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Abrasive Wear Failures*

ENGINEERED COMPONENTS fail predominantly in four major ways—by fracture, corrosion, wear, and undesirable deformation (i.e., distortion). Fracture is the growth of a single crack that leads to separation of the part, as discussed in detail in other articles in this Volume. Typical fracture mechanisms feature rapid crack growth by ductile or brittle cracking; more progressive (subcritical) forms involve crack growth by fatigue, creep, or environmentally-assisted cracking. Corrosion and wear are another form of progressive material alteration or removal that can lead to failure or obsolescence.

Obsolescence of a component occurs when its intended design or function is superseded by a more useful or efficient design or function. Sometimes, the improvement is related to a geometric change in the component or some part of that component; sometimes, the improvement is related to a change in the materials of construction; or sometimes, the entire mechanism/component is no longer needed. In each of these cases, an opportunity exists whereby the part or component is modified in a significant manner, with attendant changes in its operating performance.

The act of material removal or surface modification eventually affects the ability of the part to perform its intended function. Figure 1 shows a schematic diagram of the "loss of usefulness of material objects" due to obsolescence (15%), breakage (15%), and surface deterioration (70%) (Ref 1). Of the 70% loss of usefulness due to surface deterioration, wear accounts for approximately 55%, while corrosion accounts for the other 15%. Thus, wear can be a serious problem in design engineering and materials selection. Moreover, of the 55% due to wear, the loss of usefulness from abrasion is 20%. Consequently, abrasive modes of wear are a significant factor in the loss of usefulness of materials.

Wear is the gradual (or sometimes not so gradual) removal of material, or the rearrangement of a surface without removal of material, from the wearing surface of a part or component. Similar to the other forms of failure, there are several well-defined wear failure types. The wear of metal parts is commonly classified into two categories: abrasive wear and adhesive wear, as described in the section "General Classification of Wear" in this article. Sometimes, erosive wear is classified as a third category. Erosive-type wear includes phenomena from liquid impingement and cavitation wear, as discussed in other articles in this Section on "Wear Failures." Another special type of wear is contact fatigue, where cyclic (rolling) bearing loads produce subsurface cracking and subsequent surface wear.

This article primarily covers the topic of abrasive wear failures. However, the section "Wear Failure Analysis" in this article discusses methods that may apply to any form of wear mechanism, because it is important to identify all mechanisms or combinations of wear mechanisms during failure analysis. Frequently, more than one mechanism may be operating simultaneously, and it may be difficult to separate the effects of one from the other. Conditions of adhesive wear may also sometimes be ambiguous relative to other forms of wear. Thus, adhesive wear may sometimes be identified by excluding other forms of wear. For example, adhesive wear may be likely if no abrasive particles are identified, if the sliding motion is greater than that of fretting, or if corrosion reduction or oxidation do not occur. Finally, the other three types of failures (fracture, corrosion, and distortion) may also be factors. For example, unwanted distortion may lead to wear, or vice versa.

Of course, the reason for conducting a wear failure analysis is to determine and describe the factors responsible for the failure for business or technical reasons. From an engineering standpoint, the proper application of failure analysis provides feedback to designers on design problems and material limitations. Specifically, an optimal design is one where the performance requirements are slightly exceeded by the part or component capabilities in all circumstances. This aim is seldom, if ever, achieved in real systems, because of the difficulty in recognizing and/or defining the various operating demands that the system is called on to meet. This consideration is only generally met by using a safety factor in the design of the part or component. However, the question remains, how best to design a component where acceptable performance and extended life are obtained without excessively overdesigning the part or component. On the other hand, if a part were underdesigned to save money or material, then premature failure is possible, with all the negative aspects related to it.

Figure 2 (Ref 2) highlights the relationship between the various aspects of the design pro-

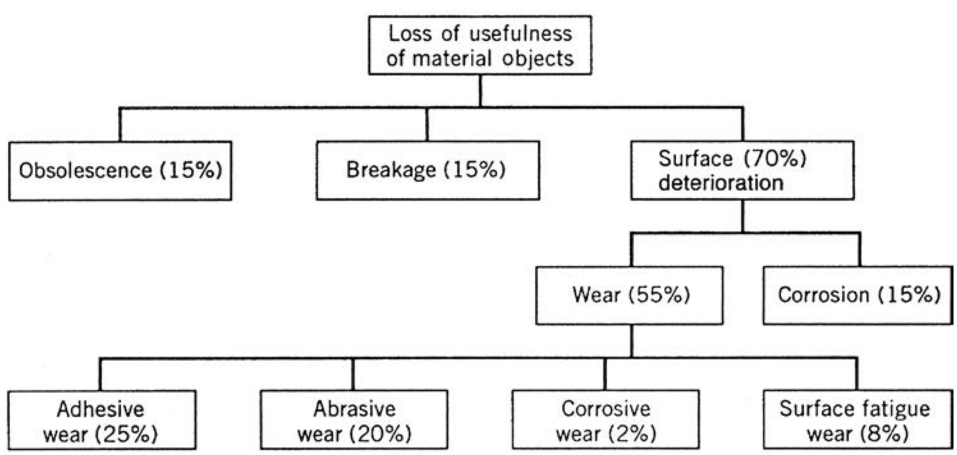

Fig. 1 The causes of loss of usefulness of material objects, with a percentage estimate of the economic importance of each. Source: Ref 1

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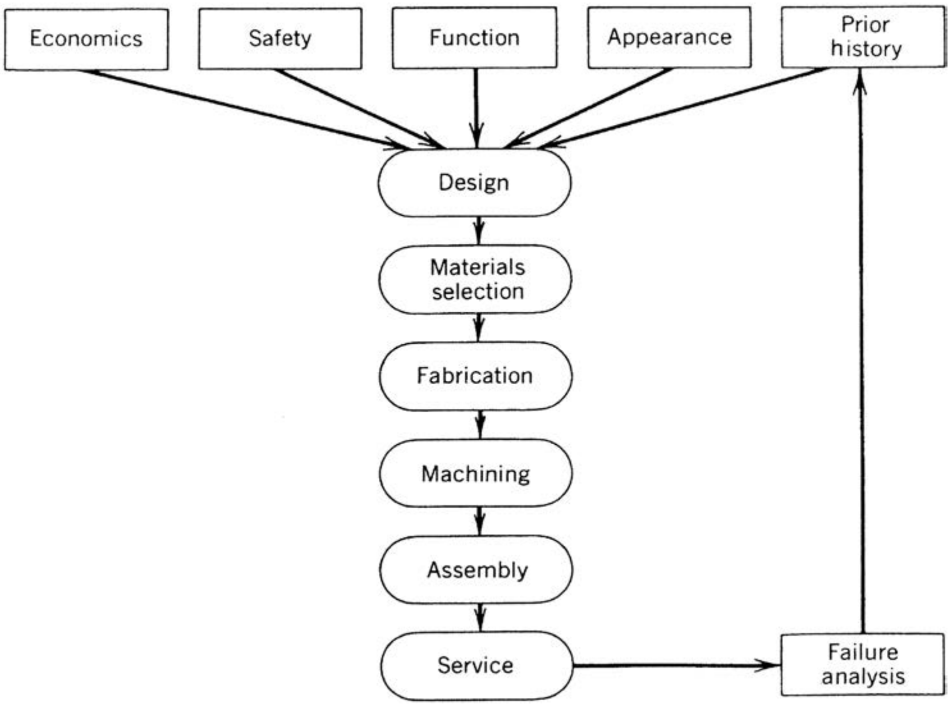


Fig. 2 Relationship of failure analysis to the design and production of a component. Source: Ref 2

cess and ways in which failure analysis is thoughtfully applied to improve the design process. Legal reasons for conducting failure analyses are also compelling, because of the shift in product liability laws from the status of the plaintiff to the nature of defectiveness in the product.

Several fundamental factors related to material failures or loss of service life have been identified, and underlying factors may be organized in different ways by different authors. (See, for example, the article "Introduction to Failure Analysis and Prevention" in this Volume.) For metallic materials, fundamental factors related to material failures can be considered to include (Ref 2):

- Design
- Improper selection of material
- Heat treatment
- Fabrication
- Improper machining and assembly

These factors may be related to the occurrence of a failure in various ways, for example, the initiation of a crack or the increased susceptibility to wear or corrosion.

General Classification of Wear

In any engineering field where various contact processes are involved, some method of classification is required to provide a convenient breakdown of that system, so it can be studied systematically (Ref 3, 4, 5). Specific reasons for classifying wear include (Ref 6):

- A good classification system promotes consistency of approach to the problem, with clarification and standardization of terms to remove ambiguity and misconceptions.
- A structured approach can facilitate understanding of the wear process, through differentiation of wear types.
- If the type of wear in a particular industrial operation is known, there is a possibility of simulating this kind of wear in laboratory tests in order to obviate extensive programs of expensive field trials.

The usual starting point in developing a wear classification scheme is to define wear. The following definition is attributed to Gates and Gore (Ref 6): "Wear is the cumulative surface damage phenomenon in which material is removed from a body as small debris particles, primarily by mechanical processes."

Although discussion exists, and probably always will, on precise definitions, the wear of metal parts is commonly classified into two categories: abrasive wear and adhesive wear, as described in the following.

Abrasive Wear

From this starting point, it is now convenient to expand the definition in order to define abrasive wear. Once again, following the discussion of Gates and Gore (Ref 6), abrasive wear can be defined as "wear in which hard asperities on one body penetrate the surface of a softer body and 'dig' material from the softer surface, leaving a depression or groove." The asperities may be small, hard particles or may be asperities of the larger, harder body. Because the most obvious manifestation of this type of wear is the groove produced in the surface, abrasive wear has also been termed grooving wear (Ref 7). Further refinements to this definition include classification into categories as to the types, or modes, of abrasive wear that occur, such as two- and three-body abrasion, sliding abrasion, gouging abrasion, high- and low-stress abrasion, impact abrasion, grinding abrasion, and so on. The more precise terminology for some of these classifications is further explained subsequently.

In the excavation, earth-moving, mining, and mineral-processing industries, the following broad classifications have generally been used to describe the manifestations of abrasive wear that are seen on worn parts (Ref 8, 9, 10): gouging abrasion; high-stress, or grinding, abrasion; low-stress, or scratching, abrasion; and solid-particle erosion. In addition to the aforementioned classification scheme, the term *two-* and *three-body abrasive wear,* that is, components of sliding abrasion, has also been used to discriminate between abrasion modes.

Gouging Abrasion

Gouging abrasion occurs under conditions where abrasive particles indent and move over the wear surfaces under high stress levels. It involves both cutting and tearing types of wear, in which small chips of metal are removed from the wearing surface by the movement of the sharp points of rock, under considerable pressure, over the wearing surface. This type of action is very similar to machining by a cutting tool. In gouging abrasion, the wearing surface is plastically deformed and work hardened by the abrasive forces, so that cutting and tearing of metal occurs on the work-hardened surface. Typical operations that involve gouging abrasion include crushing and primary grinding operations. The wear liners of crushing units are particularly susceptible to gouging abrasion. This type of wear also occurs to the liners of large grinding mills, particularly large autogenous and semiautogenous mills, where large chunks of ore (up to 250 mm, or 10 in., in diameter) are to be broken up by the tumbling action. Gouging abrasion also occurs in impact crushers or almost anywhere where coarse rocks impact a metal surface under considerable pressure or force, for example, digger teeth on power shovels and dragline buckets used to scoop up loose rock.

Gouging abrasion normally occurs in the crushing and handling of large chunks of rock. It is accompanied by heavy impact and by high bending and compressive forces on the wearing parts, which are made as heavy-section castings. As a result, the choice of ferrous alloys that can be used with confidence in these applications is limited. Traditionally, austenitic 12% Mn steels are used as crusher liners. They have fairly good resistance to gouging abrasion, combined with good toughness and the ability to be heat treated in heavy sections (Ref 9). For other applications involving gouging abrasion, such as autogenous mill liners, impactor bars in impact crushers, and earth-moving tools, the manganese steels have been partially displaced by low-alloy quenched-and-tempered steels and martensitic white irons (Ref 10).

