEPS IN DESIGN FOR WEAR LIFE WITHOUT SELECTING MATERIALS

34.2.1 The Search for Standard Components

Designers make most of the decisions concerning material selection. Fortunately, for many cases and for most designers, the crucial components in a machine in which wear may limit useful machine life are available as separate packages with fairly well specified performance capabilities. Examples are gear boxes, clutches, and bearings. Most such components have been well tested in the marketplace, having been designed and developed by very experienced designers. For component designers, very general rules for selecting materials are of little value. They must build devices with a predicted wear life of ±10 percent accuracy or better. They know the range of capability of lubricants, they know the reasonable range of temperature in which their products will survive, and they know how to classify shock loads and other real operating conditions. Their specific expertise is not available to the general designer except in the form of the shapes and dimensions of hardware, the materials selected, and the recommended practices for use of their product. Some of these selections are based on tradition, and some are based on reasoning, strongly tempered by experience. The makers of specialized components usually also have the facilities to test new designs and materials extensively before risking their product in real use. General designers, however, must often proceed without extensive testing.

General designers must then decide whether to avail themselves of standard specialized components or to risk designing every part. Sometimes the choice is based on economics, and sometimes desired standard components are not available. In such cases, components as well as other machine parts must be designed in-house.

34.2.2 In-House Design

If a designer is required to design for wear resistance, it is logical to follow the methods used in parallel activities, such as in determining the strength and vibration characteristics of new machinery. This is often done by interpolating within or extrapolating beyond experience, if any, using

1. Company practice for similar items
2. Vendors of materials, lubricants, and components
3. Handbooks

Company Practice. If good information is available on similar items, a prediction of the wear life of a new product can be made with ± 20 percent accuracy unless the operating conditions of the new design are much beyond standard experience. Simple scaling of sizes and loads is often successful, but usually this technique fails after a few iterations. Careless comparison of a new design with "similar" existing items can produce very large errors for reasons discussed below.

When a new product must be designed that involves loads, stresses, or speeds beyond those previously experienced, it is often helpful to examine the worn surface of a well-used previous model in detail. It is also helpful to examine unsuccessful prototypes or wear-test specimens, as will be discussed below. An assessment should be made of the modes or mechanisms of wear of each part of the product. For this purpose, it is also useful to examine old lubricants, the contents of the lubricant sump, and other accumulations of residue.

Vendors of Materials. Where a new product requires bearings or materials of higher capacity than now in use, it is frequently helpful to contact vendors of such products. When a vendor simply suggests an existing item or material, the wear life of a new product may not be predictable to an accuracy of better than ± 50 percent of the desired life. This accuracy is worse than the ± 20 percent accuracy given earlier, especially where there is inadequate communication between the designer and the vendor. Accuracy may be improved where an interested vendor carefully assesses the needs of a design, supplies a sample for testing, and follows the design activity to the end.

Contact with vendors, incidentally, often has a general beneficial effect. It encourages designers to revise their thinking beyond the logical projection of their own experience. Most designers need a steady flow of information from vendors to remain informed on both the new products and the changing capability of products.

Handbooks. There are very few handbooks on selecting materials for wear resistance. Materials and design handbooks usually provide lists of materials, some of which are highlighted as having been successfully used in wearing parts of various products. They usually provide little information on the rates of wear of products, the mode of wear failure, the limits on operating conditions, or the method by which the wear-resisting parts should be manufactured or run in (if necessary).

Some sources will give wear coefficients, which are purported to be figures of merit, or rank placing of materials for wear resistance. A major limitation of wear coefficients of materials as given in most literature is that there is seldom adequate information given on how the data were obtained. Usually this information is taken from standard laboratory bench tests, few of which simulate real systems. The final result of the use of handbook data is a design which will probably not perform to an accuracy of better than ±95 percent.

34.3 WEAR EQUATIONS

There is a great need for wear equations. Ideally, a wear equation would provide a numerical value for material loss or transfer for a wide range of materials and operating conditions of the wearing parts.

