

# **Rotating Wheel Abrasive Wear Testing**

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# **Measurement Good Practice Guide No. 55**

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### **Abstract**

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

Specific guidance on how test conditions should be set and the procedures that should be used are given in Appendix A.

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# 1 Introduction

Friction and wear results from the interaction of contacting bodies that 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 indicated that the cost of wear to UK industry was of the order of £650 million per year. Also for companies who have 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. Furthermore, reductions in friction are often linked to reductions in wear such that as the friction is reduced, wear is also decreased.

This Measurement Good Practice Guide introduces the different wear mechanisms which occur in various types of industrial plant and machinery. It then focuses on the specific mechanisms that take place in abrasion.

This is followed by specific guidance on abrasive wear tests, and gives recommended procedures for the conduction of rotating wheel abrasion wear tests. This Measurement 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. It is published in parallel with a number of other Measurement Good Practice Guides on friction and wear testing on unlubricated sliding wear testing, ball cratering (microabrasion) testing of coatings, and gas borne particulate erosion testing [2-4].

## 2 Types of Wear

### 2.1 Different 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. 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 dragging 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 that takes place 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 occur in rolling contact where the passage of a ball or roller over a surface causes alternating tensile and compressive stresses, which can then 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.

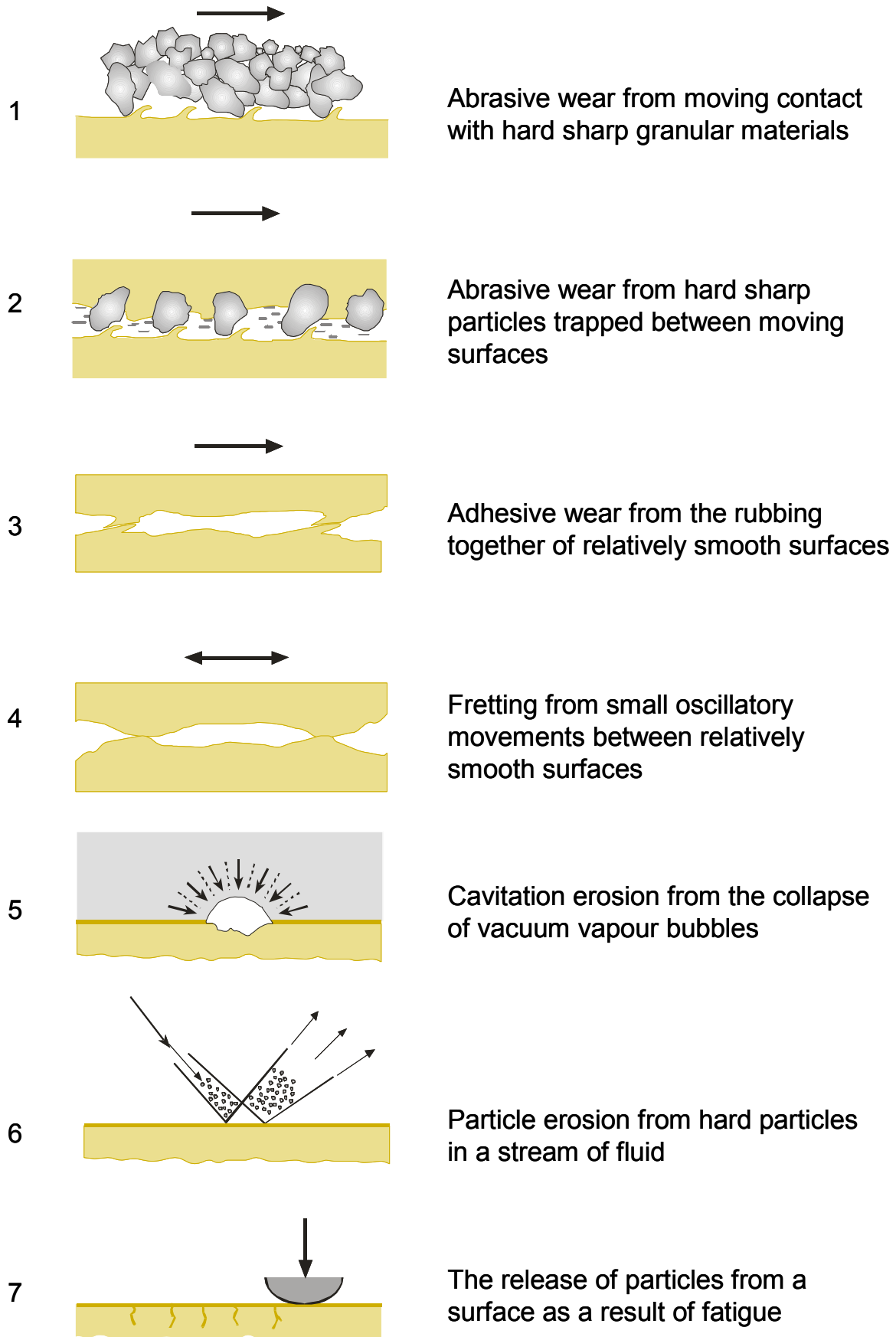
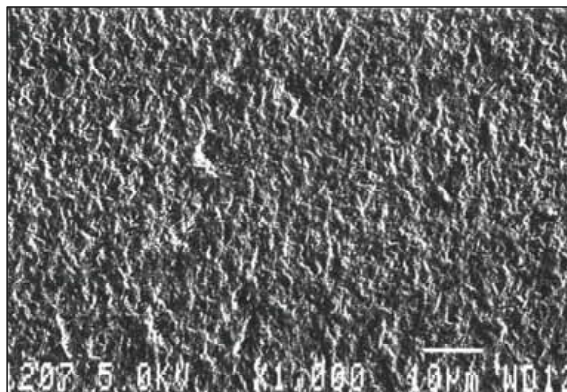


Figure 1, The types of wear that occur in industrial machines

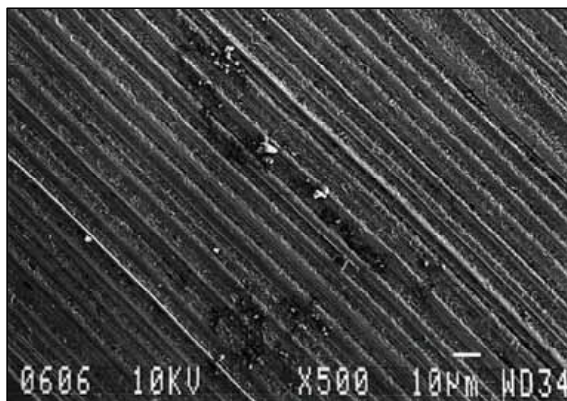
## 2.2 Terminology of Abrasion

Abrasive wear involves the presence of small hard particles and sliding surfaces. These particles may either be fixed to a counterbody leading to ‘two-body abrasion’ or be loose and free to slide and roll in ‘three-body abrasion’. It is better for many purposes to refer to the motion of the particles in the contact which leads either to ‘grooving (or sliding) abrasion’ or ‘rolling abrasion’ [5] (Figure 2). The conditions of abrasive wear are also sometimes classified as either ‘low stress’, in which the abrasive particles themselves are relatively undamaged in the wear process, or ‘high stress’, when the particles experience extensive fracture.

It should be noted that the terminology for abrasion is very confusing and contradictory, with a term such as “two body abrasion” having two contradictory definitions that are accepted in the literature. Thus, the abrasion of a surface by abrasive particles freely rolling down an inclined plane, and the abrasion of a surface by abrasive particles fixed in a grinding wheel are both termed “two body abrasion” by different authorities. This subject is cogently described in a recent paper [6] whose authors suggest that a classification scheme based on the severity of the wear is most appropriate.



a)



b)

Figure 2, Different types of abrasive wear, a) rolling abrasion; high abrasive concentration, b) grooving wear; low abrasive concentration. Tests performed in same conditions apart from abrasive concentration in ball cratering test on steel.

## 2.3 Mechanisms of Abrasion

Mechanisms of abrasive wear can involve both plastic flow and brittle fracture. Under some circumstances plastic flow can occur alone, but both sometimes occur together, even in materials conventionally thought of as ideally brittle such as soda-lime glass. The simplest models for abrasion assume that either plastic flow or brittle fracture is the dominant wear mechanism.

### 2.3.1 Plastic Deformation

For ‘two-body’ abrasion by hard particles, involving plastic deformation, an identical equation to the Archard wear equation [7] can be derived [8]. However, it is derived from completely different assumptions.

The equation is of the form:

$$V = K \frac{WS}{H}$$

Where  $V$  is the wear volume,  $K$  is the dimensionless wear coefficient,  $S$  is the sliding distance,  $W$  is the total applied normal load, and  $H$  is the indentation hardness.

This equation predicts that the volume of material removed should be proportional to sliding distance, as well as to normal load. This behaviour is often seen in practice. Pure metals also show fair agreement with the prediction that wear rate should vary inversely with hardness, but alloys often show more complex behaviour. Generally the benefits to wear resistance of increasing the hardness of an alloy are lower than would be predicted, unless the strengthening mechanism leads to increased strength at the high strains associated with abrasive wear. Fine carbides in steels, for example, do give such an increase, but precipitation hardening in aluminium-copper alloys does not. The equation also indicates that wear should be inversely proportional to bulk hardness, which is often obeyed, but in many cases it is not (Figure 14). The equation ignores strain (work-) hardening by plastic flow in the surface material; bulk hardness of the worn surface is often found to correlate better with abrasion resistance than hardness of the bulk material. One of the consequences of the high strains imposed by abrasion is that any cold work done on the metal before wear will have a negligible effect on its abrasive wear resistance

### 2.3.2 Brittle Fracture

Abrasive wear by brittle fracture is usually modelled by analogy with the crack patterns caused by a hard, sharp indenter [9]. Material removal is associated with the growth of lateral cracks towards the surface from beneath the indentation, or in scratching, from beneath the plastically-formed groove. Both hardness,  $H$ , and fracture toughness,  $K_{IC}$ , are important in determining the occurrence and extent of such fracture, and hence the rate of wear. Several

different models have been proposed, based on different underlying assumptions; such models predict wear rates which are inversely proportional to both  $H$  and  $K_c$ , raised to powers of about  $\frac{1}{2}$ . However, these models do not take account of the strong microstructural influences on wear rate in brittle materials such as polycrystalline ceramics, nor are they applicable to the wear of hard ceramic materials by rather softer abrasive particles.

Abrasion processes occur not only in engineering contacts, but also in nature. One example, involving large length scales, is associated with the movement of glaciers, which typically drag boulders along their path over the underlying bed of rock. Not only are the linear features of predominantly plastic grooving produced, but there are also often features associated with indentation fracture, in the form of partial cone cracks which leave characteristic crescent-shaped crack patterns on the rock surface [10].

At a much smaller scale, scanning probe microscopes have been used not only to study the topography of abrasion damage, but also to produce it. Controlled scratching by a single indenter provides a method of probing fine-scale mechanical properties, and has been applied, for example, to study the response of silicon on a sub-micrometre scale which reveals a significant size effect at very low loads [11]. Very recently, the use of multiple indenters to ‘plough’ furrows across solid surfaces and produce precisely controlled grooves has been demonstrated, as a novel method of device fabrication. Lithographic processing has been used to produce a silicon plough, which is then dragged across a surface coated with photoresist or with metal; cobalt wires only 150 nm wide have been made by this method [12].

### 3 Simulation of Abrasive 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, thus 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, counterface material, abrasive material, abrasive shape, abrasive size, test-piece surface condition and the test environment.

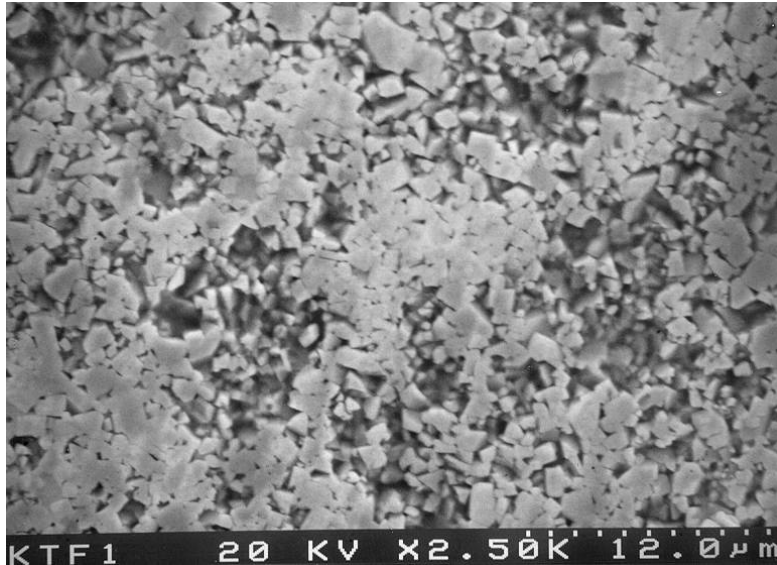
Control of some test parameters is normally straight-forward, but there are some areas where this is much more difficult to achieve. In particular, in abrasion testing the results depend very critically on the shape of the abrasive particles, with many observers noting quite large changes in the magnitude of wear for different abrasives that had very similar shapes [13].

