

REPORT

WEAR TESTING METHODS AND THEIR RELEVANCE TO INDUSTRIAL WEAR PROBLEMS

M G Gee and S Owen-Jones

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ABSTRACT

This report gives a summary of the results of two industrial surveys. The first was a survey of industrial wear needs that also obtained information on the economic importance of wear problems to the individual firms that were contacted. This survey found that the most important wear problems were caused by abrasion of different types. The second survey was concerned with the test methods that are currently available and used by industry. This survey was supplemented with an analysis of literature and a compilation of the standards for wear testing. This analysis showed that there was a mismatch between the test methods that were used and the industrial need, with the most common test method reported in the literature being pin-on-disc wear testing.

The information from the surveys and the analysis was used to draw up a list of test methods which was felt to satisfy the industrial need. These test methods are briefly described.

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1 EXECUTIVE SUMMARY

This review describes work carried out under two projects on wear testing funded by the DTI under the materials measurement programme. These are project CAM 8, *The production of a guide to wear testing for industry*; and project CAM 9, *Performance related wear testing of ceramics and hardmetals*.

1.1 Requirement for wear testing

The first part of the review discusses the different types of wear that occur in industry, and the justification for laboratory wear testing. Laboratory wear testing offers the potential benefits of better control of testing and lower cost. However, for laboratory testing to have any relevance, it is important that the results from laboratory tests should compare well with results obtained in the field. Confidence in laboratory tests can be achieved if care is taken to make sure that the conditions that are used in the laboratory simulate the real life conditions, and that the wear mechanisms observed in laboratory tests are the same as those observed in practice.

1.2 Wear Surveys and Test Method Review

Several industrial surveys were carried out. The first of these was a survey on industrial wear problems that was carried out by Neale Consulting Engineers in collaboration with NPL. A parallel survey was carried out by NPL on the use and satisfaction of industry with wear testing methods. The surveys covered a wide range of industrial sectors including materials processing, aerospace, packaging, automobile components, and materials producers.

The main result of the industrial survey of wear problems was that the most significant cause of wear was through abrasion. The survey also found that there was the potential for significant economic benefits to UK industry through the use of wear testing. The survey on the use of wear testing methods showed that wear testing is used quite widely throughout industry, but that the degree of satisfaction with current testing was very mixed, with some firms expressing satisfaction with their testing strategy, and others showing strong dissatisfaction.

To obtain further information on the wear test methods that could be used by industry, an analysis was performed of the wear test methods that are currently available. Several different sources of information were used in this analysis. These were:

- VAMAS Compilation of Wear Testing Standards.
AN ANALYSIS OF THE LITERATURE HELD BY NPL AND RECENTLY SURVEYED.
- A search of the Standards databases.
- An analysis of the 10th Wear of Materials Conference held in April 1995.

This analysis showed that there was a mismatch between the test method reported to have been used most frequently (pin-on disc test for sliding wear), and the industrial need for abrasion testing. It was also noticeable that few reports of wear testing in the literature noted the eventual application area for the testing.

1.3 Test Methods

The review finishes by listing and describing the test methods that are most likely to be a reasonable match to the industrial need established by the survey of industrial wear problems. The tests are:

- Fluid jet erosion testing
- Gas blast erosion test
- Three body abrasion testing
- ASTM B611, wet slurry steel wheel
- ASTM G65, dry sand rubber wheel
- ASTM G105, wet sand rubber wheel
- Ball cratering
- Scratch testing
- Pin-on-disc sliding wear
- Reciprocating sliding wear
- Fretting wear
- Thrust washer sliding wear

Most of these tests (excluding erosion and fretting testing) are the subject of further work with projects CAM 8 and CAM 9 to improve the testing procedures and to demonstrate their relevance to industrial concerns.

2 TYPES OF WEAR

There are many different types of wear that occur in practice, and there has been considerable discussion about the classification of these different types of wear. A simple classification has been used here which is based on the mechanism that is operating to produce the wear damage. (Table 1). The simplified descriptions in this table have been taken from the classification of in the Elsevier Materials Optimiser [1] to which the reader is referred for a more complete description of basic wear mechanisms.

Table 1, Simple classification of types of wear.

Type of Wear	Description
Abrasion	Removal of material by the mechanical action of an abrasive. Abrasives are substances which are usually harder than the abraded surface and have an angular profile
Particle Impact Erosion	Erosion is the wear of a surface due to the flow across it of a suspension of small solid particles in a fluid, or a suspension of liquid particles in a gas. The contact pressure between the particles and the surface results from their kinetic energy as they encounter the surface
Cavitation Erosion	Hydrodynamic cavitation is the formation of bubbles or cavities in an otherwise inhomogeneous fluid flow when the local pressure falls to the vapour pressure of the liquid at the ambient temperature. The cavities become unstable when carried by the flow into regions of higher pressure and consequently collapse. Continual bombardment of a surface by imploding cavities can lead to cavitation erosion of the surface.
Adhesive	When one surface slides over the other interaction between the high spots produces occasional particles of wear debris
Scuffing	Scuffing occurs particularly when a high degree of sliding occurs under poor lubrication conditions, and is particularly likely to start from local high spots due to poor surface finish. Scuffing occurs by the local welding of two heavily loaded surfaces followed by the tearing away of the welded material. This gives very high rates of material removal.
Fretting	Fretting occurs where two contacting surfaces, often nominally at rest, undergo minute oscillatory tangential relative motion. Small particles of metal are removed from the surface and then oxidised.
Mechanical Surface Fatigue	Surfaces can wear by fatigue when they are subject to fluctuating loads. High surface stresses cause cracks to spread into the material, and when two or more of these cracks become joined together large loose particles are formed.
Thermal Surface Fatigue	Occurs when high repetitive stresses are generated through the heating caused by the contact of the two contacting components which result in cracking of the surface and the loss of small chunks of material.
Diffusion Wear	Occurs particularly in cutting tools when the constituent elements of the tool diffuse into the workpiece at the high temperature caused by the cutting operation

3 REQUIREMENT FOR WEAR TESTING

There are several different reasons for performing wear tests [2]. These are:

1. To obtain fundamental information on the mechanisms that occur in the wear of materials. These studies are normally carried out in the laboratory with simple test systems.
2. To characterise materials performance and determine how variations in materials structure can affect wear and friction. These studies are normally carried out in the laboratory with simple test systems.
3. To compare the wear performance of materials using simple laboratory tests, aimed at simulating in-service conditions, as a guide to material selection for actual machine components.
4. To perform component trials, where assemblies of components are tested on the bench in new component development.
5. To perform prototype testing, where new components (or components from new materials) are tested in the intended final application in better controlled conditions than the real life application.
6. Field trials to determine performance in real life situations.
7. Troubleshooting to determine the cause of failure of machinery.

Troubleshooting is different from the rest of the list since it is concerned with the identification of the failure mechanism and then developing ways of alleviating the problems. A large element of this work is 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 its primary objective is to reproduce the failure mechanism so that corrective measures can be designed and tested in an informed way.

The other types of wear testing fall into a spectrum where the degree of control of the test decreases as it moves from fundamental studies through to field trials. This is described pictorially in Figure 1 which is taken from the German DIN standard that discusses wear testing [3]. As the real application is approached it becomes increasingly difficult to define the complex set of intermeshing factors which combine to determine the performance of the unit over a range of loads, speeds, temperatures, pressures and environments. In most cases, there is also an obvious cost benefit from running simple laboratory tests, particularly in applications where field trials would involve interruptions production. However, there are some exceptions to this where components or assemblies are cheap and readily interchangeable, so that it becomes cost effective to perform a carefully planned series of field trials.

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. Confidence in laboratory tests can be achieved if care is taken to make sure that the conditions that are used in the laboratory test simulate the real life conditions as closely as possible or target important parameters. Because of the difficulty of defining the conditions in applications, and because of limitations in the test system that is

being used to simulate the application, the match is unlikely to be perfect. It is then important to check that the wear mechanisms that are observed in the laboratory tests are the same as those observed in practice.

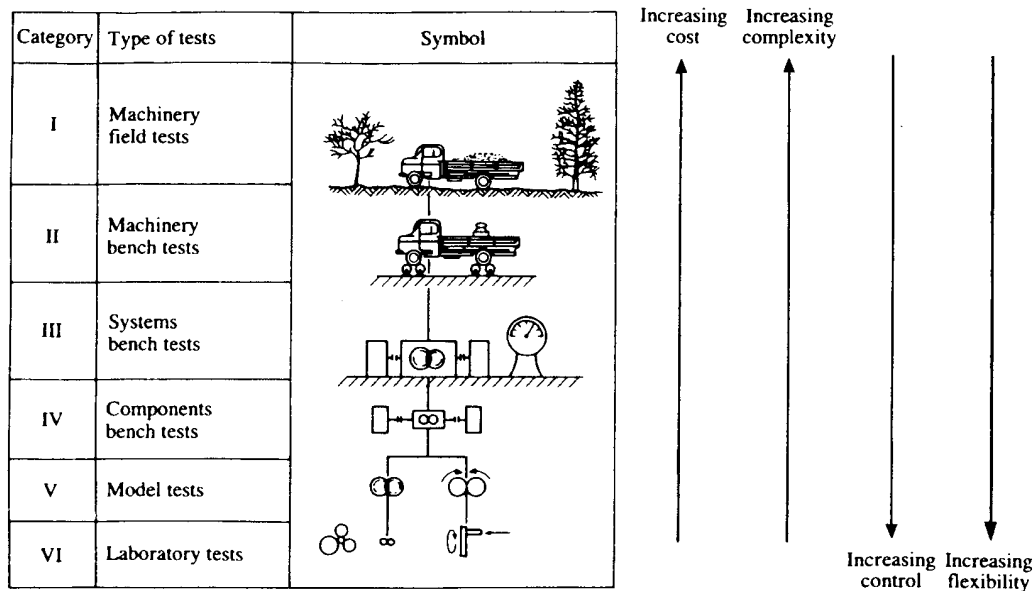


Figure 1, Schematic diagram describing different types of wear testing [1,2]

4 SUMMARY OF INDUSTRIAL SURVEYS AND TEST METHOD REVIEW

Several industrial surveys were carried out. The first of these was a survey on industrial wear problems that was carried out by Neale Consulting Engineers in collaboration with NPL. A parallel survey was carried out by NPL on the use and satisfaction of industry with wear testing methods.

