

Wear and wear particles—some fundamentals

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Abstract

Each of the various processes by which material can be lost from a surface in service leaves its fingerprint both in the topography of the worn surface and in the size, shape and number of the particles which make up the wear debris. To use debris examination as a diagnostic aid in assessing the health of operating plant, which may contain many tribological contacts, requires not only careful and standardised procedures for debris extraction and observation but also an appreciation of the mechanisms by which wear occurs and the regimes in which each of the contacts of interest operates when displayed on an appropriate operational map.

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1. Introduction

The phenomenon of wear was given a formal definition in 1968 by the OECD as ‘the progressive loss of material from the operating surface of a body occurring as a result of relative motion at its surface’ [1]. This might today be thought a slightly curious definition as there is no mention of what it is that is moving relative to the surface in question, or indeed, of the need for the transmission of some contact force between the wearing surface and its counter-face—even if this transmission is through a low-strength, intermediate film such as that formed by a lubricant. Notwithstanding this difficulty, common usage of the term wear implies some mechanical action on the wearing surface—so that, for example, corrosion per se would not be classified as a wear mechanism whereas corrosive wear involving some form of mechanical interaction in a corrosive environment certainly would be.

Having divided wear mechanisms into two principal categories, the first adequately described as ‘mechanical wear’ and a second covering those situations where there is an additional element of active chemistry (typically oxidation and/or corrosion) it is tempting to subdivide the former large category into some number of smaller classes—the extent of this sub-division being to some

extent a function of the enthusiasm of the author. Fig. 1 illustrates a typical set of mechanical wear processes grouped under four general headings and arranged, within each of these, in increasing order of severity. All these mechanisms have the capability of removing material from the surface in question though the rates of degradation, measured as rates of loss of mass per unit time, can vary over many orders of magnitude. All can, and often do, operate in the presence of a lubricant, very often a mineral oil, whose function may be both to limit friction and to convect away heat so reducing the severity of thermal stresses or distortions in vital machine elements. Mechanisms of wear are not mutually exclusive and in some complex pieces of machinery several may be operating simultaneously at different sites and different internal contacts. Techniques of wear debris analysis are based on the hypothesis that the morphology of debris particles examined in a representative sample of the lubricant circulating through the machine can indicate which is the most active operating wear mechanism and, furthermore, that changes in the concentration of such particles within the circulating fluid will be indicative of changes in the state of surfaces of these potentially critical components [2,3]. A reduction in the rate of particle production and detection in the early stages of device operation is associated with the *running-in* process as a benign and acceptable wear regime is established; whereas a later increase in the rate of particle concentration may herald a transition to a higher wear regime as the surfaces *wear out*—perhaps with catastrophic results.

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Nomenclature

H	indentation hardness	V	sliding speed
K	constant of proportionality	w	wear dimension
P	applied load	κ	thermal diffusivity
p	pressure	μ	coefficient of friction
k	flow stress	τ	shear stress
R	representative length dimension	θ	slope or angle
t	time	Ψ	plasticity index

Surveys of industrial wear problems often highlight abrasion as being of particular concern. Within the general area of abrasive wear a distinction is often made between so-called *two-body* abrasion when material is removed or displaced from the softer surface by the asperities or protuberances on the harder surface and *three-body* abrasion when the damage is done by some form of free, discrete abrasive particles rolling and sliding between the opposing surfaces of the contact: often such particles are contaminants from the outside environment. In practice, the distinction between the two sub-divisions may be somewhat blurred, as if the free particles become lodged in one of the bearing surfaces the situation either temporarily, or even permanently, becomes one of two-body abrasion. So-called *open* three body abrasion occurs when the two surfaces are sufficiently far apart to be effectively independent of one another; for example, this is the type of wear to which earth moving equipment is subject when soil particles abrade the shovel faces. If the particle velocities are large, say more than a few m/s, perhaps because they are carried in a gas stream or entrained in a flow of liquid, the wear process becomes one of erosion.

2. The modelling and the mapping of mechanical wear

No simple and universal model is applicable to all situations. In the dry, unlubricated or perhaps marginally lubricated sliding of a pair of, usually dissimilar, loaded surfaces, i.e. two-body conditions, the rate of surface

degradation or damage of each depends (at least) on the factors of Table 1.

