

# FRICION, WEAR AND LUBRICATION

MEMM 1343

## WEAR

The term “wear” is defined as the progressive loss of material from the surface of a solid object due to mechanical causes – that is, the contact with and frictional motion against a solid, liquid, or gaseous counter-body.

The occurrence of wear is undesirable, and is related to a deterioration of functional capability and a depreciation of value. Only in exceptional cases, such as run-in procedures, is wear desirable from a technical standpoint.

“Wear damage” occurs when the function of the tribo system is no longer ensured. Therefore, based on the definition of value depreciation, all production processes such as lapping, polishing, and so on that lead to a value increase are not considered as wear processes but rather as machining processes, even though the functional principle is identical.

Whilst wear processes are the result of mechanical loading, chemical processes may be interfacially superimposed on them, and can also influence such loading. Wear processes cause a number of material, and also geometric, alterations in the tribological system.

Material alterations are understood here to mean the formation of tribological reaction layers and metallurgical compounds between the materials of the tribo elements in the tribocontact.

Geometrical alterations arise by the abrasion of material on the surface of the object. The causes are to be found in the four “wear mechanisms” which will be described below.

Alterations to the surface, as well as the type and form of particles that arise due to wear, are described as “wear phenomena forms”.

In real tribo systems, there is nearly always a superposition of several wear mechanisms. Hence, in order to simplify the analysis, for the most important basis tribological systems “wear types” have been defined from the superposition of the possible wear mechanisms. The alteration in the form or mass of a body due to wear is designated by parameters which are standardized as “wear parameters” in the Society for Tribology.

## WEAR MECHANISMS

Wear is the result of the four wear mechanisms:

Abrasion

Adhesion.

Tribochemical reaction

Surface fatigue

These mechanisms lead to material and form alterations, and also to the formation of wear particles, and occur in the form of characteristic wear phenomena as shown in Figure 1.

Although each wear mechanism can occur alone, the examination of wear damage indicates that there is nearly always a superposition of several wear mechanisms, which complicates any wear analysis and wear prevention.

Figure 2 shows, schematically, how such a superposition might appear; frequently, the individual wear mechanisms will mutually reinforce each other.

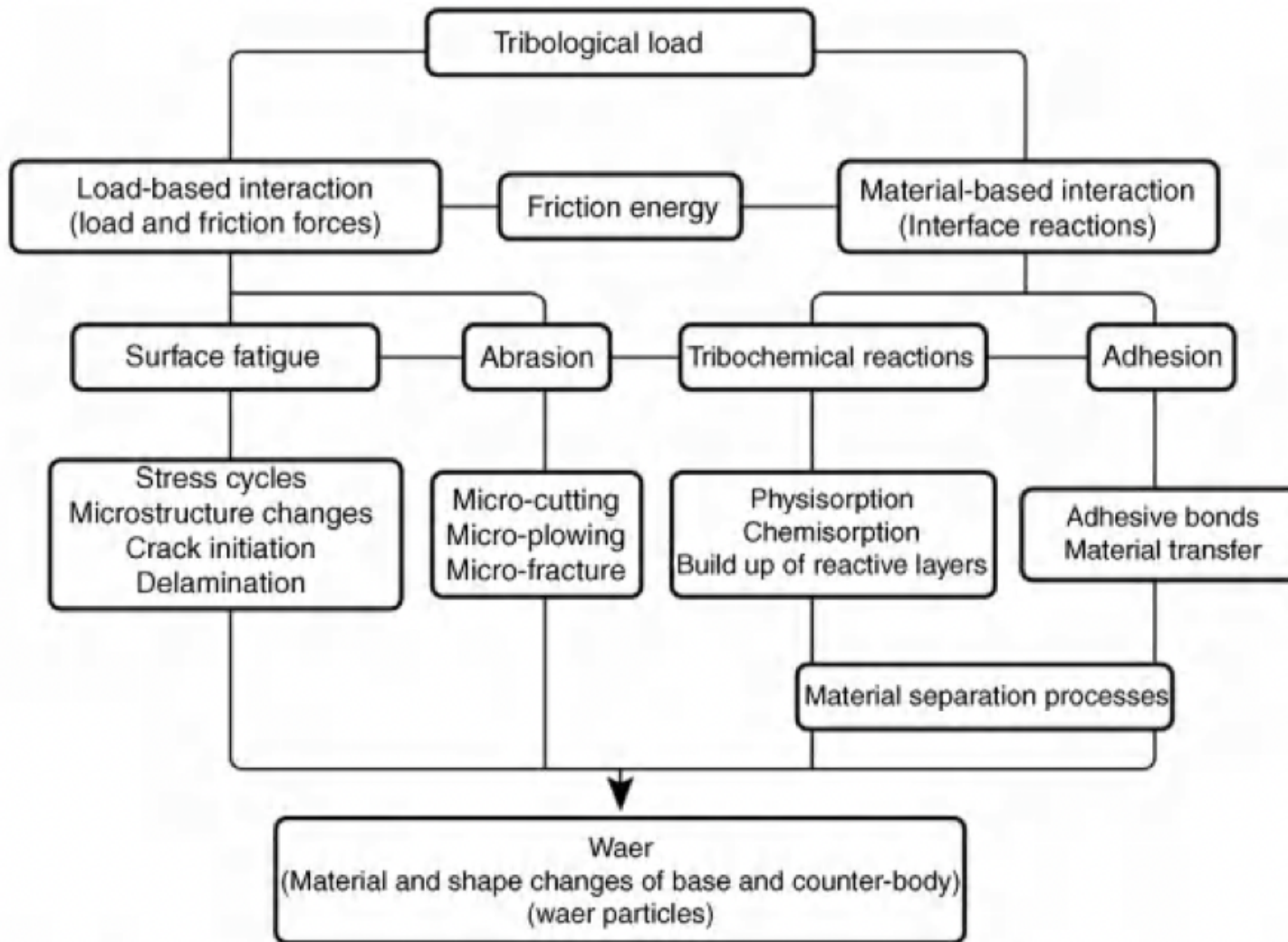
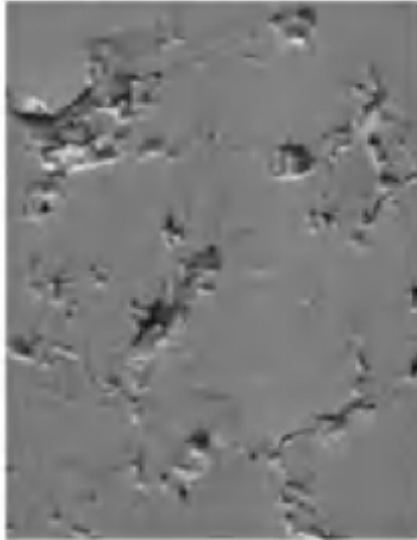


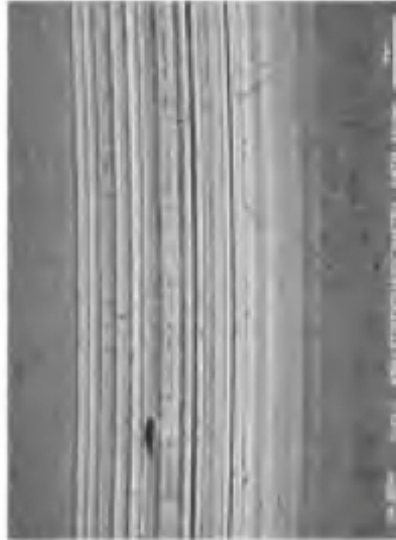
Figure 1(a): Wear mechanisms. An overview of material and form alteration processes due to tribological loading.