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.

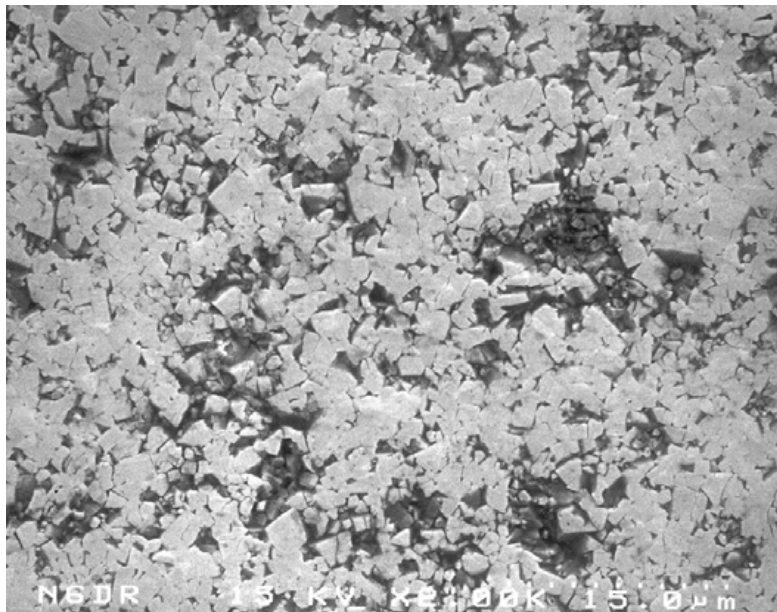
It is important to ensure that the results from laboratory tests compare well with observed performance in practice. The final test for any product is obviously that it performs as expected in real life applications. The aim of laboratory testing must be to supply data on friction and wear behaviour that, 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. Figure 3 shows an example where the examination of the surface of the worn concrete tile forming component and the laboratory

sample showed identical wear processes had occurred to both. The laboratory wear test was used in a study to explore more cost effective choice of materials.

Techniques for determining wear mechanisms are described in the companion Good Practice Guide on unlubricated sliding wear testing [2].



a)



b)

Figure 3, Comparison of worn surface, a) worn concrete tile tool, b) sample tested using rubber wheel test under alkaline aqueous conditions.

## 4 Test Machines for Abrasive Wear Testing

### 4.1 General Considerations

There is a strong need for robust methods for the laboratory study of abrasive wear for various purposes:

- to investigate fundamental wear mechanisms; to evaluate and compare wear rates of different materials
- to simulate and optimise related manufacturing processes (such as free-abrasive grinding, lapping and polishing)
- as quality assurance tests for engineered surfaces.

An early method of abrasion testing was to use a grindstone, and such a device was described by the Russian chemist and poet M V Lomonosov in 1752 [14]. Lomonosov listed it among the eight instruments required for a course in experimental chemistry, with the intention that the students should ‘investigate substances, especially metals, by long continued abrasion’. Several abrasive wear tests were developed during the early years of the twentieth century, but one of the few to be standardised was the dry sand rubber wheel test (ASTM G65) in which a stream of dry silica abrasive particles is fed into the contact between a flat specimen and a rotating rubber-rimmed wheel. This method has recently been modified to improve control of the experimental conditions and the influence of test parameters has been investigated in some detail [15]. Details of the various modifications made to the standards ASTM G65 rig are given in the next section.

There are many other different test machines that have been developed [1]. However, these can be reduced to a small number of basic types characterised by the constraint on the abrasive, and the presence or otherwise of a monolithic counterbody and the compliance of the counterbody. Table 1 describes the basic types of test system that are available.

**Table 1, Classification of abrasion test systems.**

| Counterbody         | None                        | Compliant                      | Stiff                                                                  |
|---------------------|-----------------------------|--------------------------------|------------------------------------------------------------------------|
| Abrasive Constraint |                             |                                |                                                                        |
| Fixed               | NA                          |                                | Grinding Wheel, Scratch Test, Abrasive paper                           |
| Free                | Slurry Erosion, Free Column | ASTM G65 and G105 Rubber Wheel | ASTM B611 Steel Wheel, Ball Cratering (Microabrasion), Miller Abrasion |

In this table the classification on abrasive constraint refers to the initial state of the abrasive, and not the state of the abrasive when abrasion takes place. Thus even in the ASTM G65 and 105 tests the abrasive sinks into the rubber counterbody that grips it and holds it stationary with respect to the rubber when abrasion takes place (see later discussion on counterbody and sample hardness).

## 4.2 Specific Tests

### 4.2.1 Fixed Abrasive – Abrasive Paper or Grinding Wheel

The simplest types 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 the degradation of the abrasive medium as the test sample is repeatedly moved against it. This has been recognised 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 [16].

#### *Test conditions*

Load; normally in the range 5-100 N

Speed; normally up to 1 m/s

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)

#### 4.2.2 Steel Wheel, Wet Abrasive Slurry, ASTM B611

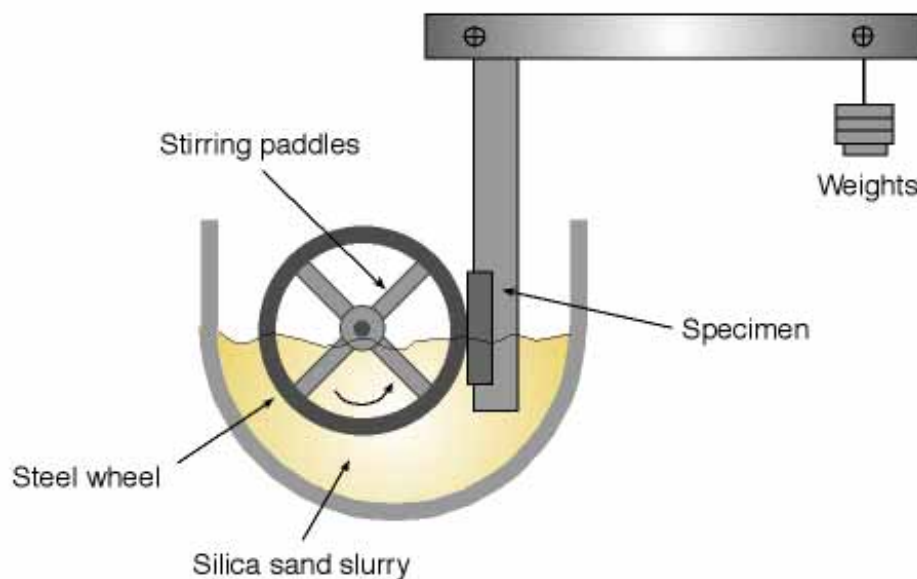


Figure 4, ASTM B611 test system

In the ASTM B611 test for hard metals used in mining applications [17], 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 stirring and lifting needs to be observed during the test to ensure that the operation is consistent. The abrasive specified in the test standard is alumina about 600  $\mu\text{m}$  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 as described in the Standard*

Test load; 20 N

Duration; 1000 revolutions of the wheel

Abrasive; alumina slurry, 30 mesh grit in proportion of 4 g to 1  $\text{cm}^3$  of water

Wheel speed; 100 r/min

Wheel diameter; 165 mm

##### *Measurements made*

Volume of wear

Examination of worn surface

### 4.2.3 Rubber Wheel, Wet Abrasive Slurry, ASTM G105

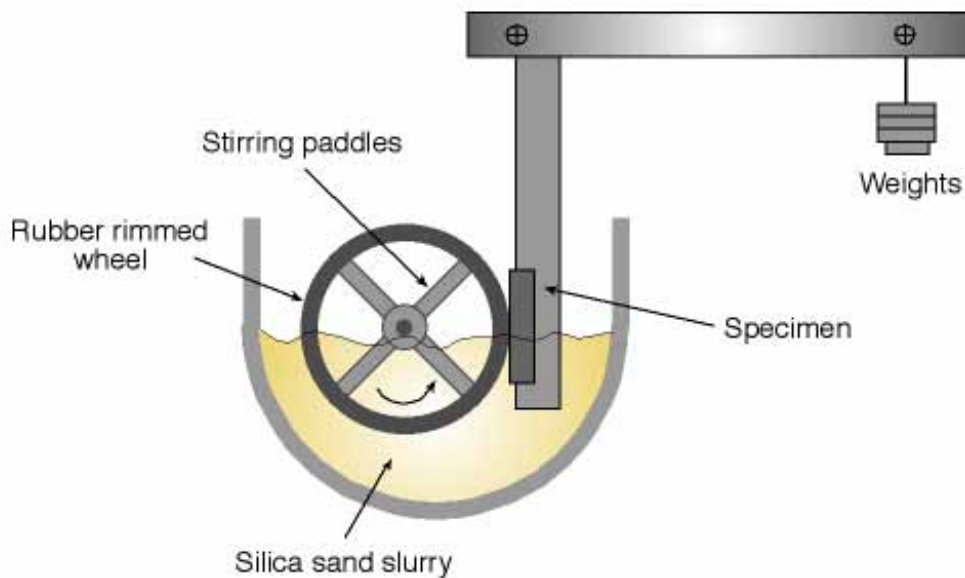


Figure 5, ASTM G105 test system [18]

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. 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. The test operation needs to be observed to ensure that adequate mixing is occurring. 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 as described in the Standard*

Test load; 222 N

Number of revolutions; 5000

Wheel diameter; 178 mm

Wheel speed; 245 r/min

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

#### 4.2.4 Loose Slurry Abrasive Testing

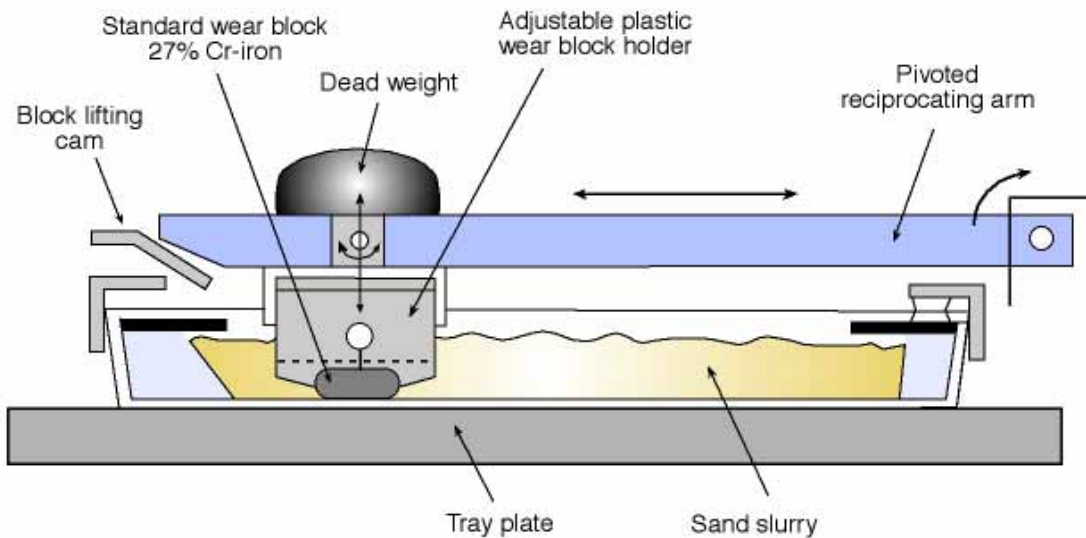


Figure 6, Miller abrasivity test, ASTM G75 [19].



Figure 7, Struers micro wear test based on an automatic polishing system

There are several loose slurry abrasive 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 machine where a sample is pressed into a dish of abrasive slurry. 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. This test is standardised as the Miller abrasivity test ASTM G75 to test the abrasivity of abrasives; it is also commonly used as an abrasion test [19].

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 especially difficult if large abrasives need to be used, and careful consideration needs to be given to strategies for mixing the abrasive slurry as the test proceeds. This is achieved in the Struers micro-abrasion test which uses a semi-automatic polishing system [20]. 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 (Figure 7).

