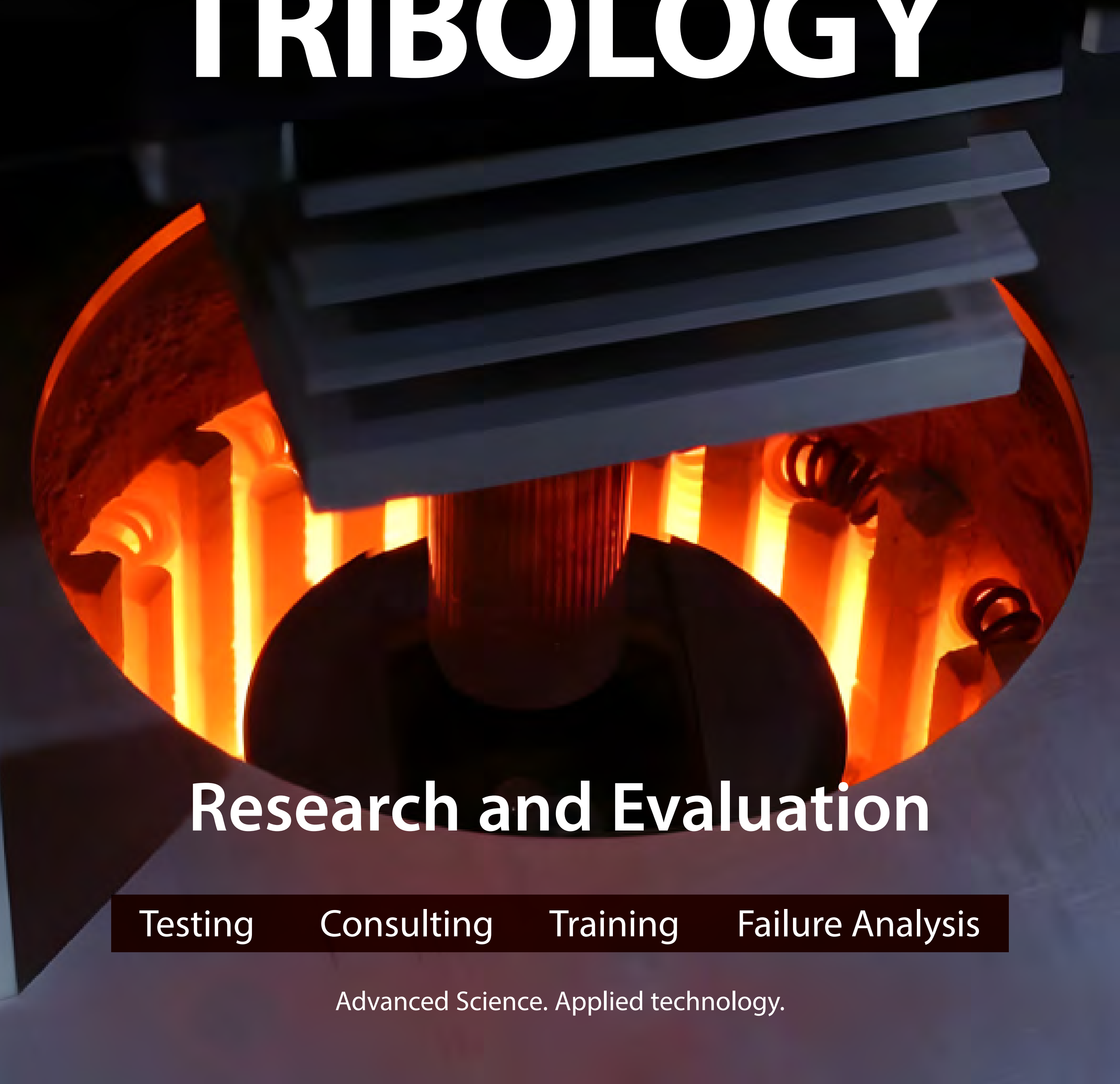
SOUTHWEST RESEARCH INSTITUTE

TRIBOLOGY



Research and Evaluation

Testing | Consulting | Training | Failure Analysis

Advanced Science. Applied technology.

Contents

Examples of SwRI Quality Accomplishments

- The Institute has been inducted into the U.S. Space Foundation's Space Technology Hall of Fame.
- SwRI has received two Department of Defense James S. Cogswell Outstanding Industrial Security Achievement Awards.
- The American Society of Mechanical Engineers has recognized the Split-Hopkinson Pressure Bar apparatus as an ASME National Historic Engineering Landmark.
- Numerous departments and divisions have achieved certifications and accreditations from ISO and other organizations.
- Examples include:
  - ISO 9001:2015, Quality Management System Requirements
  - ISO 14001:2004, Environmental Management Systems
  - ISO/IEC 17025:2005, General Requirements for the Competence of Testing and Calibration Laboratories
- The Ford Motor Company has designated the Institute a Tier 1 product development engineering services supplier and has presented the Institute a Q1 award.
- Since 1971, SwRI has earned 52 R&D 100 awards (including three in 2021) for developments recognized by R&D Magazine as among the 100 most significant technical accomplishments of the year.

On the cover: 1200°C pin-on-disk coating test (see page 20)

SwRI Tribology Research and Evaluation

Recognized worldwide as a leader in many fields, Southwest Research Institute® (SwRI®) established extensive tribology test facilities in 2011. The Tribology Research and Evaluation group combines world-class expertise from across the Institute's eleven technical divisions to offer testing, test rig design, consultancy, training, and failure analysis in a variety of tribology fields from deep sea to deep space.

Testing

We have over 3,500 square feet of tribology laboratories housed in ten discrete rooms, allowing the option of confidential testing and rig development. We offer a wide range of services, from test-for-fee to comprehensive research program design and implementation. Clients often visit our labs to observe and direct the testing undertaken for them. This works exceptionally well for research projects where the initial outcome is unknown. Test results can be discussed and a quick decision made on the next test material or condition. An in-house machine shop is available for machining test parts, client-supplied components, and holders for our test rigs.

Our rigs range from standard and adapted tribometers to purpose-built rigs. Our work is roughly 50% automotive. Examples of work in other fields include medical devices, biomedical, construction, infrastructure, warranty services, space, pharmaceutical, cutting fluids, wind turbines, and green tribology.

Consulting

We are flexible in our consultancy, offering immediate support with a monthly retainer to individual project consulting. This can be remote (phone, email, or Teams) or face-to-face meetings at SwRI or on site.

Training

We have two PhD tribologists on staff, both with teaching experience. We offer training for individuals or groups at SwRI or at your facility. We offer generic tribology training or we can adapt the training to your specific requirements. Training is normally between one and three days depending on your requirements and desired outcomes.

Failure Analysis

We perform failure analysis on many different components and have access to additional equipment and expertise at SwRI to complement our efforts. A more complete description of this service is given on page 34.

This brochure gives a high-level overview of the capabilities at SwRI. Contact us today to develop test programs to meet your requirements, develop your products, and solve your tribological challenges.

What can we do for you? **tribology.swri.org**

SwRI Tribology Staff (left to right): Mike Moneer, Jereme Arellano, Carlos Sanchez, Greg Hansen, Andrew Velasquez, Peter Lee, Isaiah Reyes, Steve Marty, Anthony Rodriguez, Robert Gray

See page 35 for contact information.

TriboEngine
Highly Versatile Research Tool

SwRI offers the TriboEngine for use in a wide range of fuels, lubricants, and hardware testing. The TriboEngine is a highly versatile single-cylinder research engine with unprecedented instrumentation and control, developed at SwRI specifically for tribology research.

TriboEngine test bed

Mechanical Specifications

The SwRI TriboEngine is based on an in-line four-cylinder, two-liter gasoline engine operated using the Prism® data acquisition and control system for precise control of the engine variables and real-time data access. The TriboEngine is coupled to a Dyne Systems static DC four-quadrant dynamometer. This system permits both fired and motored tests.

Oil Supply and Control

The engine has been designed to accept a split oil supply with external sumps, thereby allowing tight control of the sump oil temperatures and pressures. One supply feeds the valvetrains (top end) and a second supply feeds the piston assembly and crankshaft (bottom end). Both the top end and bottom end oil supplies can be changed on the fly while the engine is operating.

Fuel Supply and Control

The fuel supply to the engine can be changed on the fly while the engine is running. All fuel lines are circulated to prevent "hot spots" in the fuel lines and maintained at the same pressure and temperature to ensure the behavior of the engine at fuel change is only due to the different fuels. Emerson Micro Motion sensors are used to accurately measure fuel consumption.

TriboEngine Mechanical Specifications	
Displacement	0.5 L
Bore and stroke	86 mm x 86 mm
Compression ratio	11:1, may be decreased
Cylinders	1
Aspiration	Natural, may be forced
Fuel delivery	Port injection
Valvetrain	Direct-acting overhead cam with hydraulic bucket lifters
Camshafts	1 intake, 1 exhaust
Valves	2 intake, 2 exhaust
Liner	Sleeve, removable
Oil pump	External electric
Coolant pump	External electric

Fuel Supply Specifications	
Fuel temperature	10 – 40°C
Fuel pressure	30 – 70 psi
Fuel	Client-specific

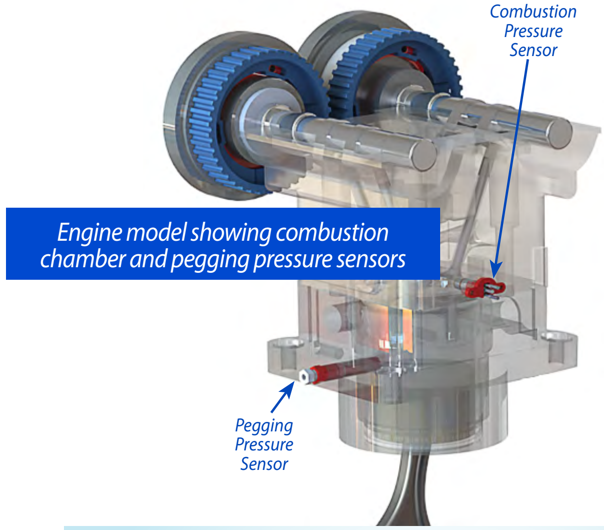
Sump Lubricant Specifications	
Lubricant volume	1.0 – 4.0 L
Sump lubricant temperature	10 – 150°C
Lubricant	Client-specific

Prism® DATA ACQUISITION AND CONTROL SYSTEM

A Technology of SwRI

Pressure Sensors

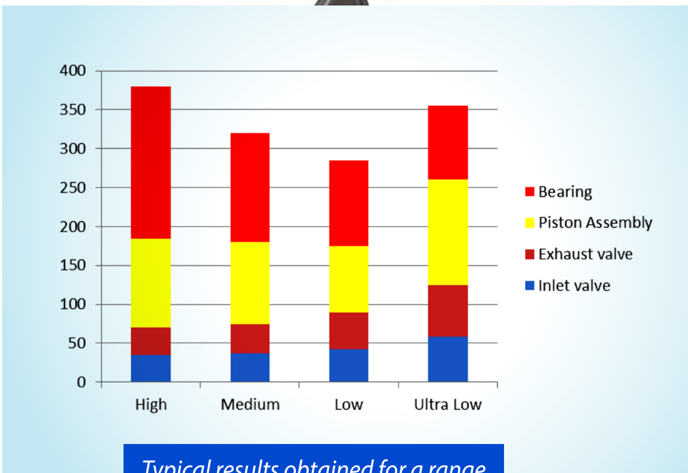
The engine is furnished with two sets of pressure transducers: those involved in measuring combustion pressure and those measuring fuel, oil, crankcase, and exhaust pressure. Two transducers are used to measure combustion pressure. The first, located directly in the top of the combustion chamber, is recalibrated every cycle to correct for transducer drift. This correction is achieved by taking a calibration measurement using a second pressure transducer located in the cylinder wall at 110° after TDC. The intake, crankcase, exhaust, and coolant pressures are also measured. The exhaust back pressure can be controlled.



Engine model showing combustion chamber and pegging pressure sensors

Blow-by Gas Measurement

The blow-by from this single-cylinder engine can be accurately measured using a blow-by meter developed by SwRI that compensates for pulsating gas created in a single-cylinder engine (U.S. Patent 10,190,717 B1).

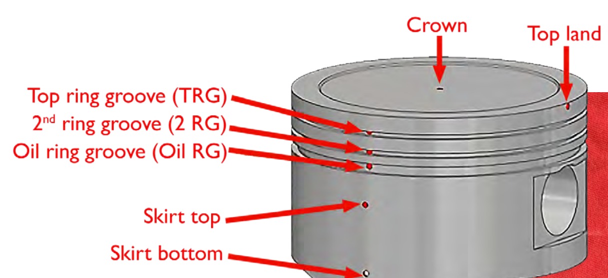


Typical results obtained for a range of viscosity lubricants

Engine Friction Measurement

The engine is instrumented to independently measure friction of the piston assembly, valvetrains, and total engine. Frictional losses from the oil pump, coolant pump, and alternator need not be considered, as they are mounted externally. The ability to isolate friction measurements of the valvetrains and piston assemblies facilitates in-depth analysis of lubricant and additive behavior as well as material performance. Similarly, the engine is run with a dry sump to remove frictional losses associated with the crankshaft churning oil in the engine sump. Data acquisition rates of 250 kHz, combined with an average of numerous consecutive engine cycles, achieve accurate and repeatable results.

- Piston assembly friction is calculated from the gas force acting on the piston crown, piston assembly inertia forces, and connecting rod force. The connecting rod axial extension is measured using an array of strain gauges. Prior to testing, the connecting rod complete with strain gauges undergoes a simultaneous temperature and load calibration using a tensile testing machine with an oven enclosure.
- Valvetrain friction is measured using two instantaneous torque transducers mounted between the cam shafts and the cam wheels. These are free to rotate and require a slip ring coupling to enable a wire connection.



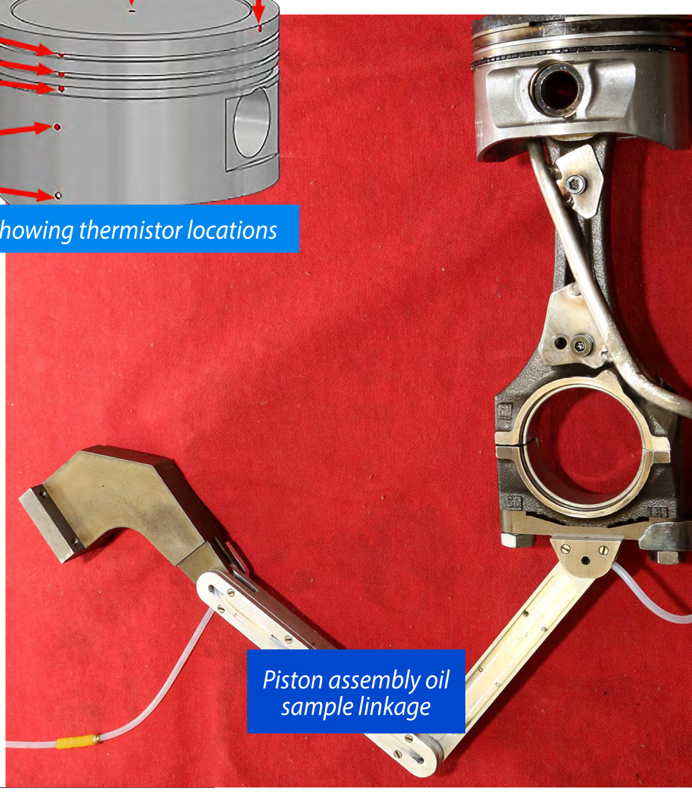
Piston showing thermistor locations

Piston Assembly Temperature Measurement

The piston can be instrumented with an array of thermocouples situated very close to the surface and located in recesses behind the crown, top land, top ring groove, second ring groove, oil ring groove, skirt top, and skirt bottom. Thermocouple response times permit the engine to be operated through a range of speeds and loads for multiple data sets.

Lubricant Oil Sampling

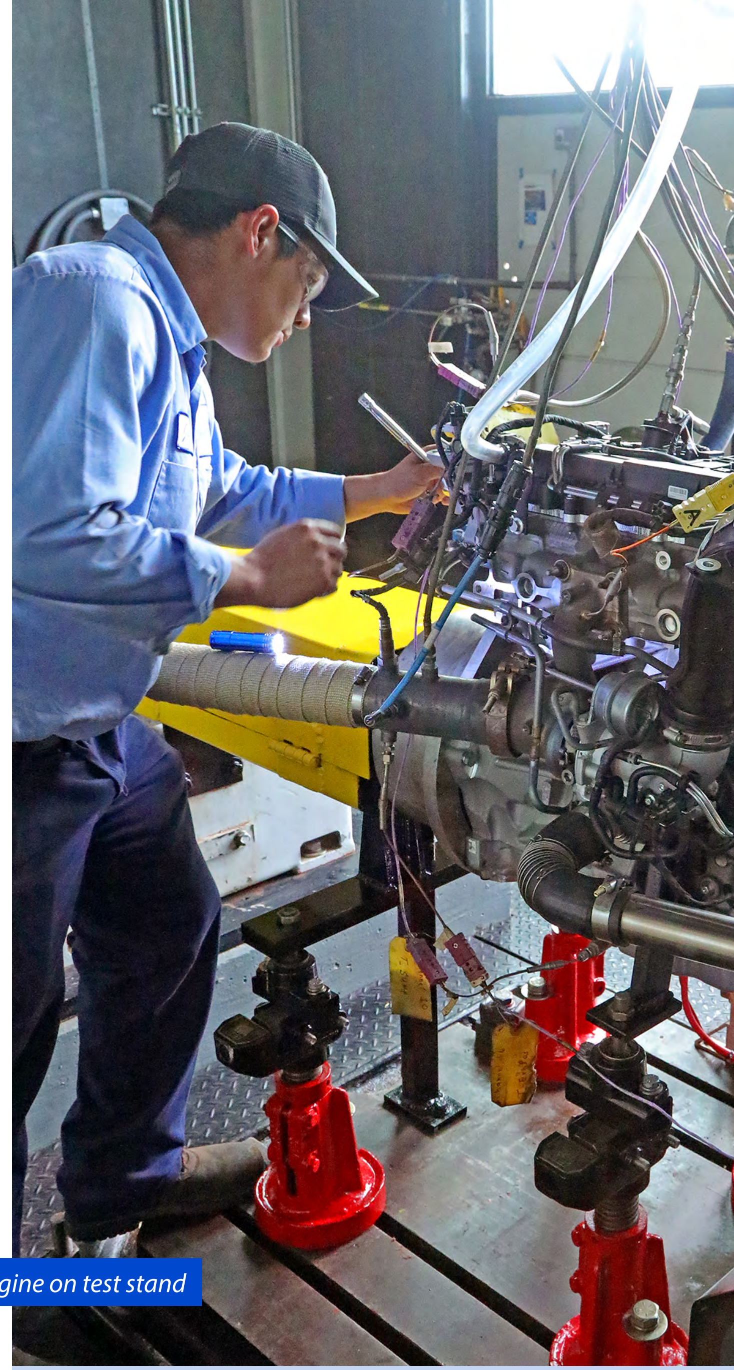
Lubricant can be sampled from a range of locations in the operating engine both while being fired and motored. Sump samples are taken to keep track of lubricant degradation and chemical markers. Lubricant may also be sampled from the liner at a number of chosen locations as well as from the rear of the top or second piston ring.


Piston assembly oil sample linkage

Radioactive Tracer Technology

For more than 60 years, SwRI has used radioactive tracer technology (RATT®) to make highly accurate and sensitive real-time wear measurements in operating engines and other mechanical systems. Friction and wear are typically measured in engines to evaluate lubricant chemistries, component design, and surface coatings. Wear measurements of components can be made using bulk-activated and surface-layer-activated methods.

SwRI's Tribology Research and Evaluation engineers have built a dedicated RATT engine test cell capable of heating and cooling the sump lubricant to replicate hot and cold starts. Research programs may include the use of an actual vehicle to map the engine set points for specific engine-transmission combinations. These set points are then transferred to the test engine control system. To determine wear data, the SwRI-developed flow-through radioactive tracer detector is coupled to a high-speed multichannel analyzer to count and process radiation from multiple radionuclide tracers. This technology can be used in any closed system (e.g., fuel pumps and drivetrain components).



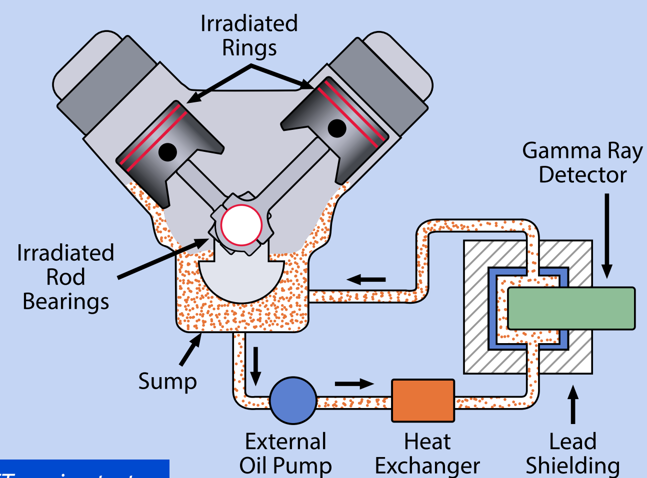
RATT engine on test stand

Advantages of Radioactive Tracer Technology

SwRI engineers study real-time wear to instantly detect wear and wear rate changes. Advantages of radioactive tracer measurement techniques include:

- High sensitivity
- Cost-effective testing
- Repeatable measurements
- Real-time wear data
- Meaningful results from short tests
- Easily measured transients
- Identification of cause and effect relationships
- Wear associated with:
  - Specific design parameters
  - Fuel and lubricant characteristics
  - Engine operating conditions
- Continuous testing without disassembly for parts inspection
- Ability to measure wear that is not detectable or measurable by other means

SwRI's radioactive tracer technology can quantify very small changes in wear information in a matter of minutes and includes the benefits of historical data and trending, whereas conventional test-and-measure procedures can require hundreds of hours to develop a single data point. Because periodic physical inspection is not required, RATT avoids possible changes in the way materials fit together or in the system's wear state; hence, test-to-test continuity is maintained and sequential experiments yield more meaningful results.



RATT engine test cell schematic

Radioactive Tracer Technology Techniques

Three radioactive tracer techniques are typically used to measure component wear in internal combustion engines and other mechanical components:

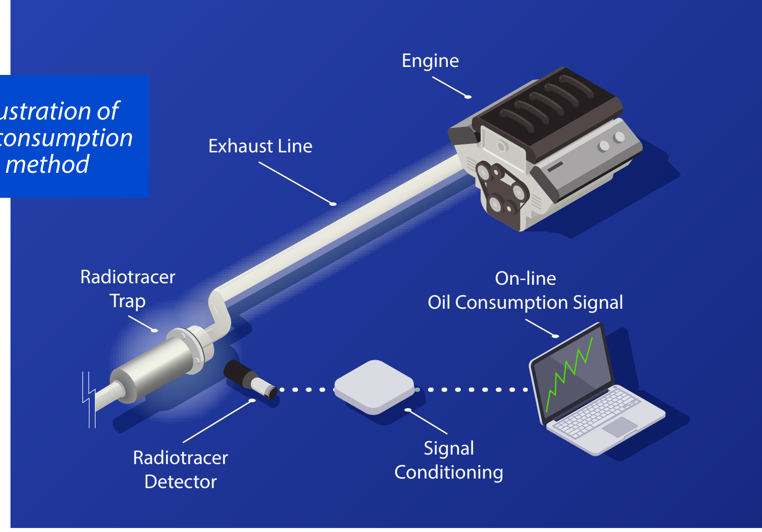
- Bulk activation (BA)
- Surface-layer activation or thin-layer activation (SLA/TLA)
- Nuclear recoil implantation (NRI)

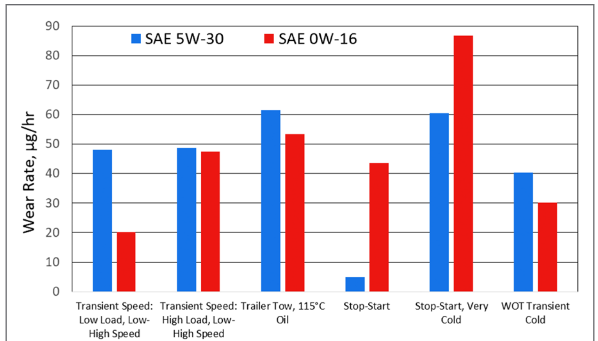
SwRI engineers select the appropriate method based on specific test objectives, component material composition and configuration, or site particulars. Bulk activation and SLA/TLA are often employed together to increase the number of wear surfaces that can be interrogated simultaneously. For non-metallic parts, or for metal parts that do not produce suitable radioactive tracers during standard irradiation, wear is measured using radioactive atoms implanted into the test piece by NRI.