To obtain further information on the wear test methods that could be used by industry, an analysis was performed of the wear test methods that are currently available. Several different sources of information were used in this analysis. These were:

- VAMAS Compilation of Wear Testing Standards [4].
- An analysis of the literature held by NPL and recently surveyed [5].
- A search of the Standards databases [6].
- An analysis of the 10th Wear of Materials Conference held in April 1995 [7].

The results of the analysis of this information are available as three reports (referenced above), and the literature database and the standards database are also available as a Microsoft Access Database.

It should be noted that the literature analysis was largely based on the literature accumulated at NPL. As previous work at NPL has largely been directed towards wear testing of ceramics and hardmetals there is a bias in the analysis towards the wear testing of these materials, but it is expected that the analysis of test methods will be reasonably valid for all materials.

4.1 Industrial Wear Problems

To determine the most significant wear problems in the UK, an extensive industrial survey and analysis was carried out by Neale Consulting Engineers Ltd. They circulated a short questionnaire to about 1800 companies to determine the kind of wear problems that were being experienced, together with the costs. About 100 companies responded with details of about 200 wear problems. These were analysed to determine the basic wear mechanism involved, together with its importance assessed in terms of the cost of the problem as a proportion of the company's turnover. By combining the results together it was then possible to determine the relative priorities for UK industry for the development of reliable tests to simulate the various wear mechanisms.

The results of this analysis are given in Table 2 which shows that the cost of wear to UK industry is about 0.25% of turnover and abrasive wear is by far the most significant problem followed by adhesive wear and fretting.

Table 2, Significance of wear mechanisms to individual companies

Wear Mechanism	Cost of wear as a % of turnover	Percentage contribution
Abrasive wear*	0.1505	63 %
Adhesive wear	0.0455	19 %
Fretting	0.0175	7 %
Thermal fatigue	0.0111	5 %
Fatigue	0.0108	5 %
Fluid erosion	0.0039	2 %
Cavitation erosion	0.0003	<1 %
Electrical erosion	0.0001	<1 %
Total	0.2397	=100 %

* Note that abrasive wear includes erosion for the purposes of this analysis

From the analysis of the responses to the postal survey, 22 representative companies were chosen for follow up visits. These companies were from a wide range of industrial sectors. The visits enabled the causes and nature of their wear problems to be assessed in more detail.

It should be noted that the information given by the companies in both the postal survey and the industrial visits was confidential and thus cannot be reported in this review. It nevertheless enabled a clear picture of the most economically significant wear situations to be obtained. The six most significant wear situations are listed in Table 3 and in terms of economic significance they broadly follow the order given in this table.

Table 3, Significant industrial wear problems

Type	Industrial Wear Problems	Significant Characteristic	Examples
1	The wear of surfaces by hard particles in a stream of fluid	Erosion with one supply of erodant being continuously renewed in a gas or fluid	Valves controlling flow of crude oil laden with sand Gas pumping equipment
2	The wear of surfaces by hard particles in a compliant bed of material	Abrasion, with supply of abrasive continuously renewed by movement of bed of material	Digger teeth. Rotors of powder mixes. Extrusion dies for bricks and tiles
3	Wear of metal surfaces in mutual rubbing contact, with abrasive particles present	Three body abrasion (solid-abrasive-solid) with an on-going supply of new abrasive particles	Pivot pins in construction machinery. Scraper blades in plaster mixing machines. Shaft seals for fluids containing abrasives
4	The wear of metal components in rubbing contact with a sequence of other solid components	Adhesive wear and abrasion, but with one component in the wear process being continuously renewed	Tools used in manufacture, such as punching and pressing tools, sintering dies and cutter blades
5	The wear of pairs of metal components in mutual and repeated rubbing contact	Adhesive wear, but with a wear rate that can be very variable depending on the detailed operating conditions	Piston rings and cylinder liners. Coupling teeth and splines. Fretting between machine components
6	Component wear from rubbing contact between metals and non-metals	Adhesive wear between two consistent components	Brakes and clutches. Dry rubbing bearings. Artificial hip joints

4.2 Survey of Test Methods Used by Industry

The survey of wear test methods used by industry was carried out by NPL and is fully described in Annex 2. The questionnaire was sent to 600 firms in a wide spread of industrial sectors, and there were 50 responses.

The results showed that wear testing was used in a wide variety of industrial concerns, and it was encouraging that abrasive test methods such as the ASTM G65 test method were being used in industry. This reflects how industry is meeting the industrial need for abrasive wear testing to help to solve the problems revealed by the industrial wear survey. Nevertheless,

there was still a noticeable majority of firms that used pin-on-disc and reciprocating sliding wear test systems. (Table in section 12, Annex 2).

The degree of satisfaction in currently available tests varied from one extreme to another. Thus although many firms stated that they were happy with the test methods that they used, many more firms were dissatisfied with their current procedures. A common theme that emerges is the need for additional information on the applicability of different test methods to specific industrial wear problems.

4.3 Wear Testing Standards

The compilation of wear testing standards [6] lists 424 wear testing procedures. This list of standards covers both those for the specification of products, and also more general test methods. The standards originate from many countries around the world. However, the strong output of the ASTM G 2 committee on wear testing is evident in the number of standards that have been issued by ASTM. There is also a strong representation from the German wear testing community through DIN standards.

There is likely to be considerable duplication within this list of standards, with the same test method listed several times within standards originating from different countries and for the specification of different products.

Where possible, the test methods listed in the standards have been analysed to obtain information on the different types of test method. The results are given in Table 4 and Figure 2.

Table 4, Number of Different Test Methods Reported in Standards Database*

Test Method	Label in Graph 1	Number Reported
Specific component test	1	53
Terms and definitions, guidelines	2	19
Abrasive wheel	3	14
Dry or wet sand / rubber wheel	4	14
Rotating drum	5	14
Four-ball test	6	12
Jet erosion	7	12
Pin-on-disc	8	11
Abrasive paper	9	8
Rubbing	10	7
Falling abrasive	11	6
Sliding block test	12	6
Slurry erosion test	13	6
Vibrating Tray	14	6
Reciprocating	15	5
Block-on-ring	16	4
Flat-on-flat	17	4

*Note that categories where less than four reports are given are not listed in this table.

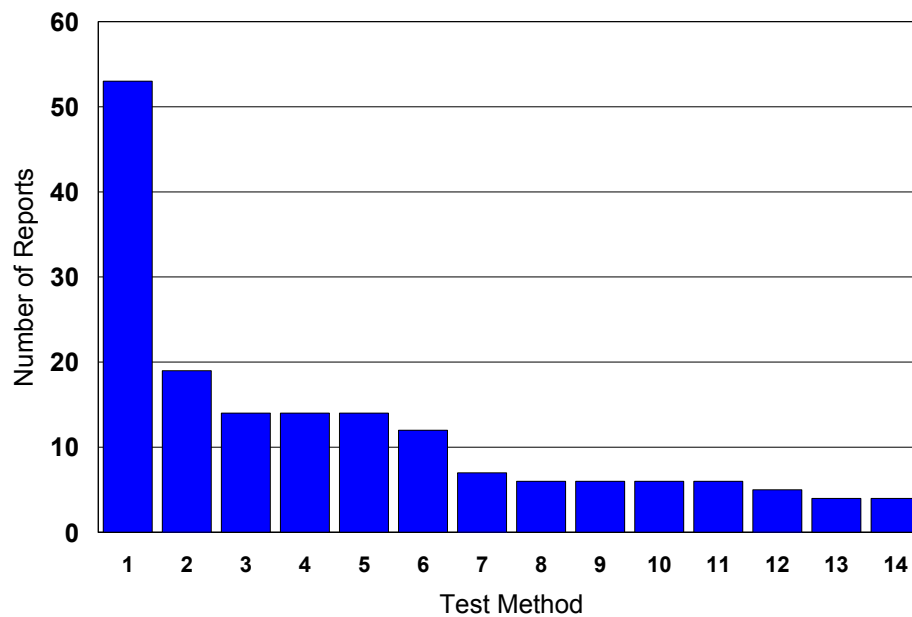


Figure 2, Number of reports of different test methods in standards database. For test method number see Table 4.

It can be seen that the commonest category listed is specific component tests where particular components are tested in specially designed test systems or in the normal application environment. The next largest category is not for test methods as such, but is for documents describing terms and definitions. The next largest category of standards is a number of different types of abrasive test methods. There is also a number of sliding wear tests listed.

The large number of mentions for abrasive wear testing standards shows an encouraging agreement with the industrial need identified by the survey of industrial wear problems. However, the sheer number of standards that are listed, with the duplication that is inherent, gives considerable scope for rationalisation.

4.4 Literature Review

The review of literature [5] concerning wear testing examined 286 papers and other documents. It was quite noticeable when the papers were being read that only a small fraction of them mentioned any applications that were relevant to the wear testing described in the paper. When the frequency with which different test methods were listed in the literature was analysed, sliding wear tests such as pin-on-disc and reciprocating tests were by far the most frequently quoted tests (Table 5 and Figure 3). Many abrasion test methods were also listed, but there is clearly a mismatch between the type of test methods reported in the literature by research workers and the industrial need identified in the survey of industrial wear problems.

Table 5, Number of Different Test Methods Reported in Literature*

Test Method	Graph Label	Number Reported
Pin-on-disc	1	65
Reciprocating	2	43
Scratch test	3	25
Block-on-ring	4	19
Erosion	5	17
Specific component test	6	11
Thrust washer	7	10
Solid particle erosion	8	8
Rolling contact test	9	6
Ball cratering	10	5
Four-ball test	11	5
Abrasive wheel	12	4
Dry or wet sand / rubber wheel	13	4
Fretting test	14	4

*Note that categories where less than four reports are given are not listed in this table.

