

General Approach
and Procedures
for Unlubricated
Sliding Wear Tests

M G Gee and M J Neale

Measurement Good Practice Guide No. 51

General Approach and Procedures for Unlubricated Sliding Wear Tests

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Foreword:

This Good Practice Guide aims to provide introductory guidance on unlubricated sliding wear testing. It contains a discussion on the most effective approach to friction and wear testing and considers the different aspects that should be taken into account when designing a programme of friction and wear testing under unlubricated sliding wear conditions.

Specific guidance on how test conditions should be set and the procedures that should be used are given in Appendix A, and the results of an interlaboratory exercise that was used to validate the procedure are described in Appendix B.

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1. Introduction

Friction and wear result from the interaction of contacting bodies which are in relative motion. They are a function of the detailed nature of the tribological system and the operating parameters.

Wear is a process in which material is removed from the surfaces of components, or by which these surfaces are seriously disturbed. There are a number of different types of wear and each one requires a different practical approach to wear testing.

A national survey in 1997 has indicated that the cost of this wear to UK industry was of the order of £650 million per year. Also for companies who have these wear problems the costs were typically about 0.25% of their turnover. In many cases these costs can be at least halved by making appropriate design and/or material changes.

Control of friction is also important. Often the goal is to reduce friction as much as possible to increase the efficiency of machinery. Also reductions in friction are often linked to reductions in wear such that as the friction is reduced, wear is also reduced.

This good practice guide introduces the different wear mechanisms which occur in various types of industrial plant and machinery.

It then gives specific guidance on sliding wear tests, and gives recommended procedures for the conduction of sliding wear tests. This good practice guide is complementary to the handbook *A Guide on Wear Problems and Testing for Industry* [1], which contains information on the wear performance of different materials and reviews the different types of laboratory wear tests that are available for simulating practical wear conditions.

2. Types of Wear

The seven main types of wear are shown diagrammatically in Figure 1, and are described in more detail in the following paragraphs:

Abrasive wear occurs when material is removed from the surface of a component by a cutting action or by a process of multiple indentation from abrasive particles (e.g. by rolling particles in 3-body abrasion). This may be an intended and controlled process in component manufacture, such as filing or grinding, or it may occur randomly in machine operation, such as the wear of digger teeth when working in gravel. It can also occur with two smooth surfaces rubbing together but with small hard contaminant particles getting in between them. Abraded surfaces show damage which can range from fine scratching to deep gouges. If the component is made from a ductile material, such as steel, the wear debris can be spiral in

shape, similar to machining swarf. For very hard materials, the wear debris tends to be in the form of chips.

Adhesive wear is the surface damage and material removal which can occur when two smooth surfaces rub against each other. Such surfaces are never perfectly smooth and have high spots where the rubbing occurs. These local areas experience concentrated contact loads and interactions, and tend to adhere to each other and drag material away along the surface. This type of wear can occur in plain bearings and other interacting machine components, particularly if they are inadequately lubricated. The wear of brakes and clutches occurs by the same mechanism, and is kept under control by the use of dissimilar materials. Surfaces subject to adhesive wear can end up polished, with the generation of fine flakes of wear debris, or can show severe surface damage associated with surface dragging or even seizure.

Fretting is a particular form of adhesive wear which occurs when there are small oscillatory movements between two surfaces. These movements can arise from the deflection of machine components with clamped joints or press fits, or they may be intended small movements as in gear couplings. Fretting often produces fine powdered and oxidised wear debris around the components and there is usually surface damage and roughening of the joint surfaces. Fretting is also a limiting factor in the life of wire ropes. The individual steel wires rub against each other due to relative deflections when the load on the rope changes or when it is bent around a pulley. The oxidised wear debris often produces a red staining on the surface of the rope.

Erosion involves the removal of material from the surface of a component by the high speed impact of a liquid or of a stream of hard particles carried in a fluid flow. The two common types of erosion are cavitation erosion and particle erosion. **Cavitation erosion** occurs on components subject to low transient fluid pressures, such as ships propellers, and arises from the intense local impact of the collapse of low pressure vapour bubbles onto the component surface. **Particle erosion** occurs when a stream of hard particles is directed at a surface. This may be intended as in shot blasting processes, or it may arise incidentally, such as in pipe lines and associated components carrying slurries or crude oil containing sand.

Fatigue of surfaces can also lead to the loss of material when fatigue cracks in the surface join together to create loose particles. This surface fatigue can arise from a contact stress fatigue mechanism or from a thermal stress fatigue mechanism. Contact fatigue can arise in rolling contact where the passage of a ball or roller over a surface causes alternating tensile and compressive stresses, which can create fatigue cracks. Thermal fatigue cracking can arise from the transient heating and cooling of a surface, particularly when combined with surface frictional forces such as in clutch plates and heavily loaded plain bearings. It can be particularly severe if a surface is in intermittent contact with a very hot material, such as molten metal.

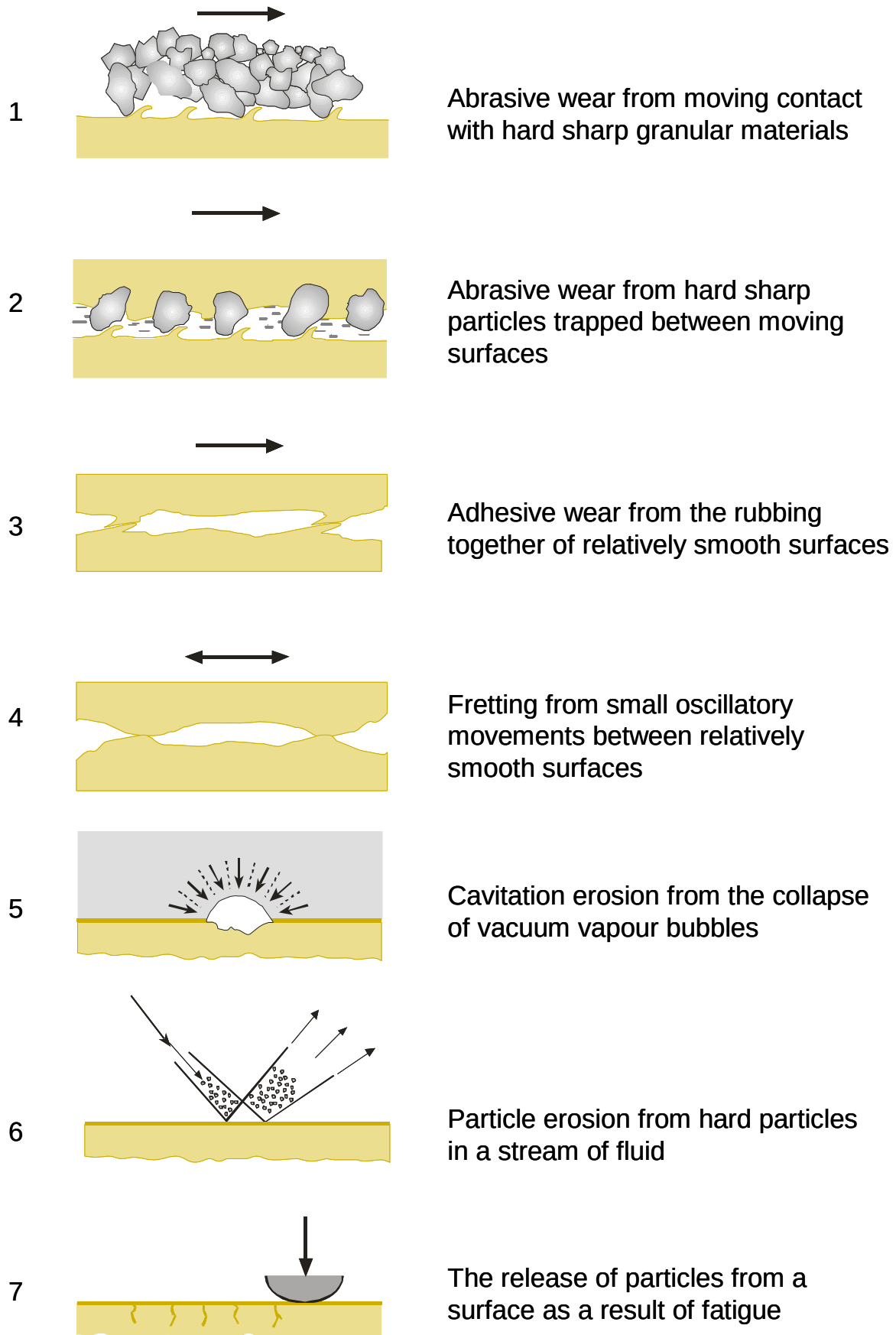


Figure 1: The Types of Wear That Occur in Industrial Machines

3. Requirements for Friction and Wear Testing

There are several different reasons for performing friction and wear tests. These are:

- 1) Field trials to determine performance in real life situations.
- 2) Prototype testing, where new components (or components from new materials) are tested in the intended final product in more controlled conditions than the real life application.
- 3) Component trials, where assemblies of components are tested on the bench in new component development.
- 4) To characterise materials' performance, and determine how different materials or variations in their structure can affect friction and wear. These studies are normally carried out in the laboratory with simple test systems.
- 5) To obtain fundamental information on the mechanisms that occur in the friction and wear of materials. These studies are normally carried out in the laboratory with simple test systems.
- 6) Troubleshooting to determine cause of failure of machinery.

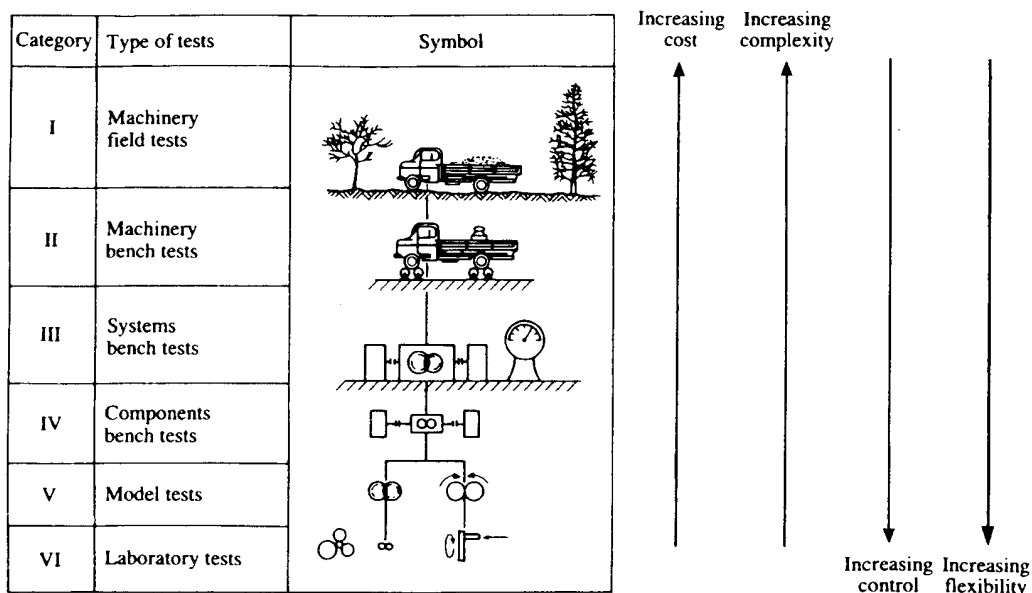


Figure 2 Different categories of wear testing, according to DIN 50322: 1986.