Oil Consumption Measurements

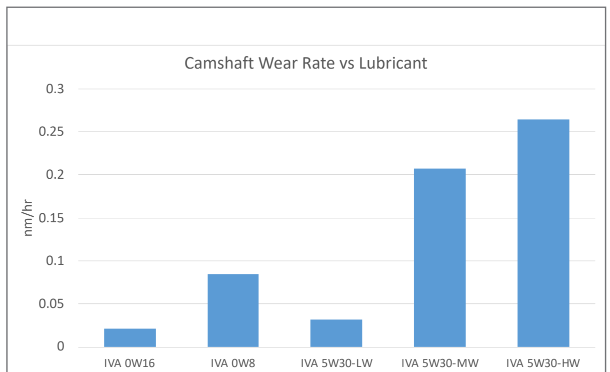
SwRI uses the DSi C-Lube for real-time oil consumption measurements. Separate monitoring of oil consumption is possible for the engine block, ventilation system, and turbocharger.

Illustration of oil consumption method

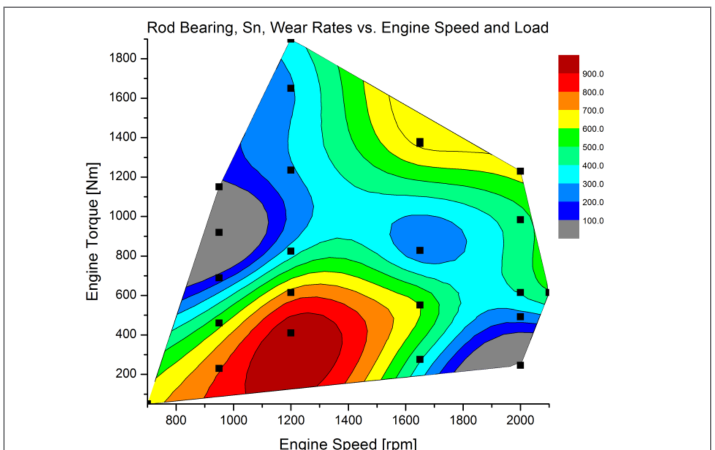




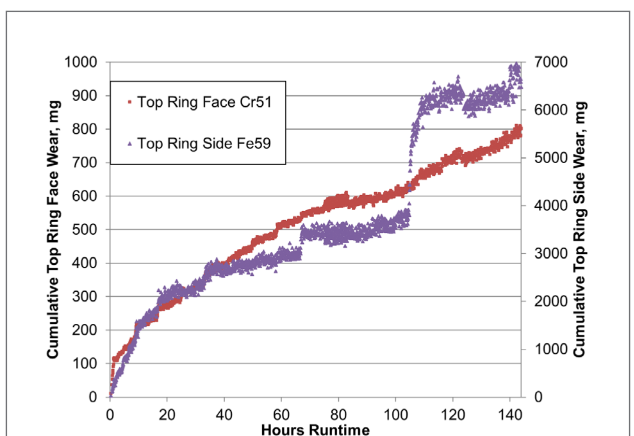
***A)** Interactions between drive cycle type and lubricant viscosity on top ring face wear*



***B)** 2.0L TGDI engine, observed camshaft wear for 5 oils on simulated sequence IVA test profile*



***D)** 12-liter natural gas engine; map of light load, medium-speed rod bearing wear driven by oil hole location and piston/rod mass*



***C)** 3.6-liter gasoline engine; observed stochastic wear event on top ring at 105 hours*

***A)** Both oils were fully formulated and had the same anti-wear package. This work was sponsored by Coordinating Research Council Project No. AVFL-28, Gasoline Direct Injection (GDI) Engine Wear Test Development (crcao.org).*

***B)** Internal research was undertaken to develop a Sequence IVA low-temperature camshaft wear test for use with a modern 2.0L TGDI engine. The 0W16, 0W8, and 5W-30 oils were blended using the same additive package to study the effect of viscosity. The three 5W30 oils were the same viscometrics but were known low wear (LW), medium wear (MW), and high wear (HW) blends.*

***C)** Wear rates before and after event were nominally equivalent. Likely buildup of ring-side debris in top ring groove and subsequent shedding were observed in real time. (Gauba, V., Bera, T., Reitz, J., Hansen, G., Lee, P.M., Wileman, C. and Nelson, E. 2017. Investigation and Analysis of Wear in a 3.6L V6 Gasoline Engine: Phase I – Use of Radioactive Tracer Technology. SAE* International Journal of Fuels and Lubricants, *10 (1), pp. 126-137.)*

***D)** Wear rates from 50 to 950 micrograms per hour on the rod bearing.*

Engine Hardware Screeners
Custom-Designed Research Tools

SwRI has developed two Engine Hardware Screeners (EHSs) to investigate wear mechanisms in engine valvetrain components. These EHSs are custom-designed to fit the engine architecture for specific testing needs and serve as platforms for detailed lubricant research.

The engine components in these benchtop rigs provide reduced costs over engine testing and enhanced understanding of wear mechanisms over standard tribology instruments.

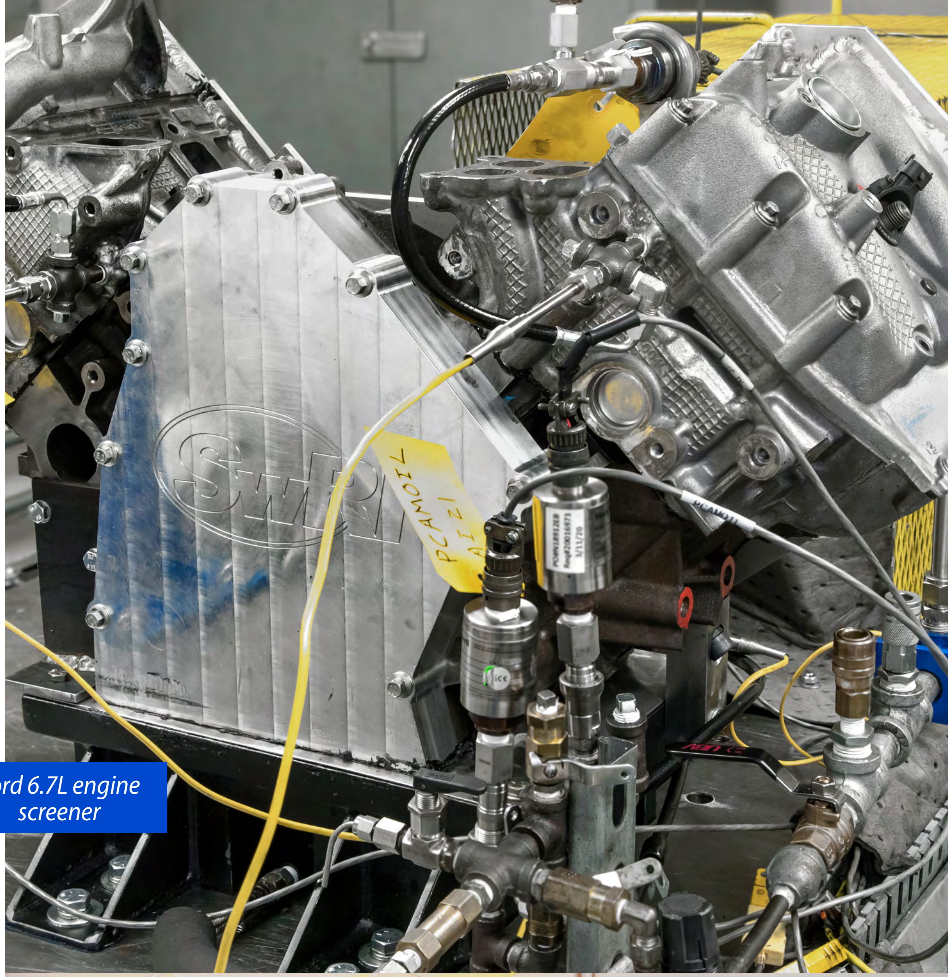
When the same lubricants are used in the EHSs as the full-scale engine tests, these benchtop rigs can be validated as low-cost screening tools for experimental and future lubricants.

The EHS based on a Cummins ISB has the unique capability to measure lifter rotation without interfering with the natural motion of the valvetrain components. Contact potential between the lifter and cam can also be measured. These results help to understand film formation and wear at the cam and tappet interface.

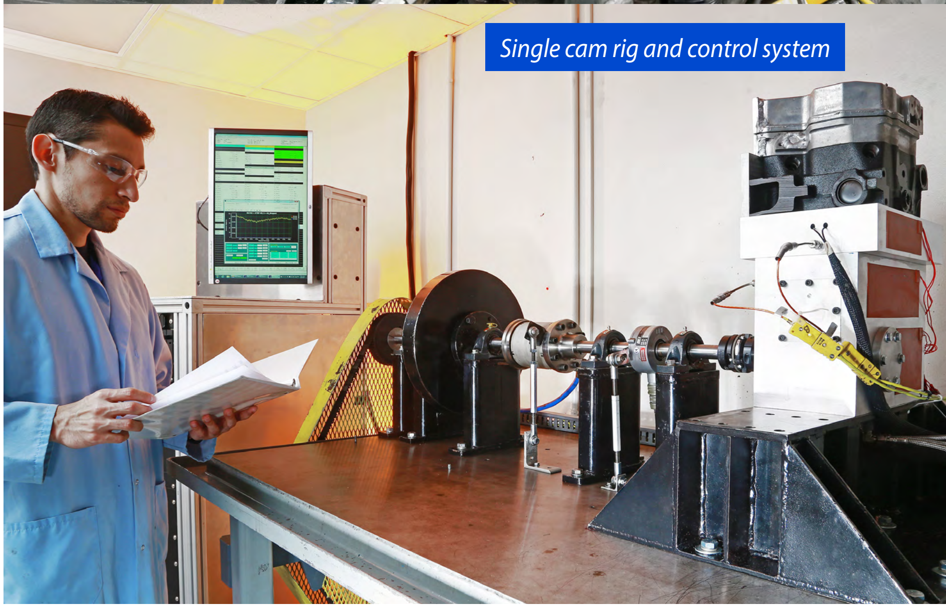
The EHS based on a Ford 6.7L is specifically designed to understand wear on the rocker arm balls in addition to the pushrods, camshaft, and hydraulic lifters.

Full computer control of the input shaft and oiling system allows for the replication of any engine test cycle (API, SAE, ASTM, NATO).

The EHSs were also designed for use with radiotracer wear investigations as described previously. Measuring online wear through radiotracers allows for direct comparison of the wear state with operating conditions.

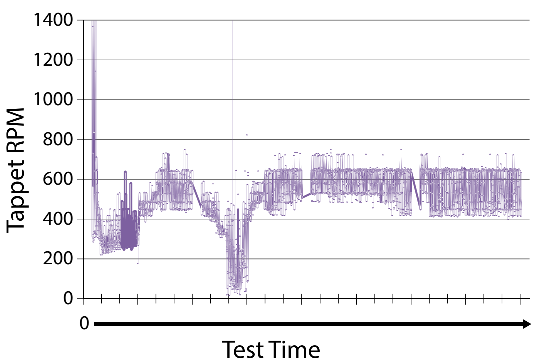


Ford 6.7L engine screener



Single cam rig and control system

Tappet rotation as a function of test time



Engine Hardware Screener Specifications	
Input shaft speed	Client-specific, up to rated engine speed
Oil temperature	Ambient to 125°C
Oil pressure	0 – 100 psi
Current valvetrains	Cam-in-block with flat tappet or hydraulic roller
Valvetrain options	OHC, DOHC
Instrumentation	Inline torque Lifter rotation* (flat tappet only) Contact potential

*US Patent 9,316,509

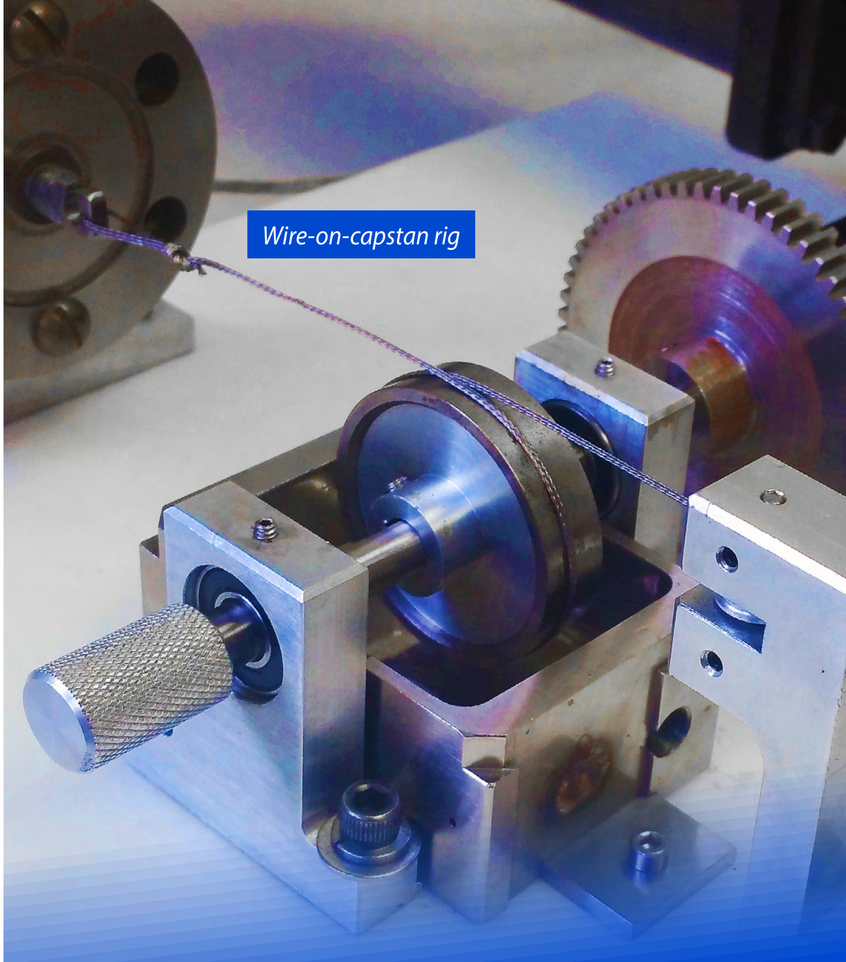
Wire-on-Capstan Rig

SwRI developed the Wire-on-Capstan Rig to investigate lubricant performance at low contact pressures and high friction forces. The test rig measures the force required to rotate a cylinder (capstan) that is restrained with one or more loops of wire. Minute changes in friction coefficient are readily observed and the design is considerably more sensitive to friction modifier additives than conventional test geometries.

For an applied tension, T1, the ratio between friction force, T2, and friction coefficient increases exponentially with the number of wire loops around the capstan. Optimizing the tension ratio and contact angle can tune the sensitivity of the measurement, allowing for discrimination of various lubricant types, additives, and coatings.

Wire-on-Capstan Specifications	
Load	1 – 50 N
Temperature	Ambient – 200˚C
Speed	1 – 200 rpm
Sliding speed*	2.5 – 500 mm/s
Lubricant charge	30 ml
Test duration	User-defined
Wire	Customizable
Capstan	Customizable

*With typical capstan size



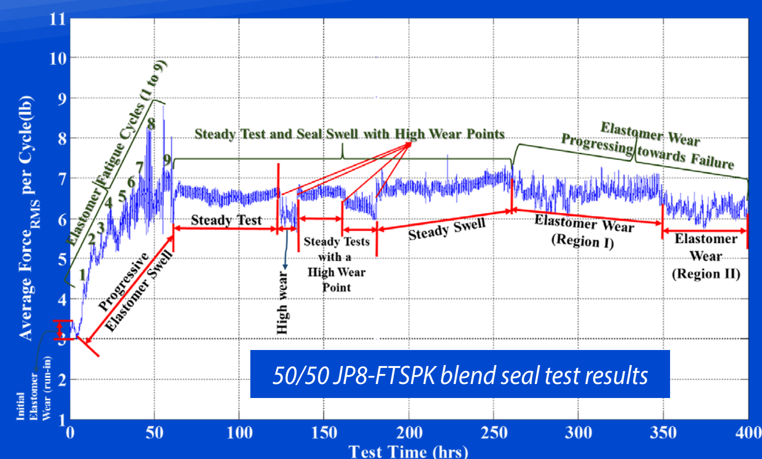
Wire-on-capstan rig

Dynamic Elastomer Seal Tester

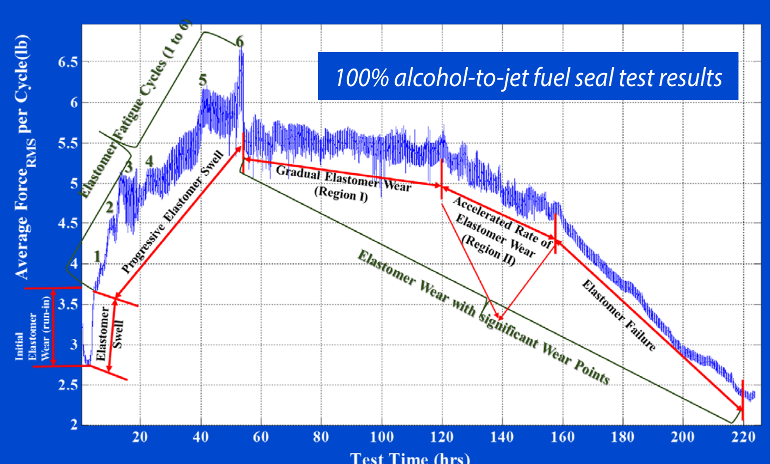
Elastomer O-rings are used extensively for sealing applications in automotive and aviation system hardware components for both static and dynamic applications.
In dynamic sealing applications, the relative motion between the moving components causes elastomer wear leading to seal failure. Static soak tests do not simulate actual engine operating conditions.

The test rig consists of a heated test block under pressure containing a reciprocating shaft housing the test elastomer O-rings, simulating real-world dynamic motion. The rig measures the resistance to reciprocating motion experienced by the O-rings in real time. As the elastomer wears down due to the combination of lubricant/fuel effects, temperature, and dynamic motion, the elastomer resistive force decreases.

Performance of elastomer fatigue, swell, wear, and failure mechanism has been mapped, showing the variation in elastomer resistive force as a function of test time.



50/50 JP8-FTSPK blend seal test results



100% alcohol-to-jet fuel seal test results

U.S. Patent 10,662,766 B2 May 26, 2020.

Bearing Test Rig

SwRI engineers have developed a new test rig to perform bearing and lubricant research under realistic loading conditions. Originally developed in support of SwRI's Clean High Efficiency Diesel Engine (CHEDE) consortium, the Bearing Test Rig (BTR) offers access to measure parameters that would be nearly impossible in an engine.

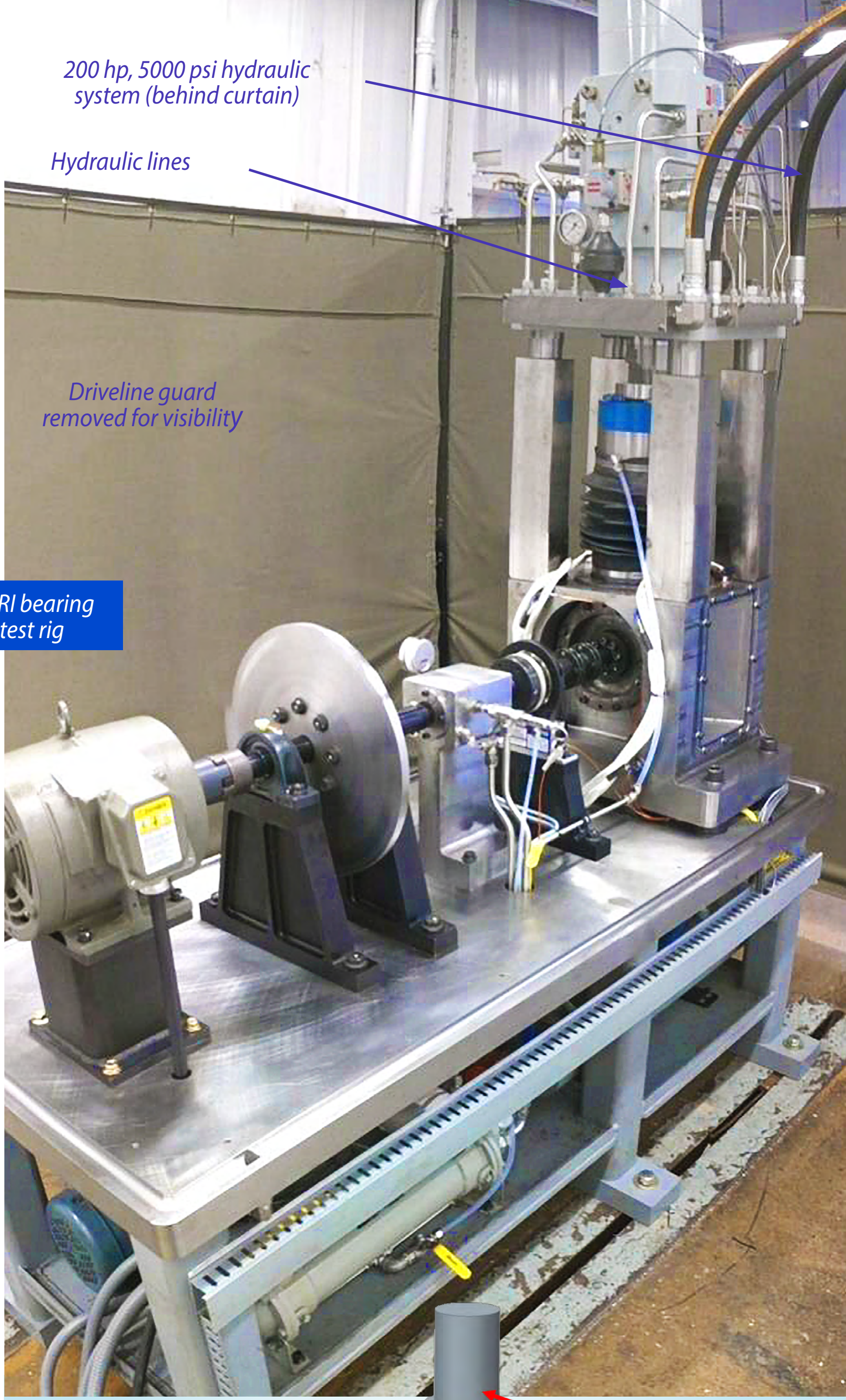
While currently configured for heavy-duty diesel operation, the BTR can be modified to represent a wide range of engine sizes and applications. It uses an electric drive motor to rotate a crankshaft while a high-speed hydraulic actuator applies compressive and tensile loads on the stationary connecting rod to simulate loads experienced by the connecting rod in a fired engine. Lubrication is provided to the bearing through the crankshaft, which has been specifically machined to match OEM specifications.

From fundamental research and early prototyping to production-intent testing, SwRI's Bearing Test Rig enables rapid and repeatable testing of engine bearings, connecting rods, and lubricants.