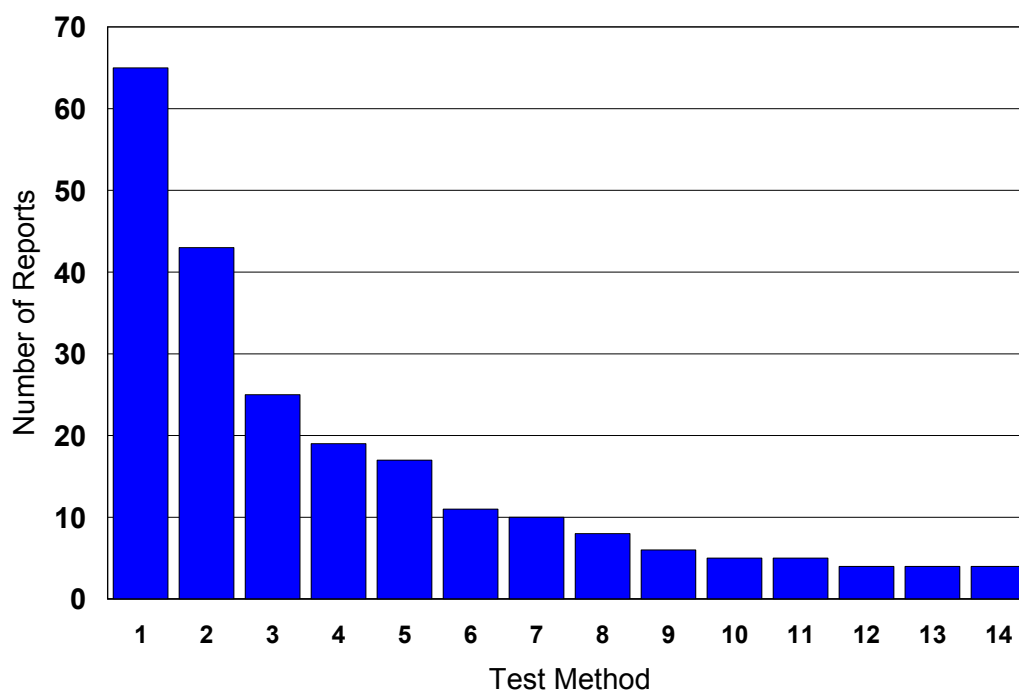


Figure 3, Number of reports of different test methods in literature database. For test method number see Table 5.

5 CURRENTLY AVAILABLE TESTS

There have been many tests developed over the last few decades. However, although surveys like the 1973 ASLE listing of test methods describe 300 methods [8], most of these are slight variants on particular types of test.

With this number of tests and the related numbers listed in Tables 4 and 5 there is clearly a need to evaluate these various tests and compare them in terms of their relevance to the industrial wear problems listed in Table 3. Also since these test methods have been found from VAMAS surveys to give very variable results, and many industrial users have expressed dissatisfaction with them, there is a need to select a few tests, which could meet the industrial needs, so that it would then be possible to concentrate on their development and improvement.

The available test methods have therefore been evaluated in terms of their match to the important industrial wear problems listed in Table 3, and a limited number with the closest characteristics have been chosen. These tests are:

1. Fluid jet erosion testing, Type 1 in table 3.
2. Gas blast erosion test, Type 1.
3. Loose slurry abrasion testing, Type 2.
4. ASTM G65, dry sand rubber wheel, Type 2.
5. ASTM G105, wet sand rubber wheel, Type 2.
6. ASTM B611, wet slurry steel wheel, Type 3.
7. Fixed abrasive, Type 3.
8. Ball cratering, Type 3.
9. Scratch testing, Type 3.
10. Pin-on-disc sliding wear, Type 5.
11. Reciprocating sliding wear, Type 5.
12. Fretting wear test, Type 5.
13. Thrust washer, Type 6.

The test methods themselves are each described in separate description sheets. However, a few general remarks concerning the main test parameters for each main category of test are appropriate, and are given in Annex 3. It should also be noted that when a standard is quoted which specifies particular test conditions, these are given. In many cases other conditions of testing are also possible and will yield useful information.

The fourth type of wear listed in Table 3, the wear of metal components in rubbing contact with a sequence of other solid components, is difficult to simulate because of the renewal of

one of the contacting materials. However, some of the sliding wear tests (9, 10, 11, 13) may yield useful information, but considerable care needs to be taken in the choice of test conditions and the interpretation and application of results.

5.1.1 Fluid Jet Erosion Test

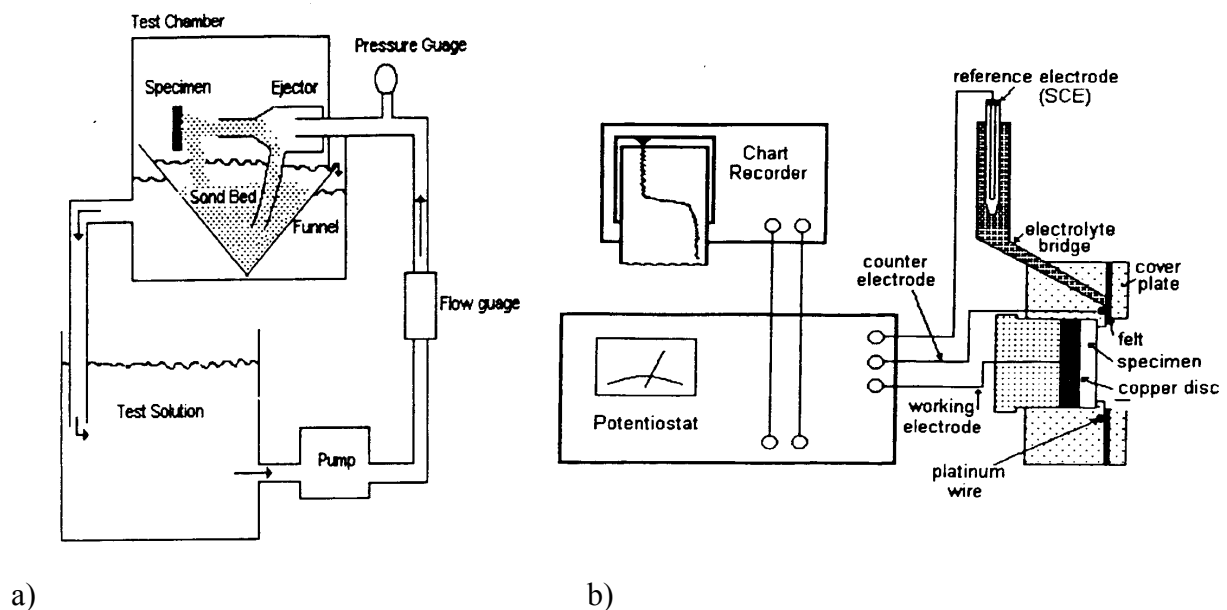


Figure 4, Typical fluid jet test system, a) test system, b) electrochemical measurement cell [9]

A major source of industrial wear problems is through the erosive wear of components from hard particles carried in a jet of fluid. There are currently no recognized standards for this type of test, but there has nevertheless been some work carried out in this area [9,10].

A typical test system is shown in Figure 4. A jet of fluid is circulated around a closed loop by a pumping system. The jet carries the appropriate concentration of erodent. The sample is placed at the appropriate angle and distance from the nozzle, which sends the jet of erodent containing fluid onto the sample. The fluid is caught and recirculated.

The key parameters that need careful control in this test are the placement (angle and position) of the sample, the shape of the fluid jet (defined by the nozzle), the fluid pressure, the abrasive loading, and the abrasive shape and size.

Although wear takes place through the abrasive action of the abrasive particles, a major effect also comes through corrosion that is controlled by the chemistry of the fluid. Thus small variations in the chemical composition such as the pH of the fluid (if water based) can cause major changes in the rates of material loss from the sample, sometimes with dramatic increases in the rate of material loss through synergy between the abrasion and the corrosion.

These corrosion effects need to be carefully controlled. One of the methods that has been used in this respect is to control the electrical potential that is applied between the fluid (via the nozzle) and the sample (Figure 4b).

Test Conditions

- Jet impact velocity; 2-30 ms⁻¹
- Fluid; normally water but other fluids possible
- Impact angle; 20-90°
- Erodent; often silica, but other erodents possible
- Duration; several tens of minutes

Measurements Made

- Volume of wear
- Examination of worn surface

5.1.2 Gas Blast Erosion

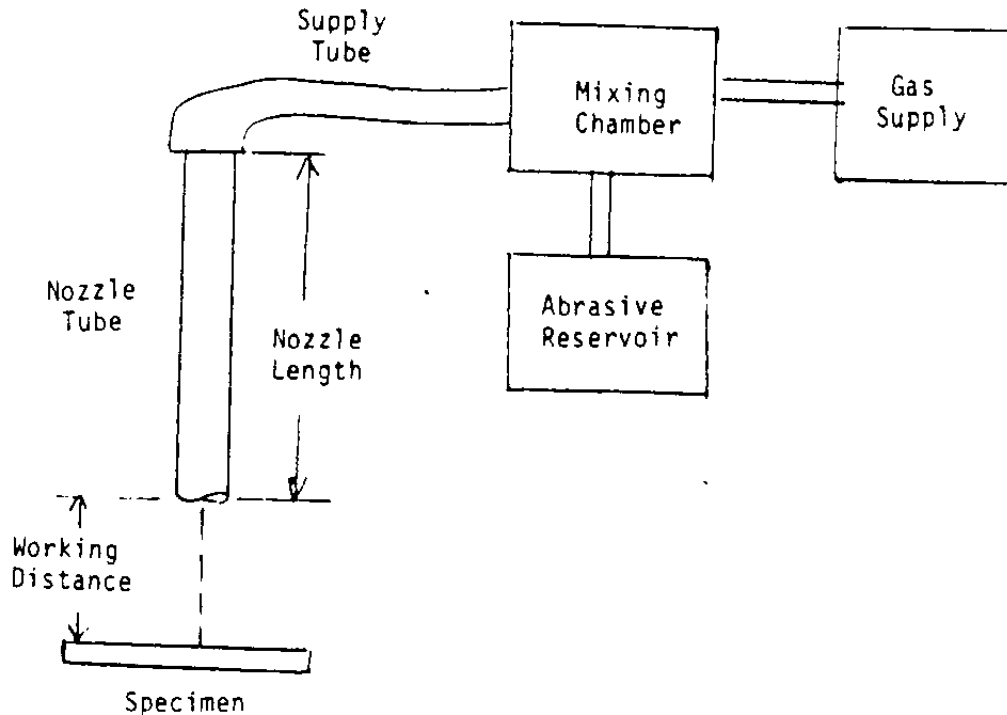


Figure 5, Schematic diagram of gas blast erosion test system, ASTM G 76 [11].

The gas blast erosion test system [11] uses a stream of high pressure gas to accelerate a stream of particles through a nozzle towards a test sample. The erodent is only used once before being discarded. The sample is held at a defined distance and angle to the nozzle for the test system.

