

General Approach
and Procedures
for Erosive Wear
Testing

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Measurement Good Practice Guide No. 56

General Approach and Procedures for Erosive Wear Testing

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Foreword:

This Good Practice guide aims to provide guidance on erosive wear testing. It contains a description of the four common erosion test systems (gas jet; centrifugal accelerator; wind tunnel; whirling arm), and a discussion on the important variables in erosion such as particle impact velocity, particle impact angle, particle size, shape and material, and ambient temperature. A short review of techniques for data analysis and interpretation is also included.

It also 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.

In Annex A, specific guidance is given on gas jet erosion, on how test conditions should be set and the procedures that should be used.

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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 estimated to be £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 so 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.

The Guide then gives specific information on erosion testing, and gives a recommended procedure. 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, abrasion testing of monolithic materials, and ball cratering wear testing for coatings [2-4]. A directory containing information on the expertise and facilities in tribology has also recently been produced [5].

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

Adhesive wear is the surface damage and material removal which can occur when two smooth surfaces rub against each other. Such surfaces are never perfectly smooth and have high spots where the rubbing occurs. These local areas experience concentrated contact loads and interactions, and tend to adhere to each other 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.

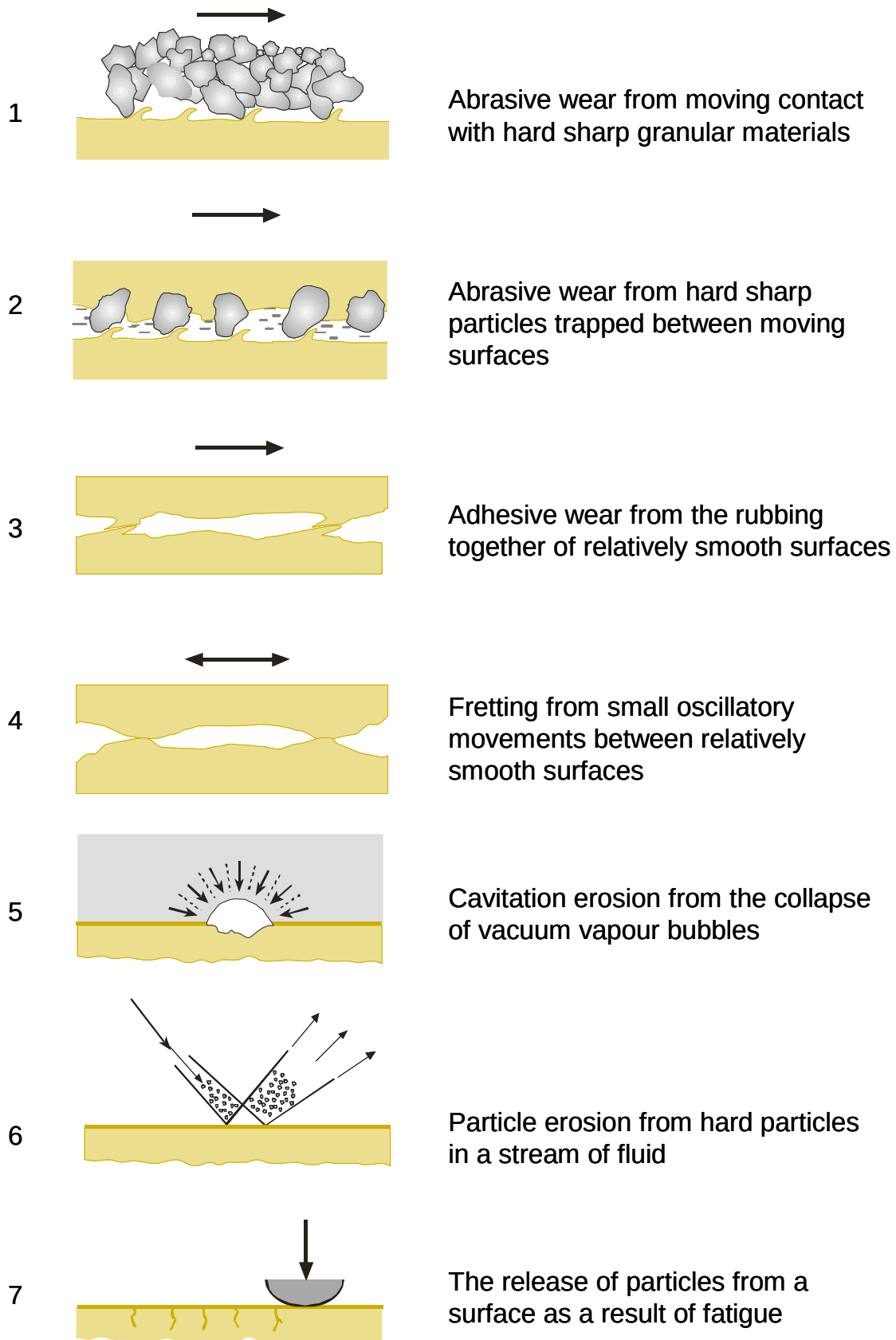


Figure 1, The types of wear that occur in industrial machines

3 Simulation of 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 [6].

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.

4 Erosion

Erosion is defined as “progressive loss of original material from a solid surface due to mechanical interaction between that surface and a fluid, a multi-component fluid, or impinging liquid or solid particles” [1]. Because of the broad nature of this definition, it is usually qualified by indicating the relevant mechanism or context, for example as cavitation erosion, liquid impingement erosion, slurry erosion or solid particle erosion. This Good Practice Guide focuses specifically on erosion by the impact of solid particles, which can be a serious cause of wear in powder handling and transport systems, gas wells, chemical plant and gas turbine engines.

The particles responsible for erosion are typically between 5 and 500 μm in size, and impact velocities can range from less than 10 m s^{-1} to supersonic speeds. Erosive particles are usually, but not inevitably, suspended in a flowing gas stream, although the particle velocity may differ significantly from that of the gas.

4.1 Measure Of Erosion Rates

The amount of material removed from a surface by erosion generally increases with the time of exposure to the particle stream, as shown schematically in Figure 1. Several methods can be used to express the dependence of erosion on exposure time. Since in erosion testing it is often most convenient, as well as most accurate, to determine material removal by periodically weighing the specimen, erosion is often quoted in terms of mass removed from the surface by unit mass of erosion particles striking it (e.g. in milligrams eroded per kilogram).

This measure of erosion has the advantage that it is dimensionless, but for practical purposes it is sometimes preferable to express it as volume removed per unit mass of erodent (e.g. mm^3 eroded per kilogram of erodent). In many applications, the surface is exposed to a constant flux of erodent particles and it is straightforward to convert a value of erosion expressed, for example, as mass removed per unit mass of particles striking the surface to depth removed in unit time. However the erosion is expressed, it is important to note that under some circumstances the rate of material removal will not be constant and that a significant incubation period may occur after a fresh surface is exposed to the particle stream before the rate of erosion reaches a steady state. An example is shown in Figure 1.

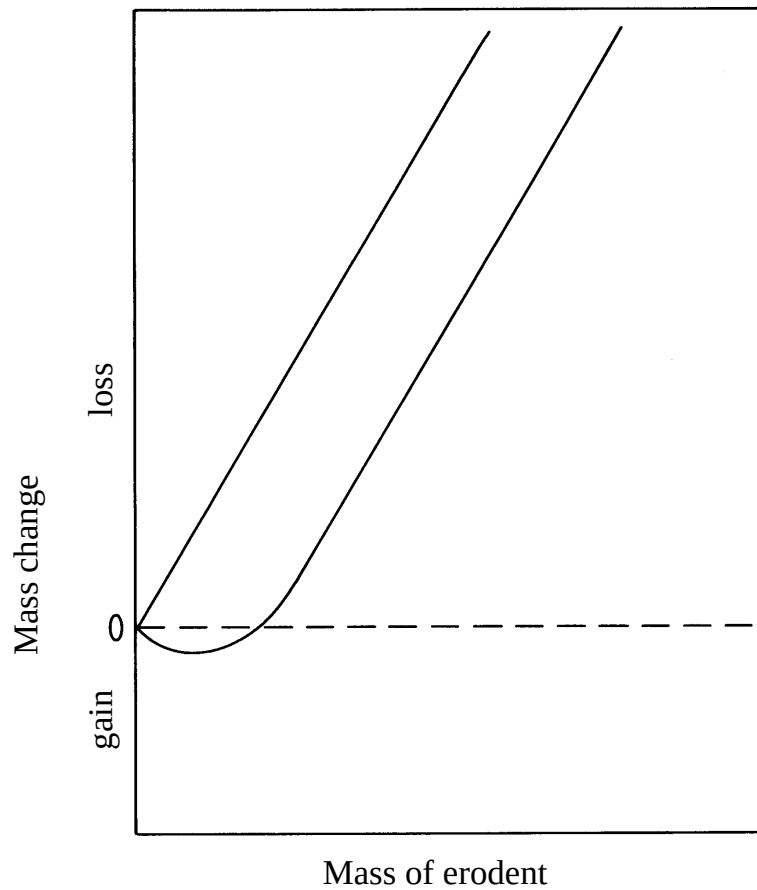


Figure 1 Typical dependence of mass lost from a specimen on the total mass of erodent particles that have struck it. In many cases, the mass loss increases linearly with mass of erodent from the start of the test, but under some conditions there may be a significant incubation period when the specimen gains mass.

5 Important Variables In Erosion

Erosion, or the mass removed from the surface per unit mass of impacting particles, depends strongly on

- particle impact velocity
- particle impact angle
- particle size, shape and material
- ambient temperature

as well as on the properties of the material being eroded. In a reproducible erosion test, all these factors should be well controlled, and, if possible, measured.

5.1 Particle Velocity

The most important variable is the particle velocity, since under most conditions, it has a very strong influence on erosion rate. For many materials, once steady-state conditions have been reached the erosion E (expressed as the mass removed by unit mass of erodent particles) can be expressed [8] as a simple power function of particle impact velocity V .

$$E = kV^n \quad (1)$$

Where the constant of proportionality k includes the effects of all the other variables. The value of n , the velocity exponent, is typically between 2 and 3, although much higher exponents are seen under some circumstances. A value of about 2.4 is commonly experienced for the erosion of ductile metals. The value of n does not vary much with impact angle, although there is some suggestion that higher values of n are associated with steeper impact angles.

5.2 Particle Impact Angle

Erosion also depends markedly on impact angle, often in one of two distinctive ways. Ductile metals eroded by angular particles show maximum erosion at shallow angles of incidence. The impact angle in erosion is often defined as the angle between the direction of particle motion and the plane of the surface, so that normal incidence corresponds to an impact angle of 90° . Peak erosion for ductile metals occurs typically at an angle of 20° to 30° , and is associated with impact under the most favourable conditions for the removal of material by ductile ploughing and cutting mechanisms. The erosion of a ductile metal at 90° incidence may be about one half to one third of the peak value. An example of this angular dependence is illustrated in Figure 2.