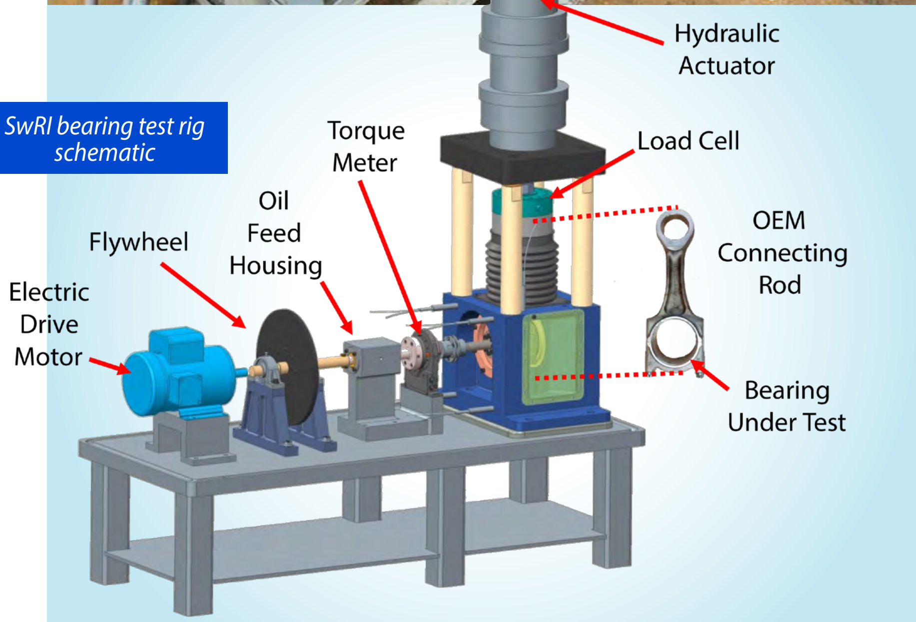
Advantages

- Cost-effective compared to full engine testing (one connecting rod and bearing pair, no fuel burned)
- Automated operation for excellent repeatability and maximized test up-time
- Dynamic load profile closely matches fired engine
  - Completely customizable to match any engine condition
  - More representative than static load or Sapphire rig
- Unique measurements that are challenging to obtain in an engine
  - Instantaneous bearing friction
  - Oil flow rate to bearing
  - Lubricant temperature within the bearing
  - Oil film thickness at multiple locations
- Independent control of many variables to provide variable levels of lubrication, from boundary to hydrodynamic
- Fast removal/installation of device under test
  - Access port to quickly change bearing set or connecting rod

The rod load profile is generated from cylinder pressure data from a firing engine. Therefore, operation can be tuned to particular conditions specific to your application (e.g., minimum speed, maximum load, maximum cylinder pressure).



SwRI bearing test rig



SwRI bearing test rig schematic

Example Research Programs

- Effect of oil additive packages on bearing oil film thickness
- Effect of oil soot content on bearing wear
- Effect of bearing coating materials and thicknesses on friction and bearing durability
- Effect of engine calibration on bearing wear during engine start/stop
- Effect of bearing and journal design on bearing oil drain time

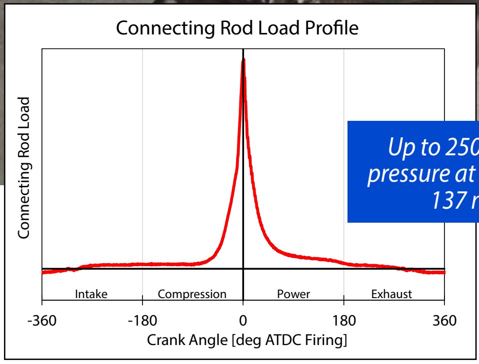
Bearing Oil Film Thickness Measurement

Measurement of oil film thickness has been demonstrated via installation of high-precision eddy current sensors. Multiple sensors are used to enable triangulation of the journal position and calculation of minimum oil film thickness. Unlike in an engine, the BTR's connecting rod is stationary, so there is no need for complex instrumentation linkages or IR transmission devices. The stationary connecting rod can also be leveraged for other measurements including lubricant temperature in the bearing, bearing shell temperature, bearing shell strain, and many more.

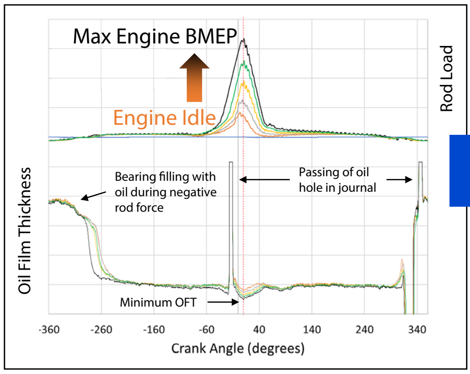
Start/Stop Test Conditions

With increasingly stringent fuel economy regulations, the number of engine start/stop applications is constantly growing in passenger cars, heavy-duty, and non-road segments. Leveraging in-house control and automation, SwRI's Bearing Test Rig provides repeatable and cost-effective testing of start/stop conditions. The rig's crankshaft and oil pump are decoupled, which allows engineers to match any application start/stop process, simulate oil starvation testing, and worst-case cylinder oil pump delay testing. SwRI has also developed a method to accelerate oil drainback to simulate an application's first start in the morning after sitting all night. This capability enables the rig to execute multiple start/stop tests per hour while providing variable levels of oil film development and breakdown.

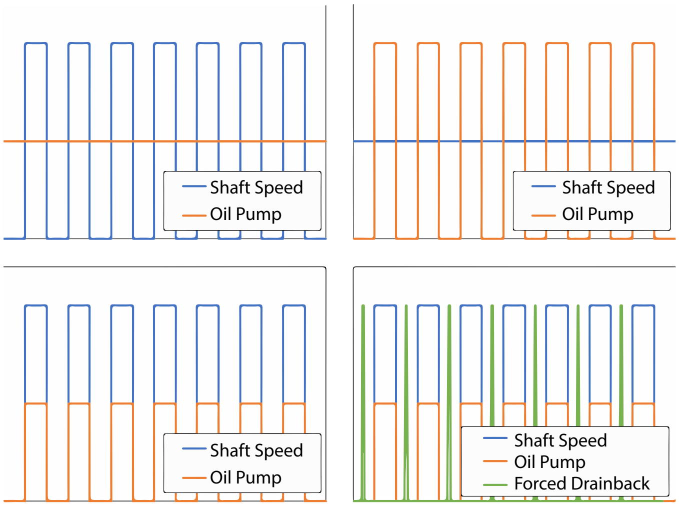
Connecting rod instrumented with high-precision eddy current sensors for live oil film thickness measurement



Up to 250 bar cylinder pressure at 1800 rpm with 137 mm bore



Load sweep at a single speed



Example test profiles

Reciprocating Tribometer

SwRI utilizes highly versatile Phoenix Tribology TE 77 and TE 90 Reciprocating Machines to investigate the frictional response and wear characteristics of materials, coatings, and lubricants. These tribometers provide in-test control of load, reciprocating frequency, and temperature; stroke length is set prior to testing. Friction, friction response, and contact potential are measured throughout the test program.

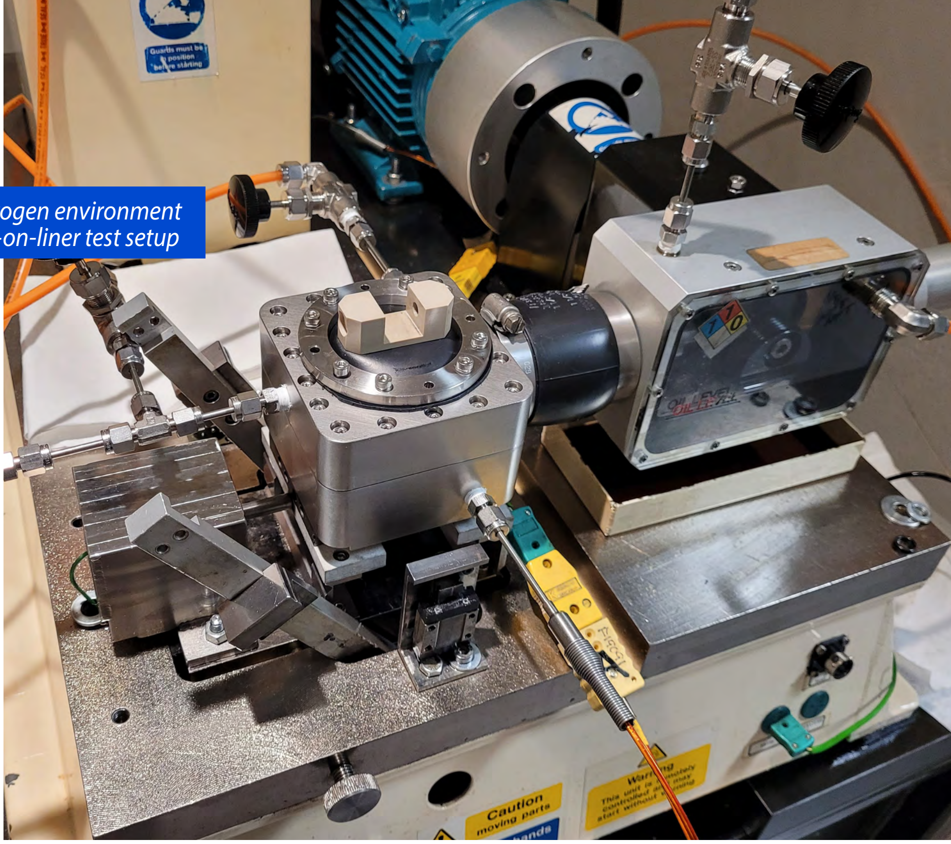
Standard test methods are available, as well as custom test designs. The test specimens can be manufactured from the materials or components under investigation, and may also be surface-finished and/or textured as desired.

Using the tribometers, it is possible to investigate a wide range of contact geometries such as point, line, ring and liner, and area contact. This versatility permits the study of lubricants (solid, grease, and fluid) and lubricant additives. Lubricants may be introduced to the contact in several ways, such as drip-fed, and may be changed during testing.

Post-test wear scar analysis, volumetric loss, and component surface film analysis offer a more in-depth understanding of wear mechanisms and component/additive interactions. The TE 90 allows four test coupons to be run simultaneously. Radionuclide online wear analysis allows for independent investigation of components at high resolution in-situ. All are available at SwRI.

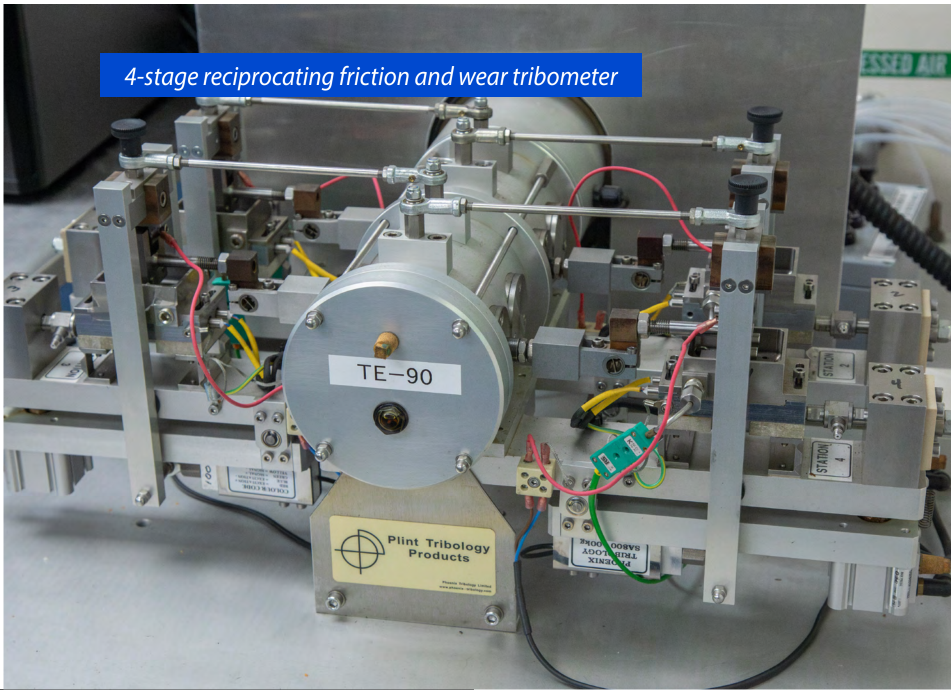
Standard Test Methods

- ASTM D5706 – Determining Extreme Pressure Properties of Lubricating Greases Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D5707 – Measuring Friction and Wear Properties of Lubricating Grease Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D6079 – Evaluating Lubricity of Diesel Fuels by the High-Frequency Reciprocating Rig
- ASTM G181 – Conducting Friction Tests of Piston Ring and Cylinder Liner Materials Under Lubricated Conditions
- ISO/DIN 12156-2 – Diesel Fuel Lubricity: Performance Requirement Test Method for Assessing Fuel Lubricity

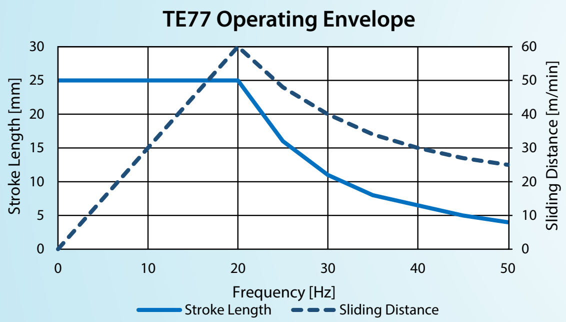


Hydrogen environment ring-on-liner test setup

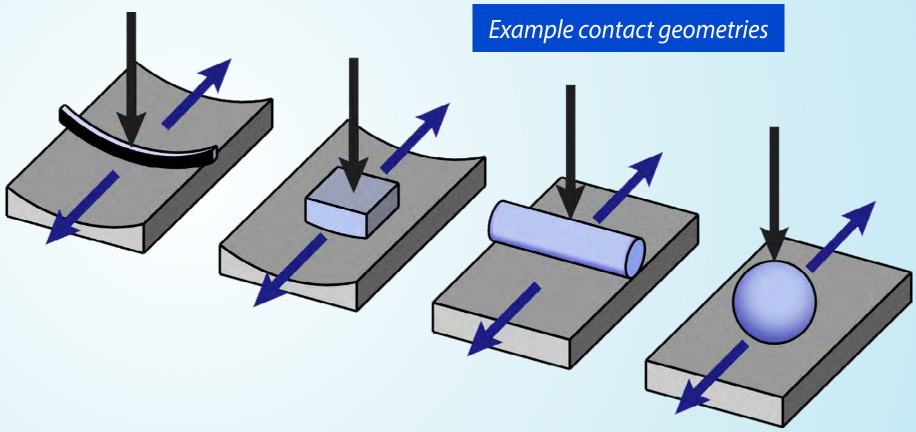
Tribometer Specifications		
Parameter	TE 77	TE 90
Load	20 – 1000 N	25 - 500 N
Temperature	Sub-ambient – 800°C	Ambient - 250°C
Stroke length	1 – 25 mm	10 mm
Frequency	1 – 50 Hz	1 - 25 Hz
Friction force	–500 – 500 N	-250 - 250 N
Test duration	User-defined	User-defined
Contact geometry	User-defined	User-defined

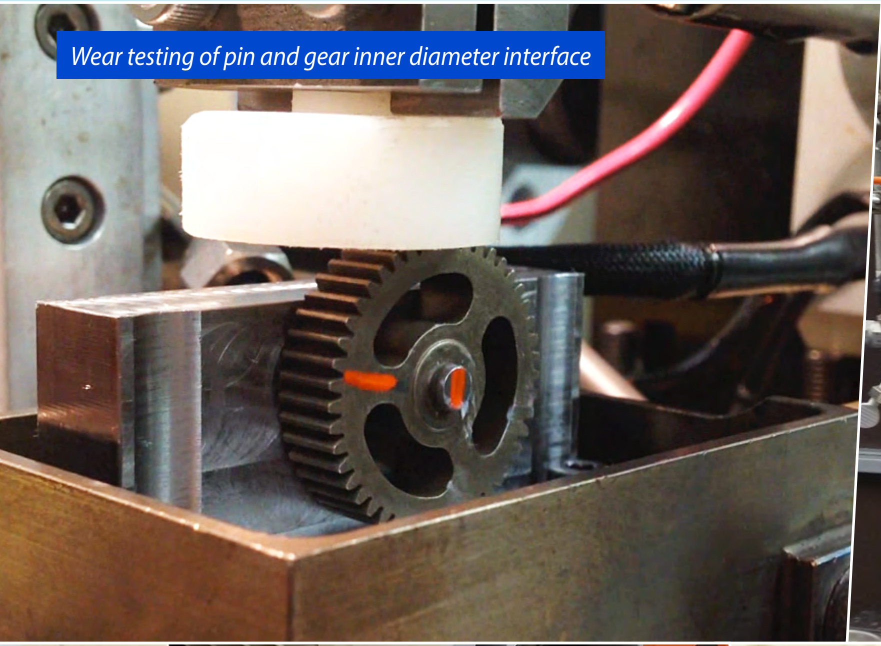


4-stage reciprocating friction and wear tribometer

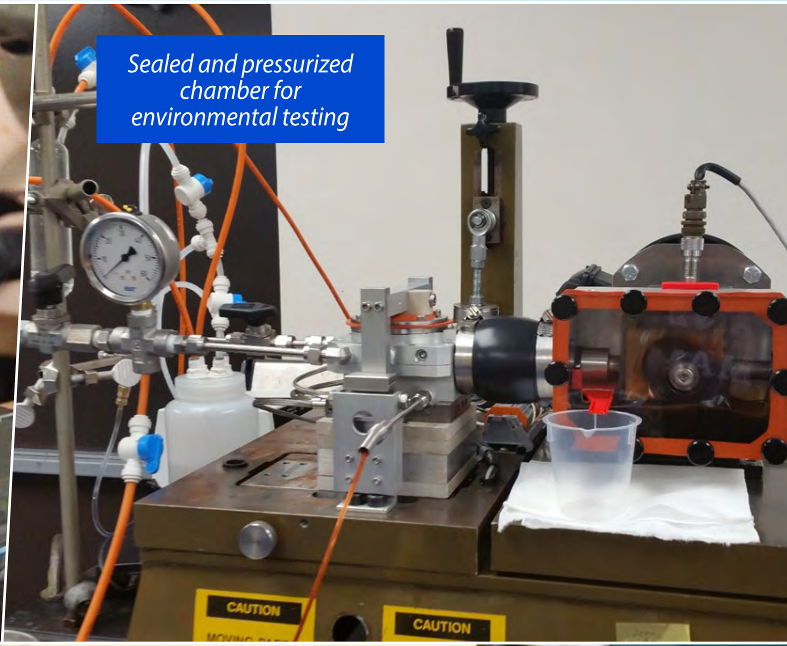


Example contact geometries

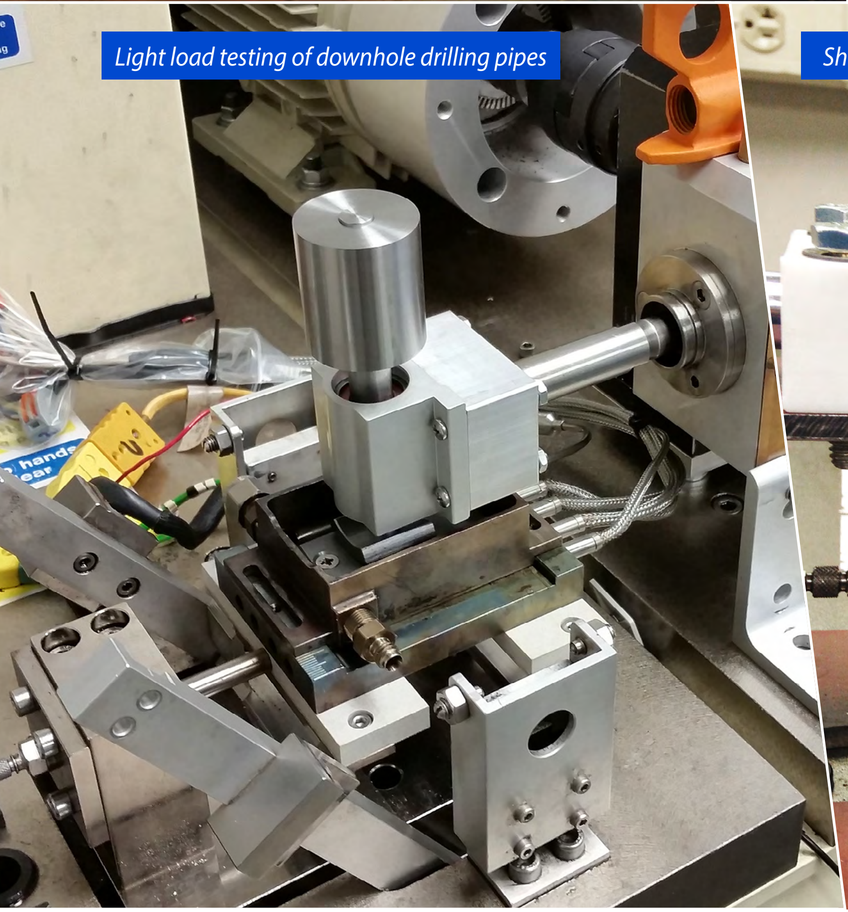




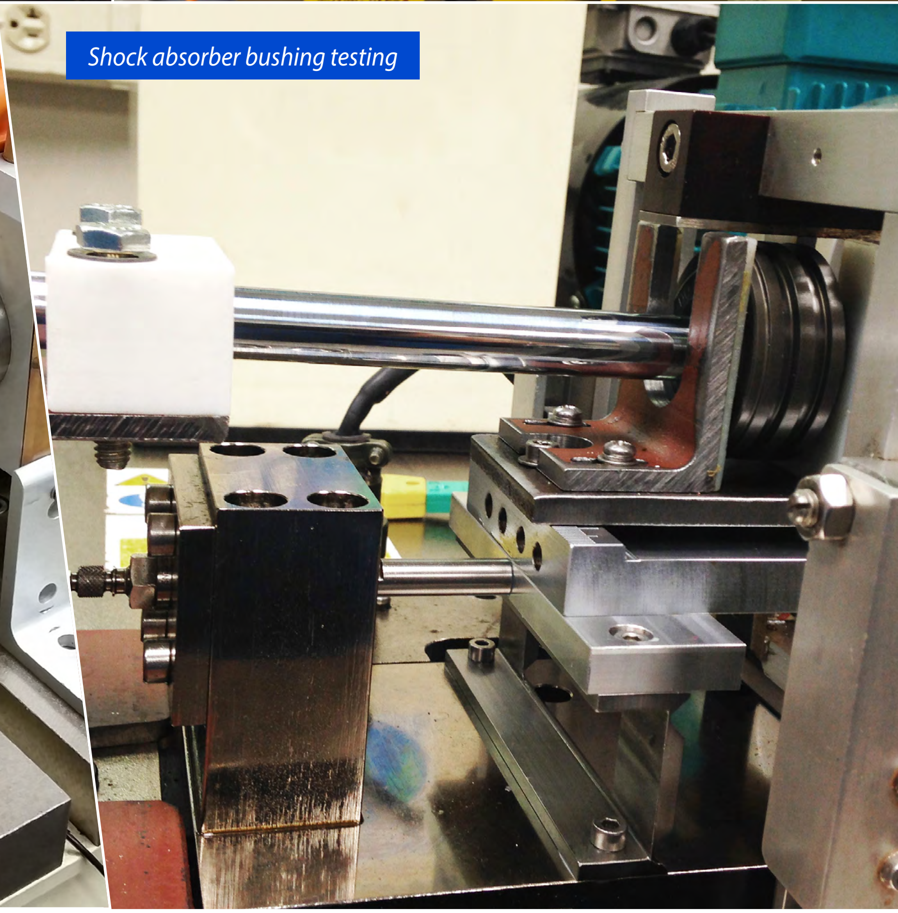
Wear testing of pin and gear inner diameter interface



Sealed and pressurized chamber for environmental testing



Light load testing of downhole drilling pipes



Shock absorber bushing testing

High-Frequency Reciprocating Tribometers

HFRR

Standard test samples are commonly used in fuel testing. However, the samples can be manufactured from materials of the components under investigation and these components can also be coated, hardened, surface-finished, and/or textured as desired.

Post-test wear scar, volumetric loss, and component surface film analyses offer more in-depth understanding of wear mechanisms and component/additive interactions. All are available at SwRI.

The PCS Instruments HFRR (High-Frequency Reciprocating Rig) uses ball-on-disk contact geometry and is the rig used for ASTM standard testing of fuel lubricity. The SwRI Tribology Research and Evaluation group routinely runs this test in controlled temperature and humidity conditions, as this improves measurement repeatability.

