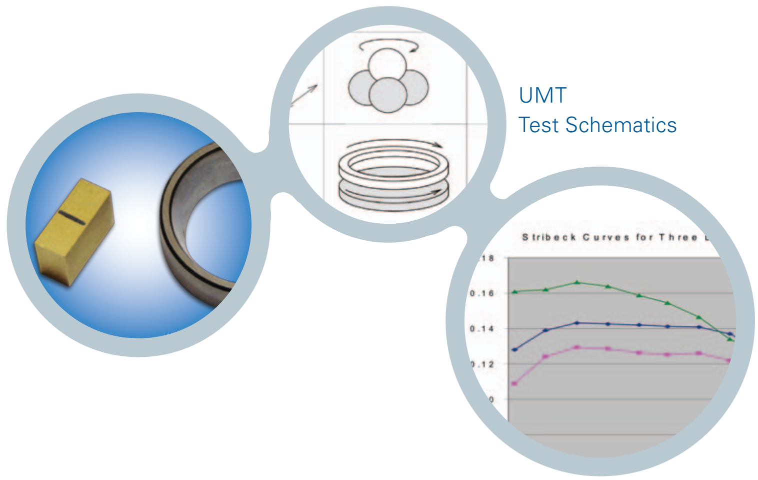


Application Note #1000

Characterization of Lubricants for Research and Development, Quality Control and Application Engineering

Lubricants play a critical role in nearly every type of machinery, and their performance is often critical to the speed, reliability, and life of the machines. As part of the product development process, lubricant manufacturers are continually faced with the need to evaluate the performance of candidate lubricants under many different conditions. Likewise, manufacturers of machinery frequently need to test the performance of alternative lubrications in order to determine the formulation that will enable their products to deliver the best performance and life. In the past, lubricant evaluation was typically based on intuition and experience. Today's requirements for products to run faster, longer, and more efficiently make it essential to use a scientific approach in lubricant development and application. This application note provides an overview of lubrication science and engineering and then discusses the latest methods for comprehensively characterizing the performance of lubricants in nearly any application.

Functions of Lubricants

The primary function of lubrications is to reduce friction and wear, but lubricants also play a number of other important functions, including;

- Cooling moving parts
- Removing contaminants and debris, and preventing them from entering the system
- Reducing shock, vibration, surface fatigue
- Preventing corrosion and oxidative damage
- Sealing gases

Types of Lubricants

Lubricants can grouped into several categories based on their formulation:

- Mineral oils derived from petroleum
- Bio-based lubricants, including triglyceride esters, from plants such as canola, rapeseed, castor, soybean and palm oil, as well as from animal-based products, such as lanolin, which is derived from sheep's wool, and animal fats

- Synthetic oils, such as poly-alpha olefin; synthetic-, phosphate- and silicate-esters; alkylated naphthalene and ionic fluids
- Solid lubricants, including polytetrafluoroethylene (PTFE), graphite, Hexagonal Boron Nitride (HBN), MoS_2, WS_2; Cd, Au, Pb, Sn, Zn, Cd and bronze
- Aqueous lubricants, such as brush polymers (polyethylene glycol)