Surface fatigue



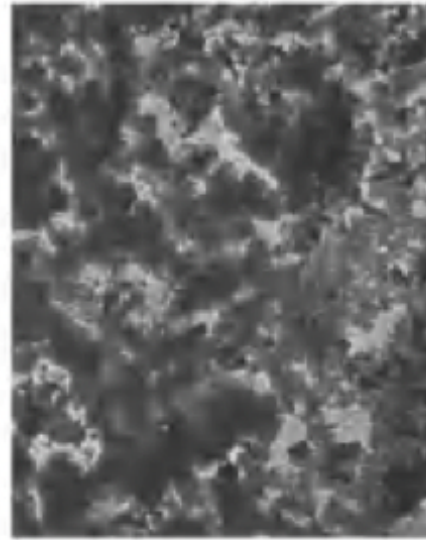
Cracking, pitting,  
particle formation by  
progressive cracking  
and the break-out of  
platelets

Abreasion



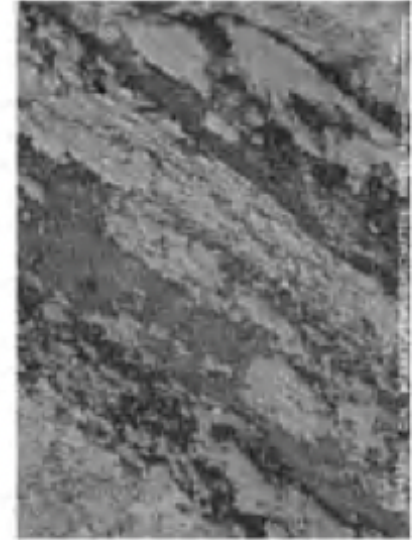
Channelling, scratches,  
hollows, waves,  
particle formation by  
abrasion

Tribochemical reaction



Reaction products such  
as particles or layers

Adhesion



Material transfer,  
corrosion pits, holes  
crests, scaling

Figure 1(b): The forms of wear.

## Abrasion

Abrasion occurs predominantly in tribo systems in which the tribo elements possess widely different hardness values. The harder material acts abrasively, in that harder roughness peaks or harder particles in the object penetrate the surface of the softer object.

As a result of the relative motion, channeling and scratches are formed, and for the case of stronger attack the material breaks away from the surface, causing an extensive amount of wear. The process of material abrasion consists of the following diverse processes, which usually occur simultaneously, as shown in Figure 3.



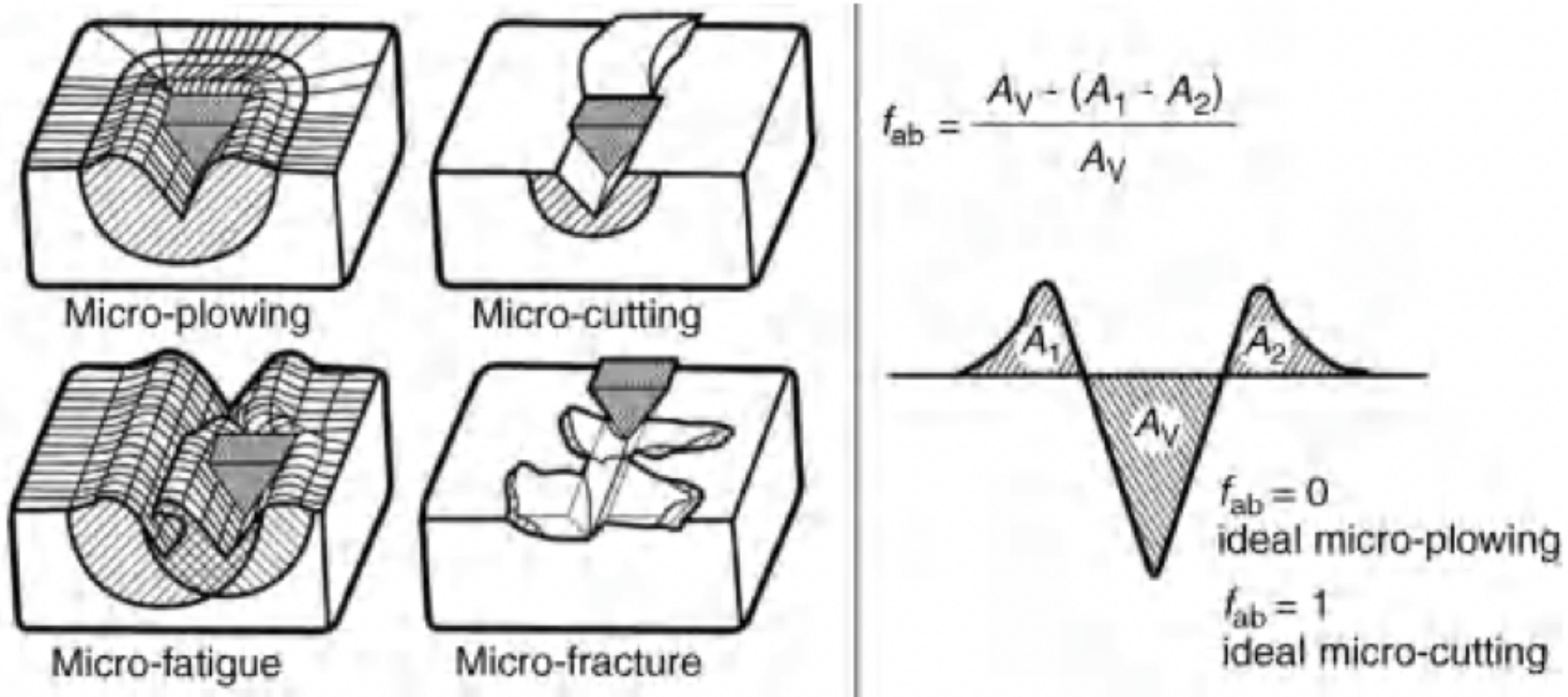


Figure 3: Abrasion processes.

$A_V$  is the cross-section of the wear furrow.

$A_1$  and  $A_2$  are the cross-sections of the material pile-up due to micro-plowing.



Micro-plowing:

Pronounced plastic deformation of the material by the abrasive counter-body gives rise to pile-up at the edge of the channel, so that material abrasion is not compelled to occur.

Micro-cutting:

Hard roughness peaks or abrasive particles cut the surface, with the formation of micro-shavings.

Micro-fracture:

The supercritical loading of a brittle material by an abrasive particle leads to the formation and spreading of cracks, and ultimately to material break-away.

Micro-fatigue:

Repeated micro-plowing results in local material fatigue, causing material abrasion. This partial process is part of the process of surface fatigue.

The preferred measure for protection against abrasion is the use of harder materials. The greatest hardness is achieved with highly covalent bonding fractions (e.g., diamond, CBN, or B<sub>4</sub>C).

It is necessary to consider that very hard materials are often also very brittle. Under supercritical loading, these materials tend to fail due to the presence of micro-fracturing, so that sufficient fracture toughness is required in addition to hardness.

Compound systems comprised of a tough metal matrix with embedded hard materials (MMC or metal-matrix composite) exhibit good properties in respect of abrasive wear. In order that hard material particles are not torn away by the abrasive material, the mean free path of the hard phase must be less than the mean diameter of the abrasive particles.

