Guidance - Machining, Forming and Forging Tests

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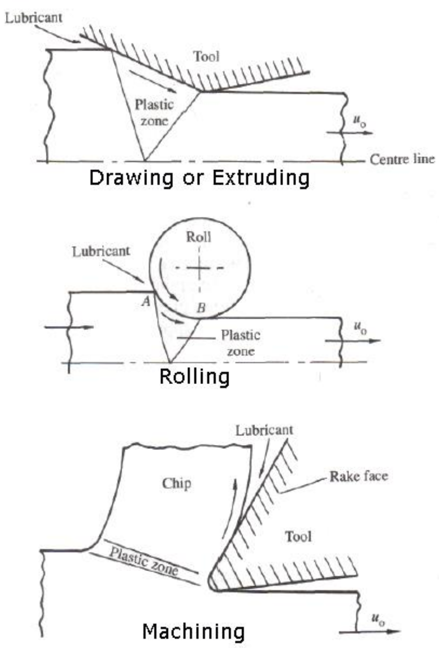
Introduction

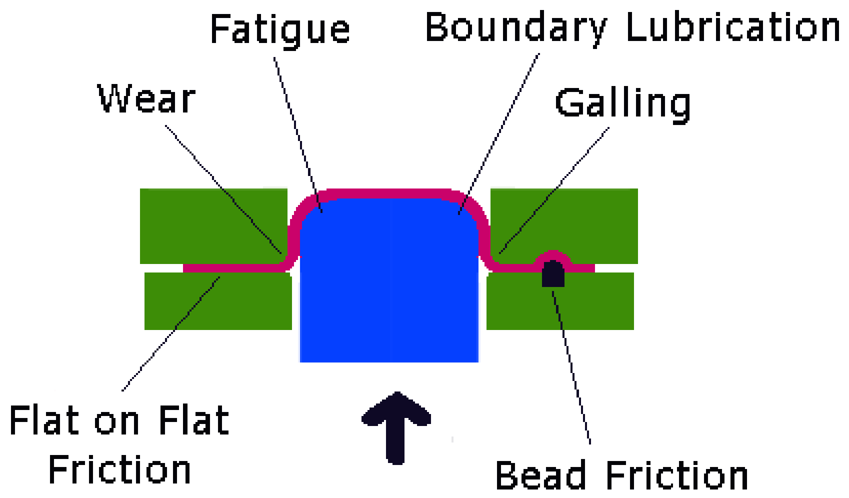
Of all the processes we might wish to attempt to model in a laboratory bench test, machining, forming or forging processes are perhaps the most difficult. In all cases, the process involves substantial and rapid modification of one side of the tribological contact, either by removal of material (machining) or plastic deformation of the material (forming and forging). All processes involve both macro and micro changes to the microstructure and surface topography. This results in a significant variation of the friction coefficient during the forming process. An adequate model thus requires continuous replacement of one side of the contact. Most conventional tribometers involve continuous sliding on the same wear track, thus rendering them ineffective as models for machining, forming or forging processes.

A further complication is that the majority of lubricated contacts are complex, involving a wide variety of different regimes (boundary, mixed and hydrodynamic) in a single system and the lubricants involved must provide lubricity, additive protection, corrosion protection and cooling. In both dry and lubricated systems, tooling and coatings must be chosen to be resistant to material transfer (pick-up and galling), thermal and mechanical shock, wear and surface fatigue.

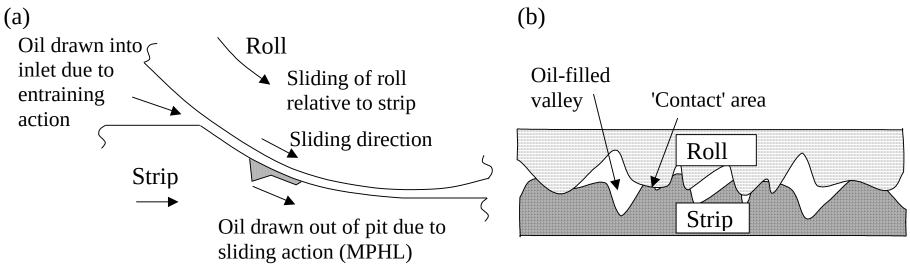


Tribological Processes

(John Williams – Engineering Tribology)



Contact Conditions – Forming/Deep Drawing



Contact Conditions – Rolling

Micro-plasto-hydrodynamic Lubrication of pits

(Michael Sutcliffe – Cambridge)

It will be apparent from these figures that any experiment that relies on external measurement of force will suffer from an inability to separate deformation or cutting forces from friction forces. Further to this, the majority of such tests will give nothing more than the mean value of the measured force and will fail to identify how the different force components may vary through the contact. Because frictional forces are difficult to measure directly, many models have been developed to estimate what it is in many different metal-forming situations.

Sheet metal friction test	Modelling equation
Strip draw test	$\mu = \frac{F_f}{F_N}$
Drawbead simulator test	$\mu = \frac{1}{\pi}\frac{D_{d+f} - D_d}{C_{d+f}}$
Capstan friction test	$\mu = \frac{2(F_2 - F_1 - F_B)}{\theta(F_1 + F_2)}$
Tensile strip test	$\mu = \frac{1}{\pi}\ln\left(\frac{F_p}{F_b}\right)$
Bending under tension test	$\mu = \frac{1}{\theta}\ln\left(\frac{F_p - F_B}{F_b}\right)$
Ohio State University friction test	$\mu = \frac{1}{\beta}\left(\ln\frac{F_p}{F_b}\right)$
Band brake equation	$\mu = \frac{1}{\theta}\ln\left(\frac{F_2}{F_1}\right)$

F_f is the frictional force, F_N is the normal force, D_{d+f} is the drawing force with a fixed roller, C_{d+f} is the clamping with a fixed roller, F_1 is the inlet tension, F_2 is the outlet tension, F_B is the force due to bending, F_p is the pulling force, F_b is the back force, and θ and β are bend angles in radians.

Equations used for calculating coefficient of friction in testing lubricants in sheet metal forming (Jeswiet, Wild and Sefton).

To conclude, it follows that a wide variety of different tests and measurement techniques may be required to investigate the multitude of different processes within a different application.

