ABRASIVE WEAR

INTRODUCTION

- ABRASIVE WEAR, is due to hard particles or hard protuberances that are forced against and move along a solid surface. Wear, in turn, is defined as damage to a solid surface that generally involves progressive loss of material and is due to relative motion between that surface and a contacting substance or substances.

- The cost of abrasion is high and has been estimated as ranging from 1 to 4% of the gross national product of an industrialized nation.
- The effect of abrasion is particularly evident in the industrial areas of
  - agriculture,
  - mining,
  - mineral processing,
  - earth moving, and
  - essentially wherever dirt, rock, and minerals are handled.

EXAMPLES INCLUDE

- plows,
- Ore loading
- moving buckets,
- crushers,
- dump truck beds.

FOR EXAMPLE,

- An individual walking up the stairs of a building would be more likely to think that his shoes, rather than the stairs, were experiencing abrasive wear,
  - whereas the maintenance staff would have the opposite opinion.
- In actually, both surfaces are being subjected to abrasive wear.

THE RATE AT WHICH THE SURFACES ABRADE

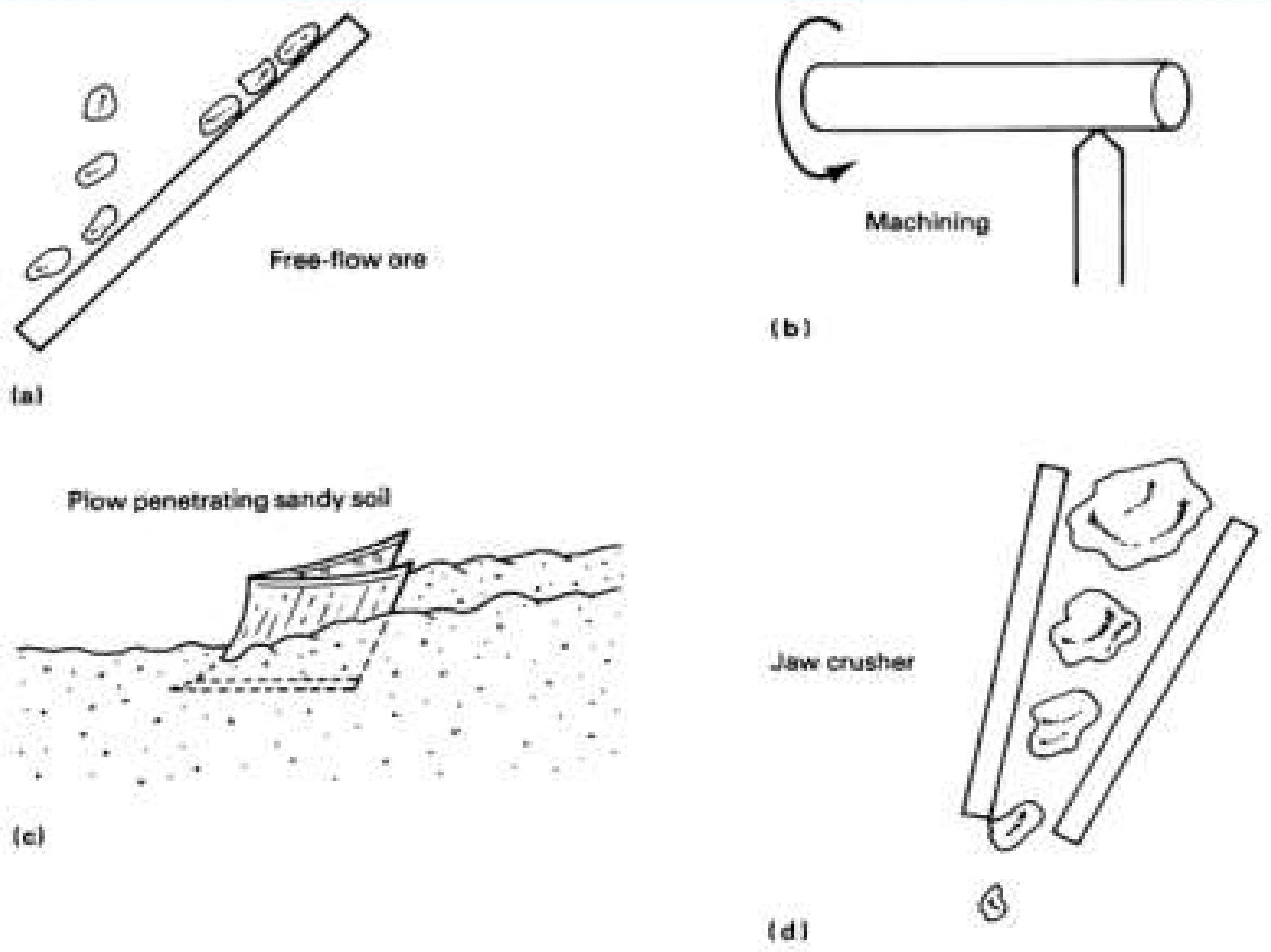
- depends on the
  - characteristics of each surface,
  - the presence of abrasives between the first and second surfaces,
  - the speed of contact, and
  - other environmental conditions.
- In short, loss rates are not inherent to a material.

- With reference to the stairs example, changing the material of either the shoes or the steps could, and often would, change the wear on the opposite counter-face.
  - The addition of an abrasive, such as a layer of sand, on the steps would further change the situation, in that the sand would be the second surface that contacts both the shoes and the steps.

ABRASION IS TYPICALLY CATEGORIZED ACCORDING TO

  - types of contact,
  - contact environment.
- Types of contact include
  - two-body
  - three-body wear.
- The former occurs when an abrasive slides along a surface , and the latter, when an abrasive is caught between one surface and another.

TYPES OF CONTACT DURING ABRASIVE WEAR. (A) OPEN TWO-BODY. (B) CLOSED TWO-BODY. (C) OPEN THREE-BODY. (D) CLOSED THREE-BODY



- Two-body systems typically experience from 10 to 1000 times as much loss as three-body systems for a given load and path length of wear.
- Contact environments are classified as
  - open (free)
  - closed (constrained)

- There are two general situations for abrasive wear, In the first case, the hard surface is the harder of two rubbing surfaces (two-body abra sion),
  - for example, in mechanical operations. such as grinding, cutting and machining; and
- In the second case, the hard surface is a third body,

BY PLASTIC DEFORMATION AND FRACTURE

- Abrasive wear occurs when asperities of a rough, hard surface or hard particles slide on a softer surface and damage the interface by plastic deformation or fracture.
  - In the case of ductile materials with high fracture toughness (e.g. metals and alloys), hard asperities or hard particles result in the plastic flow of the softer material,