High-Stress, or Grinding, Abrasion

High-stress, or grinding, abrasion occurs when abrasive particles are compressed between two solid surfaces, as, for example, between grinding rods or balls. The high-stress abrasion that occurs in grinding mills takes place over a very small contact region, where the ore particles are caught between the grinding balls or between grinding balls and the mill liner. The high contact pressure produces indentations and scratching of the wearing surfaces and fractures and pulverizes the abrasive ore particles. Hard minerals, such as quartz, indent and scratch martensitic steels having yield strengths of 2100 MPa (300 ksi) (Ref 9). High-stress abrasion is sometimes referred to as three-body abrasion, although two-body, high-stress conditions can sometimes exist. High-stress abrasion implies that the abrasive particle is fractured and broken apart during the wear process. How these small abrasive particles affect the actual removal of material in mineral processing is not well understood. It has been speculated that high-stress grinding abrasion produces wear by a combination of cutting, plastic deformation, surface fracture on a microscopic scale, as well as by tearing and fatigue, or spalling (Ref 9).

In ore-processing plants, high-stress abrasion produces practically all of the wear on grinding balls and liners in ball mill grinding units. In rod mills that accept larger chunks of ore, during the first stage of grinding, the wear of the grinding rods and liners proceeds by both gouging abrasion and high-stress grinding abrasion. In autogenous grinding mills, charged with ore from 250 to 0.2 mm (10 to 0.01 in.) in diameter, both gouging abrasion and grinding abrasion occur.

In high-stress grinding abrasion, the microstructure of the balls and liners influences the wear rate. In unalloyed or low-chromium white iron balls, an Fe_3C-type carbide (Vickers hardness of 7.8 to 9.8 GPa, or 1130 to 1420 ksi) structure coexists in a relatively soft ferrite or pearlite (HV of approximately 1.0 to 2.9 GPa, or 145 to 420 ksi) matrix. This results in a composite HV for the alloy of between 4.9 and 5.9 GPa (710 and 855 ksi). However, in spite of the relatively high hardness of the composite structure, the balls tend to wear at a rate equivalent to that of the ferrite or pearlite matrix. The abrasive forces that occur during grinding are sufficient to fracture and crumble the carbides, which are poorly supported by the ferrite or pearlite matrix. In a matrix that contains martensite, however, the carbides do not fracture as readily, and consequently, better abrasion resistance is obtained.

Low-Stress, or Scratching, Abrasion

Low-stress, or scratching, abrasion occurs when lightly loaded abrasive particles impinge on, and move across, the wear surface, cutting and plowing it on a microscopic scale. In aqueous or other liquid environments, corrosion may also contribute to the overall wear rate, in which case erosion-corrosion is the operative wear mechanism. In both cases, low-stress abrasion is the primary mode of wear. The wear rates in terms of metal thickness removed per day are quite low in low-stress abrasion, so a significant portion of the total wear is probably due to the abrasion of a continually reforming oxide film. This may be especially true in the handling of particulates in a wet environment, such as slurries.

Low-stress scratching abrasion in ore-processing machinery occurs primarily in the pumping of sand slurries; in size-classifying equipment such as cyclones and gravity classifiers; in chute liners, screens, and flotation impellers; and in hydraulic and pneumatic conveying operations. Generally, the impingement angles and particle impact forces are so low that hard and brittle constituents of the microstructure are not fractured or microspalled by the abrasive forces. Under these circumstances, ferrous alloys containing hard carbides have good to excellent wear resistance. Ceramics and synthetic stone (e.g., fused silicates) are also used for these applications. Molded rubbers and polyurethanes can also work well in low-stress abrasive conditions, particularly in pump and flotation impellers, linings for cyclone classifiers, and in pipes and screen decks in some screening applications (Ref 10).

Table 1 summarizes each of these classifications in terms of the abrasive size, the nature of contact, and the environmental factors. Figure 3 shows in schematic form the four classifications. All of these mechanisms are similar in that a hard particle moves across the component surface in some manner. Particle type, shape, size, and hardness ultimately determine the type and severity of abrasive wear.

Sliding Abrasion

Contrary to gouging abrasion is sliding abrasion. Sliding abrasion more precisely refers to two- and three-body situations where the relative motion between the abrasive particle and the wear surface is 100% sliding, or nearly so. The term *sliding abrasion* is typically used to describe the two-body situation where there is little to no tumbling or rolling of the abrasive particles. The differentiation between the two-body and three-body concept, on the one hand, focuses on whether the abrasive particles are rigidly fixed (two-body) or free to move (three-body). Alternatively, two- and three-body abrasion can be thought of as whether there is a separate material counterface backing the abrasive. Two-body abrasion implies unconstrained abrasive material, while three-body abrasion holds that the abrasive particles are constrained by a counterface. A typical cited example of two-body abrasive wear is the action of an abrasive particle sliding across a stationary surface, with the abrasive comprising one body, while the stationary surface of the component or part being worn comprises the second. This situation is encountered in materials handling situations where grain or minerals slide in a chute or trough. The contact pressure between abrasive and wearing surface is controlled by the size, shape, and quantity of the abrasive. Three-body wear implies that the abrasive is trapped between two other independent bodies, for example, rock in a rock crusher or specks of dirt between a computer hard disk drive and the reading head. The imposed constraint is pivotal in the level of contact pressures generated between abrasive and wear surface. The relative motion is also directly affected. In some cases, the trapped body may roll much more than it slides, as a consequence of being constrained. In other cases, an abrasive embedded in a material, for example, a polymer, may not be able to rotate at all, and any encounter with the third surface results in pure sliding. The problem with the nuances in terminology is confusion as to the precise meaning of the terms. However, the reader should be aware of the

Table 1 General classification of abrasive wear in mining and minerals processing equipment

Classification	Gouging abrasion	High-stress abrasion	Low-stress abrasion	Erosion-corrosion
Abrasive size	Large	Medium	Small	Fine
Contact conditions				
Impact	High	Low	Low	Low
Force	High	High	Low	Moderate
Velocity	Low	Low	Variable	High
Impingement angle	Low	Low	Medium low	Variable
Environmental	Generally dry	Generally as slurry, variable pH	Variable	Generally as slurry, variable pH
Principal mechanisms	Plowing, cutting	Cutting, some fragmentation and corrosion	Cutting, some corrosion	Cutting, plowing, fragmentation, and corrosion

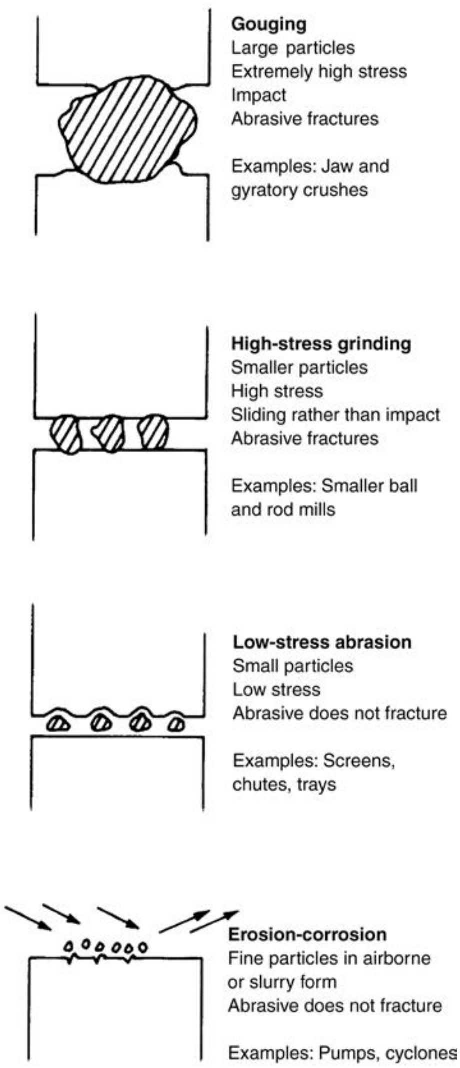


Fig. 3 Schematic representation of the four abrasive wear classifications. Source: Ref 5

terminology used in the literature to describe manifestations of abrasive wear.

Adhesive (Sliding Contact) Wear

As previously noted, the types of wear are sometimes classified as abrasive and adhesive wear. Adhesive wear is the result of microscopic welding at the interface between two mutually soluble metals. Adhesion is a major contributor to sliding resistance (friction) and can cause loss of material at the surface (wear) or surface damage without a loss of material at the surface (e.g., galling or scuffing).

Adhesive wear typically occurs from the sliding contact of two surfaces, where local adhesion causes separation and transfer of material from the surface. Sliding contact can also produce special forms of surface damage, such as galling and fretting. In most cases (except in the case of fretting), sliding or adhesive wear can be entirely prevented by use of a proper lubricant. Wear rates depend on the type of contact and lubrication conditions.

Galling

Galling is considered to be a severe form of adhesive wear that occurs when two surfaces slide against each other at relatively low speed and high load. With high loads and poor lubrication, surface damage can occur on sliding metal components. The damage is characterized by localized macroscopic material transfer, that is, large fragments or surface protrusions that are easily visible on either or both surfaces. This gross damage is usually referred to as galling, and it can occur after just a few cycles of movement between the mating surfaces. The terms *scuffing* and *scoring* are also used to describe similar surface damage under lubricated conditions. Scuffing is the preferred term when the damage occurs at lubricated surfaces, such as the piston ring virgule cylinder wall contact. Scoring typically describes damage that takes the form of relatively long grooves.

Severe galling can result in seizure of the metal surfaces. Materials that have limited ductility are less prone to galling, because under high loads, surface asperities tend to fracture when interlocked. Small fragments of material may be lost, but the resultant damage is more similar to scoring than to galling. For highly ductile materials, asperities tend to plastically deform, thereby increasing the contact area of mated surfaces; eventually, galling occurs.

Another key material behavior during plastic deformation is the ease with which dislocations cross slip over more than one plane. In face-centered cubic materials, such as austenitic stainless steels, dislocations easily cross slip. The rate of cross slip for a given alloy or element is usually indicated by its stacking-fault energy. Dislocation cross slip is hindered by the presence of stacking faults, and a high stacking-fault energy indicates a low number of impeding stacking faults and an increased tendency to cross slip and hence gall. Nickel and aluminum have poor galling resistance, whereas gold and copper have good galling resistance. Austenitic stainless steels with high work-hardening rates have relatively low stacking-fault energies and have been shown to have less tendency to gall.

Materials that have a hexagonal close-packed structure with a high c/a ratio have a low dislocation cross-slip rate and are less prone to galling. This explains why cobalt-base alloys and cadmium-plated alloys resist galling, while titanium alloys tend to gall.

The factors that affect wear and galling can be design, lubrication, environmental, and material related. Component design is probably the most critical factor. When stainless steels are required, proper design can minimize galling and wear. Similar applications, such as valve parts, can often result in wear-related problems for one company or be of very little concern for another, despite their use of the same alloy.

In dies, common causes of galling are stretching sheet metal beyond practical limits, tool fitting with poor alignment or insufficient die clearance for the given sheet thickness, wrinkles, the use of galling-susceptible tool steel, and rough finish on the surface of tools. Correct lubrication of the parts being drawn is essential to reduce friction, wear, and galling. In actual practice, die materials are selected after trials employing the production lubricants. If excessive wear or galling occurs, a better lubricant is usually applied. For extremely difficult draws, the best lubricants are usually applied at the outset.

Fretting

Fretting is a special form of sliding contact wear that proceeds by mild adhesive wear in combination with abrasive wear. Fretting wear is material loss that is due to very small-amplitude vibrations at mechanical connections, such as riveted joints. This type of wear is a combination of oxidation and abrasive wear. Oscillation of two metallic surfaces produces tiny metallic fragments that oxidize and become abrasive. Subsequent wear proceeds by mild adhesive wear in combination with abrasive wear.

Fretting wear is influenced by contact conditions, environmental conditions, and material properties and behavior. Key parameters in fretting include load, frequency, amplitude of fretting motion, number of fretting cycles, relative humidity, and temperature. Fretting wear rate is virtually independent of amplitude up to a critical value. Beyond that, the wear rate increases almost linearly with the amplitude. Fretting also is different from general adhesive wear in one important way. True fretting cannot be remedied completely by lubrication, while general adhesive wear can be prevented by lubrication.

