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Machining, Forming and Forging Tests

Commentary

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Tribology Trust Silver Medal 2017

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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.

With this in mind, I anticipate that this talk may generate more questions than answers.

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Machining, Forming and Forging

Processes involve:

- substantial and rapid modification of one side of the tribological contact
- both macro and micro changes to the microstructure and surface topography

Test models require:

- continuous replacement of one side of the contact

Further complication:

- lubricated contacts are complex, involving a wide variety of different regimes in a single system
- lubricants must provide lubricity, additive protection, corrosion protection and cooling

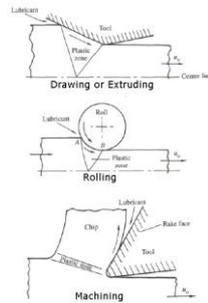
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In all cases, the process involves substantial and rapid modification of one side of the tribological contact, either by removal of material (machining) or plastic deformation of the material (forming and forging). All processes involve both macro and micro changes to the microstructure and surface topography. This results in a significant variation in the friction coefficient during the process. An adequate model requires continuous replacement of one side of the contact. Most conventional tribometers involve continuous sliding on the same wear track, thus rendering them inadequate as effective 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; 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.

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Machining, Forming and Forging Tests



Tribological Processes

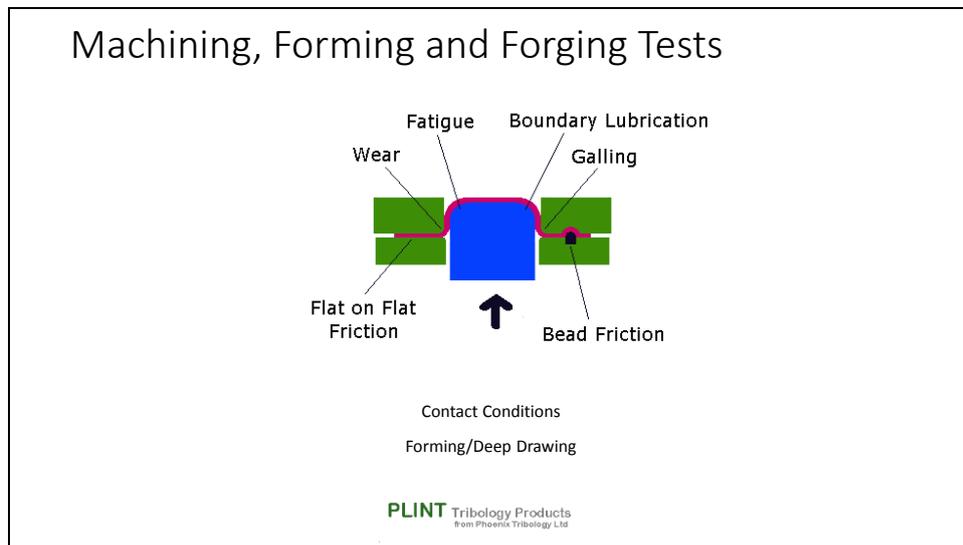
John Williams

Engineering Tribology

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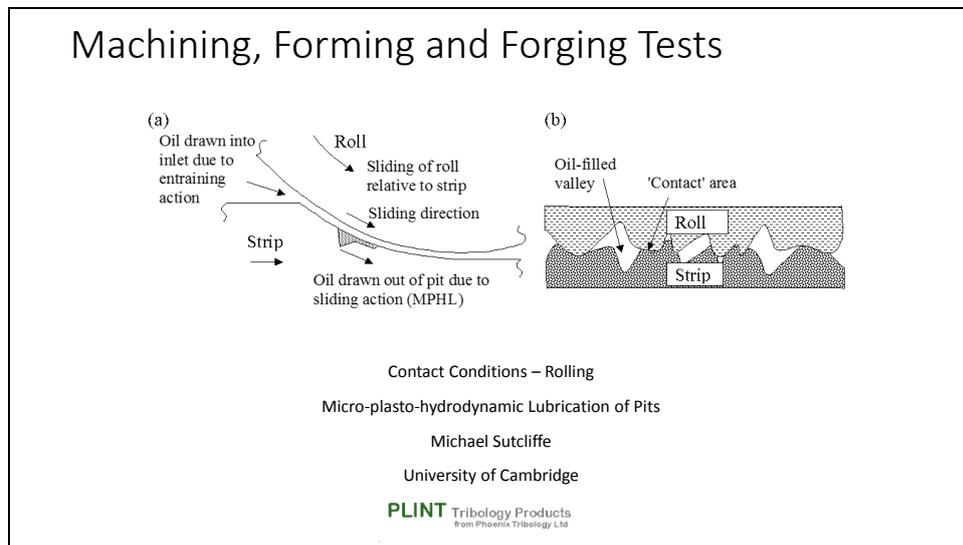
It will be apparent from these figures that any experiment that relies on external measurement of force will suffer from an inability to separate deformation or cutting forces from friction forces.