#### *Test conditions*

Abrasive; silica, silicon carbide, alumina or other abrasive

Load; often in the range 5-100 N

Relative speed; up to about 0.5 m/s

Abrasive loading; up to 50 percent by weight loading (slurry needs to be of such a consistency that it can be pumped like a liquid)

Test duration; up to 6 hours

#### *Measurements made*

Volume of wear

Examination of worn surface

### **4.2.5 Rubber Wheel Abrasion Test; ASTM G65**

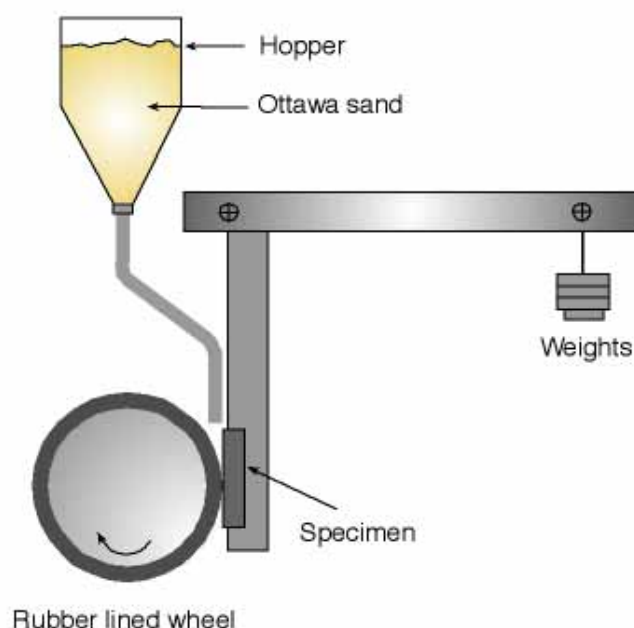


Figure 8, ASTM G65 test system

The ASTM G65 test [21] uses a rubber-rimmed wheel as the bed for silica abrasive that is fed from a hopper by a nozzle between the sample and the wheel. 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 the volume of material lost through mass loss and density measurements.

The flow of sand into the gap between the surfaces 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.

Developments of this standard test by placing the specimen on top of the wheel and feeding the abrasive, under controlled conditions, to the rising upper side of the wheel, give more consistent results. The properties of the rubber lining of the wheel also have a major effect on the results and need to be carefully controlled.

There are several limitations to the standard ASTM G65 test. The specimens are relatively large (76.2 x 25.4 x 12.7 mm) and are recommended to be used once only, the test is of long duration (5000revs for a wear resistant material) and hence uses large quantities of abrasive (3-4 kg per test). The standard only specifies one abrasive type (212-300µm Ottawa sand), which is not realistic for many applications. For these reasons many workers have made significant changes to this test system. These are described in the next section.

#### *Test conditions as described in the Standard*

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 r/min

Wheel diameter; 228 mm

#### *Measurements made*

Volume of wear

Examination of worn surface

### **4.2.6 Ball Cratering (microabrasion)**

There has been considerable interest in an abrasive wear test which is often called the ‘micro-scale abrasion test’ or ‘ball-cratering’ method. In this test a sphere or crowned disc rotates under a fixed load against the surface of the specimen in the presence of a slurry of abrasive particles, and a wear scar in the shape of a spherical cap is progressively formed in the surface. Although its development as a tribological test is relatively new, the method is well established for measuring coating thickness and also to prepare surfaces for rapid depth profile analysis. Its history, both for these applications and as a wear test, has been reviewed by Rutherford and Hutchings [22].

This particular test is the subject of another good practice guide [3] and will therefore not be described further here.

#### 4.2.7 Free Column Test

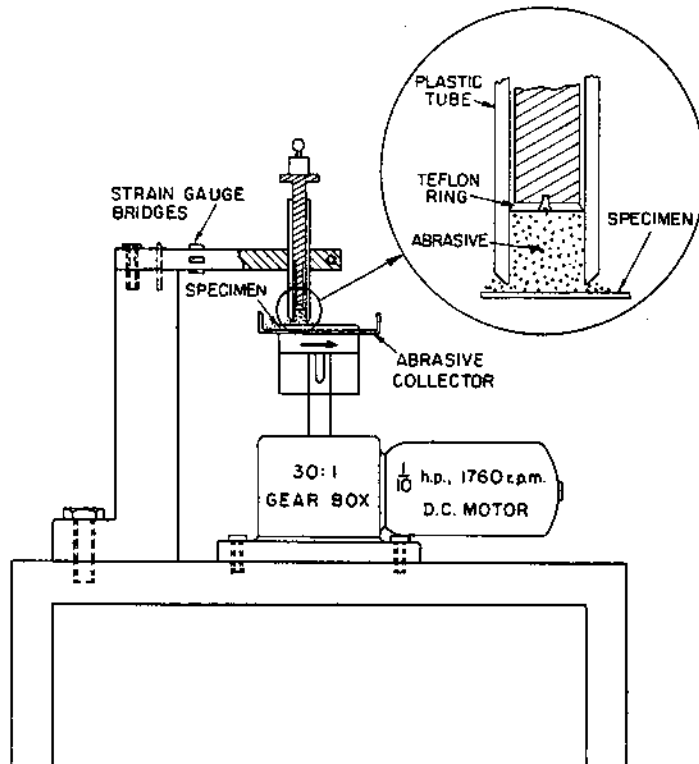


Figure 9, Free column test system, reference [23].

Another relatively popular test that has had some popularity is the free column test where a tube filled with abrasive is placed against a rotating sample. The abrasive is pressed onto the sample with a weight placed into the open top end. Wear is measured by mass loss measurements and a knowledge of the sample density.

This test is the only one where dry abrasive is used in which the only constraint on the movement of a single particle is the other abrasives packed around the particle. The gap between the end of the tube and the rotating sample is an important parameter. Thus, if the gap is large the abrasive flows between the tube and the sample, giving a free flowing condition where a single abrasive particle is quickly removed from contact with the sample. When the gap is small the same abrasive particle remains in contact with the sample for a long period.

## 5 Variants of the ASTM G65 Test

One of the most common abrasion test systems is the ASTM G65 test. The standard format of the ASTM G65 test has been modified to different, and sometimes similar, designs by several groups of researchers in order to increase flexibility (to enable the test to run under different environmental conditions) or to improve repeatability.

## 5.1 Feed Mechanism Changes

Simple changes have been made to the feed mechanism of the ASTM G65 test system by Grigoroudis and Stephenson [24]. An auger screw feeder was added to the system to feed the abrasive in a controlled manner into the nozzle of the ASTM G65 test system. This gives very accurate and reproducible control of the abrasive feed rate.

The basic ASTM G65 format has also been modified in a design reported by Ellis and Armstrong [25]. The design was altered to give greater flexibility in terms of abrasive type, abrasive particle size, nominal particle loading, particle packing density, speed and moisture level. The method is shown in Figure 10; it uses a small chamfered specimen loaded horizontally onto the peripheral surface of a relatively large wheel. The abrasive particles pass out of a feed hopper via a vibratory feed unit (which regulates flow rate) and a horizontal feeder onto the wheel, in front of the specimen and are then drawn between wheel and specimen. When saturated conditions are required, water is introduced to the wheel surface ahead of the abrasive particles. Abrasive grits pass under the specimen once only. For a given wheel speed, selection of a specific particle feed rate affords control of the packing density of the particle monolayer in the wheel specimen interface region. Nominal particle loading is then controlled by selecting appropriate values for applied load. A large wheel diameter:specimen contact length ratio was adopted and both specimen and wheel widths are identical so that after a brief running in period the whole of the specimen wear surface conforms to the curvature of the wheel.

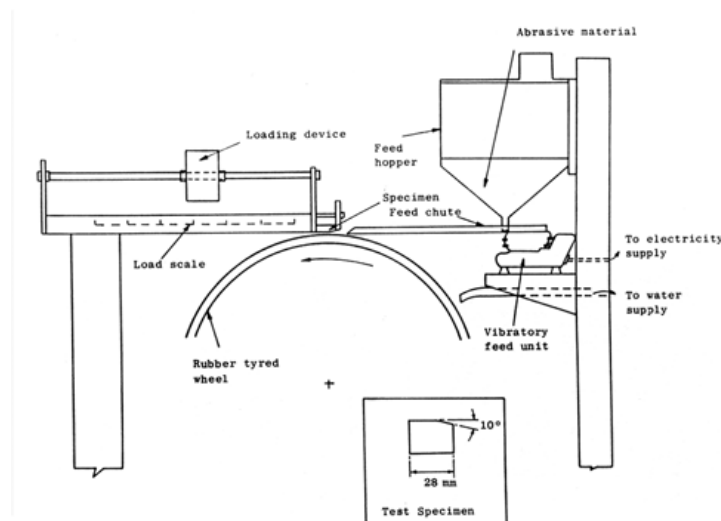


Figure 10, Test system developed by Ellis and Armstrong

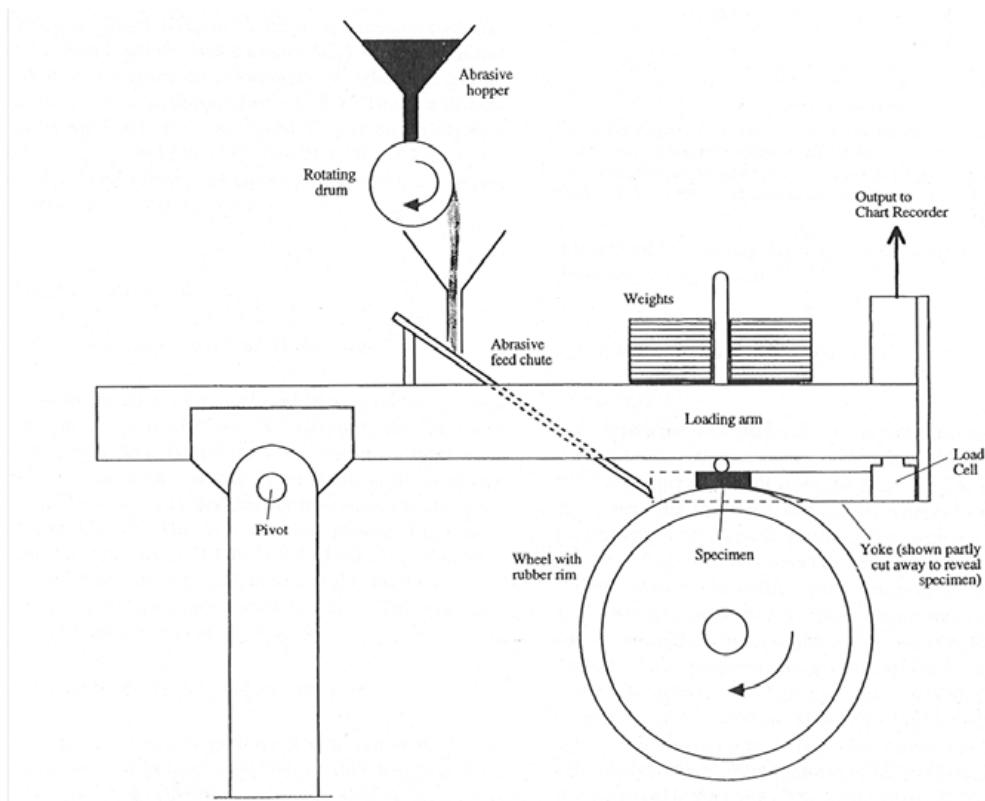


Figure 11, Test system developed by Stephenson and Hutchings.

Another rig, illustrated in Figure 11, has been designed by the University of Cambridge [15]. Like the rig reported by Ellis, it utilises a horizontally orientated specimen, but in other important aspects, it is different from both the Ellis rig and the standard ASTM G65 format. The horizontal specimen is loosely constrained in a yoke, and the normal load is transferred to the specimen by contact with a fixed ball pressing against its upper surface. This allows the specimen to “float” freely on the wheel. Loads are applied by adding weights to the arm directly above the specimen. The other principal change to the standard format is the abrasive feed system; it gives a constant feed rate and produces an even monolayer of particles on the wheel. The abrasive feed rate is controlled by a rotating drum with a shallow groove on its surface, driven by a variable speed motor. The width of the groove matches the internal diameter of the base of a sand hopper in contact with the drum. Abrasive flows freely down the inclined aluminium chute at angles steeper than approximately  $40^\circ$  from the horizontal. Some abrasive is lost from the edge of the wheel, but this can be quantified by collecting it separately from the sand which passes through the specimen contact. The quantity of abrasive actually passing the specimen can be determined in this way, which is not possible with the ASTM design.

## 5.2 Sample Orientation

In a design reported by Wirojanupatump and Shipway [26] the specimen is held at  $40^\circ$  to the horizontal (see Figure 12) in an inclined specimen holder in order to allow both slurry and dry abrasive to pass over the specimen surface. The specimen is the same width as that of the

wheel (12.7 mm). Both the specimen and the wheel sit in a trough (width 12.9 mm) in the specimen holder so that the abrasive medium is constrained to pass through the wear zone. The wheel is driven directly from a d.c. motor; both are mounted on a lever arm, and can be loaded against the specimen by the application of weights as shown. One advantage of this system is that the slider mount on the moment arm can produce an infinitely variable applied load. The pivot for the wheel/lever assembly lies on the line of the tangent between the wheel and the specimen to ensure that frictional forces generated here do not affect the applied load.