The first five of these can be correlated with the categories presented in a German DIN standard (Figure 2). The last item, troubleshooting, requires a different approach since it is concerned with the identification of the failure mechanism and the development of procedures which will help to clarify and alleviate the problem; a large element of this work is a forensic study of the failure, and the identification of the conditions that were operating at the time of failure. Laboratory testing can be an important element of troubleshooting, but the primary objective of this testing is to reproduce the failure mechanism, so that corrective measures can be designed and tested in an informed way.

In general the degree of control of the test decreases as one moves from fundamental studies (1) through to field trials (5). As the real world application is approached, it becomes increasingly difficult to define the complex set of interacting factors which determine the performance of the unit over a range of loads, speeds, temperatures, pressures and environments. There are also often obvious cost benefits from running simple laboratory tests, where in some applications field trials just cannot be contemplated because of the huge costs involved in interrupting production. However, it should be noted that there are occasions where the most cost effective testing can be to use the components themselves in their final configuration in the product.

It is important to ensure that the results from laboratory tests compare well with observed performance in practice. The final test for any product is obviously that it performs as expected in real life applications. The aim of laboratory testing must be to supply data on friction and wear behaviour which, if not completely equivalent, is relevant to the application. One way of ensuring this is to check that the mechanisms that are observed in the laboratory tests are the same as those observed in practice. Techniques for determining wear mechanisms are described in a later section (section 6).

4. Simulation of sliding wear with laboratory tests

It is important that in laboratory tests the conditions that are used should be appropriate and relevant to the real life conditions. It is generally not possible to completely simulate the conditions found in the application. This is because of the difficulty of defining the conditions that occur in applications, and also because of limitations in the test system that is being used to simulate the application, which mean that the match is unlikely to be perfect. Indeed, it is often desirable to simplify the conditions so that more control of the testing is obtained leading to a better understanding of the results of the testing and their relationship to the test conditions.

When considering the design of a laboratory test and how well it simulates an application, it is useful to consider aspects of the different test parameters. These are:

- How important are the different parameters

- How controllable are the different parameters
- How measurable are the effects of the different parameters

In general, the importance of the various parameters will depend to some degree on the application that is being considered, but the most important parameter in any test must be the material structure and composition. Other parameters which have a major impact are load, speed, contact geometry, motion type, surface finish and test environment.

Control of most test parameters is normally straight-forward, but there are some areas where this is much more difficult to achieve. Thus the local (flash) temperature at contact points on the wear interface, which depends on the heat generated by friction, cannot be easily predicted. Another parameter which cannot be altered easily is the dynamics of the test machine which has been shown to have an effect on results [2].

Measurement of many of the test parameters is also straight-forward, but again there are some difficult areas such as interface temperature measurement where practical methods do not exist for most materials.

An important check on the adequacy of the simulation is that the mechanisms of wear should be the same in the application as in the laboratory tests. The examination of surfaces to determine such mechanisms is discussed later.

5. Test Machines for Uniaxial Sliding Wear

There are hundreds of different test machines that have been developed historically [3]. However, these can be reduced to a small number of basic geometries characterised by the motion used. These are unidirectional sliding, reciprocating sliding, combined rolling and sliding, and pure rolling. Unidirectional machines include pin-on-disc, block on-ring, ring-on-ring, pin-on-plate and crossed cylinder (Figure 3). Machines of this type have simple test specimen designs. They have the ability to cover wide load and speed ranges to establish the performance of a material under a wide range of conditions.

In the choice of a suitable test system, it is important to consider the orientation of the test system. For example, in pin-on-disc systems, the disc is rotated in the horizontal plane, with the pin pressed into it from above. However, other orientations are possible with the disc plane vertical, or the pin pressed up from beneath the disc. Debris entrapment, which can have a large effect on friction and wear, is different for these different orientations. Also the test system orientation can dictate other aspects of the test such as access to specimens, the type of loading system that is possible, in-situ observation of the contact area, and the collection of debris for future examination.

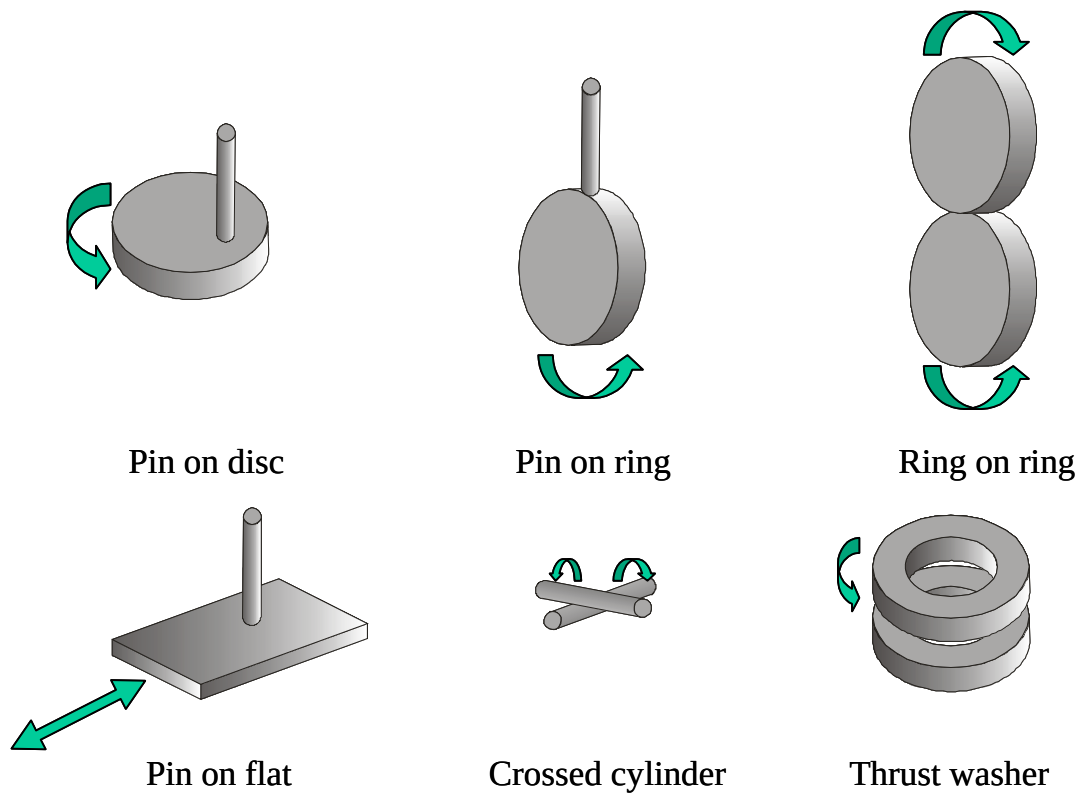


Figure 3 Different geometries of uniaxial sliding wear tests

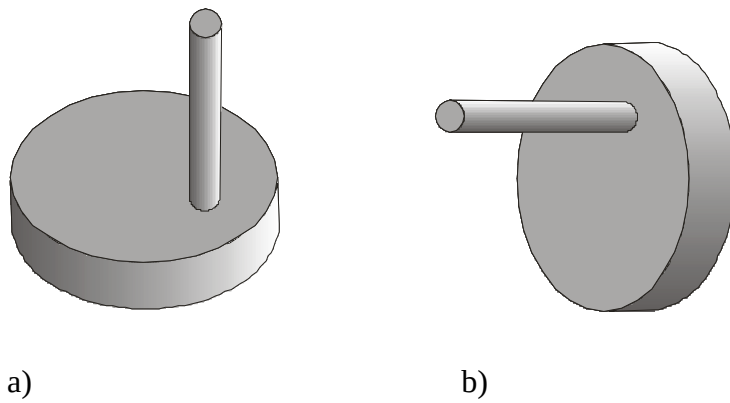


Figure 4 Pin-on-disc configurations leading to a) debris entrapment, b) reduced debris entrapment.

The design of the test system also dictates the dynamic response of the test system to the loads imposed during testing. These dynamic effects can have a dramatic effect on the wear results that are obtained [2].

6. Choice and Control of Test Conditions

6.1 Overall Considerations

The choice of test conditions must be determined either by the engineering application, or to achieve the appropriate mechanism in fundamental studies. In the development of materials, a range of conditions can be chosen to represent those likely in actual use of the material.

There are many test factors that need to be controlled during a test. These can be grouped into those concerned with the mechanical test conditions such as contact load or pressure, speed, motion type and test environment, and sample parameters such as materials composition, structure, and the surface finish of the samples. A full programme of testing under all combinations of these factors would be very expensive, and may well not be required. Often a single factor can be identified as "key" to the material response, and in this case a good approach is to fix all the other factors at constant values, and vary the chosen factor in a controlled way in a series of tests. This approach is termed a parametric study. More complex statistical, experimental design procedures can be used, but care needs to be taken in the design of experiments account for the scatter that is normally observed in the results of wear tests.

Mapping techniques can be used where two (or more) factors are changed in a controlled way (normally more coarsely than in parametric studies) with the friction and wear results plotted either as individual points or as contours. Regions on the map are then delineated on a mechanistic basis, with the region boundaries either defined on the basis of identification of wear mechanism by microstructural techniques, or by the identification of transitions in friction and wear behaviour as sudden changes in wear rate or friction coefficient (Figure 5) [4,5]. The mapping procedure is a very efficient way of determining the overall behaviour of a material, because it provides useful information about the position of transitions in wear behaviour in a systematic controlled way. This is at the expense of a reduction in the detailed variation of friction and wear with any one factor, but once the regime of interest is better defined through the use of mapping studies, then a more detailed parametric study can be conducted.

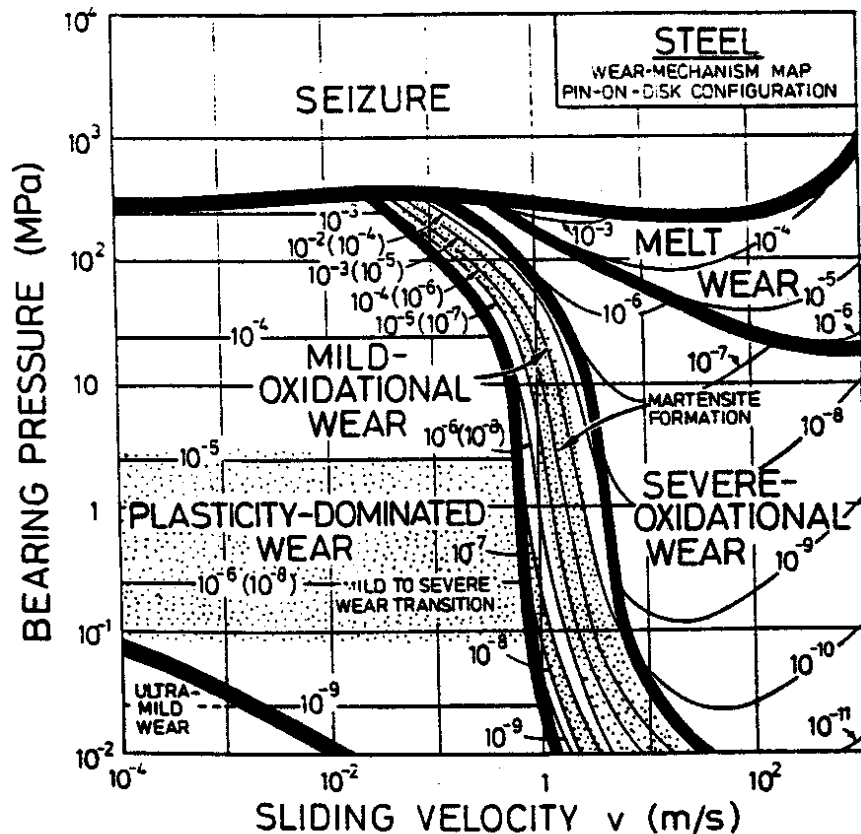


Figure 5 Wear mechanism map for low carbon steel [4].

