Choice of Test Machines

Wear & Failure Mechanisms

The more we can characterize the full scale problem the easier it becomes to ensure that the bench tests we run will provide useful information. Critical to the characterization process and ultimately to the interpretation of the test results, is the determination of the mechanisms of wear at work in the contact.

Wear processes must be analysed and defined before they can be modelled, for example abrasion, erosion, corrosion or other chemical action, de-lamination or adhesive wear, the involvement of wear debris identified, the appearance of failed surfaces established (for example, cracking, phase transformations, melting, chemical layers).

The type of wear process will, to a large extent, govern whether it can be modelled at reduced scale and whether accelerated testing is valid. As a general rule, contacts involving both sliding friction and wear can be modelled at reduced scale and with accelerated testing. This is because it is usually possible to increase the loading conditions in the contact without changing the wear regime.

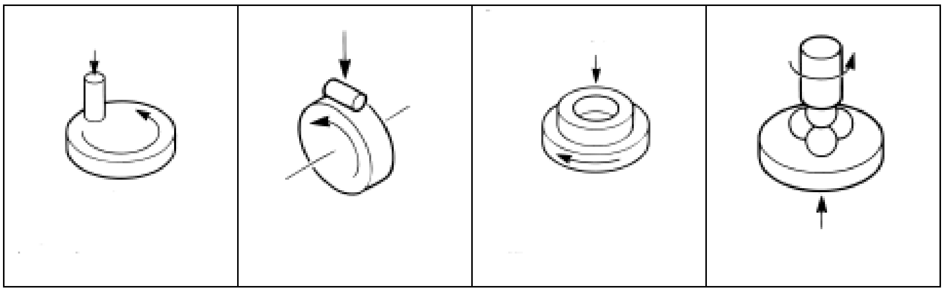
Processes involving surface fatigue can in some cases be modelled at reduced scale, but for obvious reasons, not at a reduced number of cycles. These processes include rolling contact fatigue and fretting.

Abrasive and erosive wear processes, where particle size, distribution, angle of incidence and, in the case of erosive wear, particle velocity, are critical to the wear process essentially have to be modelled at full scale, but this is possible in an appropriately designed test.

Bench Test Machine Categories

There is no shortage of choice when it comes to friction and wear test machines. Selection will depend very much on what kind of test you wish to perform and/or the application for your product. Available test rigs can usefully be divided into four categories.

Thermally Self-Regulating Continuous Energy Pulse



These are machines in which the point of contact is stationary with respect to one of the specimens and subject to constant speed uni-directional sliding. It is important to recognize that there are virtually no real life applications other than perhaps braking systems in which this occurs, thus introducing a degree of unreality to the test.

However, these machines are widely used because they are simple. Examples include pin on disc, block on ring, crossed cylinder and sliding 4-ball test machines. Data generated by such machines rarely correlates with known field data.

In each case the specimen geometry is simple and relatively easy and cheap to manufacture. This may be an important consideration when studying new materials where batch quantities are small.

Uses

Historically, this type of machine has been used for fundamental wear studies of materials including metals, plastics, composites, ceramics and coatings in solid lubricated or dry conditions. They are less successful with liquid lubrication. Their principal advantage is that it is easy to cover wide load and speed ranges and therefore obtain a broad sweep of material performance. Wear mapping and parametric studies are readily performed.

Limitations

For liquid lubricated tests, aimed at investigating lubricant additive performance, entrainment conditions associated with constant speed sliding result in a requirement for heavily loaded contacts in order to overcome hydrodynamic lubrication and thus promote mixed or boundary lubrication, and ultimately, film failure. Increasing the load to achieve film failure may bring to significance specimen material properties, which one may otherwise wish to eliminate from the test parameters.

These machines typically do not emulate real lubricated contacts. The Energy Pulse for the fixed point of contact specimen is continuous: it lasts for the duration of the test. This highlights one of the main limitations of these machines as models of real surfaces. Instead of brief rubbing episodes frequently repeated, the machine subjects one specimen to continuous rubbing and the associated temperature field dominates.

The test configuration defines the thermal conditions in the contact. The contact temperature (unlike the bulk temperature) is self-regulating and cannot be controlled as an independent variable. High contact temperatures result in a number of problems, depending on the material under test.

