EXPERIMENTAL TECHNIQUES FOR TRIBOLOGY

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//// Tribological Testing

"A badly designed experiment is likely to generate useless information"

In industry, tribology is very interdisciplinary meaning that:

•Chemists attempt to do engineering, for which they may have no training or experience

•Engineers design experiments from a mechanical point of view, but with often no regard for the chemistry or physics of the tribo processes they are trying to model

//// Tribological Testing

•Tribology testing is often a last resort

•Many aspects are poorly understood, ill-defined or indeterminate

•Not concerned with single “properties” of materials, but how materials behave when placed in a complex system

•Friction and wear are not intrinsic material properties but are properties of the system in which the material operates

•Mostly concerned with what happens at the interface between materials in contact and this is fundamentally inaccessible

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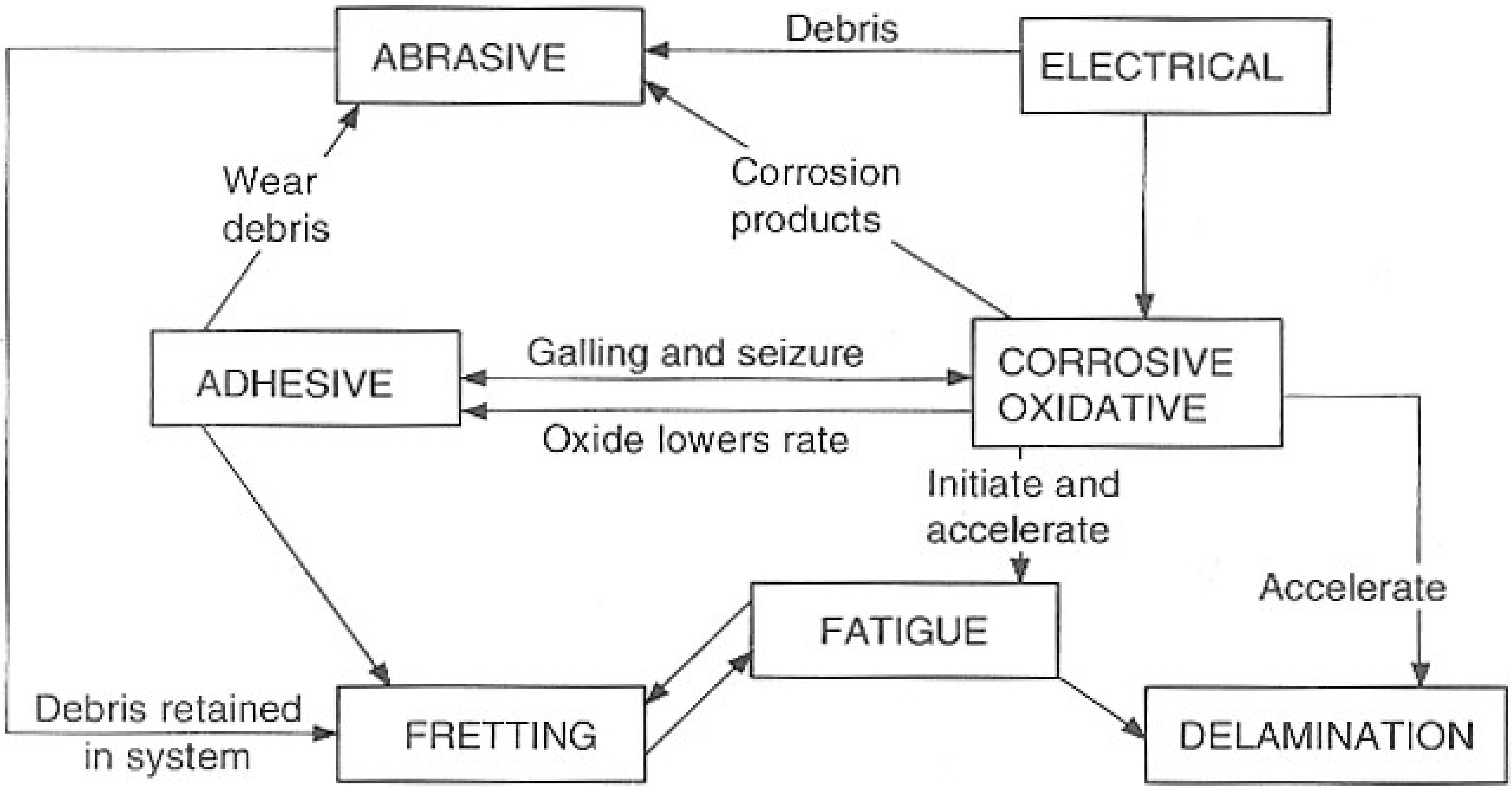
The in-service wear conditions may involve more than one wear mode:



Hence importance of a "systems" approach !