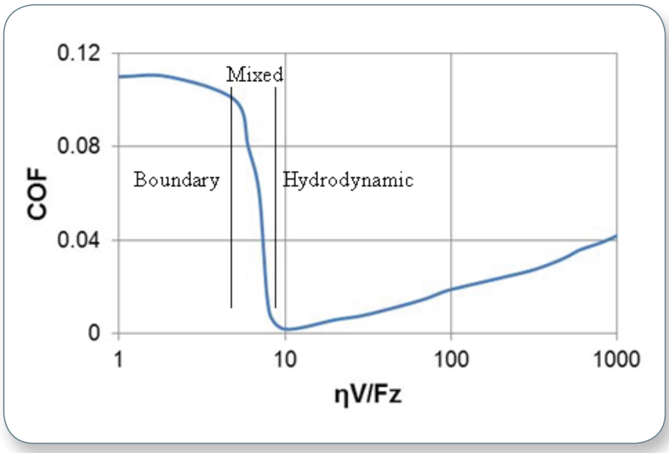
Lubrication Regimes

Lubrication processes show boundary, fluid film (hydrodynamic and hydrostatic), and mixed (elastohydrodynamic) regimes. In the first regime, called boundary film lubrication, the load is carried by the surface asperities rather than by the lubricant. In this regime, the coefficient of friction is the ratio of the effective shear stress and the plastic flow stress of the contact materials and is typically in the range of 0.1 and higher. In other words, the properties of the two mating surfaces play a far more significant role than the lubricant. Lubricant additives help reduce friction by forming a low-shear strength interface between hard metal contacts. At relatively low temperatures of 100°C to 150°C and pressures up to 1 GPa, friction can be minimized by covering the contacting surfaces with adsorbed mono-molecular compounds, such as fatty acids and Silane, that form a low shear-strength layer that minimizes friction. At higher temperatures, reactions between lubricant additives containing sulfur, such as dibenzyl disulphide, chlorine or phosphorus, and the metal surface result in the formation of sacrificial films of inorganic materials. These films prevent metal-to-metal contact and reduce wear. Lubrication under such conditions depends on achieving a working temperature high enough to form the film. The presence of oxygen and water can also influence sacrificial film formation.

In both the hydrodynamic and hydrostatic lubrication regimes, the load is carried entirely by the lubricating film. With hydrodynamic lubrication, the two contacting surfaces are completely separated by a film of lubricant that reduces friction and wear. The coefficient of friction is maintained at a very low level of about 0.005 and is due only to the shearing of the fluid. Under these conditions, failure brought about by friction rarely occurs. There are two necessary conditions to achieve hydrodynamic lubrication. Relative motion between the two contacting surfaces must be maintained with sufficient velocity to generate a load-carrying lubricating film. In addition, the surfaces must form a converging gap into which the fluid is drawn to create a pressure field to support the load, and separate the solid surfaces. Any liquid or gas can be used as the lubricant in this regime, provided that its viscosity is appropriate for the load and speed, with the caveat that it should not react chemically with the bearing surfaces. Hydrodynamic lubrication is the preferred form of lubrication in most bearing systems, piston/liner assemblies and so on, however, damage during start and stop and vibration during operation are potential dangers to be aware of with this regime.

With hydrostatic lubrication, the two contacting surfaces are again completely separated by a lubrication film. This lubrication regime is similar to hydrodynamic lubrication with the significant difference that the pressure is generated by an external pump that maintains a continuous supply of pressurized lubricant. Friction force is minimal at a very slow sliding speed, making this type of lubrication useful for precision control systems and other mechanisms that operate at low speeds. A disadvantage of hydrostatic lubrication is that the process depends upon the reliability of the pump. The potential for damage to the bearing surfaces exists if the pump fails.

In the elastohydrodynamic regime, elastic deformation of the asperity contacts enlarges the load-bearing area to the point that the viscous resistance of the lubricant helps support the load. The very thin 0.1μm to 1μm lubricating film separates the contacting surfaces, reducing friction and wear. The contacting surfaces deform elastically due to the presence of hydrodynamic pressure in the film. Elastohydrodynamic lubrication involves a rapid change in the lubricant properties from nearly an ideal liquid state outside the contact zone to an extremely viscous solid-like state within the contact zone. Mineral and synthetic oils are primarily used for elastohydrodynamic lubrication because they exhibit pressure-dependent viscosity, also known as piezo-viscosity.



Stribeck curve.

Mixed lubrication is the regime where the conditions are between hydrodynamic and boundary, either because the viscosity or velocity are too low, or the load is too high to permit complete separation of the surfaces.

