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Abrasion and Erosion Tests

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Tribology Trust Silver Medal 2017

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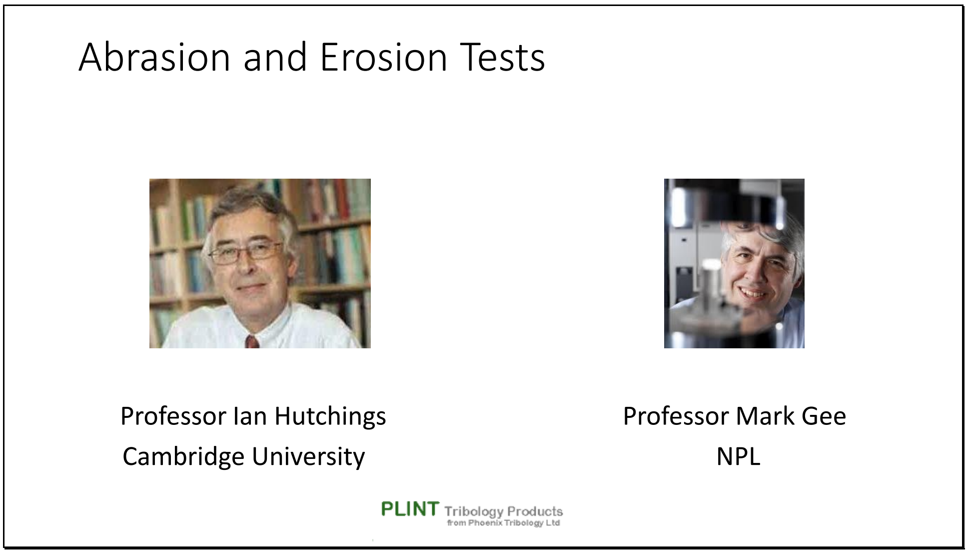

This talk draws heavily on the work of Professor Ian Hutchings at the University of Cambridge, Professor Mark Gee at the UK National Physical Laboratory, and others.

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Abrasion and Erosion Tests

- Although size of test samples may be small, compared with real life applications, satisfactory data can only be generated by matching conditions within the real life process

- Successful tests rely on close control of particle size, shape and fracture toughness

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In abrasive and erosive wear testing, although the size of test samples may be small, compared with real life applications, satisfactory data can only be generated by matching conditions within the real life process, hence these are effectively “real life” and not scale model test devices. It is not possible to extrapolate wear response from one type and size of particle, to another.

Tests rely on close control of particle size, shape, hardness and fracture toughness of the particles, and this can only be achieved by careful sourcing and grading.

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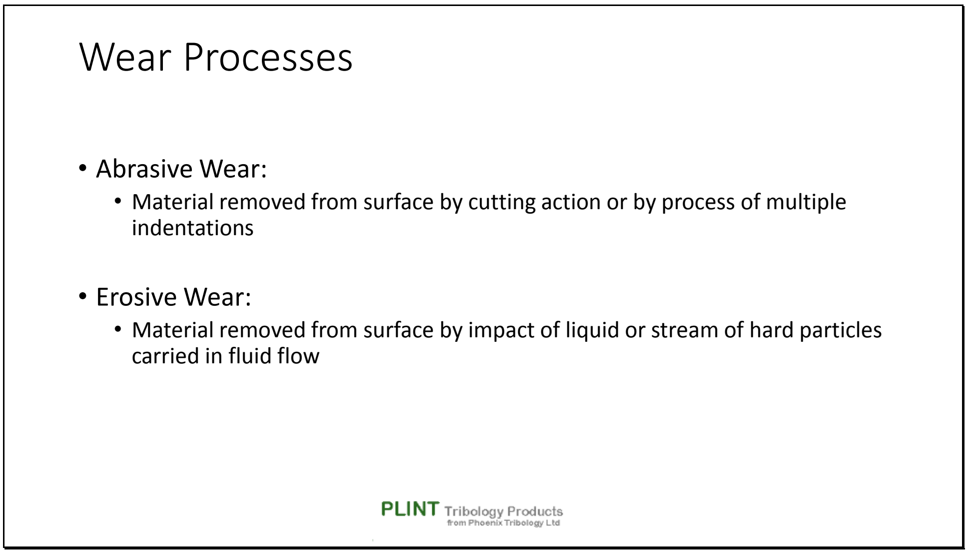

Abrasive wear occurs when material is removed from a surface by a cutting action or by a process of multiple indentations from abrasive particles. This may be an intended process as in component manufacture, such as grinding or polishing, or unintended, as may occur in machine operation, such as the wear of digger teeth, when working in gravel.

Erosive wear involves the removal of material from a surface by impact of a liquid or of a stream of hard particles carried in a fluid flow. There is also cavitation erosion, which is caused by the collapse of low pressure vapour bubbles onto the component surface. I will not be covering cavitation in this presentation.

As with abrasive wear, erosion may be an intended process, as in shot or sand blasting, or unintended, as in the erosion of pipes, solar panel coatings and other surfaces. Some surfaces, for example wind turbine blades, may be subjected to water droplet erosion.

A number of standards exist for abrasion and erosion testing, usually specific to a material or product group.

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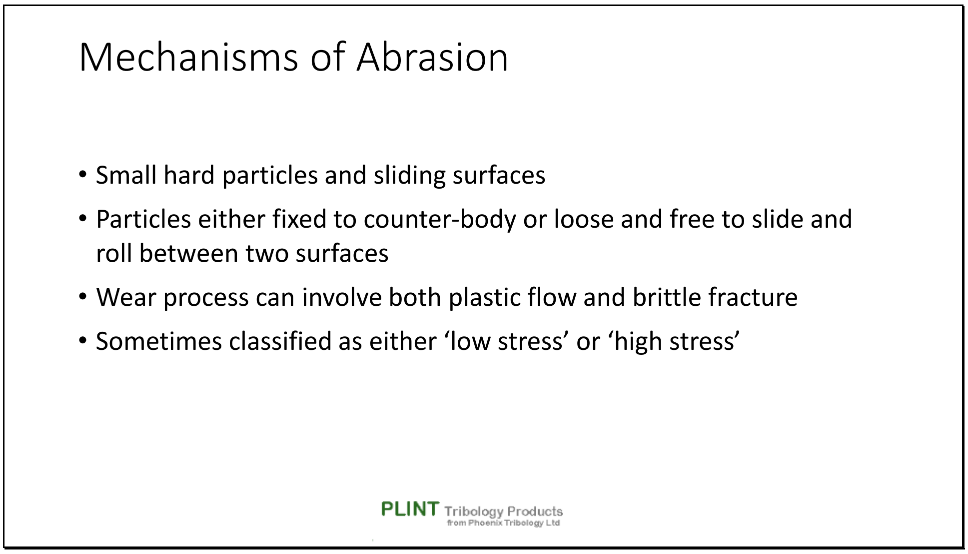

Abrasive wear involves the presence of small hard particles and sliding surfaces. The particles may either be fixed to a counter-body, as in carborundum paper or a grinding wheel, leading to ‘two-body abrasion’, or be loose and free to slide and roll between two surfaces, which is usually termed ‘three-body abrasion’.

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 brittle. The simplest models usually assume that either plastic flow or brittle fracture is the dominant wear mechanism.

The conditions of abrasive wear are further classified as either ‘low stress’, in which the abrasive particles are relatively undamaged in the wear process, or ‘high stress’, where the particles experience extensive fracture.