The ratio of the two partial processes is influenced by the angle of attack  $\alpha$  of the abrasive material which, in this regard, represents the “cutting angle” as shown in Figure 4.

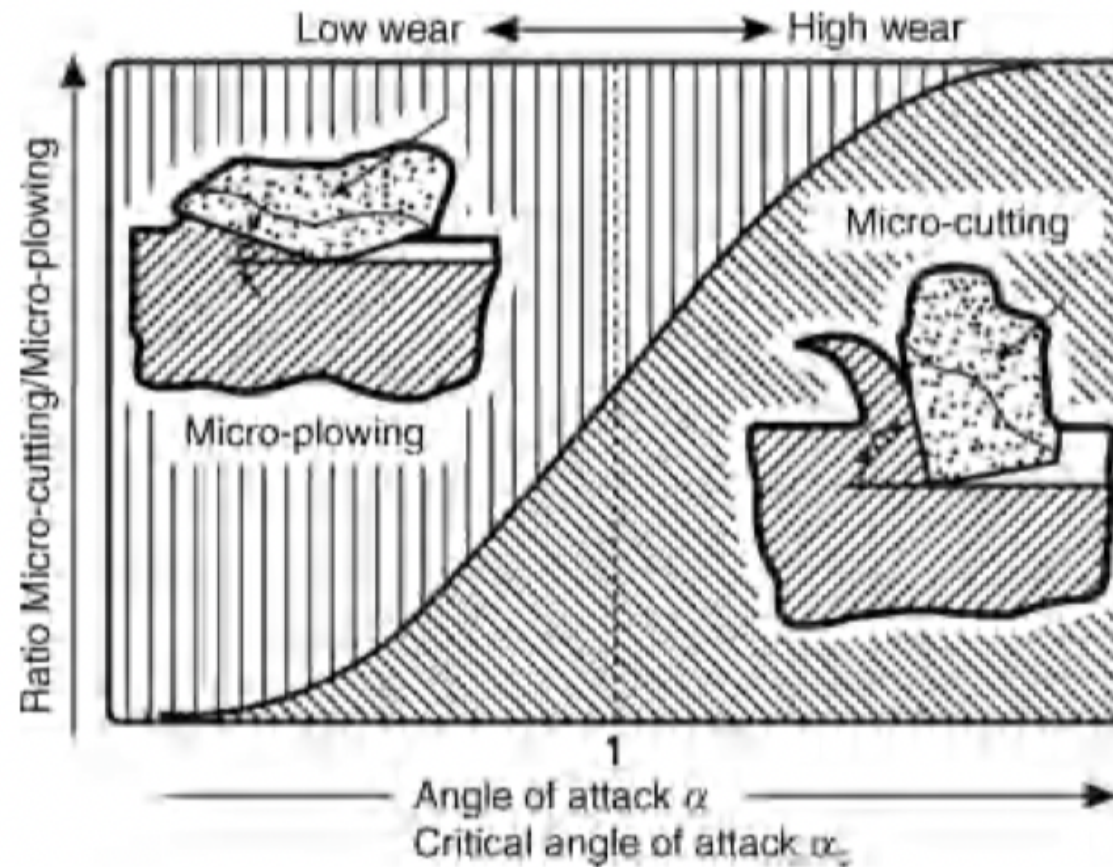


Figure 4: Influence of the cutting angle of the abrasive material on the abrasion process.

## Modes of Abrasive Wear

The way the grits pass over the worn surface determines the nature of abrasive wear. The literature denotes two basic modes of abrasive wear:

two-body abrasive wear

three-body abrasive wear.

Two-body abrasive wear is exemplified by the action of sandpaper on a surface. Hard asperities or rigidly held grits pass over the surface like a cutting tool. In three-body abrasive wear the grits are free to roll as well as slide over the surface, since they are not held rigidly. The two- and three-body modes of abrasive wear are illustrated schematically in Figure 5.

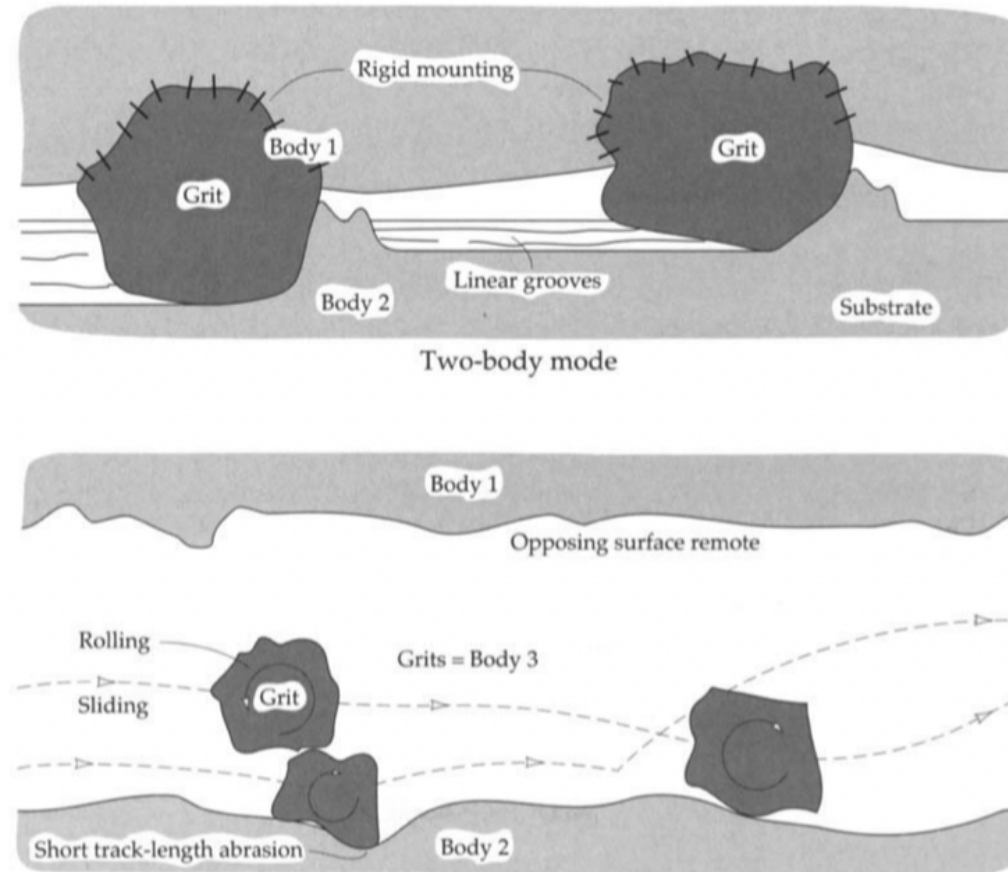


Figure 5: Two and three-body modes of abrasive wear.

Until recently these two modes of abrasive wear were thought to be very similar; however, some significant differences between them have been revealed.

It was found that three-body abrasive wear is ten times slower than two-body wear since it has to compete with other mechanisms such as adhesive wear. Properties such as hardness of the 'backing wheel', which forces the grits onto a particular surface, were found to be important for three-body but not for two-body abrasive wear.

Two-body abrasive wear corresponds closely to the 'cutting tool' model of material removal whereas three-body abrasive wear involves slower mechanisms of material removal, though very little is known about the mechanisms involved.