The Stribeck curve shows friction as a function of viscosity, speed and load. The vertical axis depicts the coefficient of friction (COF) and the horizontal axis plots a dimensionless parameter that combines viscosity, speed and load

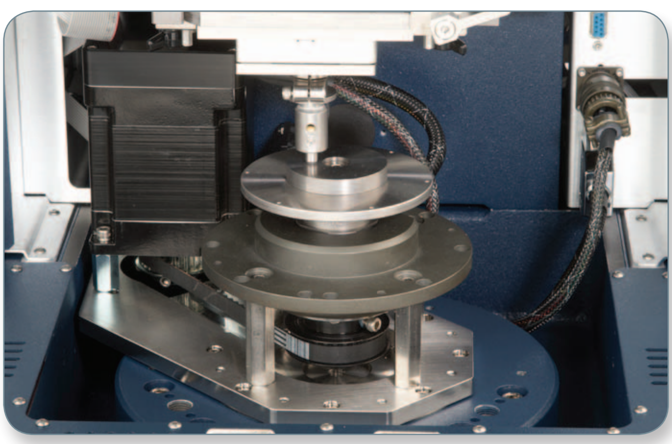
$$\frac{\eta V}{F_z}$$

where η is the viscosity of the lubricant, V is the sliding velocity and F_z is the normal load. This curve can be used to determine the optimal speed for the lubricated contact that minimizes the coefficient of friction.

Lubricant testing can be performed on a variety of tribometers, each addressing a particular lubrication regime. Bruker's UMT Nano+Micro Tribometer is designed to provide comprehensive materials testing for mechanical and tribological properties with a load range of 1mN to 200 N. Interchangeable lower and upper drives perform rotary, reciprocating and block-on-ring tests using the same tool. All motions are independently programmable for custom wear tracks. Automatic COF versus load and velocity curves are generated to provide the tribological finger print. The UMT is capable of performing ISO, ASTM and DIN tests, is available with environmental chambers, and is able to monitor and record in situ acoustic emission, electrical data, friction, wear, down force, temperature, humidity, etc.

Rotary Test

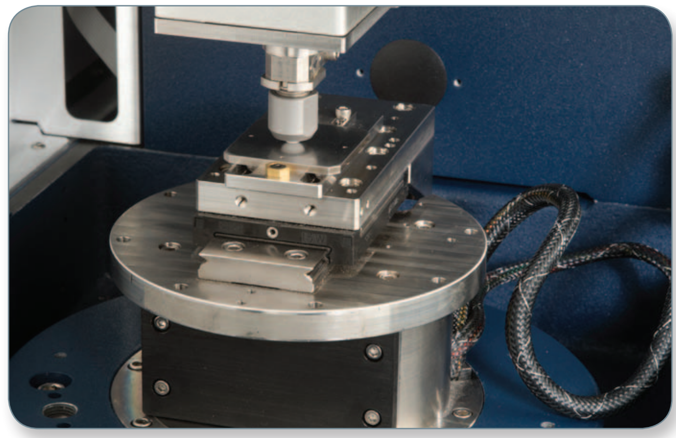
In the rotary test, a ball or pin is installed under the load sensor and a standard disk is installed inside a liquid holder. During the test Fx and Fz are measured to obtain the COF. This test setup can be used to perform ASTM standard tests, including test for low temperature torque of ball-bearing grease. It can also be used to produce a Stribeck curve. Electrical contact resistance and acoustic emissions can be monitored, and the test can be performed at ambient or elevated temperatures.



Rotary test module.