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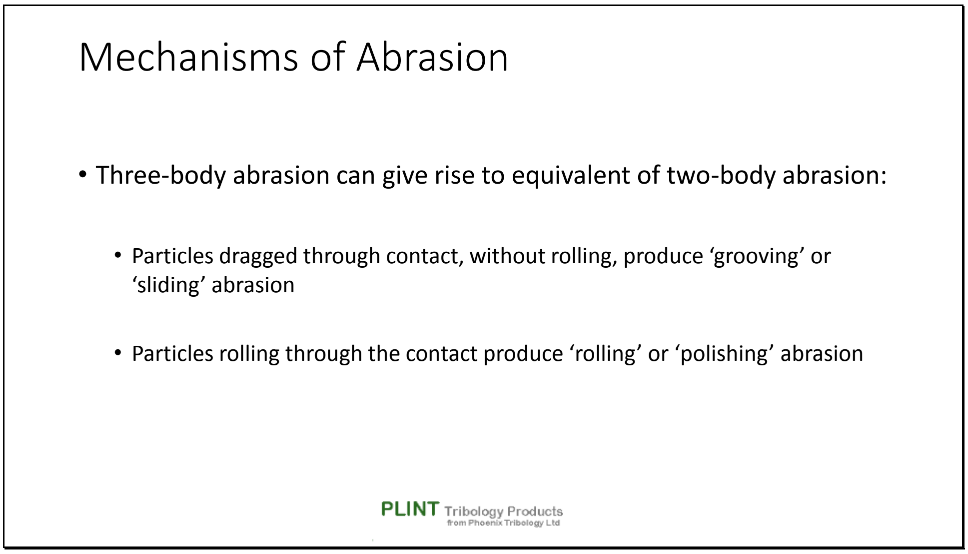

Somewhat confusingly, three-body abrasion can give rise to the equivalent of two-body abrasion, if the particles are dragged through the contact, without rolling, as opposed to rolling through the contact. The former gives rise to ‘grooving or sliding abrasion’ and the latter to ‘rolling or polishing abrasion’.

The fewer the particles in the contact, the higher the load per particle and the greater the tendency for a particle to become embedded, either temporarily or permanently, in the softer surface, and then be dragged across the harder surface. As the number of particles goes up, the load carried by each particle goes down and the easier it is for the particle to roll.

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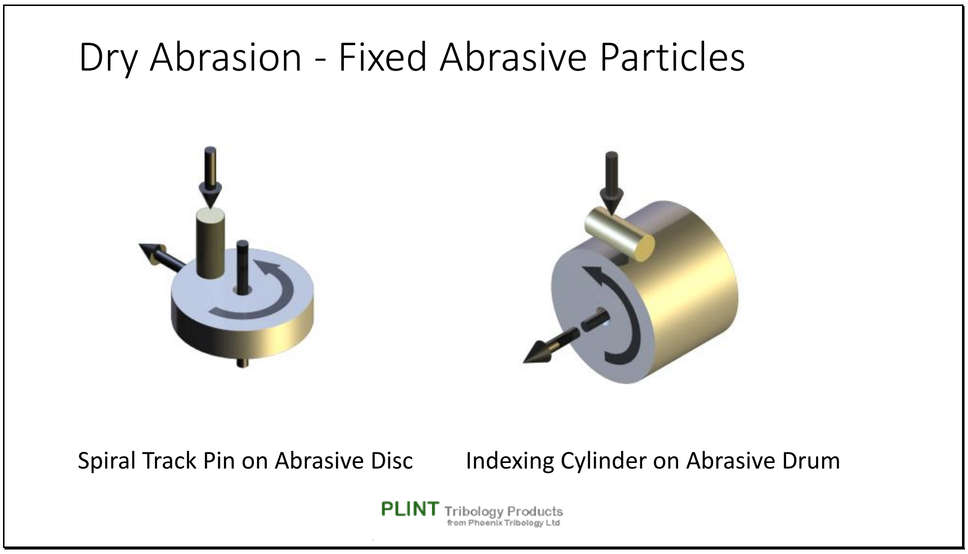

The simplest types of two-body test systems are those using either abrasive papers or abrasive grinding wheels, with a test sample in sliding or sliding-rolling contact with the abrasive surface. In these rigs, the principal problem is controlling the condition of the abrasive surface.

If a pin-on-disc test is carried out with abrasive paper attached to the disc, the paper rapidly degrades or becomes clogged with wear particles. Indexing the pin across the disc in a spiral pattern, ensuring that fresh abrasive paper comes into contact with the pin at all times, overcomes this problem. Another arrangement is the indexing block or cylinder on abrasive drum.

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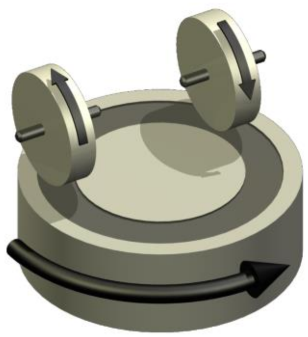
Dry Abrasion - Fixed Abrasive Particles

Taber Abraser



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The Taber Rotary Platform Abraser is a long established industry standard tester, for a wide range of different materials. In the Abraser, a flat specimen is mounted on a turntable, which rotates on a vertical axis. Two abrasive wheels are loaded against the specimen surface on horizontal axles, off-set from the centre of rotation of the turntable. As the turntable rotates, the wheels are free to rotate, producing rolling-sliding, which results in wear.

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ISO 23233:2009 Rubber, vulcanized or thermoplastic — Determination of resistance to abrasion using a driven, vertical abrasive disc

This standard test involves loading a rubber wheel sample against an abrasive disc, with an imposed load and slip angle, hence the geometry is similar to the Taber Abraser, but with specimen and abrasive components switched around.

Tests on candidate samples are used to determine comparative wear rates and the method is recommended for abrasion tests for various rubber products, especially tyres.

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Free Abrasive Particles

- Specimen loaded against rotating disc with abrasive particles fed into contact
- Either dry or with a liquid transport medium
- Hopper fed systems for abrasive particles used for control of supply
- Particles passed through contact once to avoid contamination and comminution

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Free particle abrasion test rigs typically comprise a stationary specimen loaded against a rotating disc or drum, with abrasive particles introduced into the contact either dry or with a liquid transport medium.

The use of hopper fed systems for abrasive particles improves the uniformity of supply, which in turns enhances control of the particle loading in the contact.

In order to avoid contaminating the abrasive particles, whether dry or wet, with wear debris from the test specimens, plus to avoid particle comminution, it is normal to use a single pass system and not re-circulate or re-use the abradant.

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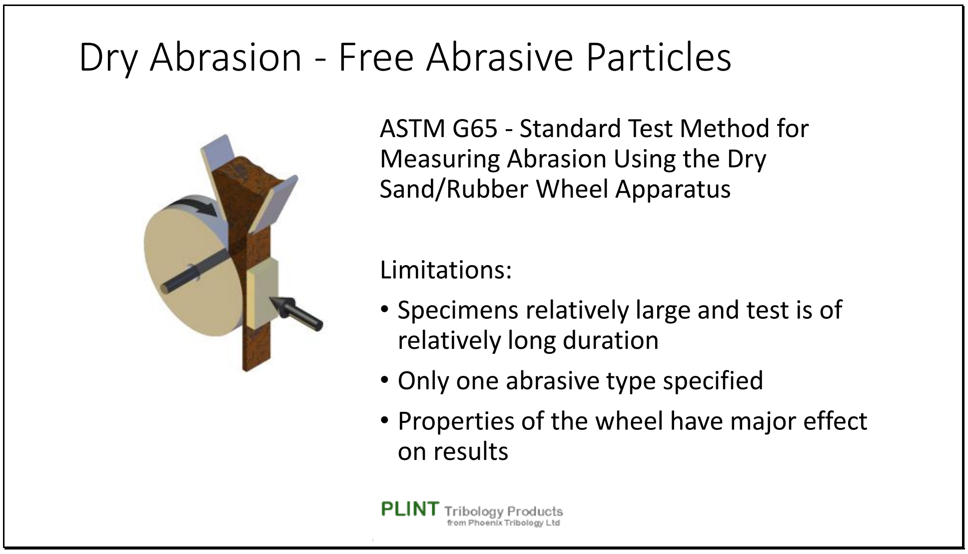

The most widely used test is ASTM G65 - Standard Test Method for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus.

In this test, a sample is pressed against a rubber-rimmed wheel as silica abrasive is fed from a hopper, via a nozzle, above the converging inlet between sample and wheel.

There are several limitations to the standard ASTM G65 test:

1. The specimens are relatively large and the test is of relatively long duration, requiring 3 to 4 kg of abradant per test.
2. The standard only specifies one abrasive type: Ottawa sand, which is not realistic for many applications and not necessarily suitable for testing very hard materials.
3. The properties of the wheel rubber have a major effect on the results.