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The most obvious means to obtaining information about friction and wear performance is to try the material or lubricant in the final application.

BUT : How much will it cost?
How complex is the system?
How can the parameters be accurately controlled?
How flexible?
How reproducible?

EXAMPLE : Using a 100,000 mile road test is not the best or cheapest way to evaluate a new engine lubricant

A simple bench-scale test procedure may provide information more quickly, cheaply and reproducibly than a full-scale test

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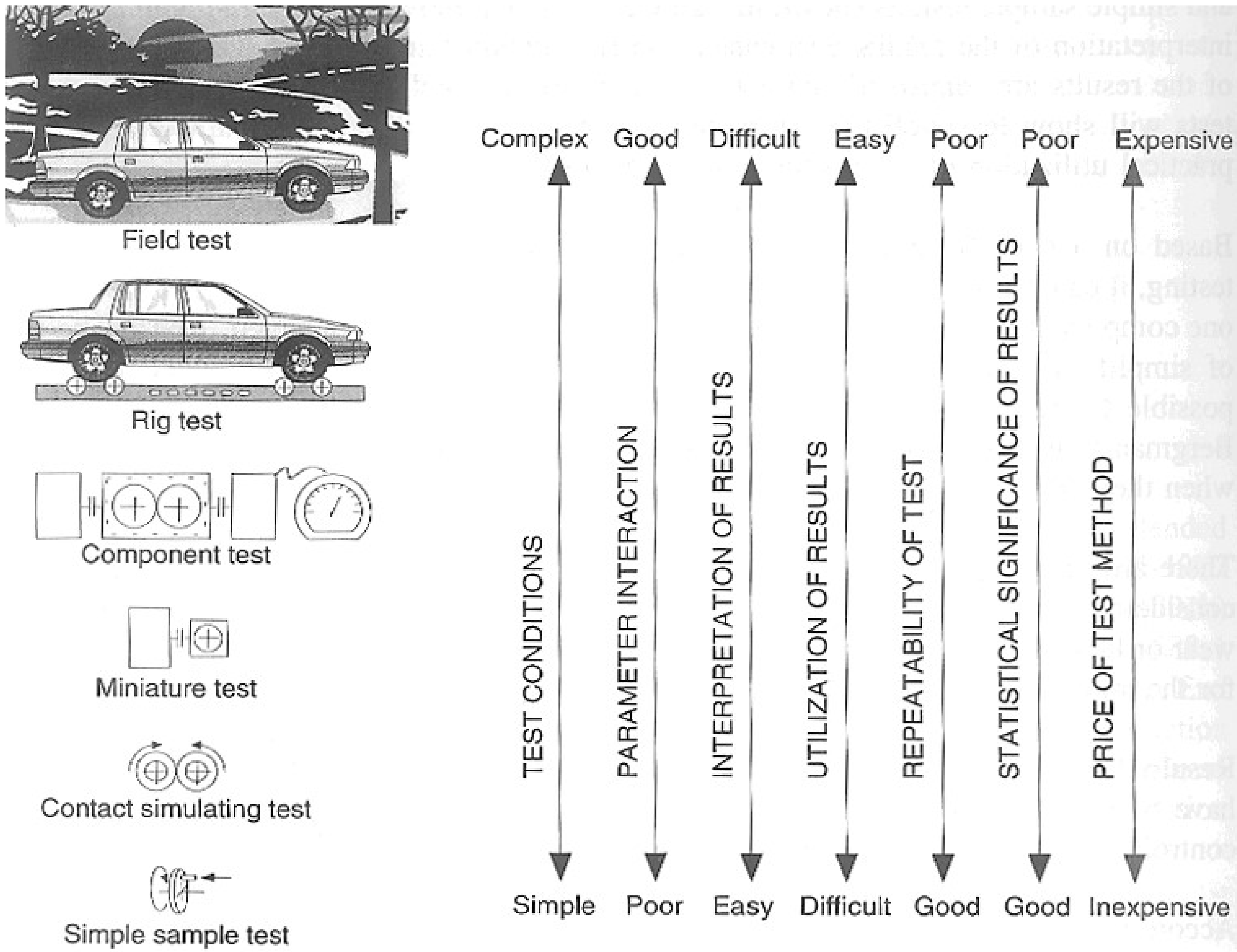
What level of testing is appropriate ?