Useful equations derived from fundamental principles are not yet available. Some empirical equations are available for very special conditions. The strictly empirical equations usually contain very few variables and are of the form

$$VT^n = f^a d^b K \tag{34.1}$$

which applies to metal cutting, and in which V = cutting speed, T = tool life, f = feed rate, and d = depth of cut. Experiments are done, measuring T over a range of f while holding V and d fixed at some arbitrary values, from which a can be obtained. The experiments are repeated over ranges of d and V to obtain b and K. It is generally assumed that the results will not depend on the selection of the variables to hold constant, which therefore assumes that there is neither any limit to the range of valid variables nor any interdependence between variables, which ultimately means that there is no change of wearing mechanisms over any chosen range of the variables. Wear equations built by strictly empirical methods are therefore seen to be limited to the case under present study; they have limited ability to predict conditions beyond those of the tests from which they were derived, and they have little applicability to other sliding systems.

A common method of building equations from fundamental principles is to assume that wearing will take place in direct proportion to the real (microscopic) contact area. These equations omit such important considerations as the presence of oxides and adsorbed gases on surfaces, and few of them recognize the role of repeated contact on sliding surfaces, which may lead to fatigue modes of material loss (wear).

In a recent study [34.1], over 180 wear equations were analyzed as to content and form. Though the authors collectively cited over 100 variables to use in these equations, few authors cited more than 5. The fact, then, that quantities such as hardness are found in the numerator of some equations and in the denominator of others leads to some confusion. Overall, no way was found to harmonize any selected group of equations, nor was there any way to determine which material properties are important to the wearing properties.

The parameters that may be included in the equation are of three types, as listed in Table 34.2. It may be readily seen from Table 34.2 that many of the parameters are difficult to quantify, and yet these (and perhaps several more) are known to affect the wear rate. Further complexity is added in cases where wear mechanisms, and therefore wear rates, change with time of sliding.

This state of affairs seems incomprehensible to designers who are steeped in mathematical methods that promise precise results. To use a specific example: For calculating the deflections of beams, simple equations are available that require only one material property, namely, Young's modulus. All other quantities in these equations are very specific; that is, they are measured in dimensions which not only seem available in four or five significant figures, but have compatible units.

Wear is far more complex, involving up to seven basic mechanisms that are operative in different balances or ratios under various conditions. Moreover, many of the mechanisms produce wear rates that are not linear in the simple parameters, such as applied load, sliding speed, surface finish, etc. Thus, in summary, there are at this time

TABLE 34.2 Parameters Often Seen in Wear Equations

a. Operational parameters
1. Surface topography
2. Contact geometry
3. Applied load
4. Slide/role speed
5. Coefficient of friction
6. Etc.
b. Material parameters
1. Hardness, cold and hot
2. Ductility
3. Fracture toughness
4. Strength
5. Work hardenability
6. Elastic moduli
7. Material morphology
8. Type and thickness of surface film
9. Thermal properties
10. Etc.
c. Environmental parameters
1. Type and amount of lubricant
2. Type and amount of dirt and debris
3. Rigidity of supporting structure
4. Ambient temperature
5. Multiple pass of continuous contact
6. Continuous, stop-start, reciprocating
7. Clearance, alignment, and fit
8. Matched or dissimilar material pair
9. Etc.

SOURCE: From Ludema [34.2].

no complete first principles or models available to use in selecting materials for wear resistance. However, there are good procedures to follow in selecting materials for wear resistance.

34.4 STEPS IN SELECTING MATERIALS FOR WEAR RESISTANCE

When designing for wear resistance, it is necessary to ascertain that wear will proceed by the same mechanism throughout the substantial portion of the life of the product. Only then is some reasonable prediction of life possible.

Certain considerations are vital in selecting materials, and these may be more important than selecting a material for the best wear resistance. These considerations are

1. The restriction on material use
2. Whether the sliding surface can withstand the expected static load
3. Whether the materials can withstand the sliding severity
4. Whether a break-in procedure is necessary or prohibited
5. The acceptable modes of wear failure or surface damage
6. The possibility of testing candidate materials in bench tests or in prototype machines

These considerations are discussed in detail in the next several pages.

34.4.1 Restrictions on Material Use

The first step in selecting materials for wear resistance is to determine whether there are any restrictions on material use. In some industries it is necessary for economic and other purposes to use, for example, a gray cast iron, or a material that is compatible with the human body, or a material with no cobalt in it such as is required in a nuclear reactor, or a material with high friction, or a selected surface treatment applied to a low-cost substrate. Furthermore, there may be a limitation on the surface finish available or the skill of the personnel to manufacture or assemble the product. Finally, there may be considerations of delivery or storage of the item before use, leading to corrosion, or false brinelling, or several other events that may befall a wear surface.