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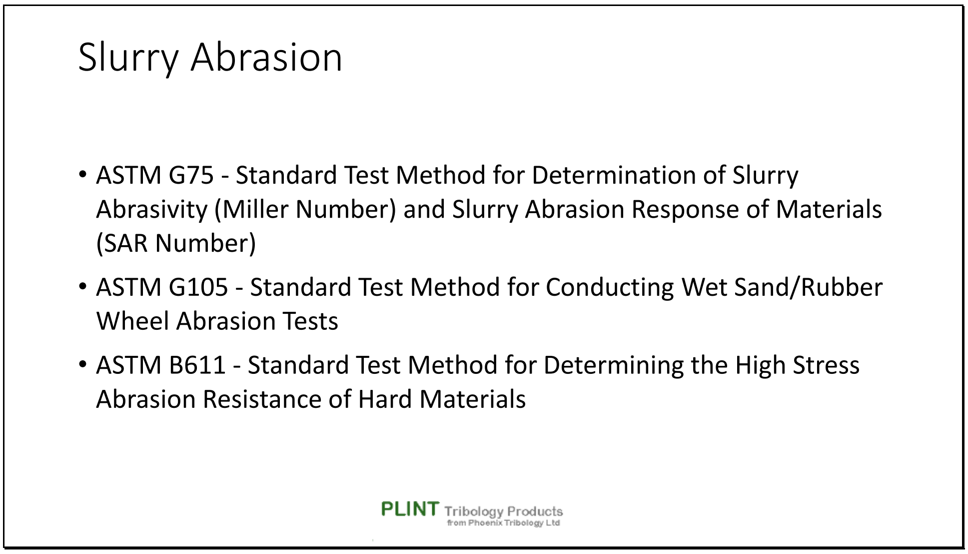

There are numerous loose slurry abrasive test systems, of which the most familiar will be:

ASTM G75 - Standard Test Method for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)

ASTM G105 - Standard Test Method for Conducting Wet Sand/Rubber Wheel Abrasion Tests

ASTM B611 - Standard Test Method for Determining the High Stress Abrasion Resistance of Hard Materials

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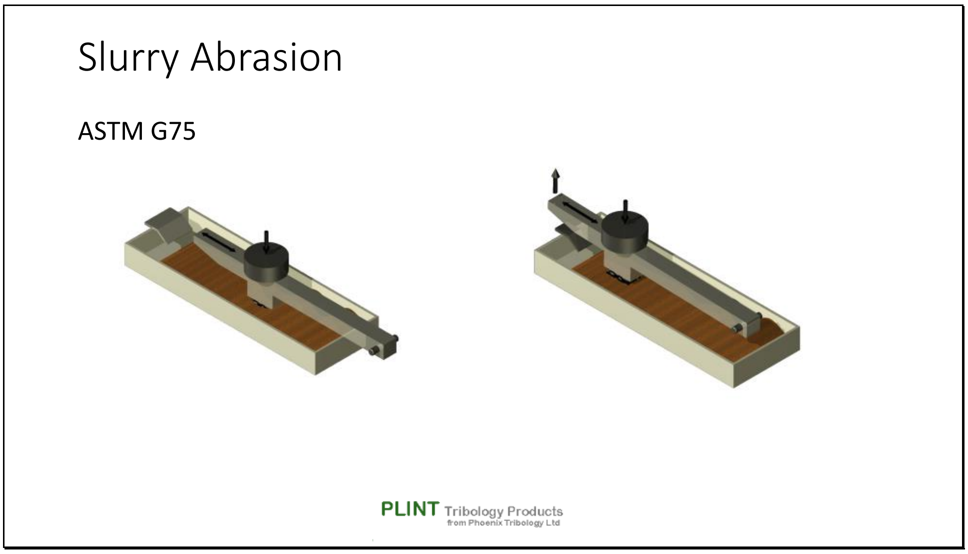

ASTM G75 is a reciprocating test in which a dead-weight loaded specimen is moved against a bed of abrasive slurry, contained in a tray, with the specimen lifted out of contact at the end of the stroke. This allows the slurry bed to reform, before the next sliding stroke. Attention may be required to ensure consistent mixing of the slurry as the test proceeds.

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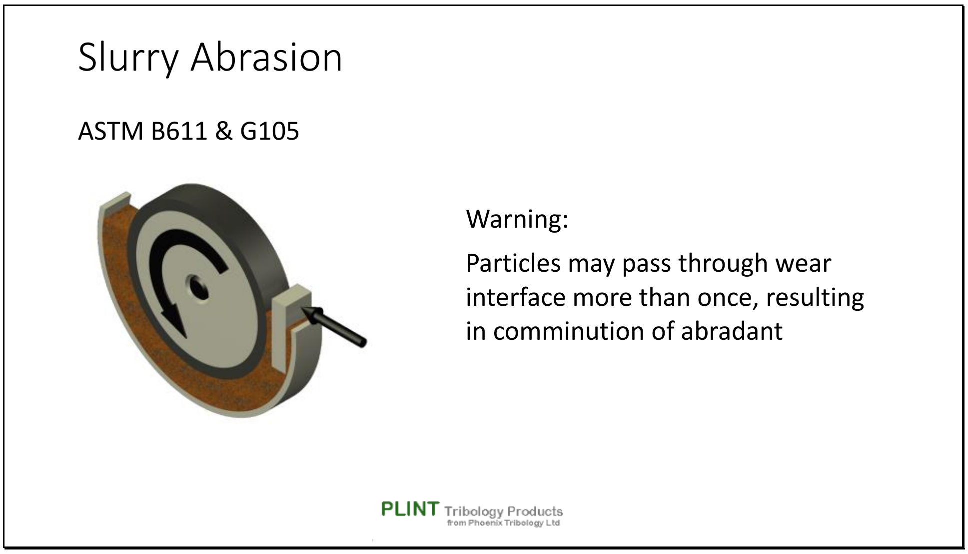

ASTM B611 is frequently used to test hard metals used in mining applications. A sample is pressed against a rotating steel wheel, partially immersed in a tank of slurry. The abrasive specified in the test standard is alumina, which is far harder than the abrasive particles likely to be encounters in the real-life application.

ASTM G105 uses similar test geometry to the ASTM B611, but with a rubber-rimmed wheel as opposed to a steel wheel.

With both B611 and G105, abrasive particles may pass through the wear interface more than once, so comminution of the abradant may take place.

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Abrasion Test Alternatives

- Better control of particle flow rate
- Reduced risk of particles falling outside contact
- Choice of abrasives
- Single pass dry or wet

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An alternative to the ASTM dry and wet specimen on wheel test configurations is one in which the specimen is mounted horizontally and loaded on the top of the wheel. The abrasive particles are then fed via a chute to be delivered onto the surface of the wheel, immediately in front of the contact. The rate of delivery of particles is controlled by a precision feed system, giving accurate and repeatable feed rates. The problem of particles falling past the contact, as with the standard G65 configuration, is avoided.

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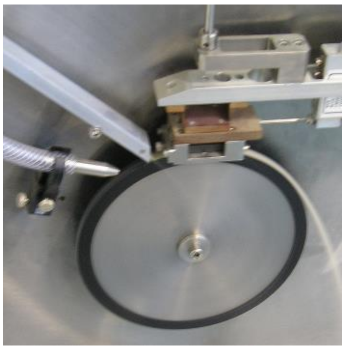
Abrasion Test Alternatives



- Better control of particle flow rate
- Reduced risk of particles falling outside contact
- Choice of abrasives
- Single pass dry or wet

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For slurry tests with this horizontal specimen configuration, particle are fed as for a dry test, with liquid fed onto the wheel surface, immediately before the end of the chute. Liquid and particles then mix, on the wheel surface, immediately upstream of the contact.