6.2 Contact Geometry

One of the most important factors that needs to be considered in the design of a friction and wear testing study is the geometry of the contact between the two specimens. Conformal contacts (e.g. flat-on-flat) seem to be easier to simulate, since all that would appear to be necessary is to use specimens and applied loads which give the nominal contact pressure required. However, there are several problems with this approach. It is very difficult to align the specimens so that true plane contact is achieved, so that, at least in the early part of the test, wear will be concentrated at the few points where the two specimens are in contact and the material experiences higher contact pressures than expected from simple estimates. Even when alignment is perfect, contact mechanics shows [6] that there will inevitably be concentrations in contact stresses at the edge of the specimen contact area. These may cause chipping or other damage to the edge of the specimens, particularly in brittle materials such as ceramics, and although they may be alleviated by chamfering the edge of the specimens, some stress concentration will always remain.

The other alternative approach is to use a non-conformal specimens' geometry (which will be a close simulation of many applications) where it is recognised that the stress at the contact

between the specimens will be changing as the wear takes place, but now this is occurring in a well controlled way which can be calculated using Hertzian contact equations [6]. However, there may still be unwanted changes in mechanism that occur as the contact pressure drops.

6.3 Test Load and Speed

The test load and speed have a major impact on the results of tests as the source of the energy dissipated in the generation of friction, and in the loss of material from the surface as wear [7].

The frictional energy is generated by a combination of load and sliding speed and its dissipation is influenced by the material properties and the contact area. The wear rate can therefore be expected to be related to these same factors.

In most cases the volume of material worn from a surface is broadly proportional to the load and the sliding distance. This is perhaps not surprising, because the true contact area between surfaces depends on the load, and so the volume of material worn away will be expected to be related to this area multiplied by the distance slid.

The relationships can be expressed as formulae where (see notation in Appendix C):

$$\text{Volume wear } V = k \cdot WL$$

$$\text{Depth wear } h = k \cdot \frac{WL}{A}$$

$$\text{Depth wear rate} = \frac{h}{t} = k \cdot \frac{WL}{At} = k \cdot \frac{Wv}{A} \quad (A)$$

This depth wear rate is the critical factor in many practical applications, because it determines the running time to reach a critical amount of wear.

It is also significant in that it relates to the frictional power intensity at the wearing surface.

Since:

$$\text{Frictional power input to the surface} = \mu W \cdot v$$

Frictional power intensity

$$\begin{aligned} \text{(or power input per unit area)} &= \frac{\mu W v}{A} \\ \text{(B)} \end{aligned}$$

The similarity of these two formulae (A and B) confirms that the rate of material removal is generally directly related to the amount of energy going into a sliding contact.

This is particularly significant when choosing a wear test for a component which has intermittent contact, because it indicates that if a representative depth of wear h_c is to occur during each fractional contact period t_c , then this amount of wear is represented by

$$k \cdot \frac{WV}{A} \times t_c$$

and there must be an equivalent energy pulse input in the test arrangement of

$$\mu \cdot \frac{WV}{A} \times t_c$$

In practice this means that the pattern of contact and non contact in the test should ideally correspond to that which occurs on the real component.

6.4 Control of Debris

As mentioned earlier, the wear process will produce debris and this can interact with the ongoing wear process, either as individual particles or by agglomeration into larger particles or layers.

It is therefore important to ensure that the wear debris in the test interacts in the same way as in the practical case. The most critical feature is whether the debris remains in the contact in the practical case, or falls away, and this needs to be reproduced in the test. In some cases, when needed to simulate the application more closely, the debris can be largely removed from the wear interface by means of a brush or scraper placed behind the pin.

6.5 Accelerated Tests

Since wear components are expected to have a long life in many applications, it is tempting to try to perform accelerated testing where the timescale of the laboratory tests has been reduced to a more practical level. This is normally attempted by increasing the load and/or speed so that wear takes place at a faster rate that can be measured easily in a shorter interval. However, accelerated testing is fraught with many dangers. This is because any increases in load and speed may well bring about changes in the mechanisms of wear that take place, so

that the results of the accelerated test cannot be used in the prediction of wear behaviour in the application. Even if the mechanism stays the same, the necessary extrapolation of the short-term accelerated test results cannot usually be made because of a lack of validated models; there also may be unforeseen transitions in wear rate after quite a long period due to mechanisms which only start after the accumulation of damage in the surface of the specimens.

6.6 Test Machine Dynamics

As indicated earlier, the test machine dynamics can have a major effect on the results of sliding wear tests. Unless there are particular reasons dictated by the dynamics of the engineering application that is being simulated, it is normally best to try to minimise the effect of the test machine dynamics on results. This is normally achieved by increasing the stiffness of the test system as much as possible so that the natural frequency of the test system is increased, and is considerably higher in frequency than any repetitive impulse generated in the test, for example, from rotation of the test system.

In any case, if a compliant test system is required, the best method for designing this is often to take an intrinsically stiff test system and to reduce the stiffness of the test system with specifically introduced compliant elements.

6.7 Environmental Control

The control of the environment around the test system also has a major effect on test results. Clearly the correct gas mixture must be used to replicate the application of interest. Many tests are performed in air, but even so the temperature and humidity need to be considered. The humidity has a particularly important effect, with changes in wear of several orders of magnitude in wear observed for some materials over small changes in humidity (Figure 6) [8,9].

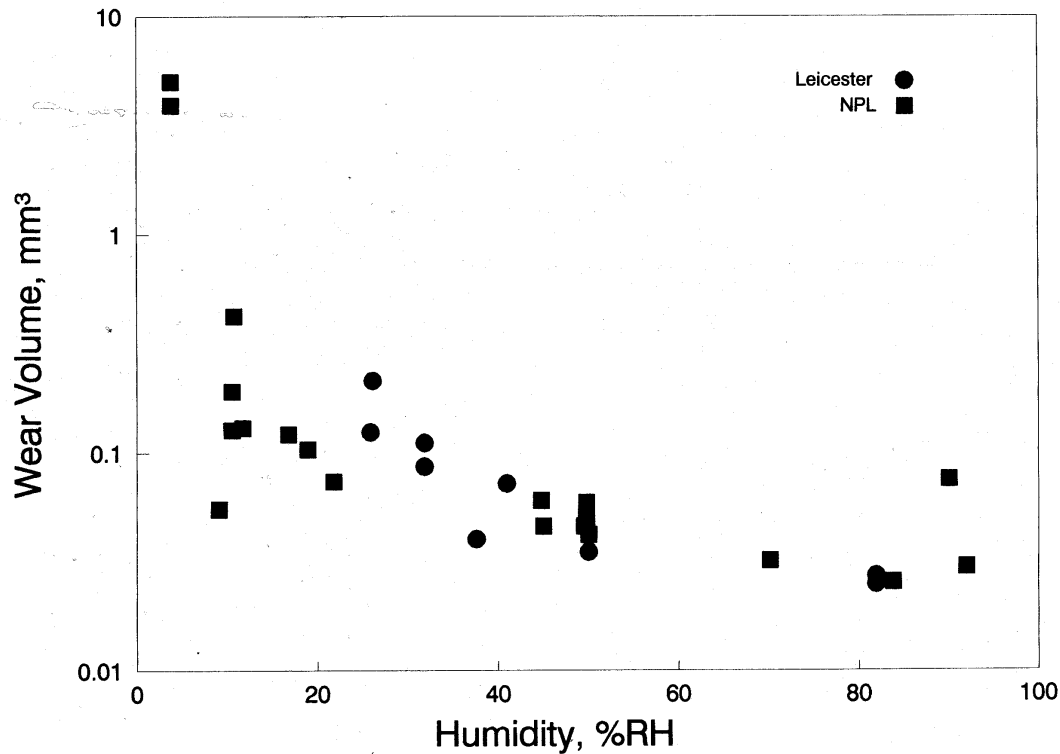


Figure 6 Effect of environmental humidity on wear of polycrystalline alumina.

Although control of both temperature and humidity is desirable, many laboratories do not have this capability. In any case measurement of temperature and humidity is required so that results of tests can be correlated with changes in the environmental conditions.

7. Surface Examination Techniques

Surface examination is a crucial element in the determination of the mechanisms of wear that occur. There are a very wide range of techniques available that give information on the appearance, topography and composition of surfaces.

Most of this section is concerned with the most commonly used techniques of optical, scanning electron microscopy, and surface profilometry. These and other techniques are listed in Table 1 with some details of the lateral and depth resolution, and some details of the analysis capabilities.

7.1 Visual examination

It is always important to examine worn samples and components by eye before using any other technique. This visual examination gives information about the whole component that other higher resolution techniques can easily miss, such as (smooth, shiny, rough etc) colour,

and inter-relationship between different features on the surface. The use of different lighting directions (vertical, oblique, glancing angle) should be explored.

Visual examination can be augmented by close-up photography (Figure 7). Modern high resolution digital cameras can be useful for this purpose as they eliminate the need for photographic developing and printing, and allow for computer archiving and image processing.