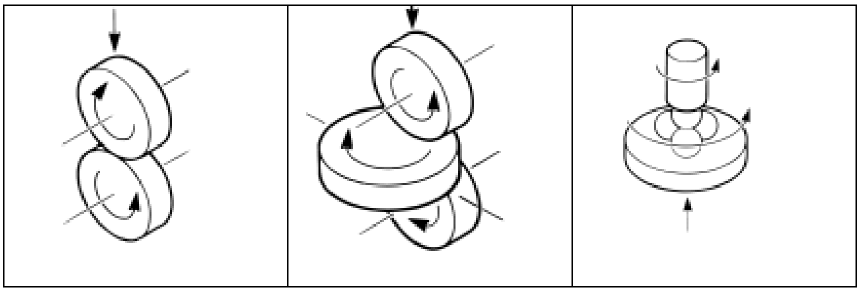
In plastics, the limit is the melting point (this usually is given the name PV - pressure/velocity limit and is in reality the melting point). Thermal collapse limits the contact at high velocity, whereas mechanical strength limits the contact at high pressure. With ceramics, which are poor thermal conductors, the heat is locked in at the surface and the heat/quench cycle generated can result in thermal fatigue of the specimens.

For liquid lubricants, temperature drives chemical reactions of additives with the specimen surfaces and these will change the friction and wear conditions in the contact.

Standards

The majority of existing standards in sliding wear use uni-directional sliding machines. For the most common, the pin on disc, there are two generic standards (ASTM G-99 and DIN 50324), giving recommendations on their use, but acknowledging that the application will actually influence the final choice of test conditions. A further, more detailed guideline is available in the form of a publication from the UK Wear and Friction Forum, which looks at aspects of methodology and rig design.

Thermally Self-Regulating Cyclic Energy Pulse



These are machines where the point of contact moves with respect to both contacting surfaces and there is a close approximation to the motion in actual machine components (for example, gears, cams, joints and mechanisms). These include a number of component test machines, using idealized or standardized components such as gears, cam/follower and rolling element bearings.

Uses

These machines are essentially designed to emulate real contact conditions and typically operate under conditions broadly similar to those found in practical applications. To all intents and purposes these machines are "full scale" and are hence emulators of the real contact. Test piece production must be carefully controlled to ensure optimum reproducibility. These machines can usefully be divided into two subgroups:

Pure Rolling Machines

Here two specimens (usually rollers) are loaded together and are rotated at the same speed. The motion is pure rolling and such machines are used to address particular problems in the lubrication of gears and drives in the piezo-viscous region (elastohydrodynamic). They are also used to study pitting failure (rolling contact fatigue), caused by the cyclic stressing of the surfaces. Rolling element bearing test rigs and rolling four ball machines are included under this general heading.

These are important machines because there is no other method of emulating these real life contacts. The important rider to this statement is that the thermal characteristics of the contact again come into play and exactly how the heat is conducted away through the test specimens will have a profound effect on the lubrication condition in the contact and the resulting performance of the test components.

Combined Rolling/Sliding

Here two specimens (usually rollers) are loaded together and are rotated with an enforced speed difference between them. These are used to emulate the conditions found in highly loaded contacts and to assess the performance of materials, coatings, treatments and lubricants under conditions of traction.

It should be noted that here we are already adding a complication to the proceedings by mixing rolling and sliding. Rolling introduces an element of elastohydrodynamic lubrication giving rise to mixed lubrication within the contact. If we are concerned with lubricant additive failure, this may add unnecessary confusion and it may be more appropriate to concentrate on the chemistry of the lubricant under pure sliding conditions.

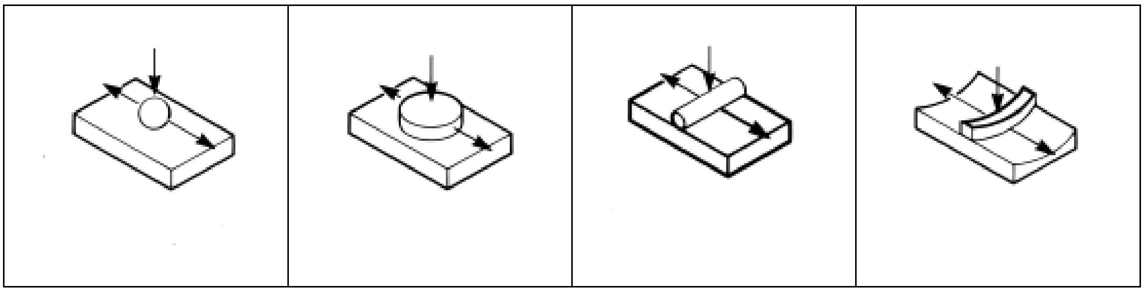
Limitations

The test configuration in these machines, as with the previous category, defines the thermal conditions in the contact. The contact temperature is thus self-regulating and cannot be controlled as an independent variable. So while the machines can be considered emulators of real contacts, there is a lack of control over temperature.

Standards

There are a few standards for rolling or slide/roll testing but they refer more or less exclusively to the performance of the lubricant rather than the materials.