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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.

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Because frictional forces are difficult to measure directly, many models have been developed to estimate what it is in many different metal-forming situations.

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Machining, Forming and Forging Tests

Sheet metal friction test	Modelling equation		
Strip draw test	$\mu = \frac{F_f}{F_N}$	F_f	frictional force
Drawbead simulator test	$\mu = \frac{1}{\pi} \frac{D_{d+f} - D_d}{C_{d+f}}$	F_N	normal force
Capstan friction test	$\mu = \frac{2(F_2 - F_1 - F_B)}{\theta(F_1 + F_2)}$	D_{d+f}	drawing force with a fixed roller
Tensile strip test	$\mu = \frac{1}{\pi} \ln \left(\frac{F_p}{F_b} \right)$	C_{d+f}	clamping force with a fixed roller
Bending under tension test	$\mu = \frac{1}{\theta} \ln \left(\frac{F_p - F_b}{F_b} \right)$	F_1	inlet tension
Ohio State University friction test	$\mu = \frac{1}{\beta} \left(\ln \frac{F_p}{F_b} \right)$	F_2	outlet tension
Band brake equation	$\mu = \frac{1}{\theta} \ln \left(\frac{F_2}{F_1} \right)$	F_B	force due to bending
		F_p	pulling force
		F_b	back force
		θ & β	bend angles in radians

Equations used for calculating coefficient of friction in testing lubricants in sheet metal forming

Jeswiet, Wild and Sefton

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

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.

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.

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Lubricant Screening Tests

Lubricant evaluation problematic in conventional bench tests if lubricant is intended for use in water based emulsion

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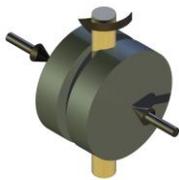
Lubricant evaluation presents a particular problem in conventional bench tests, especially if the lubricant is intended for use in a water based emulsion. At atmospheric pressure, tests with a bulk temperature above 100°C will cause the water to boil. A decision has to be made whether to test the lubricant 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.

For many years, a number of basic continuous sliding lubricant screening tests have used, each claiming to provide useful data, but in reality, data 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.

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Continuous Sliding Lubricant Tests

Pin on Vee Block Test



Application:

- Used extensively on neat oils (not emulsions) to evaluate extreme pressure additives
- Primarily used for evaluating forming and cutting oils

Advantages:

- Different block and pin materials may be used
- Specimen configuration produces four line contacts that widen quickly

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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.

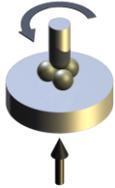
Different block and pin materials may be used, which is an advantage over the limited material combinations available with the similar aged four ball machine. A further advantage over the four ball machine is that the specimen configuration produces four line contacts, which widen quickly, so the pressures 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.

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Continuous Sliding Lubricant Tests

Sliding Four Ball Test



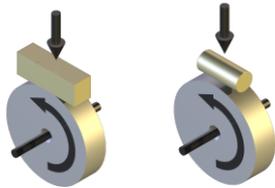
Four ball wear and four ball extreme pressure tests have been used for evaluating metal working fluid performance

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Both four ball wear and four ball extreme pressure tests have been used for evaluating metal working fluid performance, but it is hard to see how a sliding contact between bearing steel balls models anything much to do with machining, forming or forging.