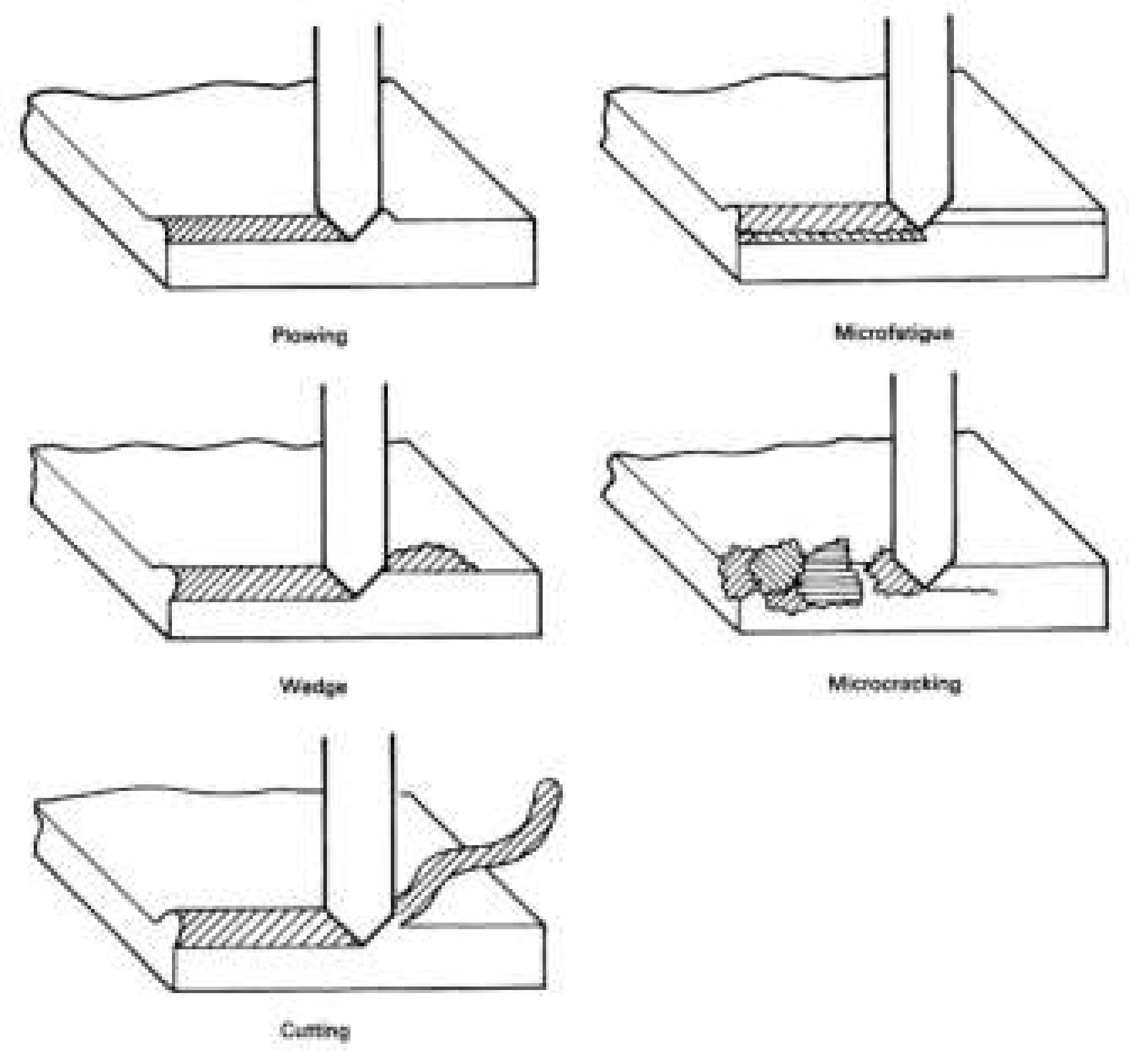
- Most metallic and ceramic surfaces during sliding show clear evidence of plastic flow, even some for ceramic brittle materials.
  - Contacting asperities of metals deform plastically even at the lightest loads.
- In the case of brittle materials with low fracture toughness, wear occurs by brittle fracture. In these cases, the worn zone consists of significant cracking.

- *for a given load and path length of wear, the wear rate* is about the same for both open and closed systems. However, measurements of the loss in closed systems will often appear higher than the loss in open systems. This probably occurs because most closed systems experience higher loads. Abrasion is often further categorized as being low stress, high stress, or gouging.

- Low-stress abrasion occurs when the abrasive remains relatively intact, for example,
  - when sanding wood with sandpaper.
- High-stress abrasion exists when abrasive particles are being crushed, for example,
  - in a ball mill where both the grinding balls and the ore are down.

- In gouging abrasion, a relatively large abrasive will cut the material that is not fully work hardened by the process from the material of concern, for example,
  - when rocks are crushed in jaw crusher.

FIVE PROCESSES OF ABRASIVE WEAR



PLOWING

- Plowing is the process of displacing material from a groove to the sides. This occurs under light loads and does not result in any real material loss. Damage occurs to the near surface of the material in the form of a build up of dislocations through cold work.
  - If later scratches occur on this cold-worked surface, then the additional work could result in loss through micro fatigue

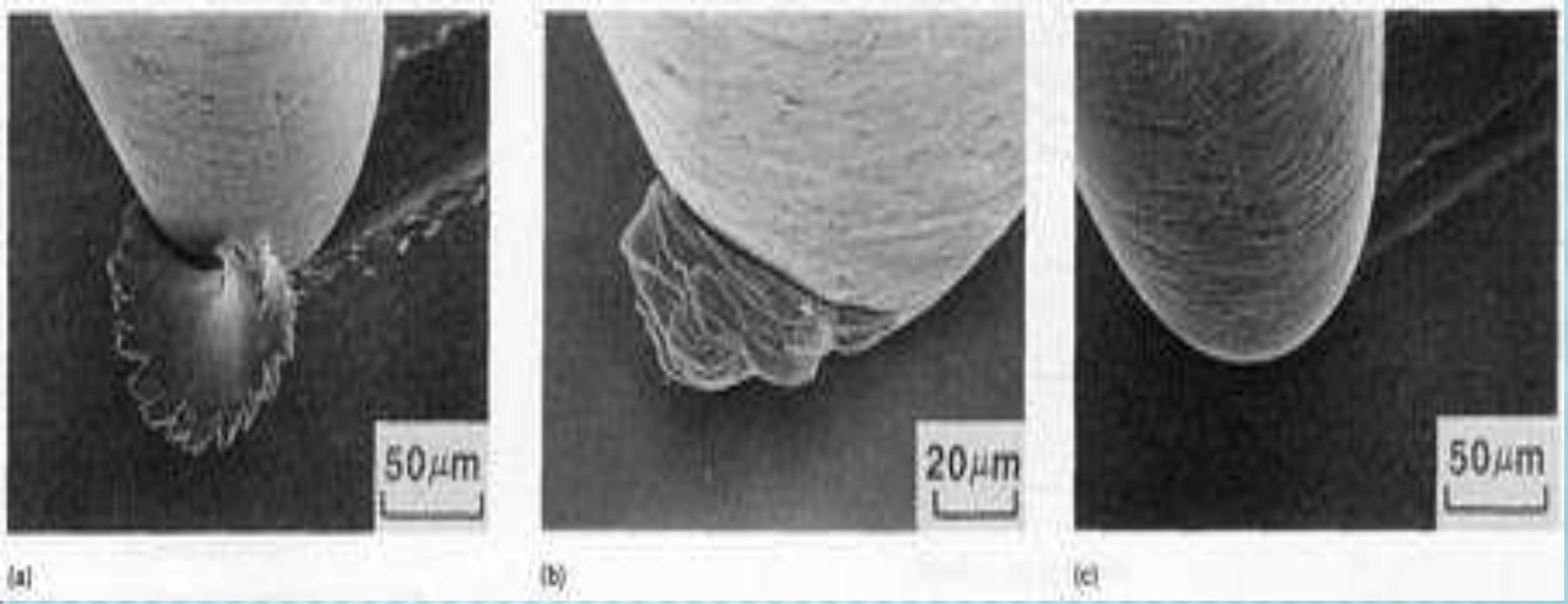
- When the ratio of shear strength of the contact interface relative to the shear strength of the bulk rises to a high enough level (from 0.5 to 1.0), it has been found that a wedge can develop on the front of an abrasive tip. In this case, the total amount of material displaced from the groove is greater than the material displaced to the sides. This wedge formation is still a fairly mild form of abrasive wear.

CUTTING.

- The most severe form of wear for ductile material is cutting. During the cutting process, the abrasive tip removes a chip, much like a machine tool does. This results in removed material, but very little displaced material relative to the size of the groove.
  - For a sharp abrasive particle, a critical angle exists, for which there is a transition from plowing to cutting.