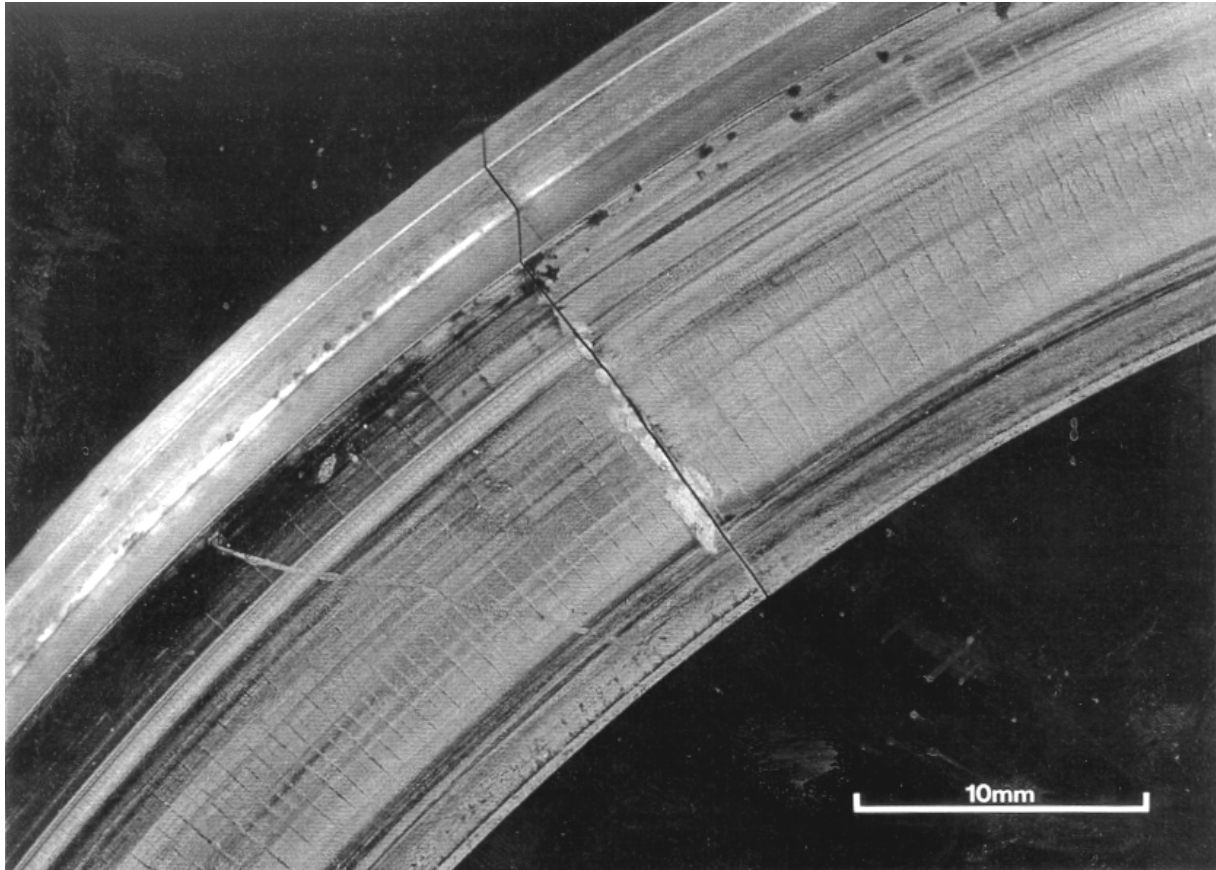


Figure 7 WC/Co mechanical sealing ring which has failed through thermal fatigue

A hand held magnifying glass giving magnifications in the range x 2 to x 5 is an effective addition to direct visual inspection. Also if the component is small enough to be handled, a binocular microscope with a magnification of up to x15 is probably the most effective method of all for direct practical surface examination.

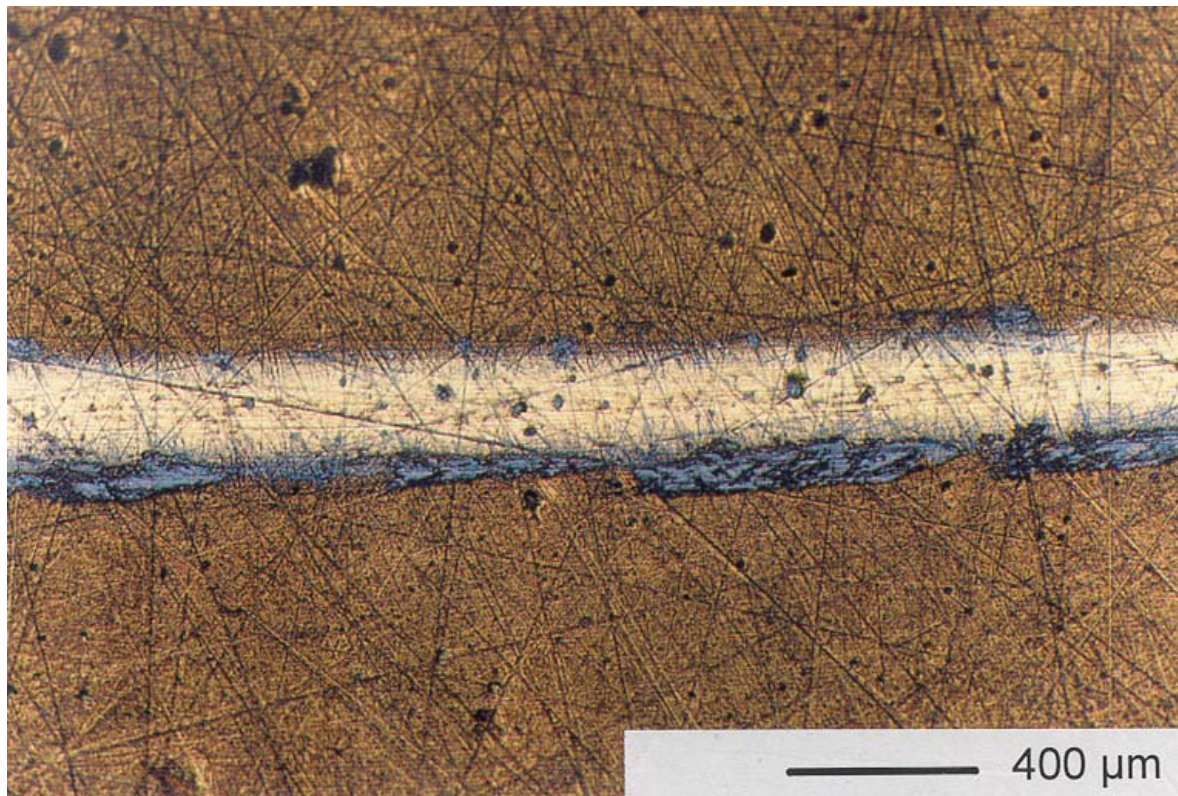
If a much more detailed laboratory examination is required, optical microscopes with magnifications up to x1500 are available.

Images reveal information about the colour and placement of different features on the surface (Figure 8). One of the limitations of conventional high powered optical microscopy is the small depth of focus (dependent on microscope objective and thus magnification). This

limits the usefulness of conventional microscopes for the examination of rough surfaces, and curved components.

Although most optical microscopy is performed using brightfield imaging, additional information can often be obtained under other imaging conditions. Thus crossed polarising filters can give different contrast depending on the optical activity of the different phases being examined, and differential interference contrast gives contrast that depends sensitively on the topography of the surface being examined (Figure 9).

The general approach with surface analysis must be to start with the simplest techniques, moving to the more difficult techniques only if sufficient information has not been amassed in the earlier stages of examination. Thus in many cases all that is needed is to examine samples visually.



a)

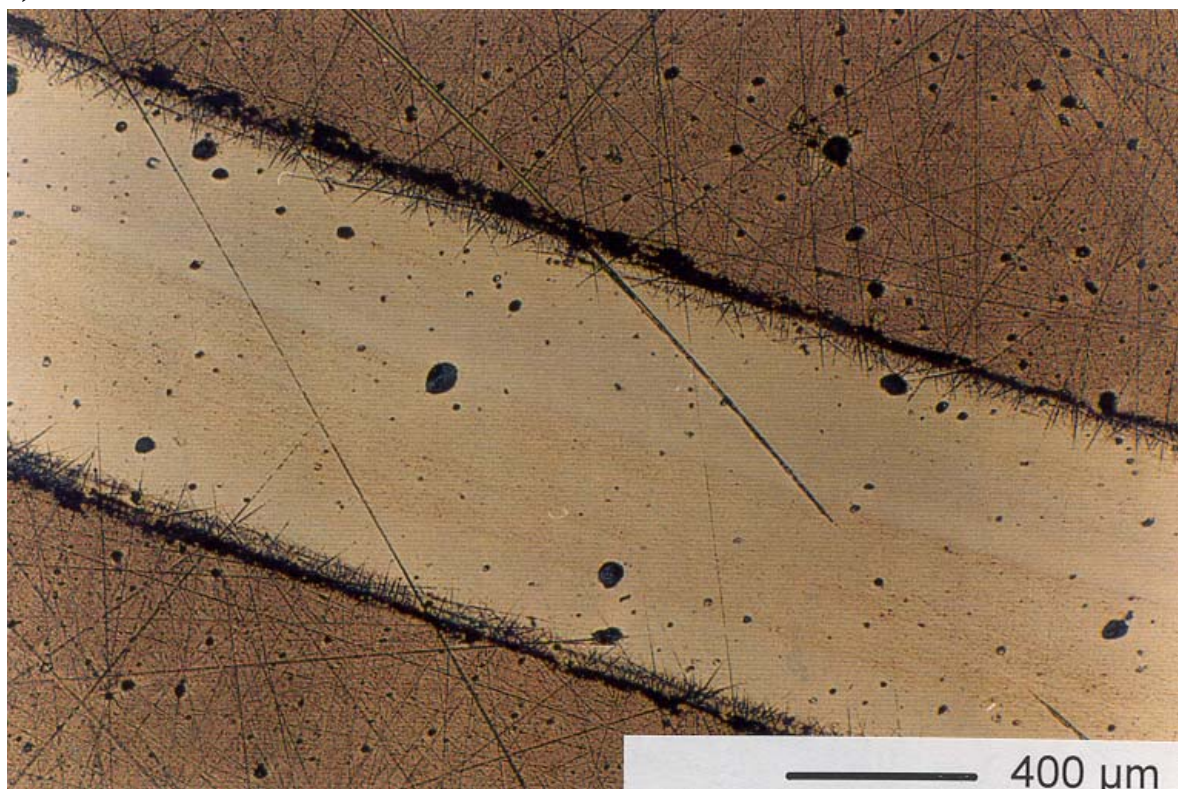


Figure 8 High magnification images showing surface features.

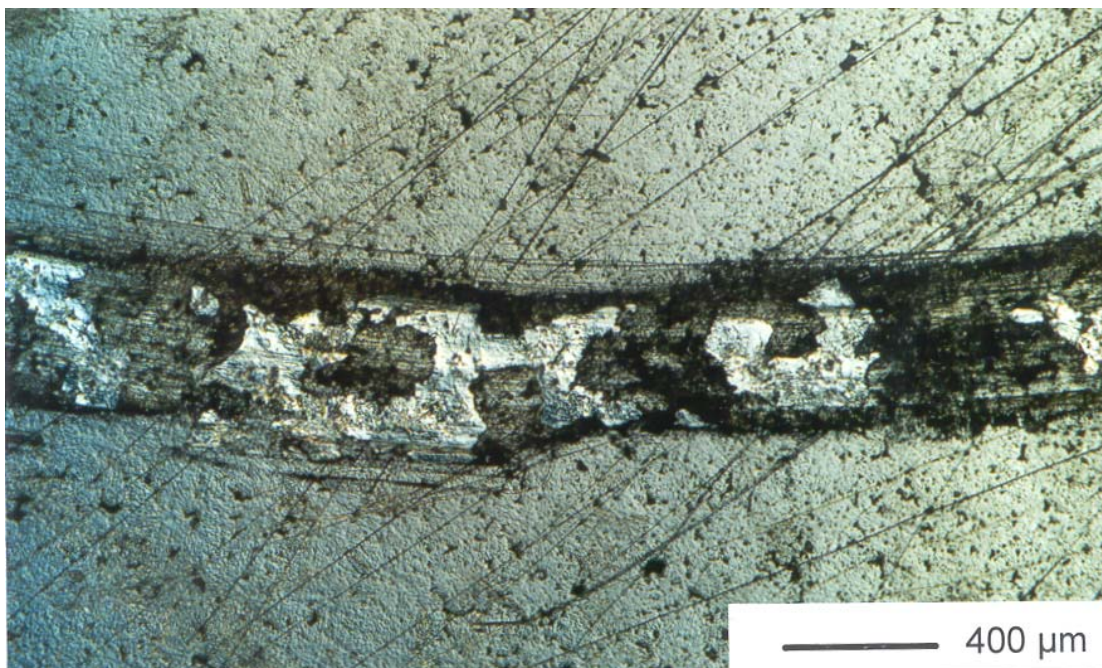
Wear track on TiN coated samples worn in pin-on-disc configuration.

a) light wear showing build up of titanium oxide

b) more heavily worn wear track with removal of scratches from centre of wear track by wear process.



a)



b)

Figure 9 The effect of different lighting arrangements on the images.