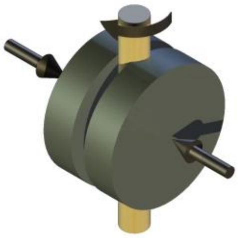
Lubricant Screening

Lubricant evaluation presents a particular problem in conventional bench tests, especially if the lubricant is intended for use in a water-based emulsion. At atmospheric pressure, tests with a bulk temperature above 100°C will cause the water to boil. A decision has to be made whether to test the lubricant neat at temperatures above 100°C or as a water-based emulsion at temperatures below 100°C. This raises questions as to whether either approach represents a valid model of the real application.

Continuous Sliding Tests

For many years, a number of basic continuous sliding lubricant screening tests have been in existence and extensively used, each claiming to provide useful data but in reality, of limited scope. The machines are all thermally self-regulating continuous energy pulse devices, in which contact temperature is both uncontrolled and cannot be measured.

Pin on Vee Block

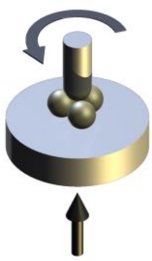


In the pin on vee block test, a load is applied to a pair of vee-notched jaws loaded on either side of a rotating pin, immersed in a test fluid sample. The test may either be run with progressively increasing load, in order to generate a scuffing failure, or under steady state load in order to measure wear. The machine is used extensively on neat oils (not emulsions), to evaluate extreme pressure additives.

Different block and pin materials may be used, which is an advantage over the limited material combinations available with the similar aged four ball machine. A further advantage over the four-ball machine is that the specimen configuration produces four line contacts, that widen up very quickly, so the pressures are substantially less than those generated in the four-ball machine.

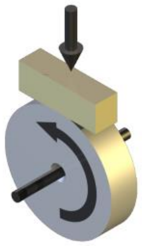
The most successful application areas for the Pin and Vee is in evaluating forming and cutting oils.

Four Ball Test



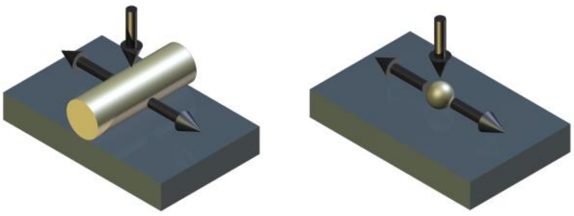
Both four ball wear and four ball extreme pressure tests have been used for evaluating metal working fluid performance.

Block on Ring Test



The Block on Ring test configuration has been used in an attempt to simulate the inlet conditions between plate and roll, in rolling mill applications. The use of a closed fluid chamber, with a nozzle to spray the liquid direct in the inlet, facilitates testing with pre-heated emulsions at inlet temperatures near to the boiling point of water.

Reciprocating Tests



A number of users have attempted to model rolling processes using a long stroke reciprocating rig and claim to have generated some useful data. They found that because of the low frictional energy input to the contact, tests could be run under almost isothermal conditions.

In rolling processes, the same lubricant is used throughout the different stations and temperatures and pressures vary throughout the rolling train. As different chemicals react differently at different temperatures, the lubricant additive package must provide consistent performance (in friction reduction, wear prevention, etc) over a range of temperatures.

To simulate the behaviour of additive packages over a range of temperatures, reciprocating tests are run using a plate sample of sheet metal (the material to be rolled) and a hard moving counter body, representing the roll, with stepwise increasing temperatures.

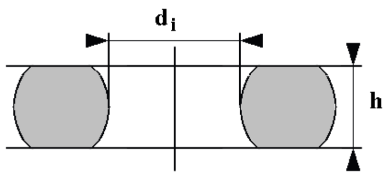
Tests have been done with Steel, Zinc, Copper and Aluminium work-pieces. The temperatures for Aluminium and Copper rolling are higher than for Steel and Zinc and a very important consideration here is to identify whether essential metal soaps can be formed once the temperature of the tooling and work-piece exceed the working temperature of the mineral oil. This point is identified by a change in the friction forces. In the case of Zinc, which is normally termed cold rolling (but actually it is hot rolling) the crystallisation temperature of the metal is around 50°C and the process actually runs up to about 200°C.

These tests give results about the performance of the oil (Coefficient of Friction and Isothermal Stability). It is also claimed that they produce similar waste products to those produced in actual rolling processes. These are of importance as it is essential to ensure that in the real process, they do not form corrosion catalysts.

An important point to note is that at lower temperatures the coefficient of friction must not be allowed to be too low as this will cause an increase in the sliding component in the contact, which may subsequently give rise to transfer of work-piece metal to the rollers and damage to the plate.

Basic Friction Tests

Ring Compression Test



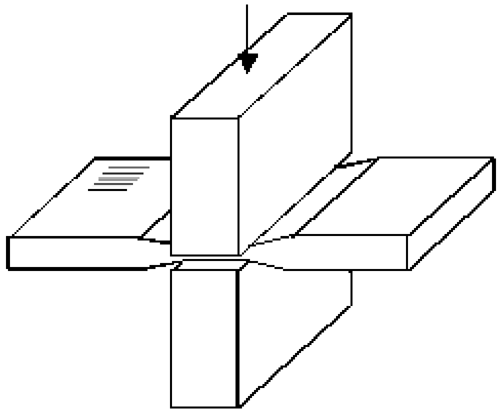
The ring compression test (Male and Cockroft – 1965) was developed to investigate the friction at the interface between a workpiece and a pair of platens. A flat ring-shaped specimen is loaded between platens in a servo hydraulic test machine and subjected to axial compression. If there were no friction, the ring would increase in diameter radially with both the inner and outer diameters increasing.

The presence of a small amount of friction at the interface will cause the outside diameter of the compressed ring to be less than that in the zero-friction case, but the inside and outside diameters will be greater than the non-compressed state.

As the interface friction increases, a transition occurs, causing the ring material to flow both outwards and inwards, respectively increasing the outer diameter and reducing the inner diameter.

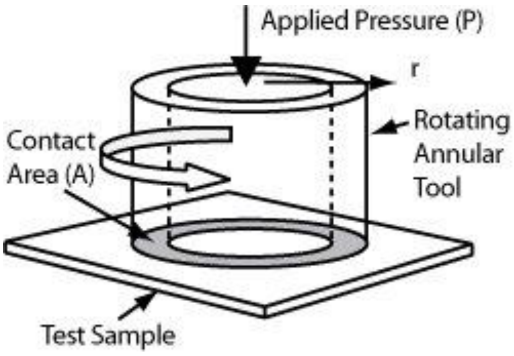
Because the inside diameter increases with low interface friction, but decreases at high interface friction, measurement of this diameter provides a sensitive measure of the friction.