Independently Thermally Controlled Minimal Energy Pulse



These are machines in which sliding velocities are maintained at very low levels in order to minimize frictional heating and to ensure boundary lubrication (in the case of lubricated tests) at representative contact loads. These are the short stroke reciprocating rigs, in which, although sliding velocities may be low, the rate of events (specimen passes or asperity contacts) are high and by definition, cyclic. High repetition rates can be achieved without significant increases in sliding speed and corresponding loss of control of contact temperature.

These devices (except in the case of the piston ring on liner contact near end stroke) do not model exactly the real contact to be investigated, but aim to emulate the intimate contact conditions in a controllable and accessible way.

One of the principal advantages of the reciprocating test is that the direction of motion and the direction of surface finish can be the same. With the uni-directional specimens, for example, pin on disc, the orientation of grain structure or surface finish as presented to the pin varies as the disc rotates.

Uses

Historically these rigs have been used for fundamental and applications studies in the lubricants field with a particular emphasis on the lubricant chemistry and lubricated wear mechanisms. These rigs have an obvious similarity to the motion experienced by many practical components that have cyclic energy inputs, such as gears and cams and followers. They are also used for wear studies of coatings, ceramics and ceramic composites.

Similar parametric studies to the uni-directional machines can be performed with limitations on the absolute sliding speed. However, sliding speed is simply a heat generator. By minimizing frictional heating we have the opportunity to control the contact temperature by controlling the bulk temperature of the test specimens, thus allowing contact temperature to be controlled as an independent variable.

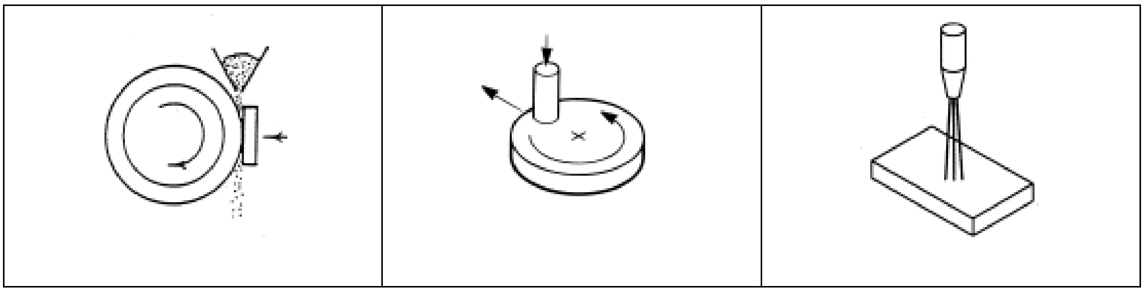
Limitations

In these machines, the Energy Pulse has been replaced by external heating and this has implications for the development of wear in the contact. Establishing correlation between wear generated in these machines with real component performance has proved a worthwhile task. Satisfactory techniques have now been developed for a number of real contact conditions, including the piston ring and cylinder liner contacts, cam and follower contacts and gear tooth contact simulations.

Standards

There are an increasing number of standards based on short stroke reciprocating tests covering dry and lubricated wear of ceramics, metals and ceramic composites, measurement of friction, wear and extreme pressure properties of lubricating greases and measurement of the diesel fuel lubricity.

Abrasion and Erosion



Abrasive and erosive testing of materials requires different types of machine from the primarily adhesive wear test machines discussed above, as a free body is usually involved. 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.

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

Abrasion Testers

Abrasion tests either use loose particles of a well-defined shape and size or particles bonded to a substrate in the form of abrasive paper. The former results primarily in three-body abrasion and the latter in two-body abrasion.

Three body abrasion test rigs typically comprise a stationary specimen loaded against a rotating 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 on the contact. To avoid contaminating the abrasive particles, whether dry or wet, with wear debris from the test specimens, it is normal to use a single pass system and not re-circulate the abradant.

A key point to note with three body slurry abrasion is that increasing the particle loading on the contact may ultimately give rise to a two body abrasive mechanism, with abradant particles effectively trapped within the contact.

In two-body abrasion rigs the principal problem is controlling the condition of the abrasive paper. If a pin-on-disc test is carried out with abrasive paper attached to the disc, the paper rapidly degrades and becomes clogged with wear particles. Indexing the pin across the disc in a spiral pattern, thus ensuring that fresh abrasive paper comes into contact with the pin at all times, overcomes this problem.

Erosion Testers

Erosion testers involve the impact of a stream of particles against a test sample. The particles may be introduced in an air or liquid jet. The use of hopper fed systems for abrasive particles 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. The particle velocity and angle of impact both affect the dynamics of the erosive particle and the wear mechanism produced. The sharpness or angularity of the particle also affects the wear process.

