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**Guidelines for unlubricated
sliding wear tests:
Part 1, general approach**

M G Gee

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M G Gee
Division of Materials Metrology
National Physical Laboratory
Teddington
Middlesex
United Kingdom
TW11 0LW

FOREWORD

This document has been prepared by the author on behalf of the UK Forum on Friction And Wear Testing. The Forum has the overall objectives of improving the reproducibility and repeatability of friction and wear testing in the UK by open discussion and participation in national and international pre-standardisation activities. These guidelines build on the results of two international interlaboratory exercises [1,2] under the auspices of Technical Working Area 1 - Wear Test Methods of VAMAS (the Versailles Project on Advanced Materials And Standards), and two national interlaboratory exercises which were organised by NPL [3,4].

This document serves as a general introduction to friction and wear testing in sliding. It contains a discussion on the most effective approach to friction and wear testing, and considers the different aspects that should be considered when designing a programme of friction and wear testing.

Other documents in this series are being prepared which give more specific guidance on how test conditions should be set and the procedures that should be used in friction and wear tests. The first of these documents is also available, and describes unlubricated pin-on-disc testing (part 2) [5].

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National Physical Laboratory
Teddington, Middlesex, United Kingdom, TW11 0LW

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1 INTRODUCTION

Friction and wear result from the interaction of surfaces in contact, and are a function of the operating parameters and the detailed nature of the tribological system. In order to carry out useful laboratory testing, it is necessary to be able both to specify and control the features of the tribological system and operating parameters.

These guidelines have been produced in response to the need, identified by the UK Forum on Friction And Wear Testing, for a document to provide guidance and procedural recommendations to be adopted for testing. There are no general British Standards in this area.

2 SOURCES OF GUIDANCE

The first part of these guidelines is intended to be a simple introduction to friction and wear testing and to the design of a testing strategy. There are a number of books and other documents which are available if more information is required.

A useful introduction is given in *Tribology: a systems approach to the science and technology of friction lubrication and wear* by H Czichos [6].

A good introduction to the subject of tribology is the book *Tribology of engineering materials* by I M Hutchings [7].

General information on tribology is also available in several handbooks such as the *Wear control handbook* by Peterson and Winer [8], *The ASM metals handbook: Vol. 18, friction, lubrication and wear technology* [9], and the *Handbook of tribology: materials, coatings and surface treatments* by Bharat Bhushan and B K Gupta [10]

Compilations of data are available in the *Tribology handbook* by M J Neale [11] and the *Elsevier materials selector* [12].

Specific information of testing is given in papers by Almond and Gee [13], Alliston-Greiner [14], Eyre [15], in ASTM (American Society of Testing and Materials) Special Technical Publications on friction and wear testing of metals [16], plastics [17], coatings [18], elastomers [19], ceramics [20], and advanced materials [21], and an ASTM STP on the fretting fatigue test methods [22]. Other useful papers on wear testing for elastomers are given by Mitsuhashi [23] and Muhr and Roberts [24]

Other more general information on wear testing is given in books such as the *Fundamentals of friction and wear of materials* edited by Rigney [25], *New directions in lubrication, materials, wear and surface interactions* by Loomis [26], *Fundamentals of friction: macroscopic and microscopic processes* edited by Singer and Pollock [27], *Failure atlas for hertz contact machine elements* by Tallian [28], and *An atlas of metal damage* by Lothar and Klingele [29].

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* [30], and the Archival Journals *Wear* [31] and *Tribology international* [32].

3 REQUIREMENTS FOR FRICTION AND WEAR TESTING

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

1. 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.
2. To characterise materials performance, and determine how changes in materials composition or variations in their structure can affect friction and wear. These studies are normally carried out in the laboratory with simple test systems.
3. To develop new components, in bench tests of component assemblies.
4. To test prototypes, where new components (or components made from new materials) are tested in the intended final product in more controlled conditions than the real life application.
5. To determine performance in real life situations through field trials.
6. To determine the cause of failure of machinery in troubleshooting.

The last item, troubleshooting requires a different approach from the previous five 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 over 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 both to define and control 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, particularly to pre-screen candidate materials for a field applications.

Of course the acid test for all laboratory evaluations is: does the test compare well with observed performance in practice. Obviously, the final proof for any material is that it behaves as expected in the real 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 wear 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 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. Generally it is not possible to completely simulate the conditions found in the application. This is because of the difficulty of defining the conditions in applications. Also the test system itself will have some limitations 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.

In some cases conditions in the application may not be well enough known to reproduce closely in laboratory tests. Here screening tests are sometimes carried out under conditions which are thought to be relevant to the application. This is done to rule out samples before more expensive field trials. However, caution is needed with this approach; there have been cases where the best materials in a set of screening tests did not necessarily perform well in the application.

When designing a laboratory test and how well it simulates an application, it is useful to consider the different test parameters with some care. The systems approach defined by Czichos can be helpful [6], as it provides a formal framework for the consideration of the whole test system and reduces the chance of ignoring important test parameters.

The importance of the various parameters will depend to some degree on the application considered, but the most important parameter in any test must be the material structure and composition. Other parameters which have a major impact (and which are listed in descending order of likely importance) are contact geometry, load, speed, test environment and surface finish.

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 predicted easily. Another parameter which cannot be altered easily is the dynamics of the test machine which has been shown to have a substantial effect on results [33].