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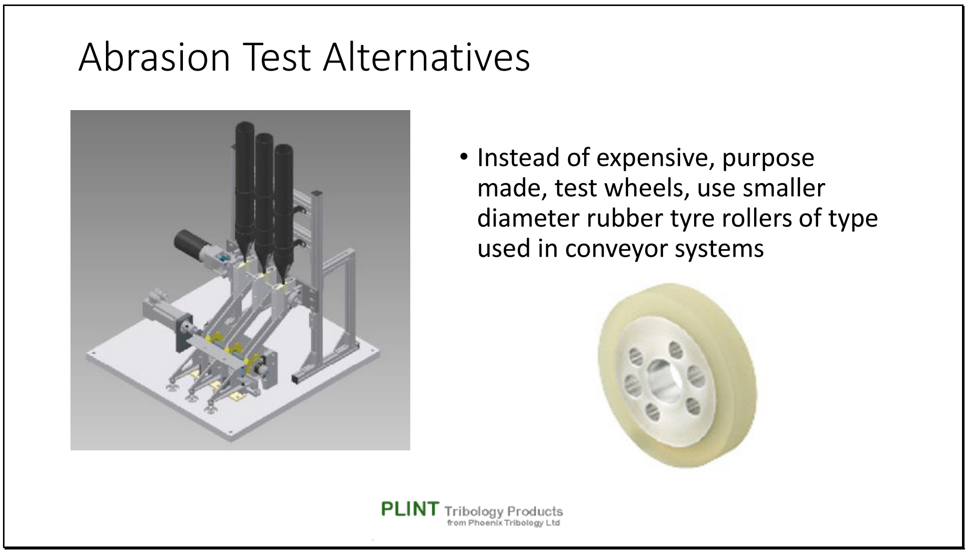

Having moved away from the standard geometry, there is also potentially some merit in moving away from the standard wheel materials, in particular, for those tests with rubber rimmed wheels. The effect of rubber hardness and composition on the wear mechanism is well documented and the difficulty of sourcing standard compliant rubber wheels, for G65 in particular, has been a long term issue. There is some merit in devising systems that, instead of using expensive, purpose made, test wheels, use smaller diameter rubber tyre rollers of the type used in conveyor systems; these can typically be purchased for as little as $10 per roller.

For what is essentially a comparative test, it should be relatively easy to establish the equivalence between a test in accordance with the standard and the test as performed on a modified device.

One final point to note with regard to the G65 test wheels, is that the sliding speed affects the bulk temperature of the rubber, which in turn affects its hardness and its subsequent interaction with the abrasive particles. To run the actual procedure, it is important to ensure that the wheel cools down between test runs. When running with reduced diameter rollers, it is sensible to run at reduced sliding velocities, to minimise unwanted heating. It follows that these tests have to be run with much reduced particle flow rates, hence requiring a precision feed system.

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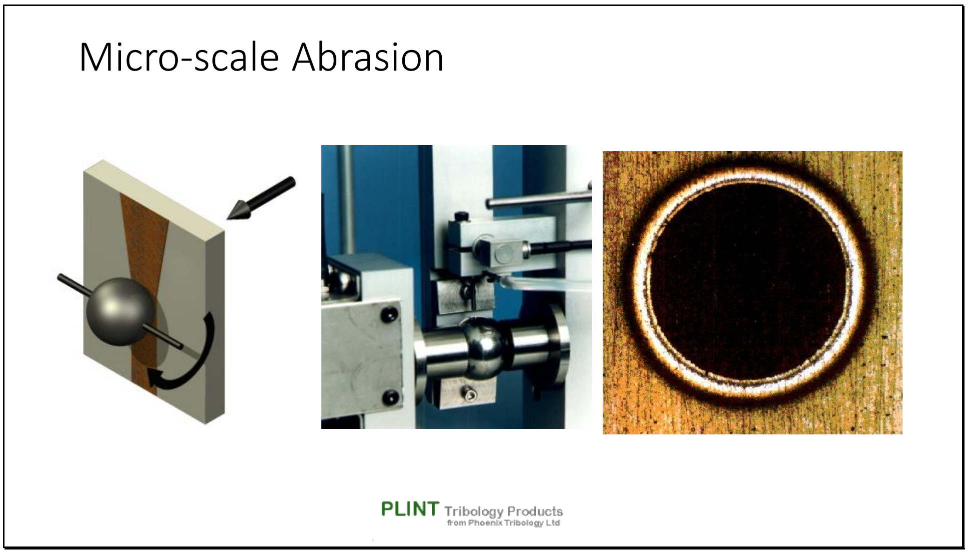

For testing thin coatings, using abrasive particles that are orders of magnitude greater in dimension than the coating thickness, will produce the equivalent of a sort of multiple contact random scratch test. The thickness of the coating limits the depth of material that can be removed before the coating is penetrated and, once penetrated, the subsequent wear rate is then dependent on the wear performance of the substrate, not the coating.

Ball cratering by micro-scale abrasion has long been used as a means of measuring coating depth and there are established means of relating wear scar dimensions to coating thickness. The measurement requires penetration of the coating through to the substrate.

For wear tests, the same procedure is used, but the wear process is stopped before the coating is penetrated.

It is important to note that the micro-scale abrasion test, depending on slurry concentration, can produce both two-body abrasion (grooving wear) and three-body abrasion (polishing wear). At low concentrations, the applied load is carried by a smaller number of particles, such that the load on each particle is high, causing said particle to be dragged through the contact without rolling, thus producing grooving wear. At high concentrations, with the applied load carried by a larger number of particles, the load per particle is low, allowing the particle to roll through the contact, producing polishing wear.

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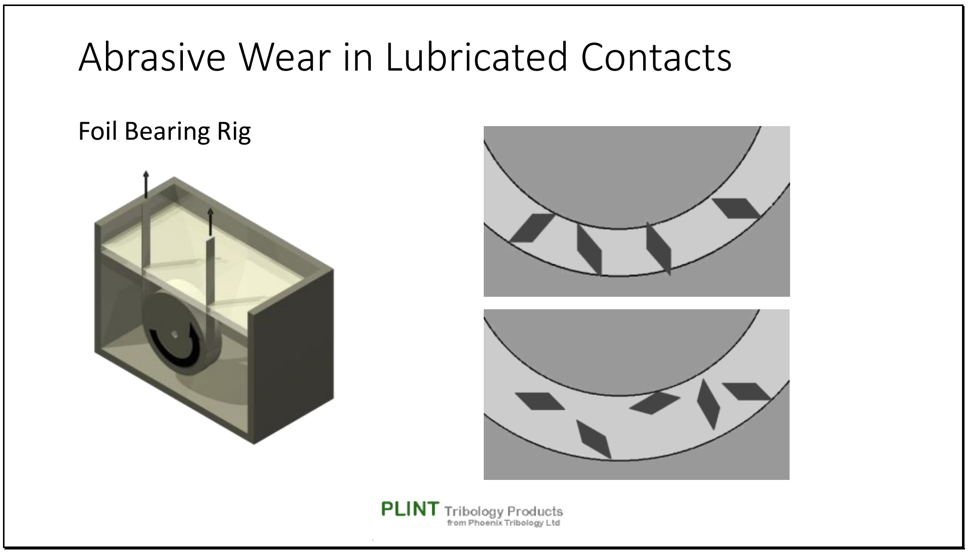

Journal bearings, except during start up, are essentially designed to operate with comparatively thick lubricant films between the loaded surfaces. Transit of particulate contaminants through the bearing gap can give rise to different wear mechanisms, each producing different wear rates.

When the size/gap ratio is small, worn surfaces may consist of a large number of small pits and indentations, usually with no obvious orientation in the direction of relative sliding, indicating either free movement of the particles through the fluid film and subsequent impact with the surfaces or the rolling of the lightly loaded particles through the contact. In both cases, the actual load on the bearing is of no relevance other than as a mechanism for setting the bearing gap. This mechanism, perhaps similar in nature to conventional polishing wear, has been termed “tumbling” wear. With polishing wear, we would expect the free particles to roll through the tribo-contact, in continuous contact with both sides. The term “tumbling” is used to describe the situation in which particles are not in continuous contact with both surfaces, but are free to tumble through the bearing gap.

Above a certain size/gap ratio, the particles are no longer free to roll through the contact, instead being dragged through, generating grooving wear. As with the pitting wear mechanism, the actual load on the bearing is of no relevance other than as a mechanism for setting the bearing gap. It will be apparent that the load on a particle will be a function of the size/gap ratio, the relative hardness of the particle and the bearing surfaces and the number of particles sharing the load. It is not a function of the load on the bearing itself.

For surfaces of similar hardness, grooving wear may occur on both surfaces of the tribo-contact. For surfaces of different hardness, there are two possible mechanisms that may not be mutually exclusive. If the surface roughness of the harder surface is sufficiently large, particles may become trapped by asperities and be dragged through the contact producing grooving or micro-machining wear of the softer surface. However, increasing the hardness ratio between the two surfaces may cause hard particle to become embedded in the softer surface, resulting in more severe grooving wear on the hard surface.