The most important test parameter is the particle velocity, with wear increasing in line with a power law relationship with velocity. The wear obtained is also dependent on the nozzle geometry (diameter, length and shape), and internal surface finish of the nozzle [12].

The volume of wear is normally measured by mass loss and density measurements.

Test Conditions

- Velocity of erodent; $30 \pm 2 \text{ ms}^{-1}$
- Erodent material; Nominally 50 μm angular alumina
- Angle of incidence; 90°
- Sample stand-off distance; $10 \pm 1 \text{ mm}$
- Nozzle dimensions; $1.5 \pm 0.075 \text{ mm}$ inner diameter, at least 50 mm long
- Test duration; 10 minutes
- Abrasive feed rate; $2 \pm 0.5 \text{ g min}^{-1}$

Measurements Made

- Volume of wear
- Examination of worn surface

5.1.3 Loose Slurry Abrasive Testing

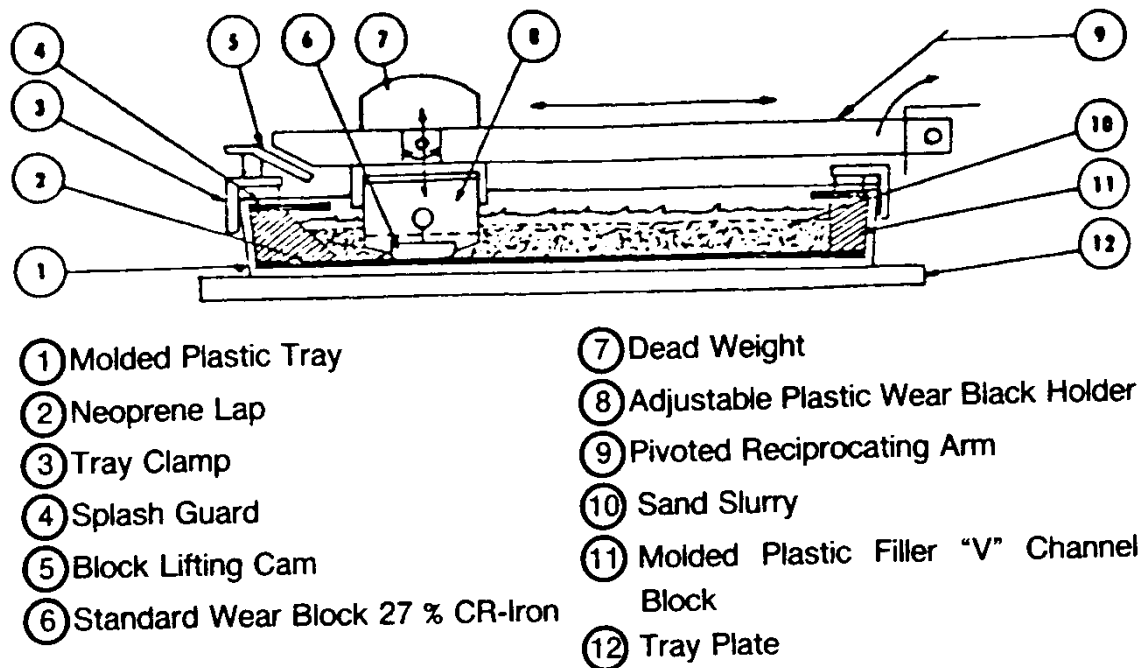


Figure 6, Miller abrasivity test, ASTM G75 [14]

There are several three-body test systems that have been used. These include test systems where a sample is pressed against a bed of abrasive material (or vice versa) which can either be dry or damp. It is also quite common to use an adapted polishing machines where a sample is pressed into a dish of abrasive slurry [13]. There is also a reciprocating test with a set of samples moved under a dead-weight loading against an abrasive slurry contained in a tray (Figure 6) [14].

A major concern with tests of this type is to ensure that the abrasive bed that is achieved in the test is realistic and well controlled. Particularly for the tests which use modified polishing wheels, there can be difficulties in maintaining a good film of abrasive slurry between the test sample and the supporting dish. This is particularly difficult if large abrasives need to be used, and careful consideration needs to be given to strategies to mix the abrasive slurry as the test proceeds. This is true for the Struers micro-abrasion test [14] that uses a semi-automatic polishing system. Three samples are mounted in a holder that is positioned eccentrically from the axis of rotation of the dish containing the abrasive slurry. The dish and the sample holder are then rotated in opposite directions, giving good mixing to the abrasive slurry.

Test Conditions

- Abrasive; silica, silicon carbide, alumina or other abrasive
- Load; often in the range 5-100N
- Relative speed; up to about 0.5 ms^{-1}
- Abrasive loading; up to 50 % by weight loading, (slurry needs to be of such a consistency that it can be pumped like a liquid [12])
- Test duration; up to 6 hours

Measurements Made

- Volume of wear
- Examination of worn surface

5.1.4 Rubber Wheel, Dry Abrasive, ASTM G65

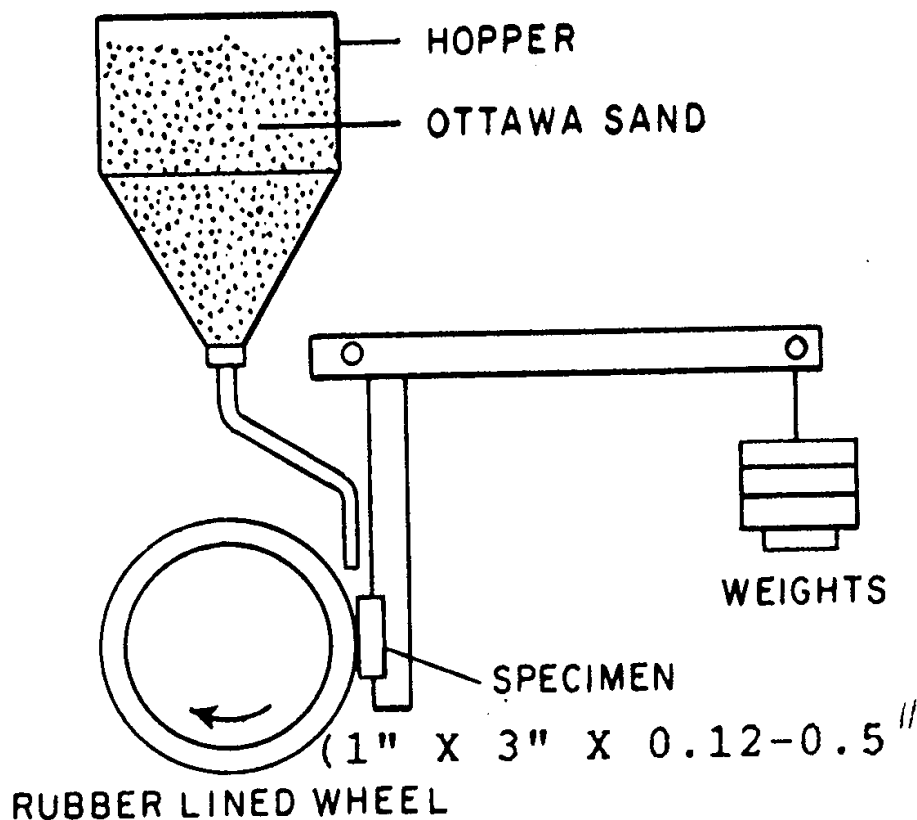


Figure 7, ASTM G65 test system [16]

The ASTM G65 test [16] uses a rotating rubber rimmed wheel as the bed for silica abrasive that is fed from a hopper by a nozzle between the sample and the wheel (Figure 7). The sample is pressed into the wheel by a dead-weight loaded lever. The test is run for a set period, and the wear to the sample measured by measuring the volume of material lost through mass loss and density measurements.

The flow of sand into the gap between the wheel and the sample is controlled by the geometry of the nozzle that must be very carefully defined to obtain the required sand flow rate. The abrasive only passes through the wear interface once and is thrown away at the end of a test

Test Conditions

- Abrasive; AFS 50-70 test sand (about 200 μm in size)
- Abrasive flow rate; 300-400 g/min
- Test load; 45 or 130 N
- Number of revolutions; 100,1000,2000, or 6000
- Wheel speed; 200 rpm
- Wheel diameter; 228 mm

Measurements Made

- Volume of wear
- Examination of worn surface

5.1.5 Rubber Wheel, Wet Abrasive Slurry, ASTM G105

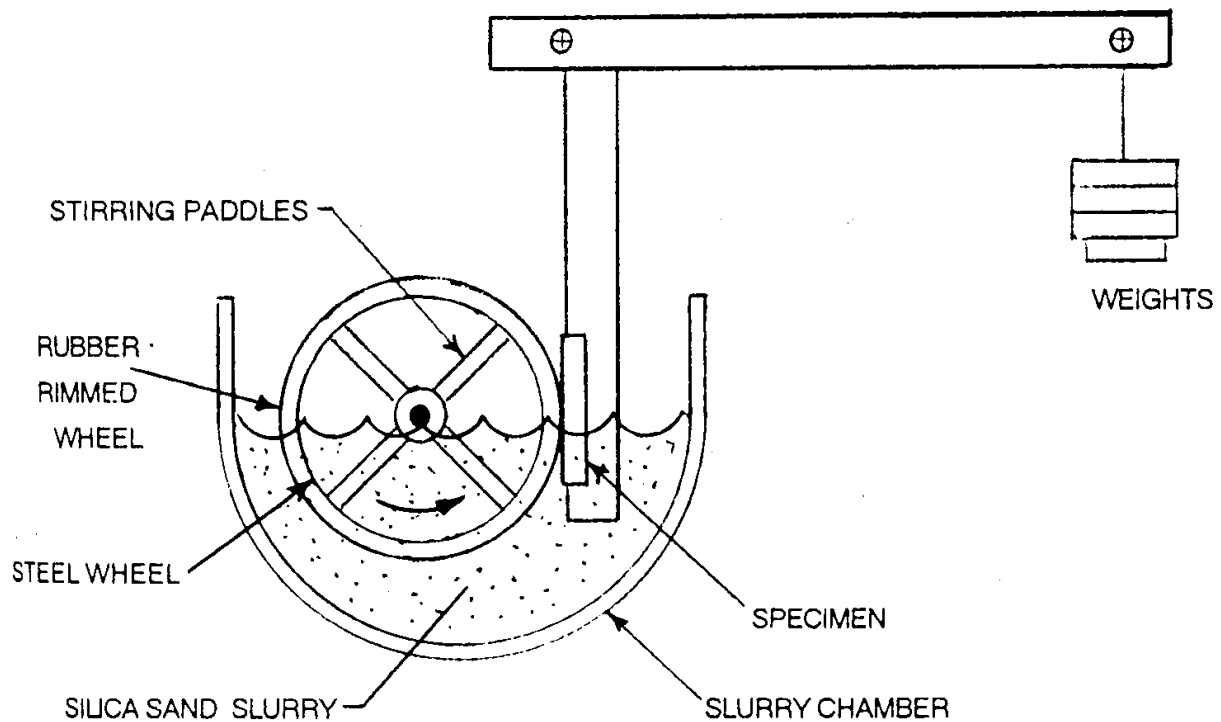


Figure 8, ASTM G105 test system [17].