When a third body is present at the interface wear may be inhibited, though not entirely eliminated, for example if the third body is a lubricant or low shear strength film with a thickness dimension at least comparable with the mean surface roughness, or enhanced as in the case of contamination by entrained dirt or even just the retained debris from previous wear events. Contamination by debris both harder and softer than the opposing solid surfaces is likely to be detrimental to the life of the contact though may involve different detailed mechanisms: the distribution of sizes, shapes and mechanical properties of the third bodies are all influential variables.

For the relatively elementary of two loaded surfaces, one hard the other softer, sliding over one another we might suppose that the loss of linear dimension, say w , in the wearing surface will depend on the applied load P , the imposed sliding speed V , the coefficient of friction μ , the hardness H of the softer surface the time they slide together t and the size of the contact measured by some representative length dimension R . Hardness, as a plastic property, is included rather than the elastic modulus since, for ductile metals, wear is generally only achieved after significant plastic flow. It is thus possible to write

$$w = f(P, V, \mu, H, t, R), \quad (1)$$

Buckingham's rule can then be used to reduce this equation to a simpler non-dimensional form,

$$\frac{w}{R} = f\left(\frac{P}{R^2 H}, \frac{Vt}{R}, \mu\right), \quad (2)$$

experimental studies have failed to find any simple dependence of wear rates on coefficients of friction and so, if, for the moment, this is excluded and we suppose

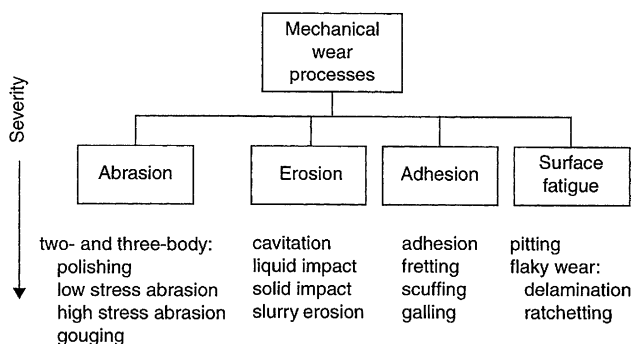


Fig. 1. A classification of mechanical wear processes.

Table 1
Factors influencing dry wear rates

Normal load
Relative sliding speed
Geometry (both macroscopic and local or topographic)
Initial temperature
Local environment
The thermal, mechanical and chemical properties of the materials involved

the simplest linear functional relation between the other non-dimensional groups, this equation simplifies to

$$\dot{w} = \frac{w}{t} = K \frac{PV}{R^2H} = K \frac{pV}{H}, \quad (3)$$

an expression for the change in dimension of a load-bearing surface as a result of wear in which K is some constant and p is the nominal pressure on the contact. We should not be surprised if this dimensional wear is dependent on the imposed pV value and indeed this is a well established design parameter in simple dry sliding situations. Eq. (3) is known in the tribology community as either the *Archard* or the *Rabinowicz* equation but is also familiar in the semiconductor industry, in connection with the polishing of silicon wafers, where it is known as the *Preston* equation [4–6]. The quantity p/H is non-dimensional and so there might well be situations in which dimensional wear increases more rapidly than linearly with load. These are indeed often observed as transitional regimes between two regimes—each separately adequately described by the linear Archard equation—when, over some relatively small range of surface loading, the observed wear rate is much more sensitive to load than simple linearity. Over this transition region wear increases with load raised to a power more very much greater than unity. These transitions, often referred to as representing a change from *mild* to *severe* wear, are characteristic of many sliding systems. The form and the morphology of the resultant debris may be very different either side of the change reflecting a change in the physical mechanism of its generation.

Abrasive wear is but one of the various mechanical processes which can lead to material loss from a surface¹. In addition to erosion, referred to above, the mechanisms of adhesion and surface fatigue can also lead to surface distress, damage and, ultimately, the generation of wear debris with a characteristic morphology. If two atomically clean metallic surfaces are loaded against one another, then at points at which opposing asperities make contact, strong adhesive junctions will be formed. If the surfaces are now forced to move tangentially, not all these junctions may shear along the original material interface, but some may be deformed in such a way that fragments of the softer surface are plucked out and removed: these particles constitute adhesive wear debris. Of course, the majority of engineering surfaces are not atomically clean, nor do they always carry normal loads sufficiently high to generate enough surface plastic deformation that will lead to the formation of such adhesive junctions; consequently, significant adhesive wear is unlikely in equipment operating within normal design constraints. However, this does not mean that adhesion cannot be important—sometimes dramatically so. It can be a particular problem when both members of the tribological