Reciprocating Test

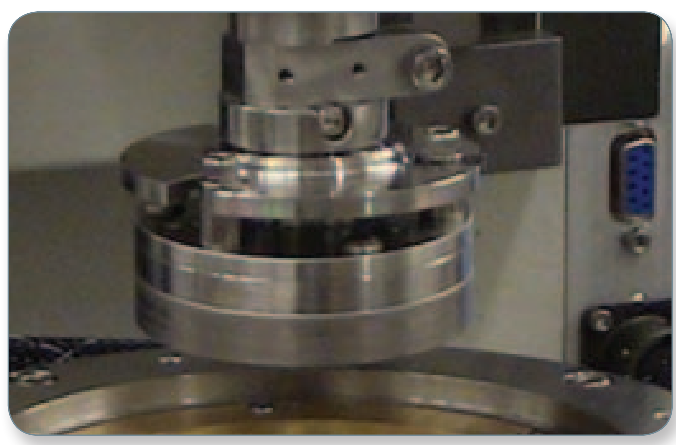
Reciprocating tests, including ball-on-plate and pin-on-plate, can be performed by installing a plate inside the liquid holder on the test machine. The piston ring-on-cylinder test (ASTM G181) can also be performed with this setup. Fx and Fz data are measured to obtain the COF. The reciprocating test can be used to perform the following ASTM standard tests: D5706: Extreme Pressure Properties of Lubricating Greases, D5707: Friction and Wear Properties of Lubricating Grease and D2981: Test Method for Solid Lubricants in Oscillating Motion.



Reciprocating test module.

Disk-on-Disk Test

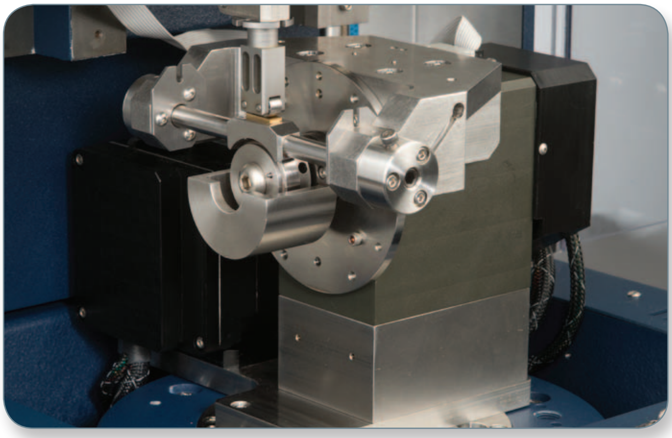
Disk-on-disk tests can be used to simulate the operation of a clutch with rotary motion. A disk is installed inside the liquid holder. Fx (converted from torque) and Fz data are measured to obtain the COF. The ring-on-disk (thrust washer) test can also be performed in this module.



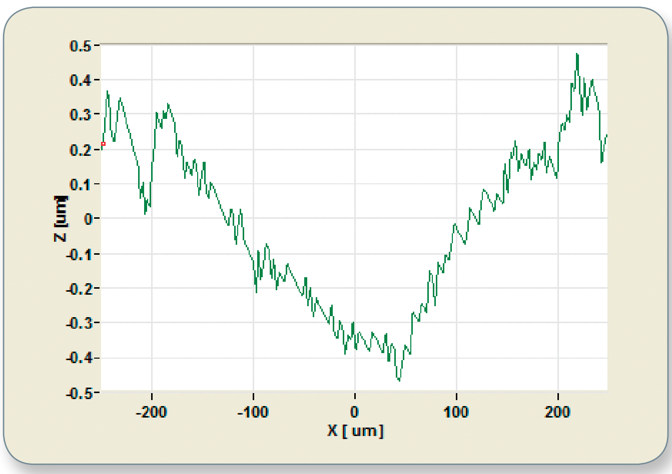
Disk-on-disk test module.

Block-on-Ring Test

In the block-on-ring test a block is loaded from the top and pressed against a rotating ring. A block holder is used to hold the block. A standard ring is installed on the arbor, which rotates in the horizontal axis. Fx and Fz data are measured to obtain the COF. The block's wear scar can be measured with a 3D microscope as shown below.



Block-on-ring test module.



Depth profile of wear scar in block-on-ring test.