Iron rich transfer films on alumina sample formed during wear of steel pin against alumina sample.

a) is imaged with near crossed polariser illumination and emphasises the iron oxide reaction layers on the surface of the wear track.

b) is the same area imaged with differential interference contrast emphasising the transferred layers of steel on the wear track.

7.2 Electron Microscopy

Another very effective laboratory technique for the examination of worn surfaces is the electron microscope. This uses an electron beam interacting with a sensitive screen, rather than a light beam reflected back to the eye.

There are two methods of use for electron microscopes. Scanning Electron Microscopy (SEM), scans the surface with an electron beam; and the other, Transmission Electron Microscopy (TEM), passes an electron beam through a very thin specimen cut from the surface.

The scanning electron microscope (SEM) uses secondary electrons that are emitted from the surface of a sample when the electron beam of the microscope hits the surface at the point being imaged. Because the generation of secondary electrons is strongly dependent on the orientation of the surface at the point being examined, the image contains a significant contribution from topographical features on the surface of the sample. The scanning electron microscope can give very high spatial resolution, and has a high depth of focus. However, because the image is formed by an electron beam, sample charging problems can occur for non-conductive samples. These are normally solved by coating samples with thin layers of conductive material such as carbon or gold, but for surfaces such as powders or tribological layers where the contact between one part of the surface and another is not very good, charging can still occur.

Another problem with the scanning electron microscope is that it gives poorer detectability for some features on the surface of the sample such as pits. A classic example of this is the imaging of Vickers hardness indentations in the SEM. Even when they are quite large and can be easily detected by optical microscopy or even with the eye, it can be very difficult to see the same indentations in the SEM.

Scanning electron microscopy of a surface can, however, reveal details of the surface very clearly at high magnification such as in Figure 10.

Scanning electron microscopy is a very effective and useful technique and can give magnifications from about 20 to 100,000. It can examine smooth or rough surfaces, flat or curved and can accept specimens up to 150 mm diameter. It can also provide information on the chemical composition of the surface by in-situ X-ray analysis. SEMs also usually have an image reversal facility by which surface replica specimens can have their image converted to that of the real surface. Stereo pair photographs can also be taken to enable height and depth size differences to be obtained by using a stereo mapping device. This can then be compared with the information obtained from surface topography measuring devices.

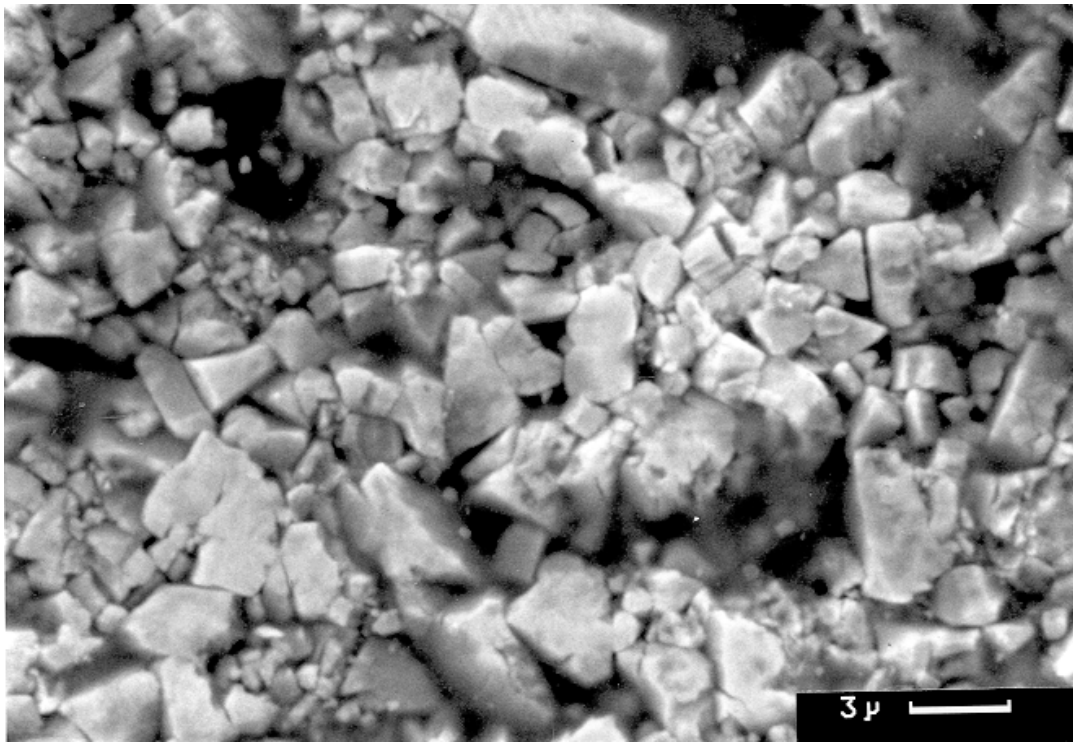


Figure 10 Scanning electron micrograph of WC/Co surface abraded by rolling silica.

Transmission electron microscopy is a useful technique where a very detailed analysis of the small scale structure of surface layers can be made. For some types of samples near atomic resolution can be achieved.

The main drawback with transmission electron microscopy is that it requires the use of electron transparent samples. These need to be less than about 200 nm in thickness, and can be very difficult to prepare from solid samples. Normal techniques used for sample preparation are mechanical grinding followed by ion-beam thinning.

One area where sample preparation is extremely easy is for the examination of wear debris. The preparation of samples consists simply of scattering the wear debris on to carbon films and shaking off the loose powder. Sufficient particles adhere to the carbon film to allow examination and analysis at high magnification.

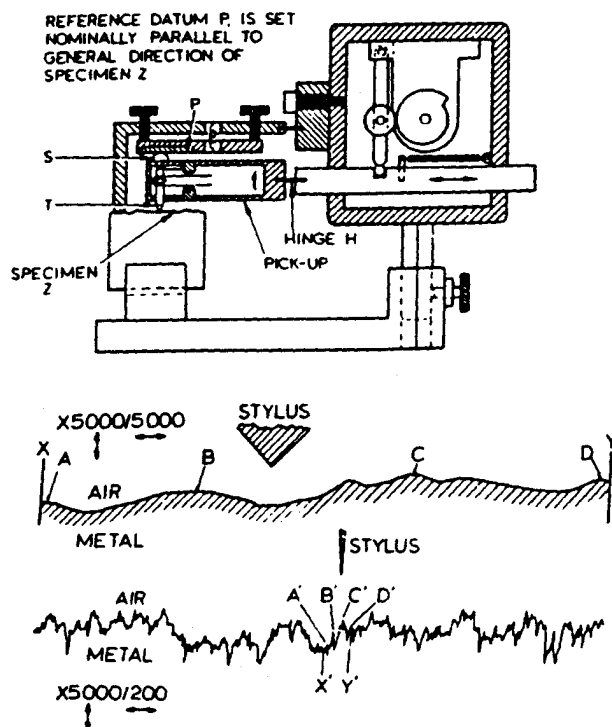
7.3 Topographical information including surface finish

The shape of a worn surface gives clues about how it was formed. For instance, the presence of deep grooves on a surface is suggestive that abrasion processes have been occurring; in fact, one definition of abrasion relies on this observation. Although considerable information on the shape of a surface can be given by direct visual information, and by optical and scanning electron microscopy, actual quantitative information can only be obtained by measuring the response of probes of different types as they move from position to position on the surface.

Height information is obtained as either a one dimensional profile of height along a line, or as height data from an area of the sample, giving a 3D data set (height + 2 lateral dimensions).

7.3.1 Mechanical probes

Mechanical probes have been used for many years in the determination of surface topography, and must be the most common technique used for the characterisation of surface topography. Normally, a diamond stylus with a well defined tip geometry (e.g. tip radius of a few micrometres) is used as the mechanical probe (Figure 11). Either the stylus is scanned over the sample, or the sample is scanned under the probe, and variations in the height of the surface from point to point result in a movement of the probe which is measured to give a measure of the sample height at that point. The geometry of the tip is well defined by national and international standards. One of the potential drawbacks with stylus instruments is the damage that occurs to the surface when soft materials are being examined.



Instrument construction

Stylus T measures the surface profile relative to reference surface P followed by stylus S.

Instrument output

Actual surface profile.

The recorded output has a compressed horizontal scale.

Figure 11 Surface topography measurement with a mechanical probe.

7.3.2 Optical probes

Optical probes are becoming increasingly popular. Their advantages are that they are non-contact devices which cannot damage the examined surface, and for full field instruments, can be much faster than mechanical systems.

There are four main types of optical instruments:

The first are systems based on interference microscopy. The basic principle is that an interference pattern is formed by the combination of light reflected from the surface with a reference beam. Often the sample is scanned in height whilst several patterns are captured (sometimes continuously) and analysed to calculate surface height information. These instruments have good spatial and height resolution, and have high measurement rates. There are some concerns that errors occur when rough surfaces are measured due to the difficulty in analysing the very complex interference patterns that result. These instruments also normally measure a single field of view at a time, limiting the area that can be examined.

The second type of instrument is the confocal microscope. The utilisation of narrow apertures in the optical sectioning, where light is only captured by the microscope from the plane in focus intersecting the sample. The height of the sample is then scanned, and a set of optical sections is collected and analysed to give surface height data. The instrument gives good spatial and height resolution, but is again normally limited to single fields of view. A particular advantage of this technique is that images of the examined area are acquired simultaneously with the height information.

The third type of optical system is based on compact disc (CD) reading technology. This has been used as the basis of optical non-contact surface topography probes. They normally use infrared lasers and gain the height information through a servo feedback mechanism which monitors the size of the spot focused from the reflected light. These systems have the advantage that large samples can be examined, but the large spot size limits the spatial resolution of the device.

The fourth type of instrument also uses laser probes, but relies on a triangulation system to calculate the surface height.

Table 1, Surface examination techniques.

Resolution and sensitivity figures are approximate guides to relative performance. There is often a trade-off between resolution and sensitivity.

Technique	Spatial Resolution	Depth Resolution	Analytical Sensitivity (Z is average atomic number)	Applicability (Z is atomic number of element)
OM	0.2 μm	-	-	-
SEI (SEM)	1.5 nm	-	-	-
NCOP	1 μm	3 nm	-	Topography
CP	0.5 μm	1 nm	-	Topography, may damage soft samples
XRD	10 mm	10 μm	5%	Crystal phase, Plastic Deformation, Particle Sizing
XRF	10 mm	10 μm	1-10 ppm	Z > 4
XPS	5 μm	3 monolayers	0.3%	Z > 2
LIMA	2 μm	1-2 μm	10-100 ppm	All Z
EDS (SEM)	1 μm	1 μm	0.1%	Z > 4
WDS (SEM)	1 μm	1 μm	100 ppm	Z > 4
BEI (SEM)	50 nm	50 nm	0.1 Z	
SSIMS	1 μm	2 monolayers	0.01%	All Z
DSIMS	20 nm	10 monolayers	< 1 ppm	All Z
SAM	5 nm	3 monolayers	0.3%	Z > 2
EDS (STEM)	10 nm	20 nm	0.1%	Thin Foil, Z > 4 Peak Overlap
EELS (STEM)	10 nm	20 nm	1%	Thin Foil, Z > 3
APFIM	1 nm	1 monolayer	0.1-1%	All Z
EBSP	100 nm	50 nm	-	Crystal phase, Orientation

Key: OM is optical microscopy; SEI is secondary electron imaging; BEI is back-scattered electron imaging; XRD, XRF and XPS are respectively X-ray diffractometry, fluorescence and photoelectron spectroscopy; LIMA is laser induced mass spectroscopy; EDS is energy dispersive X-ray analysis; WDS is wavelength dispersive spectrometry; SEM is scanning electron microscope; SSIMS and DSIMS are static and dynamic secondary ion mass spectrometry; SAM is scanning Auger spectrometry; STEM is scanning transmission electron microscope; APFIM is atom probe field ion microscope; EBSP is electron back-scattered diffraction pattern; EELS is electron energy loss spectrometry; NCOP is non-contact optical profilometer and CP is contact profilometer.