contact are made of the same sort of materials or when sliding speeds are high; severe damage of this type can result in the tearing of macroscopic chunks of material from the surface—this is known as *galling*. The term *scuffing* is used specifically to describe the onset of adhesive wear between lubricated surfaces which has arisen from the breakdown or failure of the lubricant film for whatever reasons—although this is generally associated with an excessive increase in temperature. The phenomena of fretting failures in bolted or interference joints subject to vibration or oscillation is another example of a form of tribological failure in which adhesion can play a part.

Surfaces which are loaded repeatedly, even if they display some plastic deformation in the initial stages of their history, can generate patterns of subsurface protective stresses which are sufficiently strong to enable the applied loads to be carried entirely elastically in the longer term after many applications of the load cycle—they are said to *shake-down* [7]. Despite the alleviation of stress levels that this generates, surfaces that have shaken down can still wear subsequently by processes of surface fatigue or allied phenomena. Subsurface cracks may be nucleated at micro-structural defects or inclusions in the material, giving rise to characteristic *pitting* fatigue generating wear or debris particles which are more or less equiaxed. Where the friction or traction forces are sufficient to deform the surface layer, material may be lost, in the form of thin flakes or platelets. In such delamination wear subsurface plastic shear is associated with the formation and propagation of cracks nucleating from pre-existing voids or inclusions present in the material structure. The thickness of the wear sheet is controlled by the location of these subsurface cracks, and is typically of the order of a few microns. In relatively defect-free materials, for example vacuum remelted bearing steels, local incremental plastic strains can again build up, cycle by cycle, producing a form of local surface collapse, sometimes known as *ratchetting*, occurring on an even finer scale and producing debris which is again characteristically lamellar or sheet-like in form, but is now less than a micron in thickness.

Of the various forms of abrasive mechanical wear, polishing is the mildest form, and is unusual, in that it leads to an improvement in surface smoothness; this is in contrast to other abrasion processes that invariably lead to surface roughening. Other terms sometimes used in association with three-body abrasive wear, as opposed to two-body wear, are *high-stress* and *low-stress* abrasion. In high-stress abrasion, the crushing strength of the abrasive particles is exceeded at typical concentrated contacts so that they are broken up during the wear process—the active components in ball mills and other forms of crushing equipment are subject to this form of damage. In low-stress abrasion, the particles remain essentially intact—pipework, hoppers and conveyors carrying solid particulates are typically subject to low-stress abrasion. The term *gouging abrasion* is also

¹ The literature on wear is voluminous. More details of published sources are available at: <http://www.shef.ac.uk/mecheng/tribology/tools/tools.html>.

sometimes used to describe particularly severe forms of high-stress abrasion.

3. Mapping mechanical wear processes

The purposes of laboratory testing [8] can range from very specific ‘trouble-shooting’, i.e. the entirely empirical solution of operating problems with an existing machine, to much more general and fundamental studies of the micro-mechanics and materials science aspects of the physical processes operating during the phenomenon of wear itself.

Wear rates in successfully operating industrial equipment can vary enormously, from very high values under particularly aggressive conditions, to very low values in more benign circumstances—this is reflected in the numerical value of the coefficient K in Eq. (3) which can vary from more than 10^{-2} in situations of very severe wear to less than 10^{-9} in much less hostile conditions. If component or material tests are to be carried for service in such low wear regimes, then, in order to achieve dimensionally reliable measurable amounts of wear, laboratory simulations must be run for several hundred hours. Industrial scientists and research engineers will often find themselves placed under pressure to reduce the time scale of such wear tests, and thus to speed up the production of data; it is important to appreciate that this procedure is potentially hazardous, as there is always the danger, for example when increasing loads or speeds, of moving from a regime of operation within which one specific form of wear mechanism is dominant to another controlled by quite different physical phenomena. Such pitfalls can often be prevented, and the way indicated in which changes in service conditions might be expected to influence wear response, by constructing an appropriate ‘map’ of wear behaviour for the surfaces concerned. Empirical mechanism maps are built up by plotting experimental data for wear rates on suitable axes, identifying at each point the mechanism by direct experimental observation. This approach can be complemented by the use of physical modelling: model based equations describing the wear rate of each mechanism are combined so that each ‘country’ on the map represents the combination of plotted variables for which one physical degradation mechanism is dominant.