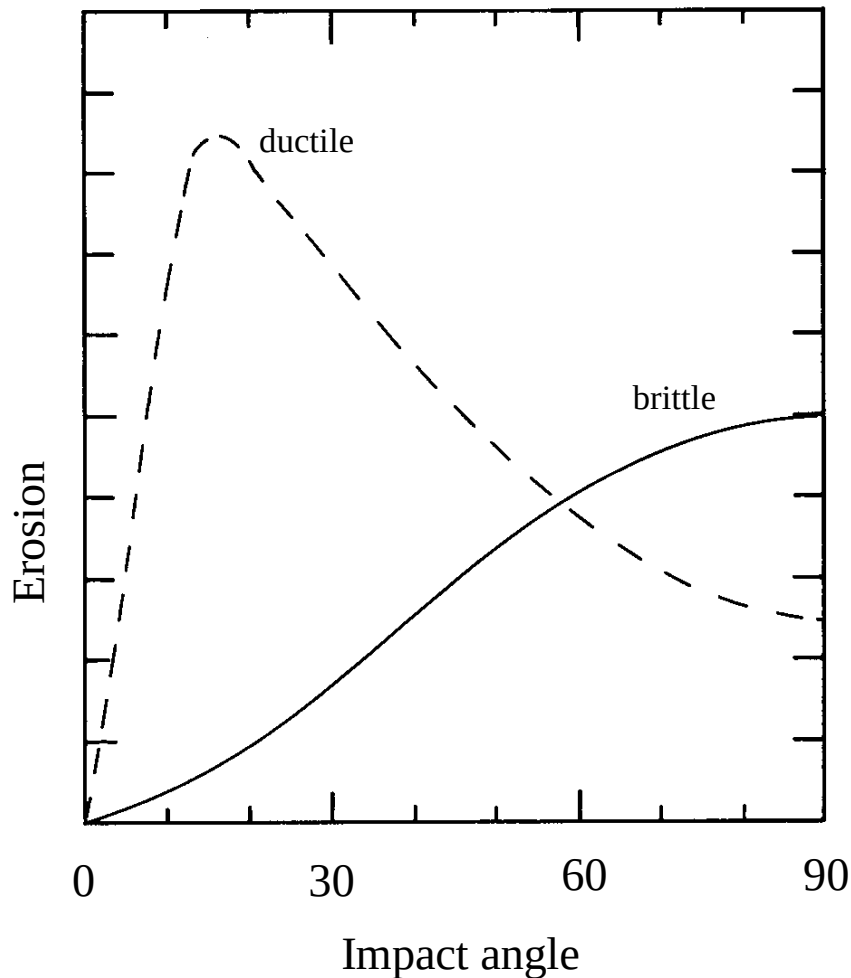


Figure 2 Typical dependence of erosion (defined as mass lost per unit mass of impinging particles) on impact angle (defined as the angle between the impact direction and the surface).

Materials which erode by the formation and intersection of brittle fractures, such as inorganic glasses impacted by hard angular particles which are large enough to cause local cracking, show peak erosion for normal incidence and a steady reduction in erosion as the impact angle falls. Figure 2 also illustrates this behaviour. The two types of behaviour are often referred to as “ductile” and “brittle” respectively. However, it is not safe to deduce the mechanisms of material removal on the basis of the angular dependence of erosion, since in some systems ductile processes can lead to peak erosion at 90° , and transitions in fracture behaviour can result in atypical angular dependence of erosion, even in a “classically brittle” material. Intermediate behaviour, with peak erosion at 45° to 60° , is not unknown.

5.3 Particle Size

The particles used in an erosion test must be well characterised. The size of the particles can influence the erosion rate in two important and distinct ways. Particles of different sizes, striking the surface at the same angle and velocity, will generally remove different amounts of material per unit mass of particles (although for particles larger than about 100 μm striking a ductile metal this variation may be small). This dependence of erosion on particle size represents a genuine size effect. In some erosion test methods (see below), the impact velocity itself varies with particle size, and since erosion is generally a strong function of velocity, this effect contributes to a further dependence of the measured erosion rate on particle size. For these reasons, it is clear that wherever possible the size range of the particles used in an erosion test should be known, and be as narrow as possible.

Particles are often classified by sieving and standard sources are available which discuss the principles and optimal procedures for this method [9,10]. Specification of the sieve sizes may be sufficient to define the range of particle size used in a test. However, granulometry is a readily available technique that can be used to provide a more accurate description of the particle size distribution.

5.4 Particle Material

The erodent particle material is an important factor, as illustrated in Figure 3, which presents results for the erosion of a glass-bonded alumina (a common erosion-resistant ceramic) tested with silicon carbide, alumina and silica particles, all of the same size (125-150 μm). The erosion caused by the silicon carbide particles was more than ten times that caused by the same mass of silica particles. A major factor responsible for this effect is the relative hardnesses of the erodent particles and the surface being eroded. In this example, both the silicon carbide and the alumina particles, which were commercial abrasives, were significantly harder than the alumina specimen (Vickers microhardness; silicon carbide 33.4 GPa; alumina particles 26.5 GPa; alumina specimen 12.7 GPa). The silica, in contrast, had about the same hardness (13.1 GPa).

It should be noted that the erodent used in erosion testing will be fractured in the erosion process leading to the formation of particulate material. This may be injurious to health and it is essential that the user should take precautions to avoid any exposure to this dust by use of sealed apparatus, filtration of the exhaust gas, ventilation and extraction as appropriate under any relevant environmental legislation.

5.5 Particle Shape

Shape also plays a role in determining the relative erosivity of different particles [11], and is difficult to separate from other properties, since particle shape is often determined by the fracture processes by which the particles themselves are formed. As in the case of particle size, there is an intrinsic effect of shape on the erosion rate, which can lead to angular particles producing up to ten or more times the erosion caused by spherical particles of the same material. Measurement of particle shape is not straightforward, since although there are many possible methods of assessing shape, it is unclear which method is most appropriate in the context of erosive wear testing. Qualitative descriptors such as “rounded”, “sub-angular” and “angular” etc, are often used and may be adequate in conjunction with a more detailed specification of the material and source of the erodent particles.

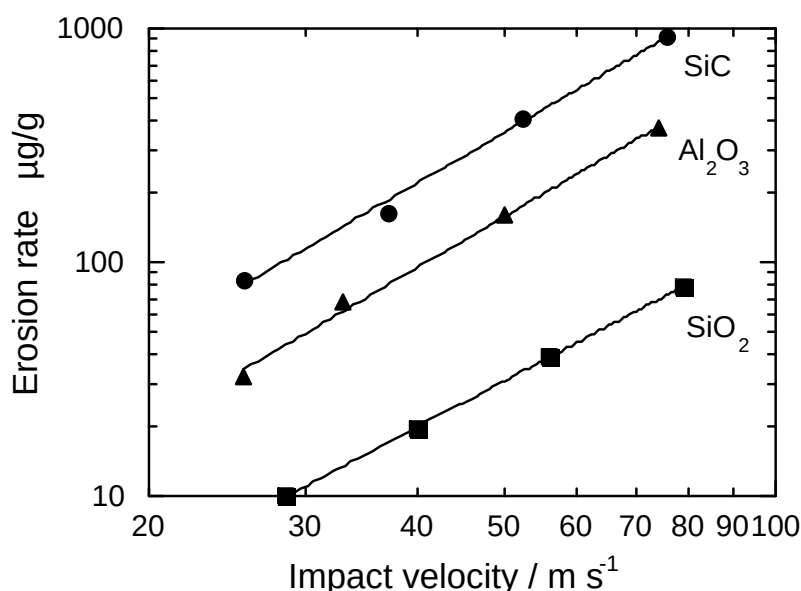


Figure 3 Influence of particle material on erosion rate, for erosion of a sintered glass-bonded alumina ceramic by silica, alumina, and silicon carbide particles, 125-150 μm in diameter, at normal incidence. Adapted from Ref 11.

For all the reasons indicated above, it is important that if the purpose of erosion testing is to compare material behaviour or obtain quantitative measurements of erosion rate in the context of a particular engineering application, appropriate erodent particles are used in the test. Not only should the particle size and shape be representative of the application in question but the particle material should also provide a realistic simulation of the properties of the actual particles. Although the ready availability of reproducible commercial abrasive particles such as silicon carbide or alumina with a well defined size may suggest their use in erosion testing, it is important to appreciate that they are much harder than most naturally occurring erosive particles, which are often silica or silicate minerals. Not only may the

absolute values of erosion rate measured with very hard particles be misleading but the mechanisms of damage and even the ranking of erosion rates of materials may be different.

Because damage is suffered by the erodent particles when they strike a surface, the properties of the particles after they have been used in an erosion test will differ, often significantly, from those of fresh particles. Even if gross fracture of the particles is avoided, subtle changes in shape can occur. If at all possible erodent particles should therefore not be re-used for erosion testing.

6 Erosion Test Methods

Laboratory-scale erosion testing is performed for several reasons:

- to provide data on absolute or relative wear rates under specific conditions
- to examine the validity of theoretical models, or
- to study the mechanisms of wear.

The first of these objectives can include data on the relative behaviour of different materials, and gives information of direct value to the design engineer, while the others are of more value in improving the understanding of erosive wear.

Methods used for laboratory erosion testing can be divided into those in which the particles are accelerated in a gas stream, and those in which circular motion is used to achieve the impact velocity. Four methods are shown schematically in Figure 4 and will be discussed in detail below. Of these, the gas jet test rig (Figure 4a) and the centrifugal accelerator (Figure 4b) are the most widely used methods. The former is described in detail in Annex A.

6.1 Gas Jet Method

In the gas jet (or gas-blast, or jet impingement) test, particles are entrained into a gas stream and accelerated along a nozzle. The particles leave the end of the nozzle and then strike the test specimen which is fixed at a known angle to the axis of the nozzle some distance from its end. The acceleration nozzle used in this test method is generally a plain cylindrical tube for ease of construction and replacement. There are national standards relating to this type of test method but non-standard designs are also commonly used.

In ASTM standard G76 [12] the use of a nozzle 50 mm long with a bore of 1.50 mm is recommended. A former German standard (DIN 50332) suggested the use of a nozzle 120 mm long with an internal diameter of either 8 or 18 mm, depending on the test conditions. Sheldon and co-workers [13] used a nozzle 305 mm long with an internal diameter of 4.95 mm, and similar dimensions have been used in many other experimental programmes. The aspect ratio (length/diameter) of this nozzle is 61.6, approximately twice that of the ASTM