It appears that the worn material is not removed by a series of scratches as is the case with two-body abrasive wear. Instead, the worn surface displays a random topography suggesting gradual removal of surface layers by the successive contact of grits.

Theoretically the total amount of abrasive wear is equal to the sum of ductile and brittle wear.

The limitations of applying hard but brittle materials as abrasion resistant materials are clear. The generally recognized hardness of the material is not the only factor critical for its abrasive wear resistance. The material's toughness is also critical.

In practice, it cannot be assumed that any grit will abrade a surface, i.e., remove material.

If the grit is sufficiently blunt then the surface material will deform without generation of wear debris as illustrated in Figure 6.



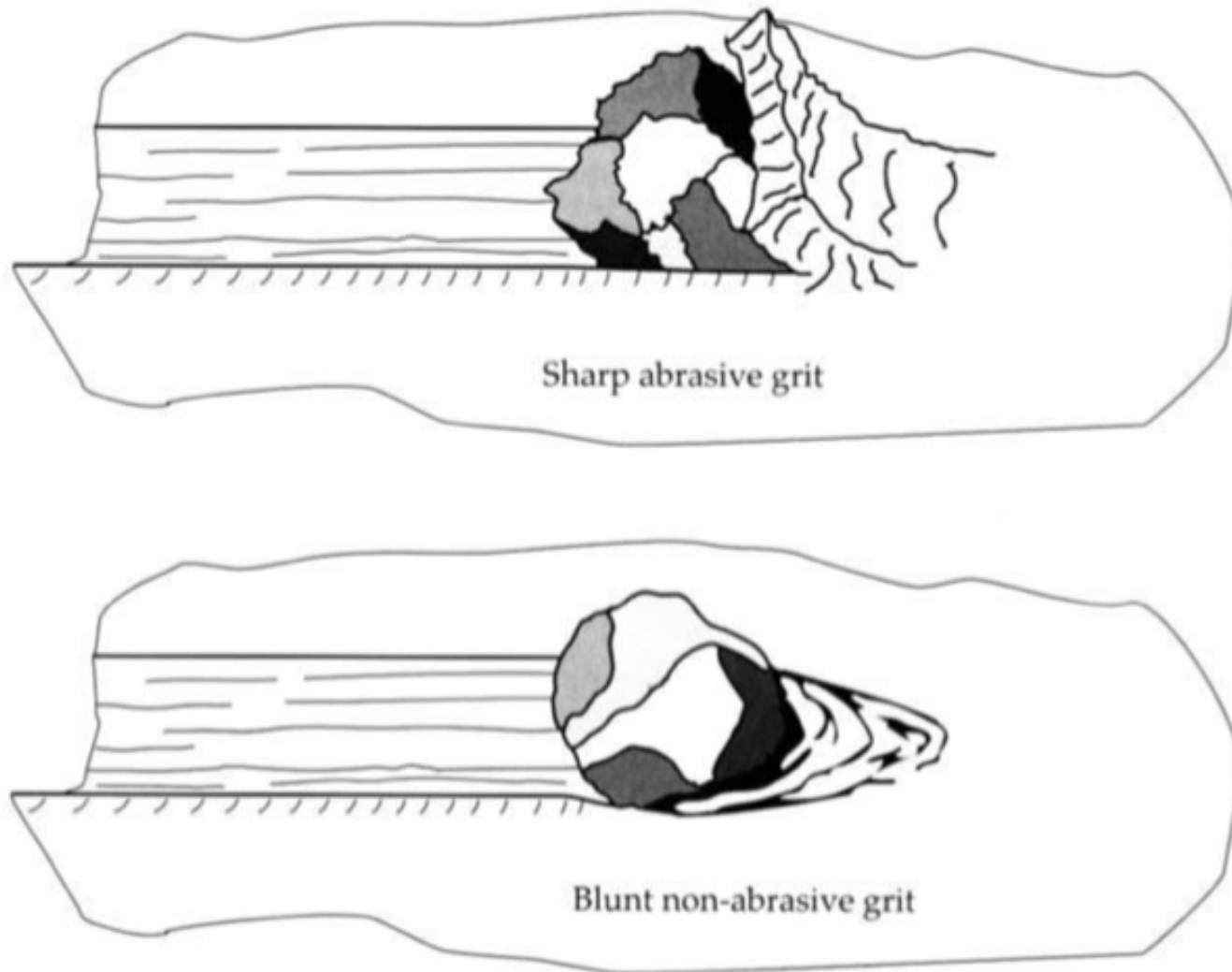


Figure 6: Cessation of abrasion with increasing grit bluntness.

## Abrasivity of Particles

A particle or grit is usually defined as abrasive when it can cause rapid or efficient abrasive wear. In most instances, the hardness of the material must be less than 0.8 of the particle hardness for rapid abrasion to occur.

It has been observed, however, that a limited amount of abrasive wear and damage to a surface (e.g., bearing surfaces) still occurs unless the yield stress of the material exceeds that of the abrasive particle.

Very slow abrasive wear persists until the hardness of abrasive and worn material are equal. Some materials with soft phases or not fully strain hardened may sustain some wear until the material hardness is 1.2 to 1.4 times the hardness of the abrasive.

A conceptual graph of wear resistance versus the ratio of material to abrasive hardness is shown in Figure 7. Wear resistance is usually defined as the reciprocal of wear rates and relative wear resistance is defined as the reciprocal of wear rate divided by the reciprocal wear rate of a control material.