5 TEST MACHINES

There are hundreds of different test machines [34], but these can be reduced to a small number of basic geometries, characterised by the motion used. These are unidirectional sliding, reciprocating sliding, and combined rolling and sliding. Unidirectional machines include pin-on-disc, block on-ring, ring-on-ring, thrust washer, pin-on-plate and crossed cylinder (Figure 1). Machines of this type have simple test specimen designs. Their principal advantage is the ability to cover wide load and speed ranges, establishing the performance of materials under a wide range of conditions.

In choosing a suitable test system, it is important to consider orientation. For example, in pin-on-disc systems, usually 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.

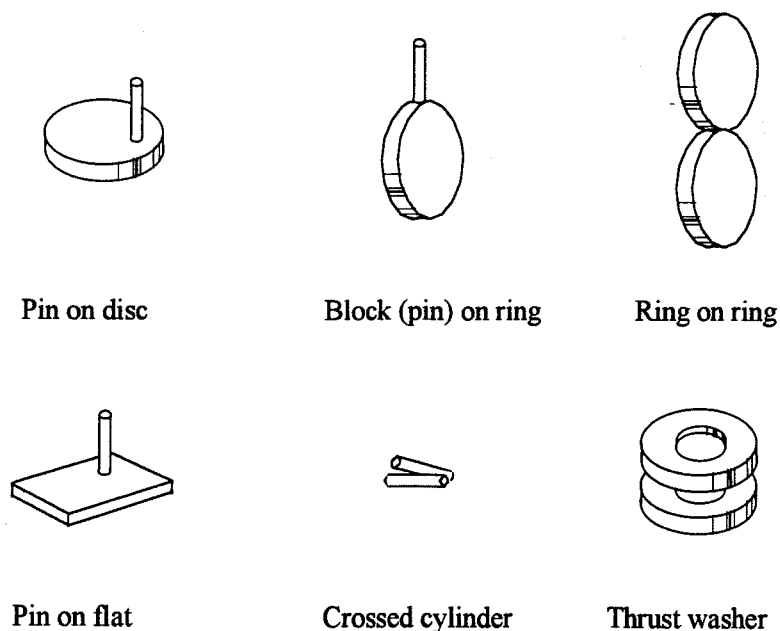


Figure 1, Test geometries for sliding wear

6 CHOICE OF TEST CONDITIONS

The choice of test conditions is determined either by the engineering application or the need 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 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 and test environment, and sample parameters such as materials composition, structure, and surface finish. 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. 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 parametric study.

Mapping techniques can be used where two (or more) factors are changed in a controlled way (but 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. The region boundaries are defined either 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 coefficient of friction [35,36]. 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.

One of the most important factors that needs to be considered in the design of a friction and wear test is the geometry of the contact between the two specimens. Conformal contacts

(e.g. flat-on-flat) seem on the face of it to be easier to simulate. All that is necessary is to use specimens and applied loads which give the nominal contact pressure required.

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 those expected from simple estimates. Even when alignment is perfect, contact mechanics shows [37] 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 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 [37]. However, there may still be unwanted changes in mechanism that occur as the contact pressure drops.

The speed of the test is also a crucial parameter that needs to be considered carefully. The power that is lost in the test is $W = \mu PV$ where μ is the coefficient of friction, P is the applied load and V is the relative speed. These frictional losses are dissipated as heat which must be removed from the interface by conduction into the specimens and cooling by any interfacial medium that is present. However, at only moderate speeds (assuming a relatively high coefficient of friction) very high local (often termed flash temperatures) temperatures are generated at the contacting asperities. Because the properties of many materials, and their reactions, are highly temperature dependent, the relative speed of the test can have a dramatic effect on friction and wear, simply through frictional heating.

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; this 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. The results cannot then be used to predict 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; also there may be unforeseen transitions in wear rate after quite a long test period due to mechanisms which only start after the accumulation of damage in or debris on the surface of the specimens.

7 SURFACE EXAMINATION TECHNIQUES

Surface examination is a crucial element in the determination of the wear mechanisms. A very wide range of techniques is available, which gives information on the appearance, topography and composition of surfaces.

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 acquired in the earlier stages of examination. It can be all too easy to move too quickly to sophisticated analytical systems when they are available without making sufficient use of simpler

techniques. In many cases all that is needed is to examine samples visually or under low powered light microscopes.

Some of the analytical techniques are listed in Table 1 with some details of the lateral and depth resolution, and details of the analysis capabilities.

There are also other techniques such as Raman infra-red spectroscopy and Fourier transform infra-red spectroscopy, but these are not universally applicable as the spectra obtained are very dependent on the materials analysed.

8 CONCLUDING REMARKS

The development of a strategy for wear testing must take into account the complexity of wear and its dependence on the conditions of test. It is also important to consider carefully the purpose for the tests, and the most appropriate choice of test geometry and test conditions for the simulation of the application under consideration.

With the systematic consideration of the different aspects outlined in these Guidelines, it is possible to conduct a meaningful programme of wear tests.

9 ACKNOWLEDGEMENTS

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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	Applicability
LM	0.2 μm	-	-	Imaging
SEI(SEM)	1.5 nm	-	-	Imaging, topography by stereology
CSLM	0.15 μm	0.1 μm	-	Imaging, topography
NCOP	1 mm	3 nm	-	Topography
CP	0.5 mm	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 mm	1-2 μm	10-100 ppm	all Z
EDS(SEM)	1 μm	1 mm	0.1 %	Z>4
WDS(SEM)	1 μm	1 mm	100 ppm	Z>2
BEI(SEM)	50 nm	50 nm	0.1 in 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
MPM	<1 μm	<1 μm	-	Mechanical properties

LM is light 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

NCOP is non-contact optical profilometer

CP is contact profilometer
CSM is confocal scanning microscope.

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