8. Sources of Guidance

The first part of these guidelines has given a simple introduction to the different mechanisms of wear and to the design of a sliding wear friction and wear testing strategy. There are a number of books and other documents which are available if more information is required; some sources of guidance (which are by no means exhaustive) are listed here.

A useful introduction in the consideration of the framework for friction and wear measurement is given in *Tribology: a systems approach to the science and technology of friction lubrication and wear* by H Czichos [10]

General information on tribology is available in several handbooks such as the *Wear Control Handbook* by Peterson and Winer [11], *The ASM Metals Handbook: Vol. 8, Friction, Lubrication and Wear Technology* [12], and the *Handbook of Tribology: Materials, Coatings and Surface Treatments* by Bharat Bhushan and B K Gupta [13]

Compilations of data of wear rates of different materials combinations under specified conditions are available in the *Tribology Handbook* by M J Neale [14] and the *Elsevier Materials Selector* [15].

Specific information of testing is given in many papers in the literature. Example are Almond and Gee [16], Alliston-Greiner [17], Eyre [18], in ASTM STP's on friction and wear testing of metals [19], plastics [20], coatings [21], elastomers [22], ceramics [23], and advanced materials [24], and an ASTM STP on the fretting fatigue test methods [25].

Other more general information on wear testing is given in books such as the *Fundamentals of Friction and Wear of Materials* edited by Rigney [26], *New directions in Lubrication, Materials, Wear and Surface Interactions* by Loomis [27], *Tribology: Friction and Wear of Engineering Materials* by Ian Hutchings [28], *Engineering Tribology* by John Williams [29], and *Friction Science and Technology* by Blau [30].

Many papers on friction and wear testing procedures are given in the proceedings of conferences such as the biennial *International Conference on the Wear of Materials* [31], and the peer reviewed Journals *Wear* [32] and *Tribology International* [33].

Practical and comprehensive guidance is also given in the *Guide to Wear Problems and Testing for Industry* [1], by Neale and Gee.

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Appendix A

Recommended Test Procedures for Unlubricated Sliding Wear Testing

This appendix gives recommended test procedures for unlubricated sliding wear testing. These are based on previous work performed in the UK and internationally through VAMAS [A1-A4], and an EU supported project on the development and validation of measurement methods for thin hard coatings [A5].

The test procedures covered by these recommendations relate to tests for wear between balls/pins and rotating discs, and between balls/pins and plates with relative reciprocating motion.

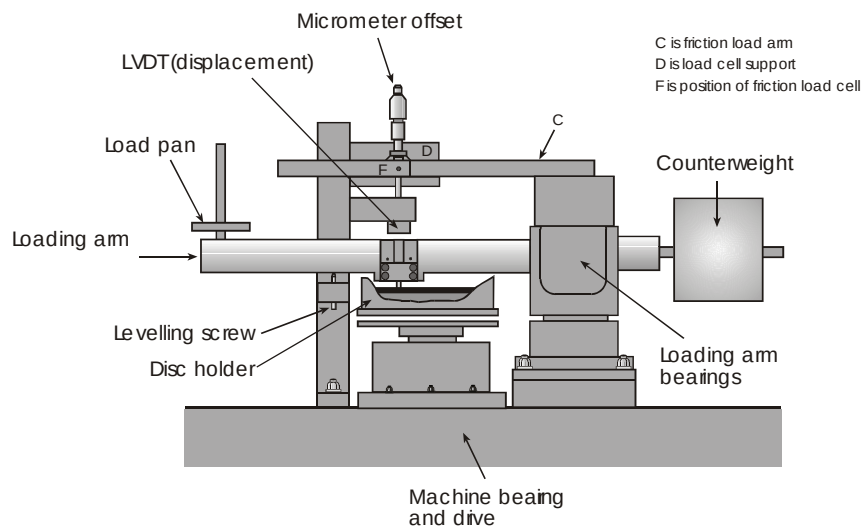
Tests can be carried out on coated or on uncoated flat samples; the differences in the procedure relevant for the two types of measurement are clearly described.

In each case the procedures cover:

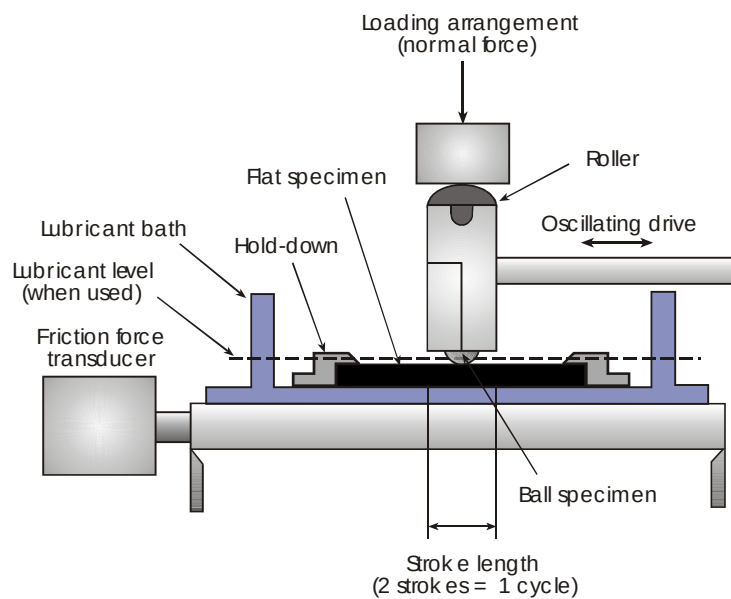
1. Important features of the test apparatus that need to be checked.
2. The preparation of the test specimens.
3. The measurement methods to be used during the tests.
4. The carrying out of the test programme.
5. The results which should be reported.

A1. Apparatus

Diagrams of typical sliding wear systems are shown in Figure A1.



a) Pin-on-disc uniaxial system



b) Reciprocating sliding system

Figure A2 Typical sliding wear systems

A1.1 Loading System

The system used to load the pin or ball against the disc or plate can be dead weight loading (with or without a lever arm), can use spring actuation with a load beam, or can be pneumatic or hydraulic.

- With dead-weight loading, any frictional forces in bearings in the loading system must be negligible in comparison with the loads used in testing. This must be checked at regular

intervals or when the loading system is altered. The masses which are used to apply the load must be calibrated and traceable to the National Standard of mass.

- With beam and spring the stiffness of the system will be constant over the entire load range and therefore reduce the effects of load dynamics encountered with dead weights. The main drawback is that in the absence of automated compensation the load recedes if there is significant wear in the contact.
- For pneumatic or hydraulic loading, the applied load must be calibrated and traceable to the National Standard of force. The loading system must be designed so that the applied load does not drift by more than 1% during the test, and so that variation in loading is not produced by movement of the specimens (e.g. by stiction for pneumatic cylinders).

A1.2 Specimen mounting and alignment

The specimens should be mechanically clamped in position.

The discs or plates should be aligned so that any variation in the surface height along the projected wear track does not exceed 10 μm . This is to ensure that there is no variation in the applied loading arising from the inertia of the components.

In the case of pin/ball on disc tests, various orientations have been used, with the disc surface horizontal or vertical, and the pin/ball above or below the disc. However, the most usual arrangement is to have the disc surface horizontal, with the pin/ball pressed against the top surface of the disc.

A1.3 Specimen test environment

The specimen holders should be designed to give the shortest possible thermal path to a sink of heat, such as the bulk of the test system, so that the thermal environment will be constant from test to test, and also so that the required contact temperature is achieved. In some cases forced cooling (cooled water or gas) may be required.

The temperature of the test does not normally have major effect on test results. Tests can be carried out under ambient conditions within the range of 15-25 °C. However the test temperature should be recorded.

The humidity of the air surrounding all tests should be controlled to $50 \pm 5\%$ RH unless some other humidity has been specified.

A1.4 Driving system

For pin/ball on rotating disc tests the motor drive must give a constant speed of rotation, and must have sufficient power to continue at a constant speed (to $\pm 1\%$) under the frictional loading that will be experienced in tests.

For reciprocating pin/ball on plate tests the drive system must give a well controlled stroke profile, and must have sufficient power to maintain this profile under the frictional loading that will be experienced in tests. The stroke profile should be checked at periodic intervals. Two stroke profiles that are commonly used are a sinusoidal variation in displacement and speed (normally achieved through crank and similar drives), and a square wave motion (normally achieved through a linear drive system). Either the plate or the ball or pin, can be driven; commercial test systems are available for either. However, it should be noted that due to the increased mass of the plate sample and its holder, the maximum frequency that can be obtained with a system which moves the plate is considerably smaller than when the ball or pin is moved.

A1.5 Machine dynamics

The test machine should be designed so that the natural frequencies of the testing system are much higher than any vibrations generated from sources such as the motor drive, disc rotation or plate reciprocation.

The specimen support must also be very rigid, particularly in the direction in which it is rubbed, in order to avoid stick-slip vibration occurring.

A2. Test Specimens

A2.1 Materials

The usefulness of the wear testing is increased if the materials under test are well characterised; conversely, if there is little materials information the wear test can never be compared with the results of other tests. A minimum description of the material would include the chemical composition, the condition of the material (e.g. the heat treatment for materials such as steel), the hardness of the material and a micrograph of the surface. Other information which would certainly be useful could be obtained from surface analysis, X-ray diffraction, examination of the microstructure of the material and surface texture analysis. If the materials conform to any national or international specifications or standards, this should be stated.

A2.2 Dimensions and surface condition

The contact dimensions of pins/balls are usually much smaller than the contact area of their mating disc or plate, so that thermal and contact duration conditions are different for the two components in contact.

An important parameter, therefore, is the overlap ratio which is defined as the ratio of the area on the disc or plate which is in contact with the pin at some stage, to the area on the pin which is in contact with the disc or plate all the time. Specimen sizes which have been used in recent interlaboratory exercises are discs 42 mm in diameter or plates 30 mm x 20 mm both used with balls 10 mm in diameter. Pins 6 mm and 10 mm in diameter are also commonly used specimens. It is recommended that if pins are used, the end of the pin in contact with the disc should be prepared to a radiused end to give non-conformal contact conditions. This will avoid alignment problems. Typically a spherical radius of 5 mm is used.

The discs or plates should be manufactured with flat and parallel faces. The finish on the specimens will be dictated by the programme of testing, but it is clear that the surface finish has a large effect on the friction and wear results that are obtained, with very rough surfaces leading to high wear, at least in the initial stages of a test. Conversely, for very high quality finishes which are very flat and smooth, wringing may occur leading to abnormally high friction and possible wear. Care must be taken in the preparation of the surfaces of the specimens to avoid sub-surface damage.