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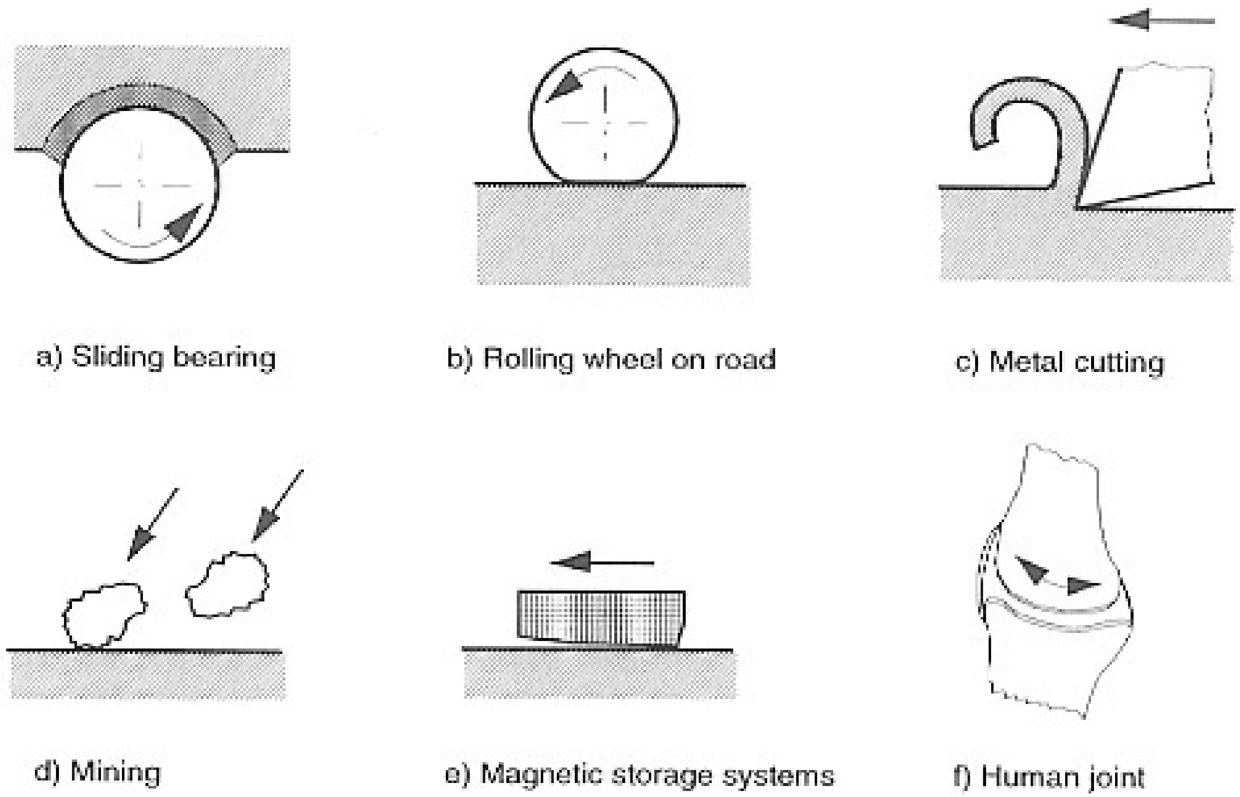
What are the true ***in-service*** conditions?



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BENCH TESTING:

•Usually want to simulate real "in-service" conditions (if we know them !)