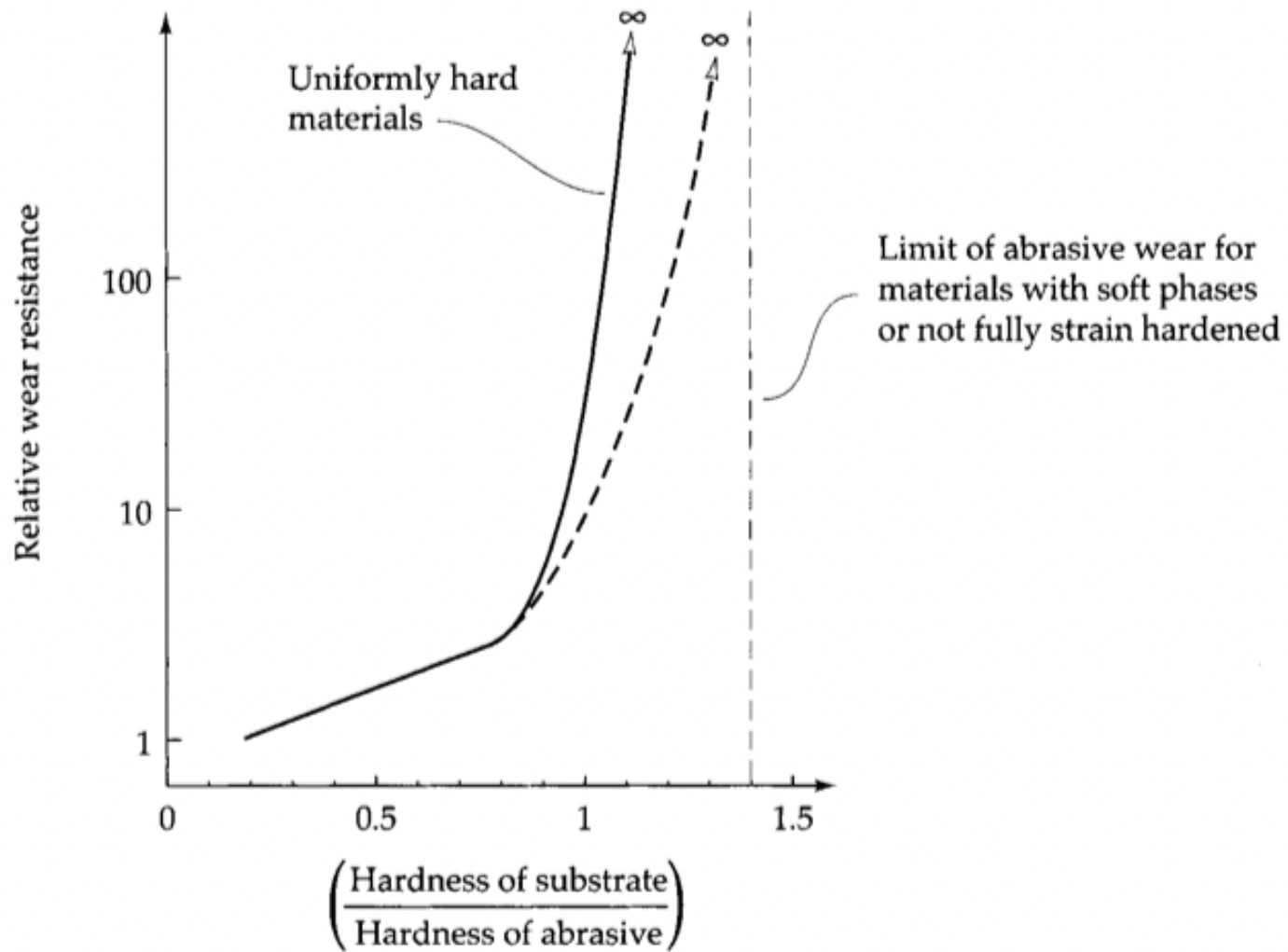


Figure 7: Relative abrasive wear resistance versus hardness ratio of worn to abrasive material.

A more complex constraint is the brittleness of the abrasive.

If the grits are too brittle then they may break up into fine particles, thus minimizing wear.

If the abrasive is too tough then the grits may not fracture to provide the new cutting faces necessary to cause rapid wear.

The sharp faces of the grits will gradually round-up and the grits will become less efficient abrasive agents than angular particles as illustrated in Figure 8.

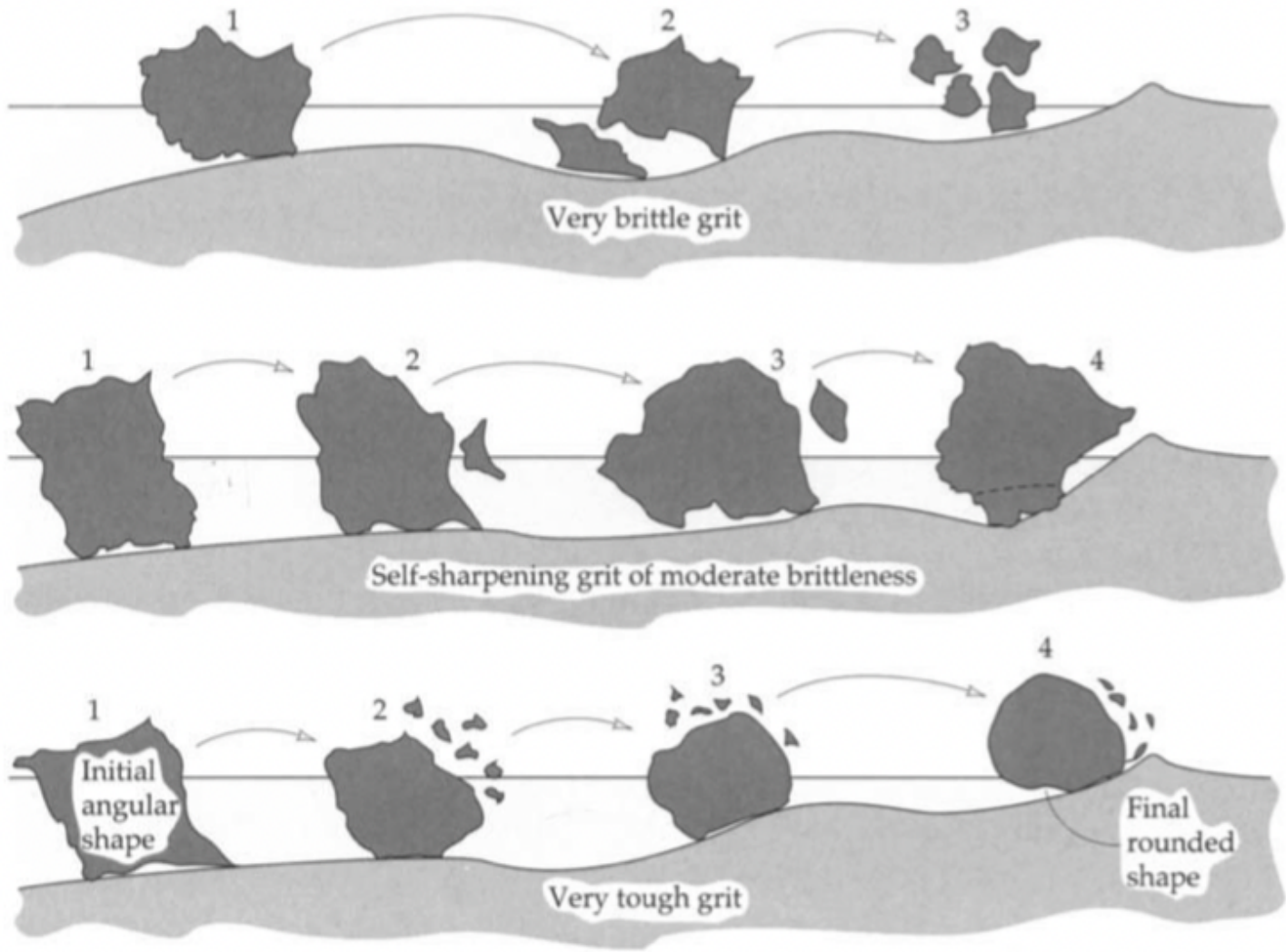


Figure 8: Effect of grit brittleness and toughness on its efficiency to abrade.

Another factor controlling the abrasivity of a particle is the size and geometry of a grit. The size of a grit is usually defined as the minimum size of a sphere which encloses the entire particle. This quantity can be measured relatively easily by sieving a mineral powder through holes of a known diameter. The geometry of a grit is important in defining how the shape of the particle differs from an ideal sphere and how many edges or corners are present on the grit. The non-sphericity of most particles can be described by a series of radii beginning with the minimum enclosing radius and extending to describe the particle in progressively more detail as shown in Figure 9.