34.4.2 Static Load

The second step is to determine whether the sliding surface can withstand the expected static load without indentation or excessive distortion. Generally, this would involve a simple stress analysis.

34.4.3 Sliding Severity

The materials used must be able to withstand the severity of sliding. Factors involved in determining sliding severity include the contact pressure or stress, the temperature due to ambient heating and frictional temperature rise, the sliding speed, misalignment, duty cycle, and type of maintenance the designed item will receive. These factors are explained as follows.

Contact Stress. Industrial standards for allowable contact pressure vary considerably. Some specifications in the gear and sleeve bearing industries limit the average contact pressures for bronzes to about 1.7 MPa, which is about 1 to 4 percent of the yield strength of bronze. Likewise, in pump parts and valves made of tool steel, the contact pressures are limited to about 140 MPa, which is about 4 to 6 percent of the yield strength of the hardest state of tool steel.

However, one example of high contact pressure is the sleeve bearings in the landing gear of modern commercial aircraft. These materials again are bronzes and have yield strengths up to 760 MPa. The design bearing stress is 415 MPa but with expectations of peak stressing up to 620 MPa. Another example is the use of tool steel in lubricated sheet-metal drawing. Dies may be expected to be used for 500 000 parts with contact pressures of about 860 MPa, which is half the yield strength.

Temperature. The life of some sliding systems is strongly influenced by temperature. Handbooks often specify a material for "wear" conditions without stating a range of temperature within which the wear-resistance behavior is satisfactory. The influence of temperature may be its effect on the mechanical properties of the sliding parts. High temperatures soften most materials and low temperatures embrittle some. High temperature will produce degradation of most lubricants, but low temperature will solidify a liquid lubricant.

Ambient temperature is often easy to measure, but the temperature rise due to sliding may have a larger influence. For a quick view of the factors that influence temperature rise ΔT of asperities on rubbing surfaces, we may reproduce one simple equation:

$$\Delta T = \frac{fWV}{2a(k_1 + k_2)J} \tag{34.2}$$

where f = coefficient of friction, W = applied load, V = sliding speed, and k_1 and k_2 = thermal conductivities of the sliding materials. The quantity a is related to junction size, that is, the few, widely scattered points of contact between sliding parts.

From Eq. (34.2) it may seem that thermal conductivity of the materials could be influential in controlling temperature rise in some cases, but a more important factor is f, the coefficient of friction. If a temperature-sensitive wear mechanism is operative in a particular case, then high friction may contribute to a high wear rate, if not cause it. There is at least a quantitative connection between wear rate and the coefficient of friction when one compares dry sliding with adequately lubricated sliding, but there is no formal way to connect the coefficient of friction with the temperature rise.

Sliding Speed. Both the sliding speed and the *PV* limits are involved in determining the sliding severity. Maximum allowable loads and sliding speeds for materials are often specified in catalogs in the form of *PV* limits. In the *PV* product, *P* is the calculated average contact pressure (in psi) and *V* is the sliding speed (in ft/min). Plastics to be used in sleeve bearings and bronze bushings are the most common material to have *PV* limits assigned to them. A common range of *PV* limits for plastics is from 500 to 10 000, and these data are usually taken from simple laboratory test devices. The quantity *P* is calculated from W/A, where W = applied load and A = projected load-carrying area between sliding members. Thus *PV* could be written as WV/A. Returning to Eq. (34.2) for the temperature rise, it may be seen that the product WV influences ΔT directly, and it would seem that a *PV* limit might essentially be a limit on surface-temperature rise. This is approximately true, but not useful. That is, wear resistance of materials cannot be related in a simple way to the melting point or softening temperature of materials. The wide ranges of f, k, and other properties of materials prevent formulating a general rule on the relationship between *PV* limits and melting temperature. Indeed, a *PV* limit indicates nothing about the actual rate of wear of materials; it indicates only that above a given *PV* limit a very severe form of wear may occur. However, the *PV* limit for one material has meaning relative to that of other materials, at least in test machinery.