Pin and Vee Test

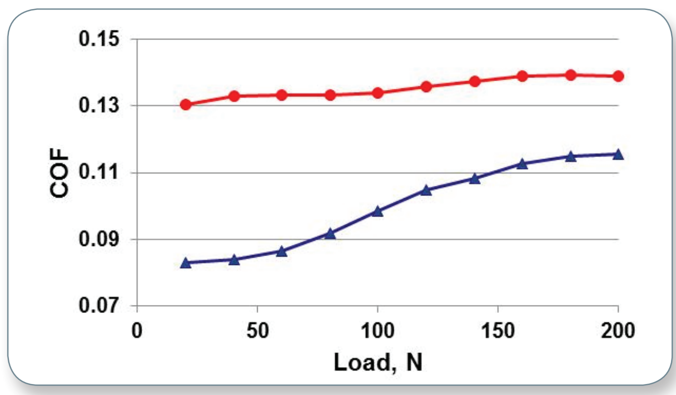
The pin-on-vee block test is performed by rotating a pin and loading it so that it is forced down against a vee groove. This setup can be used to perform several ASTM standard tests.

The ASTM D3233 test begins with a run-in for 5 minutes at 1174 N load and 290 rpm. The load is then raised to 1832 N and the test is run for 1 minute at 290 rpm. The load is raised to 2828 N for 1 minute, to 3824 N for 1 minute, and then raised in a similar progression until the lubricant fails. Failure of the oil is detected by a sharp increase of friction.

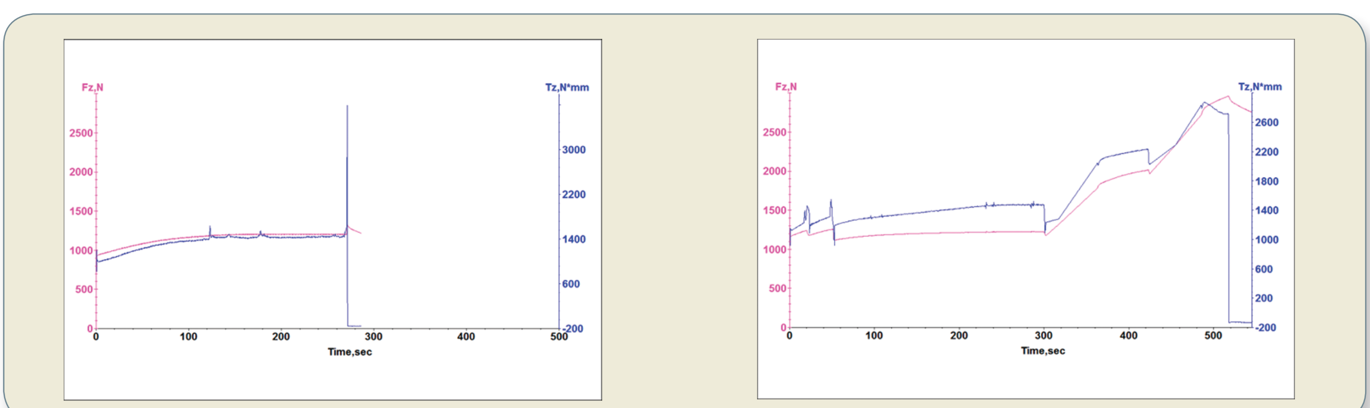
Piston Ring-on-Cylinder Liner Test

The friction of piston ring and cylinder liner materials under lubricated conditions can be determined as per ASTM G181. The loading is increased from 20 N to 200 N in increments of 20 N with holding time at each load of 1 minute. The materials are then unloaded from 200 N to 20 N in 20 N increments with a holding time of 1 second at each step. The test is carried out with a temperature of 100 ± 2°C, stroke of 10 mm and frequency of 10 Hz. The average value of friction during loading and unloading corresponding to the same load is reported as a function of load.

The results of a piston ring-on-cylinder liner friction test per ASTM G181 with two different lubricants is shown below. Lubricant A (red) showed a higher COF at every load but also a lower increase in COF over the test range. Lubricant B (blue) exhibited a lower COF and a rise in friction with the increase of load due to change toward a boundary film regime at higher loads.



Piston ring-on-cylinder linear test results.