This test uses a very similar test geometry to the ASTM B611 test system but the steel wheel is replaced with a rubber rimmed wheel [17]. In contrast to the ASTM G65 test the abrasive is carried up out of a bath of slurry surrounding the wheel and test sample into the wear interface. Straight paddles are placed on the sides of the wheel to ensure that the abrasive slurry is continually mixed. It should be noted that the abrasive may pass through the wear interface more than once, as it is contained in a closed bath and recirculated through the wear interface during the test.

The volume of wear is measured by mass loss and density measurements.

Test Conditions

- Test load; 222 N
- Number of revolutions; 5000
- Wheel diameter; 178 mm
- Wheel speed; 245 rpm
- Rubber condition; shore A Durometer hardness 50, 60 70

Measurements Made

- Volume of wear (calculated from mass loss and density measurements)
- Examination of worn surface

5.1.6 Two Body - Steel Wheel, Wet Abrasive Slurry, ASTM B611

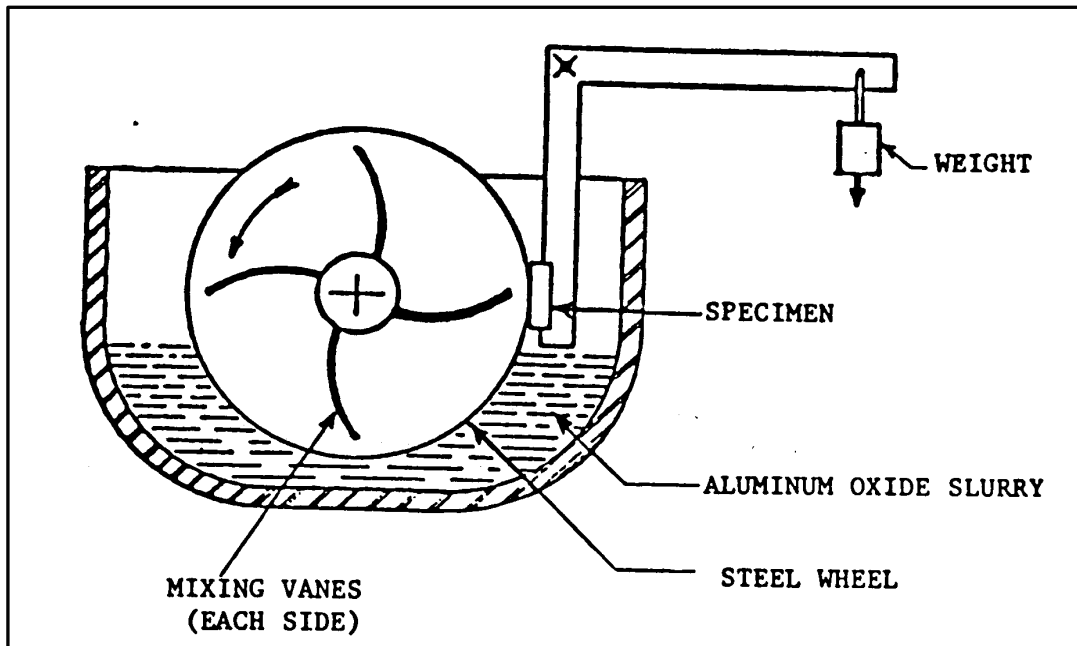


Figure 9, ASTM B611 test system [15].

In the ASTM B611 test (Figure 9) [15] for hardmetal mining grades, a rotating steel wheel is used as the bed for the abrasive that is carried up out of a bath of slurry surrounding the wheel and test sample into the wear interface. The abrasive specified in the test standard is alumina about 600 μm in size. This is industrially unrealistic since the alumina abrasive is very hard (about 2300 HV30) and rarely encountered in practice. A better choice of abrasive from this respect would be silica. The volume of wear is calculated from mass loss and density measurements.

Test Conditions

- Test load; 20 N
- Duration; 1000 revolutions of wheel
- Abrasive; alumina slurry, 30 mesh grit in proportion of 4 g to 1 cm³ of water
- Wheel speed; 100 rpm
- Wheel diameter; 165 mm

Measurements Made

- Volume of wear
- Examination of worn surface

5.1.7 Fixed Abrasive -Abrasive Paper or Grinding Wheel

The simplest type of two body test systems in concept are those which utilise abrasive papers or abrasive grinding wheels, with a test sample moved with an applied load against the abrasive medium.

A major concern with this type of test is again the degradation of the abrasive medium as the test sample is repeatedly moved against it. This has been recognized as a concern, and several strategies have been devised to move the test sample in a complex manner such that it only passes a single point on the abrasive medium once during a test. An example of this is the test devised by Krushchov where the test sample is moved in a spiral over abrasive paper as it is rotated in a similar manner to a long playing record.

Test Conditions

Load; normally in range 5-100 N

Speed; normally up to 1 ms^{-1}

Duration; few tens of minutes

Abrasive; alumina silica, silicon carbide, diamond (abrasive papers or grinding wheel)

Measurements Made

- Volume of wear (measured directly by profilometry or calculated from mass loss and density measurements)
- Examination of worn surface
- Friction
- Wear displacement (progressive movement of two samples together during wear)

5.1.8 Two Body - Ball Cratering

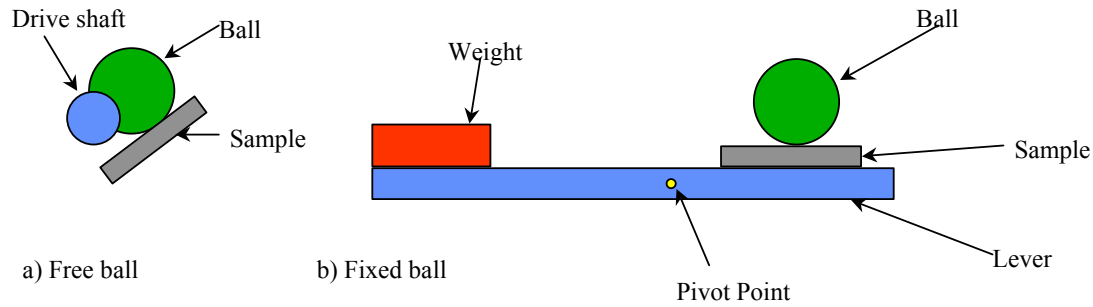


Figure 10, Schematic diagram of two different types of ball cratering equipment

Ball cratering is a miniaturised abrasion test method which has been developed over the last few years from two earlier techniques [18,19]. These were the production of TEM samples by dimpling with a wheel or ball to produce a spherical depression which was more easily thinned; the second was the use of a ball and appropriate grinding media to produce a spherical crater with known geometry which cuts through a coating. From measurements of the diameter of the crater in the substrate and the coating the thickness can be readily calculated.

Through better control of test parameters such as load, speed, abrasive type and suspension etc these techniques have been developed readily into a wear test. This has now been done, and there is now great interest in the use of the test for thin hard coatings such as TiN, polymeric films such as paints, and other monolithic materials.

One of the key points with the test is that it enables a test to be carried out on a small area (about 0.5-1 mm across), with little damage to a component which can remain in service in many cases. The test could easily be made portable, to carry round to the component rather than vice-versa.

Test Conditions

- Test load; up to 20 N
- Abrasive; alumina, silicon carbide silica, diamond, small grit size, normally 4 μm or less
- Abrasive loading; 10 % by volume or less
- Ball size; normally about 25 mm
- Ball speed; up to 200 rpm
- Test duration; up to 5000 revolutions

Measurements Made

- Size of wear scar
- Volume of wear (measured directly by profilometry or calculated from size of wear scar)
- Examination of worn surface
- Wear displacement (progressive movement of ball into sample)

5.1.9 Scratch Testing

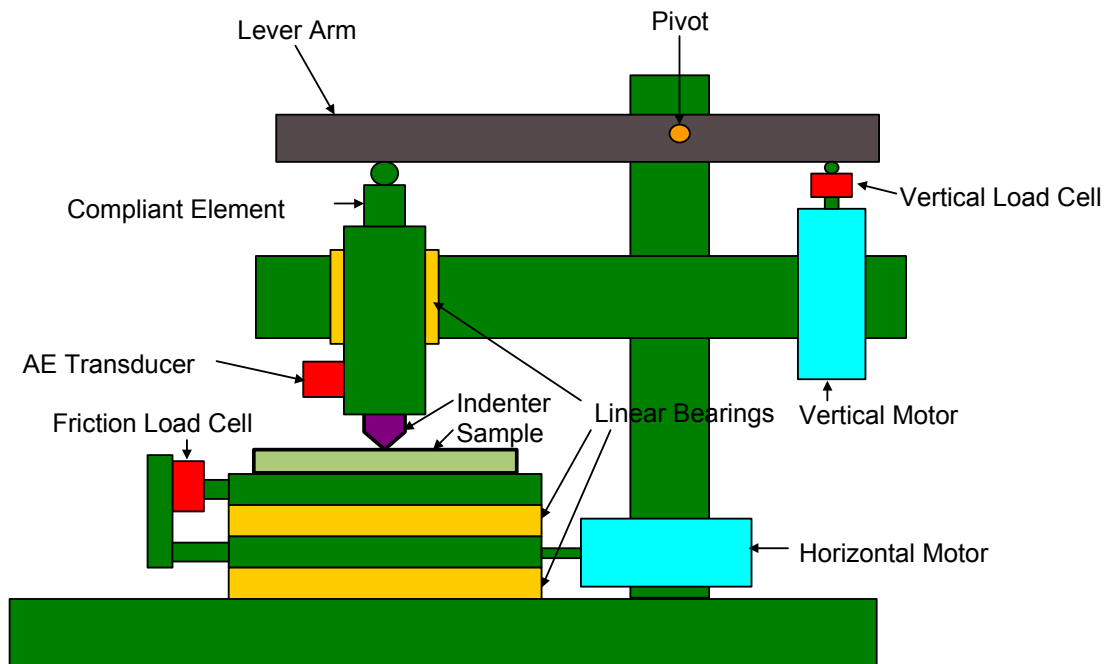


Figure 11, Schematic diagram of scratch testing system

Scratch testing was developed originally as a quality control test for the measurement of the adhesion of coatings. It is still widely used in this role, but also offers potential as a model abrasion test method where the abrasion is caused by a single abrasive point (the indenter). The advantage of this approach is that the response of a material to abrasion under these simple conditions can be controlled and modelled much more easily than in most abrasion conditions where a high number of abrasive particles are acting in very close succession.