Abrasive Wear Mechanisms

Of all the areas where abrasive wear is a problem, probably the most severe environment is in the excavation, earth-moving, mining, and minerals-processing industries, where component deterioration occurs in a wide variety of equipment, such as bulldozer blades, excavator teeth, rock drill bits, crushers, slushers, ball mills and rod mills, chutes, slurry pumps, and cyclones. However, abrasive wear is not limited to these activities. Abrasion presents problems in many wear environments at one point or another, even though it may not be the primary wear mechanism to begin with. In any tribosystem where dust and wear debris are not, or cannot be, controlled and/or excluded, abrasive wear is eventually a major problem. The wear of parts, the cost of repair and replacement of these parts, and the associated downtime related to these activities result in significant costs to many industries.

The individual factors that influence abrasive wear behavior are shown in Table 2. For both the abrasive and wear material, the majority of factors that affect abrasive wear behavior are related to their respective mechanical properties. Also of importance is the mechanical aspect of the abrasive/wear material interaction. Chemical processes, however, are also important, that is, corrosion or oxidation, because they directly influence the rate of wear of a material in the environment of interest.

The influence of the parameters listed in Table 2 can be explained by their effect on the mechanism by which material is removed from a worn surface. The simplest model of abrasive wear is one in which rigidly supported hard particles indent and are forced across the surface of the wear material. Depending on the properties of the abrasive and wear materials, one of several wear mechanisms (Fig. 4) may occur (Ref 7, 10):

- *Plowing* occurs when material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles.
- *Cutting* occurs when material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves. This mechanism closely resembles conventional machining.
- *Fragmentation* occurs when material is separated from a surface by a cutting process, and the indenting abrasive causes localized fracture of the wear material. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling.

The plowing and cutting mechanisms involve predominantly plastic deformation of the wear material, while the third mechanism also involves fracture. Thus, the dominant mechanisms that occur for a particular operating condition are influenced to a great extent by the plastic deformation and fracture behavior of the wear material. Materials that exhibit high fracture resistance and ductility with relatively low yield strength are more likely to be abraded by plowing. Conversely, materials with high yield strength and with low ductility and fracture resistance abrade through fragmentation (Ref 7, 10, 11).

Additional wear mechanisms can operate in materials that exhibit a duplex microstructure or that are made up of two or more component phases (e.g., a composite-type material, such as a high-chromium white iron, or a composite drill bit, such as diamond or tungsten carbide inserts in a steel matrix), the individual components of which vary in their mechanical properties. Under some abrasive wear conditions, removal of the softer phase (usually the matrix) can occur by one or more of the previously mentioned mechanisms. This process then leaves the harder phase unsupported, in which case it may either become detached from the wear surface by a pull-out mechanism or be more susceptible to wear by fragmentation. In addition, the presence of an interface between the various components of the composite may promote cracking and fragmentation of the harder phase, particularly under impact-abrasion conditions.

Table 2 Factors influencing abrasive wear behavior

Abrasive properties	Particle size
	Particle shape
	Hardness
	Yield strength
	Fracture properties
	Concentration
Contact conditions	Force/impact level
	Velocity
	Impact/impingement angle
	Sliding/rolling
	Temperature
	Wet/dry
	pH
Wear material properties	Hardness
	Yield strength
	Elastic modulus
	Ductility
	Toughness
	Work-hardening characteristics
	Fracture toughness
	Microstructure
	Corrosion resistance

The rate of material removal (or its wear rate) for any of the previously mentioned processes is influenced by the extent of indentation of the wear material surface by the abrasive particle. This depth of indentation, for a given load, is a function of the hardness of the wear material and the shape of the abrasive particle. Angular particles indent the wear surface to a greater extent than rounded particles, leading to higher wear rates. In addition, angular particles are more efficient in cutting and machining (Ref 11).

The hardness of the wear material, or more particularly, the hardness of the worn surface, is an important parameter in determining the resistance of a material to abrasion. An increase in the surface hardness of the wear material reduces the depth of penetration by the abrasive particle, leading to lower wear rates. However, an increase in the hardness of a material is also accompanied by an attendant reduction in its ductility, resulting in a change in the abrasion mechanism, for example, from predominantly plowing and/or cutting to fragmentation (Ref 12).

For mechanisms involving predominantly plastic deformation, that is, plowing and cutting, the wear rate can be expressed through the following parameters (Ref 7, 9): the probability of wear debris formation, the proportion of plowing and cutting processes, the abrasive particle shape and size, the applied stress, and the hardness of the wear surface.

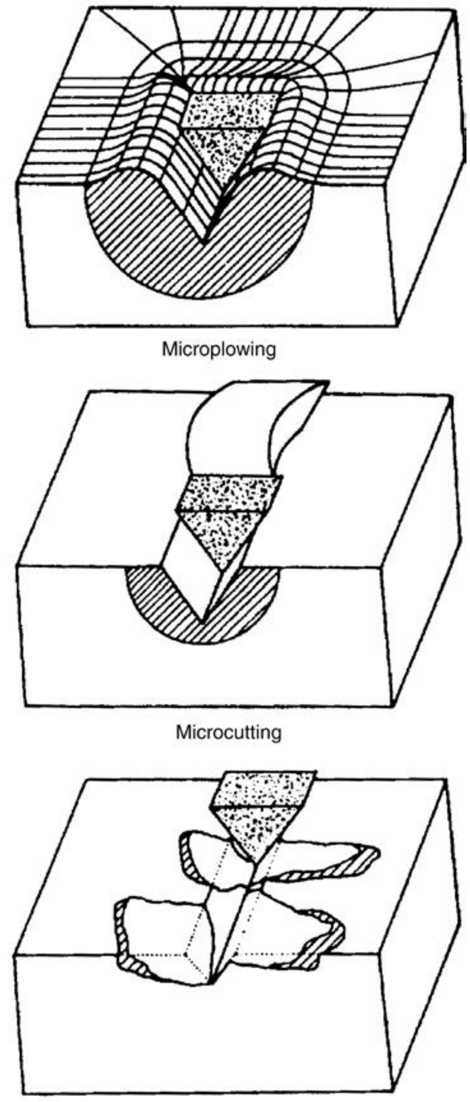


Fig. 4 Microscopic mechanisms of material removal between abrasive particles and the surface of materials. Source: Ref 6

For brittle materials (e.g., ceramics), a transition from a purely cutting mechanism to one that also involves fragmentation occurs when the nature of contact changes from elastic-plastic indentation to Hertzian fracture (Ref 11). The conditions under which this transition occurs are dependent on the size and shape of the abrasive particles, the applied stress, and the hardness of the wear surface. In addition, the fracture resistance of the wear material, as measured by the fracture toughness, is also important. Decreasing the hardness of the wear material, and increasing the fracture toughness, increases the critical abrasive size at which the transition to fragmentation occurs. Thus, reducing the hardness of brittle materials, or alternatively, increasing their fracture toughness, leads to lower wear rates (Ref 7, 10).

Abrasive wear mechanisms involving plastic deformation, cutting, and fragmentation occur predominantly in materials with relatively high elastic modulus, that is, metals, ceramics, and rigid polymers. As the elastic modulus decreases, the nature of the abrasive/wear material contact changes, with localized elastic deformation becoming more significant. The probability of wear occurring by plastic deformation mechanisms decreases, such that for elastomers, cutting mechanisms can occur only with contact against sharp abrasive particles. For contact against blunt abrasive particles, the two main wear mechanisms are tensile tearing and fatigue.

For the abrasive wear of polymeric materials, the following material parameters are important (Ref 10): elastic modulus and resilience, friction coefficient, tensile strength and tear resistance, elongation at break, and hardness. The wear behavior of elastomers is particularly sensitive to the abrasive impingement angle, because this influences the dominant modes of deformation and hence the wear mechanisms. At low impingement angles, tensile tearing occurs, and the tear resistance of the material is important. At impingement angles close to 90°, the behavior of the elastomer is essentially elastic, and resilience is a major factor in determining wear resistance. For abrasive-wear conditions in which significant energy levels are dissipated in the abrasive/wear material contact, elastomeric linings are usually designed such that impingement angles are as close to 90° as possible.

Contact Pressure

In general, higher contact pressures between the abrasive particle and the wear surface in abrasive wear situations cause higher wear rates. As the force applied to an abrasive particle increases, the contact pressure between the abrasive and component wear surface also increases. As the contact pressure nears and exceeds the yield strength of the wear surface in the contact zone, the depth of abrasive penetration increases. For a given length of relative motion between the abrasive and the wear surface, deeper penetration generally removes more material or causes damage to a larger volume of material. The contact pressure/wear rate relationship has been discussed in more detail by several authors (Ref 13, 14, 15, 16, 17, 18, 19).

One of the more general (and generally accepted) wear equations was developed by Archard in 1953 (Ref 20):

$$W = Ks\left(\frac{P}{p_m}\right)$$

where W is the volume of worn (removed or disturbed) material, K is a constant related to probability of surface contact and debris formation, s is sliding distance, P is applied load, and p_m is flow pressure (related to hardness) of wearing surface.

The constant K is usually treated as a material property and is determined empirically. Typical values for various materials have been established through extensive wear testing (Ref 20). Sliding distance is one part of the volume aspect of affected material. Applied load combined with the flow pressure/hardness provide a measure of the depth of penetration of abrasive particles and supply the second volume dimension.

Abrasive Characteristics

Abrasive particle size has a significant effect on material wear, with the greatest effect being for nonmetals (i.e., ceramics and polymers) (Ref 21). In nonmetals, the effect of particle size is associated with changes in the predominant mechanism of material removal. Ceramics undergo a transition to fragmentation above a critical abrasive particle size, whereas elastomers undergo a transition from elastic behavior to either tearing or fatigue.

In metals, the effect of abrasive particle size is minimal for particle sizes >100 μm. Below this particle size, the wear rate decreases rapidly with decreasing particle size (Ref 11). This particle size effect is usually attributed to the nature of the abrasive/wear material contact, with decreasing size favoring elastic rather than plastic contact.

Abrasive hardness, or the ratio of hardness (Vickers) of the wear material to the hardness (Vickers) of the abrasive (H/H_a), is a critical parameter in abrasive wear. It is well known that the abrasive wear rate decreases as the hardness of the worn surface approaches that of the abrasive (Ref 10, 14, 15, 16, 19). When the hardness of the worn material exceeds that of the abrasive, the wear rate decreases rapidly. Figure 5 shows this particular effect for metals and ceramics.

This ratio effect of H/H_a on abrasive wear results from a change in the nature of the contact mechanics. At H/H_a ratios between 0.6 and 0.8, the contact conditions give rise to extensive plastic deformation. At higher H/H_a ratios, the nature of the contact becomes essentially elastic (Ref 10, 11, 22). As a result, wear rates decrease, unless material is removed by mechanisms other than cutting and plowing, for example, fragmentation.

As the hardness of the worn surface approaches that of the abrasive, plastic flow of the abrasive may occur, leading to a reduction in the cutting ability of the abrasive particle. In addition, it is possible to fracture the abrasive when the plastic zone in the abrasive particle reaches a critical size (Ref 10, 19). This effect for the abrasive particle is analogous to the transition from purely cutting to fragmentation in the abrasion of brittle materials.

The effect of H/H_a on wear behavior is also influenced by the size and compressive strength of the abrasive particles. Coarse abrasives are more likely to fracture than fine abrasives, partly due to a decrease in tensile strength with increasing particle size. In addition, fracture of the abrasive may regenerate sharp facets and produce loose abrasive fragments, which in turn increase wear rates. Loading conditions also have an effect, because increasing the contact stress between abrasive and wear material increases the probability of fracture of the abrasive particles.

Contact Conditions

It is difficult to assess the effects of individual contact conditions on the wear interactions among abrasive and wear material, because their effect is synergistic in nature. Force, impact level, velocity, and impingement angle combine to influence the wear rate of the material.

Increasing the contact stress between the abrasive and the wear surface results in greater indentation depths and an increased tendency for fracture and fragmentation in both brittle wear materials and abrasives (Ref 10, 19). This generally leads to increased wear rates, although exceptions may occur if the abrasivity of particular minerals decreases with failure of the abrasive particle. The effect of nominal contact stress on the relative abrasion rating of a range of metallic materials is shown in Fig. 6.