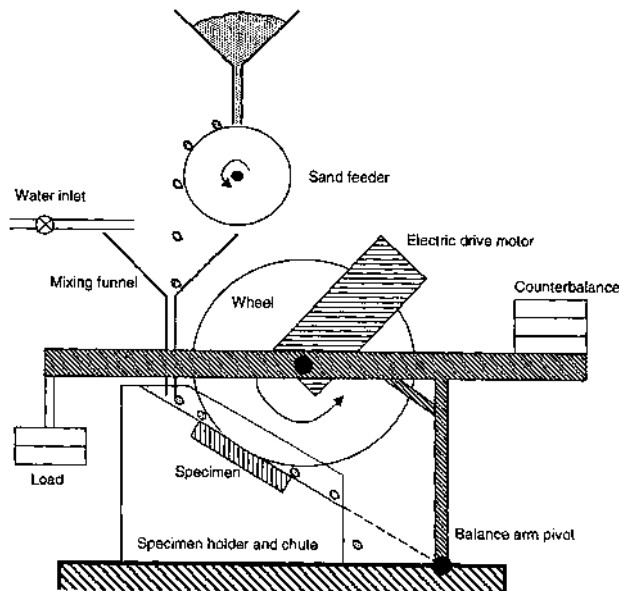


Figure 12, Test system developed by Wirojanupatump and Shipway

### 5.3 Enclosed Bath

A rather different setup has been devised at the Universität Erlangen-Nürnberg [27]. The system is basically a hybrid of the ASTM G65 and ASTM G105 type tests and is illustrated in Figure 13. The specimen is pressed against a wheel rotating at 100 rpm (10mm thick, 195 mm diameter, with side paddles). The normal load is applied in the horizontal direction by means of a linear guide bar and a cantilever arm. The arm carries a weight which may be fixed in any position along its length, thus changing the moment and producing an infinitely variable applied normal load. The wheel is continuously wetted by a controlled flow which wets the wheel upstream of the abrasive delivery. The abrasive is stored in a sand box above the rotating wheel (and outside the main enclosure). Abrasive flow is regulated by a type of paddle wheel and is delivered onto the wheel close to the contact area between wheel and specimen. Thus there is an abrasive slurry produced which passes through the specimen/wheel interface with a fixed abrasive/water ratio. With this rig the friction force and normal force can be measured with two load cells. The wear depth produced in the specimen is measured with an inductive displacement transducer. All these parameters, together with the flow rate of the medium (measured by a flowmeter) are recorded online. As with most of the variants of ASTM G65, the normal load is applied perpendicular to the wheel tangent during the entire test. In this case it is achieved by using a linear guide bar, constraining the

applied force to the horizontal direction. This rig is especially suited to the use of corrosive media due to its entirely enclosed nature.

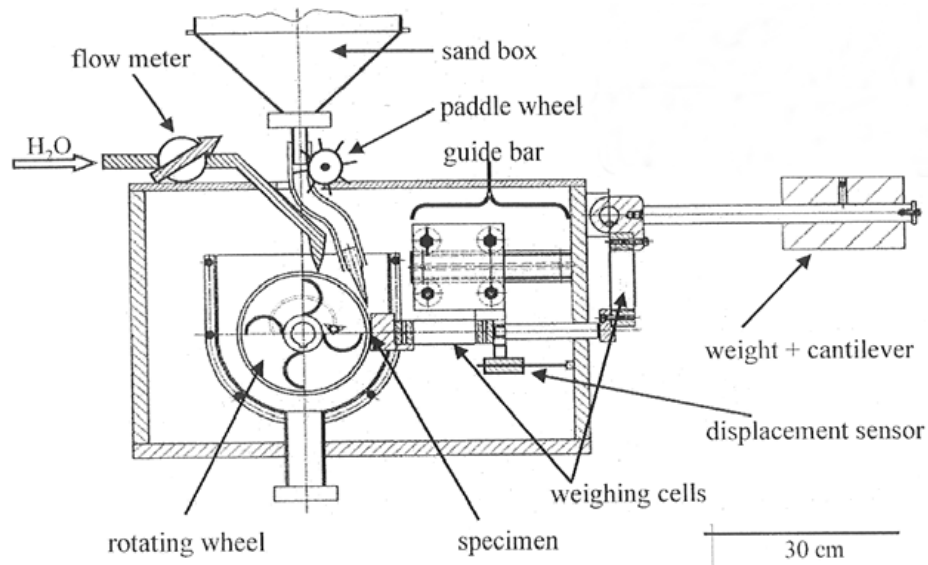


Figure 13, Test system developed by Herr et al

## 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 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. 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.

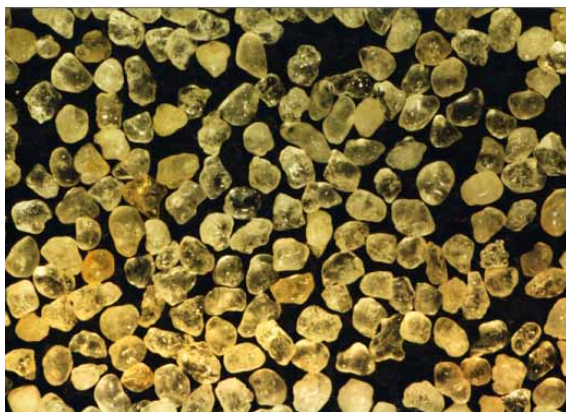
Mapping techniques can be used where two (or more) factors are changed in a controlled way (normally more coarsely than in parametric studies) with the friction and wear results plotted either as individual points or as contours. Regions on the map are then delineated on a mechanistic basis, with the 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 [28,29]. 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.

## 6.2 Specific Parameters

### 6.2.1 Abrasive

Many different abrasives are encountered in practical abrasion problems, but in many cases most of the abrasion in any situation will be caused by one particular abrasive. The most common natural abrasive is crystalline silica (quartz) with an indentation hardness (Vickers or Knoop) of about 1100 HV. Other abrasives that are often used are alumina, with a hardness of about 200 HV, and SiC with a hardness of 2800 HV. Figure 14 shows some photographs of common abrasives.



a)



b)



c)

Figure 14, Some common abrasives, a) rounded quartz about 200  $\mu\text{m}$  in size, angular alumina abrasive about 600  $\mu\text{m}$  in size, c) SiC abrasive about 4  $\mu\text{m}$  in size

### 6.2.1.1 Abrasive Hardness

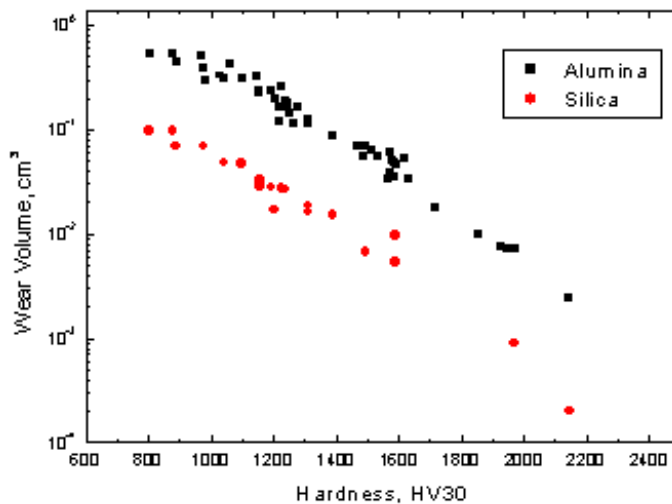
The hardness of the particles influences the rate of wear: particles with lower hardness than that of the surface cause much less wear than harder particles. It is found empirically, and can also be demonstrated theoretically, that for a solid particle to indent or damage a surface by scratching through plastic deformation, its hardness (as determined by an indentation test) must exceed that of the surface by at least a factor of  $\sim 1.2$ . This observation forms the physical basis for the Mohs scale of hardness, devised in 1824 and is still widely used by mineralogists [30]. Integer hardness values are assigned to a series of ten standard minerals, chosen so that each will scratch all those below it on the scale and itself by scratched by all those above it. The ratio of indentation hardness between neighbouring minerals (except diamond) is  $\sim 1.6$ , which allows a wide range of hardness to be spanned with only ten standards.

It is clear that even a martensitic steel is likely to have a hardness less than 1.2 times that of quartz, and it is therefore clear that steels and non-ferrous metals will be especially vulnerable to abrasive wear by natural quartz particles. Materials containing hard phases such as cermets and hard-facing alloys often contain softer constituents. Ceramic materials, in contrast, may be sufficiently hard and homogeneous to suffer little plastic deformation from common abrasive particles, and can thus offer valuable wear resistance when used as bulk materials or coatings. It is evident that very hard abrasive particles, such as silicon carbide, alumina or diamond, must be used to grind or polish such materials.

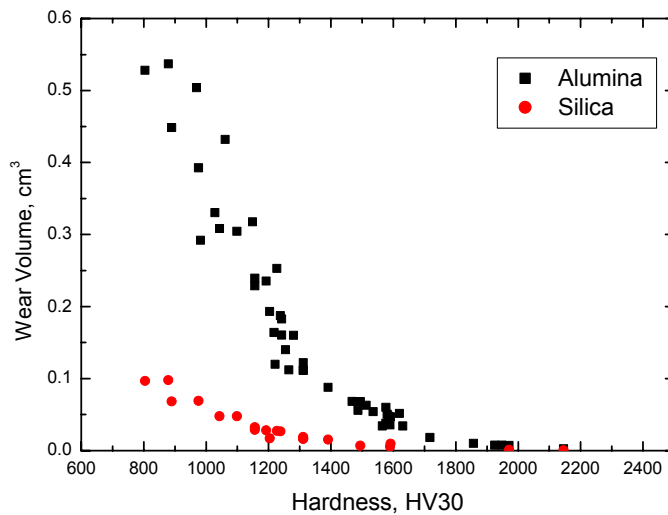
Figure 15 shows the effect of using two abrasives of different hardness in wear tests using the ASTM B611 steel wheel. The alumina abrasive, with a hardness of  $\sim 2000$  HV gives wear about an order of magnitude higher than the silica abrasive with a hardness of  $\sim 1100$  HV. However, perhaps surprisingly, for this class of materials there is no sharp change in the magnitude of abrasive wear as the hardness of the hardmetals exceeds 1.2 times the hardness of the silica. This is because abrasion occurs mainly by microfracture processes in these materials.

### 6.2.1.2 Abrasive Size

In controlled laboratory studies, it has been found that there is a size effect in terms of abrasion resistance; larger particles are more effective at material removal. This has been seen over a wide range of conditions [31]; not only in wear by hard particles (erosion, 2-body abrasion and 3-body abrasion), but also in indentation experiments and scratch testing. It is thought that the size effect is due to high local flow stresses in smaller volumes of material being higher due to the difficulty in nucleating and moving dislocations in a small volume of material.



a)



b)

Figure 15, Difference in abrasion volume for alumina and silica abrasives in tests on hardmetals, a) logarithmic volume scale, b) linear volume scale.

### 6.2.1.3 Abrasive Shape

The response of a material to abrasion is also dependent on the shape of the abradant particles; angular particles causing more wear than more rounded ones, in general terms. For materials that deform primarily by plastic deformation processes, angular particles tend to promote a “cutting” mode in which material is deflected through a shear zone and flows up the front face of the particle to form a chip. This is the same process which occurs when using a single-point tool in an orthogonal machining process. The other principal mode is “ploughing”; a ridge of deformed material is pushed along, ahead of the particle. In this mode no material is removed from the surface; material from the raised ridge flows beneath the particle. The reason for abradant angularity being important as far as material removal is concerned is that sharper particles tend to promote cutting rather than ploughing of the surface; cutting is far more effective at material removal. There is also a third deformation mode; wedge formation, in which limited slip, or even complete adhesion occurs between the front face of the particle and a raised “prow” of material.

The above-mentioned are idealised modes of deformation, assuming rigid-ideal plastic behaviour; it does not take into account work-hardening, nor that when cutting or wedge formation occurs, that not all the material displaced by the particle is removed as wear debris.

Angular particles also normally result in higher abrasion than rounded particles for more brittle materials such as ceramics and cermets. Here the angular points on the particles raise the stresses at the contact between the particle and the sample, promoting loss of material through fracture.

3-D particle shape is a difficult concept to quantify. One of the simplest is roundness factor (F) which is based on the perimeter and area of a 2-D projection of the particle [9]. F is defined as the ratio between the actual area A of the projection and the area of a circle with the same perimeter P as the projection:

$$F = \frac{4\pi A}{P^2}$$

by inspection it can be seen that for a circle,  $F=1$ .