- This angle depends on the material being abraded.
  - Examples of critical angles range from 45° for copper to 85° for aluminum.
- Abrasion is not dependent on scratches by carefully oriented abrasive grains. Kato and others have analyzed the effect of a rounded tip pushing through a surface

EXAMPLES OF THREE PROCESS OF ABRASIVE WEAR, OBSERVED USING A SCANNING ELECTRON MICROSCOPE. (A) CUTTING. (B) WEDGE FORMATION. (C) PLOWING



- When an abrasive grain abrades while cutting a surface, the maximum volume of wear that can occur is described by:
  - $W = Ad$ ………………………………..Eq.1
    - where *W is the volume of material removed, A is the cross-sectional area of the groove, and d is the distance slid. The* cross-sectional area of the groove *A is dependent on the abrasive grain shape and the depth of penetration, p:*
  - $A = k_1 p$ Eq.2
    - where k_1 *is constant-dependent on the shape.*

- *the depth of penetration, p, is again dependent on the shape of the* grain;
    - the load, *L;*
    - *the hardness, H, of the material:*

$$p = k_2 \frac{L}{H}$$

- Many factors affect *k1: the possibility of plowing rather than cutting; the abrasive grain may roll and avoid wear; the* abrasive grain may break down and not be effective during the latter part of its contact path; and others. Equation 1, 2,and 3 can be combined, forming:

$$W = k_3 \frac{Ld}{H}$$

- This is commonly known as Archard's equation (Ref 6), which was derived for adhesive wear but has proven very useful in abrasive wear, as well. Factors affecting *k3 are addressed later on.*

- Materials are described as having good or bad wear resistance, *R, which is simply defined as the reciprocal of* wear volume:
-
- $$R = \frac{1}{W}$$ **(Eq 5)**

MICROFRACTURE

- Brittle materials have an additional mode of abrasive wear, namely, microfracture. This occurs when forces applied by the abrasive grain exceed the fracture toughness of the material.
  - This is often the predominant mode of severe wear for the ceramic materials, and is active in materials such as white cast iron

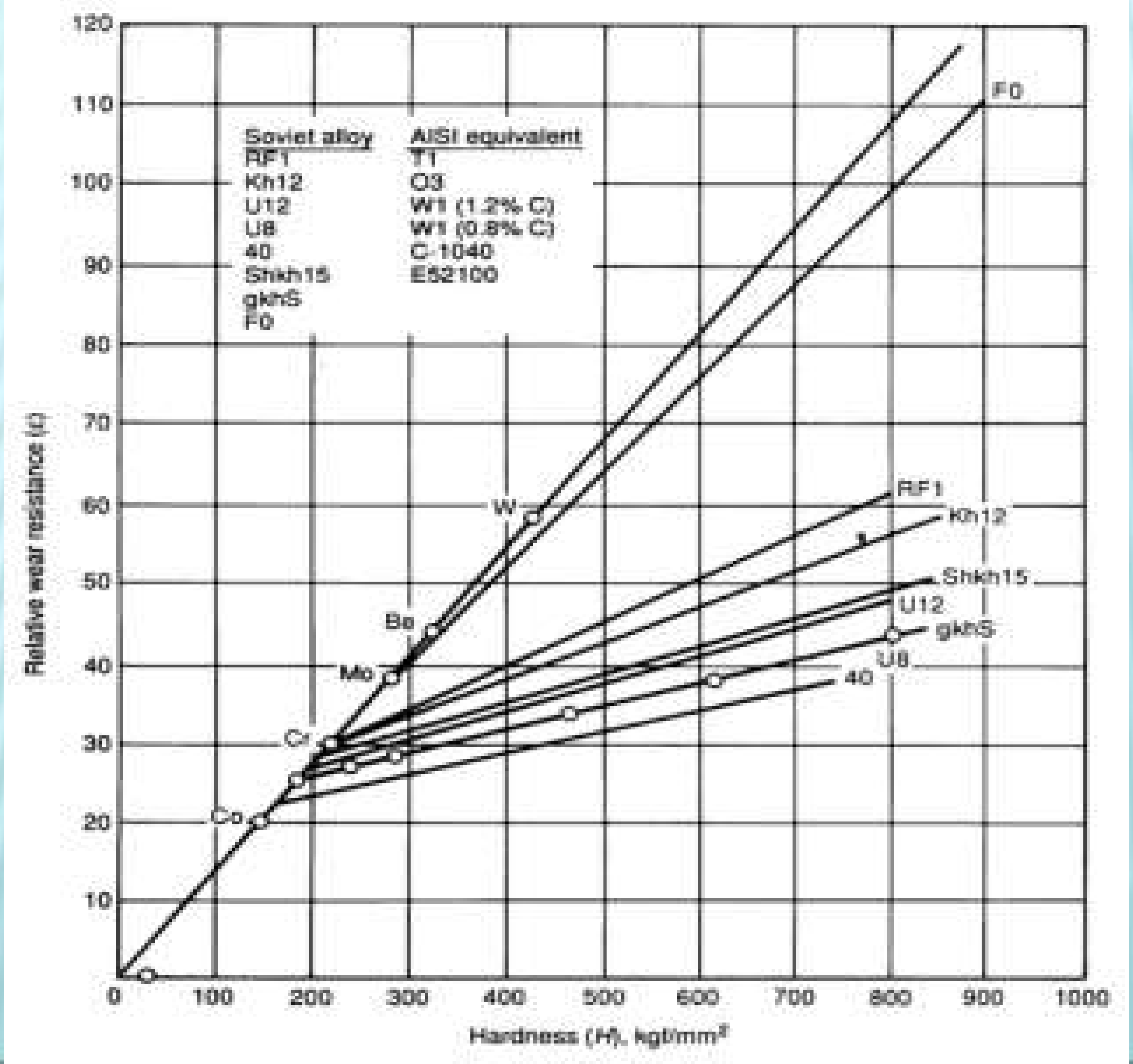
EFFECTS OF MATERIAL PROPERTIES ON ABRASIVE WEAR

- A variety of material characteristics have been shown to either form a correlation with abrasive wear or have some effect on it. These properties include
  - hardness,
  - elastic modulus,
  - yield strength,
  - melting temperature,
  - crystal structure,
  - microstructure,
  - composition.

HARDNESS

- It has been shown experimentally and theoretically that the hardness of a material correlates with its abrasion rate.
  - Khrushchov performed a large amount of testing and found an inverse relationship between abrasion rate and annealed hardness for pure materials. He also tested steels of varying hardness.
- The hardnesses were inverse linearly related to abrasive wear, except that they had a different slope from that of the pure materials.

WEAR RESISTANCE VERSUS HARDNESS FOR PURE METALS AND ALLOYS



- It is generally thought that the surface of a material is work hardened up to a very high level during the process of abrasion.
  - Richardson investigated work hardening by plowing during wear on a group of pure metals and steels.
- He compared the resulting hardness of the surface to surfaces hardened by shot blasting and trepanning, and found that abrasion produced a high hardness that was nearly the hardness of trepanning. In addition, the wear resistance of the metal was proportional to the hardness of the worn surface.

- Abrasive wear has also been found to be dependent on crystal structure and orientation. Alison showed that cubic metals wear at about twice the rate of hexagonal metals, which was attributed to the lower work-hardening rate of the hexagonal metals.
  - In addition, Steijn studied the wear of single crystals. Scratching body-centered cubic (bcc) and face-centered cubic (fcc) metals with a prepared surface on the (001) plane, he showed wider scratch width, which implied higher wear, along the <100> than the <110>direction.