Standards

A number of standards exist for abrasion and erosion, usually specific to a material or product group. All the standards define the grit to be used and wear rates are profoundly affected by the relative hardness of the grit to the material being abraded. This is an area where current research is leading to better laboratory test methods.

Choice of Test Conditions

Before attempting to design an experiment, we must ensure that we have properly analysed and understood the tribological conditions to be modelled. The contacting environment is usually defined in terms of:

Contact Pressure

Contact Speed

Energy Input

Temperature

Conditions of Lubrication and/or Atmosphere

None of these are completely straightforward to define, either for the practical contact or in the test machine model and they are also not sufficient to define fully the nature of a tribological contact.

When building a test model, considerations of scale are paramount. It is hazardous simply to attempt to define the "real life" conditions (load, speed, temperature etc) and apply them to a small test piece on a test machine. The first major concern is to do with the temperatures reached by the test specimens.

If large amounts of energy are being dissipated in small test specimens, with supporting structures that do not allow the heat to escape, the specimens may become unrepresentatively hot and the bulk temperature may exceed that experienced in practice. This is likely to produce transitions in wear or frictional response.

The temperature reached at the surface of the contact (the flash temperature) is strongly influenced by the width of the contact and flash temperature is responsible for many wear and friction effects.

Material structure and microstructure is another scale consideration. Where the scale of the microstructure is much less than the contact area, the material can be considered to be homogeneous. But where the phase size is of the same order as the contact width, then the surface roughness on the counter face material and the properties of the different phases will influence the wear and friction behaviour of the material.

The principal contact conditions are defined by the component (shape, surface condition etc), some by the operating conditions (load, sliding speed) but others are less easy to define (lubrication conditions, contact pressure, wear mechanism) as these can vary during a machine cycle and as the components wear.

The contact pressure (loading stress in the contact) is defined by the geometry of the contact, the applied load and the material bulk properties. The geometry is defined by the shape of the two surfaces in contact and any influence upon the shape, for example, thermal distortion and wear. The load is influenced by the dynamics of the contact (stiffness of the material support and genuine load cycles) and other effects such as foreign bodies (abrasive particles, dirt, wear debris etc).

The contact temperature results from the loading, the size, the speed of relative motion and the thermal resistance of the two halves of the contact. While measuring the bulk temperature of a material poses little problem (apart from accessibility), the measurement of the contact temperature is another matter. The friction heating generates enormous transient temperatures in the contact (flash temperatures), which are surface effects only.

Energy Dissipation

All wear processes are influenced by temperature, be they the formation of oxides on surfaces, the transformation of microstructure, the formation or break-down of lubricant additive or other tribochemical films, the melting of the surface (the PV limit of the material) or thermal stress induced failure. To be more specific, wear occurs in conjunction with the dissipation of frictional energy in the contact and this is always accompanied by a rise in temperature.

The frictional energy is generated by the combination of load and sliding speed and its distribution and dissipation is influenced by other contact conditions such as size and relative velocity. Different patterns of energy dissipation will give different wear patterns. Two more global parameters have been shown to be valuable in defining these conditions in sliding wear. These in fact become critical to the issue of simulation.

Friction Power Intensity

The friction power intensity as presented by Matveesky is simply defined as the amount of energy pumped into the rubbing surfaces as they pass through the contact zone. The temperature achieved in the contact and in the bulk material is directly related to the FPI and the size and thermal characteristics of the materials and their supports.

The FPI defines only the rate of energy generation and does not take into account the timescale over which this energy can be lost to the contacting materials. This timescale clearly has implications for the amount of damage caused in the contact.

Friction Power Intensity: $\mathbf{Q_F = \mu P V_s / A}$ W/mm^2

Where μ is friction coefficient, P is the normal load, V_s is the sliding speed and A is the apparent area of contact. Practical contacts have FPIs in the range 5,000 to 20,000 W/mm^2.

Energy Pulse

The Energy Pulse is the product of the FPI and the contact transit time. The EP therefore takes into account the length of time during which the material is subjected to energy input during its transit of the contact zone, where t_t is the transit time in seconds.

Energy Pulse: $\mathbf{E_P = \mu P V_s t_t / A}$ J/mm^2

The Energy Pulse is analogous to the Archard Wear Law, however, the Energy Pulse equation uses the friction force rather than the applied load. This is perhaps more logical as it takes into account the rubbing conditions (but assumes that the friction coefficient can be measured).

Archard Wear Law: $\mathbf{\Delta V = k P V_s t_t / A}$ mm^3

Each Energy Pulse can be regarded as an incremental contribution to wear or surface damage in the contact. The sum of the Energy Pulses can be used as a measure of the total wear.

Correct analysis of the EP in the real contact and subsequent modeling in the experimental design significantly enhances the probability of achieving a satisfactory emulation of sliding and combined sliding and rolling contacts.