An immediate difficulty is the choice of the most appropriate coordinate axes on which to display the chosen data. In the case of dry, or marginally lubricated, metallic sliding contacts, two, to some extent complementary, approaches have been suggested. The first, proposed by Lim et al. [9,10], plots the severity of the load expressed as the applied normal pressure p versus the sliding speed V . Such a map, which is specific to a particular material (surface topography, grain size, hardness, etc.) has the merit that it can also incorporate regimes of different chemical or surface reaction behaviour which are associated with temperature effects—although this is at the expense of

detail on the *mechanical* forms of wear associated with different states of surface topography and asperity interaction. The general form of such a map, for a metal, is illustrated in Fig. 2 in which pressure and speed have been expressed non-dimensionally as \bar{p} and \bar{V} , respectively, by using the relations:

$$\bar{p} = p/H \text{ and } \bar{V} = V/\kappa \times \sqrt{A/\pi}$$

H is the hardness of the wearing material and κ its thermal diffusivity (equal to the value of thermal conductivity divided by the product of density and specific heat). The normalised speed can be thought of as a measure of the magnitude of the sliding speed compared to the speed of heat flow through the wear material. Regions of the map associated with different wear mechanisms are traversed by contours of equal wear rate. Characteristically, the map is divided into two regions by a roughly vertical field boundary. To the left of this divide, wear is controlled by essentially mechanical processes; here the wear rate depends on the normal pressure (or load) but is not greatly dependent on sliding velocity so that contours of wear rate are more or less horizontal. On the other hand, to the right of this division, thermal and chemical effects (invariably under normal atmospheric conditions these involve oxidation) become the dominant influence and the contours of wear rate become functions of both load and velocity. For steels, this fundamental mechanism transition corresponds to dry sliding speeds of about 1 m s^{-1} ; below this, surface heating, and so oxidation, is relatively insignificant. The map immediately highlights the dangers of increasing the rate of data collection in simulation experiments by increasing the sliding speed. For example, if actual service conditions and those in the proposed accelerated test are represented by points in different countries of the map then it is clear that in moving from one set of circumstances to the other not only will the rate of wear be different but it will have its origins in quite different physical and chemical mechanisms; this then throws into doubt any evidence of material performance from such an accelerated programme.

In the regime dominated by mechanical wear, there are regions within which the spacing between contours of wear rate is equal to that between changes of load of the same factor, for example as K goes from 10^{-9} to 10^{-8} or from 10^{-5} to 10^{-4} the load also changes by a factor of 10. In each of these cases wear rate and load are directly proportional to each other, i.e. in accord with Eq. (3). But this is not the case throughout the region; the gap between the contours for K equal to 10^{-8} to that for 10^{-5} , covering three orders of magnitude corresponds to a load change of only one order. This very rapid increase in wear rate is an example of the transition from ‘mild’, and hence usually acceptable levels, to ‘severe’ (and usually unacceptable) values brought about by an increase in load. Dry or marginally lubricated contacts in machines between steel surfaces often operate at nominal pressures of a few