Misalignment. The difficulty with misalignment is that it is an undefined condition other than that for which contact pressure between two surfaces is usually calculated. Where some misalignment may exist, it is best to use materials that can adjust or accommodate themselves, that is, break in properly.

Misalignment arises from manufacturing errors or from a deflection of the system-producing loading at one edge of the bearing, or it may arise from thermal distortion of the system, etc. Thus a designer must consider designing a system such that a load acts at the expected location in a bearing under all conditions. This may involve designing a flexible bearing mount, or several bearings along the length of a shaft, or a distribution of the applied loading, etc.

Designers must also consider the method of assembly of a device. A perfectly manufactured set of parts can be inappropriately or improperly assembled, producing misalignment or distortion. A simple tapping of a ball bearing with a hammer to seat the race may constitute more severe service than occurs in the lifetime of the machine and often results in early failure.

Misalignment may result from wear. If abrasive species can enter a bearing, the fastest wear will occur at the point of entry of the dirt. In that region, the bearing will wear away and transfer the load to other locations. A successful design must account for such events.

Duty Cycle. Important factors in selecting materials for wear resistance are the extent of shock loading of sliding systems, stop-start operations, oscillatory operation, etc. It is often useful to determine also what materials surround the sliding system, such as chemical or abrasive particles.

Maintenance. A major consideration that may be classified under sliding severity is maintenance. Whereas most phosphor bronze bushings are allowed a contact stress of about 1.4 to 7 MPa, aircraft wheel bushings made of beryllium bronze are allowed a maximum stress of 620 MPa, as mentioned before. The beryllium bronze has a strength only twice that of the phosphor bronze, but the difference between industrial and aircraft use includes different treatment of bearings in maintenance. Industrial goals are to place an object into service and virtually ignore it or provide infrequently scheduled maintenance. Aircraft maintenance, however, is more rigorous, and each operating part is under regular scrutiny by the flight crew and ground crew. There is scheduled maintenance, but there is also careful continuous observation of the part and supplies. Thus it is easier for an error to be made in selection of the lubricant in industry than with aircraft, for example. Second, the aircraft wheel bearing operates in a much more standard or narrowly defined environment. Industrial machinery must operate in the dirtiest and hottest of places and with the poorest care. These must be considered as severity conditions by the designer.

34.4.4 Break-In Procedure

Another vital consideration in the selection of materials is to determine whether or not a break-in procedure is necessary or prohibited. It cannot be assumed that the sliding surfaces made to a dimensional accuracy and specified surface finish are ready for service. Sliding alters surfaces. Frequently, sliding under controlled light loads can prepare a surface for a long life of high loading, whereas immediate operation at moderate loads may cause early failure.

It is useful here to distinguish between two surface-altering strategies. The first we refer to as *break-in,* where a system is immediately loaded or operated to its design load. The incidence of failure of a population of such parts decreases with time of operation as the sliding surfaces change, and frequently the ability of the system to accommodate an overload or inadequate lubricant increases in the same time. The surfaces have changed in some way during running, and this is *break-in. Run-in,* however, is the deliberate and planned action that is necessary to prepare surfaces for normal service.

The wear that occurs during run-in or break-in can be considered a final modification to the machine surface. This leads to the possibility that a more careful specification of manufacturing practice may obviate the need for run-in or break-in. This has been the case with the automobile engine in particular, although part of a successful part surface-finish specification often includes the exact technique for making the surface. Only 30 years ago it was necessary to start and run an engine carefully for the first few thousand miles to ensure a reasonable engine life. If run-in were necessary today, one would not see an engine survive the short trip from the assembly plant to the haul-away trucks.

It is difficult to determine whether or not some of the present conservative industrial design practices result from the impracticality of effecting a run-in of some products. For example, a gear box on a production machine is expected to function immediately without run-in. If it were run in, its capacity might be greatly increased. But it is also well known that for each expected severity of operation of a device, a different run-in procedure is necessary. Thus a machine that has been operating at one level of severity may be no more prepared for a different state of severity than if it had never been run. A *safe* procedure, therefore, is to operate a device below the severity level at which run-in is necessary, but the device could actually be overdesigned simply to avoid run-in.