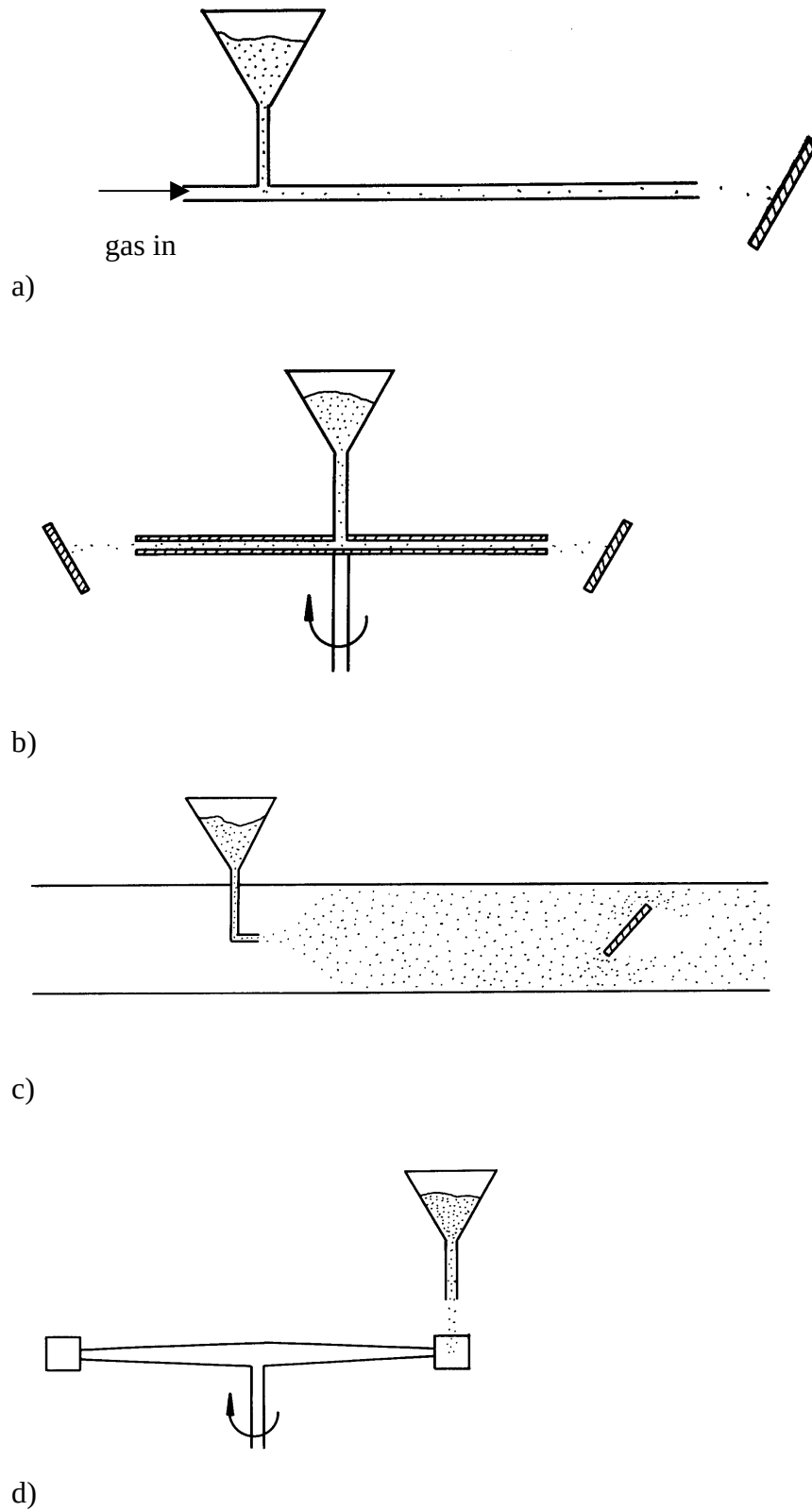


Figure 4 Schematic diagrams showing four classes of erosion test methods. (a) Gas-blast rig, (b) Centrifugal accelerator, (c) Wind tunnel, (d) Whirling arm tester.

standard nozzle. Other investigators have used considerably longer nozzles. For example, Marshall et al [14] used a nozzle 3 m long with a bore of 9.5 mm (i.e. an aspect ratio = 316), while Andrews et al [15] used nozzles 4 m long with 25 mm internal diameter (aspect ratio = 160), and 1 m long with an internal diameter of 10 mm (aspect ratio = 100). The ASTM standard suggests that a length/diameter ratio of at least 25 is desirable to achieve an acceptable particle velocity distribution in the stream.

6.1.1 Particle Velocity

The velocity with which the particles leave the nozzle and strike the specimen will depend on the velocity of the gas stream, on the drag forces acting on the particles and on the distance over which the particles accelerate along the nozzle. In long nozzles of large diameter, the particles may reach essentially the same speed as the gas stream, but in short or narrow nozzles the particle velocity may be significantly lower than that of the gas. Accurate knowledge of the particle exit velocity is therefore essential unless the purpose of that test is simply to compare material behaviour under constant, but unspecified, erosion conditions.

A long nozzle might be considered to be beneficial on the grounds that it might lead to a higher particle exit velocity for a given gas pressure. It might also be assumed that the divergence of the erodent particle stream on leaving the nozzle would be less, leading to less uncertainty in the angle with which the particles strike the target. A long nozzle might also have the advantage of reducing the spread in the velocities of particles where there is a distribution of particle sizes in the erodent supply. However, the assumption that longer nozzles give higher particle exit velocities is not necessarily correct. It is true that with a longer nozzle the particles reach a higher proportion of the gas exit velocity than in shorter nozzles. But on the other hand for the same overall pressure drop, the gas velocity will be lower than with a shorter nozzle, due to friction between the gas and the nozzle wall.

A second important influence on particle exit velocity arises from the collision of the particles against the nozzle wall, which causes a retarding effect. The internal surface topography (i.e. roughness) of the nozzle wall therefore affects the particle exit velocity.

Particles can be fed into the gas stream in various ways. One simple method is to use a pressurized particle feeder in which particles are metered by the rotation of an electrically-driven disk carrying a groove from which the powder is supplied through a pressurized tube to a mixing chamber at the high-pressure end of the nozzle. Powder feeders of this type are commercially available, for example to supply plasma-spray guns. An alternative method of erodent feeding utilises a rotating grooved disk at atmospheric pressure, from which the powder is sucked through a feed tube into a constricted portion of the air-stream in which a low pressure region is created. Screw feeders can also be used. However the erodent particles are metered, good control over the feed rate is desirable.

6.1.2 Laboratory-scale Testing

Figure 5 shows the layout of a typical laboratory-scale gas jet erosion rig. Suction created in the ejector causes the erodent particles to be drawn into a feed tube from a groove in a slowly rotating turntable, which is fed by gravity from a hopper. The particles are then mixed into the gas stream. By controlling the speed of rotation of the turntable, a constant particle feed rate can be accurately maintained. The acceleration nozzle is a stainless steel tube, typically 5 mm in internal diameter and 300 mm long. Since the nozzle wears progressively in use, the diameter should be regularly monitored to ensure constant test conditions.

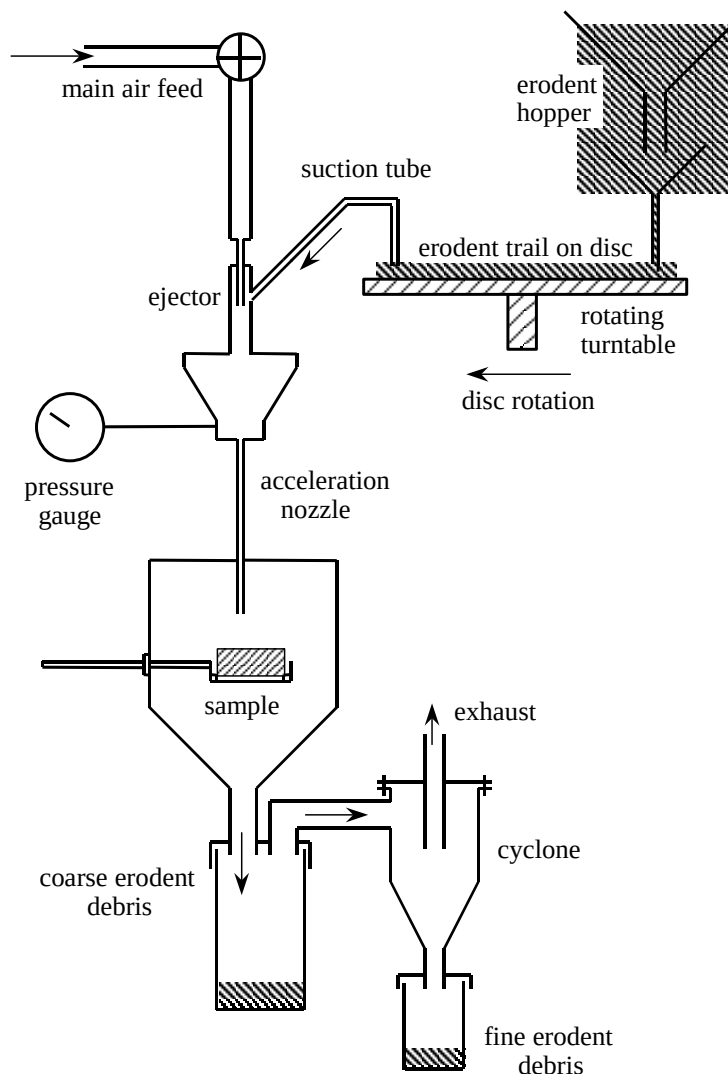


Figure 5 Typical small-scale laboratory gas-blast erosion rig. Erodent particles are accelerated in a gas stream along a cylindrical nozzle and strike a specimen fixed at the end of the nozzle. [17].

The test sample is clamped at an accurately known angle to the axis at a stand-off distance of about 5 nozzle diameters from the end of the nozzle. Arrangements are made to collect the erodent particles and debris from the air stream before they are vented from the apparatus. Since the particle velocity is controlled by maintaining a fixed pressure drop between the ends of the nozzle, it is relatively straightforward to achieve reproducible and well characterised conditions in such a rig. A typical test procedure is described in Annex A.

The specimen must be handled carefully, cleaned (to remove loose particles), and weighed before and after the test. The specimen is then replaced in the apparatus in the same position and orientation and the test run repeated to produce further erosion of the same region of the surface until sufficient data have been gathered (see Section 6).

The use of pre-weighed quantities of erodent in each test, and running the test until the particles have all passed through the rig, is preferable to running the test for a set time at a pre-set feed rate, since a constant rate cannot always be assured.

6.1.3 Computational Models.

Computational models are available to predict particle velocities in gas jet erosion testing. However, in order to make accurate predictions they must take account, not only of the size, density and drag coefficient (which will depend on the shape) of the particles, but also of the nozzle wall friction and the effects of particle-wall and even particle-particle interactions. The plume of particles leaving the end of a cylindrical nozzle contains some particles that diverge quite markedly from the nozzle axis, showing that impacts between particles and the nozzle wall can be significant [16]. ***Theoretical models for particle velocity are therefore no substitute for accurate measurements under realistic operating conditions***, performed by one of the methods discussed in Section 5.

For some purposes, however, a simple empirical model has been found to be useful. The following equation provides [17] a good fit to the dependence of particle velocity on air pressure for a cylindrical nozzle 4.9 mm in diameter and 308 mm long, with one end at atmospheric pressure, along which particles are accelerated in an air stream.

$$V^2 = \frac{kP}{d^{0.57} \rho^{1.08}} \quad (2)$$

where V is the exit velocity of the particles (in m s^{-1}), P is the gauge pressure at the high pressure end of the nozzle (in kPa; 100 kPa = 1 bar), d is the diameter of the particles (in micrometres), and ρ is the density of the particles (in Mg m^{-3}). For these conditions and with the data expressed in the units given, $k = 7900$. As shown in Figure 6, this equation provides a good fit to measured particle velocities up to ca. 80 m s^{-1} . A linear variation of (particle velocity)² with gas pressure has also been demonstrated for cylindrical nozzles

with other aspect ratios, and the functional dependence of velocity on particle size and density has been shown to be similar to that of equation (2)

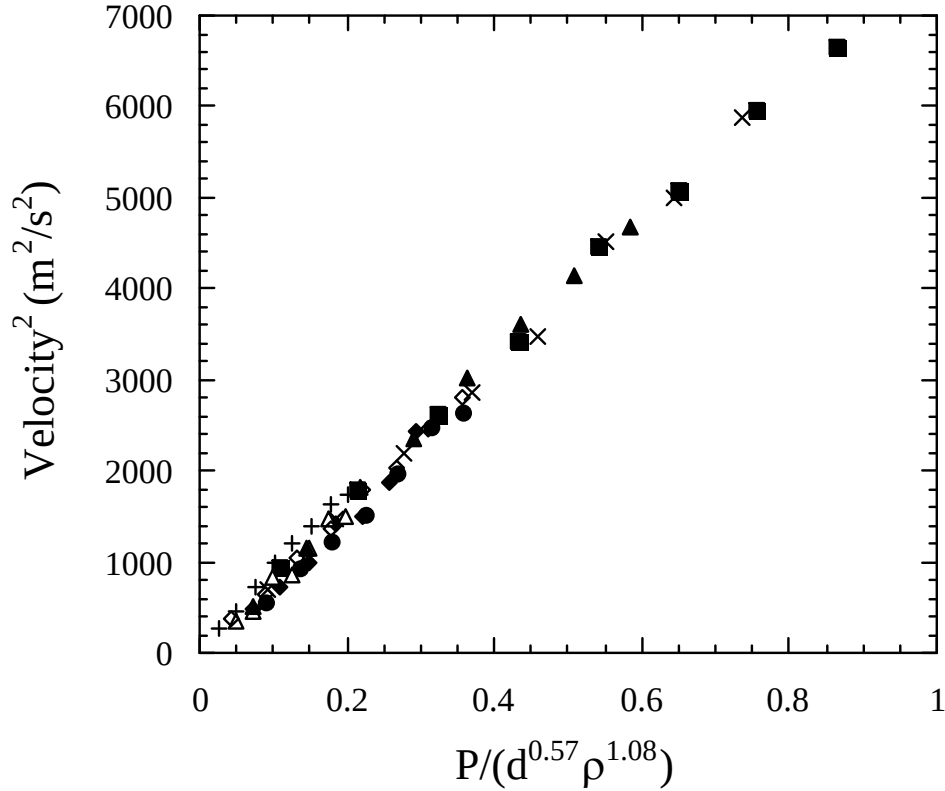


Figure 6 Empirical correlation between particle velocity and nozzle pressure drop, P ; mean particle diameter, d ; and particle material density, ρ , for erodent particles of a wide range of sizes and materials in an air-blast erosion rig with a nozzle 308 mm (12 in) long and 4.90 mm (0.19 in) internal diameter. The data are well fitted by Eq 2. Adapted from Ref 18.