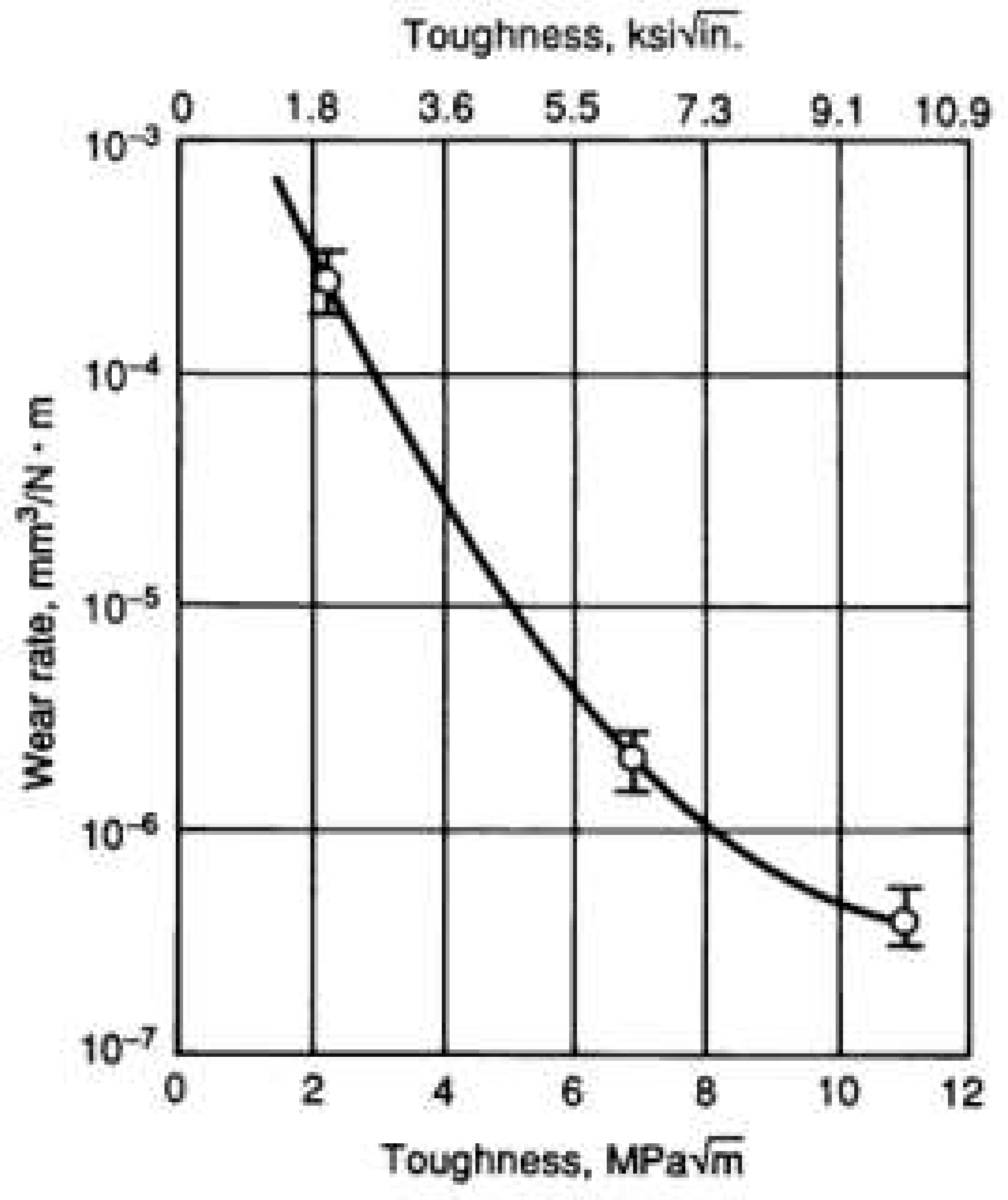
MICROSTRUCTURE

- Microstructure is also important. Austenite and bainite of equal hardness are more abrasion resistant than ferrite, pearlite, or martensite. This is because of the higher strain-hardening capacity and ductility of austenite.

TOUGHNESS

- It has been found that fracture toughness, *KIc, of the material is important in determining abrasive wear for* ceramics and, to a lesser degree, white cast irons.
  - Fischer prepared a series of zirconia samples with constant hardness, but varying toughness. He found that the wear decreased with the fourth power of the toughness This fourth power law applies to a single case of material and test parameters, but it does show the important effect of toughness on brittle materials.

WEAR RATE OF ZIRCONIUM OXIDE AS A FUNCTION OF FRACTURE TOUGHNESS



ALLOYING

- Alloying is often used to improved the performance of a material. These additions can take either interstitial or substitutional locations. Adding carbon to iron is a good example of an interstitial addition used to improve abrasion resistance.
  - Tylczak (Ref 13) studied the abrasion resistance of Zr and Ti alloys with small interstitial additions of N or O. Like carbon in iron, these alloys also decreases of wear with small increases of interstitial content. For substitutional alloy systems, he also showed that the abrasion of alloys with complete solid solubility, such as Hf-Zr, Cu-Ni, and Cr-V, follows a law of mixing, where the abrasion is proportionate to the amount of each alloy.

- Abrasion was also found to be somewhat affected by solidus temperature and hardness. For solid-solution mixtures, this indicates that deviations from a law of mixing are separately dependent on strength of the bond and distortion of the crystal lattice.

- A common way to modify the properties of a material is to produce a second phase. Treatments that cause the formation of precipitates can result in larger increases in hardness and yield stress. The small coherent particles are often sheared during plastic deformation, and the incoherent particles fail to block the dislocations that are generated. As a result, precipitation treatments are not generally a useful way to decrease abrasive wear.

- Larger, hard incoherent precipitates or particles such as carbides can be useful in decreasing abrasive wear. When the in coherent particles are somewhat larger than the abrasive grains abrading the surface, they are generally effective in decreasing the total material wear..

PARTICLE SIZE AND ABRASIVE GRAIN SIZE

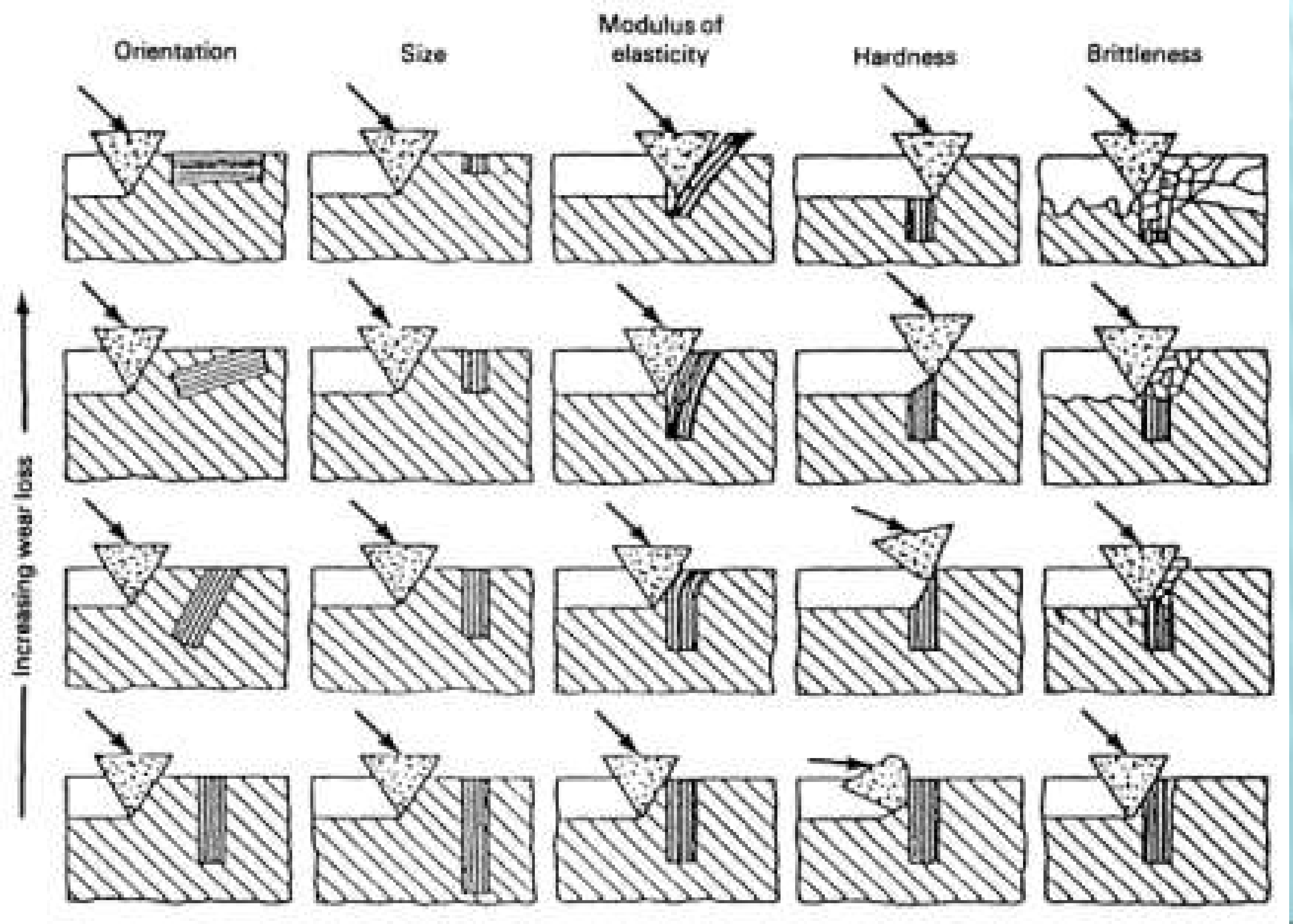
- Larger abrasive grains tend to create larger wear chips. When incoherent particles are small, relative to the abrasive grains and wear chips, they can be cut out with the matrix, adding little to the abrasion resistance of the material.
  - If the abrasive grains are very small, relative to the hard particles, and the gaps between particles are large, then the grains are able to undermine the hard particles, allowing them to fall out or be dislodged by the occasional large abrasive grain.