34.4.5 Modes of Wear Failure

The fifth consideration is to determine acceptable modes of wear failure or surface damage of machinery. To specify a wear life in terms of a rate of loss of material is not sufficient. For example, when an automotive engine seizes up, there is virtually no loss of material, only a rearrangement such that function is severely compromised. Thus in an engine, as well as on other precision slideways of machines, surface rearrangement or change in surface finish is less acceptable than attrition or loss of material from the system. Again, in metal-working dies, loss of material from the system is less catastrophic than is scratching of the product.

In truck brakes, some abrasiveness of brake linings is desirable, even though it wears brake drums away. This wear removes microcracks and avoids complete thermal fatigue cracking. However, in cutting tools, ore-crushing equipment, and amalgam filling in teeth, surface rearrangement is of little consequence, but material loss is to be avoided.

A final example of designing for an acceptable wear failure is a sleeve bearing in engines. Normally it should be designed against surface fatigue. However, in some applications corrosive conditions may seriously accelerate fatigue failure. This may require the selection of a material that is less resistant to dry fatigue than is the best bearing material, and this applies especially to two-layer bearing materials. In all these examples a study of acceptable modes of wear may result in a different selection of material than if the goal were simply to minimize wear.

34.4.6 Testing Materials

Finally, it is necessary to consider the possibility of testing candidate materials in bench tests or in prototypes. After some study of worn parts from a device or machine that most nearly approximates the new or improved product, one of several conclusions could be reached:

1. The same design and materials in the wearing parts of the example device will perform adequately in the redesign, in terms of function, cost, and all other attributes.
2. A slight change in size, lubrication, or cooling of the example parts will be adequate for the design.
3. A significant change in size, lubrication, or cooling of the example parts will be necessary for the redesign.
4. A different material will be needed in the redesign.

The action to be taken after reaching one of the preceding conclusions will vary. The first conclusion can reasonably be followed by production of a few copies of the redesign. These should be tested and minor adjustments made to ensure adequate product life. The second conclusion should be followed by cautious action, and the third conclusion should invoke the building and exhaustive testing of a prototype of the redesign. The fourth conclusion may require tests in bench-test devices in conjunction with prototypes.

It is usually costly and fruitless to purchase bench-test machinery and launch into testing of materials or lubricants without experience and preparation. It is doubly futile for the novice to run accelerated wear tests with either bench tests, prototypes, or production parts.

Experience shows time after time that simple wear tests complicate the prediction of product life. The problem is correlation. For example, automotive company engineers have repeatedly found that engines on dynamometers must be run in a completely unpredictable manner to achieve the same type of wear as seen in engines of cars in suburban service. Engines turned by electric motors, though heated, wear very differently from fired engines. Separate components such as a valve train can be made to wear in a separate test rig nearly the same way as in a fired engine, with some effort, but cam materials rubbing against valve-lifter materials in a bench test inevitably produce very different results from those in a valve-train test rig.

Most machines and products are simpler than engines, but the principles of wear testing are the same; namely, the wear mechanisms must be very similar in each of the production designs, the prototype test, the subcomponent test, and the bench test. The wear rate of each test in the hierarchy should be similar, the worn surfaces must be nearly identical, and the transferred and loose wear debris should contain the same range of particle sizes, shapes, and composition. Thus it is seen that the prototype, subcomponent, and bench tests must be designed to correlate with the wear results of the final product. This requires considerable experience and confidence where the final product is not yet available. This is the reason for studying the worn parts of a product nearest to the redesign and a good reason for retaining resident wear expertise in every engineering group.

A clear indication of the problem with bench tests may be seen in some results with three test devices. These are:

1. Pin-V test in which a ¼-in-diameter pin of AISI 3135 steel rotates at 200 rpm with four-line contact provided by two V blocks made of AISI 1137 steel.
2. Block-on-ring test where a rectangular block of a chosen steel slides on the outer (OD) surface of a ring of hard case-carburized AISI 4620 steel.
3. The four-ball test where a ball rotates in contact with three stationary balls, all of hardened AISI 52100 steel.

The four-ball test and the ring-on-block test were run over a range of applied loads and speeds. The pin-V test was run over a range of loads only. All tests were run continuously, that is, not in an oscillating or stop-start sequence mode. All tests were run with several lubricants.