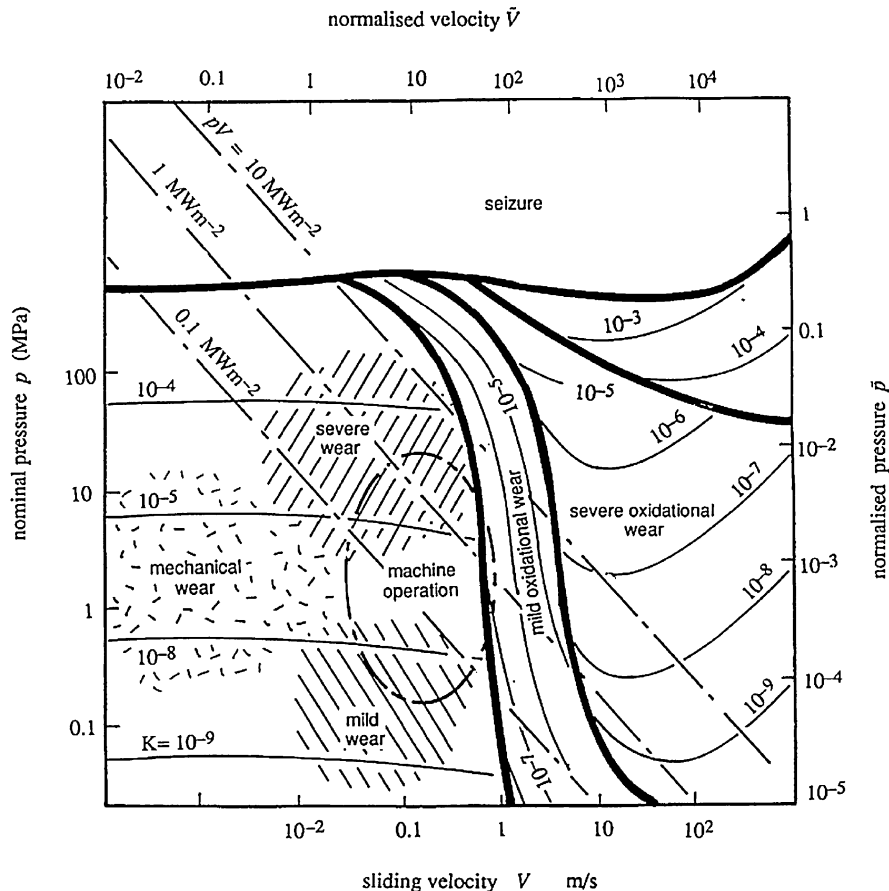


Fig. 2. Load–speed wear mechanism map for medium carbon steels based largely on pin-on-disc data. Load and speed both normalised as described in the text. Thick lines delineate different wear mechanisms and thin lines are contours of equal wear rates. Chain lines represent constant values of the pV factor. From Williams JA. Wear modelling: analytical, computational and mapping: a continuum mechanics approach. Wear 1999;225–229:1–17.

megapascals and at sliding speeds of the order of something less than a metre per second; in other words just at this level of wear uncertainty. Note that at a given level of load but at high sliding speeds, surface oxidation can be protective and provide reductions in loss of material, i.e. dips in the contours of K , when the softened oxide film acts as a protective almost lubricant layer over the metallic substrate.

The relevance of the pV factor has been mentioned as an important design guide to the consequences of dry rubbing not least as it represents the energy input per unit area. Since the map of Fig. 2 is drawn on log–log scales, constant pV values will plot as straight lines with a negative slope and three such lines are shown in Fig. 2 for specific energies of 0.1, 1 and 10 MW m^{-2} which are typical of dry running machine contacts.

An alternative presentation of wear data, suggested by Childs [11], and subsequently developed [10], which gives more emphasis to the mechanical—and so strictly abrasive—aspects of surface damage (but less to the thermal, since velocity is not considered as an independent variable) plots the regimes of wear on axes representing the shear strength of the interface between the two materials (usually normalised by the shear strength of the weaker material k

versus some roughness parameter, such as the angle θ representing the average slope of asperities on its surface. The general form of such a plot is shown in Fig. 3; note that in order to include the region of *elastic* response the roughness

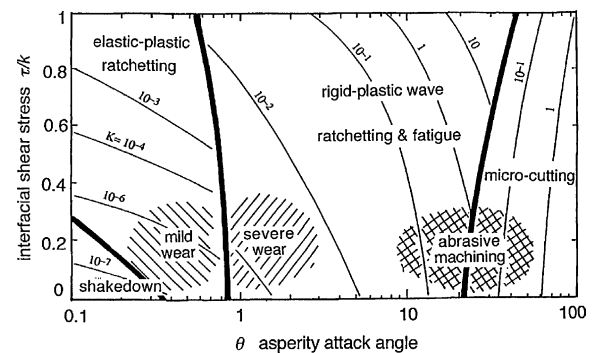


Fig. 3. Wear mechanism map for a soft surface abraded by a harder rougher counter-face. The ratio τ/k represents the relative strength of the interface and θ the mean slope of the rough surface (or the attack angle of a single asperity). Thicker lines delineate different wear mechanisms and thin lines are contours of equal wear rates. From Williams JA. Wear modelling: analytical, computational and mapping: a continuum mechanics approach. Wear 1999;225–229:1–17.