- The particle characteristics that work best for wear protection are hard, tough, and blocky.
  - A high hardness value makes them harder to cut.
  - Toughness makes them resistant to breakage.
  - Blocky particles, versus those that are plate- or rod shaped, also reduce crack propagation and breakage

REINFORCED COMPOSITES

- Reinforced composites are subjected to abrasive wear in many applications. Factors that affect the abrasive wear of reinforced composites these materials include the orientation, size, modulus of elasticity, relative hardness, and brittleness of the second phase.

EFFECT OF ORIENTATION, SIZE, ELASTIC MODULUS, HARDNESS, AND BRITTLENESS OF SECOND PHASE ON ABRASIVE WEAR SOURCE



- It has been found that a reinforcing second phase lying parallel to the surface is more easily removed than one that is anchored perpendicular to the surface. Also, when the size of the second phase is small relative to the abrasive groove depth, the second phase has little or no beneficial effect. Because most reinforcing additions have a high modulus of elasticity, a matrix with a low modulus will tend to de bond at the interfaces and lead to pull-out and abrasive loss.

- In some metals, such as alloyed white cast irons, if the second phase is harder than the matrix, then the hard phase will protect the matrix. Lastly, brittle materials tend to crack and chip to a larger area than the cross section of the abrasive grain doing the damage. An impressive amount of current research on wear-resistant materials is focusing on advanced composites.

EFFECT OF ENVIRONMENT ON ABRASIVE WEAR

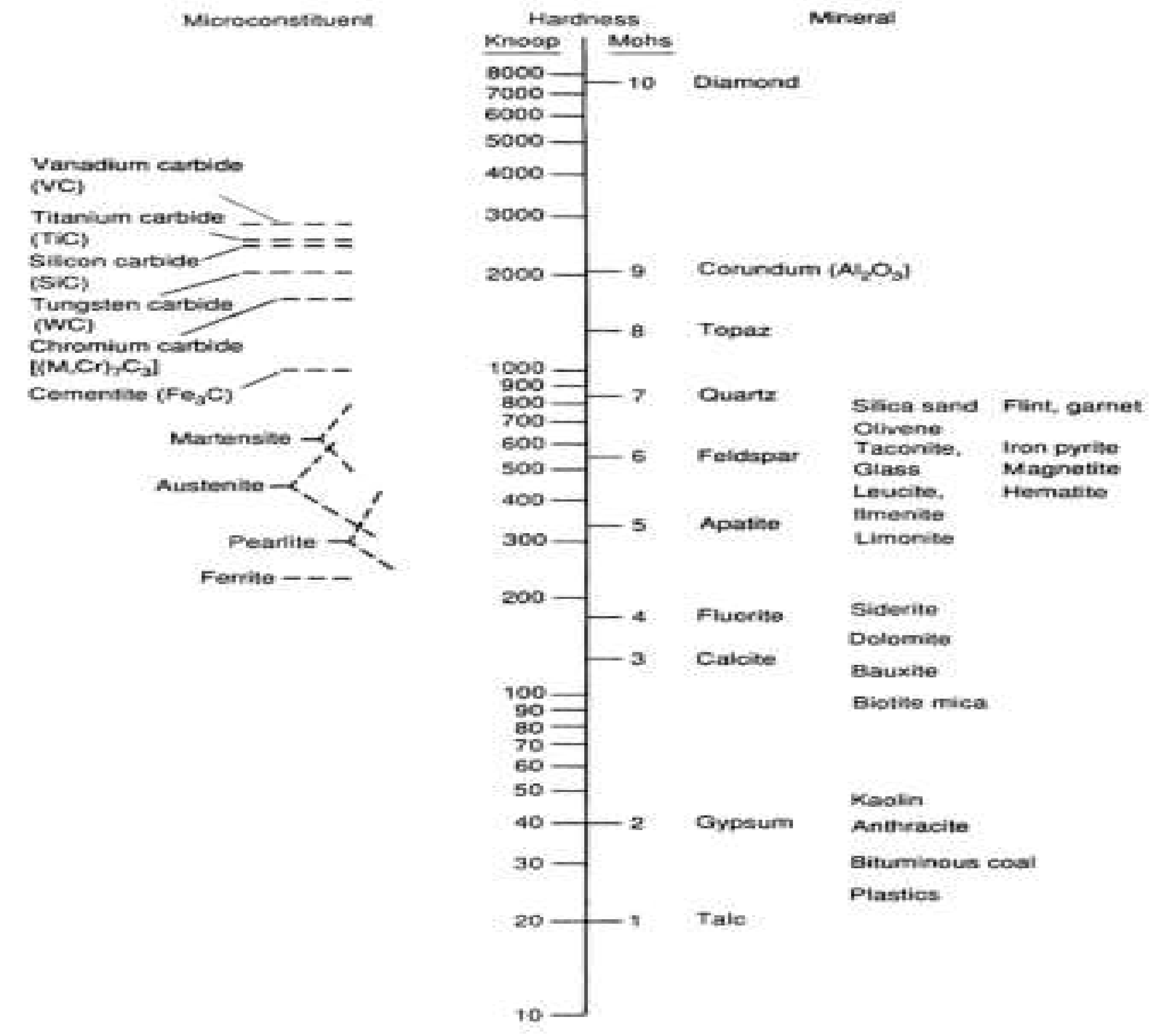
- Environmental factors that effect abrasive loss include, but are not limited to:
  - the type of abrasive and its characteristics,
  - temperature,
  - speed of contact,
  - unit load of the abrasive on the material,
  - humidity,
  - Corrosive effects,

ABRASIVE.

- Changing the abrasive will change the wear rate. Other abrasive characteristics will also contribute. Among these are hardness, toughness, and size of the abrasive.

- The hardness of the abrasive particles is important to the rate of abrasion of the subject material. As the hardness of the abrasive exceeds that of the wear material, abrasive wear typically becomes much worse .As the abrasive hardness exceeds the hardness of the material, it is able to penetrate the surface and cut/remove material without having its cutting edges broken or rounded.