•Identifying contact conditions can be difficult, both in the practical application or in the test setup

•Should try to change dependent variable of the real process into independent or non-interacting (and hence controllable) variables in the test

•To design an adequate model to emulate the wear and/or failure mechanisms of the application

//// Tribological Testing

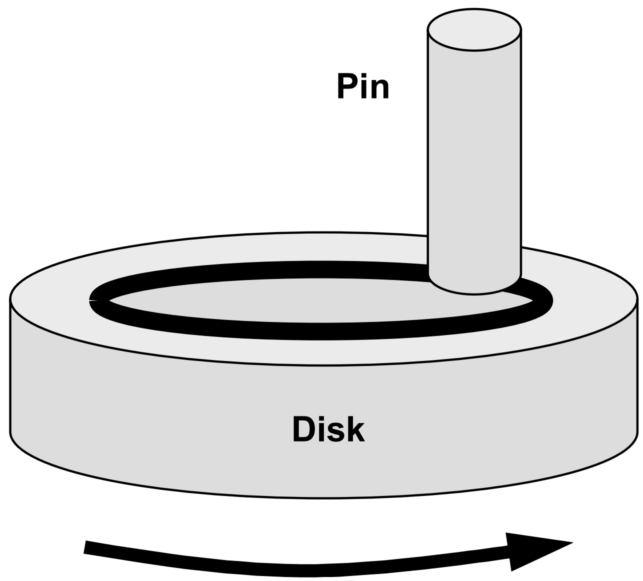
Environment (T, RH, V)

Lubrication Conditions

Hardness

Applied load

Modulus



Contact Area

Surface Roughness

Local Stress

Wear Mechanism

Thermal History

Speed/Velocity

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//// Reproducibility in Tribotesting

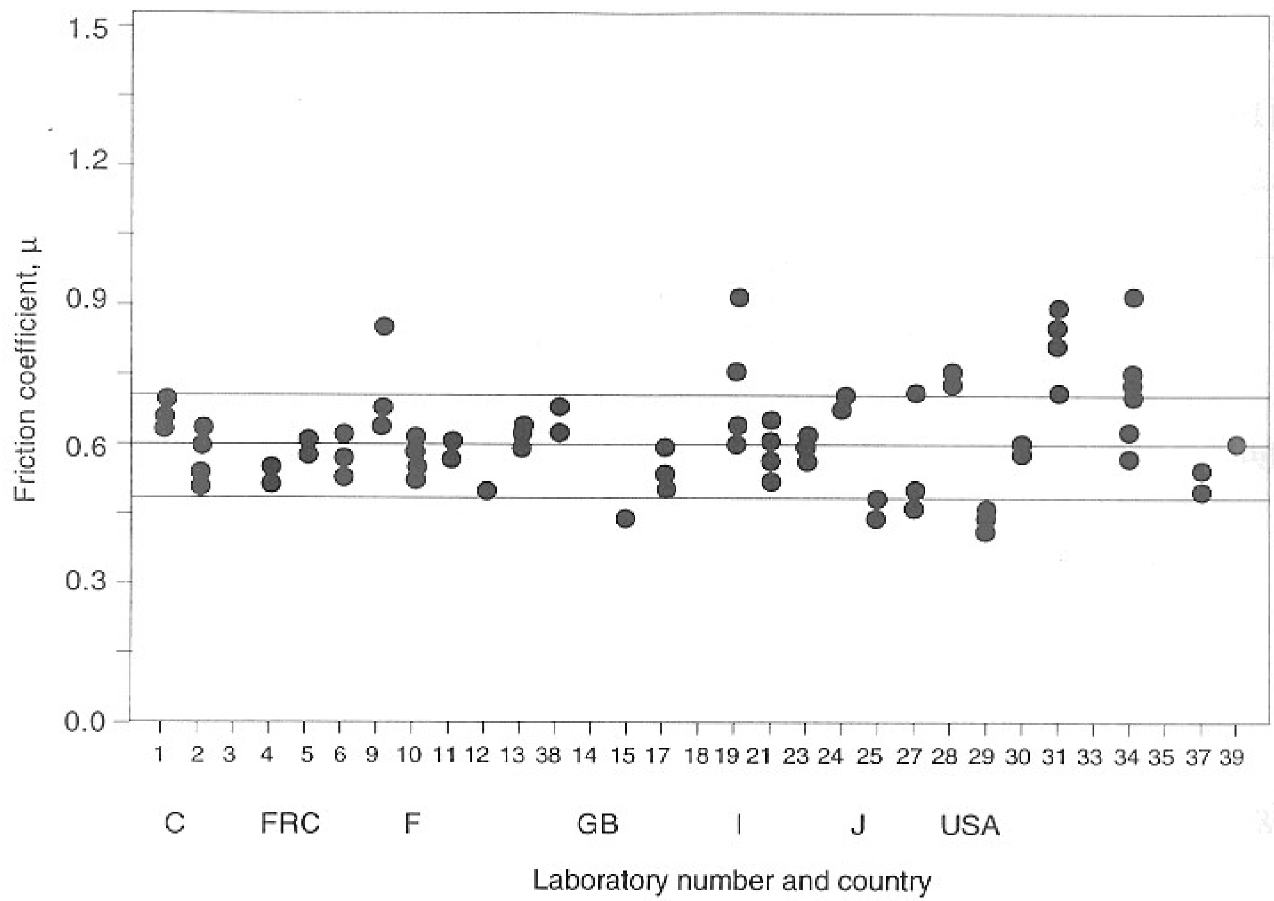
Friction tests (steel ball sliding on steel disk) performed with identical conditions in 39 different laboratories worldwide.