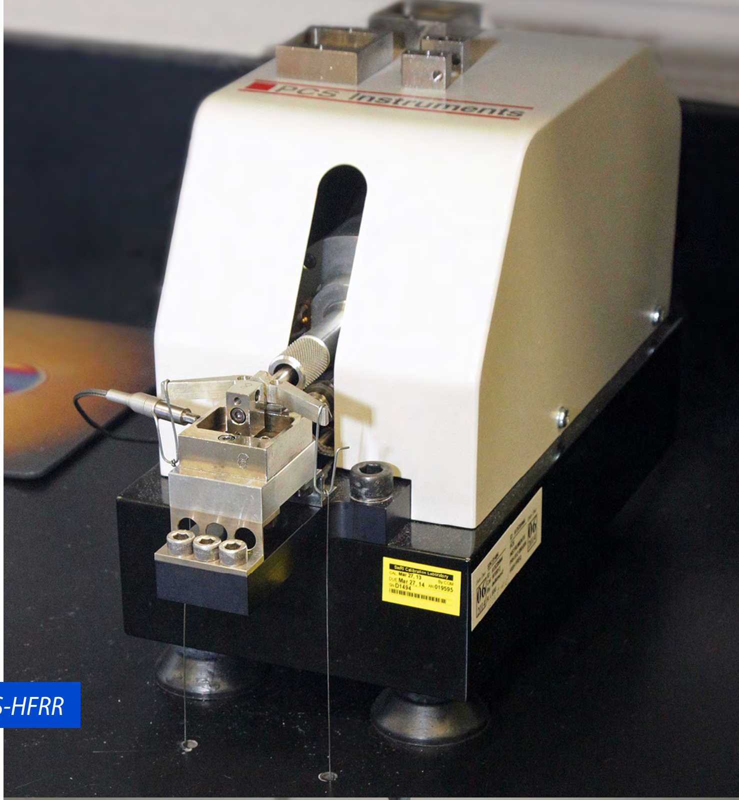
HP-HFRR

SwRI developed the High-Pressure HFRR (HP-HFRR) to investigate wear mechanisms in modern and alternative fuel systems under pressure and elevated temperature. The HFRR is custom-designed to accommodate most fuels for specific testing needs, and serves as a platform for detailed lubricity research.

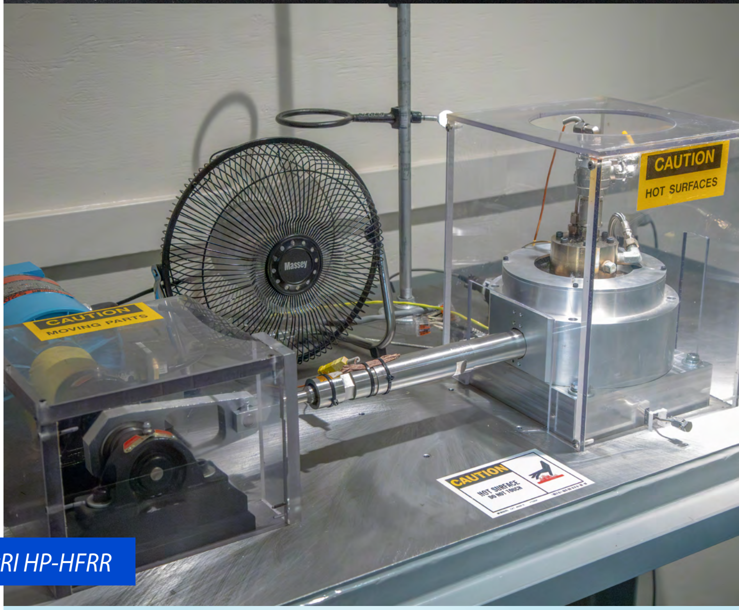
The HP-HFRR is capable of testing a variety of fuels including diesel, JP-8, gasoline, ethanol, propane, hydrogen, methane, and dimethyl ether. Investigations routinely involve fuel additives, which can be beneficial to improving lubricity and reducing wear. Tests can also be undertaken in gas mixtures.

Tribometer Specifications

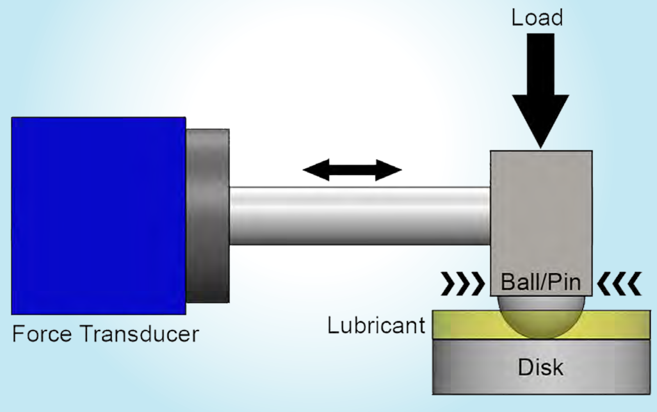
Test Condition	HFRR	HP-HFRR	HFRR-LC
Load (g)	0 – 1000	50 – 400	250 – 2000
Frequency (Hz)	10 – 200 `	0 – 60	0 – 50
Stroke length (mm)	0.02 – 2	0 – 5	0 – 5
Temperature (°C)	Ambient – 150	Ambient – 500	Ambient – 150
Environment	Controlled humidity	Controlled humidity or selected gas	Controlled humidity
Pressure (psig)	Ambient	Ambient – 1000	Ambient
Fluid charge (ml)	2	40	Flow-through system 2 – 5 ml/min
Standard upper sample	6 mm SAE 6440 steel ball, HRC 58–66	10 mm SAE 6440 steel disk, HV30, Ra<0.02 µm	15 mm SAE 6440 steel disk, HV30, Ra<0.02 µm
Standard lower sample	10 mm SAE 6440 steel disk, HV30, Ra<0.02 µm	6 mm SAE 6440 steel ball, HRC 58–66	6 mm x 10 mm SAE 6440 steel pin, HRC 62–65



PCS-HFRR



SwRI HP-HFRR

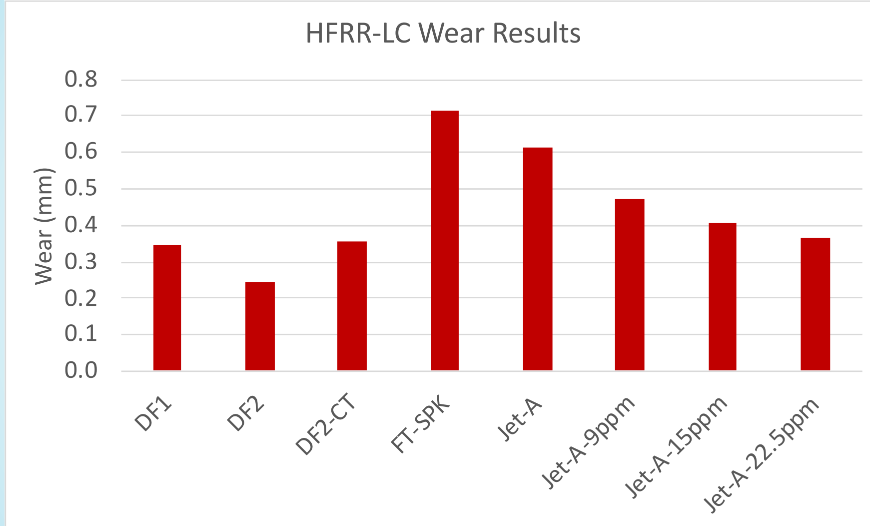


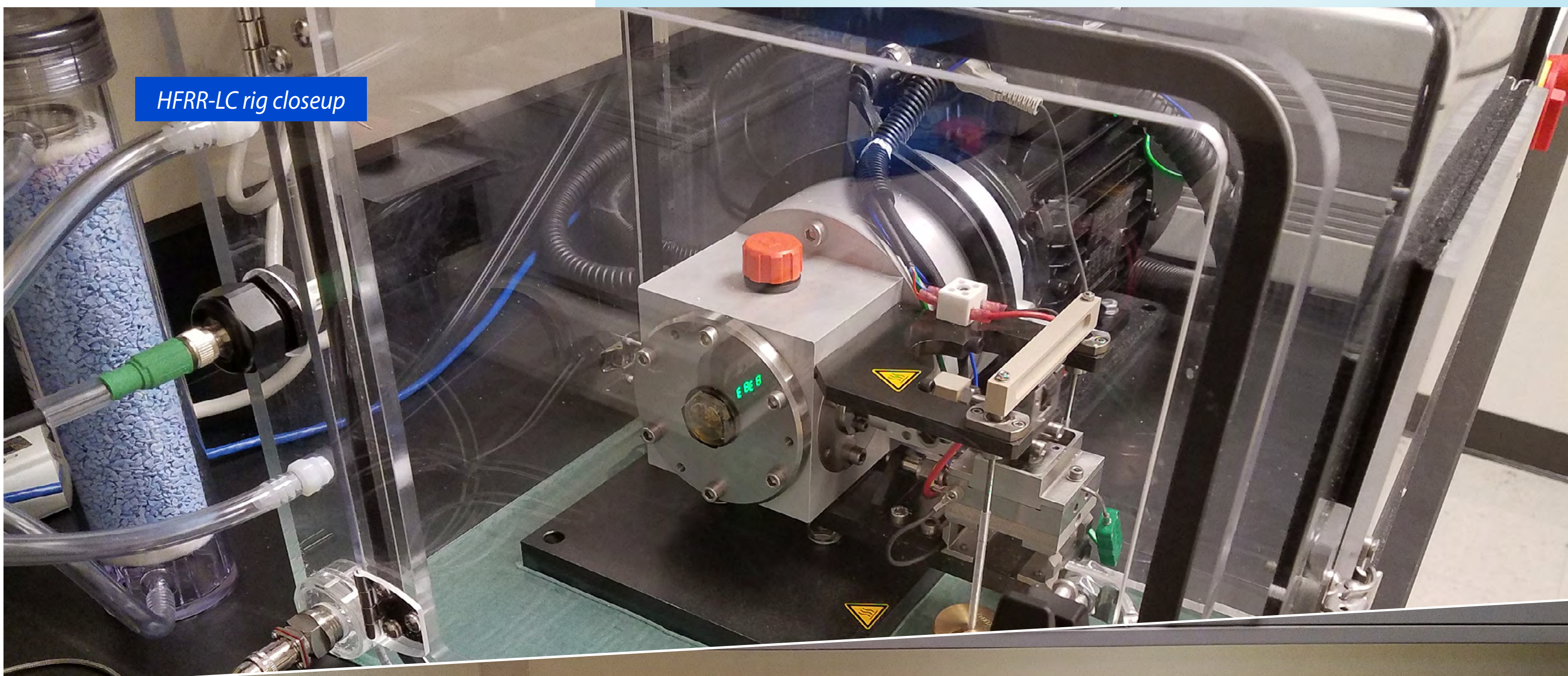
Schematic of standard contact geometry

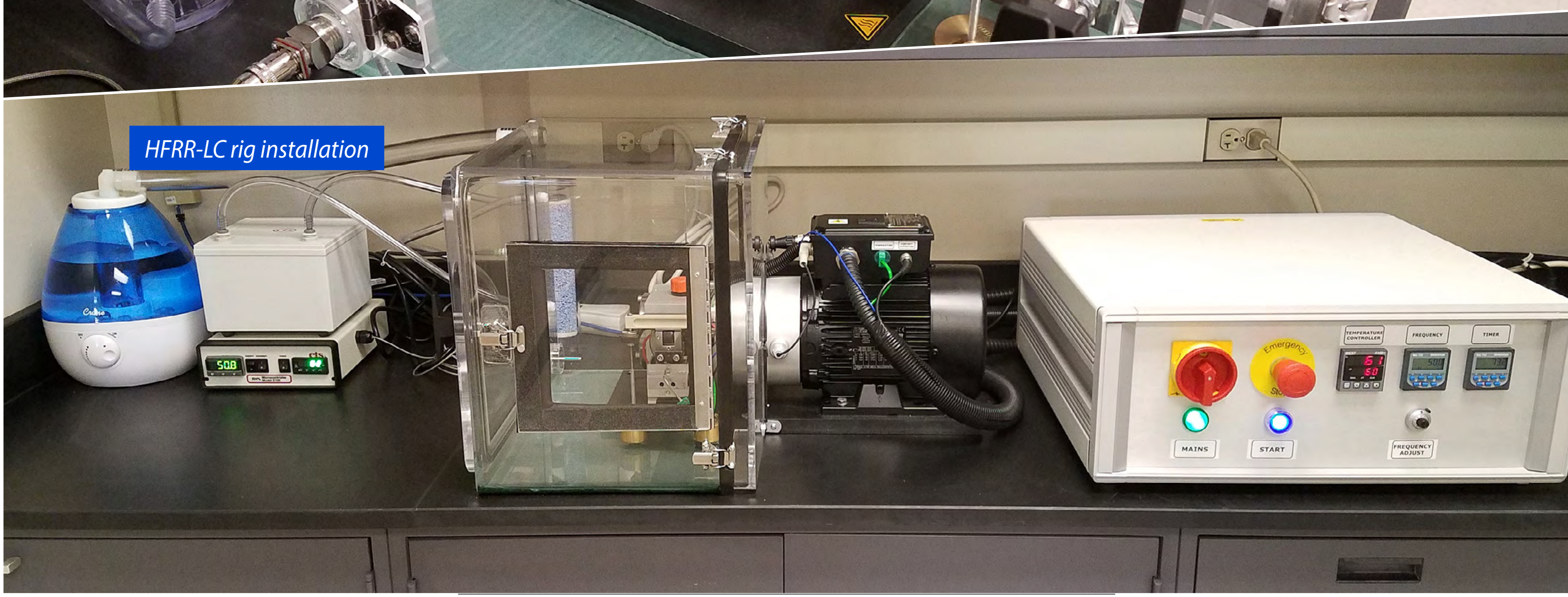
HFRR-LC

The HFRR-LC (Line Contact) is a custom rig SwRI co-developed with Phoenix Tribology. By designing a system that uses the barrel of a pin, the line contact geometry is more representative of critical contact surfaces in diesel fuel pumps.

Very low contact pressures can be achieved which are able to differentiate the performance of lubricity additives at nominal treat rates. By sweeping through a range of contact pressures, a particular additive can be examined for wear protection at a minimum acceptable film thickness (as measured by a resistance bridge). The line contact concept also allows the specimens to operate in wear regimes that are significantly less severe than in point contact.




HFRR-LC rig closeup



HFRR-LC rig installation

Tilting Reciprocating Tribometer

The Optimol SRV5 is used for reciprocating testing at angles between 0° and 90°. This high-precision tribometer measures and controls friction, temperature, speed, stroke, load, and lubricant drip feed rate. Standard Optimol test samples of balls and disks can be used.

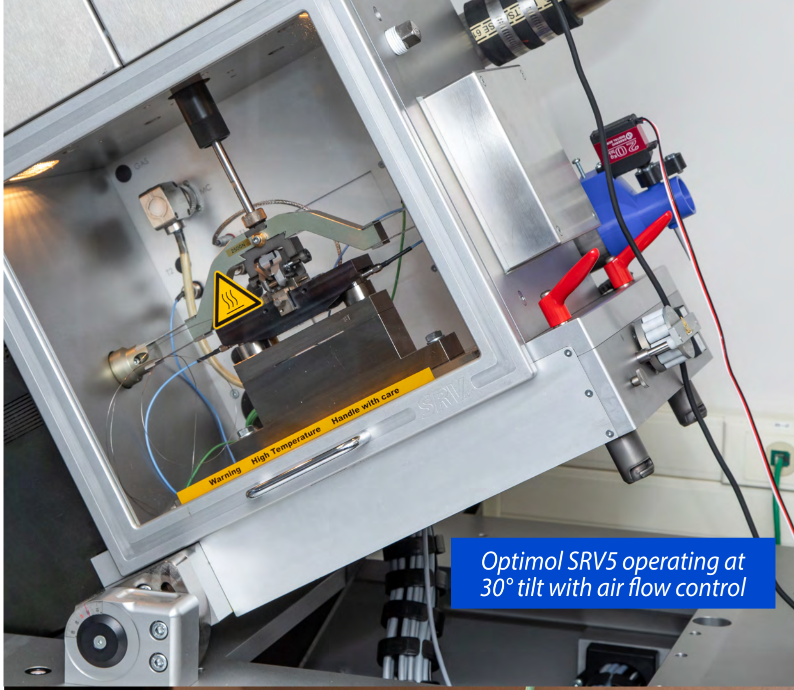
SwRI also machines test parts from real engine components that can be tested to the specifications shown in the table. Samples may be tested dry or lubricated with a bath or drip-fed. Standard test methods are available, as well as custom test designs. Wear scar analysis, volumetric loss, and film composition can also be undertaken at the end of the test.

SwRI has added air flow control as well as specimen temperature control to increase test repeatability.

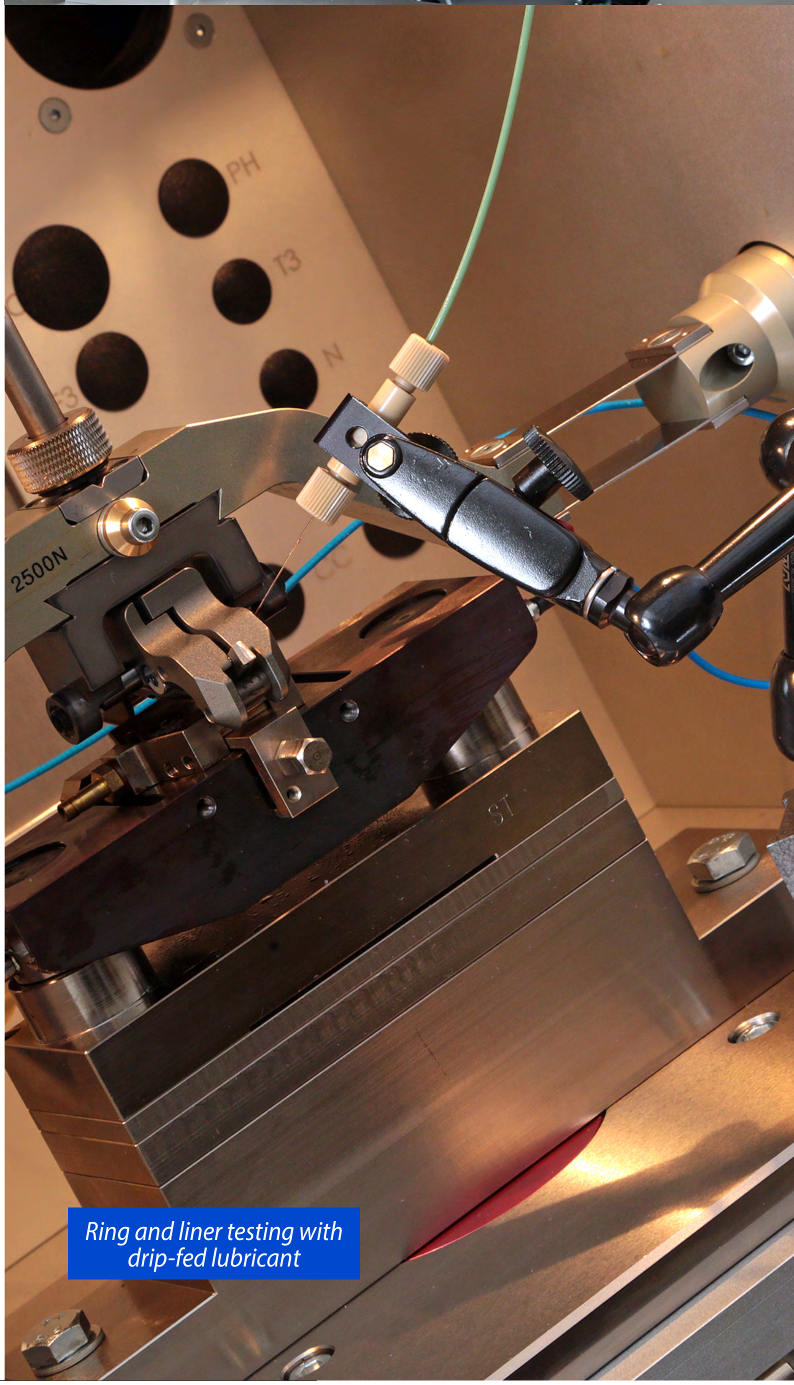
SRV Specifications	
Temperature	-45 – 1000°C
Frequency	0 – 500 Hz
Load	0 – 2500 N
Stroke length	0 – 5 mm
Inclination	0 – 90°

Standard Test Methods

- ASTM D5706 – Determining Extreme Pressure Properties of Lubricating Greases Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D5707 – Measuring Friction and Wear Properties of Lubricating Grease Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D6425 – Measuring Friction and Wear Properties of Extreme Pressure Lubricating Oils Using SRV Test Machine
- ASTM D7217 – Determining Extreme Pressure Properties of Solid Bonded Films Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D7420 – Determining Tribomechanical Properties of Grease Lubricated Plastic Socket Suspension Joints Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D7421 – Determining Extreme Pressure Properties of Lubricating Oils Using High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D7594 – Determining Fretting Wear Resistance of Lubricating Greases Under High Hertzian Contact Pressures Using a High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D7755 – Standard Practice for Determining the Wear Volume on Standard Test Pieces Used by High-Frequency, Linear-Oscillation (SRV) Test Machine
- ASTM D8227 – Standard Test Method for Determining the Coefficient of Friction of Synchronizer Lubricated by Mechanical Transmission Fluids (MTF)
- ASTM D8316-20a – Standard Test Method for Measuring Friction and Wear Properties of Extreme Pressure (EP) Lubricating Oils with Roller-Disk Geometry Using SRV Test Machine



Optimol SRV5 operating at 30° tilt with air flow control



Ring and liner testing with drip-fed lubricant

Block-on-Ring Tribometer

SwRI investigates the frictional response and wear properties of materials, coatings, and lubricants with the Falex Block-on-Ring tribometer. The computer-controlled test is capable of simulating a variety of field conditions and provides in-test control of load, rotation speed and direction, and test temperature. Friction and wear are measured throughout the test. The tribometer has been fitted with an oil circulation system for more precise control of the test lubricant temperature, and has been upgraded to enable high-speed data acquisition.

The block and ring can be manufactured from the materials to be investigated and may also be surface-finished and/or textured as desired. Using the rig, it is possible to investigate a range of lubricants (solid, grease, and fluid), lubricant additives, and coatings.

Standard test methods are available, as well as custom test design. SwRI also offers radionuclide online wear analysis, which allows independent investigation of block-and-ring wear to high resolution during the test.

Post-test wear scar analysis, volumetric loss, and component surface film analysis offer more in-depth understanding of wear mechanisms and component/additive interactions. All are available at SwRI.

Block-on-Ring Tribometer Specifications	
Load	10 – 1300 lb
Speed	3 – 7200 rpm
Temperature	Ambient – 250°C
Environment	Ambient air or selected gas
Pressure	Light vacuum – 150 psig
Friction force	0 – 250 lb
Test duration	Operator choice
Motion	Unidirectional or oscillating (5° – 720°)
Lubricant charge	100 ml (170 ml with oil circulation)
Standard block samples	H30 (27 – 33 Rc) 4 – 8 rms SAE 01 tool steel H60 (58 – 63 Rc) 4 – 8 rms SAE 01 tool steel Conformal block geometry also available
Standard ring samples	S10 (58 – 63 Rc) 6 – 12 rms AISI 4620 steel S25 (58 – 63 Rc) 22 – 28 rms AISI 4620 steel

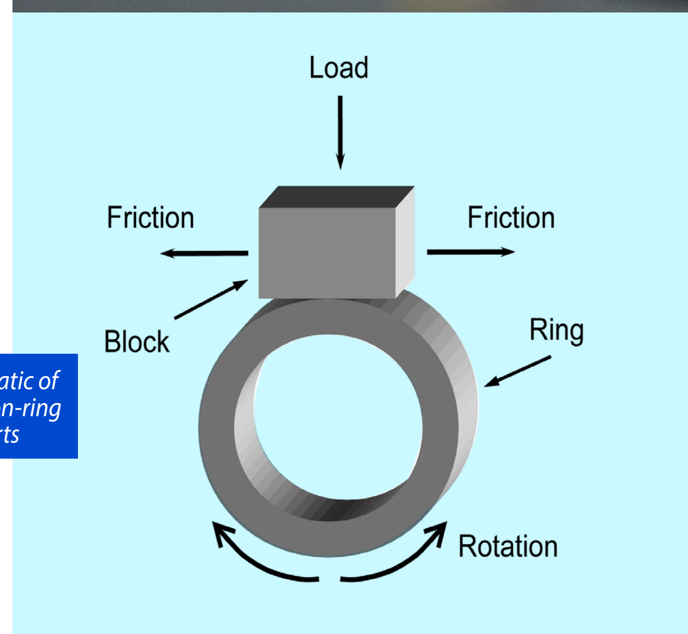
SwRI Test Method

- Valvetrain Wear Screener

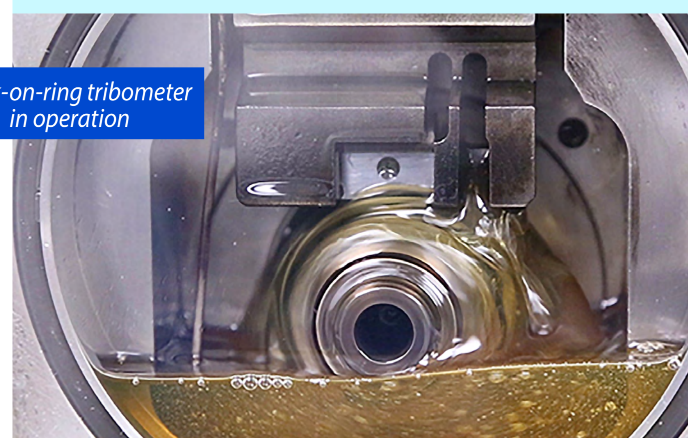
Standard Test Methods

- ASTM D2509 – Measurement of Load-Carrying Capacity of Lubricating Grease (Timken Method)
- ASTM D2714 – Calibration and Operation of the Falex Block-on-Ring Friction and Wear Testing Machine
- ASTM D2782 – Measurement of Extreme-Pressure Properties of Lubricating Fluids
- Wear Life of Solid Film Lubricants in Oscillating Motion – Verifying Nonporous Flexible Barrier Material Resistance to the Passage of Air
- ASTM D3704 – Wear Preventive Properties of Lubricating Greases Using the (Falex) Block-on-Ring Test Machine in Oscillating Motion
- ASTM G77 – Ranking Resistance of Materials to Sliding Wear Using Block-on-Ring Wear Test
- JASO M358 – Metal on Metal Friction Characteristics of Belt Cut Fluids

The Block-on-ring tribometer has been upgraded to enable high speed data acquisition



Schematic of block-on-ring parts



Block-on-ring tribometer in operation

Mini Traction Tribometer

SwRI utilizes the PCS Instruments MTM2 Mini Traction Machine to investigate the friction and wear performance of materials, coatings, and lubricants. This computer-controlled instrument provides in-test control of speed, load, and temperature. The disk and ball/barrel can be rotated at different speeds, giving slide roll ratios (SSR) from pure sliding to pure rolling.