Plane Strain Compression Test



The plane strain compression test is used to estimate values of friction coefficient under boundary lubrication in rolling processes and to investigate the generation of fresh material and deformation and cracking of oxide films. Measurements of friction correlate with build up of transfer layers.

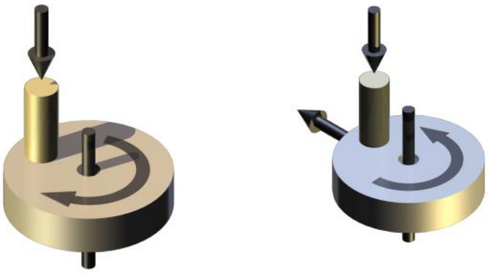
Twist Compression Test



The twist compression test was developed specifically to model hydro forming of tubes and for sheet forming operations in general. The twist compression test is used for evaluating the frictional behaviour of lubricants and die materials for metal forming applications. The test involves loading a 25 mm cylindrical specimen of tool material against a flat sheet work-piece sample and subjecting the contact to low speed rotation. The resulting torque is measured and, post test, the surfaces are examined for wear and material transfer.

The tests demonstrate comparative performance between different lubricants and material combinations and the ability of these to prevent pick-up and galling under boundary lubrication conditions. Test duration can be used as a measure of lubricant squeeze film effects. Unlike the ring compression test, the twist compression test does not involve plastic deformation of the work-piece.

Pin on Disc



A number of attempts have been made to use the pin on disc test configuration for evaluating materials and fluids for forming processes. In this case, the typical configuration is to run with a hard ball or spherical tipped pin on a soft disc. The first thing to note is that rapid work hardening of the disc takes place, resulting in subsequent running or a work hardened surface. The second point to note is that increasing the load on the contact simply increases the size of the plastic zone, making repeat tests at different loads somewhat pointless.

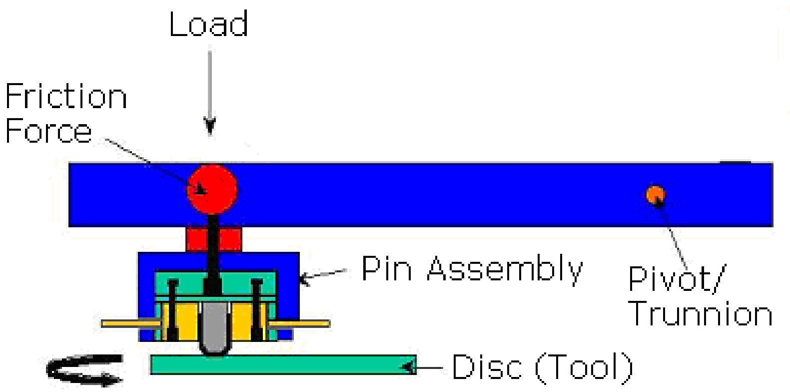
Perhaps the only pin on disc type configuration that makes sense for modelling forming processes is indexing pin on disc, where the pin follows a spiral track, thus presenting fresh work-piece material to the tool pin. There is of course a limit to the distance available on a single disc.

Friction Test at High Temperatures

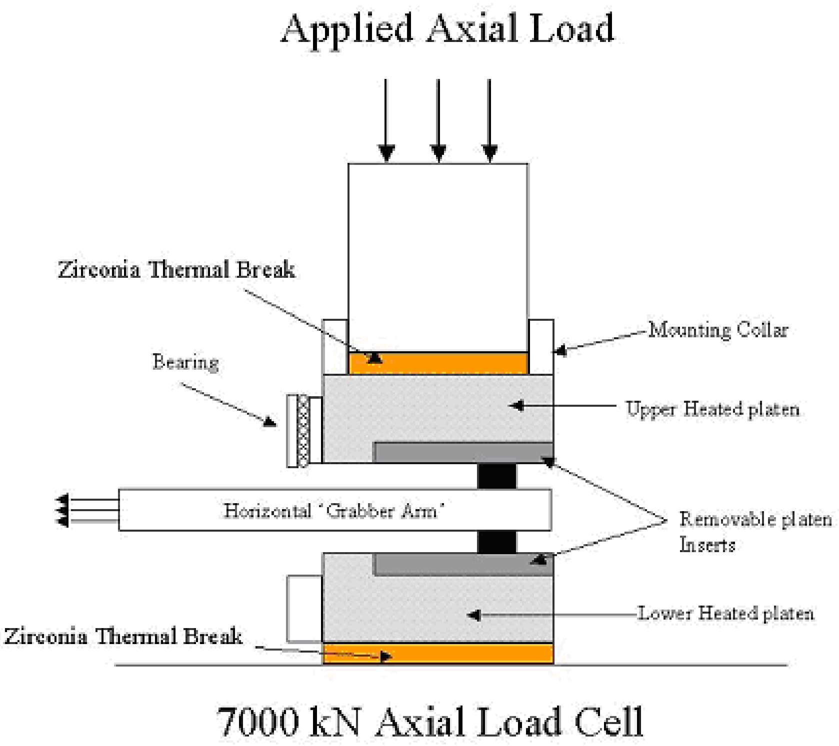
A number of test configurations may be used for generation of friction data and measurement of oxide film strength, between a deforming metal work-piece and a tool, to provide data for forging and rolling process models.

DC Heated Pin on Disc Rig (National Physical Laboratory)

In this apparatus, a U-shaped work-piece sample is heated at temperatures up to 1000°C in a few seconds, using a DC electrical current. The sample is then brought into contact with a rotating tool steel disc and the load and friction forces measured.



High Load Friction Rig (National Physical Laboratory)



Friction coefficients are obtained from the rig by measuring the ratio of the horizontal load exerted by a hydraulic ram dragging a cylindrical billet across the face of two platens, compressed in a large 700 tonne press. Either 30 mm or 50 mm diameter cylindrical billets are pre-heated in a furnace up to temperatures of 1000°C and subsequently transferred to the rig for testing. The platens may be heated using cartridge heaters, to 400°C. Removable platen inserts enable the testing of different tooling materials.

Tool Wear Tests

In general, satisfactory tool wear data can only be generated using actual machining processes and this obviously requires the consumption of a workpiece. The issue here is to work out the quantity of workpiece that must be consumed in order to generate measurable wear on the tool. The only way to minimize the quantity of workpiece used is to use the most sensitive wear measurement technique available, which effectively means surface layer activation. In this case, the technique is to use an irradiated tool and measure the transfer of radioactive material to the machining debris (chips, swarf etc).