Results from the ring-block test were not sufficiently reproducible or consistent for reliable analysis. Results from the other two tests were adequate for the formulation of a wear equation from each, as follows:

Pin-V test: $\text{Wear rate} \propto (\text{load})^2$

Four-ball test: $\text{Wear rate} \propto (\text{load})^{4.75} \times (\text{speed})^{2.5}$

These results may be compared with linear laws of wear discussed frequently in the literature, which would be of the form

Linear law: $\text{Wear rate} \propto (\text{load})^{1.0} \times (\text{speed})^{1.0}$

There are several points about the usefulness of published wear data to be derived from these results:

1. Practical wear rates are probably not linear in any parameter or variable of operation.
2. If three standard wear tests respond differently to changes in load and speed, then a practical part will probably respond differently again. Furthermore, an accelerated test with a standard wear tester will likely be misleading, since the influence of doubling load or speed would most likely be different between the test device and the product. In fact, the effect of variation in load and speed produces very irregular results with the block-on-ring test machine, which renders extrapolated values of tests useless.
3. It is not known whether the different results from the three wear testers are due to the use of different specimen materials or different specimen shapes or both. Thus rank ordering of materials from wear tests is likely to change among test devices and different testing conditions.

The point of the preceding discussion is that wear testing of materials and components must be done, but it must be done carefully. Testing should be done by experienced engineers and with a strong insistence upon close analysis of worn surfaces and wear debris. It would be useful to be able to compare one's observations with a large and comprehensive atlas of photographs of surfaces in various stages of wear, but none is available. Photographs are scattered through published papers and handbooks and are of some value only when properly described and understood.

Engineers must therefore solve most wear problems themselves by analysis of worn surfaces and wear debris from existing machinery and wear testers. Guidelines for selecting wear-resisting materials and for indirectly selecting lubricants are given in the next section using the methods of product analysis.

34.5 MATERIAL-SELECTION PROCEDURE

The previous sections have established the important point that selecting materials for wear resistance requires a study of the details of wear in order to determine which of the several conventional properties of material can best resist a particular mode of wear. The best way to proceed, therefore, is to examine the most appropriate wear system (including the solids, the lubricant, and all the wear debris), such as an old product being redesigned or a wear tester. The best tools to use are microscopes, with some photography. The most useful microscope is a stereozoom type with a magnification range of 1× to 7×, with 5× or 10× eyepieces and a 100-W movable external light source. Stereo viewing gives a perspective on the shapes of surface features, such as grooves, folds, flakes, etc. The next most useful tool is the scanning (reflecting) electron microscope (SEM). The novice should use this instrument in conjunction with optical microscopes because the SEM and optical devices produce very different pictures of surfaces. Frequently the most useful SEM observations are those done at low magnification, between 20× and 200×, although it is fun to "see" surfaces at 20 000×. The virtue of the SEM is that very rough surfaces can be seen without the high regions and low regions being out of focus, as occurs in optical microscopy. The major problem is that the SEM usually accepts only small specimens [for example, ½ in (12.5 mm) thick by 2 in (50 mm) in diameter], and the surfaces must be clean because the SEM requires a vacuum (about 10^{-5} torr).

For a more detailed analysis of surface chemistry and substrate composition, an SEM with an x-ray dispersion (EDAX, etc.) attachment can be used. The operation of these instruments requires some combination of skill and expensive automation. Optical metallurgical microscopes may be useful as well, but usually not in the conventional bright-field, reflected-light mode. These microscopes often have several special objectives for phase contrast, polarized light, interference, and dark field, all requiring skill in use and in the interpretation of results.

Sometimes it is useful to obtain a topographic profile of worn surfaces. This can be done with the stylus tracer used in conventional surface-finish measurement, but it should be connected to a strip-chart recorder. It is the surface shape rather than a numerical value of surface finish that is most useful. Traces should be made in several places and in several directions during the progression of wearing, if possible. A major precaution to observe in analysis of the strip-chart data is that the representation of the height of surface shapes is often magnified from 10 to 1000 times greater than is the "horizontal" dimension. This leads to the sketching of surfaces as very jagged peaks upon which no one would care to sit. Actually, solid surfaces are more like the surfaces of a body of water in a 10-mi/h breeze.