Electrical contact potential may also be measured during a test to obtain an indication of the presence of lubricant and chemical films. Real-time wear measurement is also possible.

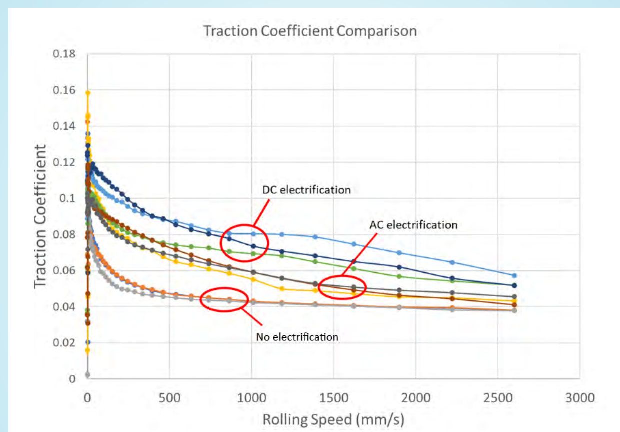
The versatile MTM2 at SwRI can be used for pin-on-disk and reciprocating tests. It can also be adapted to investigate soft materials, such as rubber O-rings running on metal disks.

Standard test components are commonly used. However, the balls/barrels and disks can be manufactured from any given material. These components may then be coated, hardened, surface-finished, and/or textured as desired.

An environmental chamber is available for controlling ambient temperature and humidity. Humidifier and dehumidifier are available (10 – 80% RH).

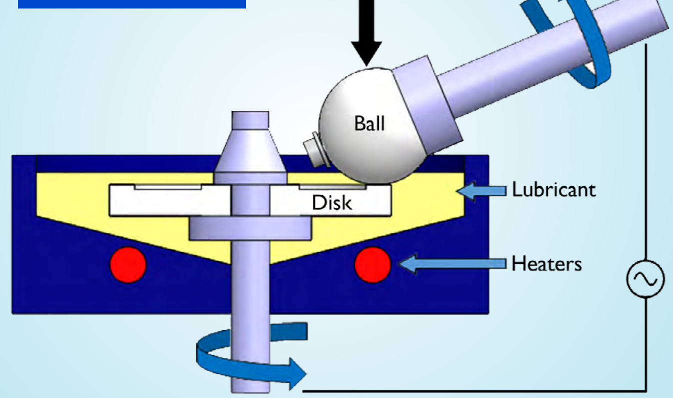
MTM2 Specifications	
Stroke length (reciprocating)	4 – 16 mm
Temperature	Sub-ambient – 150°C
Slide roll ratio	0 – 200%
Contact pressure	0 – 3.16 GPa
Load	3 – 75 N
Sample size	10 – 35 ml
Speed	0.01 – 4 ms^{-1}
Specimen material	Can be manufactured in any material to any surface finish
Standard specimens	Ball: ½ – ¾ inch Barrel: 32 mm OD Disk: 46 or 32 mm Elastomeric O-ring
Humidity	10 – 80% RH

MTM2 inside environmental chamber



MTM-generated Stribeck curves for automotive gear oil with electrification

Schematic of MTM2



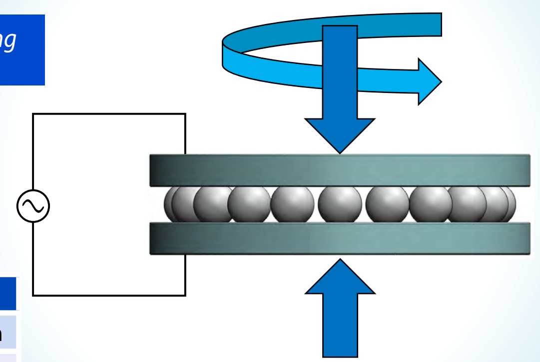
Examples of various disk materials

High Load Rotating Tribometers

SwRI uses the Hansa Press VKA 110 and the Phoenix Tribology TE 92M test machines to understand the friction and wear characteristics of lubricants, greases, materials, and coatings. The Tribology Research and Evaluation labs commonly use the VKA 110 test machine to administer the VW PV 1454 driveline lubricant test method. This method determines the steady-state temperature of transmission fluids using a deep groove axial ball bearing specimen assembly. The rigs have also been adapted to test downhole thrust washers, clutches, and brakes. The VKA 110 machine uses Prism®, a versatile data acquisition system developed at SwRI, to increase the versatility and flexibility of the rig control and signals measured and the acquisition rate.

Manufacturer's VKA 110 Specifications		SwRI Enhancements
Speed	10 – 5800 rpm	10 – 6,000 rpm
Load	100 – 12,000 N	Up to 45,000 N
Temperature	-30 – 150°C	-30 – 300°C
Movement types	Sliding and rolling	Sliding and rolling
Lubrication states	Mixed EHD	Boundary to EHD
Contact geometry	Point or flat-flat	Point or flat-flat
Recorded channels	Friction torque Lubricant temperature Ambient temperature Load, speed, and vibration	Friction torque Lubricant temperature Ambient temperature Load, speed, and vibration

High load clutch and brake tribometer



Thrust bearing test diagram

Standard Test Methods

- ASTM D2266 – Wear Preventive Characteristics of Lubricating Grease (Four-Ball Method)
- ASTM D2783 – Measurement of Extreme-Pressure Properties of Lubricating Fluids (Four-Ball Method)
- ASTM D4172 – Wear Preventive Characteristics of Lubricating Fluid (Four-Ball Method)
- Ball-on-Three-Plate (BOTP) Test
- DIN 51350 Part 2 – Determination of Welding Load of Fluid Lubricants
- DIN 51350 Part 3 – Determination of Wearing Characteristics of Fluid Lubricants
- DIN 51350 Part 4 – Determination of Welding Load of Consistent Lubricants
- DIN 51350 Part 5 – Determination of Wearing Characteristics of Consistent Lubricants
- DIN 51350 Part 6 – Determination of Shear Stability of Lubricants Containing Polymers
- VW PV 1444 – Pitting Testing
- VW PV 1454 – Determination of Steady-State Temperature of an Axial Ball Bearing

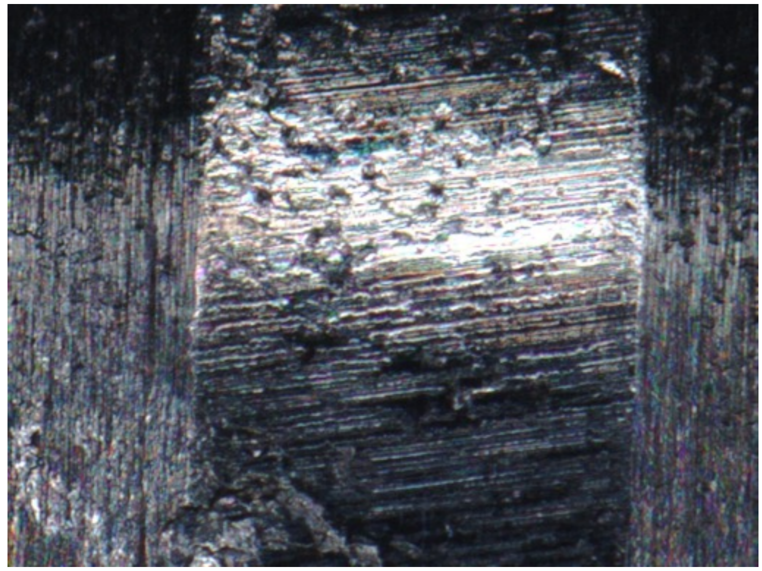
TE 92M Specifications	
Load	10 – 6,000 rpm
Speed	1 – 2,000 rpm
Temperature	40 - 200°C
Specimen diameter	25 - 286 mm
Lubricant charge	100 ml
Test duration	User-defined

VW PV 1454 driveline lubricant under test

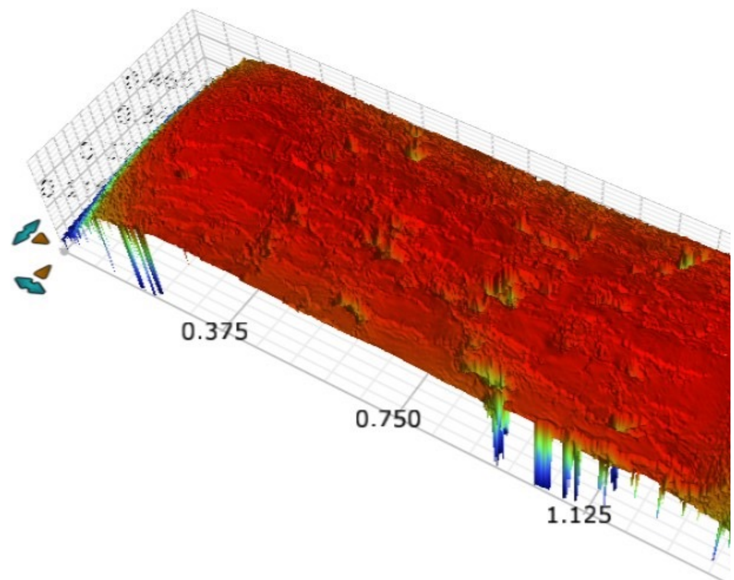
Prism® DATA ACQUISITION AND CONTROL SYSTEM

A Technology of SwRI

Macro and Micropitting Tribometer

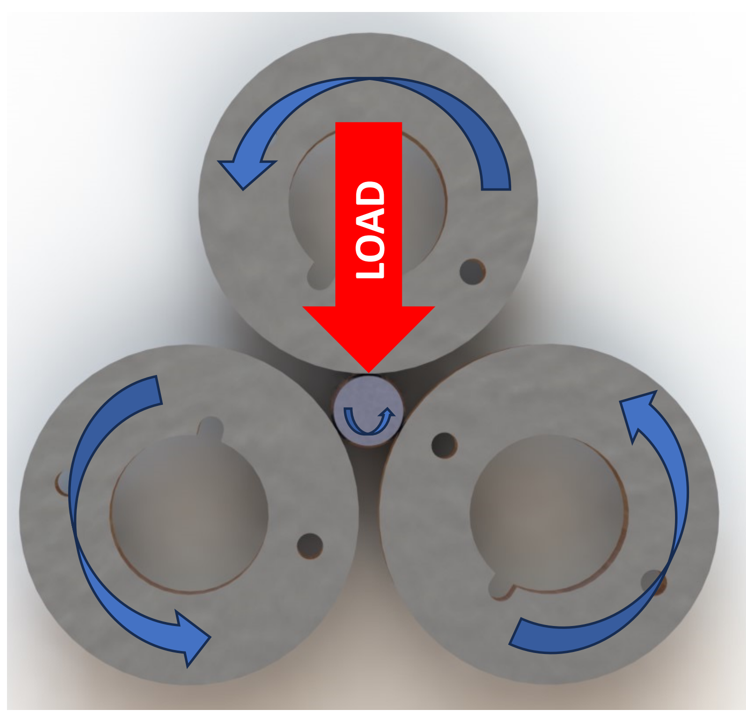


SwRI investigates rolling contact fatigue using the PCS MPR, which utilizes a set of three equally spaced rings forced onto an independently controlled roller placed between all three discs. The MPR simulates rolling contact fatigue by loading all three rings equally against the roller at a desired load, speed, temperature, and slide-to-roll ratio in a lubricated or unlubricated environment. Wear and mass measurements can be taken throughout the test run by periodically removing and analyzing the roller. Friction is constantly recorded.



Readily available roller geometries are chamfered, cylindrical, and ball, while the ring can be chosen as cylindrical or crowned for different contact geometries. Different geometries and material choices for rings and roller can be made available at SwRI, including surface coatings. SwRI offers the option to study rolling contact fatigue in electrified environments by creating a voltage potential across the roller and rings.

MPR Specifications	
Load	100 – 1250 N
Speed	0.1 – 4 m/s
Temperature	0 – 135°C
Contact pressure	0.86 – 4.7 GPa
Lubricant charge	150 ml
Voltage type	AC and DC
Current	0 – 5 A
AC waveform	Sine, square, triangle
Test duration	User-defined



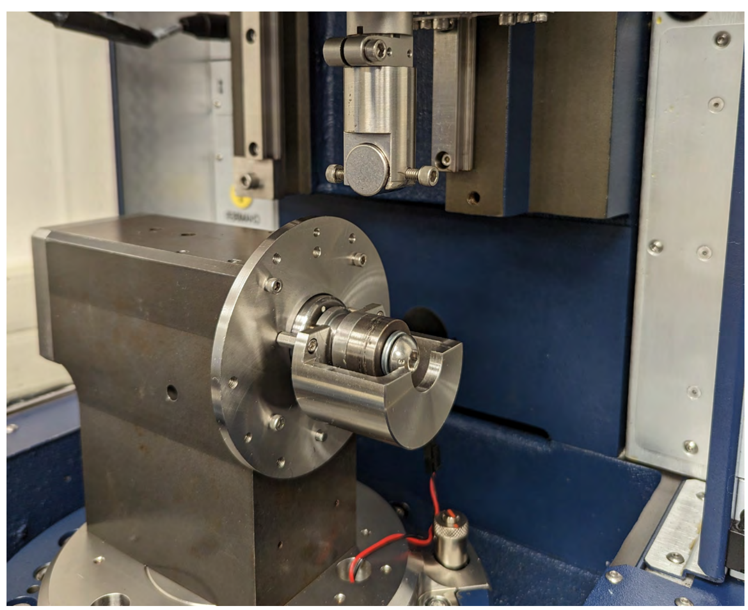
Macro and micropitting tribometer

Brugger Testing

The Brugger test is often used for evaluating hydraulic and gear oils under the boundary lubrication regime. It is useful for determining the characteristic values of lubricating oils by assigning a Brugger number (N/mm2), which describes the lubricant performance in a mixed friction regime between steel tribological contacts.

During testing, a load from a steel cylinder is applied to an already lubricated steel ring. After the desired load has been applied, the ring rotates, causing sliding stress and forming an elliptical wear scar on the cylinder. The geometry of the elliptical scar is measured and converted to the Brugger number for comparison of lubricant properties.

Brugger Specifications	
Load	400 ± 10 N
Temperature	Ambient
Speed	960 rpm
Lubricant charge	50 ml
Test duration	10 min



Universal Mechanical Testers

SwRI utilizes the Bruker UMT-3 and TriboLab tribometers for comprehensive macro-mechanical testing of ceramics, metals, plastics, elastomers, and lubricants. These are fully computerized platforms that can be configured in the following combinations:

- Linear high-speed reciprocating on the lower stage
- Linear slow-speed and high-precision reciprocating on the upper and lower stages
- Rotary vertical axis on the upper and lower stages
- Rotary horizontal axis on the lower stage
- Hot hardness testing up to 1000°C
- Scratch testing
- Clutch fluids and materials testing

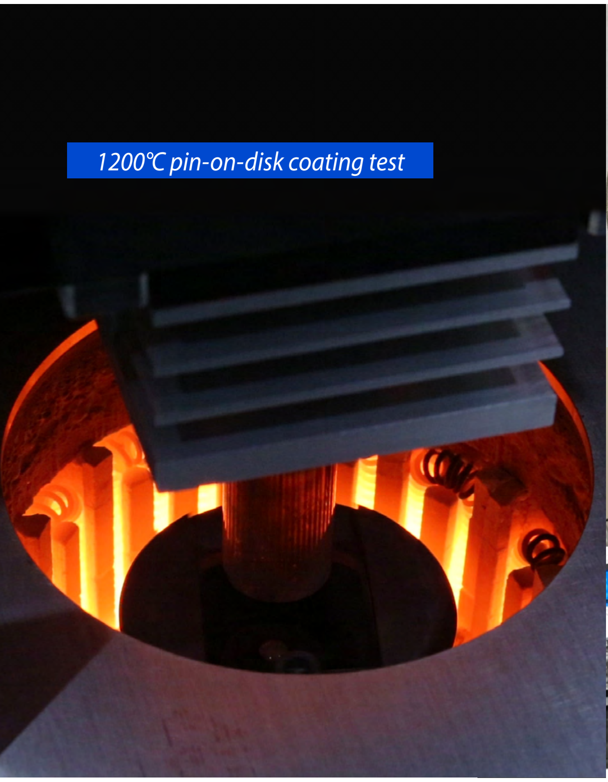
A suite of monitoring sensors and control techniques can be employed to comprehensively investigate tribological systems, including:

- In-situ acoustic emissions
- Electrical data
- Friction and wear
- Temperature and humidity
- Clutch fluids and materials testing

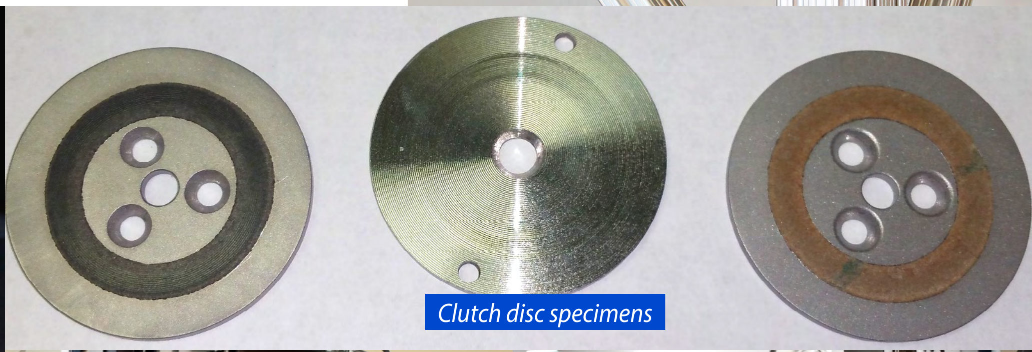
The flexibility of these systems extends to a wide array of test parameters. Tests with complex lubrication programs can be carried out confidently, facilitated by built-in computer-controlled pumps. In each configuration, automated motor controllers can be programmed independently, allowing custom wear tracks to be generated.

The Tribology Research and Evaluations group has also manufactured their own modules for specific testing.

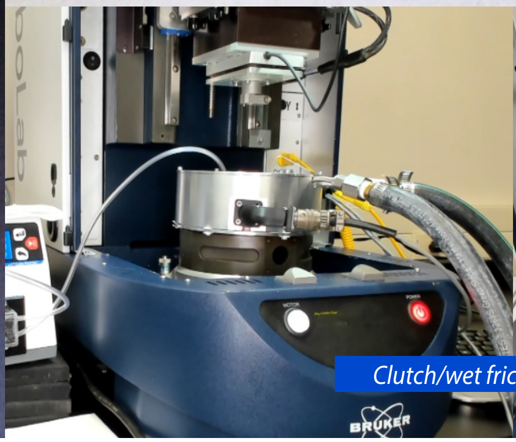
Bruker high-load tribometer with upper and lower rotating drives



1200°C pin-on-disk coating test



Clutch disc specimens

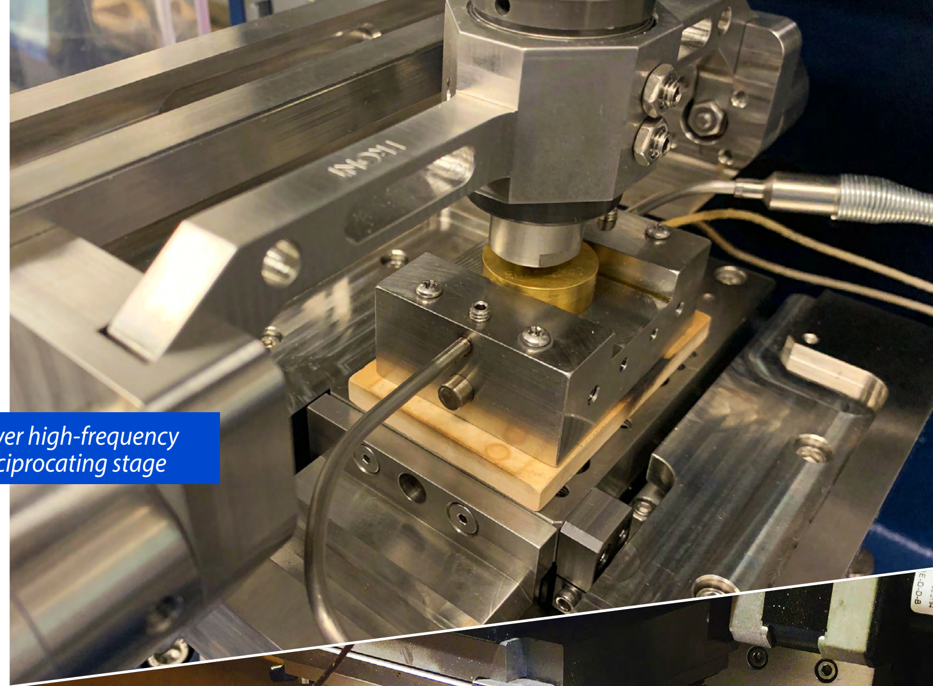


Clutch/wet friction material testing

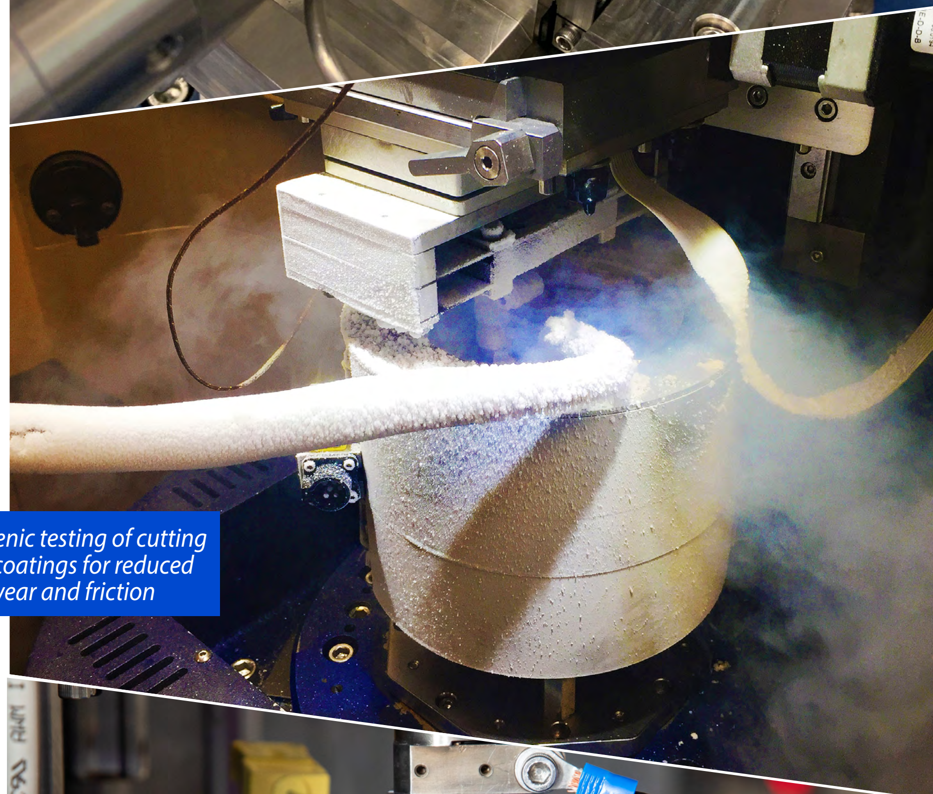
Bruker Tribometer Capabilities	
Wear	Rotary, linear, reciprocating, abrasive, fretting , galling, seizure
Friction	Static, dyamic, stick-slip
Lubrication	Hydrodynamic, mixed, boundary
Environment	Temperature, humidity, vacuum, gases, corrosive atmospheres
Scratch	Adhesion, delamination, hardness
Indentation	Young's modulus, storage modulus, hardness
Strain	Multi-axis, tension, compression, torsion, elasticity, plasticity, creep
Observation	Integrated optical microscopes with 5–25X objectives