Figure 16 shows results where the particle “roughness” was measured by this type of approach [32], and the volume of abrasion for steel samples correlated with this parameter. As expected, the magnitude of wear increased as the angularity of the particles was increased.

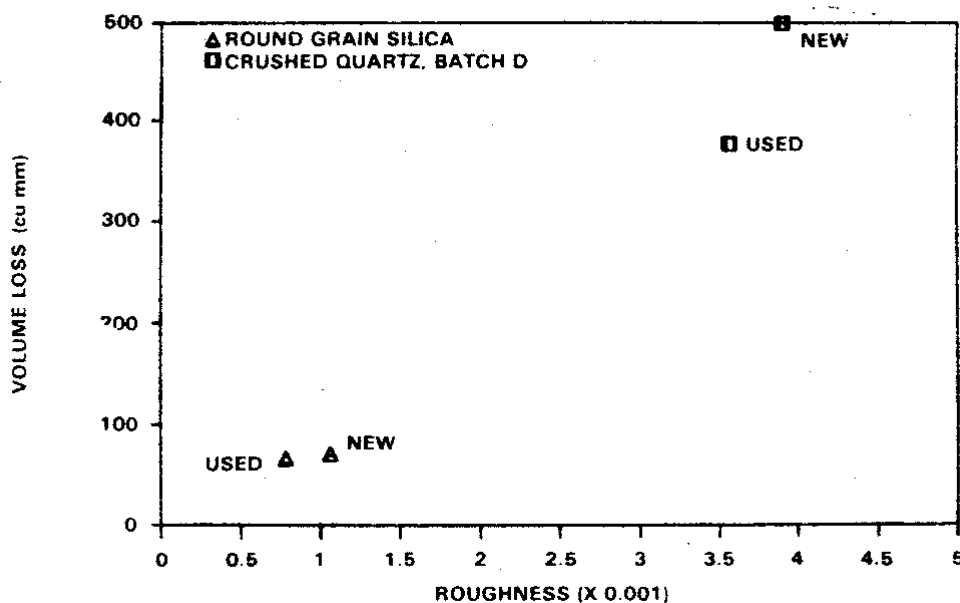
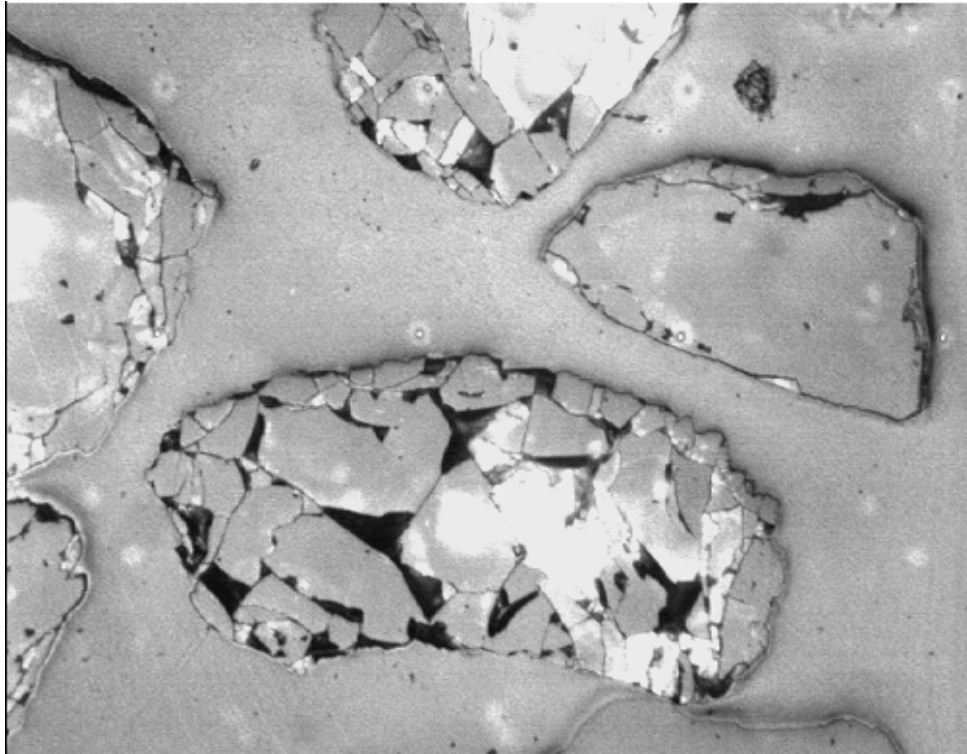


Figure 16, Correlation of abrasive wear with roughness or angularity of abrasive particles. Reference 32.

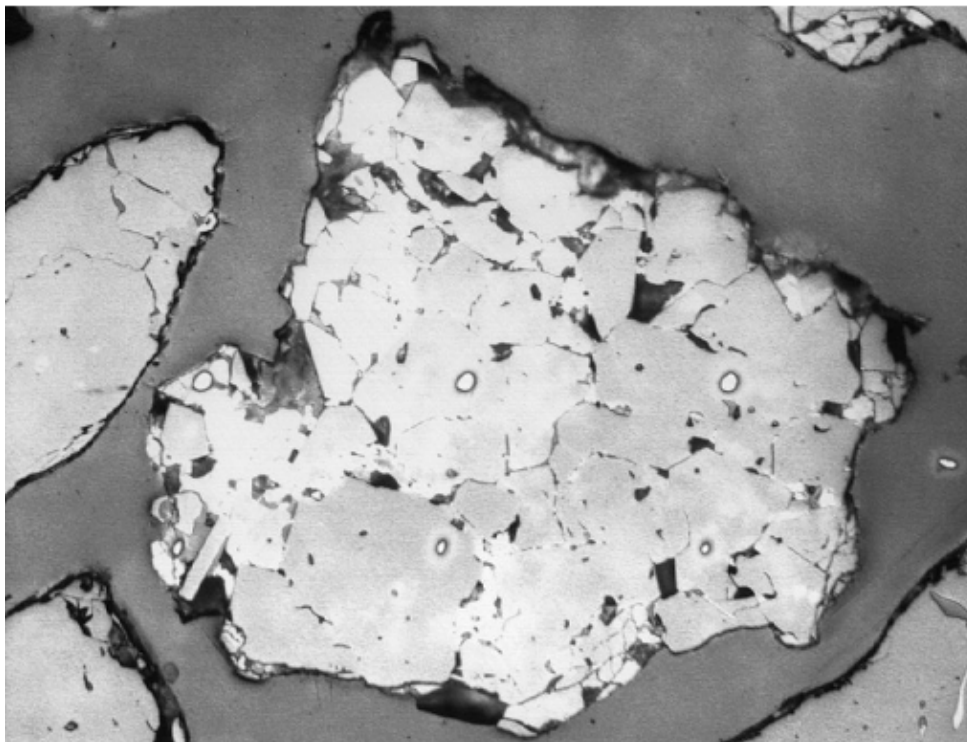
#### 6.2.1.4 Abrasive Condition

The condition of the abrasive can also be important. Thus abrasive particles that appear to be single particles have been revealed to contain multiple fractures that will cause the particle to fail easily when pressed against the surface that is being abraded (Figure 17). This will release sharp angular corners on new smaller abrasive particles so leading to increased wear.

Abrasive grains can also be polycrystalline, in some cases giving higher strength than single crystal grains with less possibility of particle failure.



a)



b)

Figure 17, Internal structure of abrasives, a) 200  $\mu\text{m}$  silica abrasive; note internal fractures, b) 500  $\mu\text{m}$  alumina; note polycrystalline structure.

### 6.2.1.5 Abrasive Concentration

The effect of changing abrasive concentration is normally to cause a proportional change in the abrasion (Figure 18) [33]. This is because the abrasion is normally caused by single abrasive particles, and whilst the concentration is such that there are few interactions between the abrasive particles, this will be true. At high abrasive concentrations, the interactions between the particles cause the linear relationship to break-down.

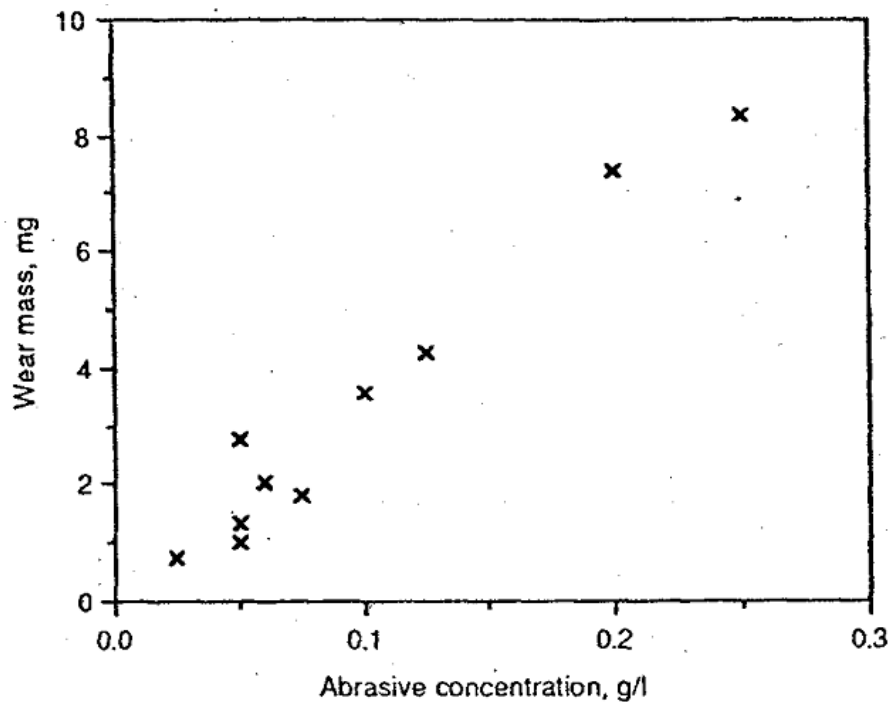
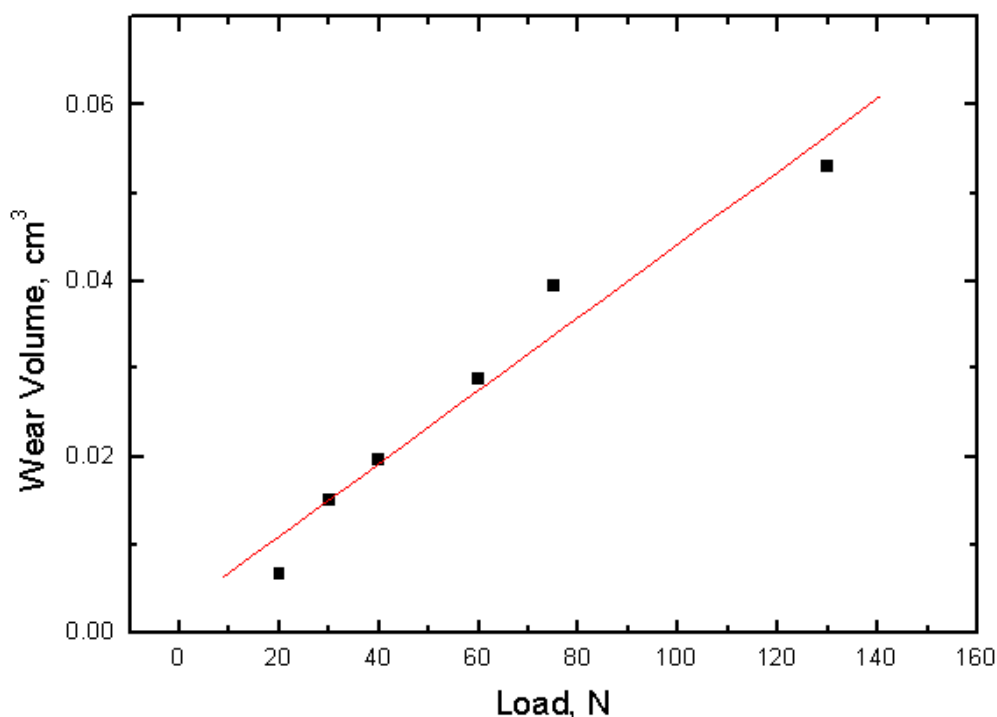


Figure 18, Increase in abrasive wear as abrasive concentration increases. Reference [33].

The above is true only if there is no change in mechanism with the increase in concentration. This does sometimes occur. Thus in ball cratering, an increase in abrasive concentration has wear



t the  
o be  
m to  
g to

b)

Figure 19, Effect of test load on abrasive wear volume, a) tests on steel with no mechanism change, b) tests on hardmetals with change from rolling to grooving wear above 130 N (the different symbols are different grades of material). In this case the variation in wear with different grade is small compared with the large effect of load through mechanism change.