Continuous Sliding Lubricant Tests

Block & Cylinder on Ring Tests



Block on Ring test configuration has been used in attempt to simulate the inlet conditions between plate and roll in rolling mill applications

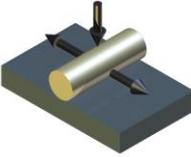
Cylinder on Ring test configuration has been used for extreme pressure additive screening test

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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 fluid directly into the inlet, facilitates testing with pre-heated emulsions, at inlet temperatures near to the boiling point of water.

Continuous Sliding Lubricant Tests

Long-stroke Reciprocating Test



Application:

- Screening test for rolling oils

Advantages:

- Results indicate friction and isothermal stability of oil
- Claimed to produce similar waste products to those produced in actual rolling processes

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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.

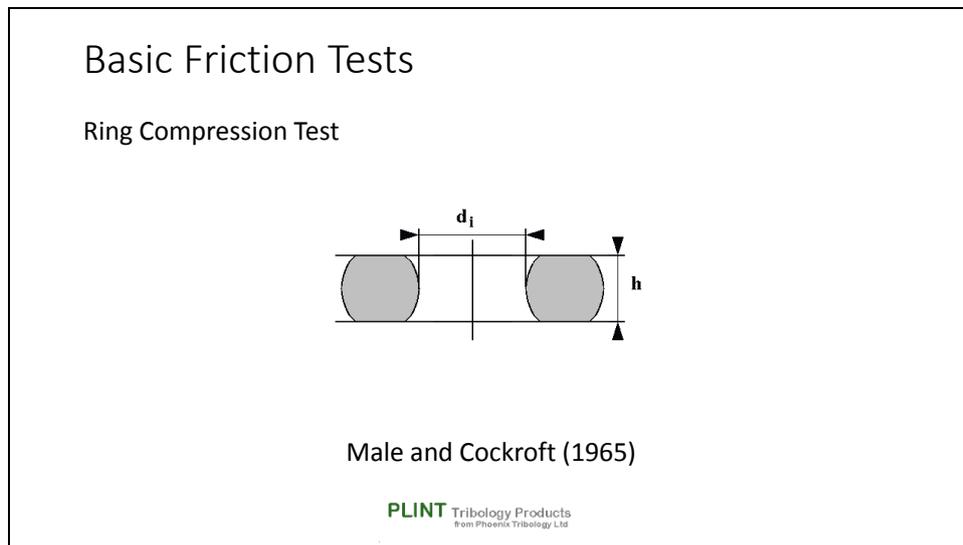
In rolling processes, the same lubricant is used throughout the different stations and temperatures and pressures vary throughout the rolling train. As different chemicals react differently at different temperatures, the lubricant additive package must provide consistent performance (in friction reduction, 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 performed 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.



The ring compression test (Male and Cockroft – 1965) was developed to investigate the friction at the interface between a work-piece 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.

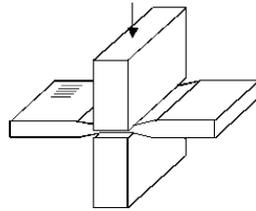
The presence of a small amount of friction at the interface will cause the outside diameter of the compressed ring to be less than that in the zero friction case, but the inside and outside diameters will be greater than the non-compressed state.

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.

Basic Friction Tests

Plane Strain Compression Test

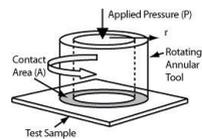


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The plane strain compression test is used to estimate values of friction coefficient under boundary lubrication in rolling processes and to investigate the generation of fresh material and deformation and cracking of oxide films. Measurements of friction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

Basic Friction Tests

Twist Compression Test



Applications:

- Model hydro forming of tubes
- Sheet forming operations in general
- Evaluate frictional behaviour of lubricants and die materials for metal forming applications

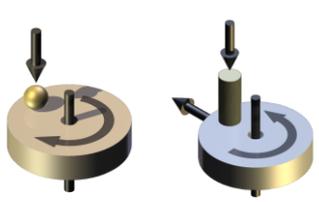
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The twist compression test was developed specifically to model hydro forming of tubes and for sheet forming operations in general. The twist compression test is used for evaluating the frictional behaviour of lubricants and die materials for metal 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.