axis is calibrated logarithmically. This axis could also be calibrated in terms of the Greenwood and Williamson plasticity index Ψ [12] whose value indicates the relative importance of elastic as opposed to plastic contact conditions: the boundary between the predominantly elastic and plastic zones corresponds to a value of Ψ close to unity. When the surfaces are comparatively smooth, so that the value of θ is small, elastic deformations cannot be neglected—indeed they may be sufficient to accommodate the applied loads alone—so that wear in repeated traversals, which is the usual situation in most tribological devices, depends on some form of fatigue or damage accumulation mechanism. At steeper values of surface slope, i.e. higher values of θ or Ψ , wear may be due to a combination of elastic and plastic effects, as is the case in delamination wear. If the surface is made even rougher, *abrasion* is initiated; this always involves severe plastic deformation and can take the form of a combination of *ploughing* (in which, although the surface topography is much modified, only a small proportion of the displaced material is actually detached from the surface) and *micro-machining* (where a much higher proportion of the plastically deforming material is lost as wear debris). Once significant volumes are lost by micro-machining, then reducing the interfacial she stress has the effect of increasing the volumetric loss, because the efficiency of the micro-cutting operation is improved; we have situation in which reducing friction (perhaps by providing or improving lubrication) enhances wear. This is in contrast to the circumstances over the rest of the map in which reducing the surface shear stress lowers the wear rate.

4. Polymers and ceramics

The common glassy polymers, such as poly-methylmethacrylate, poly-carbonate and poly-styrene, are not often used as bearing materials but rather as optical windows and in this application their resistance to abrasive wear or scratch resistance is of obvious interest. Work, principally with PMMA, has demonstrated that damage evolves through a range of severity as the imposed strain is increased: visco-elastic smoothing or ironing is followed by plastic or visco-plastic grooving, then extensive plastic flow and tearing, pronounced fracture or tearing and finally micro-cutting or chip formation [13]. As with metallic materials, each mechanism of material removal leaves its signature in the morphology of the debris which its operation generates. These regimes are illustrated in the wear map of Fig. 4: the abscissa is effectively the attack angle of an assumed conical asperity or, by extension, the slope of a rough surface which might be thought of as an array of such individual asperities.

Ceramic materials have attractive tribological properties but their Achilles' heel has been their poor resistance to sudden and potentially catastrophic failure by fracture. Improvements in both material design, integrity and

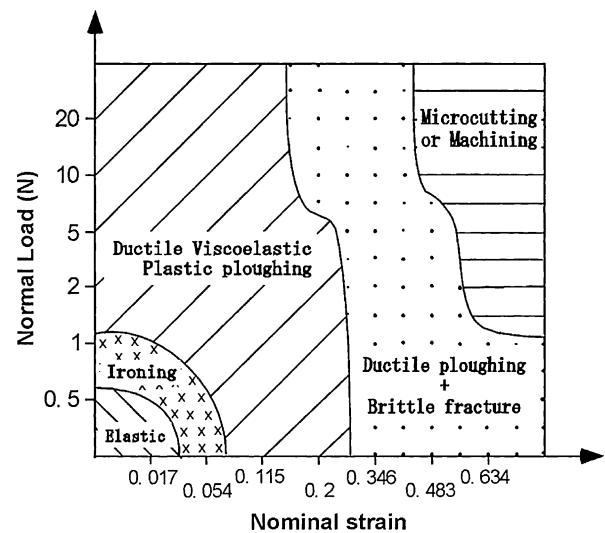


Fig. 4. Scratching mode map for PMMA Nominal contact strain taken as $0.2 \tan \theta$. Velocity 0.004 mm/s. From Briscoe BJ, Sinha PK. Wear of polymers. Proc Inst Mech Eng Part J 2002;401–413.

fabrication procedures have in recent years seen levels of fracture toughness both increase in magnitude and, most importantly, reduce in scatter, so that rational tribological design is feasible [14]. However, although it is well established that ceramic materials (just as more ductile metals and polymers) can wear by a number of different mechanisms it is not obvious what material parametric groups should be used as map coordinates when additional physical, chemical and environmental quantities must be included. One such map based on an investigation of a number of ceramics sliding against a specimen of the same material in air at 20 °C is shown in Fig. 5 where the two parametric groups $S_{c,m}^*$ and $S_{c,t}^*$ are, respectively, measures of the susceptibility of the transition to severe wear by intergranular fracture and thermal tensile stress cracking