The general effect of increasing nominal contact stress levels is to increase wear rates; however, the occurrence of significant impact during the abrasive/wear material contact may also accelerate the rate of material removal. This acceleration results from the increased amount of kinetic energy dissipated during contact. This energy may arise either from the moving abrasive particles or from the moving wear surfaces, as in the case of impact crushers. For brittle materials, increased fragmentation occurs under impact conditions, whereas elastomers may only

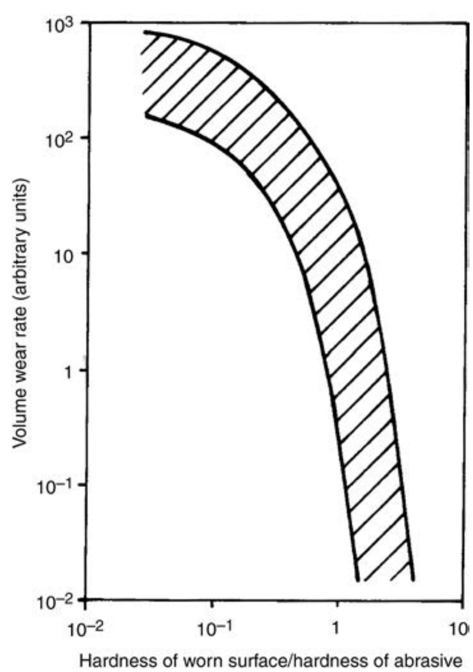
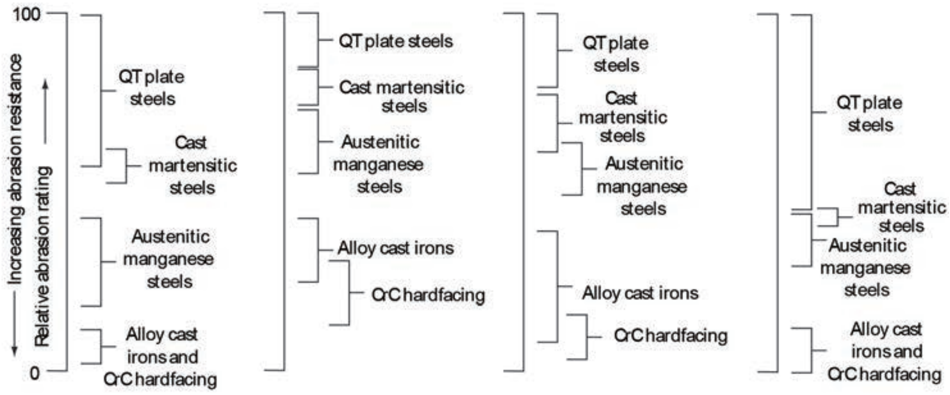


Fig. 5 Effect of abrasive hardness on wear behavior of metals and ceramics. Source: Ref 7



Abrasive type	Gouging	High stress	High stress	Low stress
Abrasive hardness	800–1100 HV	1800–2000 HV	800–1100 HV	900–1300 HV
Abrasive shape	Angular	Angular	Angular	Rounded
Nominal stress	250 MPa (36 ksi)	2.1 MPa (305 psi)	2.1 MPa (305 psi)	0.6 MPa (87 psi)

Fig. 6 Effect of nominal contact stress on relative abrasion rating of metallic wear materials. QT, quenched and tempered. Source: Ref 5

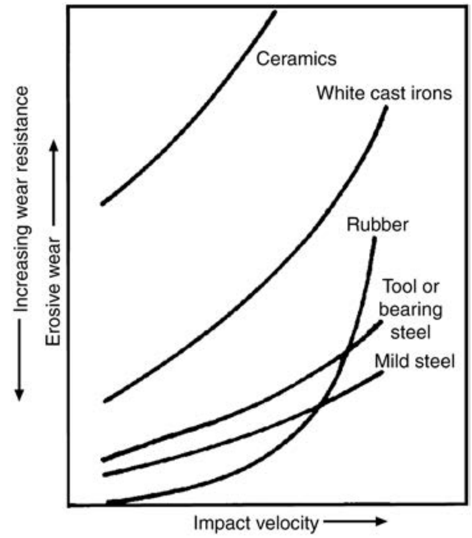


Fig. 7 Effect of impact velocity on erosive wear. Source: Ref 12

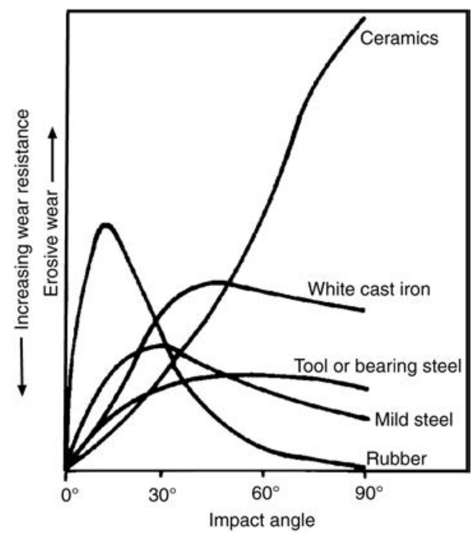


Fig. 8 Effect of impingement angle on erosive wear. Source: Ref 12

suffer an increase in cutting and tearing modes, associated with insufficient elastic recovery.

The nominal force level may also determine the level of constraint experienced by abrasive particles. Under low-stress abrasive conditions, the abrasive particles can be free to rotate as they move across the surface of the wear material and are less likely to indent and scratch the surface. The tendency for the abrasive particle to rotate also depends on the abrasive particle shape, with angular particles being more likely to slide rather than roll. Increasing the nominal force acts to constrain the abrasive particle in its orientation to the wear surface, thereby increasing the wear rate.

The effect of velocity on wear behavior is associated with the dissipation of kinetic energy during abrasive/wear material contact. For a large number of abrasive wear environments, the velocity of abrasive particles is relatively low (<10 m/s, or 33 ft/s), and therefore of little importance. However, in slurry pumps, that is, the transport of abrasive particles in slurry or pneumatic form, the effect of velocity is significant. Under these conditions, the wear rate is proportional to velocity ($W \propto V^n$, where W is the wear rate, V is the velocity of the abrasive, and n is a constant for the abrasive/wear material synergism). The value of n falls in the range of 2 to 3, although the exact value for any particular condition is dependent on the properties of both the abrasive and wear material and on the angle of impingement (Ref 10, 22, 23). For softer abrasives, n tends to increase with decreasing abrasive particle size. For brittle materials and high impingement angles, the value of n tends toward the higher extreme.

In erosion, a change in abrasive impact velocity can lead to a change in the dominant wear mechanism (Ref 24), resulting in a change in wear rate. Higher values for n are associated with increased cutting and fragmentation. Figure 7 depicts the effect of erosive particle velocity on the wear of a range of materials.

The influence of impingement angle on wear depends on the properties of the wear material and is associated with changes to the dominant wear mechanism. At high impingement angles (60 to 90°), brittle materials typically experience elevated wear rates, resulting from increased fragmentation and spalling. Conversely, elastomers are more effective under these conditions, because much of the impact energy can be dissipated through elastic deformation.

At low impingement angles (10 to 30°), elastomers cut and tear more readily, leading to increases in wear rates. Hard, brittle materials usually perform better under these conditions. For materials intermediate in their mechanical properties, for example, some metals, the effect of impingement angle depends on the ductility of the material (Ref 24). The effect of impingement angle on the erosive wear behavior of a number of materials is shown schematically in Fig. 8.

Properties of the Wear Material

The properties of the wearing material that influence wear behavior are grouped into the following categories: mechanical properties, microstructure effects, and other properties (corrosion resistance, friction, thermal effects). Because abrasive wear is primarily a mechanical process, particularly in the absence of corrosive environments, mechanical properties are of major importance, whereas the role of microstructure depends on the severity of the wear environment. The following discussion is patterned after the approach of Mutton (Ref 10) and Moore (Ref 11).

Mechanical Properties

The resistance to indentation (hardness) is an important variable in determining abrasion resistance. Laboratory wear tests indicate that the abrasive wear resistance for particular material types increases with increasing hardness (Fig. 9). However, large differences in abrasion resistance can also occur at similar hardness levels. These differences arise from variations in the plastic flow characteristics of the various materials, which in turn influence the predominant wear mechanism (Ref 7). The general relationships between abrasion resistance and hardness for plowing and fragmentation are similar to those shown in Fig. 10 for pure metals and ceramics.

In the absence of fragmentation, plowing and cutting involve plastic flow of the wear material either in front of or to the sides of the indenting abrasive particles. The plastic flow behavior of the material can be characterized by the ratio E/σ_y, where E is the elastic modulus, and σ_y is the flow stress of the non-work-hardened material.

Decreasing E/σ_y favors a cutting mechanism, in which a high proportion of material is removed as microchips. Increasing the hardness of the wear material has a similar effect, as shown in Fig. 10.

Although Fig. 10 indicates that changing E/σ_y can significantly affect the dominant wear mechanism, its impact on wear resistance is not as clearly established. For a constant value of E, a decrease in σ_y favors plowing. This should lead to lower material wear rates. However, decreasing σ_y also decreases hardness, which favors greater depths of indentation and a reduction in the wear resistance of the material. For materials of equivalent hardness, the general trend is for wear resistance to increase with higher E/σ_y values (Ref 11).

The wear material properties discussed thus far (i.e., hardness, elastic modulus, and flow strength) relate to material behavior at relatively low strains. For example, the plastic strain produced by indentation hardness testing of metals is typically between 8 and 10%. During the abrasive wear process, the extent of plastic strain experienced by a worn surface may approach these values. For these cases, the behavior of the wear material at high plastic strains is important, and here, high values of the work-hardening coefficient and ductility are favorable.

Tensile strength and ductility are also important mechanical property parameters in a wear environment, especially for polymers, which undergo elongations to fracture approaching 500%. Laboratory wear studies indicate that the wear resistance of both rigid and ductile polymers is roughly proportional to the work of rupture, which is defined as the product of the rupture stress and elongation to fracture.

The abrasion resistance of polymers also increases with increasing indentation resistance, although this relationship is not as well defined for polymers as it is for metals and ceramics. This is due in part to the viscoelastic nature of polymer deformation behavior. In addition, the absolute hardness levels for polymers are much lower than those for metals and ceramics.

For elastomeric materials such as natural rubbers and polyurethanes, the deformation behavior during abrasive wear may be entirely elastic, in which case resilience or hysteresis loss is important. High resilience favors increased abrasion resistance, while increasing hysteresis losses under high impact levels result in material breakdown, exacerbated by heat buildup.

For materials that undergo wear by fragmentation, abrasion resistance varies with fracture toughness. However, the contribution from microcracking and fragmentation depends on the severity of the wear environment, in particular the applied load and abrasive particle size.

For metals and ceramics, the general form of the relationship between wear resistance, hardness, and fracture toughness (K_c) is illustrated in Fig. 11 (Ref 25). For low-fracture-toughness materials (>14 MPa$\sqrt{m}$, or 13 ksi$\sqrt{in.}$), wear resistance increases with increasing fracture toughness, despite a marked decrease in hardness. The increase in the wear resistance of the material results from a reduction in the fragmentation contribution to the total wear rate. For materials with high fracture toughness, wear occurs by cutting and plowing only. Hence, the wear rate of the material is controlled by the indentation resistance. In this case, wear resistance decreases with decreasing hardness.

The transition from fracture (fragmentation) to plastic deformation (cutting and plowing) is dependent on the critical groove size (p_{crit}) and the contact stress. These parameters, in turn, also depend on the ratio of fracture toughness to hardness (K_c/H). From Fig. 11, maximum abrasion resistance is obtained by optimizing the ratio K_c/H while maintaining the indentation hardness or groove size slightly below that at which the transition to fragmentation occurs (Ref 11).