Now, although this method allows rapid generation of wear data, with an essentially new tool, it does not address the issue of tool life and its effect on tool wear rate, which will vary with tool life. As the tool wears there will be an increase in metallic contact at the interface with a corresponding increase in contact temperature. The experiments need to be repeated after the consumption of a lot more work-piece material, in order to evaluate influence of tool wear on wear rate.

The difficulty of both generating and measuring the wear, most probably using instrumented machine tools and substantial quantities of work-piece material, leads one to consider whether there may be simpler measurements that could be made that may indicate the wear behaviour. There is evidence that tool wear is related to chip-tool friction and also an increase in tool temperature. Some researchers have also used acoustic emissions measurements to indicate what might be going on in the process.

So, is there any alternative to buying a large lathe, a machine tool dynamometer and a large stock of work-piece material?

Cutting Tests

Falex Tapping Torque Test

The tapping torque test is one of the few bench scale tests that involves an actual cutting process. A tap is driven into a pre-drilled hole in a sample and the resulting torque measured. Results depend on the test fluid, the condition of the tool, the size and finish of the pre-drilled hole and work-piece material.

Substantial work had to be done under ASTM to arrive a test that has a good repeatability. Specimens must be extremely repeatable; taps must be 'qualified', which means that only taps that fall within a certain error when testing them in a reference fluid, may be selected. Only then are differences in performance, which may be as small as 1 or 2 %, measurable. It makes the test tedious and expensive but is to date the only ASTM laboratory method for cutting performance.

Single Chip Test

A number of experimenters have performed tests to investigate the forces and energy involved in the formation of a single chip. One approach was to use the equivalent of a small Charpy tester, but with a machine tool tip secured to the bottom end of the pendulum. A plate sample was carried in a heated bath, mounted on flexures and restrained by a piezo transducer. As the pendulum swung, the tool cuts a single chip from the plate sample. The cutting force and the energy absorbed are measured and the condition and depth of the cut and the shape of the chip evaluated.

An advantage of this type of simple test configuration is that the test tool itself may be pre-heated, out of contact with the machining fluid in the bath, before the pendulum is released. This allows tool temperatures substantially above the fluid temperature and thus facilitates tests with slurries.

Machine Tool Tests

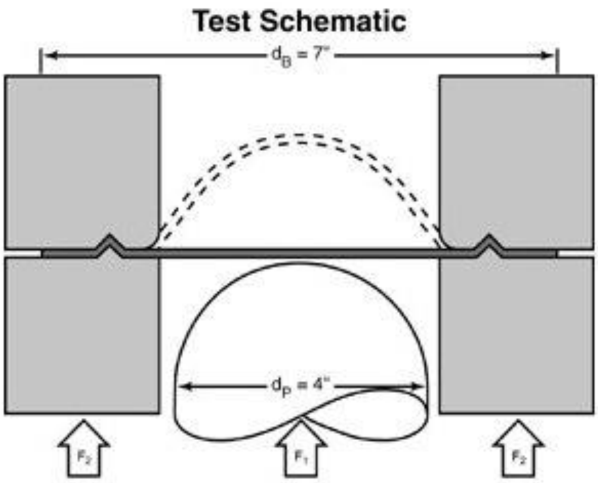
In many cases, full-scale CNC machines are used for evaluating drilling, tapping and machining processes. Tests invariable involve the consumption of large quantities of work-piece materials. The machines may be instrumented with standard machine tool dynamometers to allow measurement of forces.

Kistler 3-axis Machine Tool Dynamometer

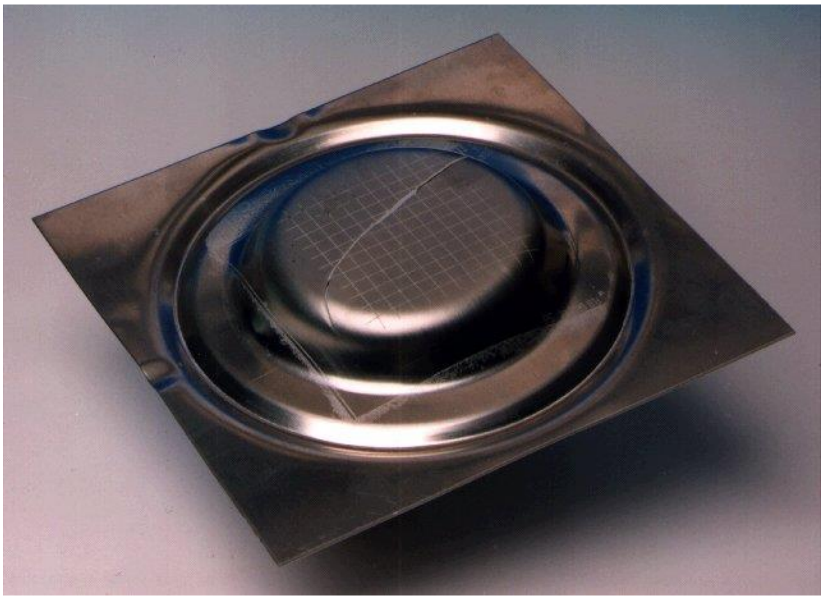
Forming Tests

Hemispherical/Erichsen and Olsen Dome Tests

These dome tests are primarily designed to assist in the evaluation of stretch formability of sheet materials. In their most basic form (Limiting Dome Height Test) involves pressing a plate sample into a dome to the point of rupture.

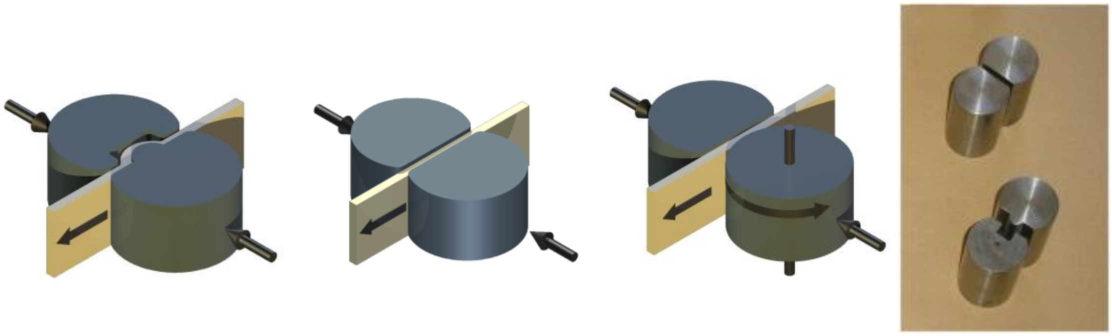


Schematic showing Tool and Specimen Dimensions for the Limiting Dome Height Test. Specimen after an increment of deformation is shown as dotted lines.