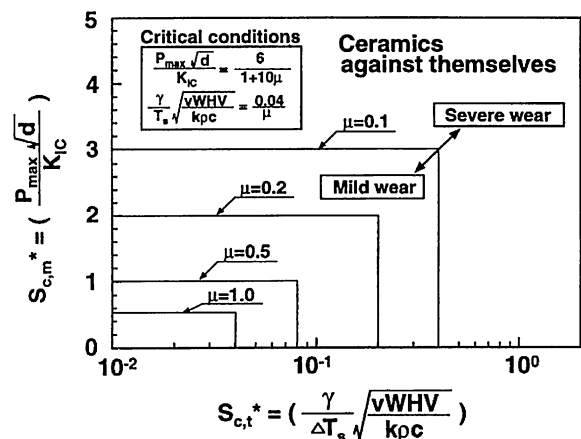


Fig. 5. A proposed generic wear map for ceramic materials indicating the transition from mild to severe wear conditions illustrating the effect of the coefficient of friction. From Adachi K, Kato K, Chen N. Wear map for ceramics. Wear 1997;203–204:291–301.

[15]. An important feature of ceramic tribology is the influence that chemical reactions with the environment exert on both friction and wear. This chemical action can take several forms depending on the particular combination of materials involved and the imposed service and environmental conditions; it can consist in modifications of surface composition and topography that decrease wear and friction, in a purely chemical form of wear by dissolution, or by chemically induced cracking and fracture which can increase wear rates. Water vapour in particular has a pronounced effect on silicon nitride, amongst other important engineering ceramics, changing not only the rate of wear but also the mechanism by which it is generated. In the absence of water vapour such ceramics can lose material at rates of up to 100 times that observed when operated with high values of relative humidity.

When ceramic are applied as thin coatings then further additional possibilities exist in the effect of surface degradation of combinations of load and speed which will be reflected in the form of the observed debris: a map for the sliding of TiN coatings on a High Speed Steel (M2) disc against pins of a similar material is shown in Fig. 6 [16]. Wear rates (in units of $\text{g m}^{-1} \times 10^8$) are indicated at the various loads and speeds investigated and the map divided into four regimes on basis of the observed operating wear mechanisms.

5. Corrosive wear and erosion–corrosion maps

Corrosive wear might be defined as covering those situations in which chemical or electro-chemical reaction with the environment predominate over mechanical interactions. However, this is not really a very satisfactory definition as the effects of mechanical wear and chemical wear may be synergistic and result in rates of material loss and surface degradation much greater than a simple sum of the two mechanisms observed independently. Any definition of corrosive wear will encompass the re-oxidation of exposed metal in a worn surface—and in general this is a beneficial phenomenon: it will also include the action of extreme-pressure or anti-wear additives in lubricants which technically rely on a form of controlled ‘corrosion’ to generate low shear strength and protective boundary films. All chemical reactions take place more rapidly at elevated temperatures—as a rough rule of thumb reaction rates may double with every 10°C increase in temperature so that corrosive wear problems tend to be exacerbated at higher temperatures. In circumstances in which loss of material is due to chemical activity alone with no addition mechanical abrasive or erosive element, the two most important variables are the electro-chemical potential applied to the surface and the pH of the surrounding medium. The surface may be immune, become passivated or actively corroded