Mean value = 0.600

Standard deviation = 0.109

Variations mostly due to differences in environment (atmosphere, temp. and RH)

(From VAMAS round robin 1987)



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<u>KEY PARAMETERS:</u>

•**CONTACT PRESSURE**: defined by geometry of contact, applied load & material bulk properties

•**GEOMETRY**: Defined by shape of surfaces and effects such as thermal distortion and wear

•**LOAD**: Influenced by dynamics of the contact and foreign body effects (dirt, debris)

•**TEMPERATURE**: Measuring bulk temp. poses little problem; measuring contact temp. is difficult, as frictional heating generates huge transient temperatures in the contact (flash temperatures) which are surface effects only

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IDEALIZED SIMULATIONS:

Fundamental Studies: Evaluating performance of an elemental component under a wide range of different but idealized conditions. Parametric tests and wear mapping may be useful.

Quality Control: Measuring a key feature of a product or component using an idealized single-point test. Outcome may be a simple pass/fail result. Procedures usually standardized to ASTM, DIN or ISO methods

REAL LIFE EMULATION:

Product Development: Investigation and prediction of in-service wear or failure mechanisms. Improvement of performance of a product in a specific application. Few standard test procedures, requires analysis and interpretation of resulting data

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//// Tribological Testing

Establishing the experimental requirements:

•Evaluation of real life performance requirements and identification of areas of critical importance

•Design of experiments and test procedures that "focus" on these requirements

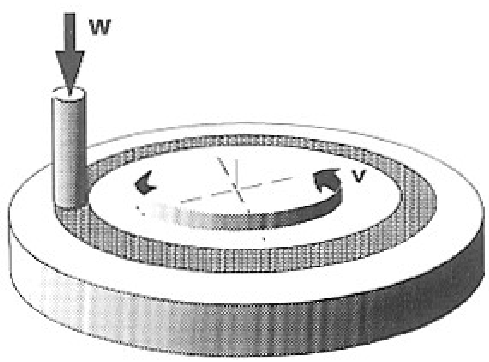
•Evaluation of whether it is possible to accelerate test without seriously compromising the mechanisms and processes to be emulated