It is likely that an empirical relationship similar to equation (2) can be used, after suitable calibration, for many designs of gas jet erosion rig. The stream of particles leaving the nozzle diverges significantly because of particle-wall collisions and particle-particle interactions. This divergence can be described by a simple function [18]. The proportion of particles travelling at angles between θ and $\theta + d\theta$ to the nozzle axis, $p(\theta)d\theta$, is given by

$$p(\theta) = \beta^2 \frac{\sin \theta}{\cos^3 \theta} \exp(-\beta \tan \theta) \quad (3)$$

where β is a dimensionless quantity which describes the spreading of the plume, and has been termed the “focus coefficient”. The value of β depends on the shape of the erodent particles and on the internal roughness of the nozzle wall, as well as on the impact velocity.

Typical values lie in the range from ca. 10 to 25, with a low value of β corresponding to a highly divergent stream. Because of this divergence, the area of the specimen exposed to the erodent stream must be significantly greater than the cross-sectional area of the end of the nozzle in order to ensure that most of the particles strike the specimen. For a typical nozzle diameter of 5 mm, and a specimen mounted at a distance of 20 mm from the end of the nozzle, a specimen width of at least 25 mm is necessary to avoid significant error from this source.

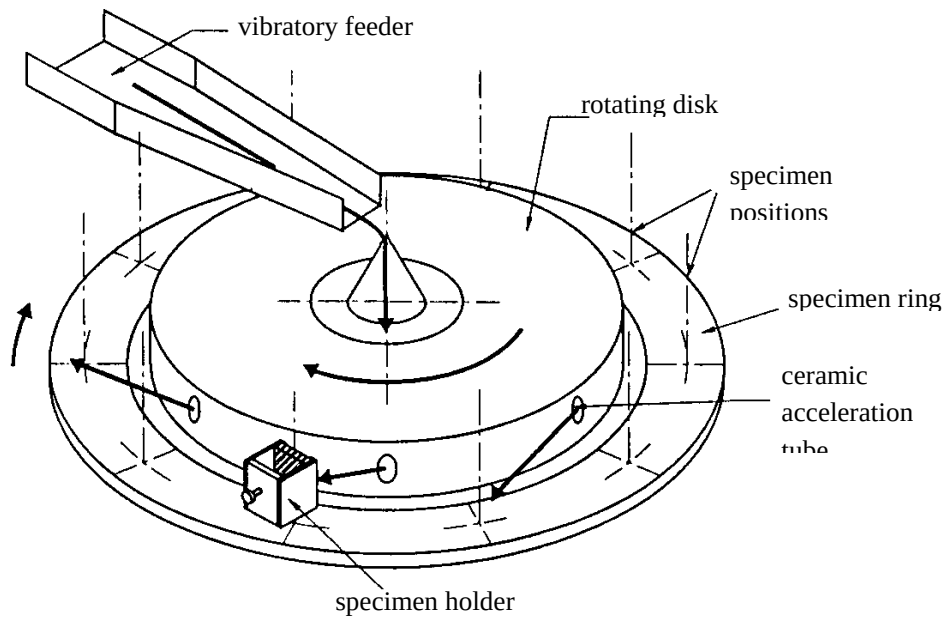
6.2 Centrifugal Accelerator

In the centrifugal accelerator, illustrated by the apparatus shown in Figure 7, the erodent particles are fed to the centre of a rotating disk, usually with a screw or vibratory feeder, and then travel outwards along radial slots or tubes in the disk. They leave the disk at the periphery with a tangential component of velocity equal to that of the disk itself, and a radial velocity component that depends on their motion within the radial channels. Specimens are mounted at points surrounding the periphery of the disk and are exposed to a series of streams of erodent particles as the radial tubes sweep past. The use of a centrifugal accelerator for erosion testing was specified in a national standard of the former USSR (GOST 23.201.78) and examples of such apparatus have been described in References 18-20.

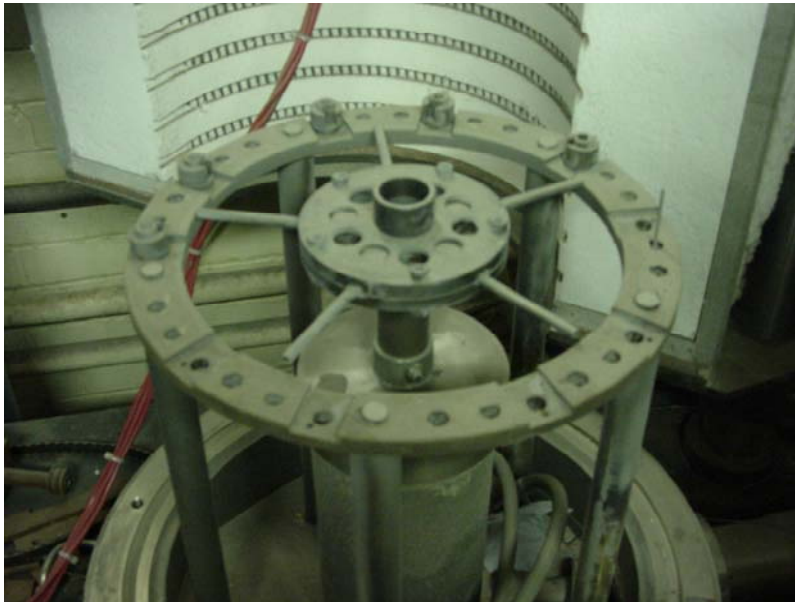
The method has an advantage over the gas jet method in that a large number of specimens can be subjected to the same erosion conditions simultaneously, and it is therefore well suited to performing screening tests on many different materials. The specimens are often mounted on a ring which itself rotates slowly around the rotating disk, to eliminate any possible bias associated with specific specimen locations. The maximum numbers of specimens per test have ranged up to 30 in different designs of rig, with rotating disk diameters between 200 and 600 mm. The apparatus shown in Figure 7 has a disk 240 mm in diameter [20], containing six radial tubes, each with an internal bore diameter of 2.6 mm. The particles are supplied to the centre of the disk by a vibratory feeder at a constant rate, and care is taken in the design to ensure that the particle flow is split evenly between the six tubes. Typically ten samples are placed symmetrically around the carrier ring, and each specimen holder can be angled independently to achieve impact angles in the range from 5° to 90°. The specimens are all mounted in the vertical plane.

Constant **particle impact velocity** is achieved through control of the disk speed, which can be readily measured. However, the velocity of the particles results from both radial and tangential motion; typical particle trajectories are illustrated in Figure 8. Accurate determination of the impact velocity and of the impact angle at the specimen surface, thus requires a knowledge of the ratio of the velocity components or the angle of motion relative to the radial direction. Probably the simplest method of determining these is to measure the direction of motion of the particles experimentally; by allowing them to pass through a

slotted shield and noting the position of impact on a specimen surface fixed beyond the shield. The particle trajectory, defined by the line joining the centres of the erosion scar and the slot, allows the relative velocity components, as well as the true angle of impact on the specimens, to be calculated.



a)



b)

Figure 7 Typical centrifugal accelerator test rig. Erodent particles are fed into the centre of a rotating disk and emerge through radial tubes to strike the specimens, which are arranged in a ring around the periphery of the disk, a) schematic diagram [19], b) high temperature test system [21]

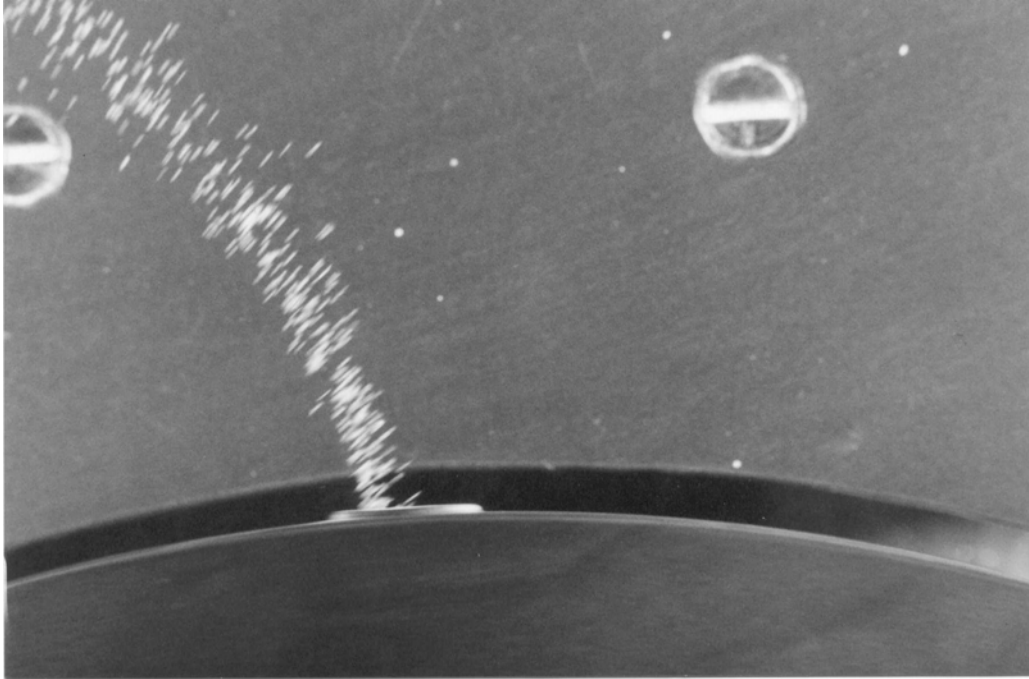


Figure 8 Single flash exposure showing streak images of particle trajectories for olivine sand particles, 150-250 μm in diameter, leaving an acceleration tube at the rim of the rotating disk in a centrifugal accelerator of the design shown in Fig 7. The disk was rotating clockwise and the mean particle velocity was 7 m/s. Courtesy of T Deng and M S A Bradley, University of Greenwich, UK.

For one particular design of centrifugal accelerator [19] the radial velocity component was found to be ca. 0.8 times the tangential component and independent of velocity and particle size. The particle trajectories were therefore at an angle of about 39° to the tangential direction.

Erosion at **different impact angles** can be achieved by varying the angles at which the specimens are mounted in the apparatus. Because of the pattern of motion of the particles in this test, the impingement angle and the particle flux vary in a complex, but generally predictable, way across the surface of a finite-sized specimen. These effects have been analysed in detail [19]. At least one edge of the specimen will also, in general, be exposed to the erodent stream. It is usual to mask both the leading and trailing edges of samples in order to prevent erosion occurring at unwanted angles of impingement. The total amount of erodent striking each specimen surface will be only a small fraction of the total fed into the rig and must be calculated from the specimen and rig dimensions. The erosion of each

specimen can then be calculated, in terms of mass removed per unit mass of impinging erodent particles, from measurements of mass loss.