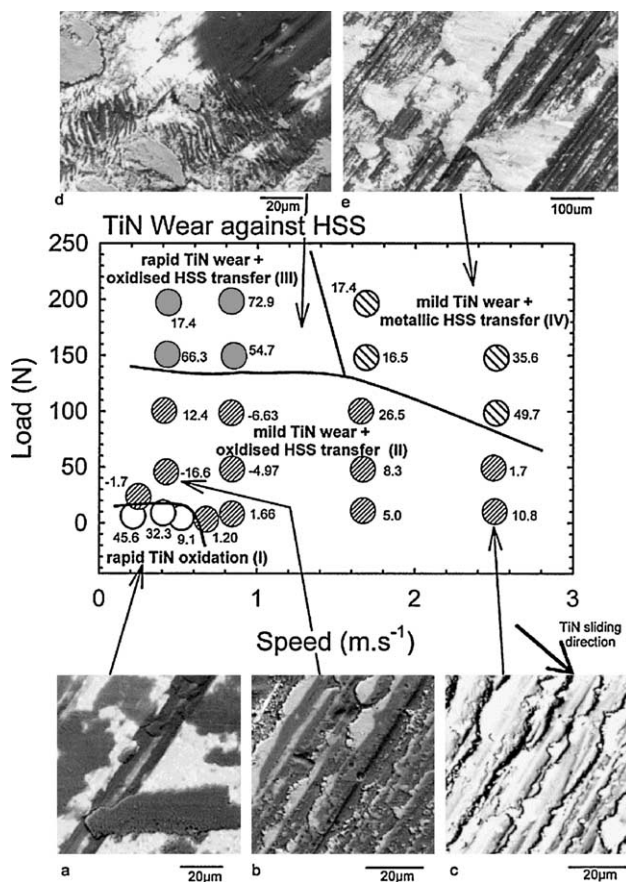


Fig. 6. Wear map showing wear rates and mechanisms for TiN in dry sliding against HSS pin material. The TiN wear rates have units of $\text{g m}^{-1} \times 10^8$. Experiments were conducted using the pin-on-disc geometry, at room temperature in air ($\text{RH}=13\%$). (a–e) SEM micrographs (back-scattered electron contrast (BSE)) of worn TiN surface morphologies from Regimes I–IV (see text for explanations): the arrow indicating TiN disc sliding direction relative to HSS pin applies to all micrographs in a–e; the continuous longitudinal features perpendicular to the sliding direction are the polishing marks left over from the original grinding process. From Wilson S, Alpas AT. Tribolayer formation during sliding wear of TiN coatings. *Wear* 2000;245:223–229.

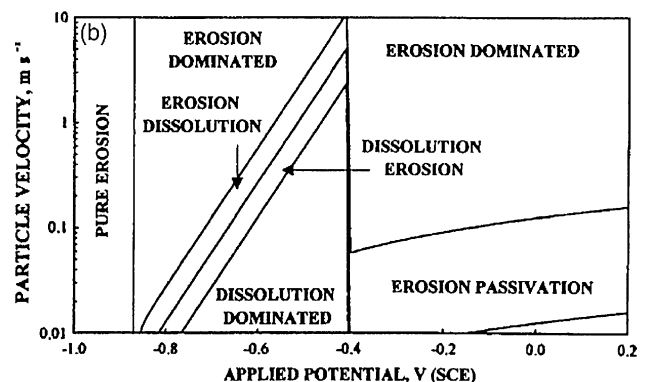


Fig. 7. Erosion–corrosion map for steel in aqueous conditions, pH 7. From Stack MM, Corlett N, Zhou S. A methodology for the construction of the erosion–corrosion map in aqueous environments. *Wear* 1997;203–204:474–488.

and these regimes can be displayed on a Pourbaix diagram [17]. When, in addition, abrasion or erosion occurs, as is often the case, the form of the map becomes more complex—Fig. 7 illustrates a possible form of the interaction between particle velocity and applied potential for a steel surface in an aqueous solution of pH 7: the boundaries between the different areas of the map are established from independently determined models of rates of mass loss due to either mechanical interaction or chemical corrosion and the details for this particular simulation are given in [18,19]. In the field, the effect of erosion and corrosion may be either simply ‘additive’ or, more usually, ‘synergistic’—this latter term implying that the effect of corrosion is to change the mechanical properties of the surface in such a way as to enhance the wear rate arising from the mechanical interaction. Wear debris in situations in which corrosion is active tends to be finely divided and fully reacted—with very little unreacted metal present. The existence of such debris is, however, no guarantee of corrosive wear as in abrasive wear it is possible for the debris to become fully transformed after removal from the surface.

6. Conclusions

When material is lost from a loaded surface either entirely or principally through some form of mechanical interaction the concentration, size and shape of the debris particles carry important information about the state of surfaces from which they were generated and thus, by implication, the potential life of the contact and of the equipment of which this forms a part. The full exploitation of this information and the ability to be able to predict quantitatively the future performance or life requires an understanding of the sources and mechanisms of generation of the extracted and sampled particulate debris. In many cases, it is instructive to display the running conditions of a given contact on some form of operational or wear map. This both enables the implications for wear of changes in design, material or operating parameters to be assessed and allows

sensible correlations to be made between laboratory-based experimental investigations and observations in the field.

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