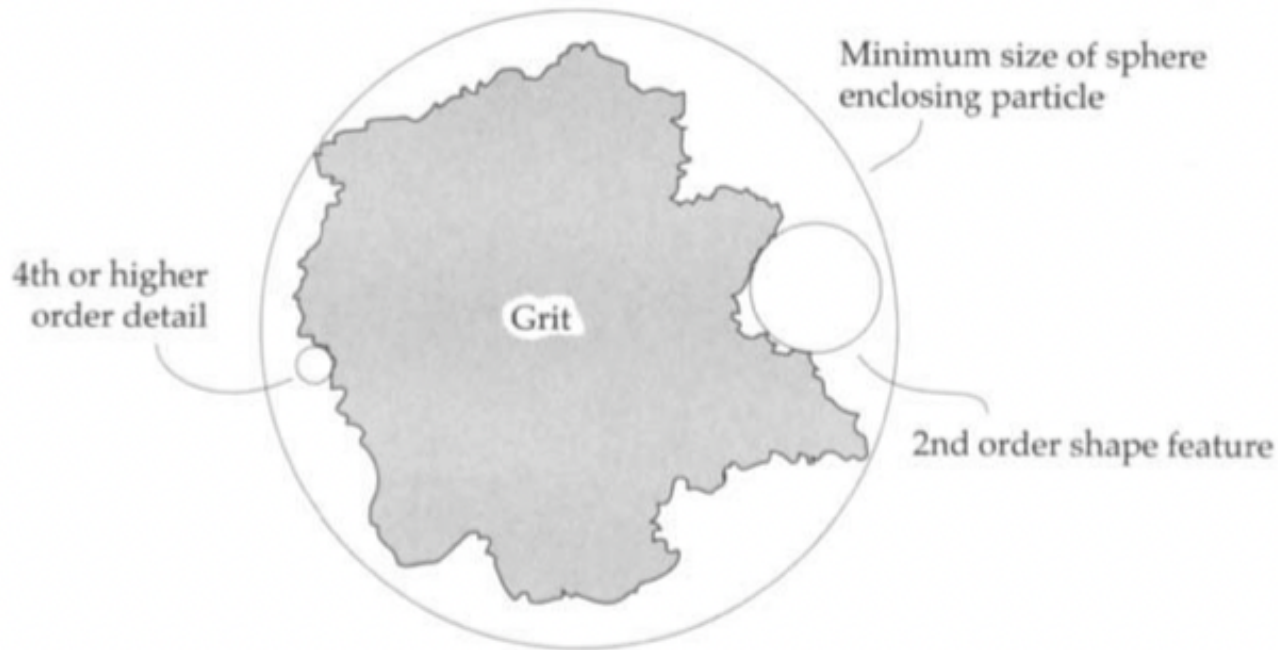


Figure 9: Method of defining grit geometry by a series of radii.

The other parameter, called “spike parameter - quadratic fit” (SPQ), is based on locating a particle boundary centroid “O” and the average radius circle, as illustrated in Figure 10.

The areas outside the circle, “spikes”, are deemed to be the areas of interest while the areas inside the circle are omitted. For each protrusion outside the circle, i.e., “spike”, the local maximum radius is found and this point is treated as the spike's apex.

The sides of the “spike”, which are between the points “s-m” and “m-e”, Figure 10b, are then represented by fitting quadratic polynomial functions. Differentiating the polynomials at the “m” point yields



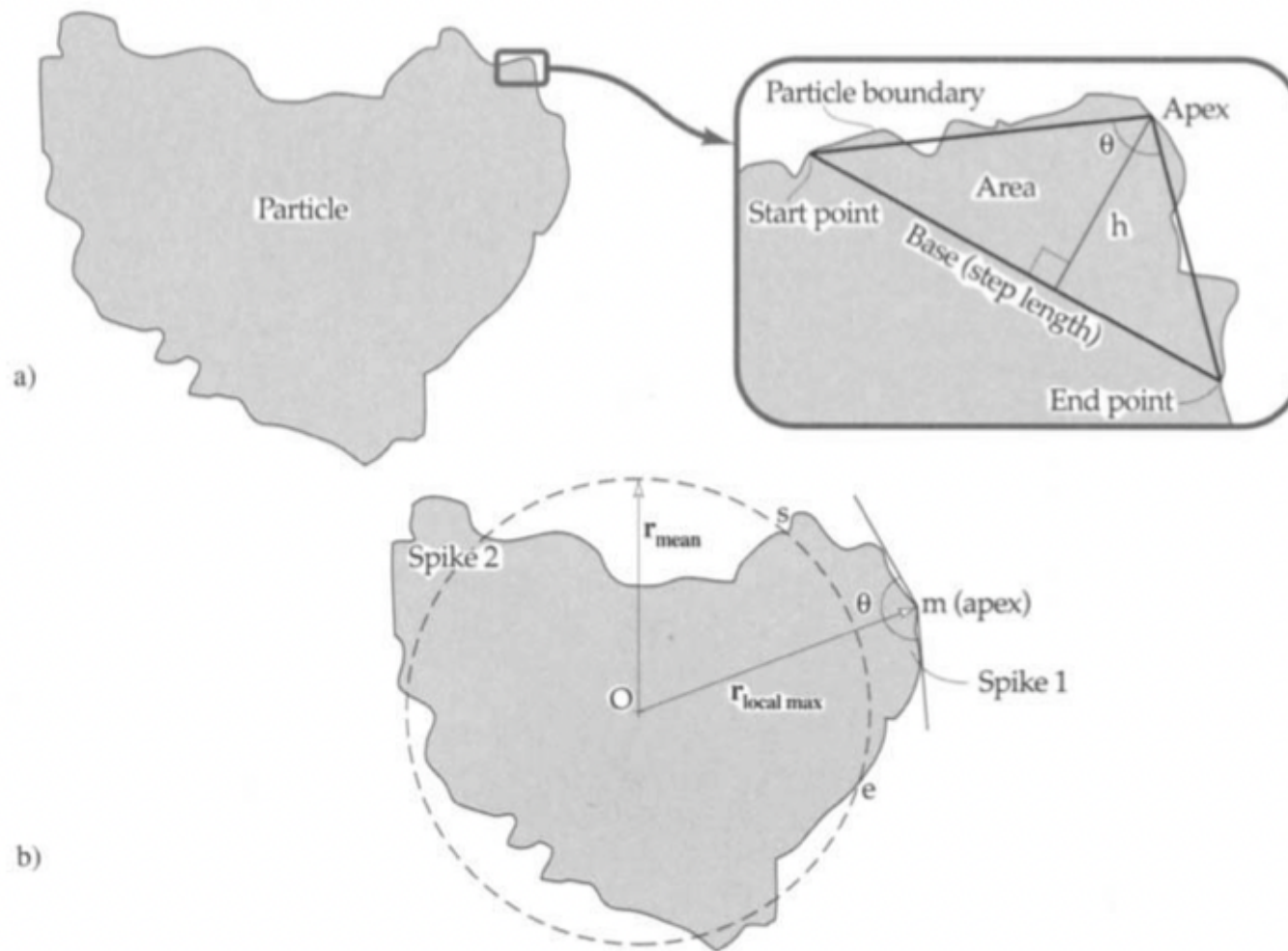


Figure 10: Schematic illustration of particle angularity calculation methods of (a) “spike parameter - linear fit” (SP) and (b) “spike parameter - quadratic fit” (SPQ).

## Abrasive Wear Resistance of Materials

The basis of abrasive wear resistance of materials is hardness and it is generally recognized that hard materials allow slower abrasive wear rates than softer materials.

This is supported by experimental data, an example of which is shown in Figure 11. The relative abrasive wear resistance for a variety of pure metals and alloys after heat treatment is plotted against the corresponding hardness of the undeformed metal.