### 6.2.2.2 Speed

The role of speed in abrasion is not clear. It is true that as the speed of an abrasive particle is increased, the heat that is generated at the contact between the abrasive particle and the sample is increased, leading to increased temperatures and possible alteration of the local mechanical properties of the sample. However, the bulk temperature increases that have been measured during abrasion are modest [15], and are unlikely to cause major changes in the wear that is found for high melting temperature materials where the changes in mechanical properties of the samples are not likely to be large. Nevertheless, in the ASTM G65 test, the rubber hardness can be reduced markedly by heating in the dry test leading to significant errors in measurement if this factor is not controlled by making sure that the wheels cool down after each test. None of these considerations explain the significant effect of speed that was observed for ASTM G65 tests on steel (Figure 20) [15].

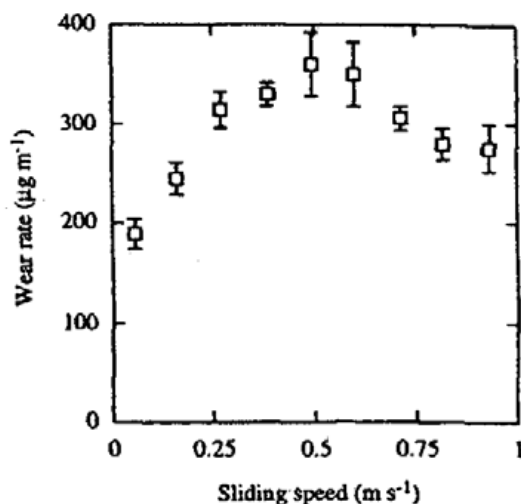


Figure 20, Effect of sliding speed on ASTM G65 abrasive tests on steel. Reference [15].

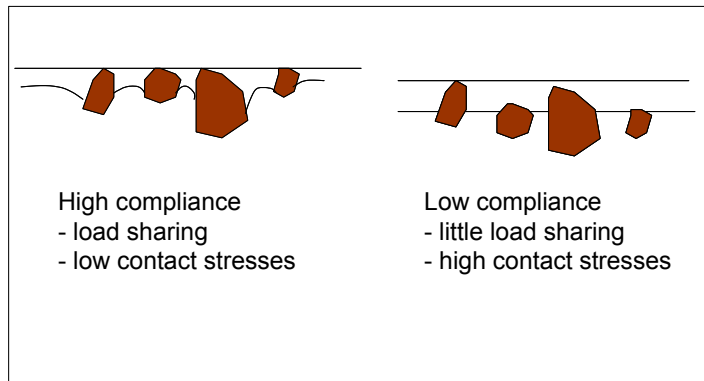
### 6.2.2.3 Counterface Material

There are several counterface material properties which can affect abrasion rates. Counterface compliance or hardness can determine both the load sharing between abrasive particles, the extent to which grooving (2-body) or rolling (3-body) abrasion can occur, and whether crushing of the abrasant takes place (Figure 21). Using a hard, non-compliant material, there are few particles to carry the load, but they tend to operate in the “cutting” regime, thus producing far higher wear rates than using a more compliant counterface (such as rubber) where the load is borne by far more particles, and hence the load borne per particle is far lower. With a non-compliant counterface the stresses on each individual particle are also much higher leading to a higher risk of particle fracture.

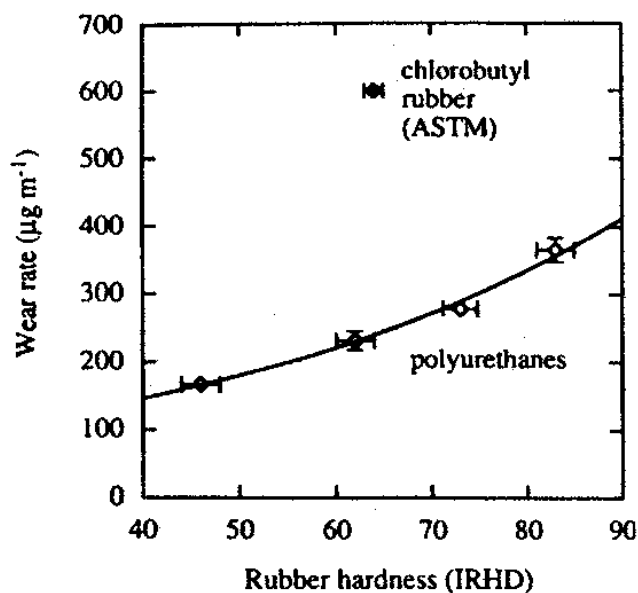
The compliance or hardness of the counterface also affects the constraint on movement for the abrasive particle. Thus in Figure 22, the particles embedded in the rubber are not free to rotate

so that grooving wear is encourage. By contrast, for two hard surfaces (two steels) rolling of the abrasive particles occurs more readily [34].

Counterface surface roughness can also dramatically affect wear rates; in the micro-abrasion test (ball cratering) it has been found that the counterface (i.e. the ball) must be of a minimum surface roughness to effect entrainment of the ( $\mu\text{m}$ -sized) abrasive particles [35].



a)



b)

Figure 21 Effect of compliance and hardness of counterface, a) schematic showing embedding and load sharing for high compliance versus low compliance counterface, b) effect of rubber hardness and composition on wear of steel in ASTM G65 test [15].

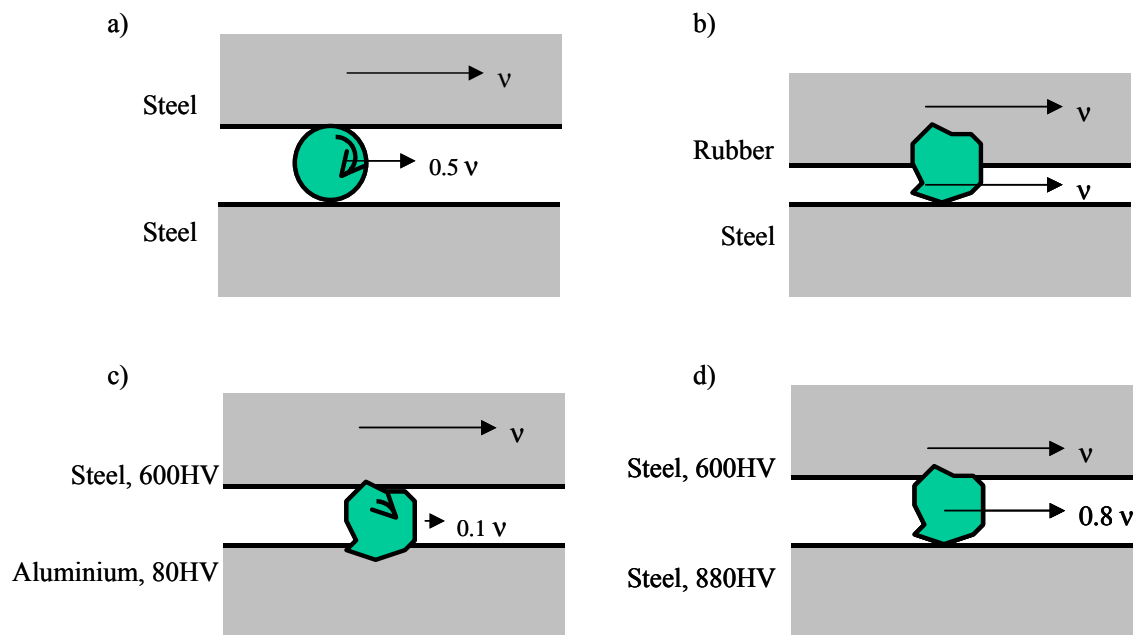


Figure 22, Effect of relative hardness between counterface and sample, a) steel-steel with ball bearing, b) rubber-steel abrasive particle, c) steel-aluminium abrasive particle, d) steel, steel abrasive particle. Figure adapted from reference 34.

#### 6.2.2.4 Environment

The environment of the test has a major effect on the magnitude of wear. In particular, the presence of a fluid normally reduces wear (Figure 23). There are several potential reasons for this, including cooling the sample. However, the most likely explanation is that wetting the interface between the abrasive particle and the sample reduces frictional forces and thus reduces the stresses acting between the abrasive and the sample so that less deformation and fracture can occur.

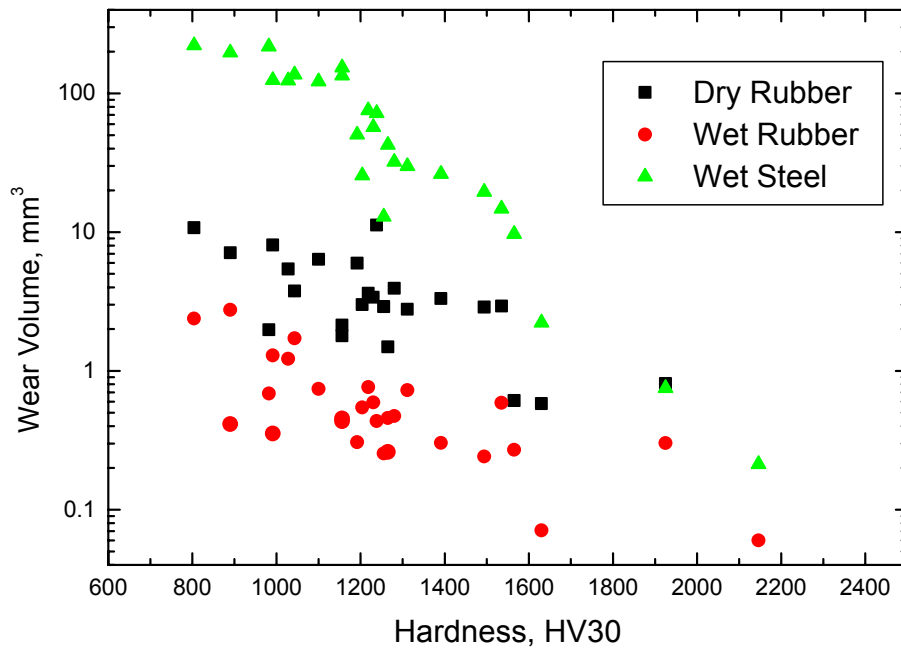
Different chemical media can also have a large effect due to the possibility of corrosion as well as wear (Figure 24). When corrosion can occur, the increase in material loss can be dramatically increased beyond that due to either wear or corrosion alone. This is due to the synergistic effect between corrosion and wear where abrasion can cause increases in corrosion by the removal of eg passivating films, and corrosion can cause increases in wear due to chemical attack and weakening of the structure of the surface [36,37].

#### 6.2.2.5 Accelerated Tests

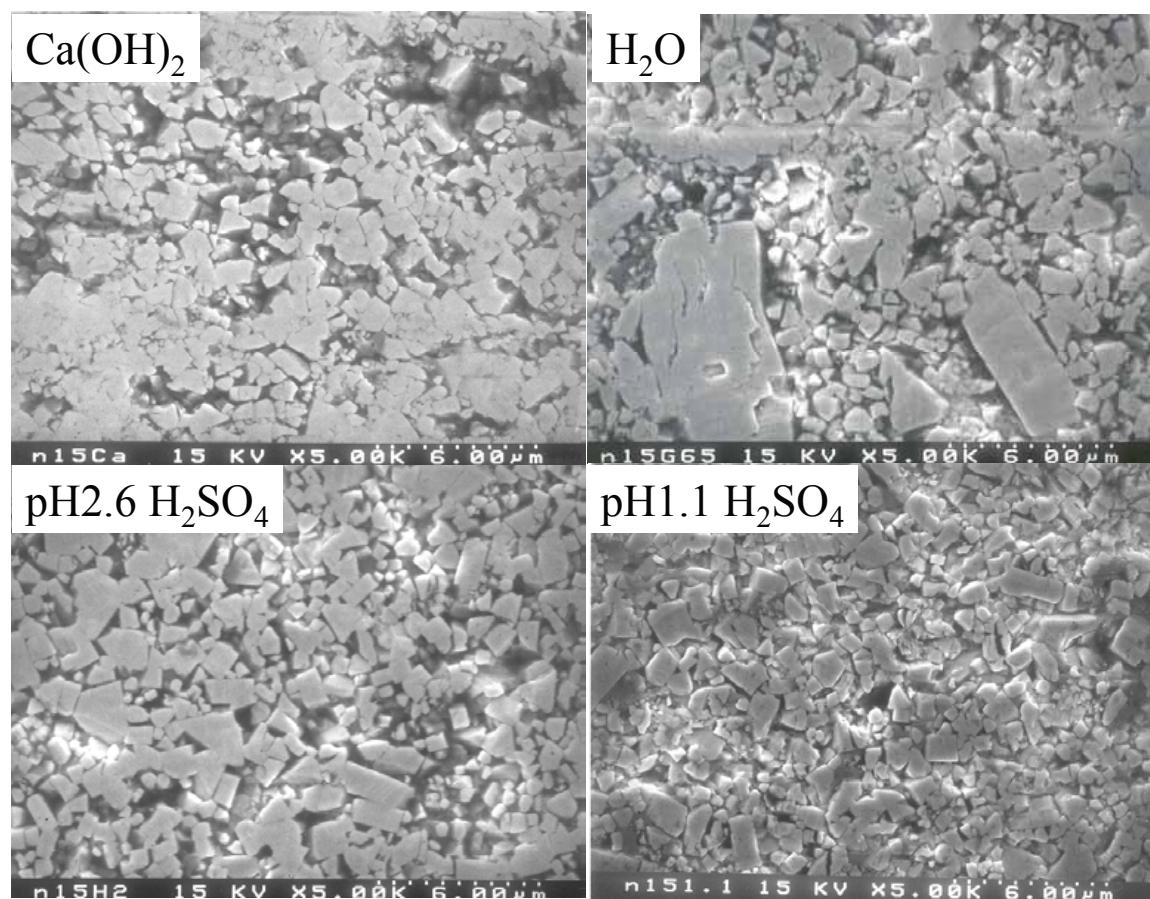
Since wear components are expected to have a long life in many applications, it is tempting to try to perform accelerated testing where the timescale of the laboratory tests has been reduced to a more practical level. This is normally attempted by increasing the load and/or speed so that wear takes place 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.