Basic Friction Tests

Pin on Disc Tests



Applications:

- Evaluation of materials and fluids for forming processes

Issues:

- Rapid work hardening of the disc takes place
- Subsequent running on work hardened surface
- Increasing load on contact simply increases size of plastic zone

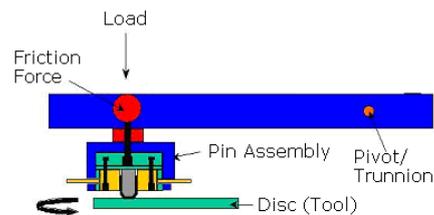
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A number of attempts have been made to use the pin on disc test configuration for evaluating materials and fluids for forming processes. In this case, the typical configuration is to run with a hard ball or spherical tipped pin on a soft disc. The first thing to note is that rapid work hardening of the disc wear track takes place, resulting in subsequent running on 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

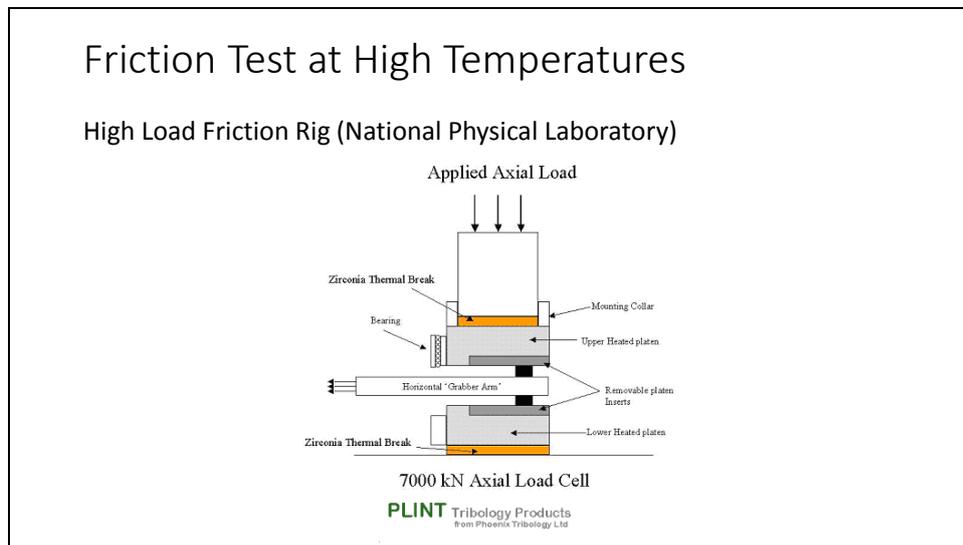
DC Heated Pin on Disc Rig (National Physical Laboratory)



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A number of test configurations have been 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.

In this apparatus, a U shaped work-piece sample is heated at temperatures up to 1000°C, in just 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.



Friction coefficients are obtained from this 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, to temperatures of up to 1000°C, before subsequent transfer 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

Tool wear data can only be generated using actual machining processes and this requires consumption of a work-piece, but:

- How much work-piece must be consumed in order to generate measurable wear on tool?

Quantity of work-piece used can be minimised by using most sensitive wear measurement technique available, but:

- How can we evaluate influence of tool wear on wear rate?

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In general, satisfactory tool wear data can only be generated using actual machining processes and this obviously requires the consumption of a work-piece. The issue here is to work out the quantity of work-piece that must be consumed in order to generate measurable wear on the tool. The only way to minimize the quantity of work-piece 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).

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. 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

Tapping Torque Test

Comparative test to evaluate performance of metal removal fluids

Test variables:

- tap geometry (thread cutting or thread forming)
- tap coating
- hole size
- metal characteristics
- fluid application
- rotational speed

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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 at 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.

Cutting Tests

Single Chip Test

- Cutting forces and energy absorbed in formation of single chip
- Depth of cut and shape of chip evaluated

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A number of experimenters have performed tests to investigate the forces and energy involved in the formation of a single chip. One approach is 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 swings, 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.