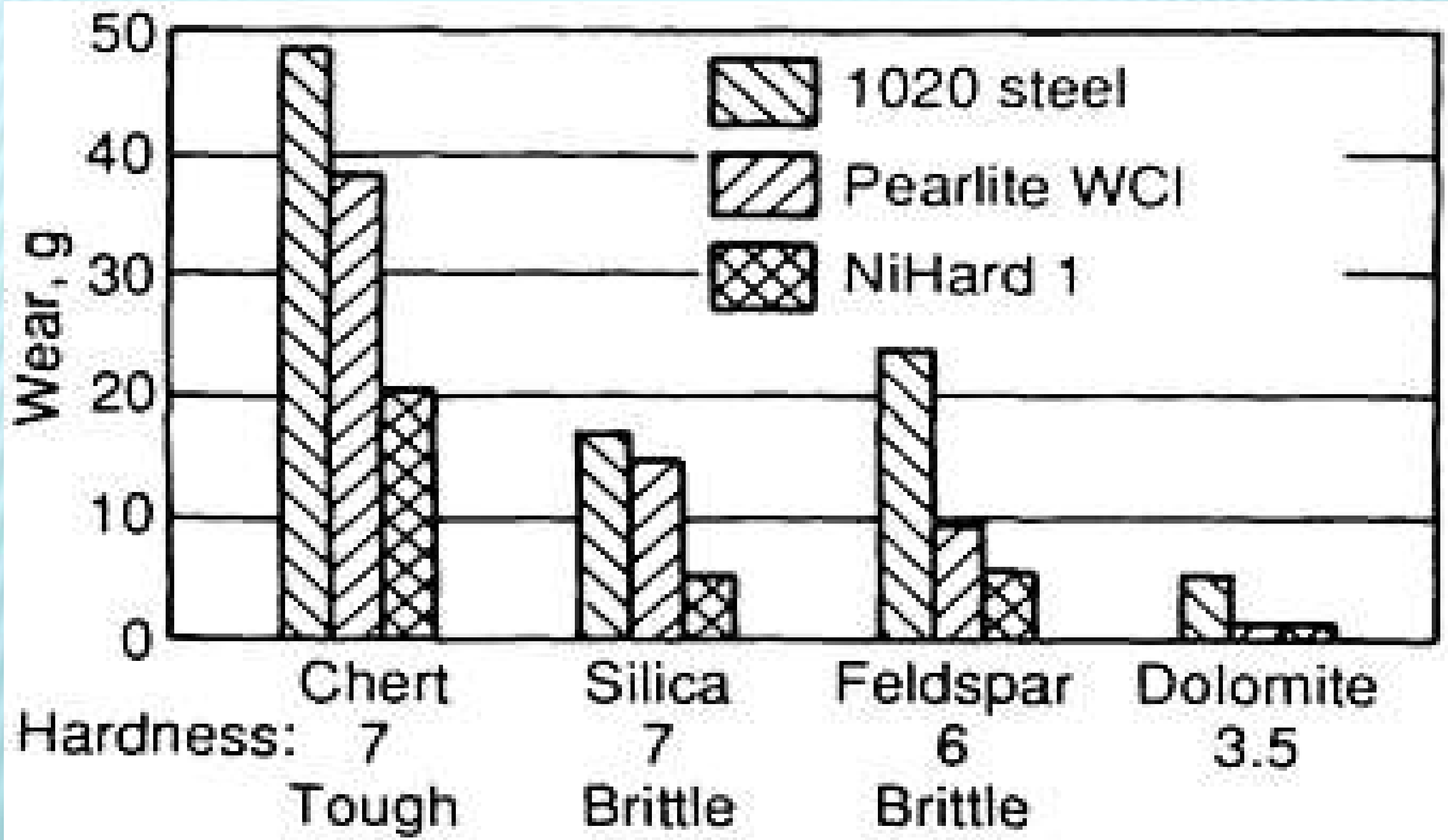
HARDNESS OF SOME MINERALS AND ALLOY MICROCONSTITUENTS



- The shape of the abrasive particle is important, because it influences the shape of the groove produced in the material. It also influences the contact load and the transition from elastic to plastic contact. Experiments have confirmed that less wear occurs when materials are abraded by rounded, rather than sharp, particles.

- The toughness of the abrasive particles is an important factor during abrasion. Material loss will increase when the toughness of the abrasive increases.
- Avery (Ref 17) gives examples of wear on several white irons and a steel when subjected to two different abrasives of the same hardness (Fig. 10). Although chert and silica both have the same hardness(Mohs 7), the chert, which is the tougher mineral, caused two to three times the wear generated by the silica.

EFFECT OF TOUGHNESS OF MINERALS ON WEAR,



TEMPERATURE.

- It might be expected that abrasive wear would increase as the temperature rises, because the hardness and yield strength decrease..

- Instead, for aluminum and copper when the temperature was increased from ambient to 673 K, very little change in the abrasive wear rate was observed. It has been proposed that the reason for this small change is that during abrasion, small areas are adiabatically heated. At higher initial temperatures, the metal flow stress is reduced. This results in less heating in the material during the abrasion process. The end result is that areas around the material that is being removed have a similar temperature, independent of starting temperature, and similar abrasion rates

SPEED OF CONTACT

- The rate of abrasive wear has been found to slightly increase with increasing speed in the range from 0 to 2.5 m/s (0 to 8.2 ft/s). This increase in wear may be attributable to frictional heating.
  - The effect is small, because all of the abrasion occurs in a near-adiabatic process.
- This should result in nearly the same peak temperature rise, independent of speed, for the tiny volume of material where the asperities are removing the material.

LOAD

- Abrasive wear has been shown to be proportional to load, following the Archard equation. However, this proportional effect breaks down when the load is high enough to fracture the abrasive particles.
  - If the forces do fracture the abrasive particles and create new sharp points, wear can increase.
  - If the abrasive particle points are rounded, wear will decrease.

HUMIDITY

- The effect of atmospheric humidity on abrasive wear is far from clear, and contrary results exist. the effect of atmospheric humidity on abrasive wear for a variety of pure metals and steels. When using SiC abrasive, wear usually increased with increasing humidity, up to 65% relative humidity. This increase is attributed to a moisture-assisted fracture of the SiC abrasive particle, which resulted in fresh sharp edges to cut into the surface of the material.

CORROSIVE EFFECTS.

- Abrasive wear is often enhanced by corrosive conditions, particularly a low pH. A synergism often occurs between abrasive wear and corrosion. The abrasion creates fresh surfaces that rapidly corrode, and the normally protective corrosion layer is removed by abrasion. Using a laboratory abrasives slurry apparatus.

- Madsen demonstrated that the synergism of an abrasive and a corrosive component could be twice that of individual components added together. In a grinding study, Tylczak showed that grinding in acid waste water increased the wear rate by about twice that of grinding in tap water.

THEORY

- A number of equations have been used for correlations between wear and other properties. The Archard equation for a relationship of wear with hardness has already been introduced. Khrushchov demonstrated the correlation withhardness and has proposed an empirical correlation with elastic modulus of the form:**(Eq 6)**

$$W = \frac{k_5}{E^{1.3}}$$

- where *E is the elastic modulus* For pure metals, relationships were found between wear and energy of melting, the combination of atomic weight and Debye temperature, and the combinations of melting points divided by atomic volume.

- All of these relationships measure interatomic cohesion. However, a fundamental understanding of abrasive wear has not yet been developed from fundamental theories. Most current theory is based on the concept that abrasion is the process of scratching. Furthermore, most theories simplify the tip of the scratcher as a sharp come. The theories then go on the explain the effect of said come sliding across the surface of a specimen

- The Archard equation, with small modifications, is still widely used as a starting point for the development of more complex equations. The more successfully the models deal with "real" complications, the more useful they will be.

- One example of an extended Archard mode proposed by Zum Gahr (Ref 26) has a factor that accounts for the proportion of displaced material to removed material. He defines a