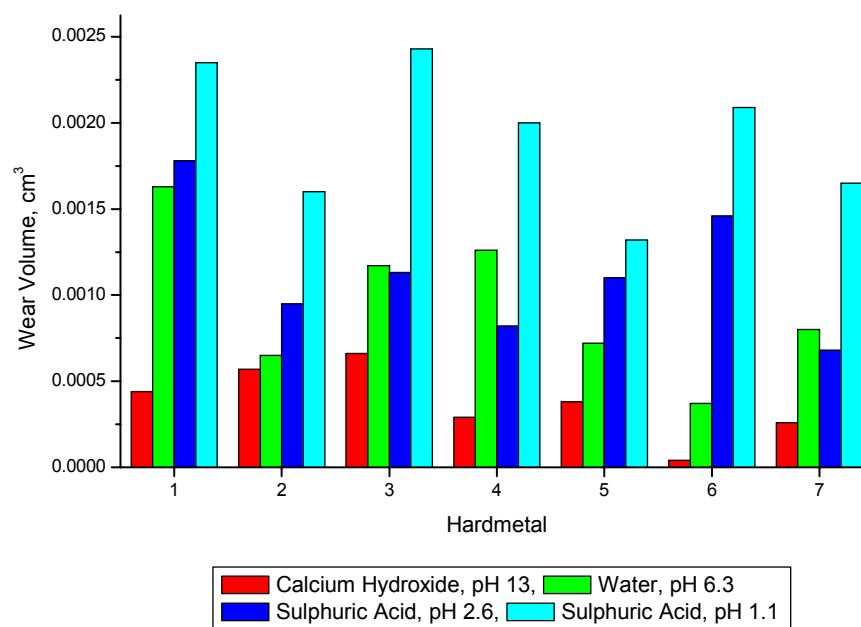
Figure 23, Results of ASTM G65 tests on hardmetals showing reduction in wear for tests



carried out in wet conditions with rubber wheel compared to dry conditions.



a)



b)

Figure 24, ASTM G65 abrasion in different media for hardmetals, a) wear volume results for 7 hardmetals, b) worn surface for one grade tested in different media.

## 7 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 an abrasive 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.

## 8 References

1. M J Neale, and M G Gee, Guide to Wear Problems and Testing for Industry, Professional Engineering Publishers, 2000.
2. M G Gee and M J Neale, General Approach and Procedures for Unlubricated Sliding Wear Testing, NPL Good Practice Guide No 51, January 2002.
3. M G Gee, Abrasion Testing for Coatings and Wear Resistant Materials by Ball Cratering, NPL Good Practice Guide, to be published, May 2002
4. M G Gee and B Richards, Erosion Testing, NPL Good Practice Guide, to be published, May 2002.
5. R I Trezona, D N Allsopp and I M Hutchings, 'Transitions between two-body and three-body abrasive wear: influence of test conditions in the microscale abrasive wear test', *Wear* 225-229 (1999) 205-214.
6. J D Gates, Two-body and three body abrasion: A critical discussion, *Wear* 214 (1998) 139-146
7. J F Archard, 'Contact and rubbing of flat surfaces', *Appl. Phys.* 24 (1953) 981-988.
8. E Rabinowicz, Friction and wear of materials, John Wiley, 1965.
9. I M Hutchings, Tribology: friction and wear of engineering materials, Arnold, London, 1992.
10. M Hambery and J Alean, Glaciers, Cambridge University Press, 1992.
11. B Bhushan, J N Israelachvili and U Landman, 'Nanotribology: friction, wear and lubrication at the atomic scale', *Nature* 374 (1995) 607-616.
12. S P Li, A Lebiib, D Peyrade, M Natali and Y Chen, 'Micropillow lithography and fabrication of submicrometer magnetic structures', *Applied Physics Letters* 77 (2000) 2743-2745.
13. J Ellis, Private communication.
14. B N Menshutkin, Russia's Lomonosov, Princeton University Press, 1952.
15. A N J Stevenson and I M Hutchings, 'Development of the dry sand/rubber wheel abrasion test', *Wear* 195 (1996) 232-240.
16. M M Kruschov, and M A Babichev, Investigations into the Wear of Metals, USSR Academy of Sciences, 1960.
17. ASTM Standard B611, 'Standard Test Method for Abrasive Wear Resistance of Cemented Carbides'.
18. ASTM Standard G105, 'Standard test method for conducting wet sand/rubber wheel abrasion tests'.
19. ASTM Standard G75, 'Standard test method for determination of slurry abrasivity (Miller number) and slurry abrasion response of materials (SAR number).
20. E Fundal, The Struers Micro Wear Test, Structure, No 20 (1989) 3-4.
21. ASTM Standard G65, 'Standard test method for measuring abrasion using the dry sand/rubber wheel apparatus'.
22. K L Rutherford and I M Hutchings, 'Theory and application of a micro-scale abrasive wear test', *Journal of Testing and Evaluation* 25 (1997) 250-260.
23. G Stevick, S Soemantri and I Finnie, An analysis of the loaded abrasive column type of wear tester, *Wear* 101 (1985) 77-80
24. K Grigoroudis and D Stephenson, Modelling low stress abrasive wear, *Wear*, 213 (1997) 103-111

25. J Ellis and B M Armstrong, Evaluation of Wear Resistant Materials for Use in Materials Handling Systems, Report Number SL/CS/P/13/90/O, British Steel Technical, Swinden Laboratories
26. S Wirojanupatump and P H Shipway, 'A direct comparison of wet and dry abrasion behaviour of mild steel', *Wear* 233-235 (1999) 655-665.
27. M Herr, T Sailer, H G Sockel, R Schulte, H Feld, L J Prakash, 'Characterisation of wear properties of ultra fine-grained hardmetals using a special abrasive wheel test', *Int. J. Refractory Metals and Hard Materials* (awaiting publication).
28. S C Lim and M F Ashby, Wear mechanism maps, *Acta Metall.* 35 (1987) 1.
29. S M Hsu, Y S Wang and R G Munro, Quantitative wear maps as a visualisation of wear mechanism transitions in ceramic materials, *Proceedings of the International Conference on the Wear of Materials*, ASME 1989, pp.723-728.
30. D Tabor, 'Mohs' hardness scale- a physical interpretation', *Proc. Phys. Soc. Lond.* 67 (1954) 249-257.
31. A Misra and I Finnie, 'On the size effect in abrasive and erosive wear', *Wear* 65 (1981) 249-257.
32. P A Swanson and A F Vetter, The measurement of abrasive particle shape and its effect on wear, 28 (1984) 225-230.
33. R S Dwyer Joyce, R S Sayles and E Ionnides, An investigation into the mechanisms of closed three-body abrasive wear, *Wear* 175 (1994) 133-142.
34. G J Gore and J D Gates, Effect of hardness on three very different forms of wear, *Wear* 203-204 (1997) 544-563.
35. D N Allsopp, R I Trezona and I Hutchings, 'The effects of ball surface condition in the micro-scale abrasive wear test', *Tribology Letters* 5 (1998) 259-264.
36. M M Stack, N Corlett and S Turgoose, Some recent advances in the development of theoretical approaches for the construction of erosion-corrosion maps in aqueous conditions, *Wear* 233-235 (1999) 535-541.
37. M M Stack and H W Wang, Simplifying the erosion-corrosion mechanism map for erosion of thin coatings in aqueous slurries, *Wear* 233-235 (1999) 542-551.

## **9 Appendix A: Procedure for Rotating Wheel Abrasion Testing**

### **1 SCOPE**

This procedure is concerned with ambient temperature rotating wheel abrasion testing. The test uses a rotating wheel against which test-pieces are pressed. Abrasive is introduced between the wheel and the test-piece to cause abrasion to the test piece. The procedure complements the ASTM Standard G65 [1] on Dry Rubber Wheel Abrasion, ASTM B611 Test Method for Abrasive Wear Resistance of Cemented Carbides [2], and G105 Standard Test Method for Conducting Wet Sand/rubber Wheel Abrasion Tests [3].

The test is appropriate for use in situations where test laboratories have a need to simulate abrasive damage. The procedure includes information which enables the test to be used in a variety of different conditions:

- with counterface wheels of different stiffness (for example, steel and rubber)
- wet and dry
- different abrasive sizes
- different chemical environments

### **2 MATERIALS**

#### **2.1 Testpieces**

##### **2.1.1 Overall size**

Test-pieces are typically larger than the contact area with the rotating wheel and are typically 40-50 mm x 20-25 mm in size. These test-pieces are designed to allow for the wear scar to be contained wholly within the area of the contact face. However, some variants of the test [4] use a test-piece with a clearly defined contact shape and size where the wear takes place across the entire contact face of the sample. The thickness of the test-piece is not important as long as it is sufficiently robust and the wear takes place entirely within the test sample.

When coated samples are tested the test duration is normally adjusted to ensure that the wear occurs exclusively within the coating. This can be determined by post test examination.

##### **2.1.2 Surface finish**

The surface finish of the test-piece may affect the results of the test. Thus the presence of a surface that is weakened by the preparation process may lead to increased initial wear. Conversely, the presence of a residual compressive stress in the surface layer may possibly

reduce initial wear. In both cases when these surface layers are worn away, the wear rate will approach the normal value for the material.

## **2.2 Abrasive**

2.2.1 The test abrasive should be obtained from a consistent source with good QC procedures to ensure that variability in its properties are minimised.

2.2.2 It is well known that the results of abrasion testing depend critically on the shape, size and size distribution of the abrasive. For this reason, if it is important to compare the results of one test with another, the same abrasive should be used in the tests concerned.

2.2.3 It is important that the abrasive is dry and free flowing to avoid blockage of the test system. If necessary it should be dried in an oven before use.

## **2.3 Reference Materials**

It is also effective in other circumstances to use a reference material in a sequence of tests to normalise test results to take account of minor uncontrolled variations in test conditions or changes in the make-up of the abrasive. This procedure is described later, see section 5.3.

In any case, a test should be carried out periodically on a reference material to ensure that the test system is operating correctly and gives repeatable results.

## **2.4 Wheel**

### **2.4.1 Material**

The wheel is either made from a solid piece of the requisite material such as steel, or for elastomeric materials a rim of the elastomer is normally moulded onto the rim of a steel wheel. Suitable steel wheels are described in ASTM B611 (AISI 1020), and chlorobutyl rubber rimmed wheels with a Shore A Durometer hardness of A 58-62 are specified in ASTM G65.

Moulded polyurethane rims can also be used, but it should be noted that even if the same ambient temperature hardness is achieved for the polyurethane as for the above specified rubber, significant differences in results can occur in dry tests, possibly due to alteration of mechanical properties relative to those of the rubber due to heating by the abrasion process.

### **2.4.2 Wheel size**

The wheel specified in the ASTM G65 standard has a diameter of 228.6 mm and a face width of 12.7 mm. There are other test systems of a similar type which have wheels of different size but unless there are special reasons to choose otherwise, the ASTM G65 conditions should be

used. For tests which use rubber elastomer rims such as ASTM G65, the thickness of the rim should be 12.7 mm. Again, if there are no special reasons to choose otherwise, the ASTM G65 conditions should be used.