As in the gas jet method discussed above, it is desirable to run the test to consume a pre-weighed total mass of erodent, rather than relying on maintaining and measuring a steady particle feed rate and running the test for a fixed time.

6.3 Wind Tunnel Method

Because of the large size and expense of the test rig, the wind tunnel method shown schematically in Figure 4(c) is used predominantly where information on the performance of shaped components (such as turbine blades is required), rather than for studies of material response alone. For tests of the former type, the wind tunnel method, in which the test specimen is immersed in a rapidly flowing stream of air or other gas-containing erodent particles, is invaluable. Figure 9 shows a typical wind tunnel test facility [22].

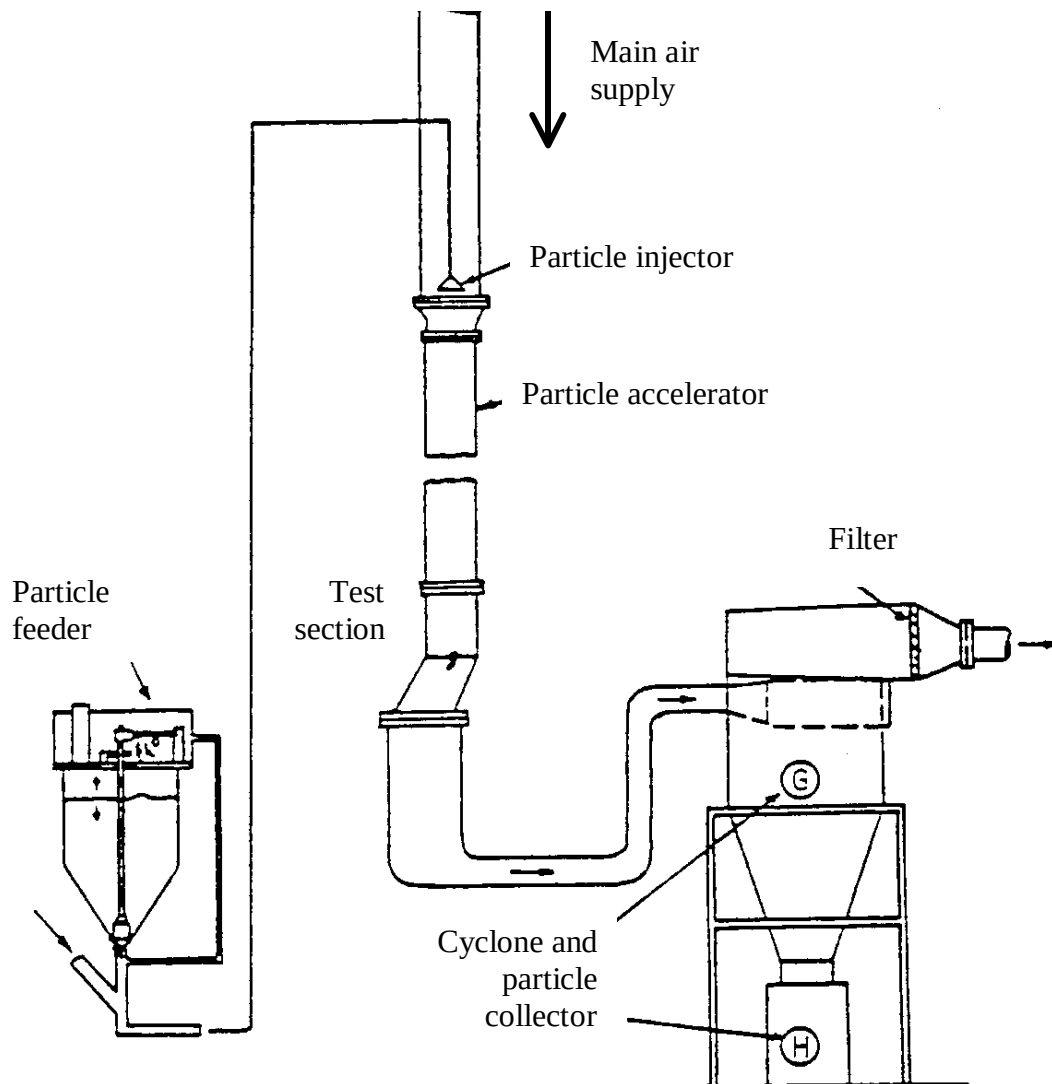


Figure 9 Schematic diagram of wind tunnel test rig. Source: Ref 23.

The specimen is located in a rectangular section (dimensions 25.4 x 76.2 mm) of the wind tunnel, following a long (ca. 4 m) acceleration duct. With this length of acceleration tunnel, relatively large particles (200 μm) are accelerated to 85% and smaller particles (20 μm) to 98% of the air speed. In order to avoid disturbing the airflow too much, the specimen area in the test section is typically restricted to <10% of the total cross-sectional area of the flow. After impact with the specimen the erodent particles, which have been supplied from a pre-weighed batch in the particle feeder, are separated from the main air stream by a cyclone separator and filter.

6.4 Whirling Arm Method

Figure 10 shows an example of a whirling arm test rig in which impact occurs between a moving specimen and a slowly falling stream of erodent particles. In this approach, which is particularly useful to study erosion at very high impact velocities, the specimens are carried at the ends of a rotating arm [18, 23]. At high speeds, accurate balancing of both the arm and the specimens becomes important and introduces extra complexity to the process of specimen preparation. Specimen materials must have sufficient strength and ductility to withstand the high centrifugal stresses to which they are subjected during testing, and satisfactory methods must be used to attach the specimens to the rotor. In some designs aerodynamic effects are eliminated by operating the rig in a vacuum or reduced air pressure, and this is essential if very high speeds are required. There are then engineering problems associated with the sealing of the vacuum against the rapidly rotating drive shaft, unless the method shown in Figure 10 is adopted, in which the motor casing itself provides the vacuum seal.

Both electric motors and air turbines have been used to rotate the specimen arm, and specimen speeds up to at least 550 m s^{-1} have been achieved. The impact velocity can be accurately calculated from the rotor radius and the rotational speed, while the impact angle can be controlled by fixing the specimens on to the rotor arm at an appropriate angle. This often involves the use of different rotors for different impact angles. The fate of erodent particles after striking the specimen must be considered since they will rebound and may cause secondary impacts (from intact particles or fragments) during subsequent rotation of the arm. Some method of capturing the particles after impact is required. The design described in Reference 23 used sheet metal traps coated with silicone oil to catch small dust fragments as well as whole particles.

The whirling arm method involves greater effort in specimen preparation and in conducting the test than other methods. The time taken to load and unload the specimens, and to

establish a vacuum in the chamber, if it is an evacuated rig, may be significant. The specimens must be of accurate dimensions, form a dynamically balanced pair on the whirling arm and be sufficiently strong and tough to withstand the high centrifugal stresses imposed during testing. These requirements have tended to restrict the use of the method to metallic samples. Despite these considerations, the whirling arm method can achieve the highest particle velocities, and in order to obtain erosion data under such conditions, it has great value.

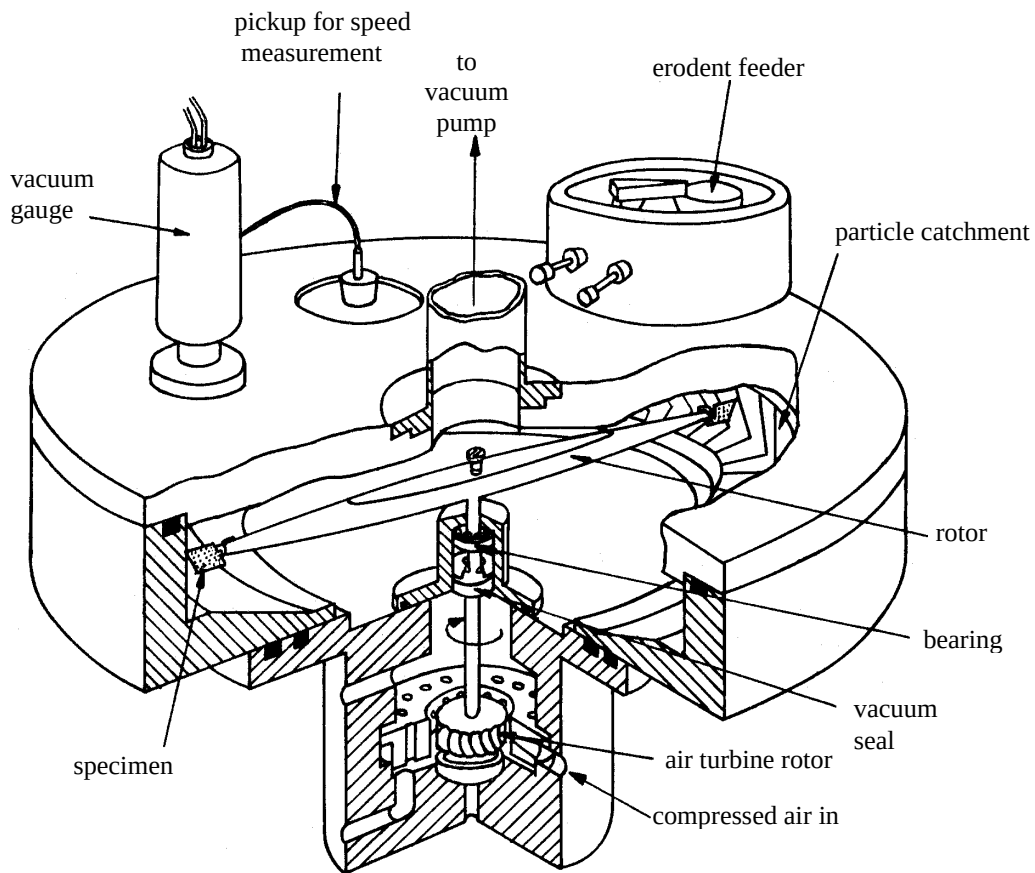


Figure 10 Schematic diagram of whirling arm erosion rig, in which particles are dropped into the path of two specimens attached to the ends of a rapidly rotating arm. Adapted from Ref 23.

7 MEASUREMENT OF PARTICLE VELOCITY

Since impact velocity is a very important variable in erosion, accurate measurement of impact velocity is essential in any quantitative erosion test. Various methods of velocity measurement have been employed.

7.1 Laser Doppler Velocimetry (LDV)

LDV is potentially the most accurate means of measuring particle velocity. It can provide statistical information on particle speed and direction of motion at any selected point close to, or distant from, the specimen surface. LDV has been applied to gas jet, centrifugal accelerator and wind tunnel tests [e.g. 22, 24], but the apparatus can be bulky and expensive, and for many purposes simpler methods are adequate.

7.2 Rotating Double Disk

An early method, still valuable and widely used, is the rotating double disk method [25] illustrated in Figure 11. Two disks are rotated on a common shaft and the stream of erodent particles is arranged to strike the upper disk which has a thin radial slot cut in it. The lower disk is coated with a thin paint or dye film to show where particles strike it. Two erosion scars are formed: one with the disk stationary, with the particles passing through the slit in the upper disk, and the other with the disks rotating at a known speed. The angular displacement θ between the two scars is measured and can be used to calculate the time taken for the particles to travel the distance L between the disks; hence their velocity, V . The velocity is given by

$$V = \frac{L\omega}{\theta} \quad (4)$$

where ω is the angular velocity of the rotating disks. In practical examples of this device, a high rotational speed is needed to achieve reasonable displacement of the scars and thus accuracy of measurement of the angle θ . Values between 3000 and 10,000 revolutions per minute are common, with a distance L of about 20 to 40 mm. The method is well suited for use in an gas jet erosion test, since velocity calibration can be carried out under exactly the same conditions of particle feed rate and air pressure as used in the erosion test. Typically the random error in measuring velocity in this way is $\pm 10\%$. There can also be a systematic error due to the aerodynamic influence of the rotating disks on particle stream, which may be 10% or even greater for very small particles of low density.