For tests on the wear resistance of thin hard coatings, the coating is put on the disc or plate and tested in contact with an alumina ball 10 mm in diameter. Polycrystalline alumina balls (better than 99% alumina) are a preferred material for these tests on thin hard coatings as it has been found in preparatory work that they are essentially inert in conditions of wear against TiN coatings. For other coatings, other ball materials may be preferable. The coated surface should be flat with a surface finish better than $0.05 \mu\text{m } R_a$, to avoid difficulties in the measurement of wear volume. The balls should have a polished finish (better than $0.025 \mu\text{m } R_a$).

A3. Measurement methods

A3.1 Friction measurement

Friction measurements are made with a load cell, or instrumented deflection beam; these must be calibrated at regular intervals. The coefficient of friction is then calculated as the ratio of this measured frictional load to the applied normal load. If a normal load cell is also monitoring the instantaneous normal load, analogue or digital dividing may be used to derive a true instantaneous coefficient of friction. Otherwise the average normal applied load should be used in the calculation of coefficient of friction.

Consideration should also be given to the mechanical attachment of the friction load cell to both the specimen holder and the machine frame. A common practice is to allow the specimen holder to rest against the measurement point on the friction load cell. Care should be taken to eliminate friction between the specimen holder and the friction load cell; this may alter the nominal load applied between the test surfaces. It should be recognised that this

arrangement gives different dynamic characteristics from the situation where the specimen holder is clamped to the machine frame through the friction load cell.

A3.2 Wear measurement by specimen displacement

Wear measurement by specimen displacement is normally carried out by a transducer which is positioned to record the movement of the pin or ball relative to the starting level of the disc or plate. The output of the transducer is then taken to be equivalent to the wear displacement. This assumes that the unworn level of the disc or plate does not change with time. There is a dependence on the position of the measurement point on the specimen holder. Instantaneous readings may require correction for thermal expansion. This method gives a value of wear which is a total of the wear for both the pin / ball and the counterface sample. If a measure of wear for either sample alone is required, one of the other methods should be used.

A3.3 Wear measurement by mass change

The mass change of the specimen is measured as the difference in mass of the specimen recorded before and after the test. The specimens should be cleaned to remove any foreign bodies or loose adherent layers from the specimens before weighing in a controlled way. Any debris collected should be retained for further analysis. The calibration of the balance must be checked at regular (e.g. Annual) intervals. It is essential that specimens are handled as little as possible before weighing, and that clean lint-free gloves or clean tweezers are used to minimise contamination of the specimens.

For mass loss measurements, the wear volume is calculated from the relationship

$$\text{Wear volume} = \frac{M}{\rho}$$

where M is the mass loss and ρ is the density. Note however, that for the coated samples the volume loss can only be calculated using this formula if the wear is contained entirely within the coating and the coating density is known.

Mass loss measurements can normally be made only at the end of the test. An alternative procedure which has sometimes been used is to interrupt the test at periodic intervals, measuring the sample mass, and then relocating the test sample and continuing the test. However, this procedure is inadvisable as it is extremely difficult to relocate samples accurately enough to preserve sample alignment. Moreover, changes in the sample condition (such as contact temperature) which result from the interruption in the test are also extremely likely to cause changes in the results that are obtained.

A3.4 Wear measurement by profilometry

Surface texture instruments should be used to characterise the texture of the surfaces before and after testing; they can also be used to make measurements of wear volumes (or measurements that can be used to calculate wear volumes).

For small areas of wear such as the wear scars on balls, 3D instruments can provide a highly accurate direct measurement. This will require the use of routines to perform a fit of a spherical surface to the remaining unworn surface of the ball. If only 2D instruments are available, the volume has to be estimated from the profile trace generated across the scar. Similarly, for wear tracks on the flat, the wear volume has to be estimated from the cross-sectional area of the wear scar at points along the track.

It is recommended that for wear scars on balls at least two perpendicular profiles are used for this estimation (one perpendicular and one parallel to the direction of sliding across diameters of scar).

If the wear scar on a ball (or spherically capped pin) is flat, then the wear volume V for the ball can be calculated from the formula.

$$V = \frac{1}{3} \pi h^2 (3r - h)$$

where h is the radial wear at the centre of the scar and r is the radius of the ball or from the approximate formula

$$V = \frac{\pi d^4}{64r}$$

where d is the wear scar diameter.

Measurement of wear to a disc should be carried out by making at least four perpendicular measurements of the profile across the wear track (spaced equally around the disc and aligned parallel and perpendicular to any lay in the texture of the disc, along radii of the disc).

Measurement of wear to a plate, from a reciprocating test, should be carried out by making at least six perpendicular measurements of the profile across the wear track (spaced equally along the wear track on the plate such that the measurements near to the end of the stroke are 0.1 x the length of the stroke from the ends of the wear track).

A3.5 Optical wear scar measurement

For balls or spherical ended pins the size of the wear scar can also be measured by optical methods using projection systems or microscopes. It is important that error in the measurement is not introduced by misalignment of the measurement systems. The particular measurement technique that is used must be calibrated at regular intervals.

A3.6 Data Acquisition

The friction and continuous wear displacement measurements should be recorded digitally, with details of the sampling rate and any data processing noted. There are several different acceptable strategies for recording data.

In many cases recording the mean or continuous rms signal is all that is needed. If this route is followed, it is recommended that a sample rate which will give sufficient detail of any transients in behaviour which may be of interest should be used. Another consideration is the overall size of data file. Many analysis programs have limitations on the amount of data that can be handled, and in any case data files that are too large are always difficult and cumbersome to use.

Another strategy that can be very effective is to capture complete cycles of data, and then use computer based analysis routines to reduce the data for storage. The advantage of this approach is that as well as mean parameters for friction and wear displacement, statistical measures such as the spread in friction or wear displacement over single cycles can also be calculated and stored. If this method is used, it is recommended that at least 100 samples per cycle are acquired so that good measurement accuracy can be achieved.

If there is an interest in high speed variations in data then snap-shots can be acquired at much higher sampling rates as required.

A3.7 Computer Control

Many modern test systems now have full computer control. If this is available, it is far easier to run stepped and ramped parametric tests and to shut off the machine when a signal exceeds a pre-determined value (thus better preserving the worn or failed surfaces). PC control also improves repeatability from test to test, as it enables predefined test sequences to be defined and stored which can be recalled and reused by the same or different operators.

A3.8 Other Measurements: Contact Resistance.

Other measurements can be made during a test to address particular needs.

An example is the measurement of contact resistance. The contact resistance gives a qualitative indication of the degree of asperity interaction, since such events produce a great reduction in the electrical resistance of the contact.

In lubricated contacts, the contact resistance is a qualitative measure of film thickness. It offers a way of assessing the reduction of metallic contact caused either by chemical additive films or by the formation of hydrodynamic or end films, and is a very useful measure of the presence (or not) of protective films.

4. Testing

A4.1 Specimen cleaning

Normally, the specimens should be ultrasonically cleaned with acetone or ethyl alcohol for 15 minutes, warm air drying, a final rinse with fresh acetone or alcohol, followed by drying for 30 minutes in an oven at 110 °C.

After cleaning they should be stored for 24 hours in the same environment that will be used for the testing to allow the sample surface condition to equilibrate with the environment.

Some materials, such as polymers, may be affected by the use of organic solvents. If this is true, then the appropriate method should be used which will leave the sample surface in a clean condition.

A4.2 Specimen installation

The specimens should be clamped firmly into position in the test machine, ensuring that the contacting surfaces of the specimens are not touched. On a rotating disc test the radial position of the pin should be adjusted to give the correct wear track diameter. The vertical run-out of the disc or plate surfaces should be checked at less than 10 µm.

Then, with the specimens out of contact, the motor control should be adjusted to give the correct speed. Then, with the machine stationary the zero of the friction measurement system should then be checked by adjusting the pin/ball holder so that no loading of the friction load cell occurs. The loading system should be adjusted to give the required applied load.

A4.3 Running in test system

The environmental conditioning system should be started, set at the required condition of 50% RH, and sufficient time allowed to equilibrate before the test commences. It is recommended that the pin/ball should be lifted clear of the disc or plate and the motor of the test machine started so that the motion does not create a difference in the environmental conditioning, during the actual test.

A4.4 Start of the test

The data recording equipment should be set appropriately and started. When the speed is constant, the pin/ball should be lowered carefully on to the disc or plate to start the test. The rate of application of the load i.e. time from zero to full load should be controlled carefully and recorded so that it can be repeated in future tests. Periodic inspection of the test is recommended to ensure that the recording equipment is performing correctly and that the test is proceeding as expected.

A4.5 Test procedures

Because friction and wear are processes where some variation in results from test to test is a natural consequence of the statistical nature of the contact between the two surfaces, it is recommended that sufficient tests should be carried out under a single set of test conditions to reach the required confidence in the measurements. The number of tests that are needed will depend on the scatter in results that is observed. This recommendation may be relaxed when carrying out friction and wear mapping, for example. The scatter from the observed trend of results then gives information about the uncertainty in the measurements.

It is recommended that the appropriate standardised analysis methods laid down in the ISO standard on accuracy (trueness and precision) of measurement methods and results should be used in the calculation of uncertainty in friction and wear measurements.

In the case of tests on the wear resistance of thin hard coatings, it is recommended that three repeat tests should be carried out under conditions where perforation of the coating does not occur. Satisfaction of this condition should be checked by initial scoping tests. These scoping tests should be carried out by varying load, test duration and rotational speed, or reciprocating frequency and stroke. The main tests should be carried out with at least three test durations, giving a total of at least nine tests for each coating system.

Test conditions which have been found to be satisfactory for 5 µm TiN coatings are:

For rotating disc tests		For reciprocating plate tests	
Load	10 N	Load	10 N
Speed	0.1 ms ⁻¹		
Wear track diameter	32 mm	Stroke	5 mm
Test duration (one test for each)	5000, 7500 and 10000 seconds	Frequency	2 Hz
		Test duration (three tests for each)	2500, 5000 and 7500 seconds

A4.6 Test termination

The test should be terminated when the appropriate test duration has been reached.

A4.7 Examination of specimens and debris after test

After testing, the specimens should be examined and the appearance of the worn surfaces and any debris adhering to the surface noted. The specimens should be cleaned, and profilometry and measurement of wear scars carried out to determine the volume of wear that has occurred. The specimens should be stored in dry clean conditions.

A4.8 Analysis of results

The detail of the analysis that will be required will depend on the precise requirements of the testing programme. However, a minimum necessary requirement is the plotting of wear and friction curves for the test; the calculation of initial, maximum and steady-state coefficient of friction; and the calculation of wear volumes for the pin and disc from mass loss measurements or from profilometry measurements.

In the case of tests on thin hard coatings it is recommended that the total energy dissipated during each test should be calculated as

$$TE = \sum v \Delta t_1 W \quad \text{for all friction coefficient data-points } f_1$$

where v is the relative speed, Δt_1 is the elapsed test time, and W is the applied load.

If the total volume of wear is then plotted against the total energy TE , a linear relationship should be observed. The slope and intercept of the linear fit to the data points should be calculated by regression analysis.