This approach is useful in the simulation of industrial abrasive wear as wear by abrasion is caused by the accumulation of many single scratching events; since the scratch test provides good quality data on one of these events, it can be often used successfully in the simulation of abrasive wear.

Another variant of the scratch test is to perform many repeat scratches either along the original scratch line, or at a carefully defined distance from the original scratch to investigate the effect of multiple scratching and interactions between scratches.

Test Conditions

- Test load; up to 100 N
- Speed; up to 1 mm/min
- Indenter geometry; 0.2 mm radius diamond, but other geometries may be used

Measurements Made

- Volume of wear (measured directly by profilometry or calculated from scartch width and indenter geometry)
- Examination of worn surface
- Friction
- Wear displacement (progressive movement of two samples together during wear)
- Acoustic emission

5.1.10 Sliding Wear - Uniaxial Motion, Pin-on-disc

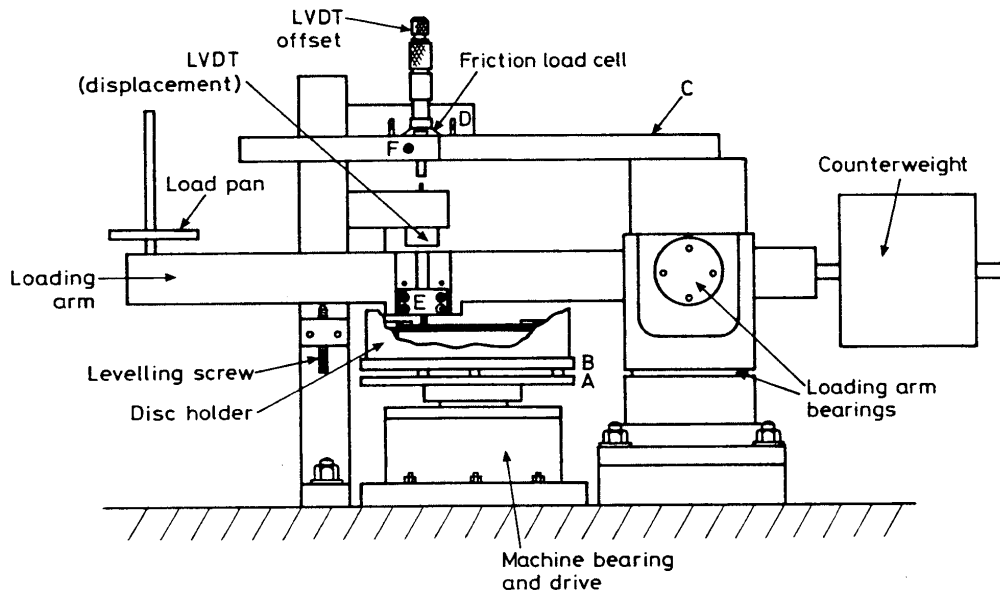


Figure 12, Schematic diagram of pin-on-disc test system

The pin-on-disc test [20] has been used very widely. A stationary pin or ball is pressed against a rotating disc. Friction is often measured by recording the force needed to restrain the pin or ball in the tangential direction. Wear displacement (the movement of the samples into one another due to wear of one or other sample) is often measured by use of a linear displacement transducer.

Wear can also be measured in several other ways after the test has been completed. These are

- mass loss measurements combined with a knowledge of the density of the samples
- change in linear dimension of samples
- optical measurement of the size of wear scars (particularly useful for samples with a rounded surface)
- profilometric measurement of wear volume

Most test systems are only intended for tests under ambient conditions, but test systems have sometimes been modified for use at high temperatures or different environments.

Test Conditions

- Test load; up to 10,000 N (in different test systems to cover different load ranges)
- Speed; 0.001 mm s^{-1} to 10 ms^{-1}
- Contact geometry; flat ended pin; chamfered pin, or rounded pin or ball (10 mm diameter is common dimension) against flat
- Test duration; 1000 s to 10^6 s

Measurements Made

- Volume of wear (measured directly by profilometry or calculated from mass loss and density measurements or calculated from size of wear scar)
- Examination of worn surface
- Friction
- Wear displacement (progressive movement of two samples together during wear)

5.1.11 Sliding Wear - Reciprocating Motion

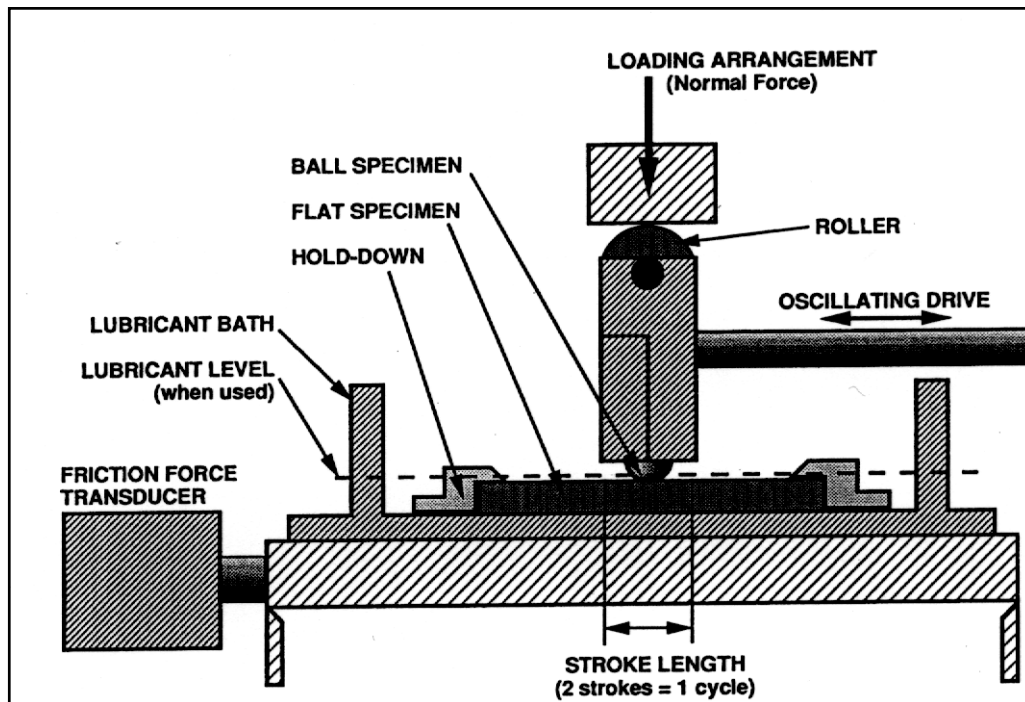


Figure 13, Typical reciprocating test system (taken from ASTM G133)

The reciprocating test system [21] has also been used very widely. A stationary pin or ball is pressed against a flat sample that is moved backwards and forwards in a reciprocating motion. There are two types of motion that have been used with reciprocating tests. These are a sinusoidal movement, often generated through some type of cam; and a linear motion, generated by linear servo systems.

Friction is often measured by measuring the force needed to restrain the pin or ball against the direction of travel. Wear displacement (the movement of the samples into one another due to wear of one or other sample) is often measured by use of a linear displacement transducer.

Wear can also be measured in several other ways after the test has completed. These are

- mass loss measurements combined with a knowledge of the density of the samples
- change in linear dimension of samples
- optical measurement of the size of wear scars (particularly useful for samples with a rounded surface)
- profilometric measurement of wear volume

Most test systems are only intended for tests under ambient conditions, but test systems have sometimes been modified for use at high temperatures or different environments.

Test Conditions

- Test load; up to 10,000 N (in different test systems to cover different load ranges)
- Frequency; 0.1 to 50 Hz
- Stroke; 0.25 to 50 mm
- Contact geometry; flat ended pin; chamfered pin, or rounded pin or ball (10 mm diameter is common dimension) against flat
- Test duration; 1000 s to 10^6 s

Measurements Made

- Volume of wear (measured directly by profilometry or calculated from mass loss and density measurements or calculated from size of wear scar)
- Examination of worn surface
- Friction
- Wear displacement (progressive movement of two samples together during wear)

5.1.12 Sliding Wear - Fretting Conditions

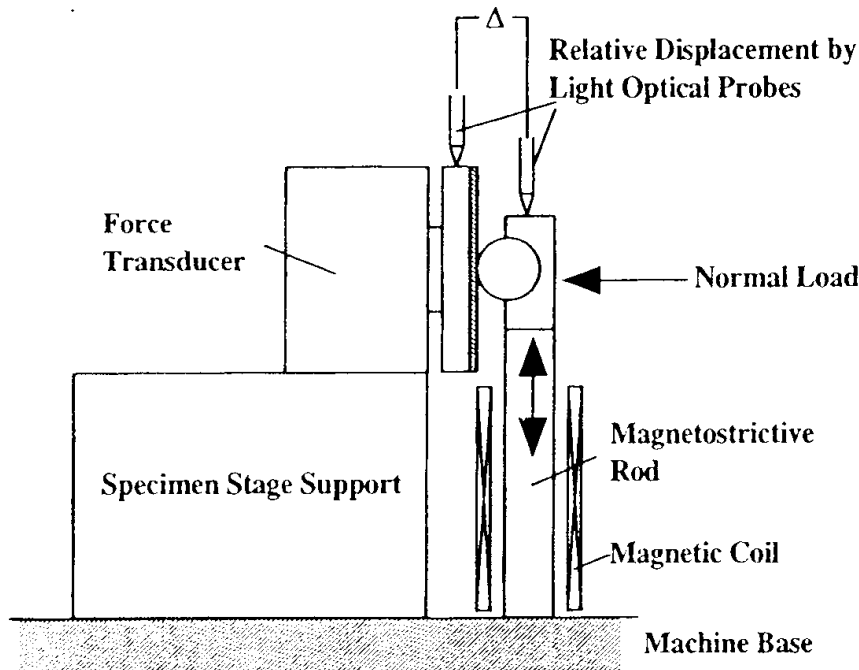


Figure 14, Typical fretting test system [22]

Fretting takes place where small amplitude motion occurs between loaded contacts. In contrast to other types of sliding wear, the amplitude of motion in fretting is so small that there is always some contact between the two samples. A practical limit on the amplitude of motion in fretting is often taken to be less than 250 μm .