A comparison of velocities measured by both the double disk method and LDV suggests that for a typical velocity in a gas blast rig (45 m s^{-1}) and for rather small particles ($50 \text{ }\mu\text{m}$ silicon carbide or alumina), the double disk method systematically underestimates the velocity by some 10%. The error would be expected to be less for larger particles [24].

7.3 Time of Flight

Another relatively simple method, which is well suited for use with the gas jet method, involves measuring the time of flight of the particles between two transverse light beams a short distance apart [16, 26]. In one version of this method, illustrated in Figure 12, the sensor contains a short glass tube that can be attached to the end of the nozzle. The small increase in length has been shown to have a negligible effect on the particle exit velocity [12]. The timer uses infra-red emitters and detectors, and the beams are collimated by two pairs of holes 1 mm in diameter, aligned perpendicularly to the axis of the nozzle.

The electronic timing system contains a clock that is triggered by a decrease in light density of ca. 0.5%. The velocity is determined from the time taken for the particle to pass between the two beams. Inevitably, there will be some particles that will interrupt one beam but not the other, while in some cases the particle that stops the clock may not be the one that started it. It can be shown by computer simulation of the system that even for a stream of particles all travelling with the same velocity, these effects will lead to a distribution of recorded flight times. However, in all cases the peak of the distribution corresponds to the true flight time, from which the particle velocity can be calculated. The use of a low concentration of particles in the gas stream helps to provide a well defined peak in the time distribution.

Figure 13 presents typical data generated using this method, for spherical glass ballotini particles, about 130 μm in diameter, accelerated along a straight nozzle at two different driving pressures. In this plot the times of flight have been converted into equivalent velocities over the timing distance.

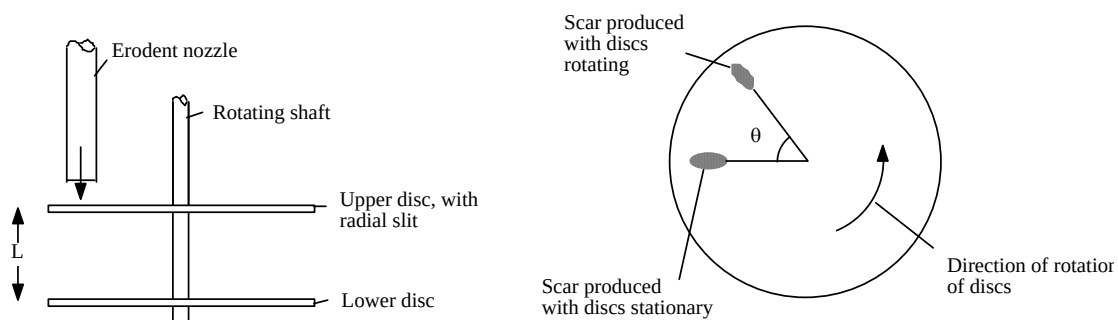


Figure 11 Rotating disk method for measuring particle velocity.

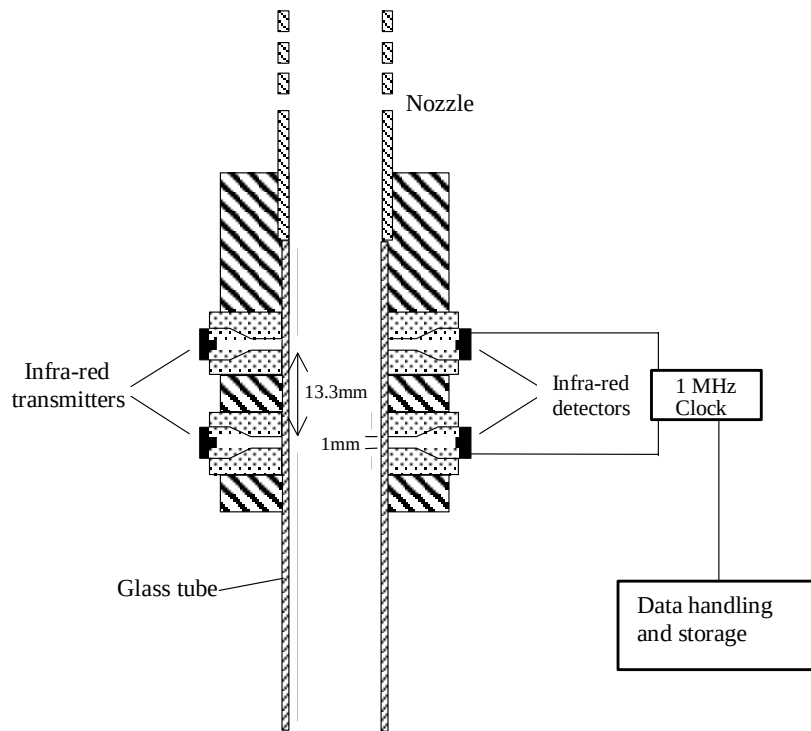


Figure 12 Optoelectronic method of determining particle velocity, by time-of-flight measurement. Source: Ref 17.

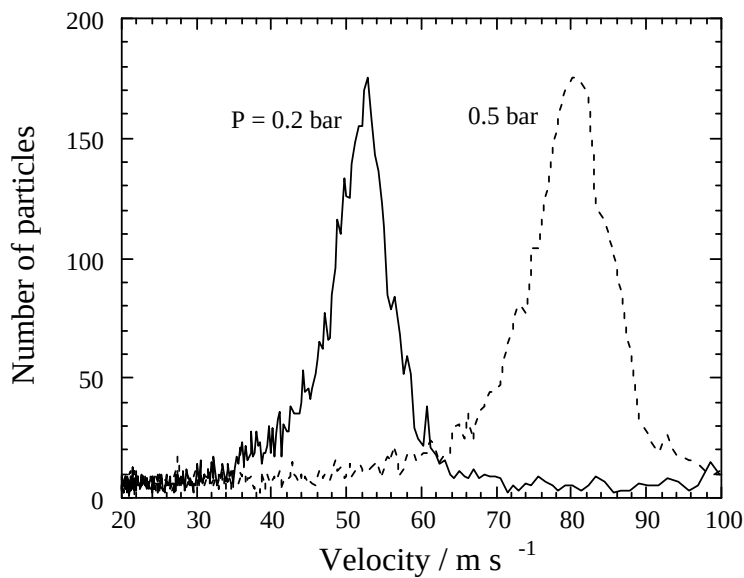


Figure 13 Typical data from the time-of-flight method shown in Fig 12, for 125-150 μm glass Ballotino accelerated in a gas blast rig at nozzle pressures (P) of 0.2 and 0.5 bar. Source: Ref 11.

7.4 High Speed Multiple-flash Photography

High speed multiple-flash photography has also been successfully used to measure particle velocities, and can provide a more economic alternative to LDV. Specialist equipment is needed to produce flashes of sufficiently short duration to “freeze” the motion of rapidly moving particles, with accurately known inter-flash timing. To image the small particles used in erosion testing, a relatively small field of view is needed, with sharp focus and a small depth of field. Conventional stroboscopic light sources tend to be too slow to be useful, and of insufficient brightness when used at the high speed needed. A means of triggering separate short-duration flash sources at precise time intervals provides a better method.

Although two flashes alone are sufficient in principle to determine a velocity, confusion can occur in identifying which images correspond to each particle if there are several images in the frame, and a sequence of several flashes can provide more reliable data. Figure 14 illustrates this method, and shows images of olivine sand particles leaving a horizontal gas jet nozzle at a mean speed of 30 m s^{-1} , produced with a four-flash sequence. The image was captured with a video camera and computer frame-grabber card synchronised with the flashes. This method provides very quick image acquisition, and since the image is already in digital form, particle velocity vectors can easily and quickly be determined using suitable image analysis software.

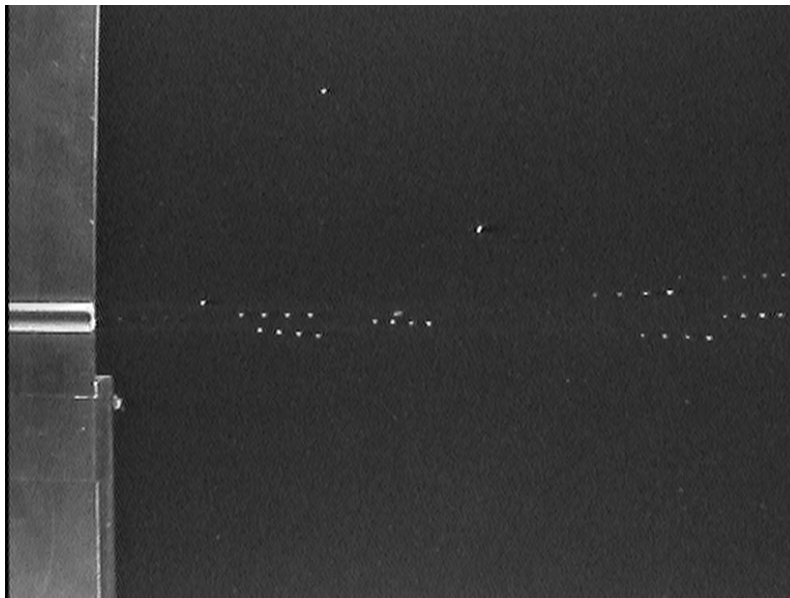


Figure 14 Multiple flash image showing olivine sand particles leaving a horizontal gas-blast nozzle (at the left of the frame) and travelling to the right at a mean velocity of 30 ms^{-1} . The particles were imaged with four short duration flashes at 0.2 ms intervals, and the frame was acquired with a video camera and computer image-grabber card. Courtesy of D N Allsopp and I M Hutchings, University of Cambridge, UK.

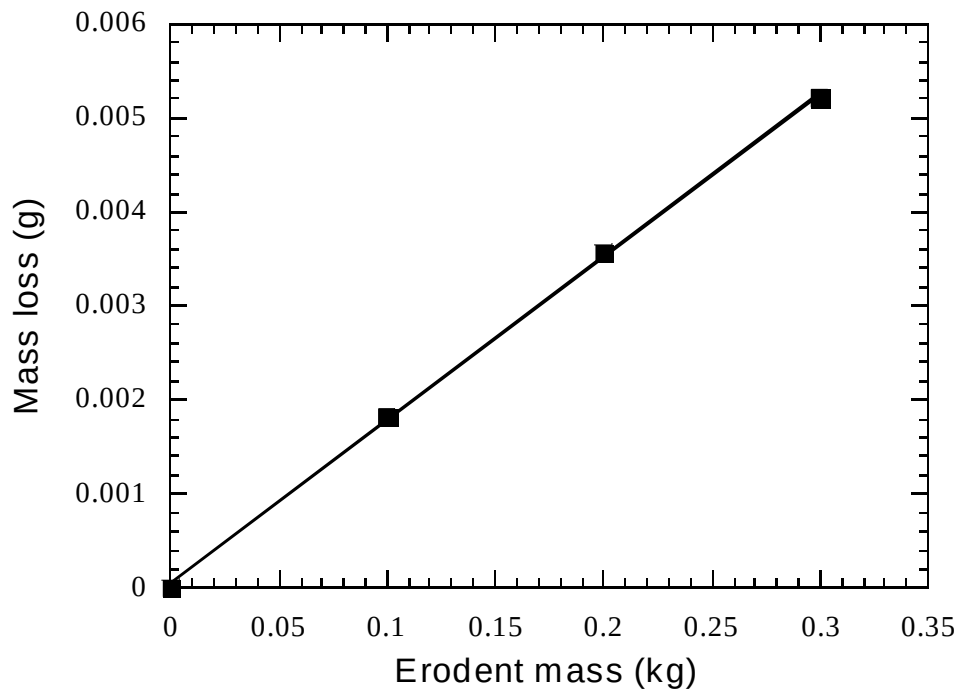
8 Data Analysis And Interpretation

Most erosion tests are performed to determine the rate of material removal, and the primary measurement of material loss is weighing. Since the mass loss to be measured will usually be small, often less than 1 mg, it is very important that the balance used to weigh the specimen has adequate sensitivity and long-term stability. The latter point is important, since an erosion experiment may last for several hours or even days, and the measurement involves determining small changes in the mass of a specimen which itself has a much larger mass. The balance must be carefully zeroed before each weighing. Temperature control in the balance room may be necessary, and a “control” specimen similar in mass to the erosion specimen, but not exposed to erosion, may be useful to reduce random errors in weighing.