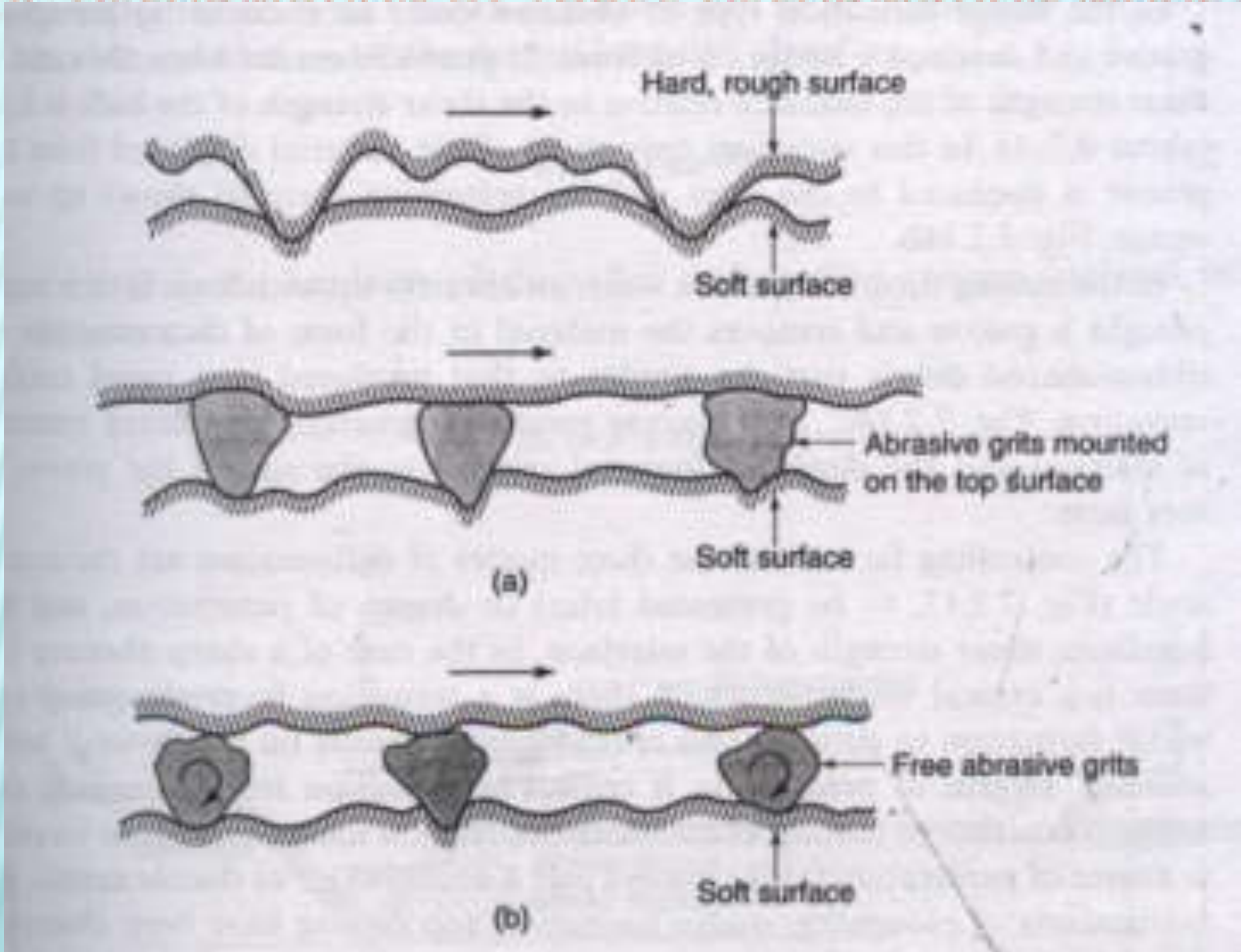
$$f_{ab} = \frac{A_v - (A_1 + A_2)}{A_v}$$

- **(Eq 7)**
  - where *Av is the cross-sectional area of the wear groove, and A1 and A2, combined, are the cross-sectional area of the* material displaced to the sides of the groove.

- For perfect cutting, this term is 1, and for pure plowing, with no material removal, the term is 0. The equation for wear, in this case, is:
  - $W = f_{ab} A_v d$ **(Eq 8)**
- Factors that will reduce f_{ab} *give greater wear resistance without requiring a modification of material hardness. In other* words, a material with a greater ability to deform will plow, rather than cut.

- This follows the results from Khrushchov, where the pure materials, which have a large capacity for deformation, had greater abrasion resistance than alloy steels of a given hardness

SCHEMATICS OF ABRASIVE WEAR PROCESSES AS A RESULT OF PLASTIC DEFORMATION BY THREE DEFORMATION MODES.



- generally a small particle of abrasive, caught between the two other surfaces and sufficiently harder that it is able to abrade either one or both of the mating surfaces (three-body abrasion).