Although the type of motion required is similar to that in reciprocating testing, the small amplitude of motion necessitates considerable care in the design of the test system so that the movement at the point of contact between the samples is correct. This is because inadequate design, particularly with compliant test systems can lead to reduced movement at the point of contact compared with the design value, leading to erroneous results.

Test Conditions

- Frequency; up to several kHz
- Stroke; up to 0.25 mm
- Test load; typically in range 2-100 N
- Contact geometry; flat ended pin; chamfered pin, or rounded pin or ball (10 mm diameter is common dimension) against flat
- Test duration; up to 10^6 cycles

5.1.13 Conformal Sliding Wear Test - Thrust Washer Test

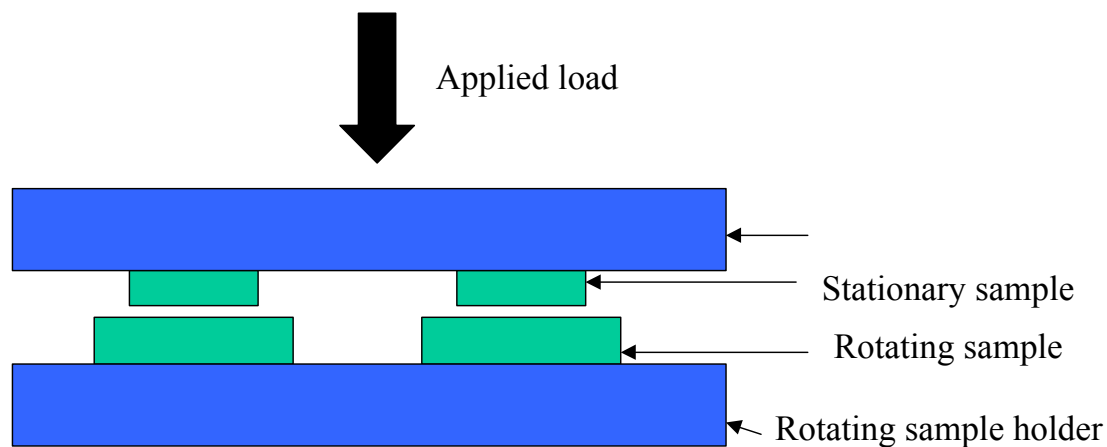


Figure 15, Thrust washer test configuration

The thrust washer test is used where testing of conformal large area contacts is required. Obtaining conformal contact is helped by the large area of the test sample, but it is also often necessary to incorporate additional alignment devices to ensure full conformal contact.

Because of the relatively large area of the sample, contact pressures are often lower than in other sliding wear tests such as the reciprocating or pin-on-disc tests.

The two test samples are often of similar dimensions, but there are advantages in using two samples with different sizes since axial alignment requirements can be relaxed. Friction is often measured by recording the torque needed to restrain the rotation of the stationary sample. Wear displacement (the movement of the samples towards one another due to wear of one or another sample) is often measured by the use of a linear displacement transducer.

Wear can also be measured by mass loss measurements combined with a knowledge of the density of the samples, and for tests with dissimilar sample sizes, by the measurement of the volume of wear in the larger test sample by profilometry.

Most test systems are only intended for tests under ambient conditions, but test systems can be developed for use at high temperatures or different environments.

Test Conditions

- Test load; up to 10,000 N (in different test systems to cover different load ranges)
- Speed; 0.1 - 10 m s⁻¹
- Contact geometry; flat face of ring against flat face of ring
- Test duration; 1000s to 10⁶ s

Measurements Made

- Friction
- Examination of worn surface
- Wear

6 ACKNOWLEDGEMENTS

The authors would like to acknowledge the financial support of the Department of Trade and Industry for this work under the Materials Measurement Programme.

7 REFERENCES

- 1) N A Waterman and M F Ashby, Elsevier Materials Selector, Elsevier Science Publishers, (1991), pp 326-331
- 2) M G Gee, Wear testing and ceramics, Proc Inst Mech Engrs, 208(1994)153-166
- 3) DIN 50322: 1986, Wear testing categories, Beuth Verlag, Berlin
- 4) P J Blau, A compilation of international standards for friction and wear testing of materials, VAMAS Report 14, September 1993
- 5) S Owen-Jones and M G Gee, Wear testing papers, reports and proceedings database, NPL Report CMMT (A)90, December 1997
- 6) S Owen-Jones and M G Gee, Wear testing standards database, NPL Report CMMT (A)89, December 1997
- 7) S Owen-Jones, Summary of wear test methods: Notes on 10th international conference on wear of materials, NPL Report CMMT (A)93
- 8) ASLE compilation of friction and wear devices, ASLE, 1976.
- 9) J B Zu, I M Hutchings, G T Burnstein, Design of a slurry erosion test rig, Wear, (1990)
- 10) E J Wentzel, C Allen, Wear, 181-183(1995)63-69
- 11) ASTM G76-95, Standard test method for conducting erosion tests by solid particle impingement using gas jets, Annual Book of ASTM Standards, 03.02(1997)305-309
- 12) A N J Stevenson and I M Hutchings, Scaling laws for particle velocity in the gas-blast erosion test, Wear, 181-183(1995)56-62
- 13) E Fundal, The Struers micro-wear test, Structure, 3(1989)
- 14) ASTM G75-95, Annual Book of ASTM Standards, Volume 03.02, (1997), pp 282-304
- 15) ASTM B611-85, Standard test method for the abrasive wear resistance of cemented carbides, Annual Book of ASTM Standards, 02.05(1995)326-327
- 16) ASTM G65-94, Standard test method for measuring abrasion using the dry sand / rubber wheel apparatus, Annual Book of ASTM Standards, 03.02(1997)239-250
- 17) ASTM G105-89, Standard test method for conducting wet sand/ rubber wheel tests, Annual Book of ASTM Standards, 03.02(1997)424-432

- 18) A Kassman, S Jacobson, L Erickson, P Hedenqvist and M Olsson, A new test method for the intrinsic abrasion resistance of thin coatings, *Surf Coat Technol* 50(1991)75-84
- 19) K L Rutherford and I M Hutchings, A micro-abrasive test, with particular application to coated systems, *Surf Coat Technol*, 79(1996)231-239
- 20) ASTM G99-95a, Standard test method for wear testing with a pin-on-disc apparatus, *Annual Book of ASTM Standards*, 03.02(1997)392-396
- 21) ASTM G133-95, standard test method for linearly reciprocating ball-on-flat sliding wear, *Annual Book of ASTM Standards*, 03.02(1997)529-536
- 22) K Schouterden, B Blanpain, J P Celis and O Vingsbo, Fretting of titanium nitride and diamond-like carbon coatings at high frequencies and low amplitude, *Wear*, 181-183(1995)86-93

8 ANNEX 1: INDUSTRIAL WEAR PROBLEMS; A SURVEY

ANNEX 4 INDUSTRIAL WEAR PROBLEMS: A SURVEY

INDUSTRIAL WEAR PROBLEMS

A BRIEF INITIAL SURVEY CONDUCTED BY

Neale Consulting Engineers Ltd

&

NPL

National Physical Laboratory

The aim of this DTI sponsored survey is to gather both technical and economic data concerning industrial wear-related problems. The dissemination of this data, without disclosure of the source, will provide a useful summary for UK industry and can be used to structure cooperative solutions. It will also culminate in the publication of a handbook on wear testing.

This questionnaire is intentionally brief in order to encourage a high response rate.

QUESTIONNAIRE**A SURVEY OF INDUSTRIAL WEAR PROBLEMS****Name:****Job title:****Company name:****Telephone/Extn:****Company activity or product:****Approx. no. of employees at your site:****Approx. turnover of your company:**

Please describe the top one or two generic wear or wear-related problems experienced by your company, in one or two sentences each.

Problem 1				
Approx. annual cost	0-£10,000	£10,000-£100,000	£100,000-£500,000	£500,000+
Problem 2				

Approx. annual cost	0-£10,000	£10,000-£100,000	£100,000-£500,000	£500,000+

Please feel free to attach further information or comments as additional pages.

The project will be focusing on a number of problems, with a view to helping to find solutions and testing methods etc. Would you be prepared to take part in this next stage (at no cost to your company)?

Yes	
------------	--

No	
-----------	--

If you have any questions regarding this survey, please call Neale Consulting Engineers Ltd on 01252 722255

Please return the completed questionnaire in the pre-paid envelope to:

Neale Consulting Engineers Ltd, Downing Street, Farnham, Surrey, GU9 7PH.

9 ANNEX 2: WEAR TEST METHODS: A BRIEF SURVEY ON INDUSTRIAL PRACTICE

9.1 Introduction

A survey (given at the end of this Annex) was sent out to about 600 firms with the aim of gathering technical data concerning the ways that industry tackles testing appropriate to wear-related problems. The firms were drawn from the members of the UK Forum on Friction and Wear Testing and the contact list of the Surface Link Programme, and therefore represented firms and contacts which were known to have an interest in friction and wear testing.

Responses were received from 51 organisations. The majority of these were industrial firms. The results are categorised by the question number in the original survey. In most cases a list of responses to the different questions is given.

A wide range of industrial sectors were covered which included:

Hardmetal wear resistant parts
Dental materials
Polymer bearings
Ceramic wear resistant parts
Gas and petroleum supply
Wear resistant coatings
Can manufacture
Footwear
Polymeric materials
Automobile components
Nuclear industry
Cutlery industry
Metal plating
Sprayed coatings
Machine tools
Mechanical seals
Ophthalmic lenses
Metal processing
Orthopaedic joints

9.2 Summary of Survey Results

In this summary of survey results the original questions are given in italics, with a summary of the response below.