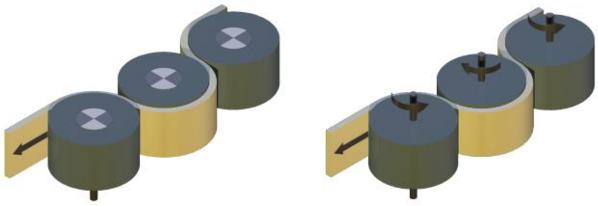
The tests can however be used to investigate a range of tribological properties including coating adhesion to the substrate in pre-coated sheet material, influence of lubricant pre-treatment on drawing force and the influence of tool design, surface finish and clamping force on “draw-in”.

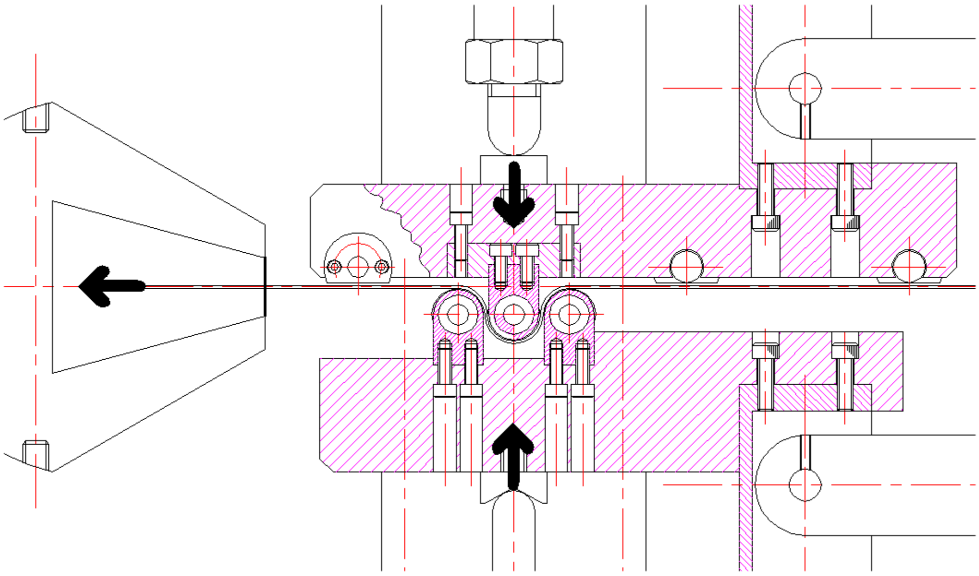
Strip Draw Test



Strip draw tests using a range of flat face and bead die sets are used for evaluating the influence on frictional behaviour of lubricants, work piece materials and tooling coatings and surface roughness and to investigate the resulting surface finish on the work-piece. Such semi-industrial type tests produce generally good correlation with full scale applications.

Roller Bead Test





Fixed and rolling bead tests are performed with the same tooling and rollers. To convert from fixed roller bead to rolling roller bead, anti-rotation pins on the rollers are removed.

A programme will start with fixed bead tests, with the tooling rollers clamped against rotation. The first action is to set the tool clearance, which may be done by using different diameter centre rollers. A minimum clearance of 10% of the sample thickness is recommended and the necessary centre roller diameter must be calculated accordingly. In the event that the resulting drawing force exceeds the tensile strength of the test sample, the clearance must be increased by reducing the diameter of the centre roller.

For each sample type, it was necessary to establish the initial clamping force needed to close the tool. The closed position for the tool is initially set by mechanical stops. The procedure for establishing the required clamping force is to load a sample and progressively increase the load while monitoring closure of the tool. The load at which the tool first closes against the stops is then taken as the clamping load set point for subsequent tests.

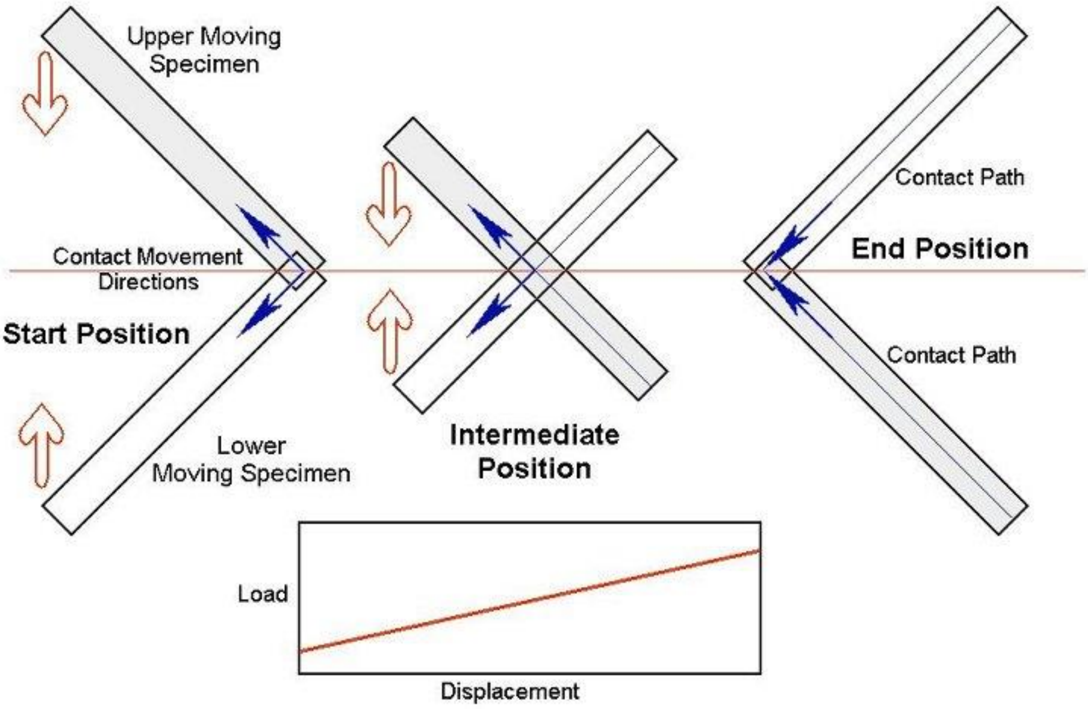
The clamping force set point established in this way should then be verified with a trial test, during which the behaviour of the tool is observed. If the tool remains shut when reacting the force normal to the sample (in the direction of the clamping force), then an adequate clamping force set point has been applied. If the tool opens, the test is repeated with a progressive increase in clamping force until the tool remains shut. It should be noted that applying too high a clamping force will simply load the tool against the stops and render measurement of the normal force on the specimen meaningless.