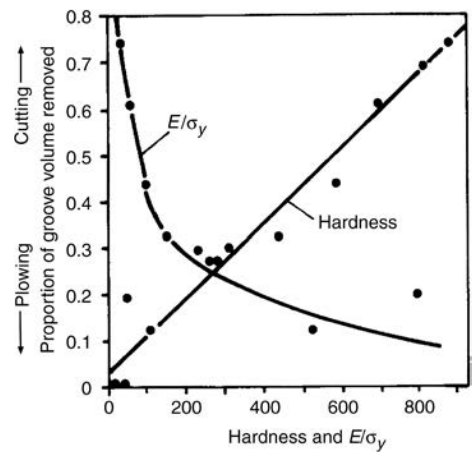


Fig. 10 Influence of hardness and E/σ_y on dominant wear mechanism. Source: Ref 5

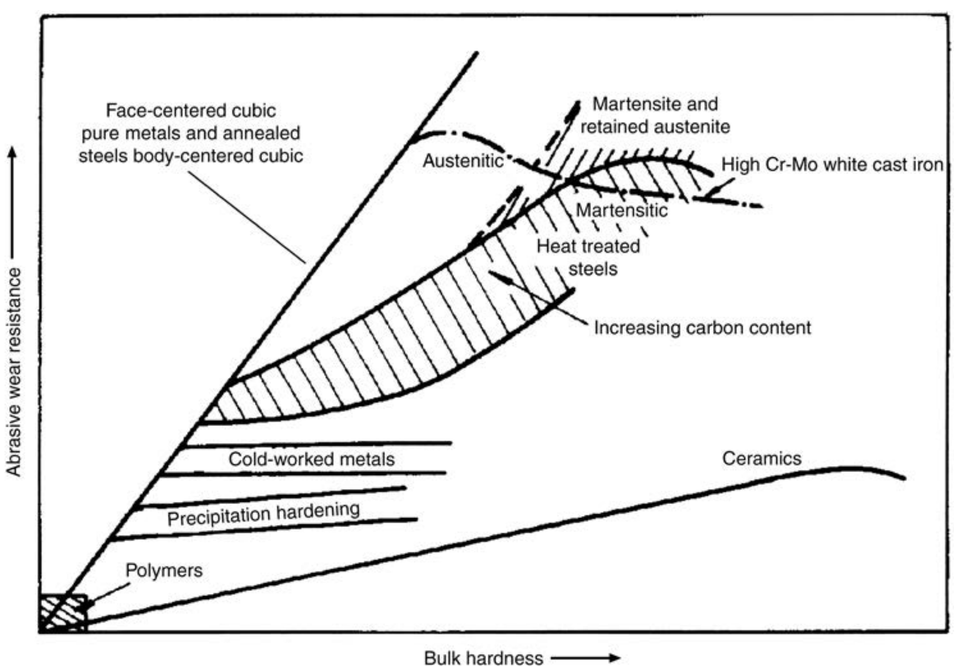


Fig. 9 Abrasion resistance versus hardness for various material types in high-stress pin abrasion tests (silicon carbide abrasive). Source: Ref 6

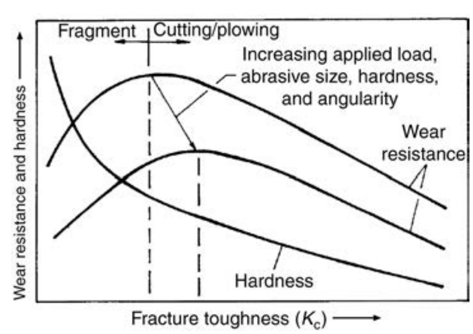


Fig. 11 Schematic relationship between wear resistance, hardness, and fracture toughness. Source: Ref 6

Increasing the severity of the wear environment, by increasing either the applied load or the size, hardness, or angularity of the abrasive particles, shifts the transition from fragmentation to cutting/plowing to higher values of fracture toughness (Fig. 11). This results in a decrease in the maximum wear resistance.

Microstructure

Microstructural effects on abrasive wear depend on the overall magnitude or scale of the wear environment. For high-impact loads, large abrasive particle size, and so on, the size of the microstructural features is generally much smaller than that of the abrasive wear damage. In this case, the role of microstructure on wear resistance is limited to its effect on bulk mechanical properties. Abrasive wear rates, particularly for materials that exhibit homogeneous microstructures, may correlate with bulk hardness (Ref 11). Figure 12 shows the effect of microstructure and hardness on the high-stress abrasion resistance of steels. Over a limited hardness range (200 to 300 HV, or 2.0 to 3.0 GPa), relative abrasion resistance decreases in the order (Ref 11): austenite > bainite > pearlite > martensite.

This effect can be attributed to the influence of microstructure on plastic deformation behavior. However, bainitic and martensitic microstructures offer greater abrasion resistance at higher hardness levels (>400 HV, or 4.0 GPa).

At lower loads, and with smaller abrasive particle sizes, microstructuralfeatures are more effective as discrete components, and the mechanicalproperties of individual phases assume increased importance. This occurs whenthe size of the microstructural features is approximately equal to, or largerthan, that of the abrasive. Under these conditions, materials with duplexmicrostructures, for example, alloy white irons and some ceramics, are moresensitive to microstructural effects. In such materials, size, spacing, andvolume fraction of the harder phase, as well as the mechanical properties ofboth hard and soft (matrix) phases, can significantly affect wear behavior.Thus, the abrasion resistance of the material either increases, decreases, orremains the same by increasing the volume fraction of the harder phase. The netpends on the various contributions of the plowing, cutting, fragmentation, and pull-out mechanisms to the total wear rate. Figure 13 shows schematically this behavior for alloy white irons and alloy carbide materials. The transition from increasing to decreasing abrasion resistance with increasing carbide volume fraction is associated with the relative contributions of fragmentation of the carbides and plowing/cutting of the matrix to the total wear. Carbide hardness, and size relative to that of the wear damage, also influences these trends (Ref 11, 26).

Other Properties

Wear processes that involve plastic deformation (i.e., cutting and plowing) also generate significant increases in temperature at the wearing surface. These increases occur as a result of frictional energy dissipation at the interface between the wearing surfaces. Under these circumstances, the wear behavior is influenced by characteristics such as the friction coefficient and thermal conductivity of the two wear bodies. In materials that exhibit low values of thermal conductivity, one of two additional effects may arise, depending on other material properties. Localized thermal expansion in ceramics may result in additional material loss by spalling; conversely, localized temperature increases in polymers may give rise to melting. Materials that exhibit low friction coefficients under dry sliding conditions (e.g., some polymers and finely ground ceramics) suffer less degradation through frictional temperature rise effects.

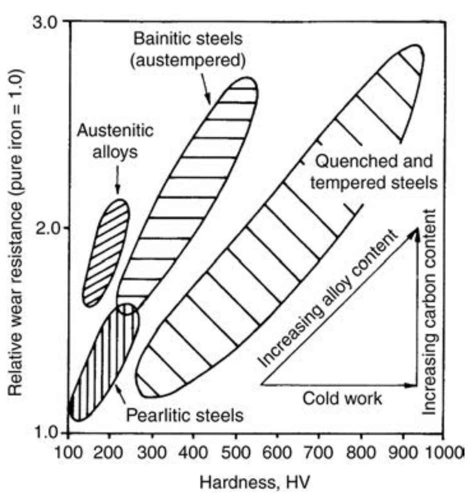


Fig. 12 Effect of microstructure and hardness on the abrasion resistance of steels: high-stress abrasion, alumina abrasive. Source: Ref 7

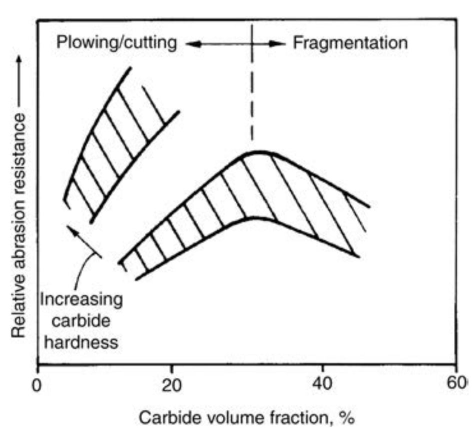


Fig. 13 Influence of microstructure on abrasive wear behavior of alloy white irons and chromium carbide materials. Source: Ref 5

Wear Failure Analysis

Table 3 presents the procedural sequence used in general failure analysis studies. Failure analysis studies can be broken down into the following major categories through the collection of documentary evidence: service conditions; materials, handling, storage, and identification; interviews; field investigation; laboratory analysis; and dimensional analysis (Ref 2). The same general procedure is used in analyzing wear failures.

Wear is a systems problem (Ref 5, 27). The process of accurately detailing an abrasive wear failure consists of a series of defined tasks undertaken by the failure analysis

Table 3 General fracture failure analysis procedural sequence

Step 1: Determine prior history
Review documentary evidence
Test certificates
Mechanical/wear test data
Pertinent specifications
Correspondence
Interviews
Depositions and interrogatoriesReview service parameters
Design or intended operating parameters
Actual service conditions
Temperature data (magnitude and range)
Environmental conditions
Service loads/stresses
Step 2: Clean failed parts or specimens
Step 3: Perform nondestructive tests
Macroscopic examination of wear/fracture surface
Presence of color or texture
Temper colors
Oxidation
Corrosion products
Contaminants
Presence of distinguishing surface features
Shear lips
Beach marks
Chevron markings
Gross plasticity
Large voids or exogenous inclusions
Secondary cracks
Direction of propagation
Fracture originDetection of surface and subsurface defects
Magnaflux
Dye penetrant
UltrasonicsHardness measurements
Macroscopic
MicroscopicChemical and microstructural analysis
Macrochemistry ("wet" chemical analysis)
Spectrographic analysis
X-ray diffraction
Electron beam microprobe analysis
Step 4: Perform destructive tests
Metallographic (light microscopy, scanning electron microscopy, transmission electron microscopy)
Macroscopic
Microscopic
Structure
Grain size
CleanlinessMechanical tests
Tensile
Impact
Fracture toughnessCorrosion testsWet chemical analysis
Step 5: Perform stress analysis
Step 6: Store and preserve parts or specimens
Source: Ref 1

specialist. Each task is designed to obtain specific information from the failed components and system. These tasks are generic to most failure analysis investigations and can be summarized as (Ref 28):

1. Identify the actual materials used in the worn part, noting also the operating environment, abrasive causing the material loss, the wear debris, and any lubricant used (as needed).
2. Identify the specific wear mechanism, or combination of wear mechanisms, that caused the loss of material or change in the surface dimensions: adhesive wear, abrasive wear, corrosive wear, surface fatigue, erosive wear, and so on.
3. Determine the change in the overall dimensions to the surface configuration between the worn surface and the original surface.
4. Determine the relative motions involved in the tribosystem that caused the loss of material, for example, abrasive wear, including the direction and velocity of the relative motion.
5. Determine the force or contact pressure between mating surfaces or between the worn surfaces, that is, the counterfaces and the abrasive particles, on both the macroscopic and the microscopic level.
6. Determine the wear rate by calculating the material loss over some unit of time or distance.
7. Determine the coefficient of friction (if possible).
8. Identify the type of lubricant used and its effectiveness in slowing down material loss, for example, was the grease, oil, modified surface, naturally occurring oxide layer, adsorbed film, or intentional foreign material beneficial or not.
9. Establish whether the observed wear is normal or abnormal for the particular application.
10. Devise a solution, if required.

In most failures, some or even most of this information is simply not available. The more information that can be accurately determined, however, the better the chances of making a successful determination of cause and therefore chance of remediation. These steps are used in each of the example failure analyses in this article.

To perform effective analyses of abrasive wear failures, it is not enough to have a broad-based knowledge of the mechanical situation found in the wear environment. A good background in metallurgy, ceramic science, or materials science is also necessary. In addition, access to investigative diagnostic tools is required for examination of worn surfaces and structures on both a macroscopic and microscopic level (Ref 29). This includes methods such as optical and electron microscopy, electron spectroscopy for chemical analysis, x-ray diffraction, low-energy electron diffraction, and Auger electron spectroscopy. Above all, a well documented plan of investigation is needed before any analysis is begun.

Once a plan of investigation is decided on, it is then necessary to develop a case history of the failure, documenting as much as possible all aspects of the problem. This may not be easy to do, because in most cases, detailed operating records are not kept. However, it is important to collect as much information about the operating history of the component as possible in this portion of the investigation. More importantly, it is necessary to determine at this stage whether the component and associated parts were operating properly, that is, as they were intended. If they were not, then it is easy to correct the problem by specifying the correct operating procedures and then to monitor subsequent operational situations to see if the same problem occurs.