The critical parameters for an adequate test model are therefore:

- A test configuration that allows precise control of the bearing gap

- A means of introducing abradant particles of carefully controlled shape and size into the contact

These conditions can be met with a foil bearing rig.

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It will be noted that load (either static or dynamic) is not considered of importance except in as much as it may provide a mechanism for setting the bearing gap.

For tests on actual journal bearing components, the key challenge is the injection of particles in a controlled fashion into the test bearing. As with any tests involving abrasive particles, there are uncertainties associated with how long the particles remain in the contact and avoid comminution.

Ideally, one would like to control the total mass, size and angularity of the particles passing through the contact. One way of achieving this is to machine a small pocket into the in-running side of the loaded bearing shell and insert a known quantity of well calibrated abrasive particles, held in place with a suitable wax.

As the bearing runs and heats up, the wax melts, releasing the particle into the contact.

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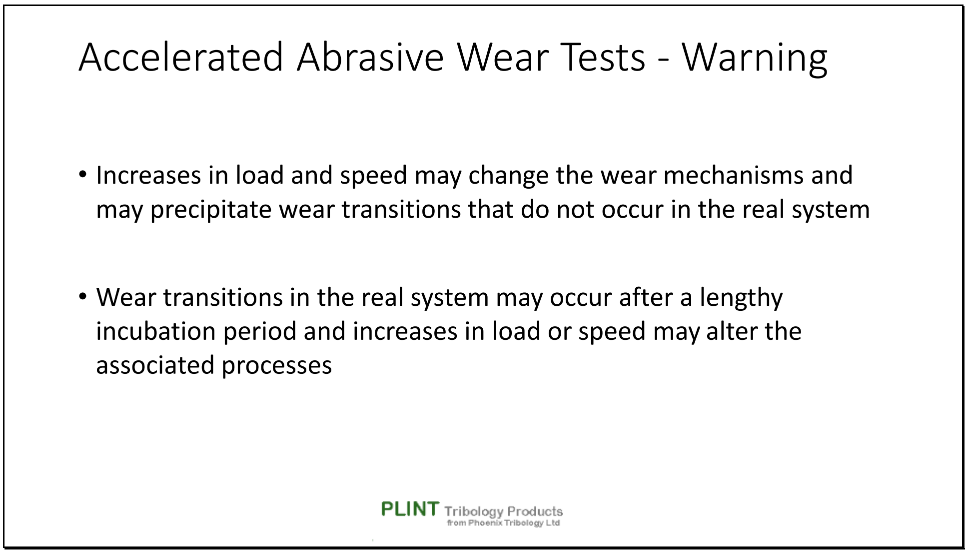

As with other types of wear test, attempting to accelerate testing by increasing load and/or speed risks precipitating changes in wear mechanism, such that it may no longer match the wear response in the real system. There may also be time dependent wear transitions, following the accumulation of surface damage.

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Erosive Particles in Real Systems

Gas jet erosion rig:

- majority of particles impact the surface

Real processes:

- particle flux may be same as concentrated jet in bench test, but the number of particles actually impacting surface may be much lower

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Solid particle erosion is the process of removal of material from a surface by impacting particles. In a gas jet erosion rig, depending on the angle of incidence, the vast majority of impacting particles can be assumed to hit the target and dissipate their kinetic energy in generating wear or surface fatigue; the majority of particles impact the surface. This may be slightly reduced when the particles impact normal to the surface, because some particles in the jet may impact rebounding particles; in effect these particles are prevented from reaching the target surface.

In real processes, for example a two phase flow in a straight pipe or bend, the particle flux may be much higher than the concentrated jet in the bench test, but the number of particles actually impacting the pipe surface will be much less and, of those actually hitting the surface, the loss of kinetic energy may also be much less.

The particle flux density and velocity in the pipe will vary across the stream, with the profiles dependent on whether the flow is laminar or turbulent. Modelling the particle properties (concentration and velocities) in a real system is a complex CFD problem, especially when it comes to modelling the behaviour of particles in the boundary layer, where drag forces have the tendency to slow the particles down, before they reach the surface.

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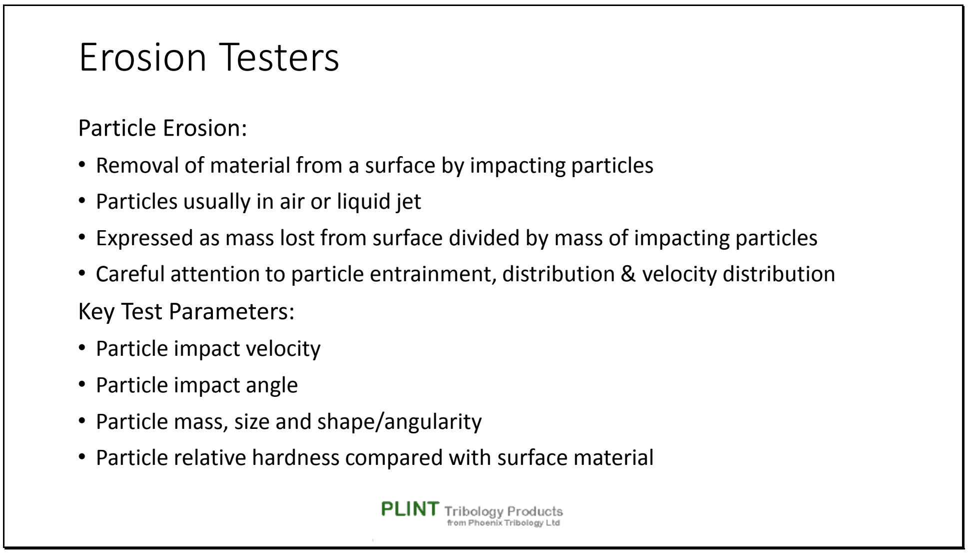

Erosion is normally expressed as mass of material lost from the surface divided by mass of impacting particles, with mass lost increasing linearly with mass of erodent, from the start of the test. It is important to note that under certain circumstances there may be a significant incubation period, before wear commences.

The use of hopper fed systems for abrasive particles once again improves the uniformity of supply, which in turns enhances control of the particle loading on the contact. Careful attention to particle entrainment, distribution and velocity distribution is essential to the generation of repeatable results.

There are a number of factors to do with the choice of particle and particle stream that affect the wear process, including:

- Particle impact velocity
- Particle impact angle
- Particle mass, size and shape/angularity
- Particle relative hardness compared with the surface material

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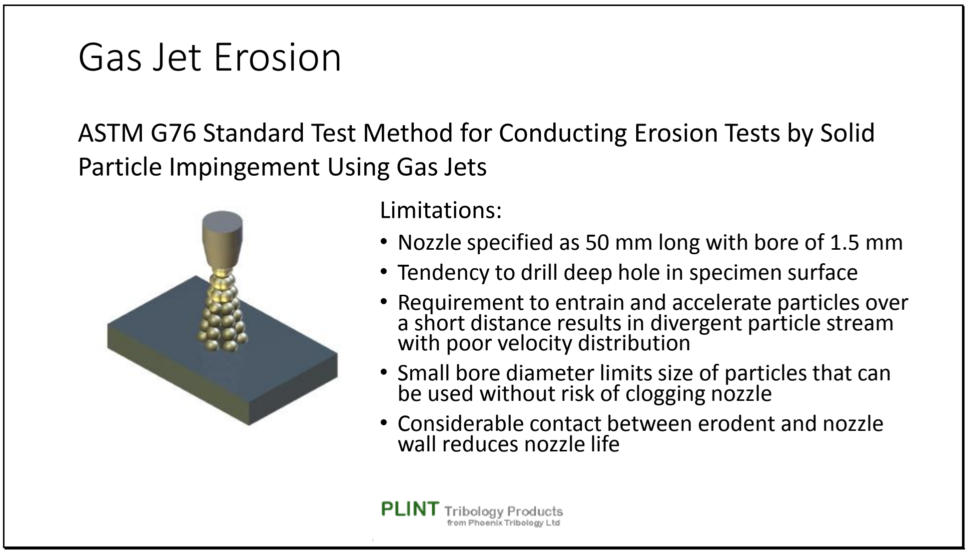

With gas jet erosion, the erosion rate under steady state conditions is normally proportional to impact velocity raised to the power n, where n is a number typically between 2 and 3.