Cutting Tests

Machine Tool Tests



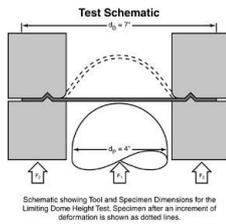
Kistler 3-axis Machine Tool Dynamometer

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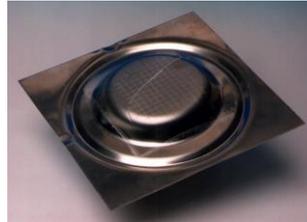
In many cases, full-scale CNC machines are used for evaluating drilling, tapping and machining processes. Tests invariably involve the consumption of large quantities of work-piece materials. The machines may be instrumented with standard machine tool dynamometers to allow measurement of forces.

Forming Tests

Hemispherical/Erichsen and Olsen Dome Tests



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

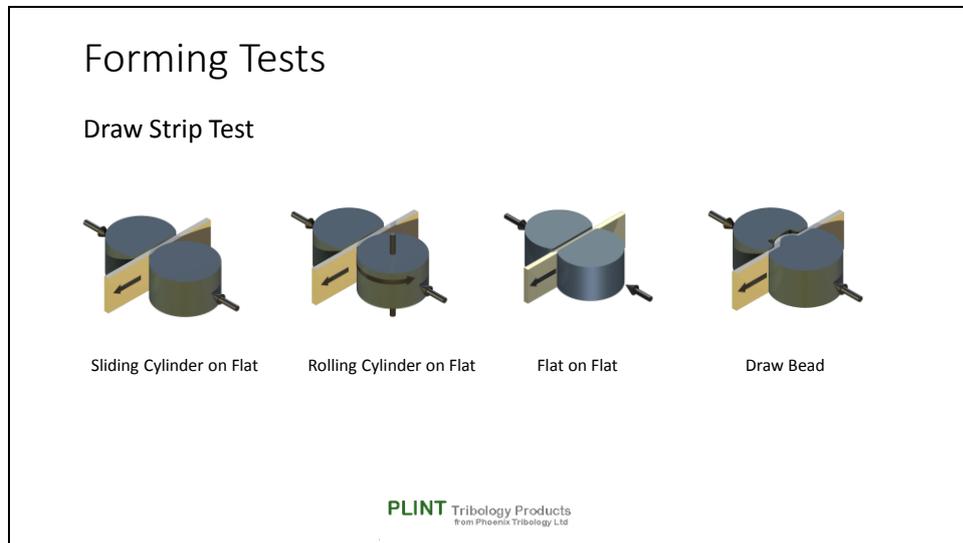


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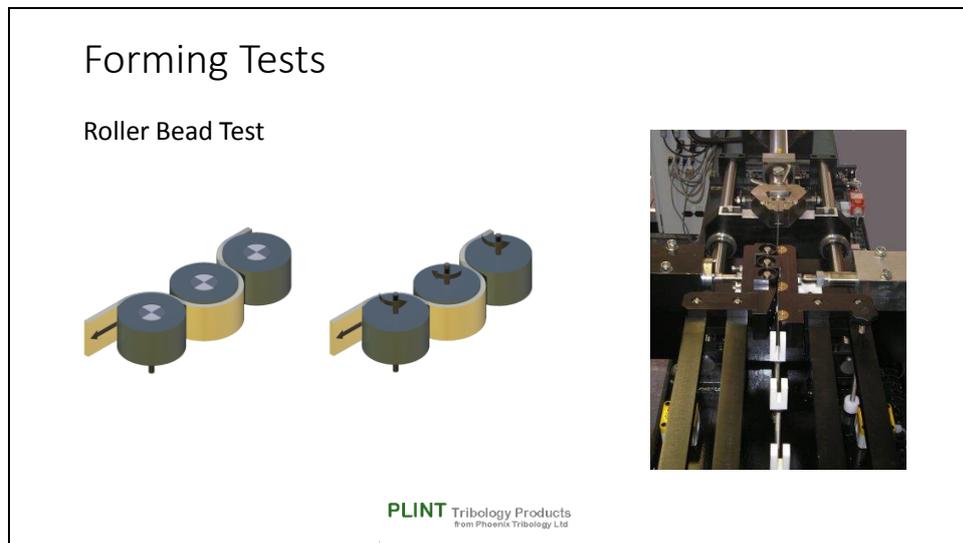
Dome tests are primarily designed to assist in the evaluation of stretch formability of sheet materials. In their most basic form, the Limiting Dome Height Test involves pressing a plate sample into a dome to the point of rupture.