However, in many cases, operation of the component and associated parts was within limits. In these instances, a thorough examination of the parts is necessary, using some or all of the analytical tools mentioned previously. It is important, however, to examine the worn surfaces of the part of the failed component prior to its disassembly. Doing this provides a broad operational overview of the failure of the component or, more precisely, how all the parts fit together and operated. At this point in the analysis process, all operational questions must be answered. Once a record is obtained, no matter how incomplete, the component can be broken down into its constituent parts, as was done in the case studies investigated in this article. Then the wear surfaces can be analyzed for manufacturing and/or material defects or any other unusual occurrences, and a preliminary determination as to the cause of the wear failure expounded. This may or may not lead to remediation procedures. If it does, these steps can be investigated on subsequent components to see if the failure was properly resolved (such as a change in material used for the parts or a redesign of the part to eliminate a possible design feature leading to accelerated wear). Of course, the material or design requirements to solve an abrasive wear failure, or any failure for that matter, may prove to be too expensive, leading to other solution approaches, such as the complete redesign of the component and the associated parts that failed.

Examples of Abrasive Wear

Example 1: Jaw-Type Rock Crusher Wear.

Although rock crushing and mineral comminution components are expected to lose surface material during their operating lifetime, this loss of material still results in reduced and/or eliminated component function and leads directly to failure. In this type of system, mineral ore flows down a feed chute into the upper portion of the crushing zone, which consists of two plates, one stationary and one moving. The chunks of rock enter at the top and are reduced in size each time the jaws cycle toward each other. The mineral then moves through the crushing zone until it reaches the desired size at the bottom, where the crushed pieces exit through the gap at the bottom of the plate assembly each time the plates separate to accept new rock.

Figure 14 shows the jaw crusher wear plates after processing a quantity of mineral ore. In this case, the crusher plates are of the size and type outlined in ASTM International G 89. The plates were quenched-and-tempered, low-alloy steel (~0.30 wt% C at 514 HB hardness), with an elliptical motion of the movable plate relative to the fixed plate (Ref 30). In this case, the entering rock is 50 to 75 mm (2 to 3 in.) in size. On exiting the jaw crusher plate assembly, the mineral is approximately less than 6 mm (0.2 in.) in size. Notice that for this jaw crusher configuration, the stationary plate absorbs the most severe gouging-abrasive wear (right side of the plate). Table 4 summarizes the damage characteristics on both the stationary and moveable plates.

Example 2: Electronic Circuit Board Drill Wear.

Very small drill bits are used for drilling holes in electronic printed circuit boards (PCBs). To be economical, the drilling process must be completed quickly, because of the large number of holes in each board. This high-speed drilling operation thus requires automatic drilling machines capable of identifying hole location, starting and stopping quickly, and changing worn drill bits as needed. The maximum drilling rate for the system is the rate of maximum drill bit breakage. Generally, the optimal drilling conditions are determined by pushing the drilling conditions to their limit, that is, until drill bit failure. The failure of the drill bits is then analyzed.

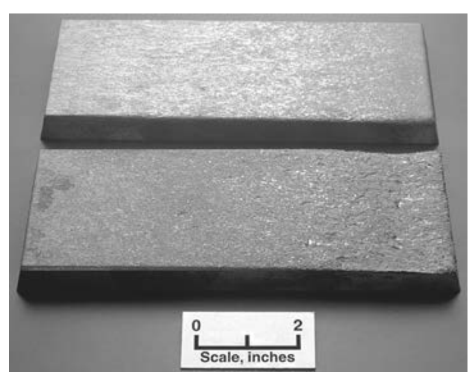


Fig. 14 Photograph of the movable (top) and stationary (bottom) wear plates from the jaw crusher. The feed moves across the plates from left to right, so the most severe wear occurs at the exit area toward the right.

Commercial drill bits vary in size, but popular sizes for drilling holes in PCBs are on the order of 0.343 to 0.457 mm (0.0135 to 0.0180 in.) in diameter by 6.35 mm (0.25 in.) in length. In this case, the drill bits are made of cobalt with approximately 50 vol% of uniformly distributed 0.1 μm sintered WC particles in the cobalt matrix. Vickers hardness of the drill bits was measured at 1589 HV. The PCBs are composite materials, with layers of fiberglass epoxy resin sandwiched between copper layers. A PCB contains as many as 14 layers of copper and fiberglass-resin layers. The glass fibers in the fiberglass have a hardness of 500 HV, while the copper has a hardness of 40 HV.

The drilling process is computer operated and numerically controlled. Typical operating conditions are as follows: the feed for drilling PCB holes is approximately 2000 mm (80 in.)/min. The speed corresponds to the number of drill bit rotations per minute, and for this application, it was between 80,000 and 100,000 rpm. The hit rate, or the number of holes drilled in a particular time interval, was 80 holes/min. After 1500 hits, the drill bits were resharpened. The material removal rate (MRR) is 4.8 mm^3/s and is given by (Ref 31):

$$\mathrm{MRR} = nf_\mathrm{r}\frac{\pi d^2}{4000}$$

where d is the diameter in millimeters, n is the rotational speed in revolutions per second, and f_r is the feed per revolution in millimeters.

In this study, a sharp, new 0.343 mm (0.0135 in.) diameter drill bit was loaded into a tool holder and operated at the appropriate drilling conditions to drill a hole in a PCB. Figure 15 shows the results of this operation: a hole 0.3404 mm (0.0134 in.) in diameter. Notice that the hole has sharp edges and round, straight internal dimensions. The drill bit made chips of fiberglass and copper foil while cutting through the PCB. The glass fibers break by brittle fracture on impact with the cutting edge of the drill bit. Intense stress develops under the surface of the glass fiber where it makes contact with the bit, generating a plastic zone and a median vent crack in the plane of the stress field. Lateral cracks also develop and curve back to the fiber surface, liberating wear debris of glass fibers and epoxy. When the drill bit cuts through the layers of copper, ordinary ductile metal chips form by shearing. The chips tend to flow up the rake face of the drill bit and deposit in the flute, causing copper buildup on the edge.

One way a drill bit fails is by catastrophic breakage from, for example, too high a load applied to the bit. A dull drill bit is susceptible to the buildup of wear debris on the flute. As wear debris accumulates on the bit, the friction force between the bit and hole increases. The increased friction generates additional heat, exacerbating wear debris buildup on the bit cutting edge. This reduces bit strength and increases hole size, a direct result of a change in bit diameter due to thermal expansion. The buildup of wear debris also rounds the cutting edge. Thus, to maintain cutting efficiency, the cutting force must be increased, which leads to increased shear stress on the drill bit shank. When the applied shear stress exceeds that of the bit material, it fractures, usually in the region between the spiral flutes and the shank.

Another way that drill bits ultimately fail is by accelerated wear. Drill bits typically have a break-in period, where sharp burrs on the drill bit are worn away. This break-in period is followed by steady-state wear when the majority of the holes are drilled with uniformly acceptable characteristics (Fig. 15). The majority of the tool lifetime is spent in the steady-state wear regime. Taylors tool lifetime equation can be used to predict this time (Ref 32):

$$VT^n = C$$

where V is the cutting speed, T is the tool life, C is a material-dependent constant, and n is a constant that depends on tool material and cutting conditions. Eventually, the sharpness of the bit degrades to a point where edge wear-debris accumulation becomes a problem. At this point, the drill bit has effectively failed, because the characteristics of the hole have significantly changed (Fig. 16). Examining Fig. 16, it is clear that the worn drill bit has slid away from the intended hole location by 0.3810 mm (0.015 in.), approximately one drill bit diameter. The margins of the hole are also rounded, and it is now oversized by 12.6%.

The microstructure of these drill bits has been optimized, so that further improvements in hardness and wear resistance may not be possible. However, some things can be done to increase the productivity of the drilling operation by properly determining drill bit life and changing them at the beginning of the accelerated wear phase of the tool. One way to do this is by measuring the drilling force on the chuck, using a three-axis force dynamometer. When the cutting force deviates from the steady-state constant force condition, the bit must be resharpened or replaced. Feeds and speeds of the drilling operation in combination with changing the cutting angle of the drill bits may also lower the number of fractured bits.

Example 3: Grinding Plate Wear Failure Analysis.

In this example, a 230 mm (9 in.) diameter disk attrition mill was scheduled to grind 6.35 mm (0.25 in.) diameter quartz particles to a 0.075 mm (0.003 in.) diameter powder. Due to severe wear on the grinding plates, however, the unit was unable to complete

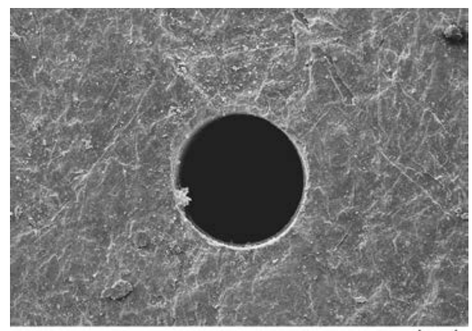


Fig. 15 Scanning electron micrograph of the details of a hole drilled with a new, sharp drill bit. Note the clean hole with only a minor amount of damage to the hole periphery.

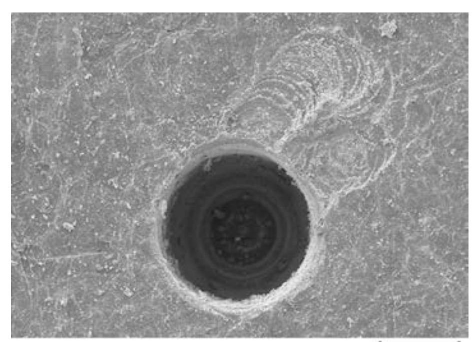


Fig. 16 Scanning electron micrograph of a hole drilled with a worn drill bit. Note that the final position of the hole is not where the drilling started (i.e., the drill wandered across the surface before "biting") and the ragged nature of the periphery of the hole.

Table 4 Jaw crusher plate damage summary

Plate		Location (from top), mm	Location (from top), in.	Damage type(a)	Typical event size, mm	Typical event size, in.	Relative material loss	Displacement direction
Moveable	Zone 1	0–50	0–2	Blunt with flow	12	0.5	None	Up
	Zone 2	50–100	2–4	Mixed rm	25	1.0	Minor	Up
	Zone 3	100–175	4–7	Sharp and deep, rm	25	1.0	Moderate	Up
	Zone 4	175–210	7–8.3	Small, direct penetration	6	0.25	Minor	Up
Stationary	Zone 1	0–50	0–2	Blunt, direct penetration	12	0.5	None	None
	Zone 2	50–100	2–4	Sharp, direct penetration	18	0.75	Moderate	Up
	Zone 3	100–210	4–8.3	Sharp, rm	12	0.5	Majority	Up

(a) rm, relative movement direction; that is, direction the surface metal is flowing the task of grinding the rock. The unit was disassembled and an analysis performed to determine the cause of plate failure. Several steps were used to analyze the disk attrition mill failure, which included both an analysis of the grinding plates and the rock to be comminuted. Historical information was collected about the disk attrition mill and used to compare the present operating conditions with previous conditions where acceptable product was produced. Several wear mechanisms were identified and used to make recommendations for future improvements.

Grinding Plates

The disk attrition mill is shown in Fig. 17. It consists of a heavy gray cast iron frame, a gravity feeder port, a runner, and a heavy-duty motor. The frame and gravity feeder weighed over 200 kg (440 lb) and, in some areas, was over 25 mm (1 in.) thick. Gray cast iron is considered ideal for the machine frame and base, because it absorbs vibration and promotes smooth, quiet operation during grinding. To obtain the operating speed of 200 rpm, a gear system is used to transmit the torque from the 2 hp motor. The runner consisted of a 50 mm (2 in.) diameter shaft and two gray cast iron grinding plates (i.e., the parts used to grind the mineral).

In Fig. 18, a new, unused grinding plate (left) is a 230 mm (9 in.) diameter and 25 mm (1 in.) thick disk of gray cast iron with a hardness of 338 HV and 0.1 mm (0.004 in.) graphite flakes, which are an excellent absorber of vibrations during mineral grinding. Radiating outward from the center are six cutting flutes that are used to shear and fracture the quartz particles. The 32 mm (1.25 in.) wear ring on the outside of the plate grinds the broken rock fragments to their final size. The procedure used to grind quartz in the disk attrition mill included: (1) setting the space between the gray cast iron plates to zero clearance, (2) turning on the unit, and (3) feeding in quartz between the plates. The quartz was precrushed to 6.35 mm (0.25 in.) diameter and then fed directly into the feed hopper at a rate of 0.5 kg (1 lb)/min. The process continued until approximately 4.5 kg (10 lb) of the 75 μm product was deposited in the collection tray. The product was removed from the collection tray and the process repeated. Eventually, the machine failed due to grinding plate wear.