Having completed a series of tests with the rollers fixed, a series of repeat tests are performed with the rollers free to rotate with the same clamping force as established for the fixed bead tests. The assumption is thus that the measured drawing force with fixed rollers is the sum of the friction force in the tooling and the deformation force, whereas with rotating rollers, the drawing force is the deformation force only.

Friction coefficients for the test series may be calculated as follows:

$$\mu = \frac{\textbf{Drawing Force (Sliding)} - \textbf{Drawing Force (Rolling)}}{\pi \times \textbf{Clamping Force (Sliding)}}$$

Load Scanner



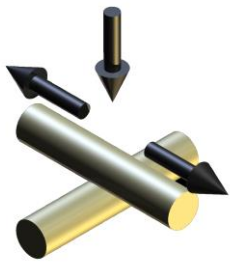
The load scanner is a concept developed by Professors Sture Hogmark and Staffan Jacobson at Uppsala University. The device offers a new test configuration for assessing the friction and wear properties of materials and lubricants. Two elongated test specimens, preferably bars or rods, are used. The orientation of the test specimens and their relative sliding motion during testing is arranged in such a way that the contact spot moves along a contact path on each specimen, and each spot along this path on one specimen will only make contact to one spot on the other specimen, and vice verse. The contact spot is the area over which the contact load is distributed.

The load is applied by means of a pulley mechanism and spring arrangement, connected between the load arm and the lower specimen carriage. The loading arrangement is such that the load increases or decreases with relative motion of the specimens, thus resulting in a unique load at each unique contact point on the two specimens.

A single pass experiment resembles the test procedure often used in scratch testing of coated specimens. In scratch testing, the tip is usually made of diamond. For coatings evaluation using the load scanner, it is normal to have one specimen coated and select another material for the counter specimen, as expected in the practical application. Thus, the friction and adhesion assessment performed better emulates actual conditions.

The load scanner may also be used for repeated reciprocating sliding tests thus demonstrating in a single test friction and wear characteristics under conditions ranging from mild wear to scuffing on a single pair of specimens.

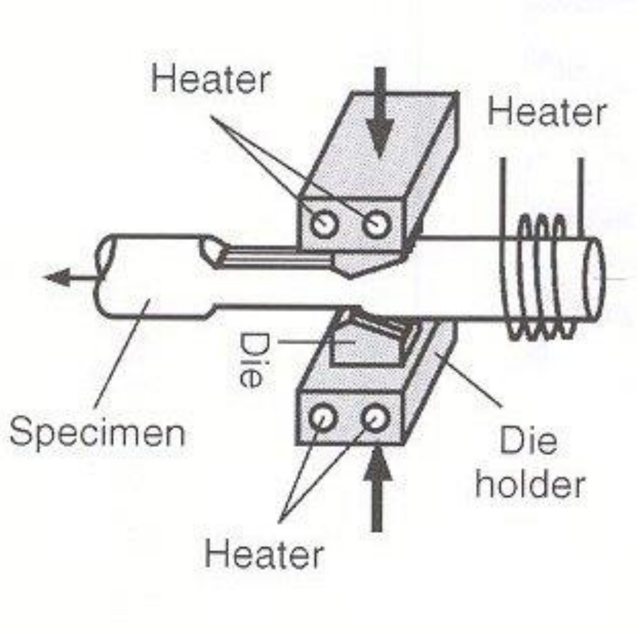
In addition to the crossed cylinder configuration with the point of contact moving on both surfaces, the specimens can be arranged so that the point of contact moves on one surface only, thus providing conditions similar to those generated in drawing processes.



Finally, it would possible to devise tooling to allow one of the rollers to rotate, thus imposing combined sliding and rolling on the contact.

The load scanner probably represents the most novel tribometer concept in recent years and is yet to be fully explored.

Forging Tests



A range of heated Up-setting Tests have been used to model hot forging processes. This tests typically involve drawing a pre-heated rod sample through a die tool in much the same way as with a standard strip draw test. It is not clear whether anyone has thought of adapting the test to provide a similar method to the roller bead test.

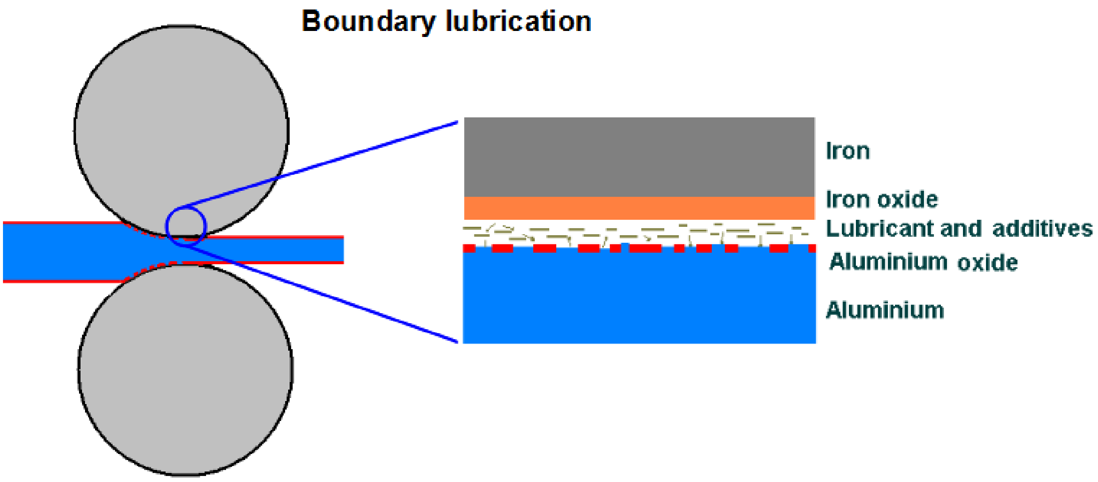
Impact Sliding Tests

The US Auto/Steel Partnership 2011 report "Impact Sliding Wear Tests on Duplex-Treated Die Materials" describes an impact sliding rig developed by the University of Windsor, Ontario, in which an actuator is used to drive a ball against an inclined sample plate, mounted at an angle on a pivot arm and pre-loaded against a stop, by a compression spring. The ball impacts the plate, which deflects through a pre-set angle, causing a wear track to be formed.