A5 Reporting the Results

The following results should be reported and recorded:

1. A description of the test system emphasising the loading system employed, and the friction measurement system.
2. Details of the specimens including composition, geometry and surface finish. For a coated sample this should include details for both the substrate and the coating.
3. Details of cleaning procedures and any pre-conditioning that has been carried out.
4. A table of test results including rubbing distance and speed, test duration, profilometric results, mass loss results, total wear volumes and wear rates. Environmental conditions should also be reported. For thin hard coating tests, this should also include the total energy dissipated.

5. Graphs of the variation of friction and wear displacement with elapsed time. For tests on thin hard coatings a graph should be included of total wear volume with total energy dissipated.
6. Files containing data on the variation of friction and wear displacement with time. The format of the data should be described.
7. Any observations on the appearance of the samples after testing should also be reported.

A6 Definitions

The test procedures have included a number of technical definitions and the meaning of each of these are:

Applied load - load applied between two contacting surfaces normal to tangent of surfaces.

Instantaneous coefficient of friction - the instantaneous value of friction divided by the instantaneous value of applied load. This is often approximated to the instantaneous value of friction divided by the mean applied load.

Cyclic average coefficient of friction for a rotating disc test - the average value of the instantaneous coefficient of friction calculated for a single cycle of rotation of the disc.

Cyclic average coefficient of friction for a reciprocating test - the average value of the instantaneous coefficient of friction calculated for a single cycle. Two possible ways of calculating this are (see Figure A2):

- to integrate the size of the friction-horizontal motion friction loop and divide this integrated value by the magnitude of the stroke to arrive at a value of friction coefficient.
- to average the absolute magnitude of the friction excluding the values of friction towards the end of the stroke where the value is affected by the flat stopping at the ends of the stroke (this avoids inertial problems, and excludes the contribution of static friction from the average value).

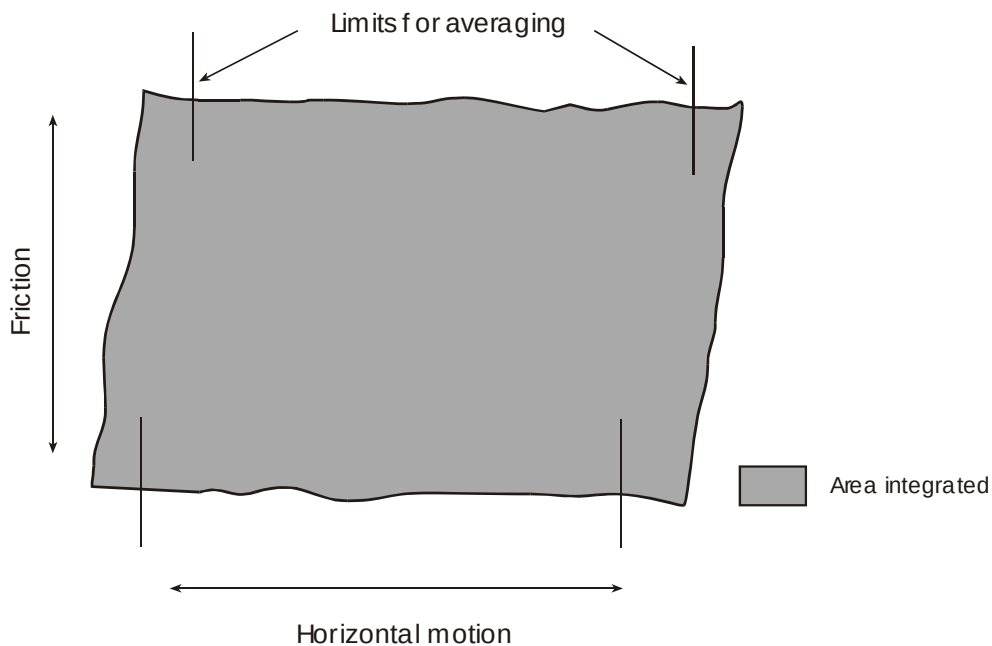


Figure A2 Calculation of friction for reciprocating test

Initial coefficient of friction - the coefficient of friction at the start of the test, during one cycle or rotation.

Maximum coefficient of friction - the maximum coefficient of friction measured during the test. In the absence of transitions in wear behaviour this often occurs shortly after the start of a test. This value is obtained as the mean value over a period in which there are five full cycles of rotation or reciprocation.

Steady state coefficient of friction - the average value (or range of values) of the coefficient of friction over a long period of time in which the coefficient of friction is essentially constant. Such behaviour occurs after the initial transient changes in coefficient of friction have taken place.

NOTE: In some tests steady state behaviour does not occur, with coefficient of friction continuing to vary over the duration of the test.

Dimensional wear coefficient, k , - defined by the equation

$$k = \frac{V}{LW}$$

where V = volume worn away
 L = total sliding distance

W = applied load

Wear volume - is the loss of volume to the specimen after a test.

A7 References

- A1 Czichos, H. Becker, S, and Lexow, J., Multi laboratory tribotesting: results from the Versailles Advanced Materials and Standards Programme on wear test methods, *Wear*, 114(1987)109-130
- A2. Czichos, H. Becker, S, and Lexow, J., International multilaboratory sliding wear tests with ceramics and steel, *Wear*, 135(1989)171-191
- A3. Almond, E. A., and Gee, M. G., Results form a U.K. Interlaboratory Project on Dry Sliding Wear, *Wear*, 120(1987)101-116
- A4 Gee, M. G., Results from a U.K. Interlaboratory project on dry sliding wear of alumina, *Wear Testing of Advanced Materials*, ASTM STP 1167, R Divakar and J Blau, Eds., American Society for testing and Materials, Philadelphia, 1992, pp.129-150
- A5 Vettters, H et al, Development and Validation of Test Methods for Thin Hard Coatings (FASTE), Final Report, SMT Contract MAT1-CT 940045

Appendix B

Validation Exercise

The magnitude of variation in results that can be expected in wear tests carried out under well controlled conditions is illustrated by the results of an interlaboratory exercise [A1]. It should be noted that this example is chosen specifically because the material that was chosen is a wear resistant material, so that the magnitude of wear is low and where any scatter is likely to be high relative to the overall results.

The exercise was carried out by eight laboratories on 95% alumina ceramic samples under a load of 40 N and with a sliding speed of 0.1 ms⁻¹ with a sliding distance of 2160 m. Samples were prepared with two surface finishes in the original study, as there was only a small difference in results between the two finishes, only the results obtained for tests on samples with a ground finish are reported here. The pins used in the exercise were 30 mm in length and 6 mm in diameter, with one end ground to give a 5mm spherical radius. The disks were 80 mm in diameter by 9 mm thick. The samples had a surface finish of 0.53 and 0.35 $\mu\text{m Ra}$ for the pin and disk respectively.

Various measures of wear were specified including the diameter of the scar on the end of the pin, the width and depth of the wear track on the disc, the mass loss of the samples, and the profiles of the worn surfaces. Wear displacement (movement of samples together because of wear) was measured by LVDT by many participants. Friction was to be measured either as individual readings or as continuous traces.

The measurements of wear scar diameter are shown in Figure B1. There is clearly some variation in results from one laboratory to another. Friction results are shown in Figure B2. Here the results for three laboratories are a significant level above the level for the other laboratories.

The reason for the variability in results from one laboratory to another is not clear but is likely to be due either to a lack of control by some laboratories of variables specified in the test procedure, or by unpredicted effects due to parameters that have not been controlled up to now.

Overall errors in measurement are given in Table B1. The scar diameter measurements had the lowest (best) value for reproducibility of 0.05, the track width measurements had a similar reproducibility of 0.06, the wear displacement measurements had a higher value of 0.17, with the disk mass loss measurements having the highest (worst) reproducibility at 0.42.

Table B1, Uncertainty in measurements in interlaboratory exercise on alumina. Note uncertainty here is expressed as 95% confidence intervals divided by mean value of result.

Measure	Uncertainty
Wear scar diameter	0.05
Track width	0.06
Wear displacement	0.17
Mass loss	0.42
Friction	0.14

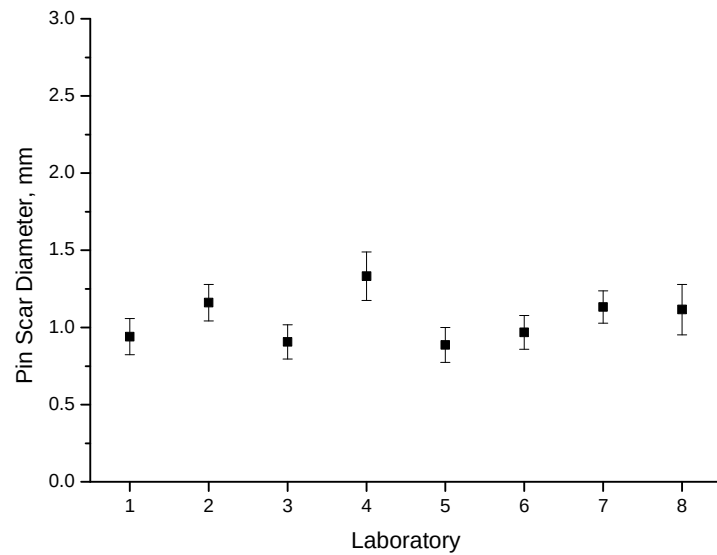


Figure B1, Results of wear scar diameter measurements from interlaboratory exercise on alumina.

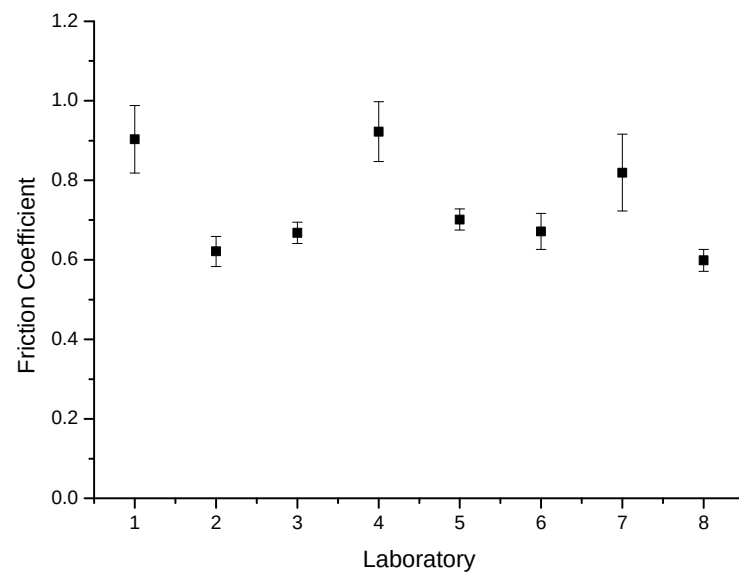


Figure B2, Results of friction measurements

Reference

B1, M G Gee, Results From a UK Interlaboratory Project on Dry Sliding Wear of Alumina, Wear Testing of Advanced Materials, ASTM STP 1167, Ramesh Divakar and Peter J Blau, ASTM, 1992

Appendix C

Guide to Notation

W	Applied load
L	Distance of sliding
A	Nominal area of wearing surface in contact
T	Time
V	Velocity of sliding
H	Depth of wear
μ	Coefficient of friction
k_d	A constant
K	Dimensional wear coefficient
V	Wear volume
M	Mass loss
ρ	Density
D	Diameter of wear scar on ball sample
R	Radius of ball sample