Fig. 17 Photograph of the attrition mill, showing placement of the attrition mill wear plates

Characterization of the Quartz Feed

Quartz from western Oregon was the primary feed material used in the attrition mill. This rock has a Mohs hardness of 7, corresponding to a Vickers hardness of between 700 and 800 kg/mm^2. The quartz mineral possesses a rupture strength of 70 MPa (10 ksi) in the transverse direction. On slow cooling, quartz forms a tetrahedral silicate structure, with silicon at the center and oxygen atoms occupying the corners. Quartz fractures conchoidally along crystallographic planes when fractured. The sharp, angular shape of the quartz particles has a significant effect on the wear behavior of the grinding plates in the attrition mill, with quartz attrition leading to failure of the part in the following way.

When the quartz particles are pulverized by the rubbing action between the rotating plate and the stationary plate, particles become embedded in the two grinding plates and abrade through, scratching the wear ring surfaces at the edge of the plate. Initially, the clearance between the plates is set to zero, but as the quartz particles flow into the space between the plates, they wedge them apart. The particles wedged between the plates can see an elastic force equal to 4.05 kN, leading to compressive stresses on the particles of 0.12 MPa (17 psi), sufficient to overcome the transverse rupture strength of 0.07 MPa (10 psi) for the quartz.

Additionally, the quartz particles are twice as hard as the cast iron grinding plates and cause severe wear by two distinct wear mechanisms, illustrated in Fig. 19. Because the quartz particles are sharp and angular, gouging abrasion was the primary mechanism of material removal (Fig. 20) at the wear ring on the edge of the grinding plate. The forces generated during gouging abrasion are higher than the yield strength of the cast iron, and these areas plastically deform under the compressive force of the quartz. The angle that the cutting edge of the particle makes with the wear surface is often referred to as the rake angle in cutting during machining operations. The plowing mechanism of material removal is illustrated in Fig. 21. In this case, a particle is oriented such that a "blunt" edge is

Fig. 18 Macrographs of new (left) and worn (right) attrition mill wear plates

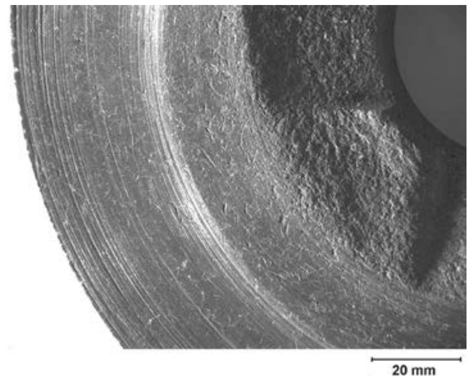


Fig. 19 Optical macrograph of a segment of the attrition mill wear plate showing gouging abrasion near the inner ring and grinding abrasion near the outer ring

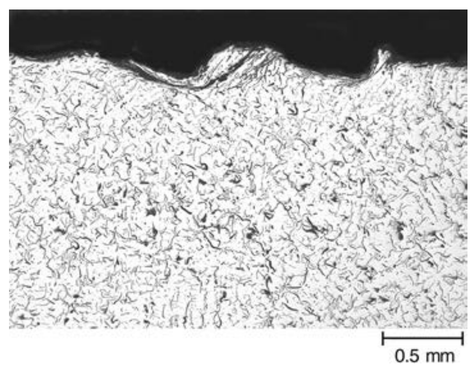


Fig. 20 Optical micrograph of a cross section at the plate ring showing gouging abrasion. Notice the deep depressions with deformed material and cracks.

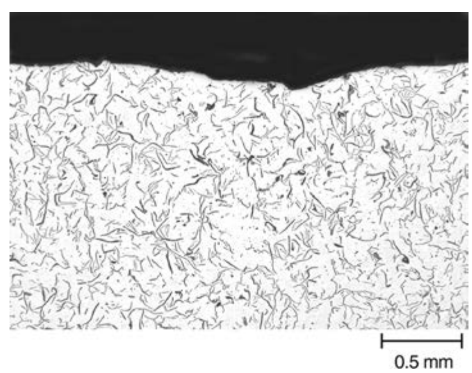


Fig. 21 Optical micrograph of a cross section of the outer section of the attrition mill wear plate showing no gouging abrasion and little plastic deformation. Along the upper wear surface are shallow wear grooves from grinding abrasion.

presented to the grinding plate, and material is pushed to the sides of the particle as it passes through the lathe, piling up material at the periphery of the wear groove. In the machining wear mechanism, also illustrated in Fig. 21, particles are oriented so a "sharp" edge is presented to the grinding plate, and these particles cut into the plate and remove a chip from the surface. The chips are discontinuous, due to the flake graphite incorporated in the gray cast iron. The gouging, cutting, and plowing process continues until the thickness of the plate has been reduced to the point where no adjustments can be made to zero, the clearance between the stationary and moving plates.

From the failure analysis study on the wear plates, suggestions for improving the wear life can be made. Evidence from the wear patterns on the face of the grinding plates suggest that modifications to plate design may reduce overall wear and improve mill efficiency. The cutting flutes on the grinding plates show uniform gouging wear on both sides of the cutting edges, as illustrated in Fig. 19. This means that the cutting edge of the grinding plate, per se, is not involved in the actual shearing of the quartz particles but only in crushing them. The clearance between the flutes could, therefore, be reduced, providing more shearing action to the particles before they reach the inner wear ring.

Several material changes could also be made that may extend the life of the grinding plates. Lower cost is the main advantage of using gray cast iron for the wear material of the grinding plates. A negative consequence of using gray iron is that it has a high wear rate and can contaminate the product with the substantial iron debris as it wears. The ratio of iron to quartz is approximately 0.5. Because no indications of severe impact wear were noted, and because fracture and spalling were not observed, a harder plate material such as white cast iron or a work-hardening manganese steel could be used. Either material would lead to a larger value of the hardness ratio, possibly leading to lower wear. The manganese steel has a second attractive property: good high-temperature strength. High-temperature strength is important, because the temperature between the grinding plates during operation can reach 900 °C (1650 °F). These high temperatures can significantly reduce the strength and wear resistance of the gray cast iron grinding plates.

Example 4: Impact Wear of Disk Cutters*.

Steel disks are used on large tunnel-boring machines to continuously cut away at rock faces. Although material is worn from the disks through indentation and scratching wear processes (Fig. 22), one of the predominant material-removal mechanisms is material fracture near the edges of the disk cutting face (Fig. 23).

*The authors would like to recognize Donald Sherman of Aterpillar Inc. for his original work in this investigation.

Because of the dominance of the fracture process on the material-removal rate, it was decided that a tougher material should be tried to provide increased fracture resistance. The original disk material was an H13 tool steel. The proposed replacement alloy was a medium-carbon steel, which had a lower hardness but greater fracture toughness and impact toughness.

Material	Hardness, HRC	Fracture toughness, (K_{Ic})		Charpy impact energy at 24 °C (75 °F)	
		MPam	ksiin.	J	ft · lbf
H13 tool steel	55–57	14–22(a)	13–20(a)	3–4	2–3
Medium-carbon steel	49–51	130	118	28–33	21–24

(a) Depending on direction of crack growth

Higher-toughness disks were placed on the head of a tunnel-boring machine, along with those made of H13. Despite having significantly less toughness than the medium-carbon alloy steel, the H13 disks exhibited what could be equated to 1.7 times longer life.

Examination of the cutting edge of the tougher steel disk revealed even larger fracture areas, similar in appearance to spalls (Fig. 24). As with many field-return worn components, further surface examination at higher magnifications revealed no useful information, due to continued wear and oxidation. Instead, nital-etched metallographic cross sections were prepared through the wear surfaces of disks made of each material. Figure 25 shows a cross section taken near the edge of the contact surface of an H13 disk. This image shows that plastic flow due to the high contact pressures has led to mushrooming at the edge of the disk cutting face. Cracking is subsequently initiating from these mushroomed regions. Figure 26 shows similar cracking in the lower-hardness alloy steel. The cracked zone is significantly larger and thus would lead to more extensive material removal, once crack growth is completed. Closer examination of these cracked regions revealed that cracks are typically following white-etching shear localization bands (Fig. 27). These bands likely form in a single impact event and are believed to be nano-crystalline ferrite, with all other elements trapped in solution (Ref 33, 34, 35). Hardness values within the band have been found to approach 1000 HV. Due to the brittleness of this layer, subsequent load cycles lead to cracking and spallation along the shear localization band. The lower hardness and plastic flow stress of the medium-carbon alloy steel resulted in the formation of larger shear localization bands and thus larger spalls with more rapid material removal.

Example 5: Identification of Abrasive Wear Modes in Martensitic Steels.

Wear modes experienced by a given component can be quite diverse, depending on wear environment and component function. The abrasive wear modes experienced by steels in typical applications may be broadly divided into three categories: low-stress scratching, high-stress gouging, and impact or indentation. Scanning electron micrographs of these

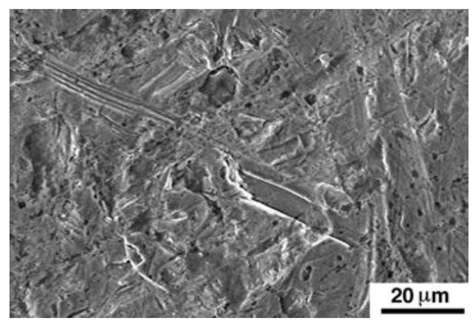


Fig. 22 Scanning electron micrograph showing the surface wear on the disk cutter, which shows elements of indentation/impact and scratching or gouging

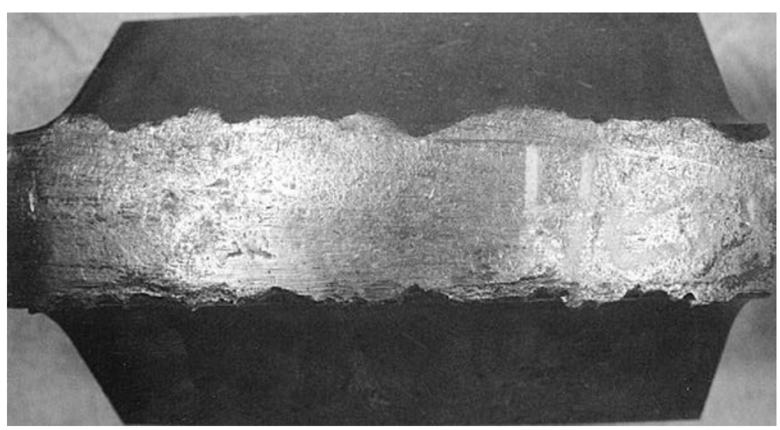


Fig. 23 Disk cutter, comprised of H13 tool steel, showing material fracture at edge of contact surface

Fig. 24 More severe material fracture/spalling on surface of disk made from tougher, medium-carbon alloy steel

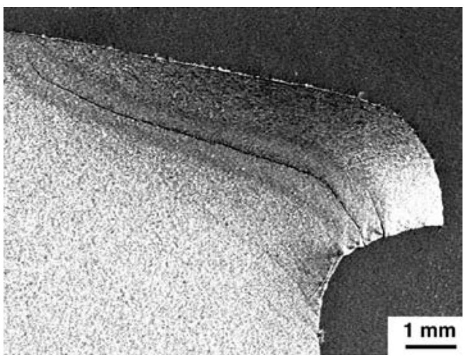


Fig. 25 Micrograph showing the edge of the contact face in an H13 disk. Mushrooming is occurring due to contact pressures and resulting metal flow. Cracks resulting from fatigue or fracture at localized shear bands are leading to material removal.