There are two basic erosion mechanisms, depending on the surfaces impacted: brittle and ductile erosion. The erosion rate for the former is typically at a maximum when the particle stream is normal to the surface, and for the latter, at an angle of incidence typically of between 20 and 30 degrees.

There are various established erosion test rigs of which the most common is the gas blast erosion rig specified in ASTM G76 Standard Test Method for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets.

ASTM G76 specifies a short and small diameter nozzle (1.5 mm). This arrangement results in non-uniform particle flow and a divergent particle stream. As the rate of erosion is dependent on both particle velocity and angle of incidence, this is not an entirely satisfactory. Particle flux has a large influence on erosion rates and may well explain the variability observed in many inter-laboratory tests.

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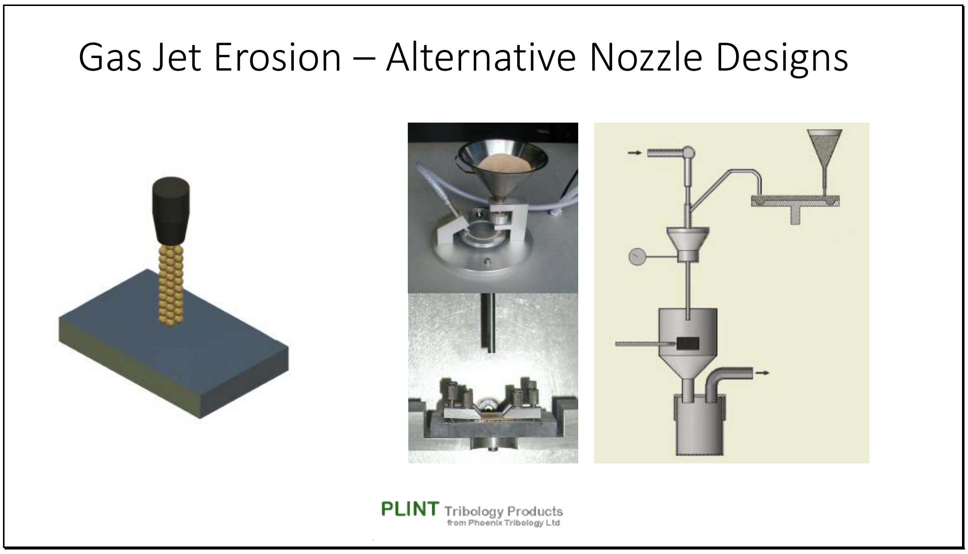

To overcome this weakness, a number of machines have been made with much longer and larger diameter nozzles, allowing equilibrium flow conditions to be established. This results in more uniform particle flow, both in terms of velocity and direction, hence more uniform particle flux.

Because of the requirement to entrain and accelerate particles to form a jet, there is a minimum gas velocity at which these devices can be made to work. This is typically about 25 ms^{-1}, hence, to run tests at much lower velocities, a different approach is required.

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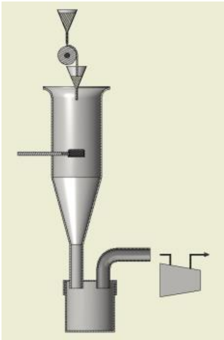
Suction Wind Tunnel Rig



- Dispersed particle flows impacting large targets
- Predominantly for testing shaped components

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A suction wind tunnel rig will allow lower impact velocities and lower particle flux. Such rigs are normally quite large and with significantly dispersed particle flows, impacting large targets. Particles are fed from a hopper system into the inlet contraction of the wind tunnel and accelerate under a combination of gravity and air velocity.

Because of the large size and expense of the test rig, the wind tunnel method is used predominantly where information on the performance of shaped components, such as canopies, turbine blades etc, is required, rather than for studies of material response alone.

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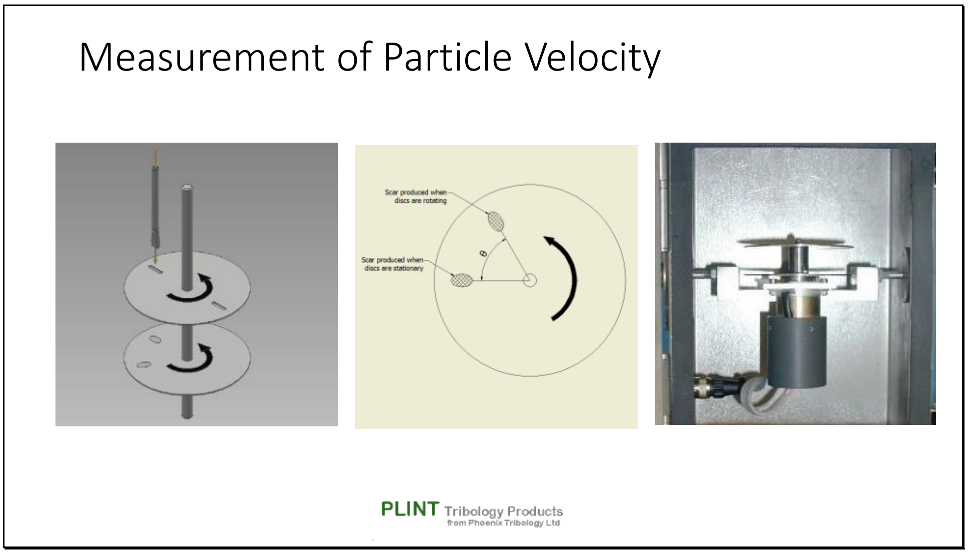

As impact velocity is a very important variable in erosion, accurate measurement of particle velocity should be an essential requirement.

Various methods of velocity measurement have been employed including Laser Doppler, time of flight between transverse light beams and high speed multi-flash photography. All these require sophisticated instrumentation, plus the ability to produce very low density particle streams.

A less accurate but simpler method is the rotating double disk method. This tends to underestimate the particle velocity, compared with Laser Doppler, but does work with a particle stream of standard test density. It does of course require a non-divergent particle stream.

In this method, two disks are rotated on a common shaft under the gas jet. The disc nearest to the nozzle has a thin radial slot. Two erosion scars are formed: one with the disk stationary, with the particles passing through the slot in the upper disk, and the other with the disks rotating at a known speed. The angular displacement between the two scars is measured and is used to calculate the time taken for the particles to travel the distance between the disks.

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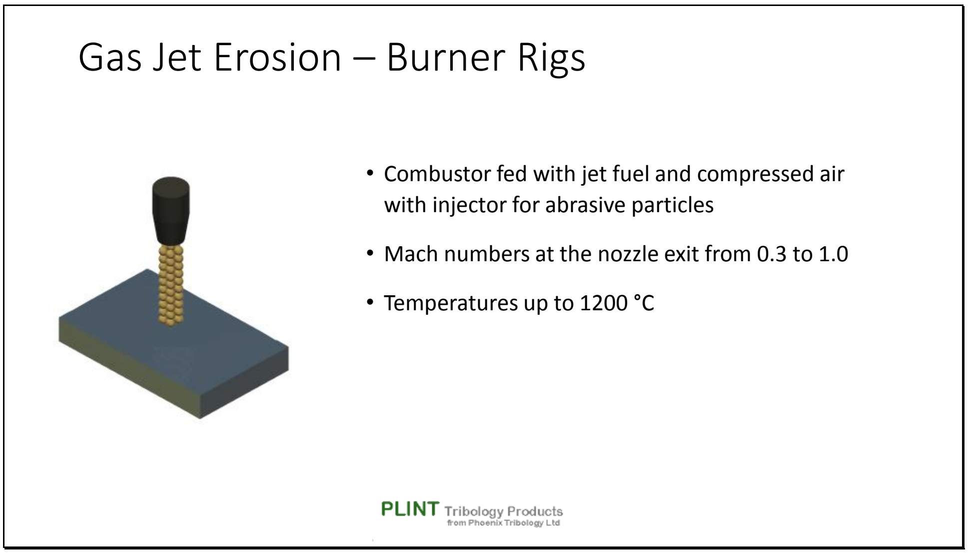