This type of device has now been used successfully to evaluate coatings and could potentially be used for evaluating forming fluids.

Rolling Tests

In most cold rolling operations, lubricant is used to reduce frictional forces, to protect the roll and strip surfaces, and to act as a coolant. The amount of oil drawn into the roll bite and the initial surface roughness are the critical factors determining friction in the contact and surface finish of the product (Michael Sutcliffe - Cambridge). In hot rolling, the role of additive chemistry is critical, as well as temperature and the development of transfer layers.



(Michael Sutcliffe – Cambridge)

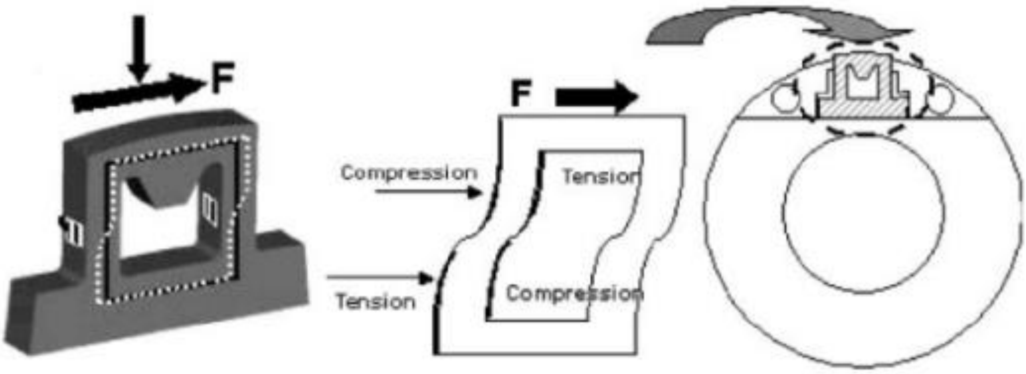
Mixed lubrication is common, with a combination of asperity interaction, chemical additive action and micro-plasto-hydrodynamic lubrication. Bulk strain/elongation drastically affects the contact because of the way this allows asperity flattening. Long wavelength asperities tend to have smaller slopes and flatten more quickly. Multi-scale roughness has important implications for friction and roughness transfer, hence surface finish. Pitting can be an important consideration, in particular in rolling stainless steel. Boundary lubrication and transfer layers are important and any sensible tribological test needs to simulate these to be useful and these depend on generating fresh surfaces.

Laboratory Scale Mill

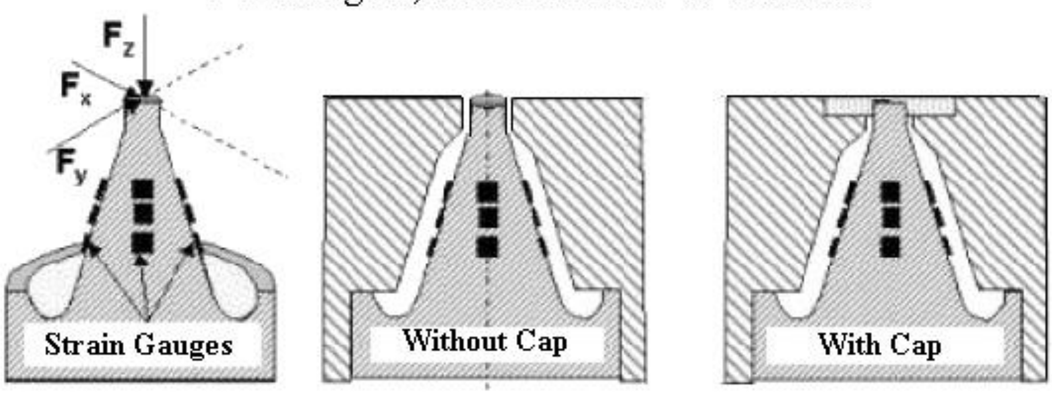
Laboratory scale mills are, for numerous reasons, invariably unable to replicate industrial conditions and are thus of limited usefulness. They typically operate at much lower speeds than full scale mills, hence under different lubrication regimes, and for much more limited duration production runs. The effects of aging of the process fluid, and the accumulation and dispersion of oxide debris, which can have a significant impact on the performance of a full-scale mill, are hard to model in a small-scale laboratory mill. For example, it is well known that with rolling aluminium, too "clean" a fluid can have a detrimental effect; the presence of dispersed oxide debris can be beneficial.

In-situ Friction Measurement

Over the years, a range of devices have been developed to allow measurement of local friction force within the roll bite, with the aim of over-coming the limitations of externally sensed total force. These have been used in both laboratory and full-scale mill rolls.



Portal Frame
P Henningsen, M Arentoft and W Wanheim



Cantilever Pin
J Jeswiet and P Wild

Although in recent years the trend has been to use mathematical models of metal-forming processes, verification of frictional behaviour with experimental data is still required. These types of sensor offer the best option for providing such process-based data.

Two Roller Machine

Two roller machines have been used for the investigation of the performance of lubricants in hydrodynamic, boundary and mixed lubrication regimes.

By altering the Slide/Roll ratio and the Sliding Velocity in the contact by varying the speed of the two rollers, the lubrication regime and corresponding wear and failure mechanisms can be varied from rolling contact fatigue at pure rolling or low slide/roll ratios, to wear at moderate slide/roll ratios and low sliding speeds, through to catastrophic scuffing failure at high sliding velocities.

In essence, changing the sliding speed changes the contact temperature and hence what happens to the surfaces and changing the rolling velocity changes the amount of lubricant entering the contact. By simply altering the test parameters, a range of different lubrication regimes can be produced from the same test configuration.