1) *Name and 3) Company name.*

Useful responses were received from:

L Rudd	DERA	
W Coles	Marshalls	*
McCabe	University of Newcastle	
A R W Barron	Railko	
C J Hampson	Morgan Matroc Ltd	*

Raj Rajput	British Gas	*
D Harrison	BP	*
R Bayliss	Morgan Materials Technology	*
D T Gawne	South Bank University	*
R J Oscroft	Morgan Matroc Ltd - AME Division	*
J G Logan	Boart Longyear TCD	*
M J Carpenter	Sandvik	*
C Fletcher	Hoybide	*
D Teer	Teer Coatings Ltd	*
A Gorton	Crown Cork & Seal	*
N Oliver	SATRA	
D O'Regan	ICI, R&T Centre	
M S Starkey	GKN Technology	
S Radcliffe	Magnox Electric	
I Birkby	Dynamic-Ceramic	*
R C Hamby	CATRA	*
Sewell	Twickenham Plating Company	*
L Brown	Lawrie Brown Consultants	
Dr Bradley	Orthodesign Ltd	*
P A Harris	C&J Clark	
G M Bedford	Frictec	
M Olsen	Ashton and Moore	*
P John	Edinburgh Surface Analysis Technology	
D J Grimes	Overton Plating	
D A Gilbert	Prosynth	
B Nelis	Philidas	
G Scrimgour	MSPE	*
G K Creffield	BOC Gases	*
I K Bloor	S L Electrotech	
D Saxton	David Brown Gear Tools and metrology	*
J Franks	Diavac ACM Ltd	*
B Woodall	P T Coatings	
M T A Herring	I P Technology	
R Wallis	John Crane UK	*
D Taylor	Fairey Industrial Ceramics Ltd	*
J M Walls	Applied Vision	*
C K Baker	Crosfield	*
G Davies	Eutectic	*
P Sharpe	Tenmat	*
S A Plumb	Lucas-Nitrotec	
J S Ellis	British Steel	*
R McIntyre	Plasma and Thermal Coatings	
W B Burdett	Rolls-Royce & Associates	
D Butterworth	BNFL	
D Thompson	Rotech Components Ltd	

* Denotes firms expressing interest in ceramics and hardmetals

5) *Approx. no. of employees at your site:*

The total number of employees at firms that stated they were using or had commissioned wear testing was nearly 24,000. Three firms declined to give figures. Ten firms had more than 500 employees (although the responses were difficult to gauge due to an ambiguity in the questions, with a reply from British Steel giving employees at 400; this being the number at the research centre).

6) *Approx. turnover of your company:*

The summed turnover of the nine largest (in terms of turnover) firms that responded was £51 billion. The summed turnover of the rest of the firms responded to this question was £219 million.

7) *Do you consider that you have a need for information about and understanding of wear and friction behaviour, including test methods and data:*

Five responses were negative, the rest were positive.

8) *What are the wear-related problems which you are trying to address (if you have already answered this question on the related initial survey sent out by Neale Consulting Engineers, then indicate this here).*

Although some of the respondents indicated that they had also replied to the NCE survey, these were not all indicated on the returns. A brief list of the types of responses is given below in terms of the types of mechanism that were thought to be encountered.

- Scuffing and fretting
- Abrasive wear
- Sliding wear of ball valves and pumps
- Third body abrasion
- Erosion/Corrosion
- Metal cutting
- Microdrilling of PCBs
- Tooling wear
- Component wear in machinery
- Constant velocity joint components
- Wear of cutting edges
- Wear of connectors
- Abrasion in milling equipment
- Impact wear

9) Please indicate the main material types that you deal with for which wear-related problems exist

The number of responses in each of the materials types are indicated below.

Ceramics	Hardmetals/ Cermets	Polymers	Metals	Composites			Other
16	18	15	25	Metal	Polymer	Ceramic	4
				6	9	2	

10) Do you carry out wear and friction testing at your site:

18 Yes

33 No

11) Do you commission wear testing at other organisations:

30 Yes

19 No

12) *If answer is yes to either question 10) or 11) then what wear test methods are being used on your behalf (make reference to any standard procedures such as the ASTM G65 dry sand rubber wheel test):*

Although the list of test methods could not be fully quantified due to the small sample, it was found that although many of the respondents did not give details of the tests that they used, twenty of the firms listed the test equipment that was used. The most common test methods are listed in the table below

Test Method	Number of mentions/ All material interests	Number of mentions/ Ceramics & hardmetals
Pin-on-disc	12	8
Reciprocating	10	6
Gas blast erosion	4	4
ASTM G65 abrasion	4	4

.

Other test methods which were mentioned include:

Taber Abraser
 ASTM B611 abrasion
 Ball Cratering
 fluid jet erosion
 Tumbe test (optical components)
 Simulated plant conditions and application related tests
 Scratch test
 Nano indentation
 Service trials
 Robotic testing
 Non-standard methods
 Falex
 4-ball

13) *Do you consider the wear test methods fulfil your needs:*

Here there was a very wide range of responses that went from the extremes of being very satisfied to being totally unsatisfied with currently available wear tests. A common theme which emerges is the need for additional information on the applicability of different test methods to specific industrial wear problems.

Yes
 More or less
 Adequate
 Nearly!
 Not totally
 Most test methods fulfil needs
 Useful guide but full scale testing also required
 Useful as screening
 Always looking at new methods
 Not sure!
 Lack of correlation
 Not often
 Take too long
 Inadequate
 No

10 ANNEX 3: NOTES ON EFFECT OF TEST PARAMETERS

10.1 Abrasive Test Methods

One of the most important considerations in abrasive testing is the abrasive. The shape, size and size distribution of abrasives can all have important effects on the wear that occurs. Thus any sharp points on abrasive particles are more effective and produce more damage when in contact with the test material.

The compliance of the support for the abrasive is also important. When pressure is applied to abrasive on a compliant support, the abrasive sinks into the compliant bed allowing load

sharing to take place between the different abrasive particles. For a stiff support, the largest abrasive particle will take most of the load. The damage from the few highly loaded abrasive contacts with a stiff support is more severe than the damage from a large number of load-sharing abrasive particles when a compliant support is used.

Two distinctly different types of abrasion are two body and three body abrasion. In two body abrasion, the abrasive is rigidly fixed, for example in abrasive paper or in an abrasive grinding wheel. In three-body abrasion, the abrasive is suspended in a slurry or other fluid and is therefore free to move and rotate. In some ways, an abrasive slurry is an extreme example of a compliant supporting medium for abrasive. Normally contact stresses are lower and wear rates are reduced for three body abrasion relative to two body abrasion.

Another classification that has been used to describe abrasion is to term it high stress or low stress abrasion. In high stress abrasion, the abrasive particles are fractured by the high contact stresses generated by the abrasion processes. This generates fresh sharp edges which cause an increase in abrasion damage. In low stress abrasion the stresses are lower and the abrasive particles are not fractured.

Many of the industrial wear problems that this test system is intended to simulate are concerned with the abrasion caused by a flow of abrasive particles that are continually renewed, for example in the pumping of crude oil contaminated by sand in the North Sea. It is then questionable whether a closed loop system where the abrasive is not renewed can correctly simulate the wear conditions encountered in practice. This is because repeated contact between the abrasive particle and the sample as the flow is continuously recirculated may change the size and shape of the abrasive, leading to changes in the wear rate.

Simple calculations can be made to estimate the likely effect of using a closed loop system. Little effect of abrasive particle degradation would probably be felt if the likelihood of a single particle striking the surface more than once was quite low.

10.2 Sliding Wear Test Methods

There are hundreds of different test machines, but these can be reduced to a small number of different 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. Machines of this type have a simple specimen design that is relatively easy and cheap to manufacture. A major advantage is the ability to cover wide load and speed ranges to determine a material's performance under a wide range of conditions.

The pin-on-disc machine is the most common machine of this type, although a reciprocating motion is likely to be appropriate to more industrial wear problems.

The contact geometry is one of the most important parameters to consider in the design of a sliding wear test. The two possibilities are conformal or non-conformal contact.

The apparent major advantage of conformal contact is that if it can be achieved, the pressure distribution is constant and well defined even if considerable wear occurs. However, it is very difficult to achieve true conformal contact, so that one side of the samples comes into contact before the other as the surfaces contact. This gives a higher pressure than expected on one side

of the contact, leading to uneven wear. It is also true that although the stress distribution is well defined, it may be unexpectedly different from the stress that is required. Thus for a punch contacting geometry (flat ended cylinder), there is a singularity in the stress at the edge of the contact zone.

One method that is sometimes used as a way of achieving conformal contact is to “run-in” a test for a period until wear has taken place evenly across the complete area of the sample. The real test is then carried forward from this point. However, the run-in period may itself affect the subsequent wear and friction that occurs by modifying the nature of the wearing surface.

With non-conformal contacts, the initial contact pressure and stresses are well defined, but will change with time as any wear takes place and the contact area increases. For the commonly used test geometry of balls or spherically ended pins and flats, the Hertz equations give the nominal contact geometry and pressure distribution at the contact.

The environment of the test can be crucially important. It is now well established that for tests carried out in air, humidity can have a major effect on results. This occurs because of the reaction of water vapour with debris produced in the wear process, or with the worn surfaces themselves under the conditions of locally elevated temperature and pressure that are present at the wear contact. Depending on the materials under test and the test conditions, the wear rate can be increased or decreased.

When friction occurs in a tribological contact, heat will be generated. The temperature of the contact will be governed at least in part by the thermal environment of the samples which will define how well the heat is conducted away from the wear contact. Often, due to the inevitable compromises in design, a test system cannot fully replicate the thermal environment that occurs in the application. In this case it can be better to reduce the test speed so that the work done against frictional heating is reduced, and then to use additional heaters to increase the sample temperature to the relevant value.

The dynamics of the test machine can also have a major effect on results in wear testing. The factors that are of concern are the stiffness of the test system, any inertial loading, and any damping that may present. All of these factors affect the dynamics of how one sample moves against another, and therefore affect the transient loads that are applied between the samples, even for a nominally constant applied load.

The ideal situation would be to have a test machine where the machine dynamics could be altered to suit the dynamical constraints that are present in the application that is being simulated. One approach to this is to make the basic test system as stiff as possible, and to then reduce the stiffness of the contact in any given test by inserting compliant elements into the loading system for that test.