Burner rigs are used to test materials for gas turbine applications. The rig are designed to replicate the conditions experienced by materials in gas turbines and typically comprise:

- A combustor fed with jet fuel and compressed air with an injector for abrasive particles
- Mach numbers at the nozzle exit from 0.3 to 1.0
- Temperatures up to 1200 °C

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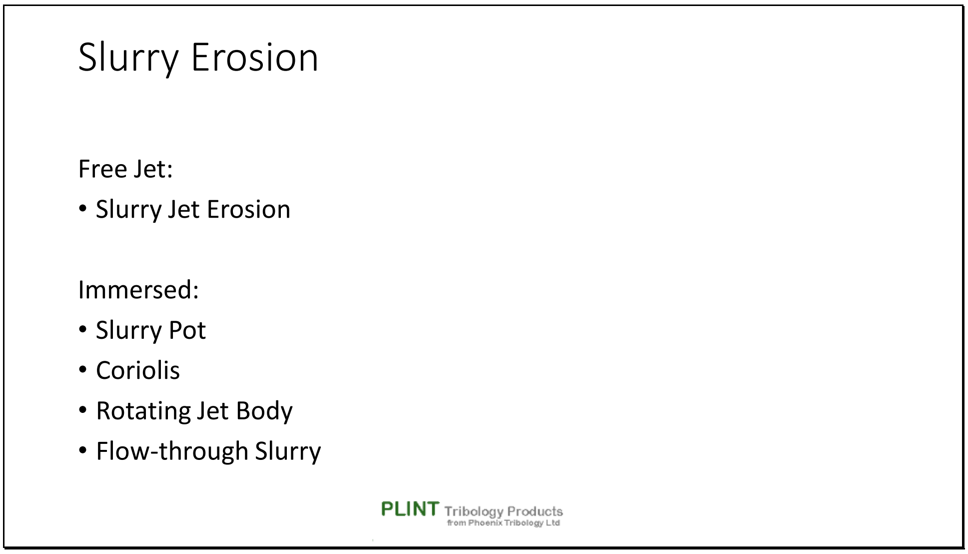

As far as I am aware, there are no standard test methods for slurry erosion and numerous devices have been used to model different slurry erosion processes. Here are some examples.

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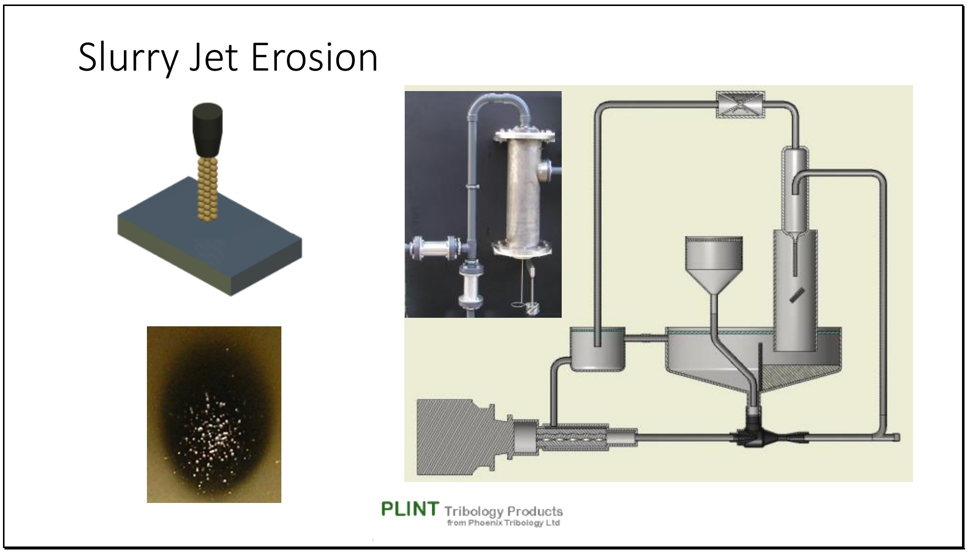

In a slurry jet erosion rig, a high velocity free jet of solid-liquid mixture strikes a flat specimen at some adjustable angle. The system comprises a pump, particle feed system, mixing chamber/amplifier and circulating system. These rigs are, in effect, the liquid equivalent of a gas jet erosion rig.

Disadvantages of this type of rig:

- pump and valve life is dependent on the erodent used and may be unavoidably compromised
- this is a free as opposed to immersed jet design
- use of a slurry pump makes this a potentially expensive solution

Advantages of this type of rig:

- the angle of incidence is fully controllable
- erodent flow can be measured by timed collection of flow in a measuring vessel

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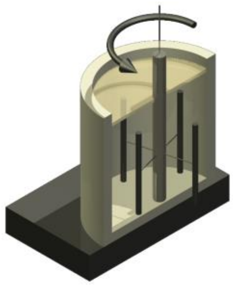
Slurry Pot Erosion



Disadvantage:

- particle flow past the specimens is indeterminate and cannot be quantified
- particle impact angle cannot be controlled in a meaningful way

Advantages:

- simple and relatively cheap to make

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In this rig, specimen rods of circular cross-section, fixed to the end of an arm, are rotated in a circular container filled with the slurry.

Disadvantage of this type of rig:

- particle flow past the specimens is indeterminate and cannot be quantified
- particle impact angle cannot be controlled in a meaningful way

Advantages of this type of rig:

- it is simple and relatively cheap to make

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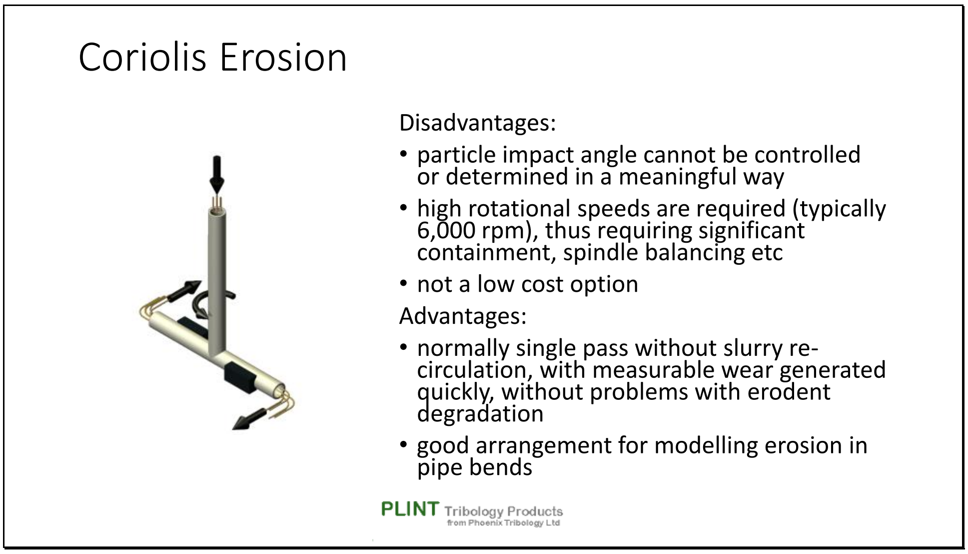

The tester comprises a rotating arm with a central slurry feed and radial tubes or channels, with specimens mounted in the walls of the tubes or channels, facing the direction of rotation. Coriolis acceleration brings the particles into contact with the specimen surface, generating a wear groove.