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".

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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, 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.



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.

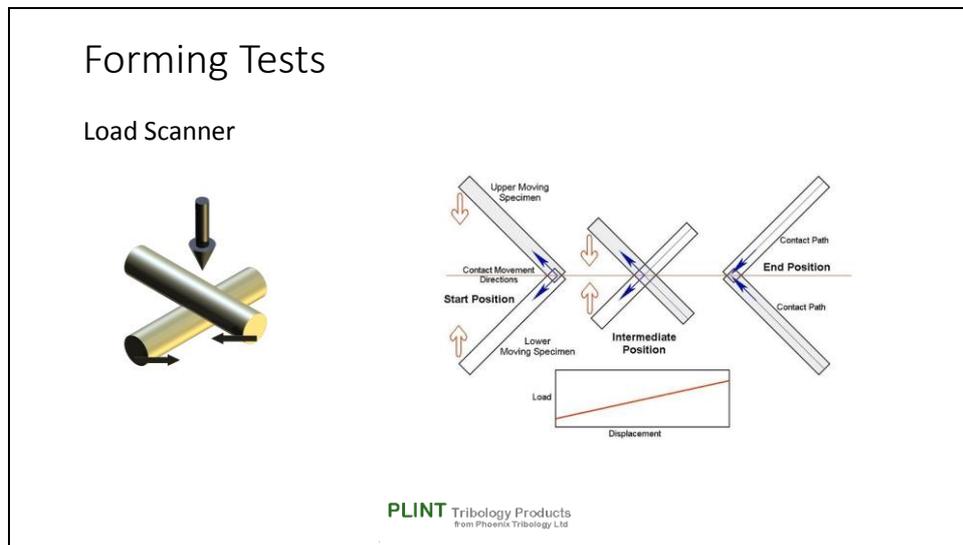
For each sample type, it is necessary to establish the initial clamping force needed to close the tool. The closed position for the tool is initially set by mechanical stops. The procedure for establishing the required clamping force is to load a sample and progressively increase the load while monitoring 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 then be calculated.



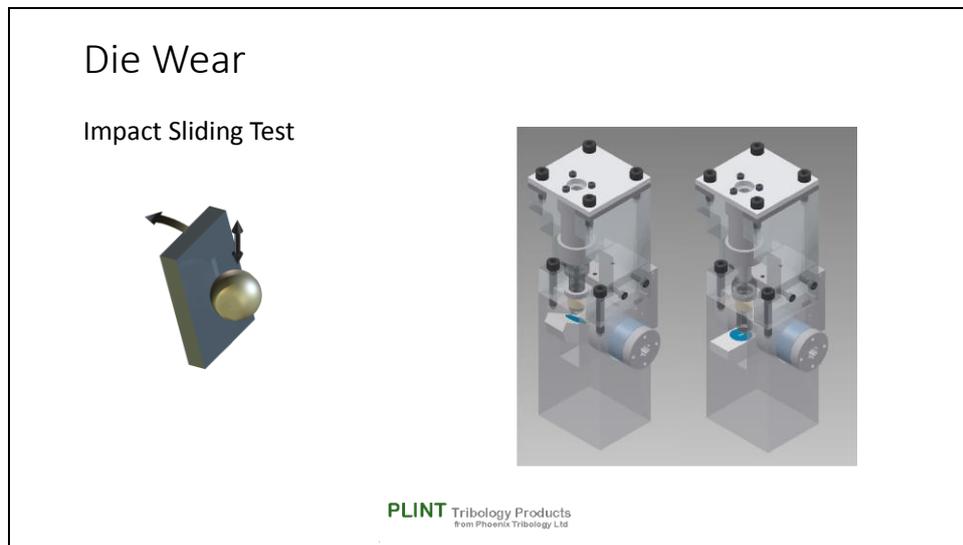
The load scanner is a concept developed by Professors Sture Hogmark and Staffan Jacobson at Uppsala University. The device offers a novel test configuration for assessing the friction and wear properties of materials and lubricants. Two elongated test specimens, preferably bars or rods, are used. The 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 versa. 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.