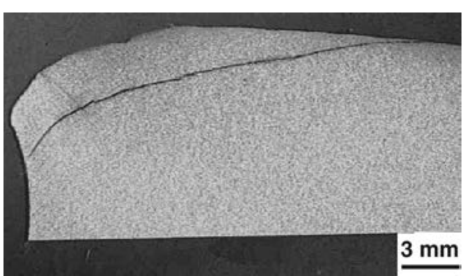


Fig. 26 More extensive cracking observed in tougher but softer medium-carbon steel

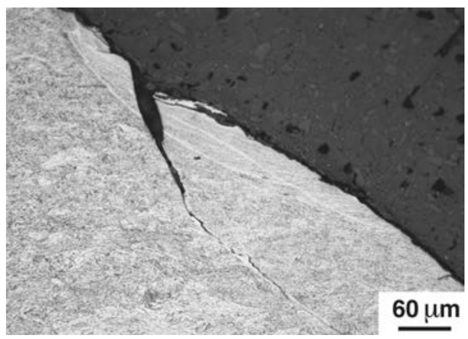


Fig. 27 Micrograph showing cracking along white-etching localized shear zone

different wear modes are shown in Fig. 28. Wear rates of a given material depend strongly on wear mode, and although a material may perform well in one mode of wear, it may not perform well in another.

For martensitic steels, wear rate is most strongly dependent on material hardness. Figure 29 shows approximate lines of normalized wear rate versus hardness for the different wear modes. Data are plotted against Vickers hardness rather than Rockwell C, because Vickers hardness directly relates to material yield strength, while the Rockwell C scale has no such direct correlation. Figure 29 shows that low-stress scratching has the strongest correlation with hardness. As the severity of wear increases, the dependence on hardness decreases. For gouging and impact wear, other material attributes, such as toughness and work hardening ability, begin to play a larger roll in dictating wear rate. This difference in dependencies leads to materials that perform well in one wear mode but not in others. Figure 30 shows some materials that change the ranking when wear mode is changed. While the 50 HRC ground-engaging steel performs as expected, given its hardness in low-stress scratching, as the severity of wear environment increases, it becomes the favored material. In contrast to the 50 HRC steel, the steel composite material performs very well in low-stress scratching (due to the presence of hard phases) but more poorly as the wear severity increased, due to its low material toughness.

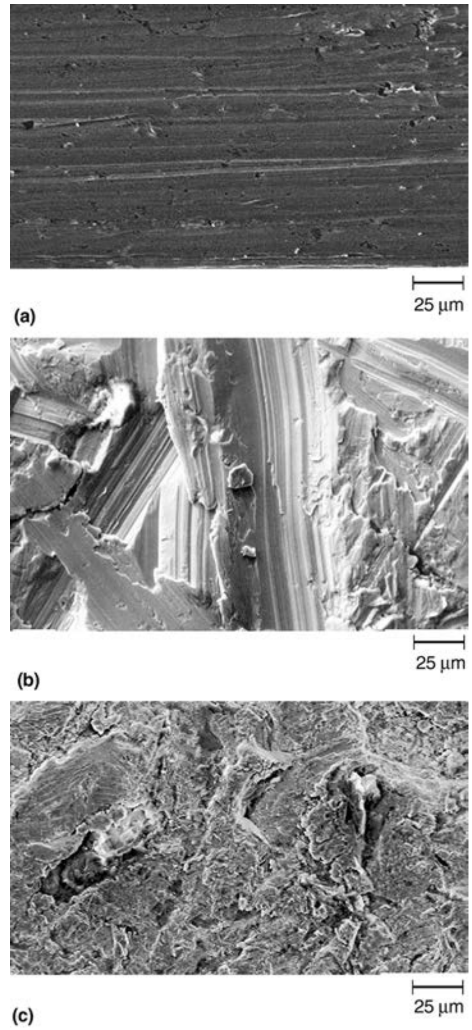


Fig. 28 Scanning electron micrographs showing the three modes of abrasive wear typically found in steels: (a) low-stress scratching, (b) higher-stress gouging, and (c) impact or indentation

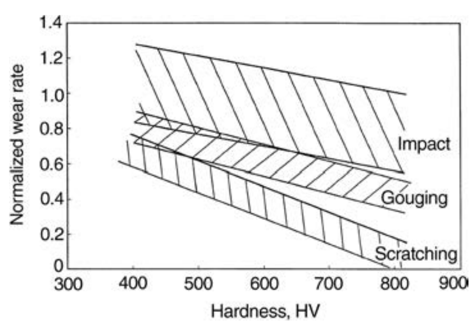


Fig. 29 Bands of normalized wear rate versus hardness for low-stress scratching, high-stress gouging, and impact wear. Low-stress scratching shows the strongest dependence on hardness, while impact abrasion shows the least. The scatter in the impact abrasion data suggests a growing contribution of material attributes other than hardness.

The dependency of the wear performance on a given material or wear mode emphasizes the need to know the wear mode being

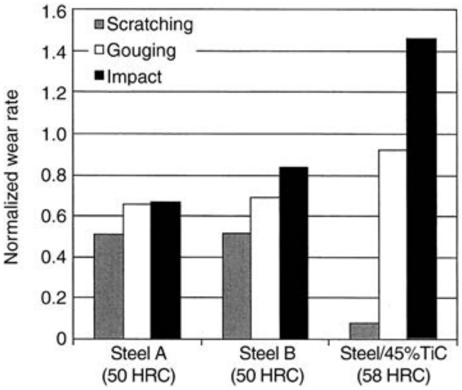


Fig. 30 Correlation of hardness with wear rate for three materials. The two 50 HRC materials both exhibit the same low-stress scratching wear resistance. However, as the wear severity increases, the steel designed for ground-engaging tools (steel A) exhibits moderate improvements in gouging wear and significant improvements in impact abrasion resistance. In contrast, due to the hard phases, the composite material performs better than would be expected, given its bulk hardness; however, due to its low fracture toughness, it performs significantly worse in more severe wear modes.

experienced by a component. Unfortunately, components returned from field service rarely reveal information as clearly as seen in Fig. 28. Such surface features are frequently damaged by corrosion. Therefore, another means of identifying wear modes is desired. One such method used for martensitic steels is to examine the polished and etched cross section of the wear surfaces. Figure 31 shows cross sections taken through the surface of components experiencing the three wear modes discussed. In low-stress scratching, there is essentially no subsurface microstructural modification of the steel. Even the few micrometers just below the surface show little or no evidence of plastic deformation (Fig. 31a). As the stress and severity of the abrasive event increase, microstructural modification becomes more evident. This may be manifested as a deep, plastically deformed layer (evident in structural deformation) or in white-etching layers (Fig. 31b). The white-etching layers are believed to be extremely fine-grained ferrite, with all alloying elements in solution (Ref 33, 34, 35, 36, 37). In most cases, the formation of white-etching layers indicates a higher-stress abrasive event. However, it is also reflective of the material condition. Figure 32 shows two cross sections that were exposed to the same high-stress abrasive conditions. The material exhibiting white-etching layer formation is approximately 20 HRC softer than that with only slight surface plasticity. Impact abrasion is manifested in the appearance of severe plastic deformation at the surface and the presence of white-etching localized shear bands below the surface (Fig. 31c). The shear bands are created in a single impact event and are again the result of very high strains leading to what is believed

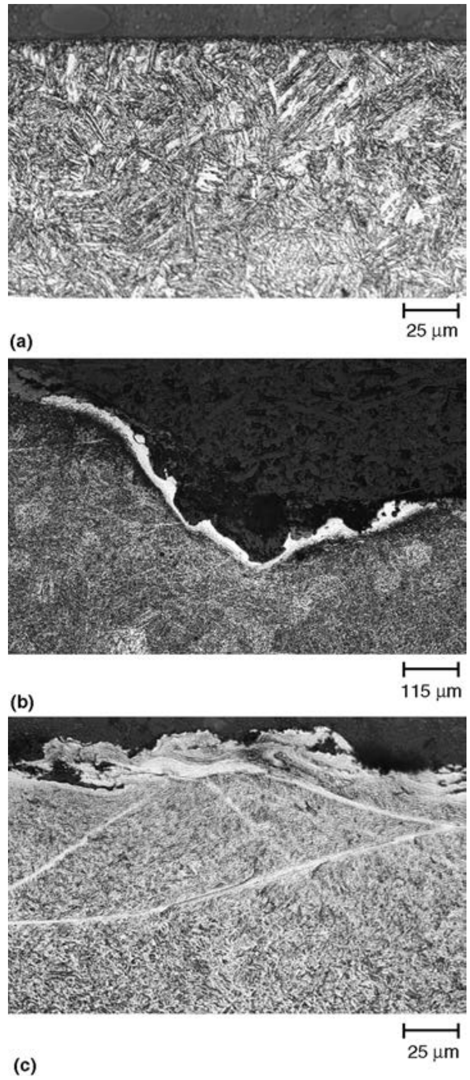


Fig. 31 Metallographic cross sections of the worn surface regions showing (a) no microstructural modification in low-stress scratching, (b) white-etching layers in high-stress gouging, and (c) subsurface white-etching shear bands resulting from impact abrasion

to be the same structure as observed on the surface of components experiencing gouging wear (Ref 33, 34, 37). Identification of these wear modes may be used to help guide materials selection and processing to improve the wear resistance of components.

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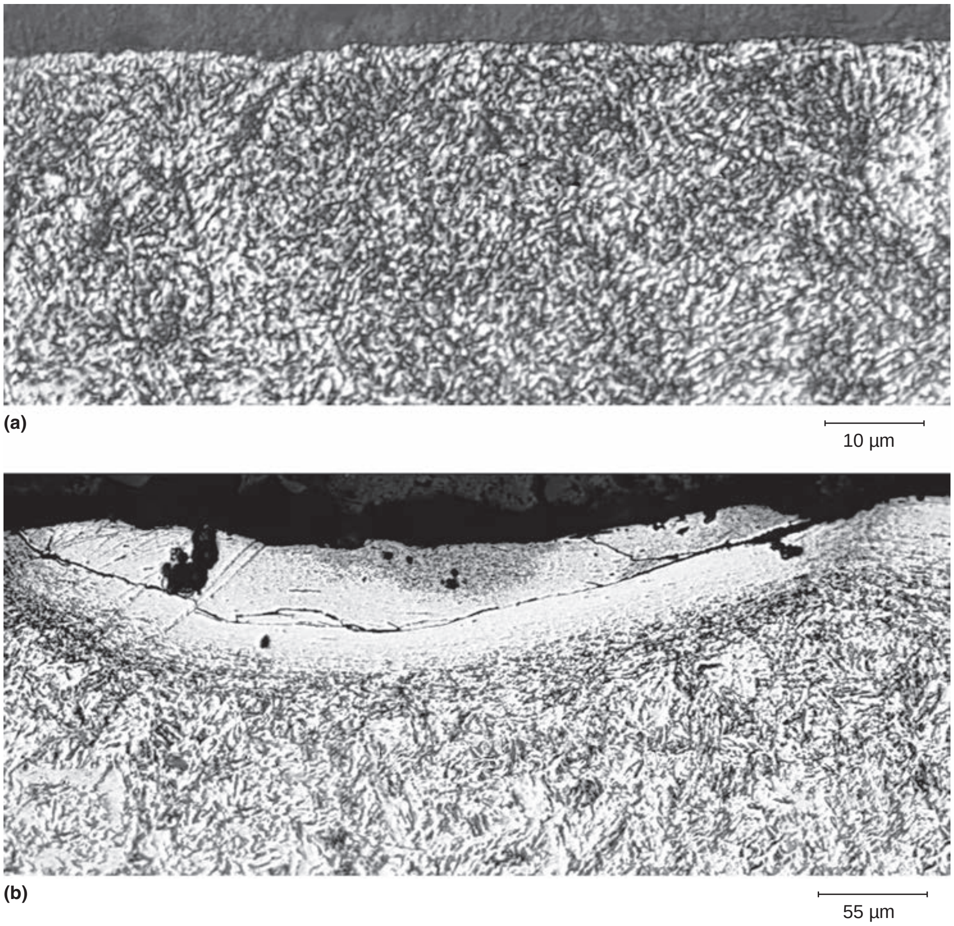

Fig. 32 Metallographic cross sections of wear surfaces of two materials that experienced the same high-stress abrasion. (a) At 60 HRC, the material exhibited no white-etching layers, while (b) at 20 HRC points softer, significant gouging and white-etching layer formation is observed.

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