Having examined a wear system, the designer can proceed through Table 34.3 and make a first attempt to select a material for wear resistance.

TABLE 34.3 Guide for Determining the Material Properties that Resist Wear

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How to use the table:

1. Observe the nature of wear in existing equipment or of similar materials from appropriate wear-testing machines.
2. Check the lists in Section A for an applicable general description of worn surfaces or type of service and note the code that follows the selected term.
3. Proceed to Section B which lists 6 terms† that describe three scales of superimposed surface changes. Verify that the code listing is an adequate description of the worn surface. (It is possible to use Section B without reference to Section A.) From Section B, find the major term (capitalized).
4. In Section C, find the detailed description of the capitalized term from Section B and note which material-loss mechanism is applicable and confirm from the nature or description of wear debris.
5. Find the material-loss mechanism in Section D, note the material characteristics and microstructure that should influence wear resistance of material, and note the precautions in material selection to prevent failure.
6. Select materials in conjunction with materials specialists.

Section A Description of worn surfaces and type of service with code for use in Section B

General surface appearance‡	Some types of service‡
Stained: *f*	Surface corrosion or Erosion/corrosion in solid machinery: *a*1 + *c* in fluids: *a*2 + *d*2
Polished or smooth wear: *a*1 + *c* + *e* or *a*2 + *c* + *e*	
Scratched (short grooves): *b*3 + *c* + *e*	Abrasive wear (multiple scratches): *b*3 + *c*
Gouged: *b*3 + *d*1	
Scuffed: *a*1 + initiated and periodically perpetuated by *d*3 + *e*	Gouging: *b*1 + *d*1 + *e*
Galled: *b*1 + *d*3 + *3* (usually very rough)	Dry wear or unlubricated sliding: *b*1 + *d*3 + *e* or *a*1 + *c* + *e*
Grooved (smooth or rough): *a*1 + periodically advanced by *d*1 + *e*	Metal-to-metal wear or adhesive wear: *b*1 + *d*3 + *e*
Hazy: *b*2	Erosion at high angle: *b*2 + *d*4
Exfoliated or delaminated: *d*4 + *e*	Erosion at low angle: *b*3 + *d*1 or *d*2
Pitted: *b*2 and/or *d*5	
Spalled: *d*4	
Melted: *a*3	
Fretted: *a*1 + *d*5 + *f*	Fretting: *a*1 + *d*5 + *f*

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†Surface geometries can usually be described in three scales, namely, macro-, micro-, and submicro. The first two scales can describe roughness; the third describes reflectivity. The worn surfaces in Section A may be described in terms of the three scales; e.g., polished surfaces are usually microsmooth (a), macrosmooth (c), and shiny (e). The numbers following the code letters explain how the suggested scale of surface geometry wa achieved, i.e., by abrasion which left a very thin film on the surface. Thus the code, polished wear—*a*1 + *c* + *e*, etc. Where a scale of geometry is not given, that scale may not be of consequence in the description of the worn surface.

‡Rigorous connection cannot always be made between the terms in the two columns in Section A because of the wide diversity of use and meaning of terms.

TABLE 34.3 Guide for Determining the Material Properties that Resist Wear *(Continued)*

Section B Code listing

a. Microsmooth, caused by
   1. Progressive loss and reformation of surface films by fine *abrasion* and/or by tractive stresses imposed by *adhesive* or viscous interaction, or by
   2. Very fine *abrasion,* with loss of substrate in addition to loss of surface film, if any, or
   3. From *melting.*

c. Macro-smooth, caused by, abrasive particles held on or between solid, smooth backing

e. Shiny, due to very thin (<25nm?) surface films of oxide, hydroxide, sulfide, chloride, or other species

b. Microrough, caused by
   1. Tractive stresses resulting from *adhesion,* or by
   2. Micropitting by *fatigue,* or by
   3. *Abrasion* by medium-coarse particles

d. Macrorough, caused by
   1. *Abrasion* with coarse particles, including carbide and other hard inclusions in the sliding materials that are removed by sliding action as the wear of matrix progresses, or by
   2. *Abrasion* by fine particles in turbulent fluid, producing scallops, waves, etc., or by
   3. Severe *adhesion* in early stages of damage, or by
   4. Local *fatigue* failure resulting in pits or depressions due to repeated rolling-contact stress, repeated thermal gradients, high-friction sliding, or impact by hard particles as in erosion, or in
   5. Advanced stages of microroughening, where little unaffected surface remains between pits.