Relative abrasive wear resistance is defined as wear rate of control material/wear rate of test material. A typical control material is EN24 steel [e.g., 30-32]. The abrasive material used in these tests was carborundum with a hardness of 2300 (VHN) and a grit size of 80 (micron). The tests were conducted in the two-body mode of abrasive wear with a metallic pin worn against a carborundum abrasive paper.

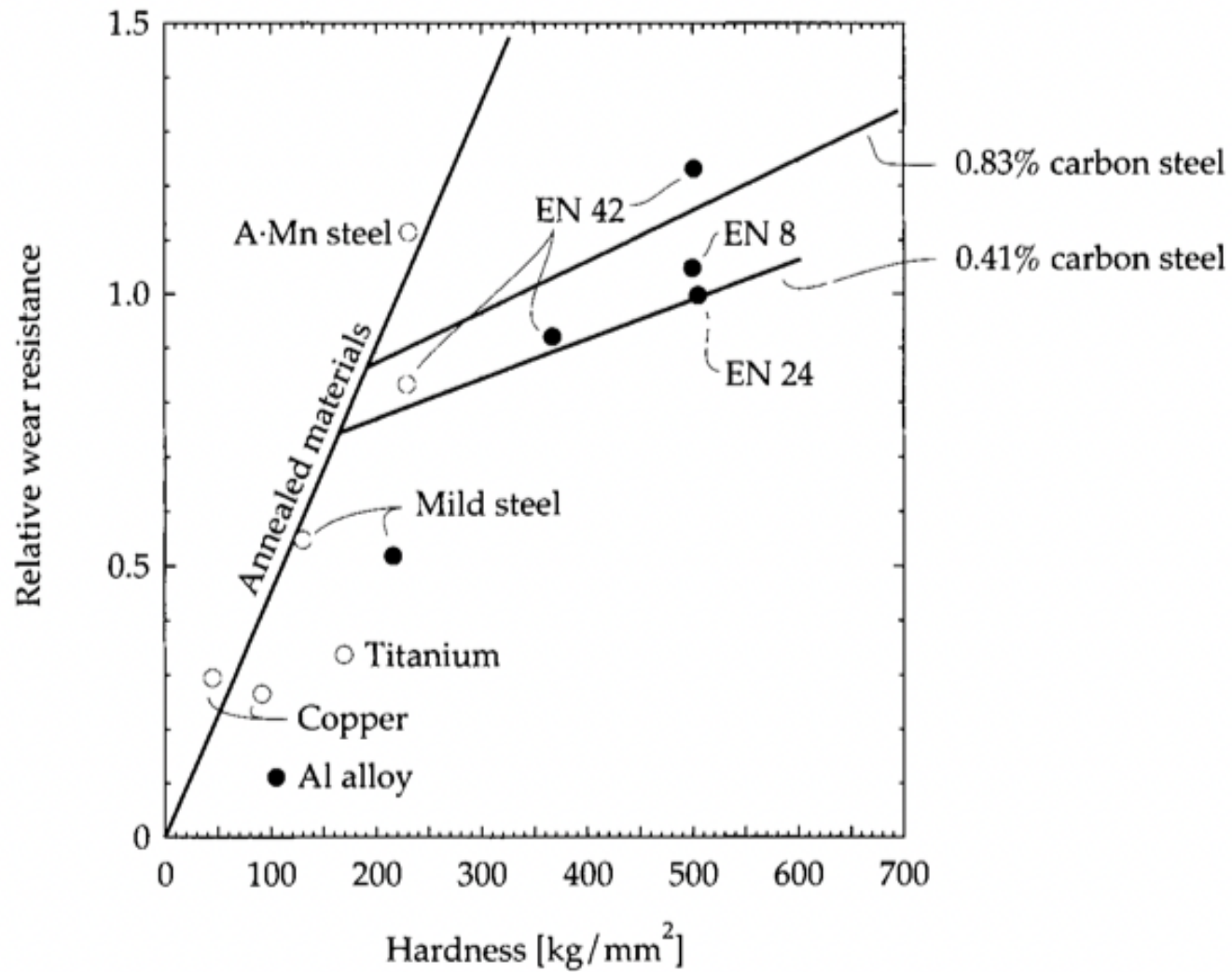


Figure 11: Relative abrasive wear resistance versus undeformed hardness for pure metals and alloys.

## Effect of Temperature on Abrasive Wear

The effect of temperature on abrasive wear can be divided into two basic understanding:

The influence of ambient temperature,

The role of temperature rises induced by plastic deformation of the worn material on contact with grits.

The effects caused by these forms of heating are not similar. The influence of elevated ambient temperature on abrasive wear has scarcely been studied, probably due to experimental difficulties.

Some limited tests of the abrasive wear of copper and aluminium showed only a small increase in wear at temperatures up to 400°C for copper and no effect for aluminium.

With the temperature increase there is a corresponding decline in the hardness of both the worn material and the abrasive grit. This trend was recorded in experiments conducted up to temperatures of 2000°C where most metals and metallic carbides and nitrides showed the same proportional decline in hardness with temperature.

It was found that when a temperature of about “0.8 × melting point” was reached the hardness of most materials was negligible, although non-metallic minerals such as silicon nitride and silicon carbide maintain their hardness until very close to the melting point.

When considering the effect of temperature on the abrasive wear of steel by, for example, silica (quartz) and alumina (corundum), the melting points of these materials, steel  $\sim 1500^{\circ}\text{C}$ , quartz  $1710^{\circ}\text{C}$  and alumina  $2045^{\circ}\text{C}$  become relevant and must be considered.

As temperature is raised, the ratio of abrasive hardness to steel hardness increases more sharply for alumina than for quartz. Alumina is therefore expected to cause more severe high temperature abrasive wear of steel than quartz. This prediction, however, still remains to be tested experimentally.

The temperature increase caused by plastic deformation during abrasion is associated with high grit speeds. Dynamic thermocouple measurements with an electrically conductive abrasive reveal that temperatures as high as  $1000^{\circ}\text{C}$  can be reached during abrasion.

The critical difference between the effects of a temperature rise in the worn metal imposed by high grit speeds and changes in ambient temperature is that the grits remain relatively cool due to the transient nature of abrasion.

Contact between a grit and the worn surface would be particularly short in the three-body abrasive wear mode, so that any heat generated in the deformed material would not diffuse into the grit. It is possible then that transient thermal softening occurs only in the deformed material while the grit remains with its hardness virtually unaltered. The localization of deformation heat during high speed abrasion is illustrated in Figure 12.