Available Force Sensors		
Type	Range	Resolution
2-axis	1 mN – 2000 N	100 µN – 100 mN
6-axis	40 – 120 N, 2 N-m	10 mN, 0.25 mN-m

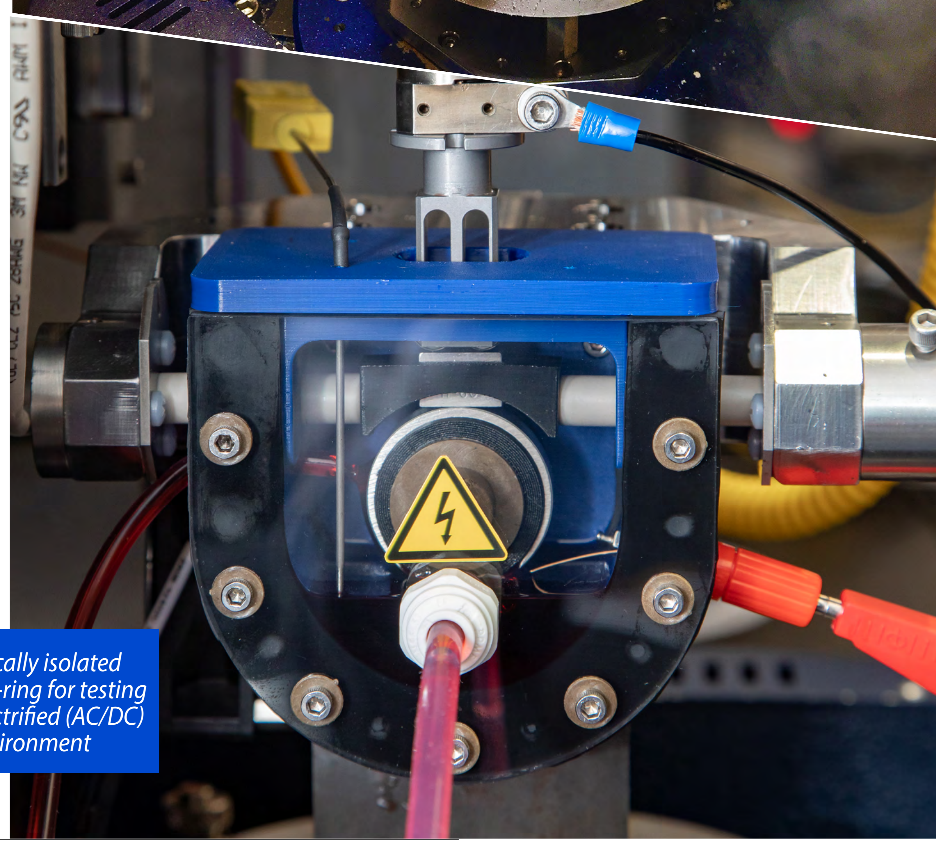
Bruker Tribometer Specifications	
Upper Translational Stage	
Vertical travel	150 mm
Lateral travel	120 mm
Speed	0.002 – 10 mm/s
Resolution	0.25 – 0.5 µm
Wear depth accuracy	5 µm
Upper Rotary Stage	
Rotational speed	0.1 – 1000 rpm
Normal load	5 – 200 N
Torque (medium)	0.002 – 0.35 N-m
Lower Linear Stage	
Travel	120 mm
Speed	0.002 – 10 mm/s
Resolution	1 µm
Lower Reciprocating Stage	
Stroke length	0 – 25 mm
Frequency	0 – 60 Hz
Lower High-Frequency Reciprocating Stage	
Stroke length	0 – 5 mm
Frequency	0 – 200 Hz
Lower Rotary Stage (Vertical)	
Speed	0.1 – 5000 rpm
Lower Rotary Stage (Horizontal)	
Speed	0.1 – 3600 rpm
Environmental Test Chambers	
Temperature	Wet up to 350°C Dry up to 1000°C
Vacuum, inert gas and humidity	Optional



Lower high-frequency reciprocating stage



Cryogenic testing of cutting tool coatings for reduced wear and friction



Electrically isolated block-on-ring for testing in an electrified (AC/DC) environment

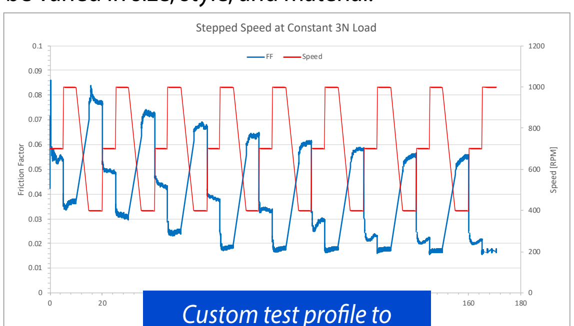
Soft Contact Tribology

Soft tribology aims to understand the frictional behavior of compliant surfaces and/or materials that experience light contact stresses. For this purpose, SwRI utilizes the tribology cell for the Anton Paar MCR 502/702e rheometers, which allows for homogenous application of light loads and sensitive measurement of the resultant friction force. Soft tribology has applications in a wide range of industries from characterizing thin coatings and lubricants for automotive use, to quantifying "mouth feel" for food science studies, to modeling biological skin friction for cosmetics.

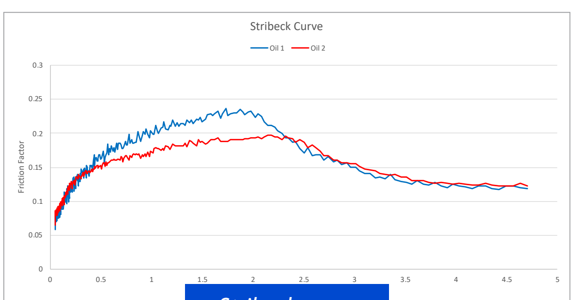
Roller bearing performance can also be investigated. This configuration allows for measurement of different bearing types, greases, and other lubricants while under controlled axial loads and rotational speeds. Configurations Include:

- Ball on 3 plates
- Ball on 3 pins
- 4 ball
- Roller bearing test

Balls, plates, and pins can be manufactured from nearly any material and/or coated to meet client needs. Roller bearings can be varied in size, style, and material.

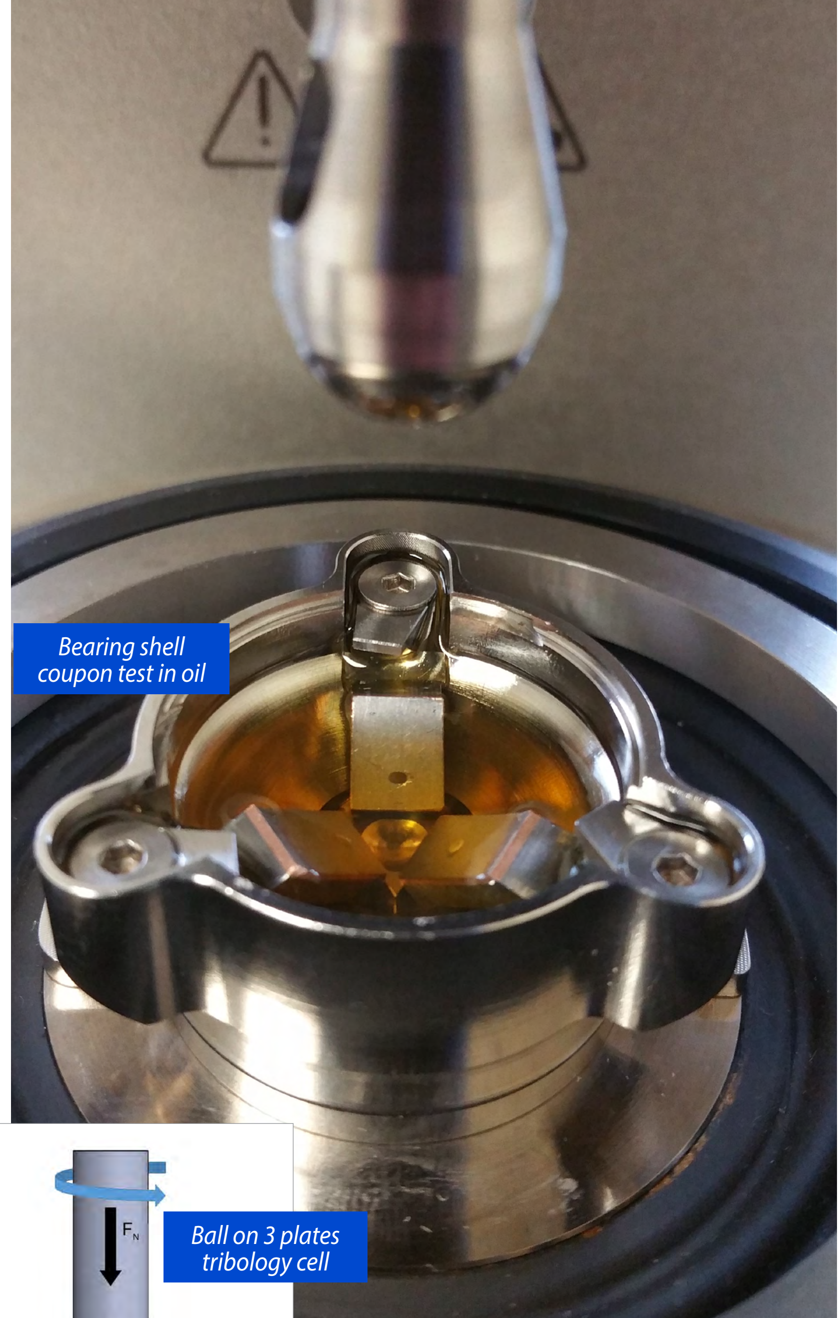


Custom test profile to simulate real system

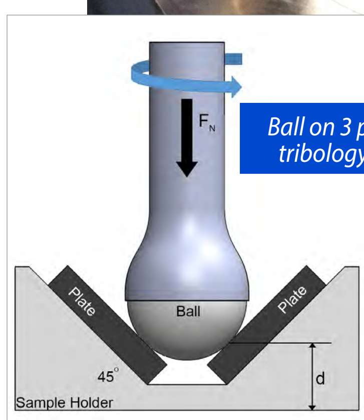


Stribeck curve generation

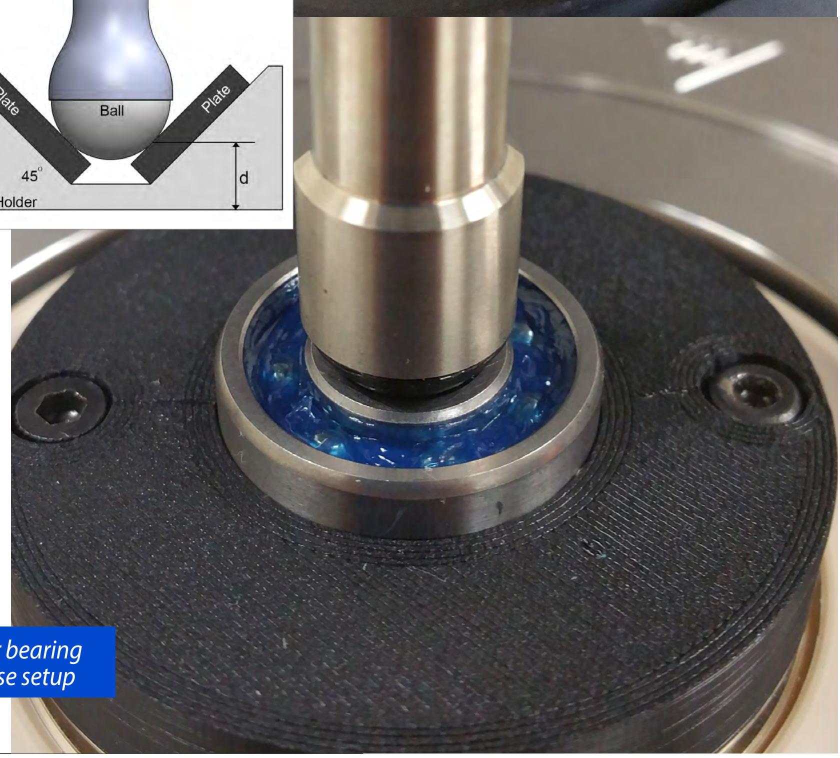
Tribology Cell	
Normal force	1 – 24 N
Sliding speed	10^{-8} – 3.3 m/s
Temperature	-40 – 200°C
Torque	2 nNm – 300 mNm
Motion	rotary, oscillation
Revolution	10^{-6} – 3000 rpm
Deflection	1 µrad – INF µrad



Bearing shell coupon test in oil

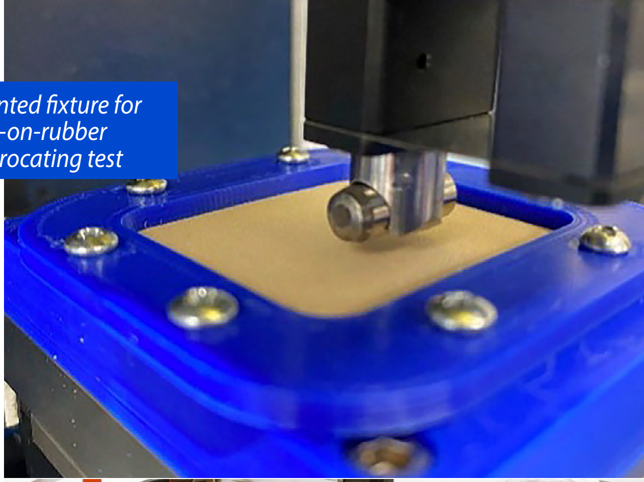


Ball on 3 plates tribology cell



Roller bearing grease setup

Tribology Support: Design to Manufacture



3D printed fixture for pin-on-rubber reciprocating test

Southwest Research Institute provides client services in communication systems, modeling and simulation, electronic design, vehicle and engine systems, automotive fuels and lubricants, polymer and materials engineering, mechanical design, chemical analysis, environmental sciences, industrial engineering, energy storage, and more. Additional information about SwRI's multidisciplinary services can be found on page 39.

SwRI's tribology engineers are highly experienced in mechanical design, modeling, and fabrication. A key aspect of tribological testing is modeling a test around the real-world system. The real materials can be cut into small sections and run in one of our benchtop rigs, or it may be necessary to use a larger part of the real system, such as a complete pump housing or half of an engine. In some cases, a full-scale system evaluation may be required.

Tribology Labs

SwRI offers extensive design services to solve engineering problems for our clients, including:

- Machining small test coupons
- Fabricating custom fixtures for our existing rigs
- Designing prototypes
- Commissioning fully operational custom rigs at the client's facility

Support capabilities of SwRI's Tribology labs include:

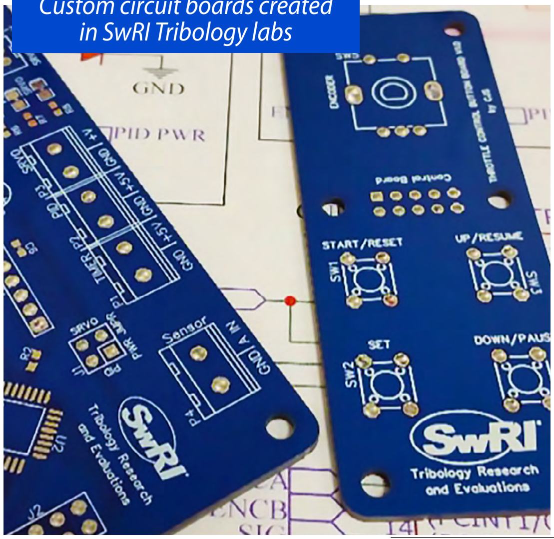
- 3D CAD modeling and simulation
- Engineering drawings
- 3D printing for prototyping and practical applications
- CAD-CAM programming
- Full machine shop with CNC
- Electronics design and fabrication

Expert machinist working on test parts in SwRI Tribology labs

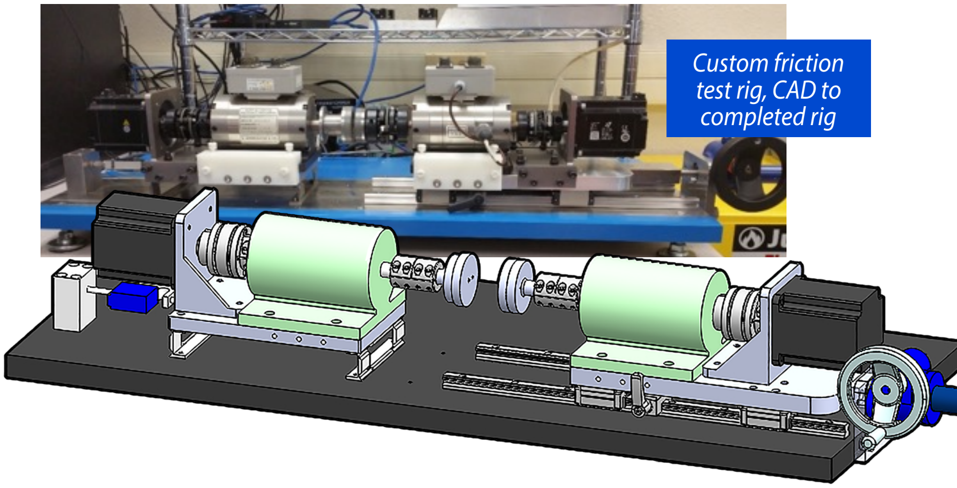
Machine Shop

SwRI's Mechanical Fabrication Center has extensive experience in the fabrication of complex precision components and parts. The Center operates under a quality program that meets the requirements for NASA and U.S. military projects and is certified to ISO 9001. Services include:

- Precision machining
- Welding fabrication
- Onsite third-party validation and verification



Custom circuit boards created in SwRI Tribology labs



Custom friction test rig, CAD to completed rig

Rheology

The MCR series rheometers have a wide range of capabilities, including electrorheology (AC and DC), pressure viscosity, vapor pressure, extensional viscosity, dynamic mechanical analysis (DMA), and dynamic thermal mechanical analysis (DTMA).

Standard test methods are available as well as custom-designed tests for various applications, such as electric vehicle (EV) fluid and grease analysis.

A separate brochure is available that comprehensively covers rheology and fluid analysis capabilities at SwRI.

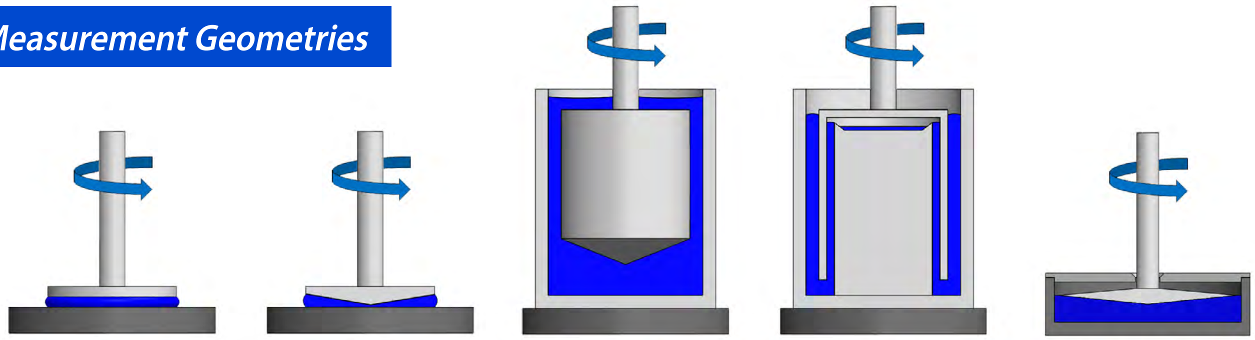
Standard Test Methods

- ASTM D4440 – Plastics: Dynamic Mechanical Properties Melt Rheology
- ASTM D7175 – Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer
- ISO 3219 – Determination of Viscosity Using a Rotational Viscometer with Defined Shear Rate

MCR Series Rheometers	
Speed	314 – 10^3 rad/s
Temperature	-160 – 600°C
Angular frequency	10^{-7} – 628 rad/s
Normal force	-50 – 50 N
Torque	1 nN-m – 2230 mN-m
Voltage	0 – 12.5 kV AC & DC
Pressure	Ambient – 1000 bar
Sample Size	0.5 – 100 ml

Anton Paar MCR 702e MultiDrive with CTD600 oven

Measurement Geometries



Measuring System Specifications			
Measuring Tool	Shear Rate (x10^3) [1/s]	Temperature (°C)	System
8 mm parallel plate	0 – 2.5	-160 – 600	Peltier hood / Convention oven
15 mm parallel plate	0 – 5	-160 – 600	Peltier hood / Convention oven
25 mm parallel plate	0 – 5	-160 – 600	Peltier hood / Convention oven
50 mm 1° cone	0 – 20	-160 – 600	Peltier hood / Convention oven
50 mm serrated plate	0 – 10	-160 – 600	Peltier hood / Convention oven
Standard cup and bob	0 – 5	-30 – 200	Concentric cylinder
High shear cup and bob	0 – 45	-30 – 200	Concentric cylinder
Bob for electrorheology	0 – 5	-30 – 200	Concentric cylinder
Double wall concentric cylinders	0 – 5	0 – 200	400 bar pressure cell
Concentric cylinder	0 – 3	25 – 30	1000 bar pressure cell
Interfacial bi-cone	0 – 2.5	5 – 70	Interfacial rheology

Scanning Electron Microscope (SEM) and Energy Dispersive X-ray (EDX) Spectroscopy

Quattro S

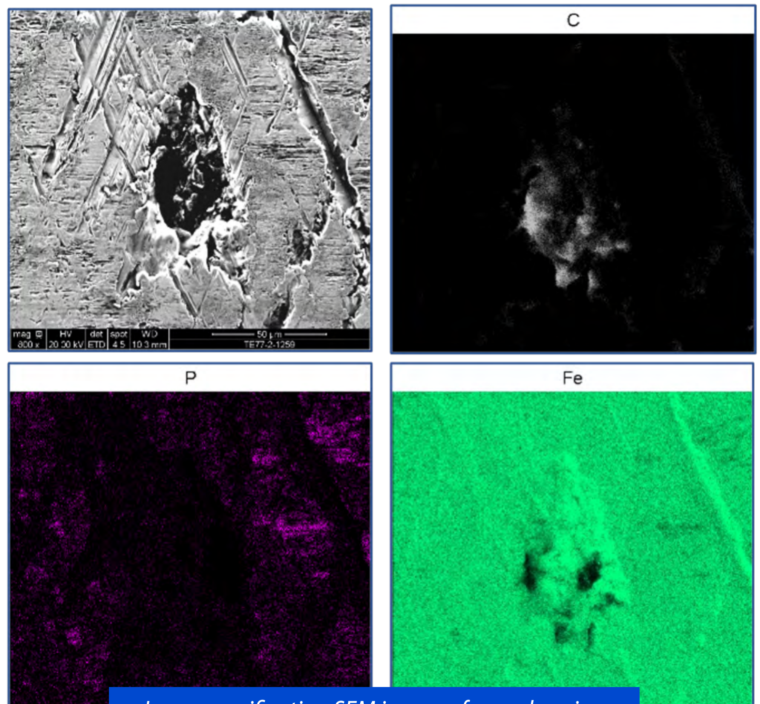
Bruker S1 Titan

SEM analysis can provide images of samples at much greater magnification and with better depth of field field than is achievable with light microscopy, we well as provide topographical and compositional information for the examined material, depending on imaging mode. Samples can be quickly evaluated at magnifications ranging from less than 25X to over 1,000,000X power.