f. Dull or matte, due to films of perhaps greater than 25-nm thickness (resulting from aggressive environments, including high temperatures), i.e., due to *corrosion*

Section C Material-loss mechanisms and nature of debris

Material-loss mechanisms (italic)	Nature of debris
Corrosion (of surface): Chemical combination of material surface atoms with passing or deposited active species to form a new compound, i.e., oxide, etc.	Newly formed chemical compound, usually agglomerated and sometimes mixed with fragments of the original surface material
Abrasion: Involves particles (or acute angular shapes but mostly obtuse) that produce wear debris, some of which forms ahead of the abrasive particle, which mechanism is called *cutting,* but most of which is material that has been plowed aside repeatedly by passing particles, and breaks off by *low-cycle fatigue.*	Long, often curly chips or strings

TABLE 34.3 Guide for Determining the Material Properties that Resist Wear *(Continued)*

Section C Material-loss mechanisms and nature of debris (*Continued*)

Material-loss mechanisms (italic)	Nature of debris
Adhesion: A strong bond that develops between two surfaces (either between coatings and/or substrate materials) that, with relative motion, produces tractive stress that may be sufficient to deform materials to fracture. The mode of fracture will depend on the property of the material, involving various amounts of energy loss or ductility to fracture, that is,	
Low energy and ductility → *brittle fracture*	Solid particles, often with cleavage surfaces
High energy and ductility → *ductile fracture*	Severly deformed solids, sometimes with oxide clumps mixed in
Fatigue: Due to cyclic strains, usually at stress levels below the yield strength of the material, also called *high-cycle fatigue*	Solid particles, often with cleavage surfaces and ripple pattern
Melting: From very high-speed sliding	Spheres, solid or hollow, and "splat" particles

Section D Material-selection characteristics

Material-loss mechanisms	Appropriate material characteristics to resist wear	Precautions to be observed when selecting a material†
Corrosion	Reduce corrosiveness of surrounding region; increase corrosion resistance of material by alloy addition or by selection of soft, homogeneous material	Total avoidance of new surface species can result in high adhesion of contacting surfaces; soft materials tend to promote galling and seizure.
Cutting	Use material of high hardness, with very hard particles or inclusions, such as carbides, nitrides, etc., and/or overlaid or coated with materials that are hard or contain very hard particles	All methods of increasing cutting resistance cause brittleness or lower fatigue resistance.
Ductile fracture	High strength achieved by any method other than cold working or heat treatments that produce internal cracks and large, poorly bonded intermetallic compounds	
Brittle fracture	Minimize tensile residual stress for cold temperature; ensure low-temperature brittle transition; temper all martensites; use deoxidized metal; avoid carbides such as in pearlite, etc.; effect good bond between fillers and matrix to deflect cracks	In essence, soft materials will not fail through brittleness and will not resist cutting.
Low-cycle fatigue	Use homogeneous and high-strength materials that do not strain-soften; avoid overaged materials and two-phase systems with poor adhesion between filler and matrix	

TABLE 34.3 Guide for Determining the Material Properties that Resist Wear *(Continued)*

Section D Material-selection characteristics

Material-loss mechanisms	Appropriate material characteristics to resist wear	Precautions to be observed when selecting a material†
High-cycle fatigue	For steel and titanium, use stresses less than half the tensile strength (however achieved); for other materials to be load-cycled less than 10^8 times, allow stresses less than one-fourth the tensile strength (however achieved); avoid retained austenite; use spherical pearlite rather than plate structure; avoid poorly bonded second phases; avoid decarburization of surfaces; avoid platings with cracks; avoid tensile residual stresses or form-compressive residual stresses by carburizing or nitriding	Calculation of stress should include the influence of tractive stress.
Melting	Use material of high melting point and/or high thermal conductivity	

†Materials of high hardness or strength usually have decreased corrosion resistance, and all materials with multiple and carefully specified properties and structures are expensive.

SOURCE: From Ludema [34.2].

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