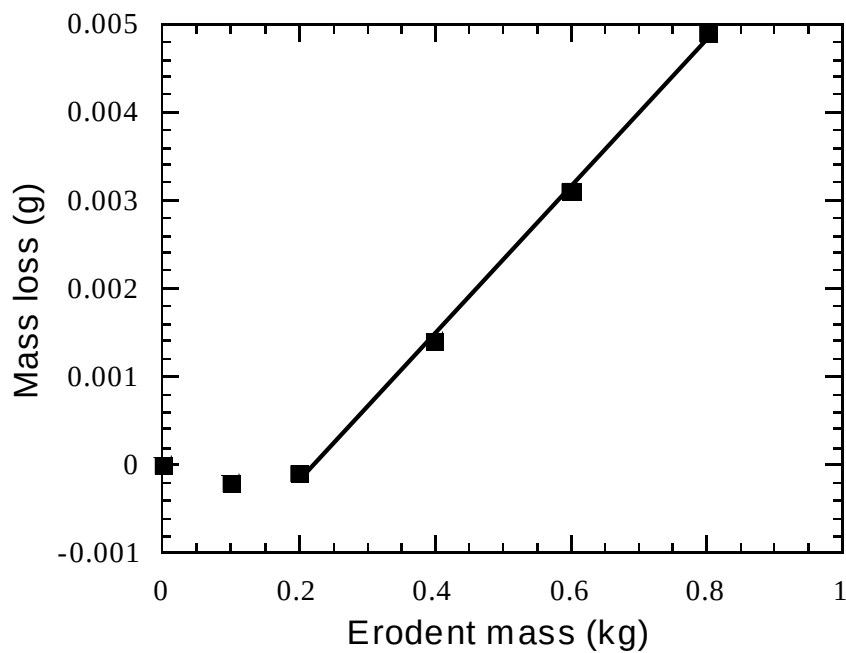
A well defined protocol must be adopted to clean the specimen (e.g. with a clean, dry blast of compressed air) before weighing. With such precautions, and using a well characterised erosion test operated under stable conditions, it is possible to achieve highly reproducible measurements of erosion rate. Figure 15(a) presents data from a low carbon steel specimen eroded by three 100 gram quantities of olivine sand in a gas jet erosion test at 20 m s^{-1} and 30° impact angle. The plot is linear (with a regression coefficient of 0.9997), leading to high confidence in the measured erosion value, and in this case a single test in which the specimen was exposed to 300 grams of erodent would have yielded essentially the same erosion rate.

In some circumstances, as noted above, materials may exhibit an incubation period of lower mass loss, or even mass gain, before steady state erosion occurs. Data showing this effect are illustrated in Figure 15(b), for a sintered alumina ceramic sample eroded at 30 m s^{-1} and 90° impact angle. Linear behaviour was exhibited only after some 200 grams of erodent had struck the specimen. But if a single measurement of mass loss had been made after exposure to, say, 400 or even 800 grams of erodent, the resulting value of mean erosion rate would not have accurately reflected the true steady-state behaviour of the sample. It is therefore essential that enough data are gathered from the sample to enable its steady-state erosion behaviour to be assessed accurately. This may involve preliminary testing to establish the exposure needed to achieve steady-state conditions.

Although reproducibility within a single laboratory can be good, erosion test results obtained in different laboratories often show greater variability [27]. The most important source of this lies in the method and accuracy of measurement of particle velocity. Different methods of erosion testing may also introduce subtle but important differences in the particle motion. For example, there is evidence [28] that particle rotation plays an important role in explaining differences in erosion rate experienced with gas jet and rotating disk erosion testers [20].



a)



b)

Figure 15 Typical erosion data from tests in a gas-blast rig with 300-425 μm olivine sand particles. (a) Mild steel specimen, 20 m/s, 30° impact angle, (b) Glass-bonded alumina ceramic specimen, 30 m/s, 90° impact angle. Courtesy of D N Allsopp and I M Hutchings, University of Cambridge, UK.

9 SOURCES OF GUIDANCE

The first part of these guidelines has given a simple introduction to erosion wear and erosion wear testing systems. However, there are several books and other documents available if further information is required, and some of these are listed below.

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 [29].

General information on tribology is available in several handbook such as *the Wear Control Handbook* by Peterson and Winer [30], *The ASTM Metals Handbook: Vol 8, Friction, Lubrication and Wear Technology* [31], and *the Handbook of Tribology: Materials, Coatings and Surface Treatments* by B Bhushan and B K Gupta [32].

Compilations of data of wear rates of different materials combinations under specified conditions are available in the *Tribology Handbook* by M J Neale [33] and the *Elsevier Materials Selector* by N A Waterman and M J Ashby [34].

Specific information of testing is given in many papers in the literature. Examples are Almond and Gee [35], Alliston-Greiner [36], Eyre [37], in ASTM STPs on friction and wear testing of metals [38], plastics [39], coatings [40], elastomers [41], ceramics [42], and advanced materials [43], and an ASTM STP on the fretting fatigue test methods [44].

Other more general information on wear testing is given in books such as the *Fundamentals of Friction and Wear of Materials* edited by Rigney [45], *New Directions in Lubrication, Materials, Wear and Surface Interactions* by Loomis [46], *Tribology: Friction and Wear of Engineering Materials* by I Hutchings [8], *Engineering Tribology* by J Williams [47], and *Friction Science and Technology* by Blau [48].

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* [49], and the peer reviewed Journals, *Wear* [50] and *Tribology International* [51].

Information on the wear performance of different materials and on the different types of laboratory wear tests (including erosion) available for simulating practical wear conditions, is presented [1] in the *Guide to Wear problems and Testing for Industry*, by M J Neale and M Gee. In addition, a comprehensive listing of expertise and wear test facilities available in the UK is contained [5] in the *Directory of Tribology Expertise and Facilities* by M Gee and B Richards.

10 REFERENCES

- 1) M J Neale, 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, *Rotating Wheel Abrasion Testing*, NPL Good Practice Guide No 55, May 2002
- 4) M G Gee, A Gant, I Hutchings, R Bethke, K Schiffmann, K Van Acker, S Poulat, Y Gachon and J von Stebut, *Ball Cratering or Micro-Abrasion Wear Testing of Coatings*, NPL Good Practice Guide, to be published, July 2002.
- 5) M G Gee, B P Richards *Directory of Tribology Expertise and Facilities*. Oct 2001
- 6) J Ellis, Private communication.
- 7) ASTM standard G40-92. *Standard terminology relating to wear and erosion*. 1992. American Society for Testing & Materials. West Conshohocken, PA.
- 8) I M Hutchings. *Tribology: Friction and Wear of Engineering Materials*. CRC Press. Boca Raton, FL. 1992
- 9) ASTM Manual 32. *Manual on Testing Sieving Methods*. 1998 American Society for Testing & Materials. West Conshohocken, PA.
- 10) BS 1796-1:1989. *Test Sieving*. British Standards Institution. London (also ISO 2591-1:1988).
- 11) S Bahadur, R Badruddin. *Wear of materials 1989*. Ed K C Ludema. ASME, New York. 1989 pp 143-153.
- 12) ASTM Standard G76-95. *Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets*. American Society for Testing & Materials. Vol 03.02. West Conshohocken, PA.
- 13) G L Sheldon, J Maji, C T Crowe. *Trans ASME J Eng Mater. Technol.* Vol 99 (1977) pp 138-142.
- 14) D B Marshall et al. *Wear*. Vol 71 (1981) pp 363-373.
- 15) D R Andrews, S M Walley, J E Field. *Proc. 6th Int. Conf. On Erosion by Liquid and Solid Impact*. Cavendish Laboratory, Cambridge, UK. 1983. Paper 36.

- 16) P H Shipway, I M Hutchings. *Wear*. Vols 162-164 (1993) pp 148-158.
- 17) A N J Stevenson, I M Hutchings. *Wear*. Vols 181-183 (1995) pp 56-62.
- 18) I R Kleis, K K Uuemyis. *Russian Engineering Journal*. Vol 51 (1971) pp 13-15.
- 19) S Soderberg, S Hogmark, U Engman, and H Swahn. *Tribology International*. Dec 1981 pp 333-343.
- 20) A J Burnett, S R De Silva, A R Reed. *Wear*. Vols 186-187 (1995) pp 168-178.
- 21) J Nicholls, Cranfield University, UK, 2000, Private Communication
- 22) W Tabakoff, M F Malak, A Hamed. *AIAA Journal*. Vol 25 (1987) pp 721-726.
- 23) J E Goodwin, W Sage, G P Tilly. *Proc. Inst. Mech Engineers*. Vol 184 (1989) pp 279-291.
- 24) V Ponnaganti, D E Stock, G L Sheldon. In *Polyphase Flow and Transport Technology*. Ed R A Bajura. ASME, New York. 1980 pp 217-222.
- 25) A W Ruff, L K Ives. *Wear*. Vol 35 (1975) pp 195-199.
- 26) T H Kosel, K Anand. In *Corrosion and Particle Erosion at High Temperatures*. Eds V Srinivasan, K Vedula. The Minerals, Metals & Materials Society. 1989 pp 349-368.
- 27) A Ruff. *Wear* Vol 108 (1986) pp 323-335.
- 28) M S A Bradley. University of Greenwich, UK. 1999. Private Communication.
- 29) H Czichos. *Tribology: A Systems Approach to the Science & Technology of Friction, Lubrication and Wear*. Elsevier (1978).
- 30) M B Peterson. *Wear Control Handbook*. American Soc of Mech Eng (1980).
- 31) ASM Metals Handbook. Vol 18. *Friction, Lubrication & Wear Technology* (1992).
- 32) B Bhushan, B K Gupta. *Handbook of Tribology: Materials, Coatings and Surface Treatments*. McGraw-Hill. (1992).
- 33) M J Neale. *Tribology Handbook*. Butterworths. (1973).
- 34) N A Waterman, M F Ashby. *Materials Selector*. Chapman and Hall. (1995).
- 35) M G Gee, E A Almond *Effects of Test variables in Wear Testing of Ceramics*. Mat Sci & Technology. Vol 4 (1988) pp 877-884.