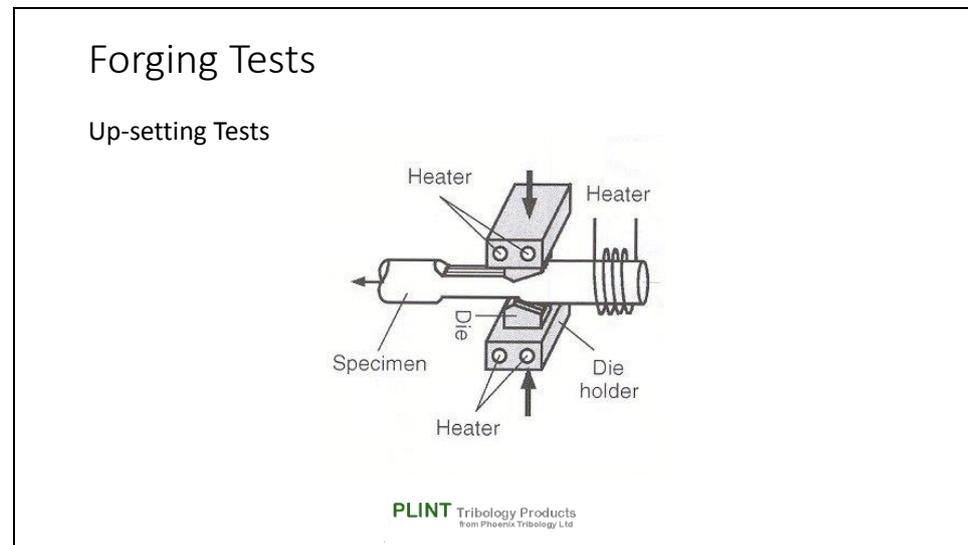
The load scanner may also be used for repeated reciprocating sliding tests thus demonstrating in a single test friction and wear characteristics under

conditions, ranging from mild wear to scuffing, on a single pair of specimens.

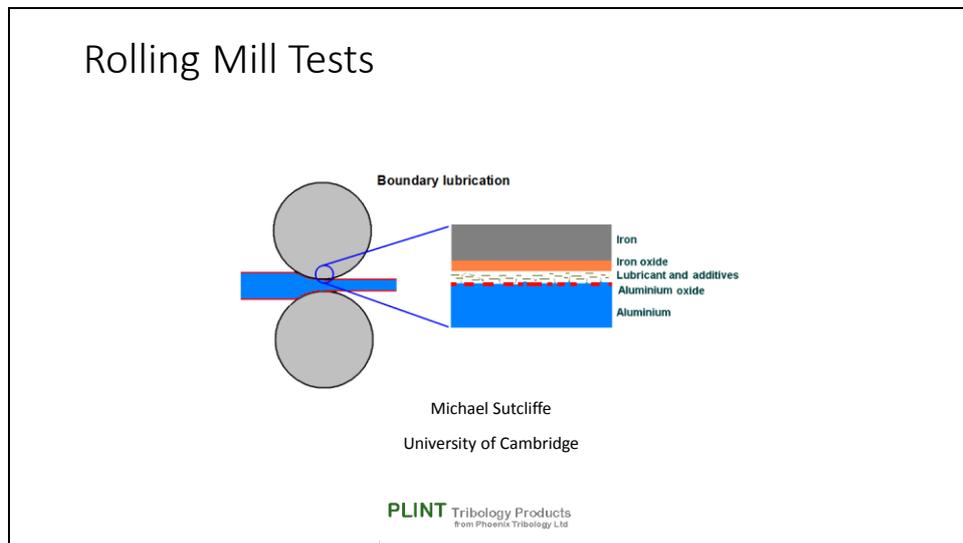


Auto/Steel Partnership 2011 report: [Impact Sliding Wear Tests on Duplex-Treated Die Materials](#), describes an impact sliding rig developed by the University of Windsor, Ontario, in which a pneumatic actuator is used to drive a ball against an inclined sample plate, mounted at an angle on pivot arm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

The test is used to evaluate PVD and CVD coatings for die wear protection.