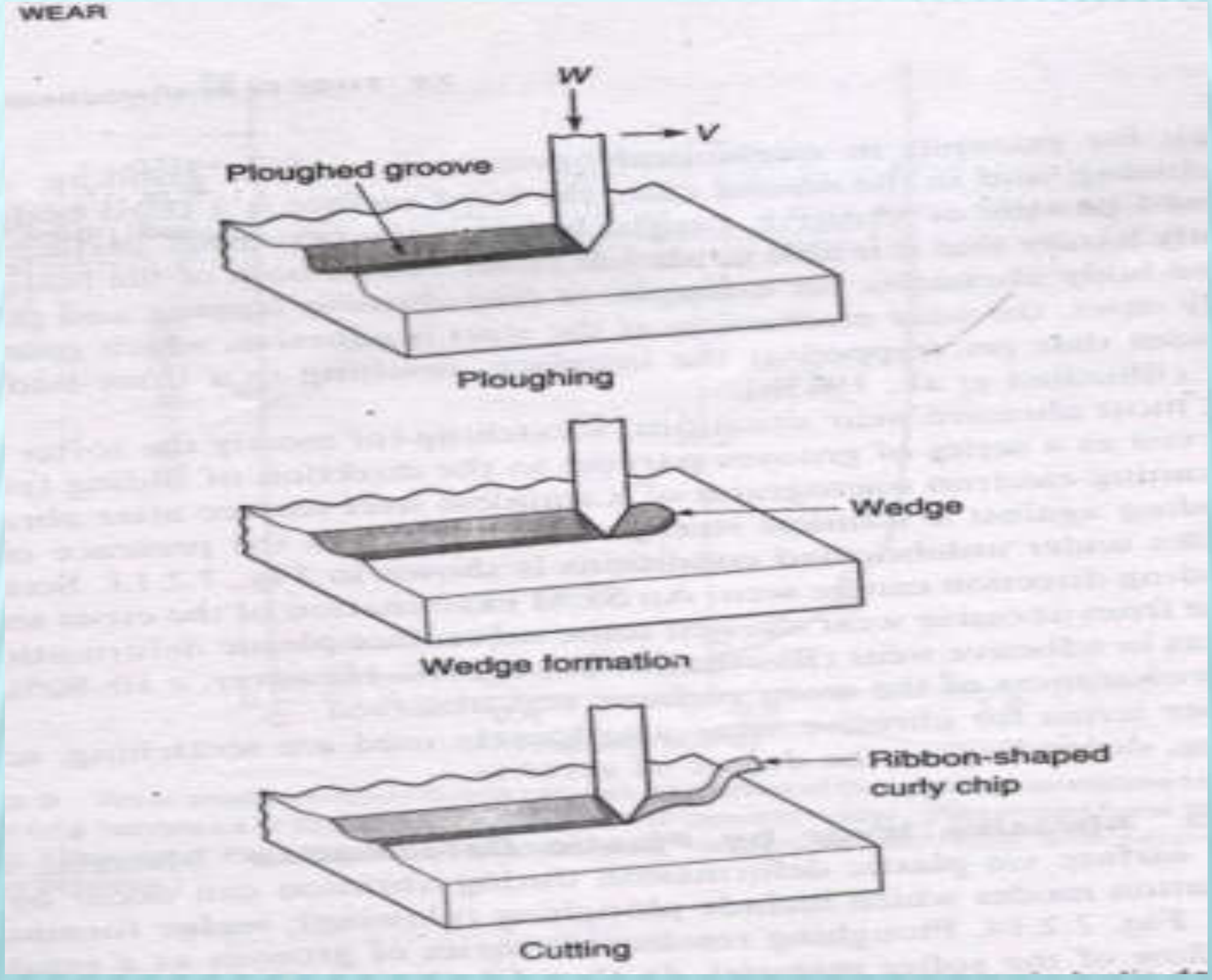
EXAMPLE

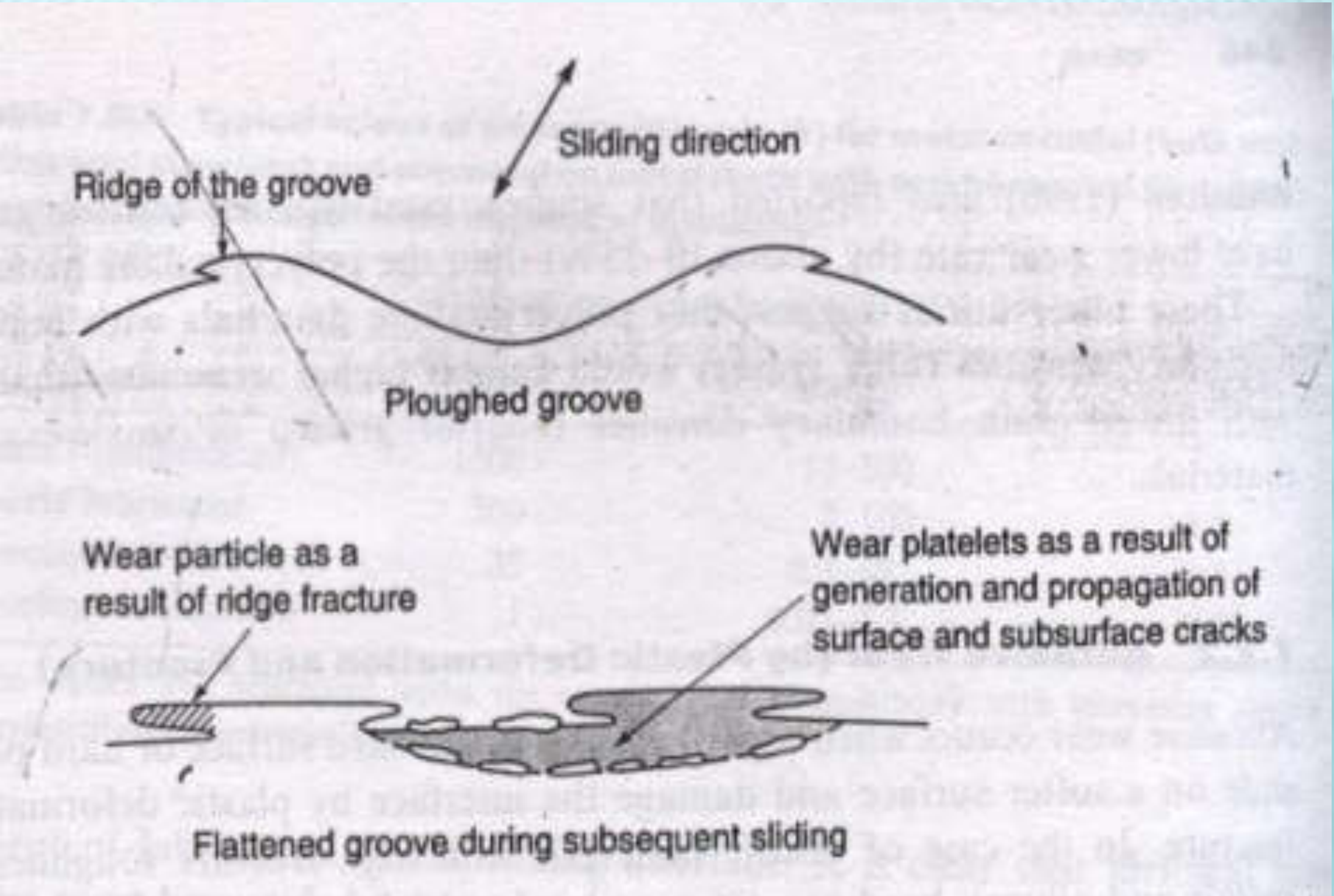
- In free-abrasive lapping and polishing. In many cases. the wear mechanism at the start is adhesive. which generates wear particles that get trapped at the interface. resulting in a three-body abrasive wear .

- In most abrasive wear situations. scratching (of mostly the softer surface) is observed as a series of grooves parallel to the direction of sliding (ploughing).

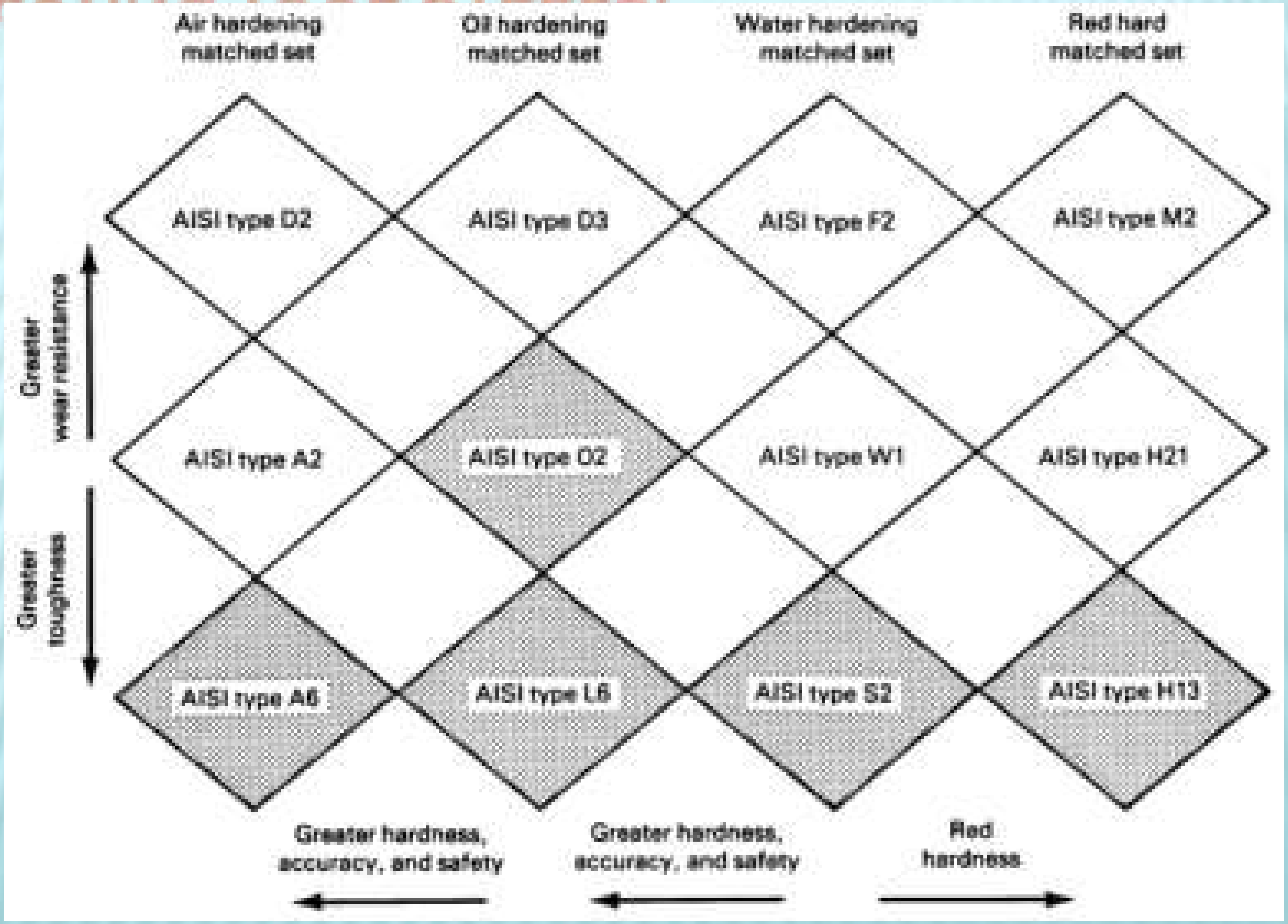
- Scratching in the sliding direction can be seen. An SEM examination of the cross section of a sample from abrasive wear showed some subsurface plastic deformation, not as much as in adhesive wear. However. a 10-80% increase in micro hardness of the worn surfaces was observed.
- Other terms for abrasive wear also loosely used are scratching, scoring or gouging, depending on the degree of severity.

SCHEMATICS OF PLOUGHED GROOVE AND FORMATION OF WEAR PARTICLE DUE TO PLOUGHING AS A RESULT OF FRACTURE OF FLATTENED RIDGE AND PROPAGATION OF SURFACE AND SUBSURFACE CRACKS




Sliding direction
Ridge of the groove
Ploughed groove
Wear particle as a result of ridge fracture
Wear platelets as a result of generation and propagation of surface and subsurface cracks
Flattened groove during subsequent sliding

BASIC DIAGRAM FOR MATCHED SET METHOD OF SELECTING TOOL STEELS.



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