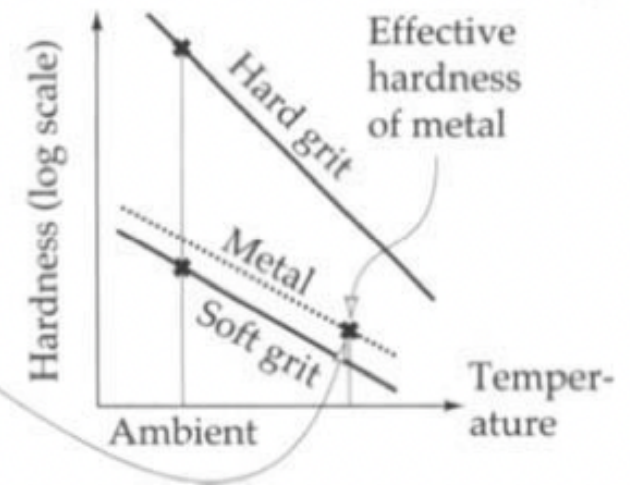
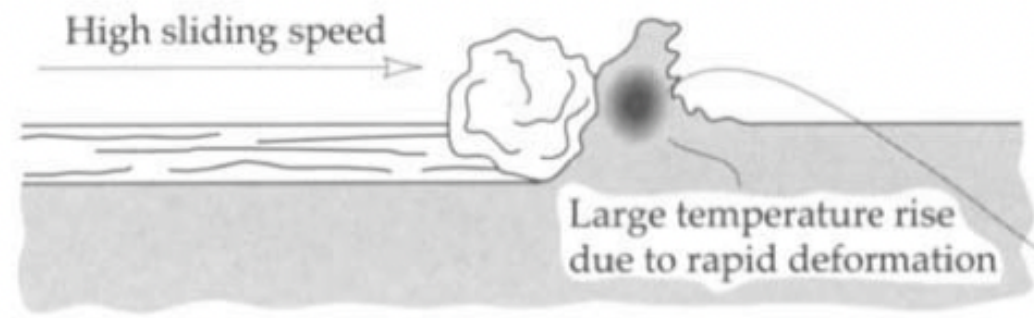
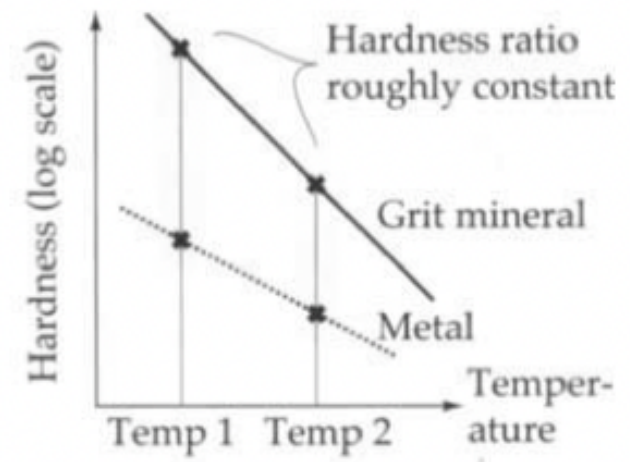
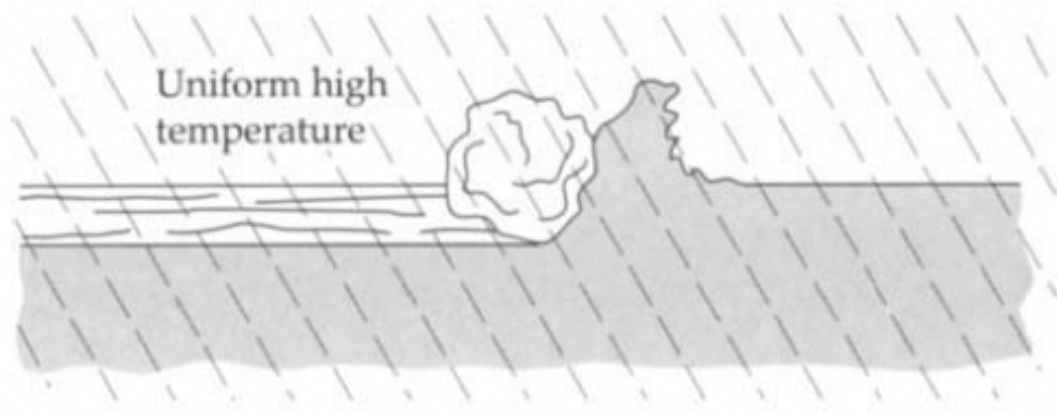


Figure 12: Temperature effects on abrasion under uniformly hot conditions and under high rates of frictional energy released during rapid abrasion.

If the grit remains relatively cool during abrasion it also maintains its hardness while the worn material effectively softens. Thus at high grit speeds, soft minerals begin to wear hard materials significantly. An example of this phenomenon is the wear of steel by coal free of hard contaminants. The speed dependent softening effect is reduced at high temperatures because of the reduced strain energy of deformation. The effect of high temperature is to soften a material so that there is less local heating of the deformed material for a given amount of deformation.

Another effect of high temperatures is to cause a form of wear which depends on the combined action of oxidation and removal of oxide layers by abrasion. The oxidation of steels in air is much more rapid at 600°C than at 20°C, and as temperature rises, the removal of steel as oxide becomes more significant. This also called as “Corrosive and Oxidative Wear”.



## Effect of Moisture on Abrasive Wear

Moisture has a strong influence on abrasive wear rates. Usually abrasive wear rates increase with moisture content in the atmosphere but there are occasions when a contrary effect occurs.

Prediction of the moisture effect for any particular case is difficult. The grit may either be just sufficiently weakened by moisture to produce a larger number of new cutting edges, or severe grit weakening may occur causing disintegration of the grits into nonabrasive, fine particles. The worn material may also be weakened by moisture, e.g., glass.

For the same abrasive and worn material, two-body abrasive wear may increase with humidity while the three-body abrasive wear rate may either increase or decrease.

Water may also introduce corrosive agents into the abrasive wear system, e.g., dilute acids. This causes a combined corrosive-abrasive wear which has certain fundamental similarities with oxidative-abrasive wear mentioned previously.

Non-aqueous fluids such as lubricants can also affect abrasive wear. When stearic acid is applied as a lubricant to a three-body abrasive wear system, the abrasion of the harder of the two metal surfaces is increased. The mechanism responsible for this may be that the abrasive is preferentially embedded in the softer material and wears the harder material by microcutting when lubrication is effective. When lubrication is absent, the slower ploughing form of abrasion predominates.

## Control of Abrasive Wear

Since abrasive wear is the most rapid form of wear and causes the largest costs to industry, several methods have been developed to minimize the losses incurred. The basic method of abrasive wear control or suppression is to raise the hardness of the worn surface until its value is at least 0.8 of the grit hardness. No other form of wear allows such a simple rationale for its prevention. There are of course complications such as the prevention of brittleness while raising the hardness which can be overcome only to a certain degree.

Abrasive wear is usually suppressed by the application of a hard material or hard coating. Most of the hard materials are more expensive than the customary materials so the first question to be answered is, what is the nature of the problem caused by abrasive wear?

If the issue is survival of the worn part against gross wear, e.g., soles of shoes, then the choice of abrasion resistant material is determined by the cost of the replacement. With industrial machinery, however, small amounts of abrasive can severely affect its overall performance, e.g., in hydraulic systems.

The assessment of performance losses imposed by abrasive wear can often be impossible to quantify or may require very elaborate testing. An example of this problem is the gradual wear of sugarcane shredder hammers by silica from the sugarcane. Sugarcane millers observed that small amounts of wear caused the hammers to become rounded and prevented the cane from being properly “shredded” before “crushing” to extract sugar. In other words, the wear of the hammers caused the sugarcane millers to lose a certain amount of sugar.

The problem of wear was solved by replacing the hardened steel hammers with tungsten carbide. Since the hardness of tungsten carbide is about 1100 (VHN) or 11 (GPa), it effectively resisted abrasive wear by the prevailing silica which has a hardness of about 1150 (VHN) or 11.5 (GPa).

The extended maintenance free period of the shredder hammers and the improved cane preparation quality justified the extra expense of using hard tungsten carbide, which is five times the cost of steel.