- 36) A F Alliston-Greiner. *Testing the Performance of Materials and Lubricants*. Private Communication.
- 37) T S Eyre, F A Davis. *The Testing and Evaluation of Materials in Tribology; Characterisation of High Temperature Materials: Surface Stability*. Ed T N Rhys-Jones. Inst of Materials. (1989) pp 186-240.
- 38) ASTM STP 615. *The Selection and Use of Wear tests for Metals*.
- 39) ASTM STP 701. *Wear Tests for Plastics: Selection and Use*.
- 40) ASTM STP 769. *Selection of Wear Tests for Coatings*.
- 41) ASTM STP 1145. *Wear and Friction of Elastomers*. ASTM (1992).
- 42) ASTM STP 1010. *Wear Tests for Ceramics*. ASTM (1988)
- 43) ASTM STP 1159. *Standardisation of Fretting Fatigue Test Methods & Equipment*
- 44) ASTM STP 1167. *Wear Testing of Advanced Materials*. ASTM. (1992).
- 45) D A Rigney. *Fundamentals of Friction and Wear of Materials*. ASM. (1981).
- 46) W R Loomis. *New Directions in Lubrication, Materials, Wear and Surface Interactions*. Noyes Publications. (1985).
- 47) J A Williams. *Engineering Tribology*. Oxford Science Publications. (1994).
- 48) P J Blau. *Friction Science and Technology*. (1995).
- 49) Proceedings of the International Conferences on the Wear of Materials. ASME (1977, 1979, 1981, 1983, 1985, 1987, 1989, 1991).
- 50) *Wear*. Journal published by Elsevier Science.
- 51) *Tribology International*. Journal published by Elsevier Science.
- 52) R Wood. Private Communication.

11 Annex A: Recommended Test Procedure for Gas Jet Erosion Testing.

This Annex gives recommended procedures for erosion testing using an ambient temperature gas jet erosion testing system. The test uses pressurized air blown through a nozzle, with the particles being introduced into the air stream by the venturi effect. This test is appropriate for use in situations in which test laboratories have a need to simulate damage of pipe work or other components that have been subjected to erosion by particles in a high velocity gas stream.

The test procedures covered by these recommendations relate to tests using nozzles having an inner diameter >3 mm and a length of >200 mm. The procedure complements the ASTM standard G76 on Erosion Testing (7).

A.1 TEST APPARATUS

A schematic of a typical test system is shown in Figure A1.

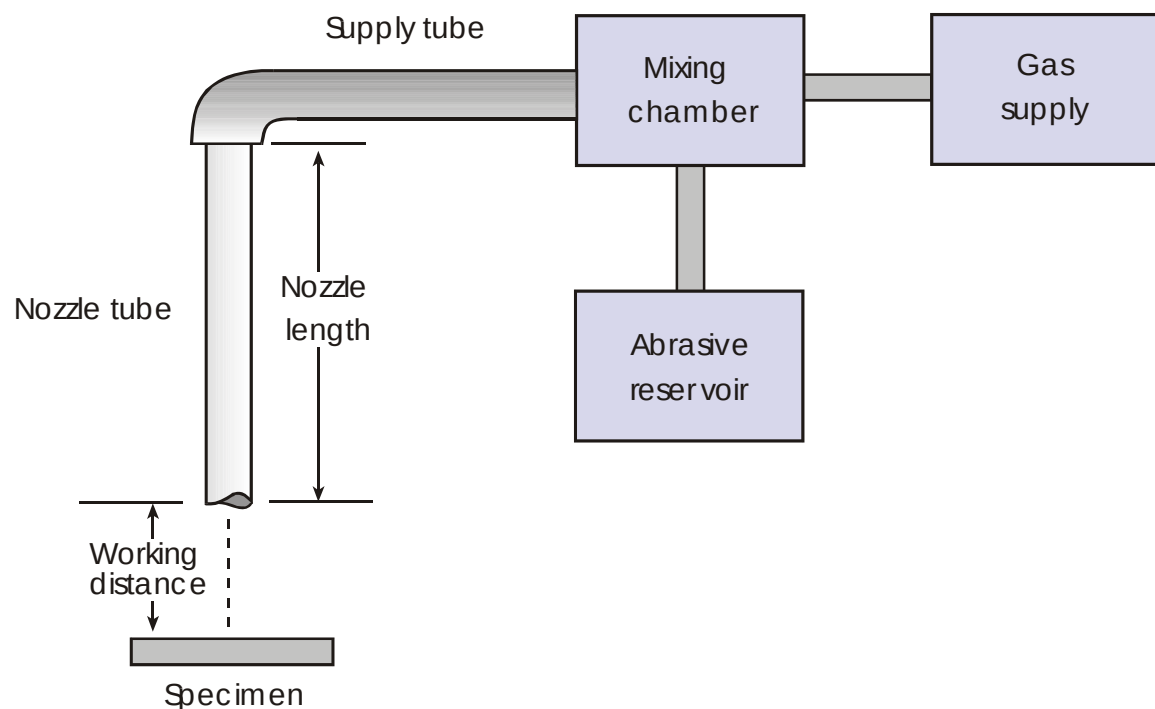


Figure A1. Schematic of gas jet erosion system (from Reference 7).

The erodent is fed from a hopper into the erodent feed system that introduces the erodent into the gas flow by means of a venturi suction device. The erodent particles are accelerated in the nozzle by the gas and emerge to hit the test-piece that is clamped at a well-defined distance and angle from the end of the nozzle. The test-piece and nozzle are enclosed in a sealed chamber that is provided with vacuum extraction to ensure that fine particulate material is removed safely. For tests at ambient temperature (e.g. between 18 and 25°C), small variations in the test temperature do not have any major effects on the test.

A.1.1 Nozzle

The length and diameter of the nozzle are both important parameters that affect the final particle velocity and divergence of the erodent particle stream on leaving the nozzle. The ASTM Standard recommends the use of a nozzle 50 mm long with a bore of 1.5 mm, but this suffers from considerable contact with erodent of the particle stream and a short nozzle life with a divergent particle stream. Other workers (e.g. 13) use longer nozzles with a diameter of about 5 mm. To achieve an acceptable particle velocity distribution a length/diameter ratio of at least 25 is recommended.

A.1.2 Venturi and Erodent Feed

The venturi is a critical element of the test system as it controls the way particles are fed into the gas stream for acceleration in the nozzle. The design of venturis is beyond the scope of this procedure. The reader is referred to test system manufacturers for further information.

The erodent can be fed to the venturi by a number of different methods. These include

- a vibrating feed
- a screw auger
- a vacuum feed coupled with a slotted rotating disk.

The essential feature of all these methods is that the erodent is fed steadily and in a well controlled way to the venturi. All these methods have been shown to be effective in giving good control of feed rates. It is important that a vacuum extraction system is fitted to ensure that used erodent and debris are collected and can subsequently be disposed of safely.

A.1.3. Control of Particle Velocity.

The gas jet velocity is adjusted by varying the pressure of the gas feed to the nozzle. As the gas jet is increased, the particle velocity will also increase. The differential gas pressure between the test chamber and the gas feed should be measured with a calibrated manometer. Typically, particle velocities in the range of 40-200 m s⁻¹ can be achieved with

this type of system, but there are some systems that are capable of higher particle velocities [52].

A.1.4. Calibration of Particle Velocity

Accurate measurement of impact velocity is essential in any quantitative erosion test. A common method is the rotating double disk method [25], which is illustrated and discussed in Figure 11 and Section 7.2 respectively. The method is well suited to use in a gas jet erosion test, since velocity calibration can be carried out under exactly the same conditions of particle feed and air pressure as used in the erosion test. Another relatively simple method, which is well suited for use with the gas jet method, involves measuring the time of flight of the particles between two transverse light beams a short distance apart [16].

A.1.5 Calibration of Mass Flow Rate

There are two methods that can be used to calibrate the mass flow rate. These are to collect erodent in an erodent trap enclosed around the nozzle for a known period of time or to measure the time taken to use a known mass of erodent. Both are subject to some error in determining the time period, so it is advisable to use a fairly large mass of erodent in these measurements (say 20 g).

Normally, the mass flow rate can be altered by adjusting the erodent feed mechanism. The calibration of mass flow rate should be carried out for all flow rates used in experiments, although usually this calibration is not of major importance as the amount of erodent used in an experiment is controlled by weighing known aliquots of erodent.

A.2. TEST MATERIALS

A.2.1 Test Specimens

Test pieces should be typically 50 x 50 mm but the key point is that the size of wear scars on test pieces should be wholly encompassed by the test piece. On small test pieces trial experiments can be conducted to ensure that this condition is met. The thickness of the test piece is not critical but it must be sufficient to completely enclose the wear that takes place.

The surface finish of the test piece may affect the results of the test. In particular, the presence of a surface which is weakened by the preparation process may lead to increased initial wear. Conversely, the presence of a compressive residual stress in the surface layer may possibly also affect the initial wear rate. In both cases these surface layers are worn away, the wear rate should return to the normal value for the material. Care must be taken

in preparing the surface finish of the samples to ensure these effects are eliminated or minimised.

A.2.2. Test Erodent.

The test erodent should be obtained from a consistent source with good QC procedures to ensure that variability in the properties of the erodent are minimised.

It is well known that the results of gas borne particulate erosion depend critically on the shape, size and size distribution of the erodent. For this reason, if it is important to compare the results of one test with another, batches of the same erodent should be used in both tests.

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

A.2.3. Test Reference Materials

In some circumstances it is desirable to normalise test results to take account of minor uncontrolled variations in test conditions or changes in the make-up or erodent. In these cases a reference test piece should be used in a sequence of tests, and the procedure is described in Section A3. In any case, a test should be carried out periodically on a surface material to ensure that the test system is operating correctly and gives repeatable results.

A.3 TEST PROCEDURE

The following test procedure is recommended:

- i) Clean the test piece before placing it in the test system, using cleaning procedures appropriate for the test materials. For many materials this can be carried out ultrasonically in acetone for 10 minutes.
- ii) Measure the mass of the test piece by weighing before the test.
- iii) Clamp the test piece on a table in the test piece chamber that can be rotated to a set angle with respect to the nozzle. Adjust the angle to give the required angle of incident of the erodent stream with the test piece surface.
- iv) Position the nozzle so that its tip is the required distance above the test piece surface. The stand-off distance influences the size of the eroded area, which gets larger as the stand-off distance increases, due to the spread of the erodent stream.

- v) Close the test piece chamber; start the vacuum extraction system; start the gas flow at the appropriate pressure to give the required particle velocity.
- vi) Introduce the first aliquot of erodent particles into the feed mechanism, to start the test.
- vii) After the first aliquot of material has been consumed, switch off the test system and remove the test piece.
- viii) Clean the test piece repeating the procedure in (i) above and reweigh.
- ix) Repeat steps (i), (ii) and (v) – (vii) until all the erodent has been used. Normally at least 5 test cycles are used.

A.4 ANALYSIS OF TEST RESULTS

The values of mass as measured in A3 above should be listed and a table of mass loss against mass of erodent calculated using a spreadsheet or equivalent program. The test piece mass loss should be converted to a volume by using the known test piece density. The volume loss is normally presented as a graph [8] with respect to mass of erodent (see Figure 1, Section 1). At least two repeat tests should be carried out under the same conditions for each material.

A.4.1. Calculation of Erosion Rate.

Normally a linear relationship is observed between the test piece mass loss and the mass of erodent. However, an incubation time is often observed before this linear relationship is seen (see Figure 1). Regression analysis should therefore be used to obtain an erosion 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.

A.4.2. Use Of Reference Materials

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 would then be calculated.

A.5 REPORTING OF RESULTS

The reported results should include:

- Operator
- Date
- Material to be tested
- Surface finish of test piece
- Erodent material
- Erodent size
- Mass of erodent used
- Nozzle size (internal diameter)
- Nozzle length
- Angle of incidence
- Velocity of erodent
- Graph of volume of wear with respect to mass of erodent
- Erosion rate
- Comments on any unusual behaviour (non-linear behaviour, incubation time etc)

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

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

A.6 TYPICAL DEFAULT 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 default conditions have been found to give useful results.

Erodent	220 μm abrasive particles
Impact velocity	75 m s^{-1}
Impact angles	20 and 90 ^o