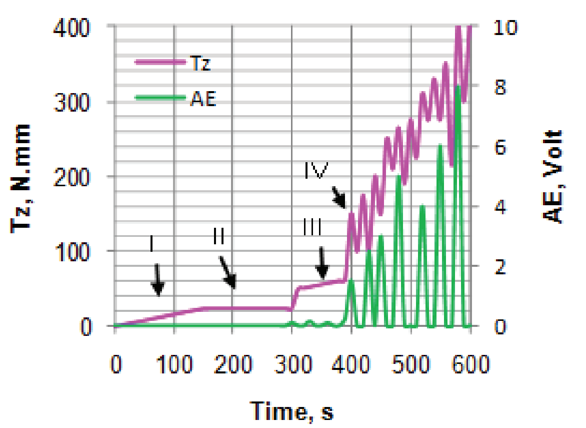
ASTM D3233 test results using pin-and-vee method.

Four-Ball Test

This test is performed with the UMT using a 4-ball test setup with the rotary drive in a heating chamber at a fixed temperature of 75°C as per the ASTM D4172 standard test method. SAE 52100 balls with 0.5 inch diameter are used. Three balls are assembled inside a ball holder with a liquid reservoir. The test lubricant is poured inside the ball holder. The fourth ball engages from the top at the center of the three balls with a load of 392 N. The liquid holder with three balls rotates at 1200 rpm for 1 hour. A torque sensor is used to measure friction and normal force to calculate COF. After the test, the wear scars on all three balls are measured and average wear scar diameter value is reported. The smaller the wear scar diameter, the better is the performance of the lubricant.

Twist Compression Test

The twist compression test is primarily used to evaluate cutting fluid used in metal cutting operations as well as sheet metal lubricants. It simulates the action of the flute of the tool on the workpiece. The friction torque plot usually exhibits four distinct stages: initial break-in (I), effective lubrication (II), depletion of lubricant (III), and failure of lubricant (IV). The time taken for Tz and acoustic emissions (AE) to rise due to the failure of the lubricant is reported as the durability of the lubricant.

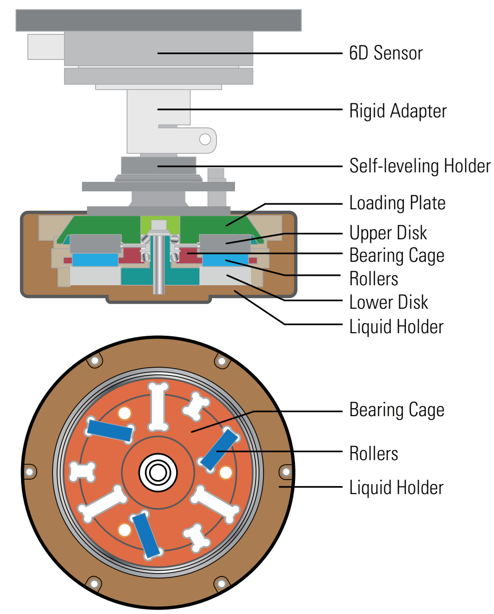


Typical twist compression test plots.

Sliding-to-Rolling Ratios

Rotary and reciprocating tests can be performed at various sliding-to-rolling ratios. The tribometer can be set up for sliding-to-rolling ratios in rotary motion as follows:

- 0% sliding when three balls are used
- 15% sliding when three short rollers are used
- 35% sliding when three long rollers are used
- 65% sliding when three long rollers are installed on three slanted slots



Configuring sliding to rolling ratios for rotary motion.

Conclusion

For comprehensive tribological characterization, lubricants need to be tested and compared under different lubrication regimes, loads, speeds, sliding-to-rolling ratios, temperatures and humidity levels. The UMT provides an ideal platform for performing standard and customized tests to accurately and efficiently characterize the tribological properties of lubricants as part of the development, quality control and applications processes. Even when in-situ testing in actual machine components is preferred, the UMT can be used to conduct screening tests on the candidate materials, allowing users to eliminate unsuitable lubricants or materials quickly. Comprehensive data gathering and rapid screening allow users to develop superior lubricants in a very efficient manner.

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