A range of heated Up-setting Tests have been used to model hot forging processes. These 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.



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.

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.

Rolling Mill Tests

Laboratory Scale Mills

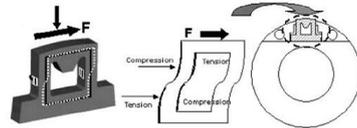
- Usually unable to replicate industrial conditions
- Typically operate at much lower speeds than full scale mills
- Short duration production runs limits effects of:
 - aging of process fluid
 - accumulation and dispersion of oxide debris

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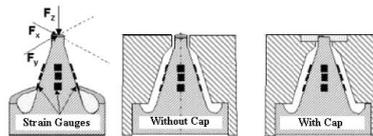
Laboratory scale mills are, for numerous reasons, invariably unable to replicate industrial conditions and are thus of limited usefulness. They typically operate at much lower speeds than full scale mills, hence under different lubrication regimes, and for much more limited duration production runs. 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.

Rolling Mill Tests

In-situ Friction Measurement



Portal Frame – Henningsen, Arentoft and Wanheim

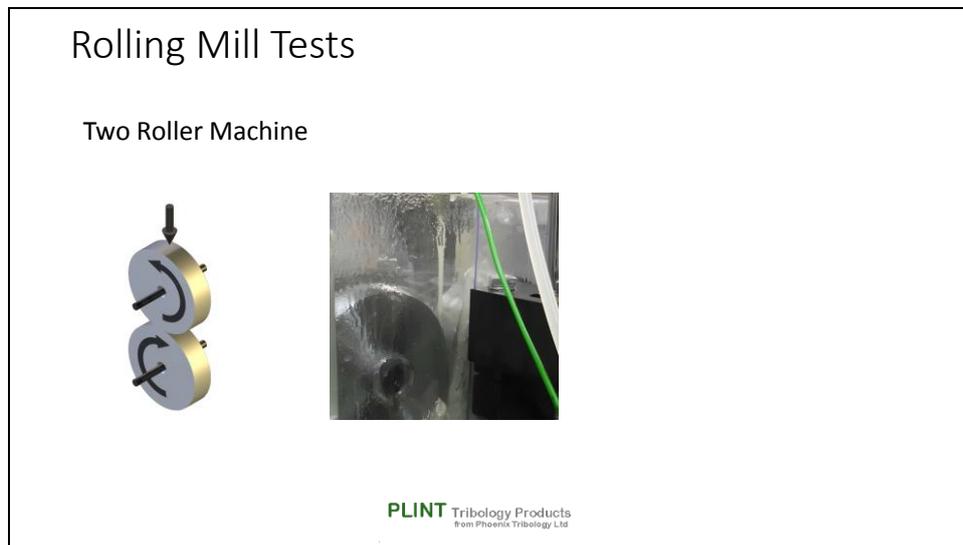


Cantilever Pin - Jeswiet and Wild

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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 overcoming the limitations of some externally sensed total force. These have been used in both laboratory and full scale mill rolls.

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 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 or roller on drum machine.

One key point to note is that although the core of the material being rolled will clearly be plastically deformed, the conditions at the surface, in the tribo-contact, remain elastic. It follows that a two roller tribological test on a two roller should not involve a plastic deformation of the rollers.

Conclusion

Bench test modelling of machining, forming and forging processes is profoundly challenging:

- Recognize the limits of a given test system to model the real process
- Do not use an inappropriate machine just because it is available
- Treat all results with caution until repeatability has been established
- Have realistic expectations with regard to correlation with field data

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