More comprehensive chemical information is obtained in the SEM through onboard EDX analysis, which measures both the spatial distribution and semi-quantitative content of elemental constituents of material. Combining SEM and EDS analysis enables the rapid and comprehensive evaluation of a variety of materials systems, making it an effective technique for failure analysis material identification and characterization and defect verification.

XRF Gun

SwRI utilizes the Bruker S1 Titan handheld XRF spectrometer to quickly and accurately perform elemental analysis on a wide range of materials. This portable system can be used to perform in-situ analysis of fluids, wear metals, organic material, and more. From simply identifying an unknown part to performing in-depth chemical analysis of failed components, this tool provides faster turnaround than other elemental analysis methods.



Low magnification SEM image of worn bearing surface and partial EDS map

Quattro S Specifications	
Chamber	340 mm inside width, 12 ports, three simultaneous EDS detectors possible, two at 180°, coplanar EDS/EBSD orthogonal to the tilt axis of the stage.
Standard sample holder	Multi-purpose holder, uniquely mounts directly onto the stage, hosts up to 18 standard stubs (Ø12 mm), three pre-tilted stubs, cross-section samples and two pre-tilted row-bar holders (38° and 90°), and does not require tools to mount a sample.
Stage	5-axis motorized eucentric stage, 110 x 110 mm^2 with -15 to 90° tilt range. Maximum sample weight 5 kg in un-tilted position.
Stage bias (beam deceleration	-4000 V to +600 V standard
Detection	ETD, LVD, DBS, GAD, GSED, ESEM-GAD, STEM 3+, CLD, IR-CCD, Nav-Cam+
Probe current range	1 pA – 200 nA
Landing energy range	20 eV – 30 keV
Low vacuum mode	10 – 4000 Pa chamber pressure
Resolution	0.8 nm at 30 kV (STEM) 1.0 nm at 30 kV (SE) 3.0 nm at 1 kV (SE) 2.1 nm at 1 kV (BD mode + ICD) 1.3 nm at 30 kV (SE in low vacuum and ESEM)

3D Imaging and Surface Analysis

SwRI utilizes a variety of imaging systems to suit nearly any type of surface analysis. Each system offers different magnifications, resolutions, lighting capabilities, and sample sizes, among others. Our engineers specialize in creating custom protocols for imaging and measuring a wide range of parts and components across all industries.

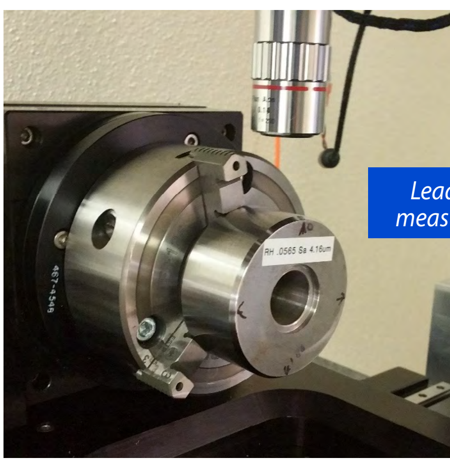
Analysis methods include:

- Dimensional measurement
- Profilometry and step height
- Line and surface area roughness
- Volume and area
- Shaft lead angle
- Particle count
- Grain size analysis and measurement
- Comparative measurements of multiple components

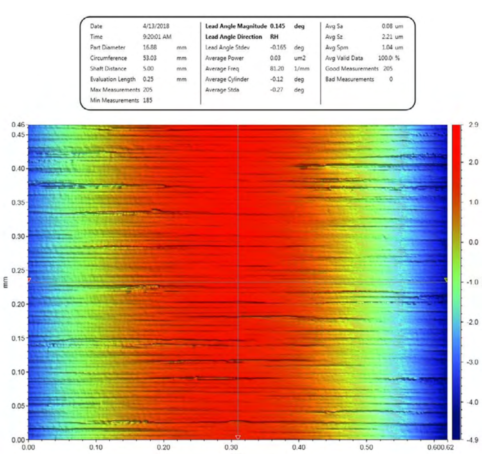
Measurement data may also be exported as point clouds or CAD files for further analysis and post-processing in other software.

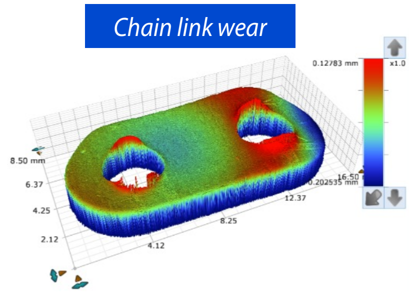
Bruker NPFLEX-LA white light interferometer

Keyence VHX-7000 digital microscope

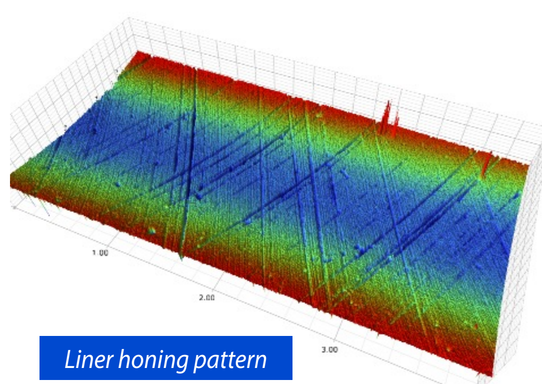


Lead angle measurement





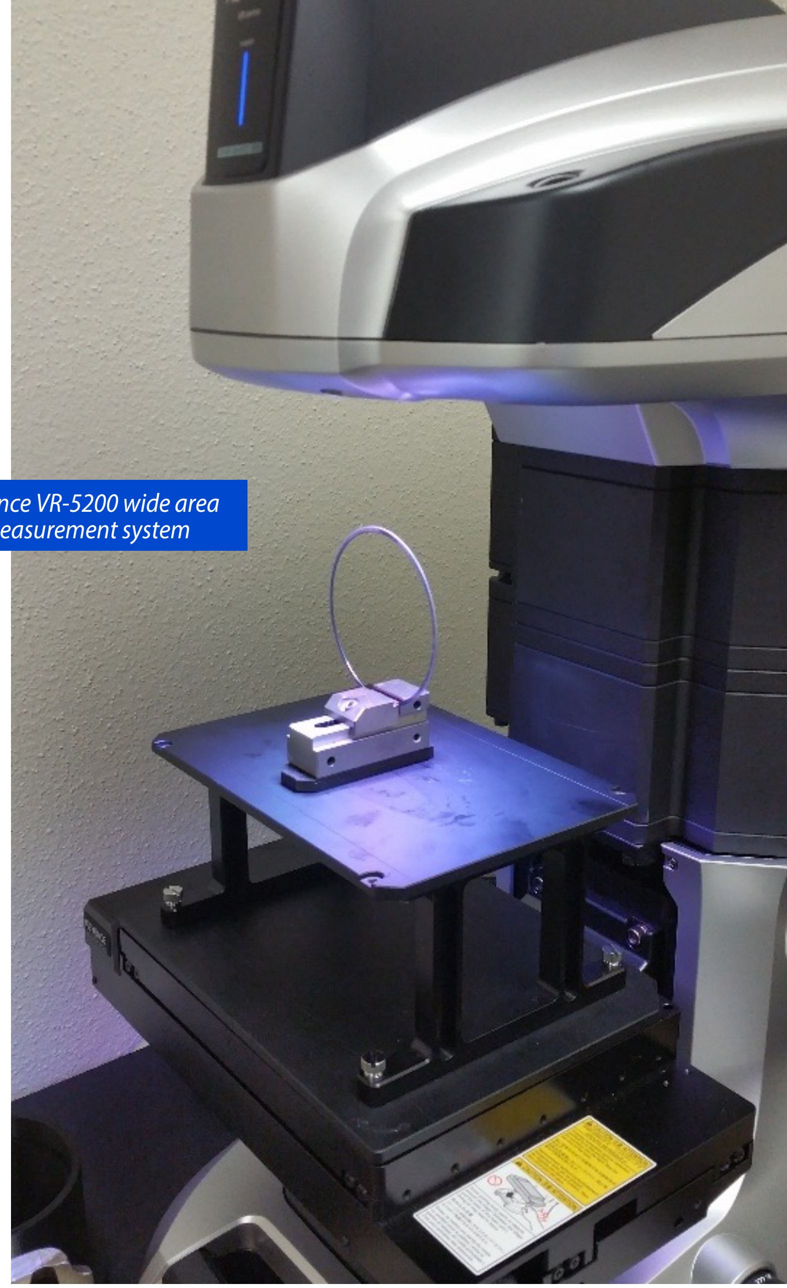
Chain link wear



Liner honing pattern

3D Imaging and Surface Analysis

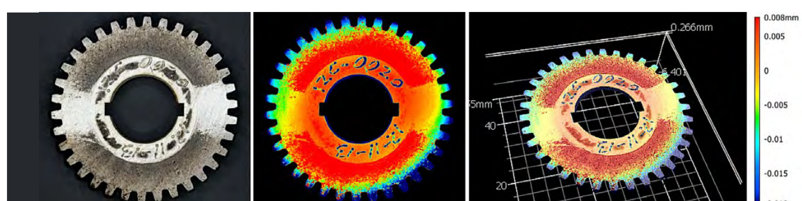
NPFLEX-LA Specifications	
Roughness repeatability	2 nm
RMS repeatability	0.03 nm
Vertical resolution	<0.15 nm
Magnification	1X – 10X
Measurable sample dimensions	294 x 304 x 450 mm
Focal range (Z-direction)	2 mm
Lead angle accuracy	± 0.025^0
Lead angle repeatability	0.005^0 standard deviation
Lead angle reproducibility	0.02^0 standard deviation
Measurable sample torque	200 lb/in
Chuck clamp range	3 – 126 mm OD 27 – 128 mm ID 32 mm thru hole



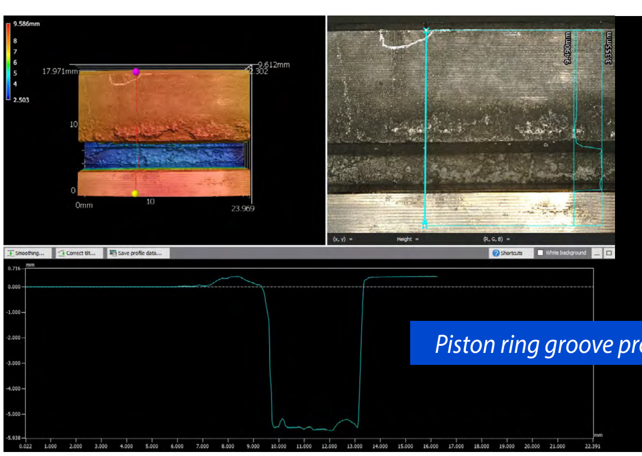
Keyence VR-5200 wide area measurement system

Keyence VR-5200 Specifications	
Roughness repeatability	50 nm
RMS repeatability	400 nm
Vertical resolution	<100 nm
Magnification	12X – 160X
Measurable sample dimensions	114 x 180 x 304 mm
Focal range (Z-direction)	15 mm

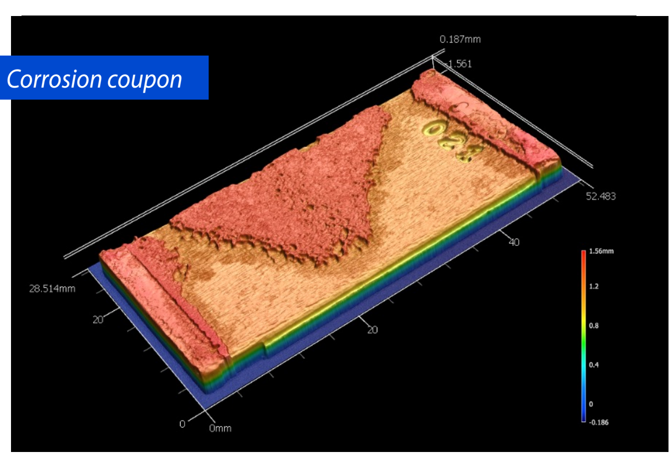
Keyence VHX-7000 Specifications	
Roughness repeatability	50 nm
Rms repeatability	400 nm
Vertical resolution	0.9 NA
Magnification	20X – 500X
Sample size	3.94″ x 3.94″ x 12″
Focal depth	0.018″ – 0.45″
Tilt (vertical orientation is 0°)	-60° – 90°



Volumetric deposit analysis of gear face



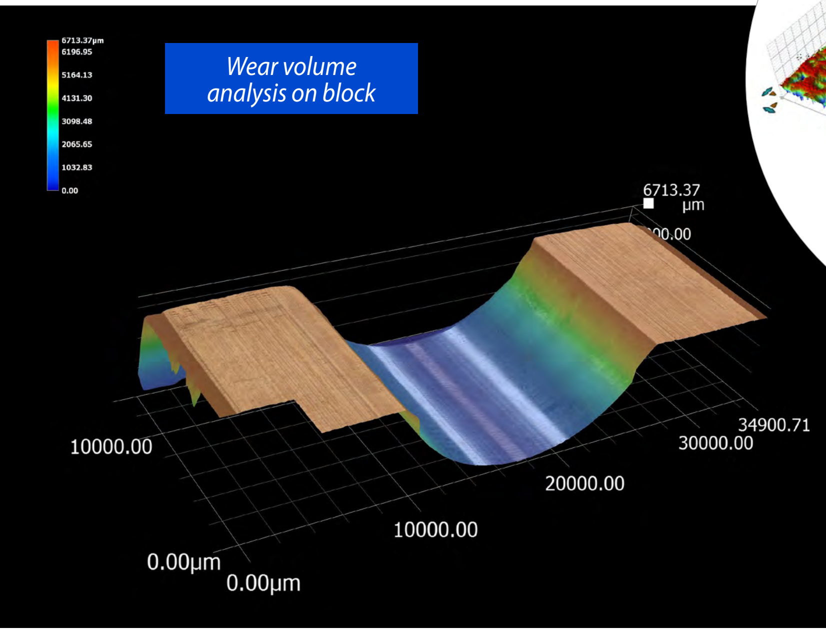
Piston ring groove profile

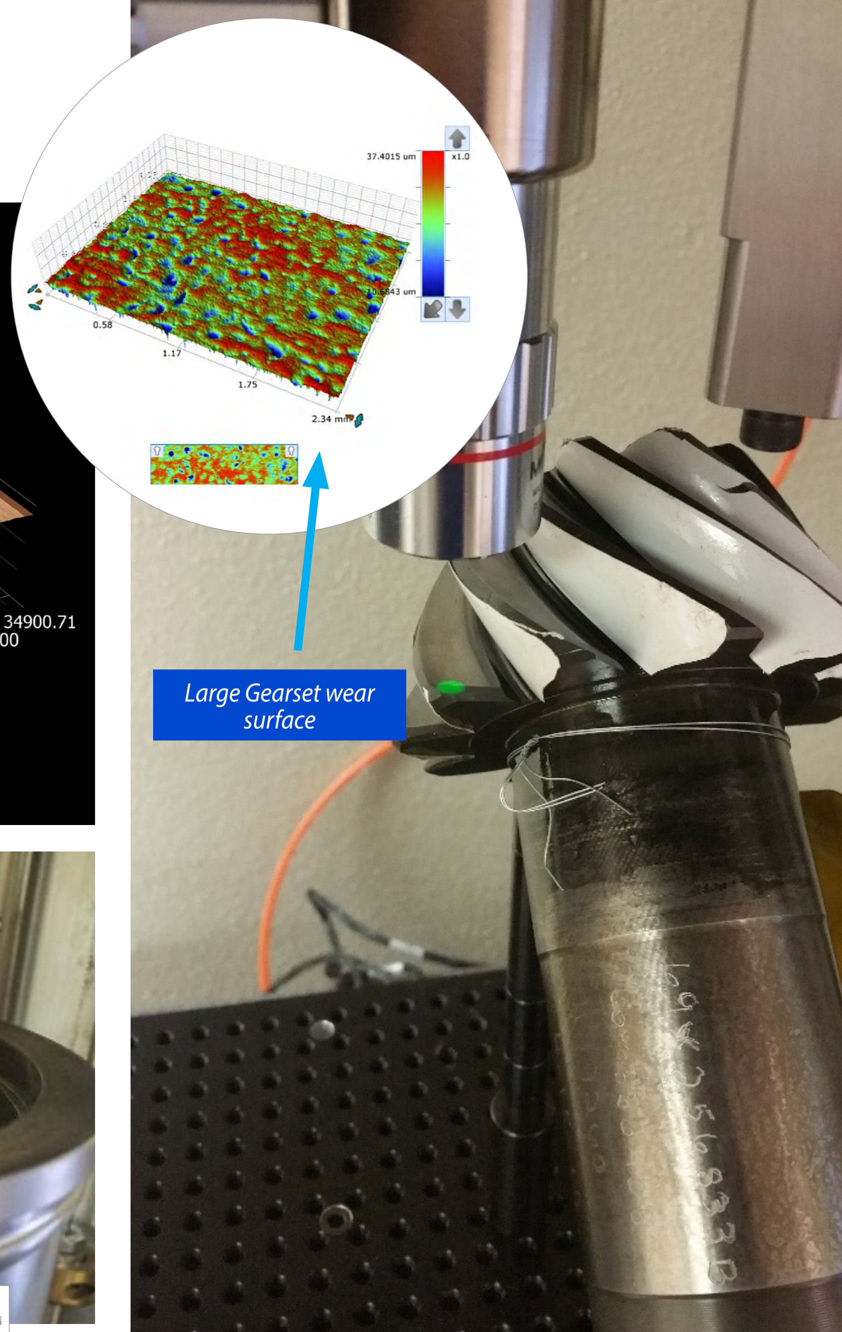


Corrosion coupon

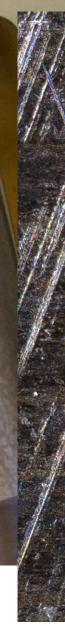
3D Imaging and Surface Analysis

Wear volume analysis on block

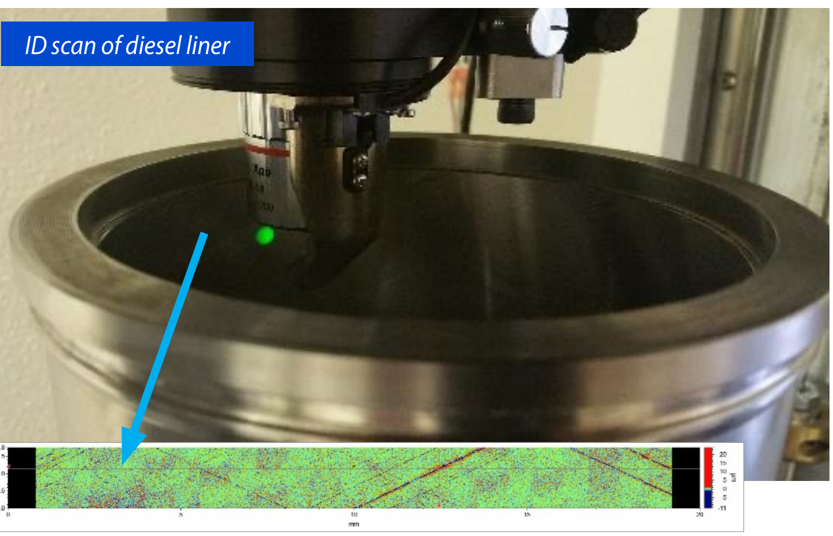




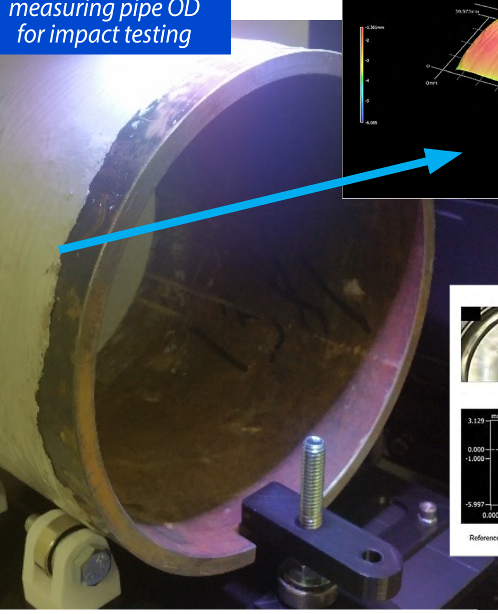
Large Gearset wear surface

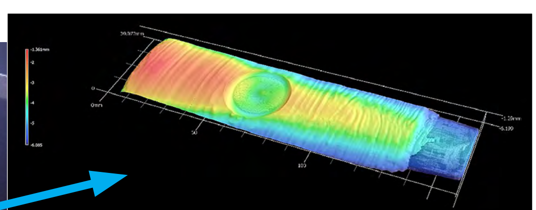


ID scan of diesel liner

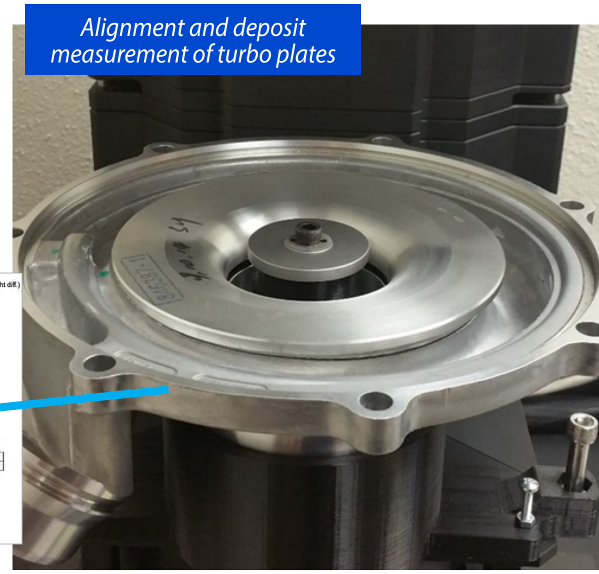


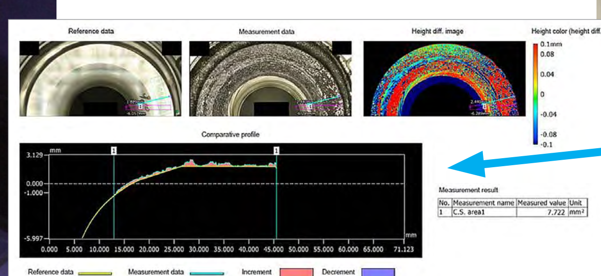
Fixture for measuring pipe OD for impact testing