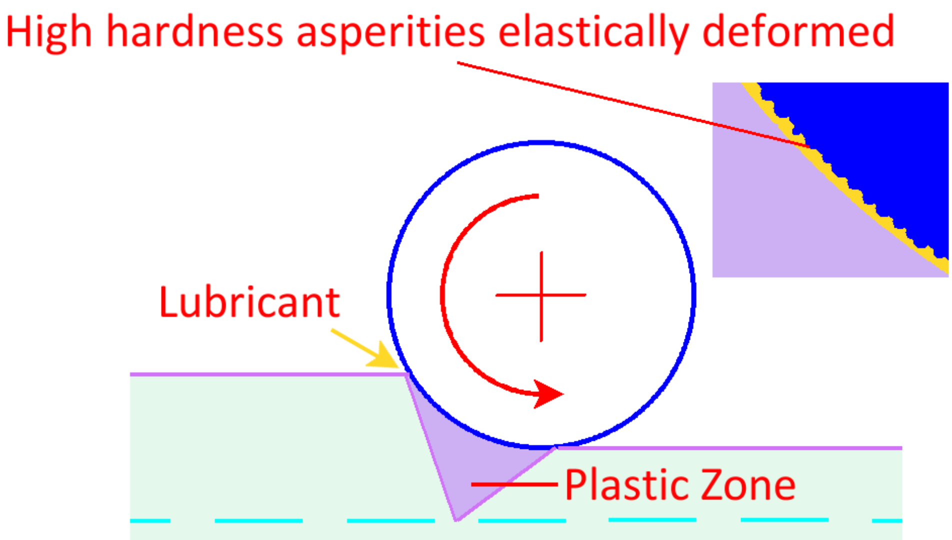
Two roller machines do however suffer from the limitation of most conventional tribometers in that one side of the contact is not continuously replaced with fresh material. This problem can be addressed with a perhaps less conventional indexing two roller machine design.

Modelling Rolling Processes with Two Roller Machine

The first point to note is that the contact in a two-roller machine, with flat rollers, is a hertzian line contact, whereas the contact in a metal rolling process, because of the size of the thickness reduction work zone, is an area contact. It follows that the contact pressure in the rolling process will be much lower than that in a two-roller machine, under the same applied load. You cannot simply take the applied load from the real rolling process and apply it to the contact in a two-roller machine, as the contact pressure in the latter will be far too high to be a meaningful model of the real process.

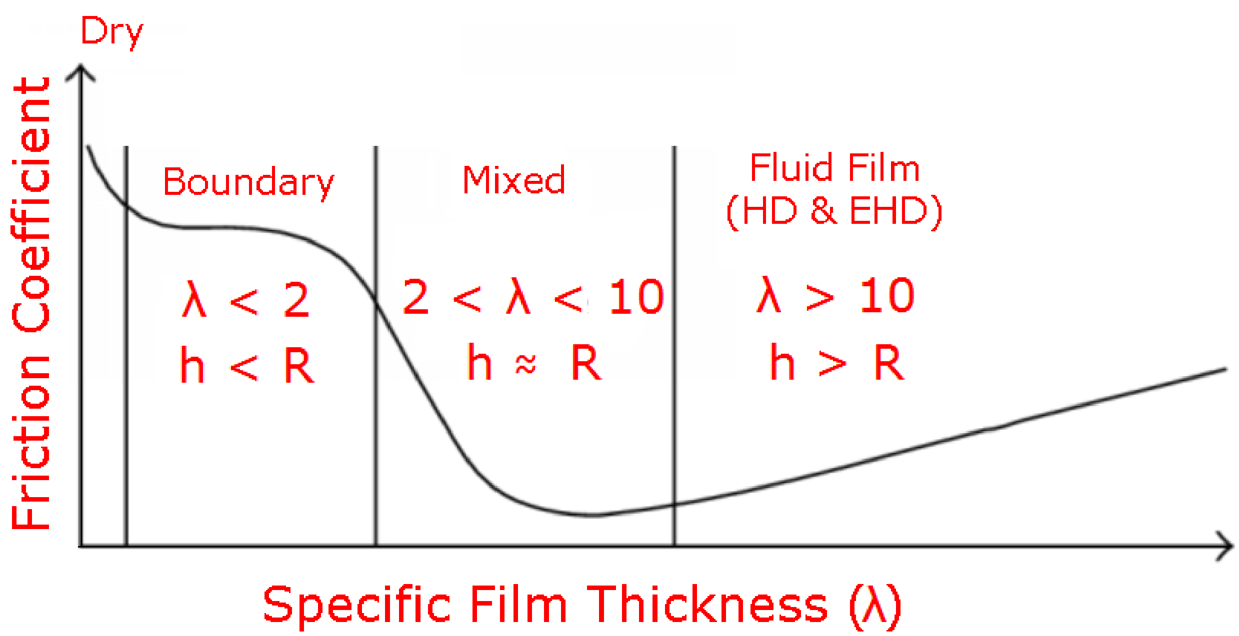
The second point to note is that although the rolling process will cause a large amount of plastic deformation within the roll strip, the high hardness asperities on the mill roller are elastically, not plastically, deformed. It follows that the correct model of the tribo-contact in a two-roller machine will be one in which plastic deformation does not occur.



The mean pressure for FULL plastic contact (analogous to a hardness test) is about 3Y where Y is the uni-axial yield stress. Initiation of plastic flow starts at a lower pressure and occurs when the maximum shear stress reaches the shear yield stress k for the material. The maximum shear stress in a Hertz contact is buried at 0.47a below the surface and is approximately 0.47 x mean contact pressure. For a Tresca material the mean contact pressure for initiation of yield is about 1.1Y. But note that the surface material is still elastic - there is a miniscule plastic enclave under the surface.

If we now add mechanical shear, because of sliding action in the contact, we can expect a decrease in either the applied load or temperature at which yield occurs. It follows that if we want to keep a model tribo-contact elastic it would be sensible not to exceed approximately 0.75Y within the contact. That means, for example, for a typical steel with a yield strength of, say, 1 GPa, the contact pressure in our tribo-test should not exceed 750 MPa.

A final consideration when designing a model experiment is to ensure that the correct lubrication regime is produced in the test contact. Rolling processes typically run under boundary or low lambda value mixed lubrication. A hydrodynamic (or elasto-hydrodynamic) regime must be avoided, as this would give rise to a loss of traction between roll and strip.



The lambda value is the ratio of lubricant film thickness to surface roughness. It follows that to model the process correctly, we not only need to calculate the tests parameters necessary to produce the required lubricant film thickness, but we also must specify and control the surface roughness of our test rollers.

Conclusion

Modelling machining, forming and forging processes, and associated tool wear and fluid performance, is by no means straightforward and easy. Before attempting to do so:

- Decide what it is you are trying to achieve
- Recognize the inherent limitations of a given test regime
- Do not use inappropriate machines just because they are available
- Have a sense of proportion and scale
- Consider temperature and thermal effects carefully
- Treat all results with caution until repeatability has been established
- Have realistic expectations with regard to correlation with field data