The wheel is subjected to damage during the testing, and should be checked periodically. If significant damage has occurred the wheel should be replaced. The overall diameter of the wheel should also be checked and when it is reduced in size by the recommended amount (12.7 mm for ASTM G65 and 4 mm for ASTM B611), the wheel should be replaced.

The flatness and squareness of the contact area on the wheel is most easily checked by examining a wear scar (Figure 2). If this is even and regular, then the contact is flat and square.

### **3 TEST**

#### **3.1 Summary of Test System**

Schematics of typical test systems are shown in Figure 1. Two variants are shown, the first [5,6] where the test-piece is horizontal and pressed into the top of the wheel; in the second [1,7] the test-piece is held vertically and pressed into the side of the wheel.

The abrasive is fed from a hopper into the abrasive feed system and thence into the contact between the test-piece and rotating wheel.

The test conditions can also be varied by adding a supply of fluid just in front of the abrasive feed, or by immersing the wheel in a bath of fluid that wets the wheel.

#### **3.2 Abrasive Feed Mechanism**

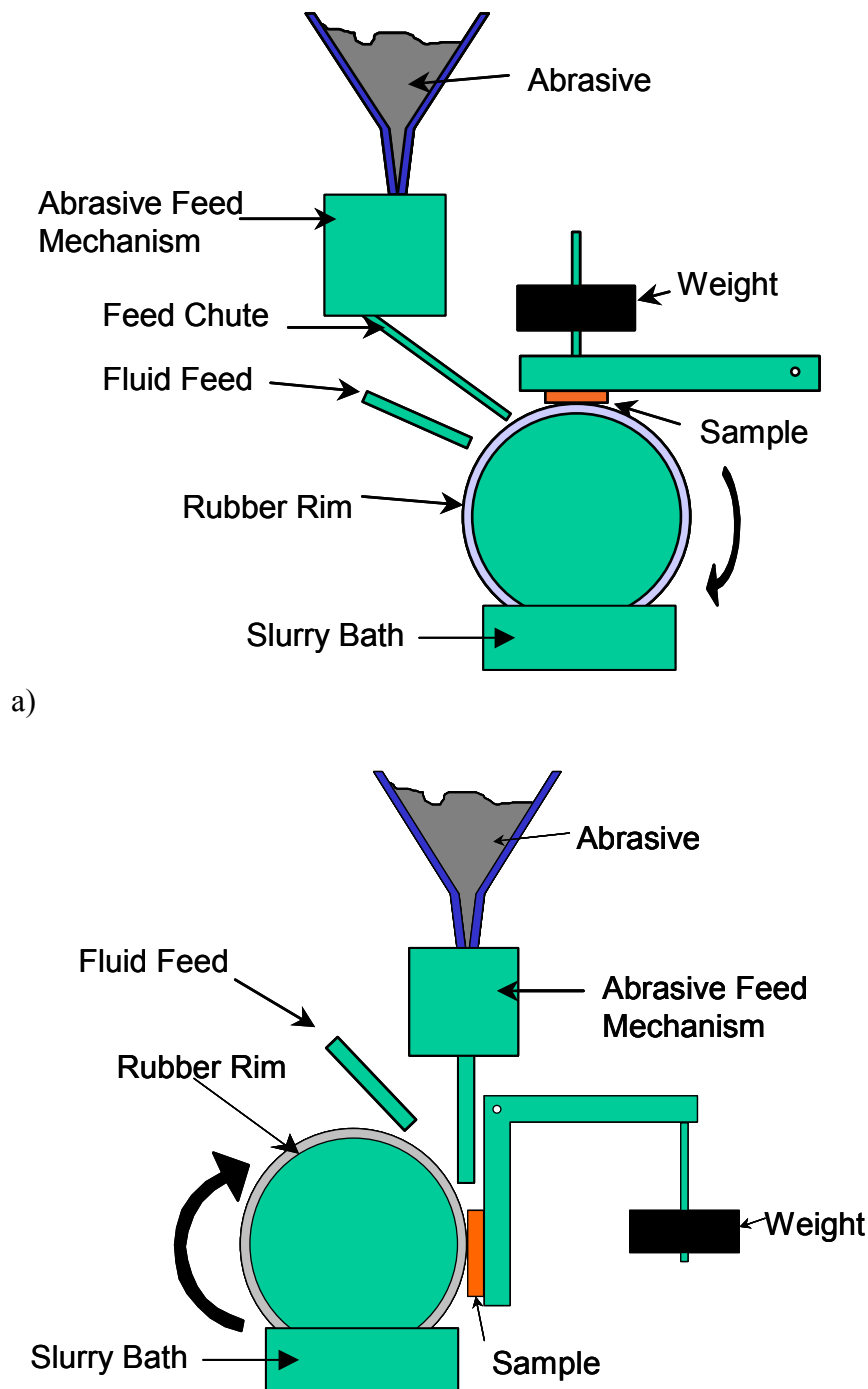
The abrasive can be fed to the test-piece / wheel interface by a number of different methods. These include

- a vibrating feed
- a screw auger
- a slotted rotating disc to control flow coupled with a chute

The essential feature of all these methods is that the abrasive is fed steadily and in a well controlled way to the test-piece / wheel interface. All of these methods have been shown to be effective in giving good control of feed rates.

#### **3.3 Vacuum Extraction**

It is important that for dry tests a vacuum extraction system is fitted to ensure that any used fine debris from the abrasive test-piece that might be a health risk is collected and can subsequently be disposed of safely.



b)

Figure 1 Schematic diagram of rotating wheel abrasion test system a) with horizontal test-piece, b) with vertical test-piece. Note that abrasive is either fed by means of a slurry bath, or by means of an abrasive feed from a hopper. Both types of supply are not required. In addition, the fluid feed is not required for dry tests.

### 3.4 Control of Wheel Speed

The wheel speed needs to be well controlled with a motor of adequate power such that a

stable constant speed is achieved independent of load applied. The rotational speed should be calibrated periodically to ensure stable operation.

### **3.5 Calibration of Abrasive Flow**

The abrasive flow is clearly a critical parameter in the testing. This needs to be carefully measured. It is important to ensure that only the abrasive that actually passes through the wearing contact is measured. This is normally achieved by arranging a series of baffles to divert away any abrasive that does not pass through the contact so that only the abrasive that does pass through is measured by collecting and weighing for a pre-determined period and calculating a rate of abrasive flow-rate.

Some test systems [4,8] are specifically designed to ensure that all the abrasive passes through the test contact. In these systems the abrasive flow can be calculated by a simple measurement of all the abrasive passing through the contact.

To enable a comparison of abrasion loading to be carried out from one rig to another, the abrasive flow rate can be converted to an abrasive coverage (AC) figure

$$AC = \frac{FR}{CA}$$

where FR is the mass flow rate of abrasive through the contact and CA is the contact area.

This procedure only makes sense where the counterface is compliant so that the contact area does not increase markedly as wear takes place during the test.

### **3.6 Test Load**

Normally the dead-weight loading is applied through a lever arm system. However, other types of loading system can be used effectively. The actual load applied should be calibrated before use of the test system and should be checked periodically.

### **3.7 Fluid Flow**

In systems fitted with a fluid feed, the flow rate should be calibrated before use. This is normally done by simple gravimetric procedures.

## **4 PERFORMING TEST**

Tests can either be carried out with a single step of a relatively long duration, or an interrupted test can be carried out with a number of abrasion steps of shorter duration with the

test-piece reweighed between each step.

The interrupted test can be useful to determine if transitions in wear are encountered, for instance due to the effect of surface damage to the test-piece. However, it should be noted that there is a possibility that interrupted tests will give different results to a non-interrupted test of the same duration. This possibility is due to the disturbance of the surface during the cleaning and reweighing process at the end of each step, and the possible effect of not being able to replace the test-piece exactly from one step to the next.

#### **4.1 Test-Piece Cleaning**

The test-piece should be cleaned before placing in the test system by the normal cleaning procedure for the test material. For many materials this can be carried out by cleaning ultrasonically in acetone for 10 minutes.

#### **4.2 Test-Piece Weighing**

The mass of the test-piece should be measured before the test.

#### **4.3 Test-Piece Clamping**

The test-piece is clamped in position in the test system. The alignment of the test-piece should be checked and adjusted if necessary to give a flat contact across the width of the wheel.

#### **4.4 Start of Test**

The test-piece should be lifted off the wheel. The motor should be started and the speed of the wheel allowed to stabilise. The abrasive flow should be switched on and allowed to stabilise before the test-piece is lowered gently against the wheel and the test is started.

#### **4.5 End of Test or Test Step**

At the specified contact duration, the motor and abrasive flow should be switched off. The test-piece should be removed and cleaned as described in Section 4.1 before being reweighed.

It is worth examining the test-piece by eye to check if the wear scar is even in shape (Figure 2). If this is not the case, the alignment of the test system and the wheel shape should be checked and the test repeated.



Figure 2 Even wear scar formed on steel test-piece with steel wheel and silica abrasive.

## **4.6 Interrupted Tests**

For tests where a sequence of steps are carried out for small durations, with the test-piece reweighed after each step followed by replacing in the test system and another test step, Sections 4.1-4.5 should be repeated until the required total test duration has been achieved. Normally this will consist of at least 5 steps.

# **5 ANALYSIS OF RESULTS**

## **5.1 Single Step Test**

The mass loss  $M$  is calculated by subtracting the value of mass measured at the end of the test from the initial mass. This is converted to a volume loss as  $V = M/r$  by using the known test-piece density  $r$ .

## **5.2 Multiple Step Test**

### **5.2.1 Tabulation**

The values of mass measured in 4.2 and 4.8 are tabulated, the mass losses calculated by subtracting these values from the initial mass, and a table of mass loss against mass of erodent calculated using a spreadsheet or equivalent program. The test-piece mass loss is converted to a volume loss by using the known test-piece density. The volume loss is normally presented as a graph with respect to mass of erodent.

### **5.2.2 Calculation of Abrasion Rate**

Regression analysis should be used to obtain an abrasion rate for the material under the conditions of the test. It is important that this regression analysis only includes data points from the linear portion of the data.

## **5.3 Use of a Reference Material**

If the results of the test are going to be compared to the results obtained with a reference material, then a test should be carried out under the same conditions. The ratio of the wear rate for the test material to the wear of the reference material is then calculated.

## **5.4 Number of Repeat Tests**

At least two repeat tests should be carried out under the same conditions for each material.

## 6 REPORTING OF RESULTS

The results that should be reported include:

- Operator
- Date
- Material to be tested
- Surface finish of test-piece
- Abrasive material
- Abrasive size
- Mass of abrasive used
- Abrasive flow rate through contact
- Test duration
- Velocity of wheel periphery
- For a stepped test, graph of volume of wear with respect to mass of abrasive
- Abrasion rate
- Comments on any unusual behaviour (non-linear behaviour, incubation time etc).

If a reference material is used, then the following parameters should also be reported.

- Reference material
- Wear rate of the reference material
- Ratio of wear rates of test material to reference material

## 7 TYPICAL OPERATING CONDITIONS

The operating conditions for the test should be designed to match the conditions that occur in the application that is being simulated. In the absence of this information, the following conditions have been found to give useful results.

|               |                           |
|---------------|---------------------------|
| Load          | 130 N                     |
| Speed         | 1 ms <sup>-1</sup>        |
| Abrasive Flow | 150 g/min through contact |
| Test Duration | 20 minutes                |

## 8 REFERENCES

- 1) ASTM G65-94, Standard test for measuring abrasion using the dry sand/rubber wheel apparatus, 1996 Annual Book of ASTM Standards, Volume 03.02, ASTM.
- 2) ASTM B611-91, Test Method for Abrasive Wear Resistance of Cemented Carbides,

1996 Annual Book of ASTM Standards, Volume 02.05, ASTM.

- 3) ASTM G105-89, Standard test method for conducting wet sand/rubber wheel abrasion tests, 1996 Annual Book of ASTM Standards, Volume 03.02, ASTM.
- 4) J Ellis and B M Armstrong, Evaluation of Wear Resistant Materials for Use in Materials Handling Systems, Report Number SL/CS/P/13/90/O, British Steel Technical, Swinden Laboratories.
- 5) A N J Stephenson and I M Hutchings, Development of the dry sand / rubber wheel abrasion test, *Wear*, 195(1996)232-240.
- 6) M G Gee, A J Gant and W P Byrne, An NPL Rotating Wheel Abrasion Test, NPL Measurement Note, CMMT(MN)30, November 1998.
- 7) K Grigoroudis and D Stephenson, Modelling low stress abrasive wear, *Wear*, 213(1997)103-111.
- 8) S Wirojanupatump and P H Shipway, 'A direct comparison of wet and dry abrasion behaviour of mild steel' *Wear* 233-235 (1999) 655-665.