Disadvantages of this type of rig are:

- particle impact angle cannot be controlled or determined in a meaningful way
- high rotational speeds are required (typically 6,000 rpm), thus requiring significant containment, spindle balancing etc
- this is thus not a low cost option

Advantages of this type of rig:

- these devices are normally single pass without slurry re-circulation, with measurable wear generated quickly, without problems with erodent degradation
- it is a good arrangement for modelling erosion in pipe bends

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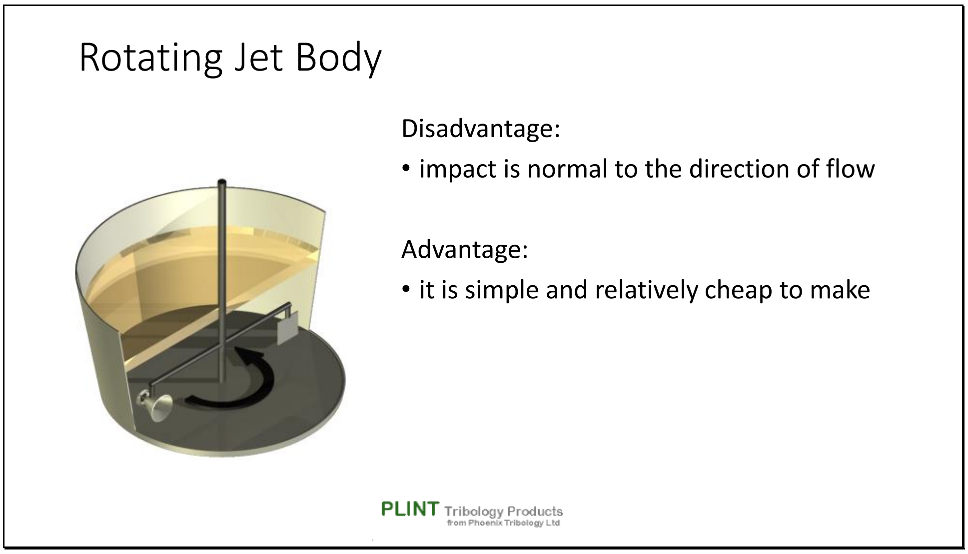

This comprises a rotating arm with a jet body immersed in a stirred vessel. The contraction in the jet body accelerates the mixture, which is discharged normally against a specimen, attached down-stream of the jet.

Disadvantage of this type of rig is:

- impact is normal to the direction of flow

Note:

A two dimensional as opposed to three dimensional contraction, with twin samples mounted in the flow, like a wedge model in a wind tunnel, would allow tests to be performed with a well-controlled oblique angle of incidence.

Advantages of this type of rig:

- it is simple and relatively cheap to make

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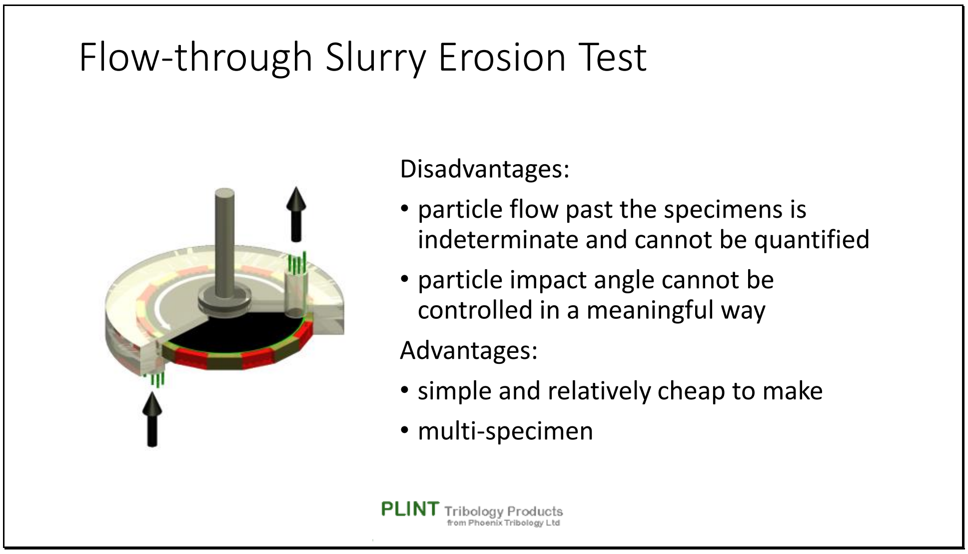

Fresh slurry is continuously fed into a test container in which slurry is circulated by an impeller. Sixteen stationary specimens form the walls of the container, alternating metal and plastic, and a standard UHMWPE gear is used as the impeller.

Disadvantages of this type of rig are:

- particle flow past the specimens is indeterminate and cannot be quantified
- particle impact angle cannot be controlled in a meaningful way

Advantages of this type of rig:

- it is simple and relatively cheap to make
- it is multi-specimen

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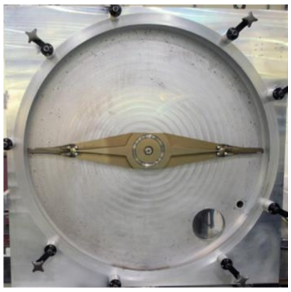
Whirling Arm Erosion Rigs

Solid Particles or Water Droplets



National Physical Laboratory (UK)

Water Droplet Erosion Rig

Maximum design speed 500 ms^{-1}

PLINT Tribology Products
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In a whirling arm tester, impact occurs between a falling particle or water droplet and a fast moving specimen, attached to a rotating arm. Because of potentially high tip speeds, rigs often operate under partial vacuum, to reduce the effects of aerodynamic heating and turbulence.

Tests with water droplets are performed to model the erosion of intermediate and low-pressure blades in steam turbines, caused by condensation in these stages.

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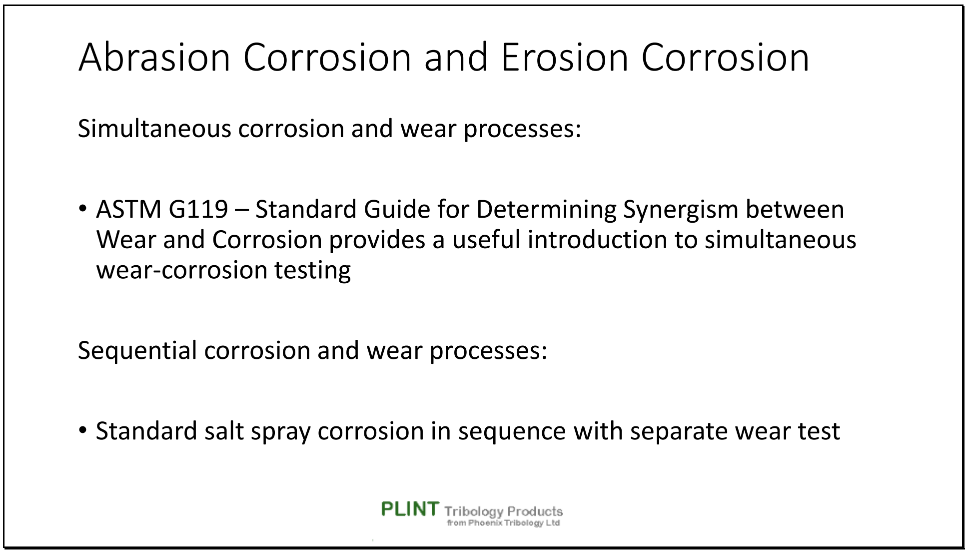

The term “tribo” implies two bodies in contact and mechanical work at the surface, hence a tribo contact in a corrosion environment combines the effects of both mechanical and chemical wear. This is usually greater than either mechanical wear in a non-corrosive atmosphere or chemical wear in the absence of work of friction. Tribo-corrosion occurs when a component is subjected simultaneously to mechanical wear and corrosion. For mechanisms that operate for long periods in a corrosive environment, it makes sense to perform tribo-corrosion experiments.

However, in some applications, corrosion and mechanical wear processes are not concurrent. For example, an out of service system may be subjected to corrosion, but with nothing moving. It may subsequently be moved away from the primary source of corrosion and into operation, subjecting components to mechanical wear. In this case, the wear is not taking place at the same time as the corrosion, but is taking place on parts previously exposed to a corrosive atmosphere; think perhaps, of putting a rusty piece of machinery back into service.

Hence there may be a requirement to investigate either simultaneous corrosion and wear processes, in other words, tribo-corrosion, or sequential corrosion and wear processes, perhaps associated with intermittent service of the system.

ASTM G119 – Standard Guide for Determining Synergism between Wear and Corrosion provides a useful introduction to simultaneous wear-corrosion testing

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Conclusion

Abrasive and erosive wear processes, where particle size, hardness, distribution, angle of incidence and, in the case of erosive wear, particle velocity, are critical to the wear process, have to be modelled at full scale.

Successful tests rely on close control of particle:

- Size
- Shape
- Hardness
- Fracture toughness

PLINT Tribology Products from Phoenix Tribology Ltd

Successful tests rely on close control of particle size, shape, hardness and fracture toughness of the abrasive or erosive particles, and this can only be achieved by careful sourcing and grading.