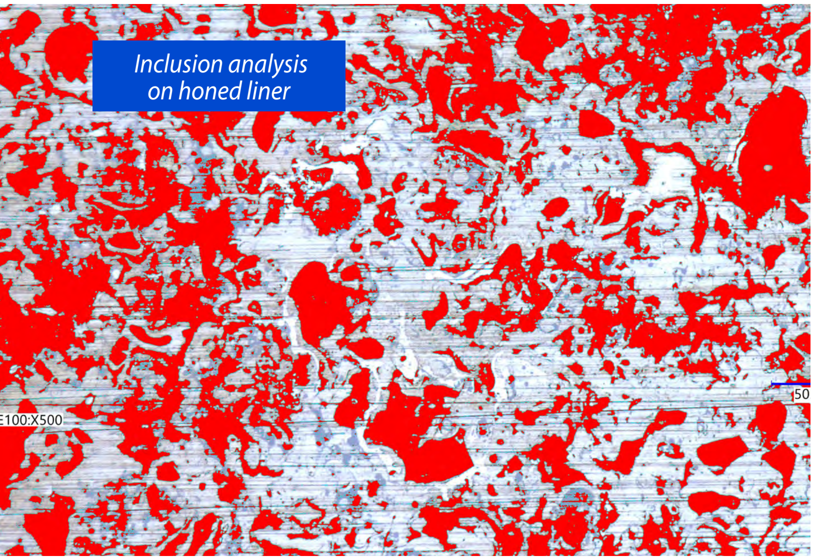


Alignment and deposit measurement of turbo plates

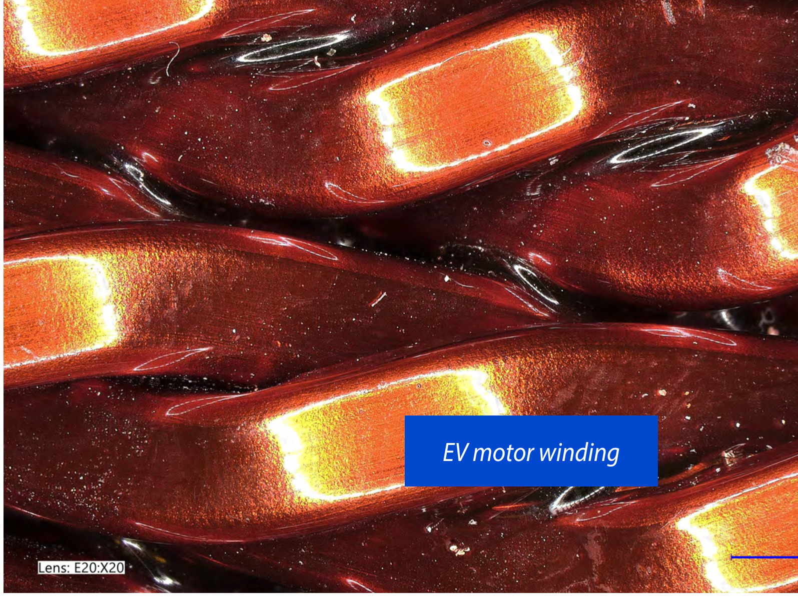




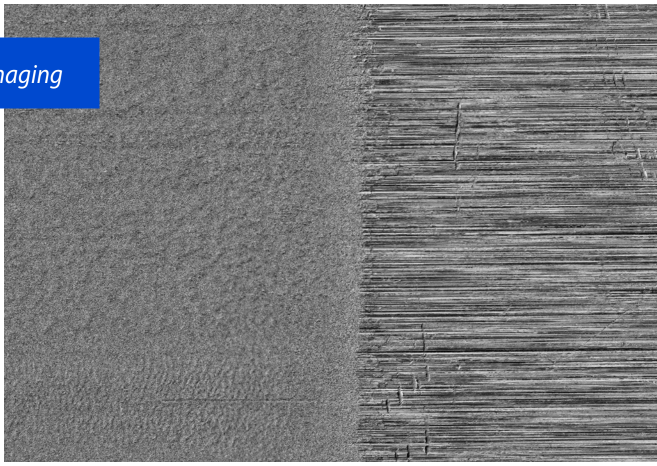
3D Imaging and Surface Analysis

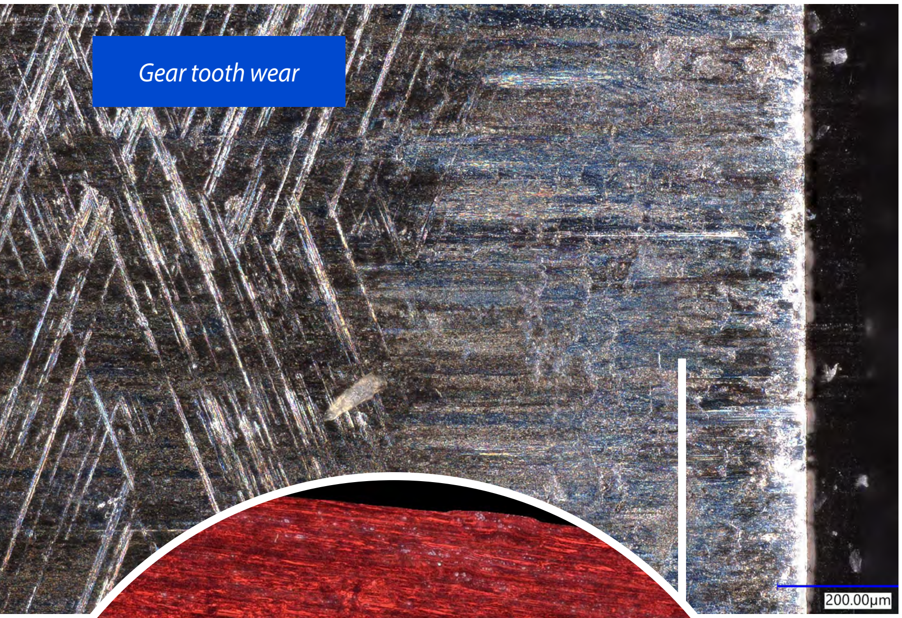


Inclusion analysis on honed liner

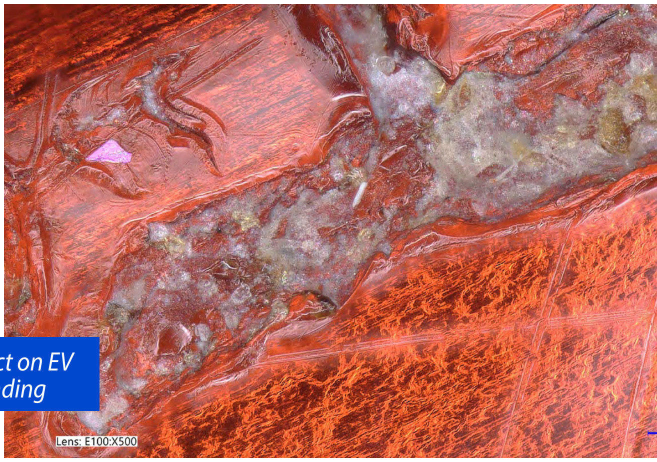


EV motor winding

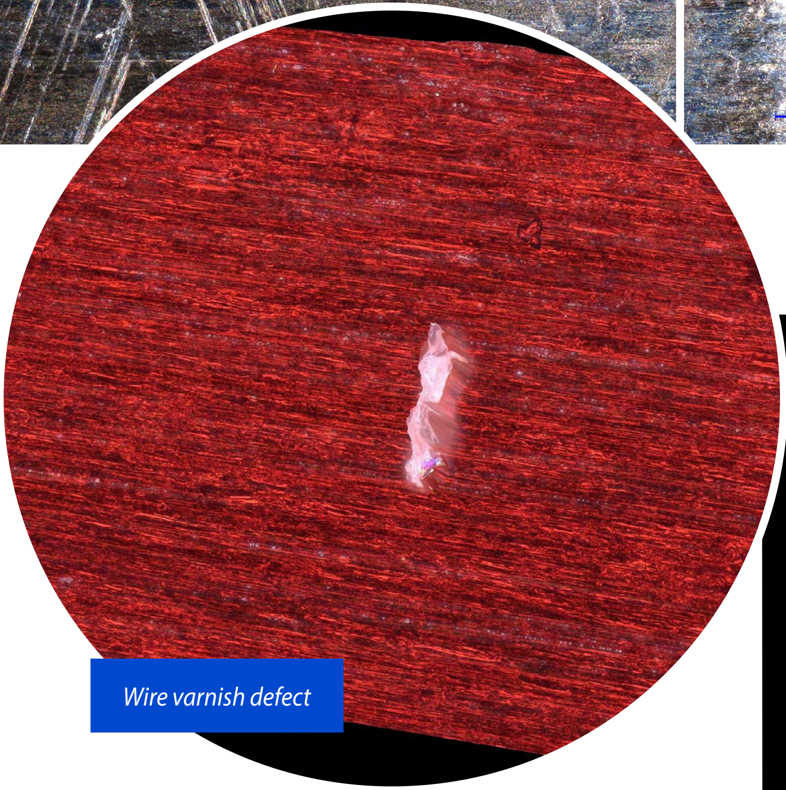

SEM style imaging

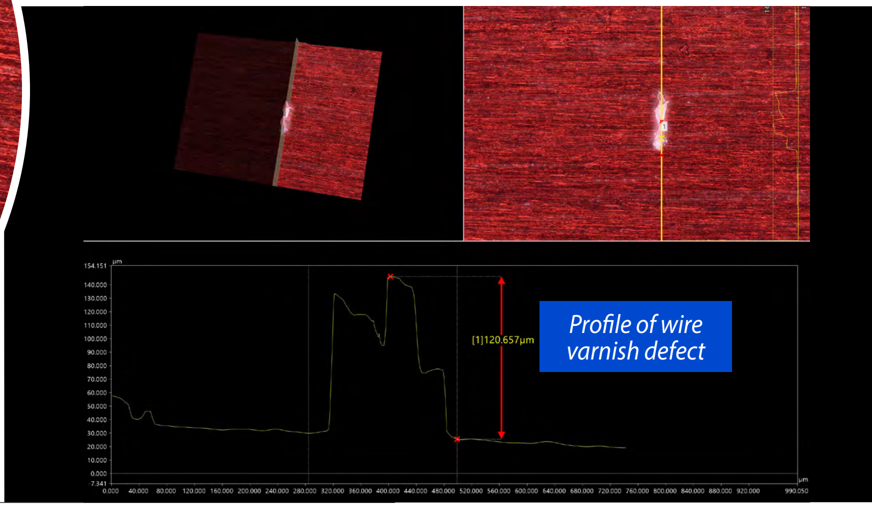


Gear tooth wear



Varnish defect on EV motor winding


Wire varnish defect



Profile of wire varnish defect

Coating Technologies

Surface Engineering Laboratory

The SwRI Surface Engineering Laboratory is a well-equipped research center with a full range of ion deposition techniques for surface modification and coating of advanced materials, such as PIID (Plasma Immersed Ion Deposition), IBAD (Ion Beam Assisted Deposition), and PVD (physical vapor deposition) processes, including magnetron sputtering and e-beam evaporation. Various characterization facilities are utilized for extensive surface and bulk characterization of coatings and plasma diagnostics so that the deposition process parameters can be correlated with the structure, properties, and performance of coatings.

Advanced coatings include:

- Nanotechnology fabrication
- Corrosion-resistant coatings
- Hard yet tough, thick nanocomposite coatings
- Low-friction tribological coatings
- Hydrophobic/oleophobic coatings

DLC Coatings

Diamond-like carbon (DLC) has remarkable mechanical and tribological properties, such as high hardness (15 GPa to 40 GPa), chemical inertness, good corrosion resistance, high electrical resistance, and optical transparency in visible and infrared spectroscopy. DLC is ultra-resistant to abrasive and adhesive wear with a low coefficient of friction (COF) (<0.12 in dry and <0.08 in lubricated conditions), and is widely used for protective overcoats to offer both lubricity and wear resistance. SwRI offers two specialized DLC processes: PIID and high-power impulse magnetron sputtering (HiPIMS).

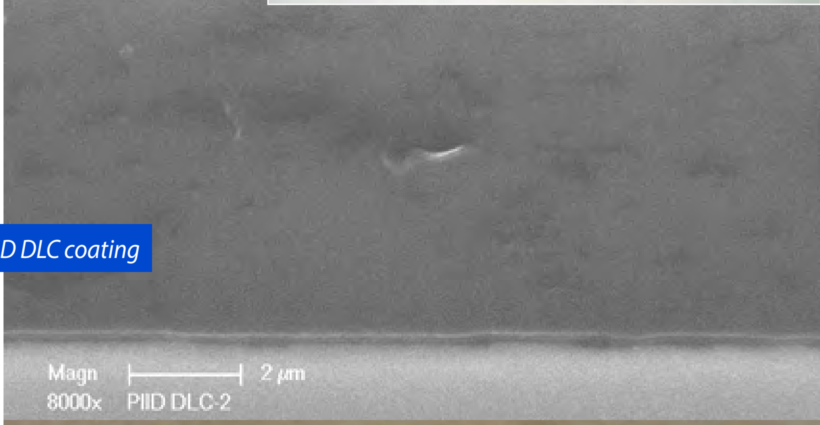
PIID is a low-cost variation of PECVD (plasma-enhanced chemical vapor deposition) that allows low-temperature deposition of DLC coatings using pulsed power. By utilizing hollow cathode assistance and controlling stress, DLC can be applied conformally with a thickness up to 30 µm over the surface of irregularly shaped parts in large volume.

HiPIMS is an advanced magnetron sputtering technique aimed at depositing hydrogen-free tetrahedral DLC (ta:C) by utilizing highly ionized carbon species. Compared to PIID DLC, HiPIMS DLC shows super-high hardness (30–40 GPa) with higher sp3 contents and denser microstructure. It is also convenient to use different metallic bonding (e.g., Ti, Cr) to improve the adhesion of DLC on various materials.

SwRI PIID system

PIID DLC process

PIID DLC coated parts



SwRI PIID DLC coating

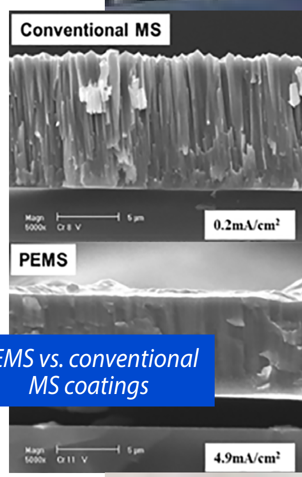
DLC coated crankshaft

PEMS and TiSiCN Nanocomposite Coatings

Plasma enhanced magnetron sputtering (PEMS) is an advanced version of the conventional magnetron sputtering technique. PEMS generates a high flux of gas ions with hot filament thermionic emission to produce an extra global plasma in the deposition system. Through enhanced ion bombardment by this highly ionized plasma, the structure, adhesion, and properties of various coatings can be significantly improved. In 2009, R&D Magazine selected PEMS as one of the 100 most technologically significant achievements of the year.

SwRI PEMS system

SwRI has developed a TiSiCN-based nanocomposite hard coating system using the PEMS technique. TiSiCN-based nanocomposite coatings consist of 5–10 nm TiCN nanocrystalline embedded in a SiCN-based amorphous phase. The coatings are super-hard with good toughness and adhesion, and show excellent wear and erosion resistance. TiSiCN-based nanocomposite coatings have been used successfully to protect industrial components from wear, erosion, and corrosion.



PEMS vs. conventional MS coatings

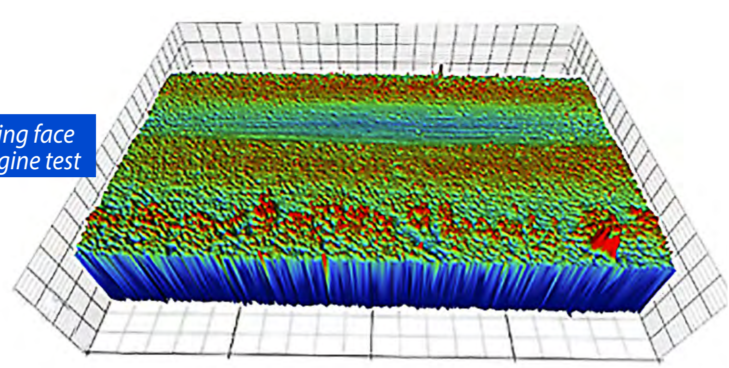

Low-friction piston ring depositions

Low-Friction TiSiCN Nanocomposite Coating for Tribological Applications (U.S. patent 9,523,146)

To minimize friction loss and improve service life of piston rings in an engine while achieving high fuel efficiency and low emission, SwRI has developed a new low-friction piston ring coating technology. Compared to commonly used CrN (chromium nitride) coatings, this TiSiCN-based nanocomposite coating offers a much lower friction (~0.15 vs. 0.6 in dry sliding). Compared to DLC coatings, which are being developed due to their low friction, the TiSiCN-based nanocomposite coating improves lubricant compatibility (COF <0.06 in lubricated conditions), enhances toughness, and improves durability.


Coated piston ring

The coating was selected through an iterative process of optimizing the deposition parameters and tribotesting using various protocols, including the final process of on-vehicle testing. EPA standard tests on coated piston rings in a four-cylinder gasoline engine on a commercial vehicle exhibited up to 1% improvement in fuel economy for the coated piston rings as compared with uncoated piston rings on the same vehicle. This product has also been used successfully in other applications in the oil and gas industry to reduce friction and increase wear resistance.


Minimal ring face wear in engine test

Failure Analysis and Prevention

Analysis

Using systematic failure analysis, SwRI isolates the causes of component failures and makes recommendations to prevent costly recurrences. SwRI has specialized failure analysis expertise in the power generation, aerospace, petrochemical, manufacturing, transportation, and medical industries.

Prevention

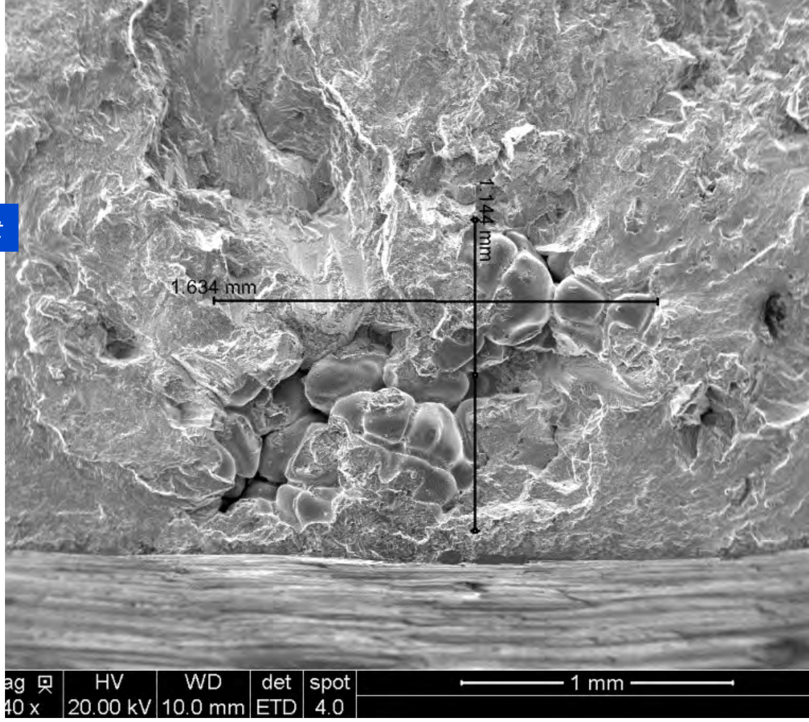
Failure investigations help clients prevent future failures, extend component service life, and establish inspection intervals. SwRI conducts analyses to:

- Determine the causes of failures
- Identify design and operating deficiencies
- Improve reliability and safety
- Lower operating costs
- Provide impartial, unbiased evaluations

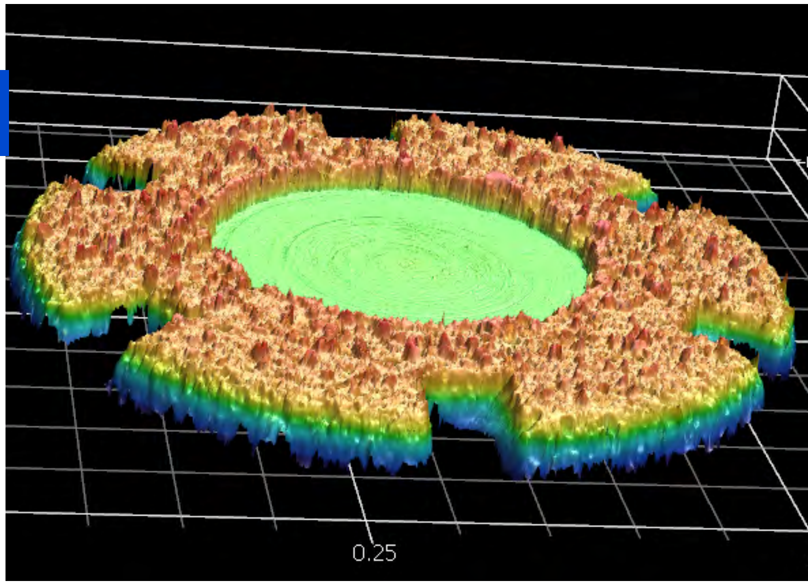
Facilities and Equipment

SwRI's mechanical and materials engineering laboratories include:

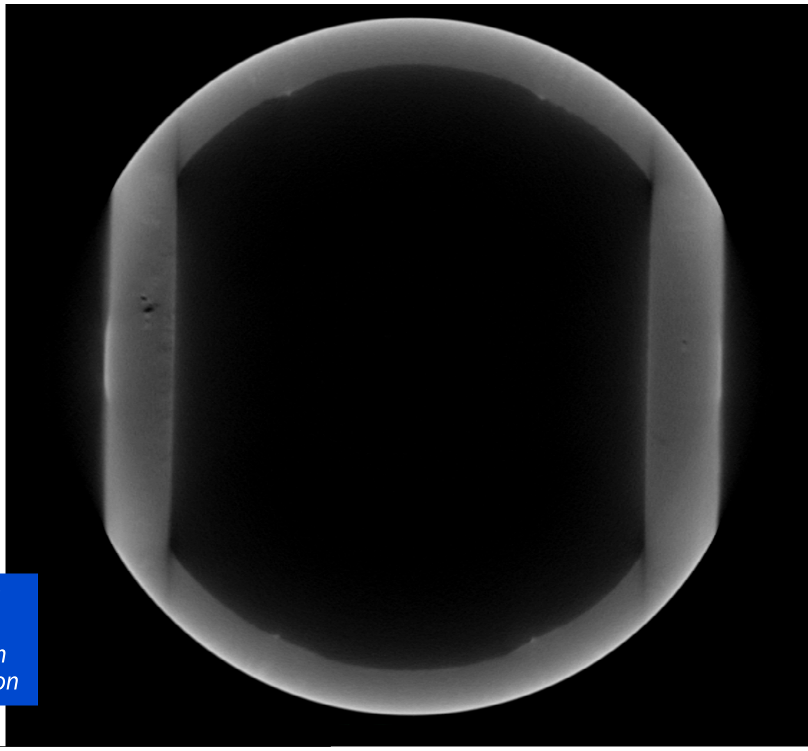
- Two scanning electron microscopes (SEM) for fractographic and metallographic analysis
- Two energy-dispersive X-ray spectrometers (EDS), coupled to each SEM, to identify elemental composition of materials
- Powder X-ray diffractometer for crystallographic analysis of materials and deposits
- Raman spectroscopic imaging and microanalysis system for spatially mapped compositional analysis of materials
- Scanning Auger microprobe spectrometer to characterize surface and interface chemistry
- Full-scale and micro-computed tomography (CT and microCT) systems for high-resolution inspection and reconstructive imaging of polymeric, metallic, and ceramic components
- Scanning-tunneling and atomic force microscopes (STM and AFM) for analysis of nanoscale surface topography
- Metallographic imaging equipment for heat treat verification, microstructural examination, and material characterization
- Bulk, micro, and nano hardness testing capability
- Autoclaves for high-pressure and high-temperature corrosion investigations



SEM casting defect



60 grit diamond cutting tool face



Computerized tomography scan of a piston showing inclusion

Southwest Research Institute

Southwest Research Institute, headquartered in San Antonio, Texas, is one of the oldest and largest independent, nonprofit, applied research and development organizations in the United States. Founded in 1947, SwRI provides contract research and development services to industrial and government clients. The Institute is governed by a board of directors, which is advised by approximately 100 trustees.

With more than 2.5 million square feet of laboratories and offices, SwRI's eleven technical divisions provide multidisciplinary, problem-solving services to research and physical sciences projects for government and industry. In 2023, we funded 103 internal research projects with a contract value of more than $9.3 million. Total revenue was $844 million.

Our staff numbers more than 3,000, including 315 staff members with doctorates and 612 with master's degrees. In 2023, staff members published 517 technical papers, made 577 technical presentations, and hosted 41 webinars and 15 podcasts. We submitted 36 invention disclosures, filed 34 patent applications, and received 42 patent awards.

A partial listing of research areas includes:

- Automation, robotics, and intelligent systems
- Bioengineering
- Chemistry and chemical engineering
- Corrosion and electrochemistry
- Emissions research
- Engineering mechanics
- Fluid systems and machinery dynamics
- Fuels and lubricants
- Geochemistry and mining engineering
- Hydrology and geohydrology
- Materials sciences and fracture mechanics
- Modeling and simulation
- Nondestructive evaluation
- Oil and gas exploration
- Pipeline technology
- Space science and engineering
- Surface modification and coatings
- Vehicle, engine, and powertrain design/R&D

Automotive engineering at SwRI encompasses engine, vehicle, emissions, lubricants, and fuels research and development. We perform design, development, and test programs on a wide range of components, engines, transmissions, vehicles, and batteries. These programs are supported by research and modeling of fuel mixing, combustion, tribology, filtration, structural analysis, noise and vibration harshness, and fluid flow analysis.

A broad range of services are available for product research, development, and qualification of automotive components and automotive fluids for on-road, off-road, rail, and water transportation systems as well as recreational vehicles and stationary power equipment.

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