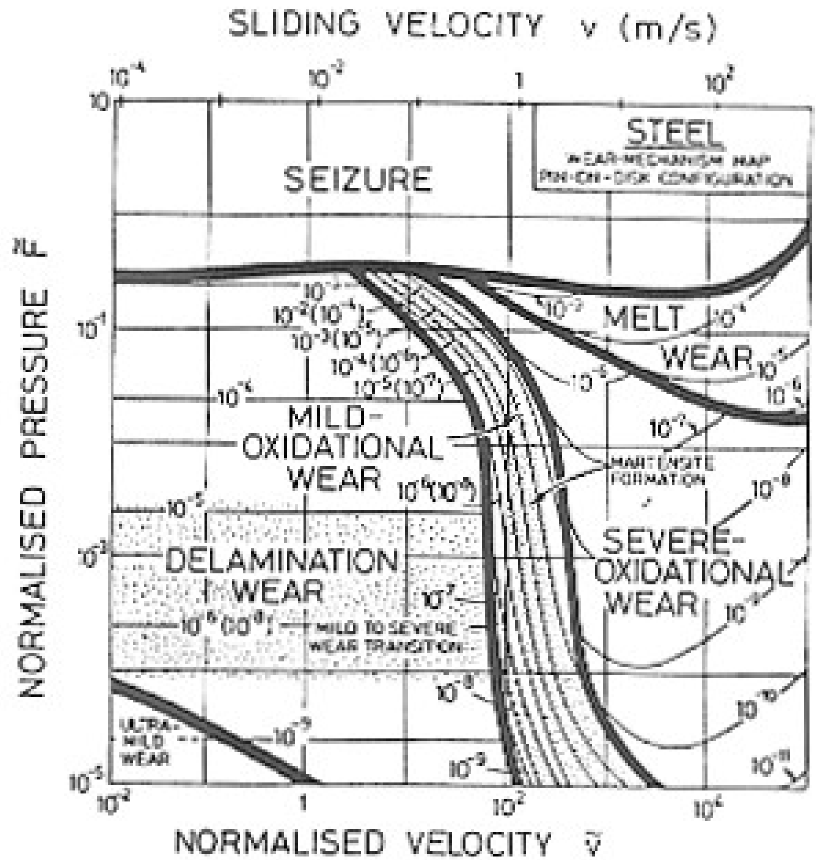
//// Tribological Testing: Wear Mapping

•Wear mapping of different wear regimes in terms of 2 parameters which are critical to the application

•Can combine experimentally derived data with other published results to understand the big picture

•Can help to evaluate where more uncontrolled transition regimes may appear





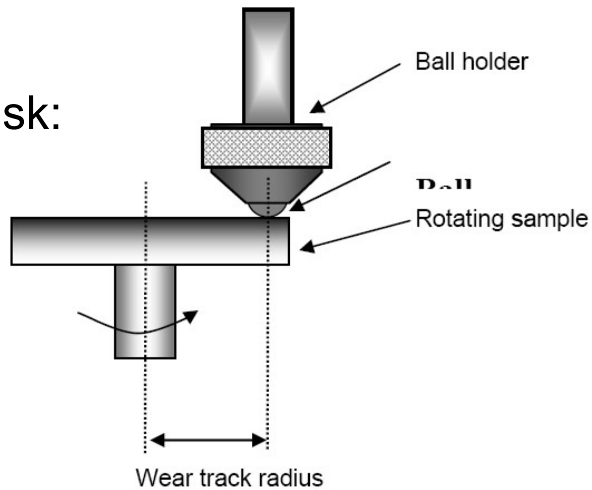
Typical wear map for steel-on-steel, using pin-on-disk

//// Overview of commonly used test configurations

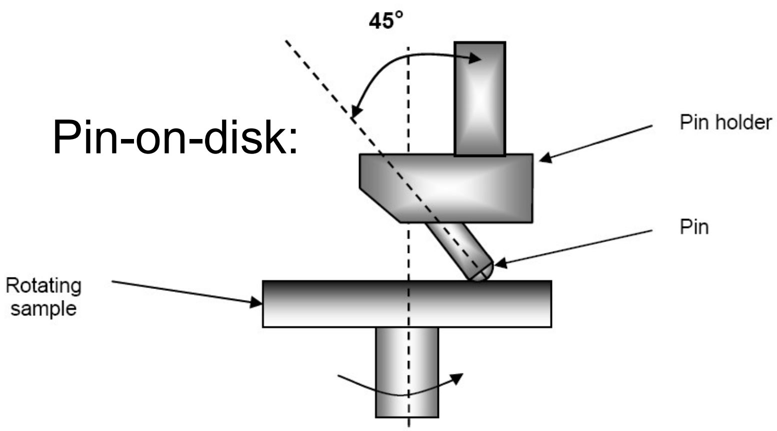
1. Pin-on-Disk Test (rotating and angular/linear reciprocating)
2. Pin and Vee Block Test
3. Block on Ring Test
4. Four Ball Wear Test
5. Fretting (SRV) Test
6. Abrasion & Erosion Test
7. Calowear Tester
8. Tabor Abraser
9. Scratch Test
10. Dedicated Tribo testing, e.g., Hip Joint Simulation
11. Custom in-situ tribology tests

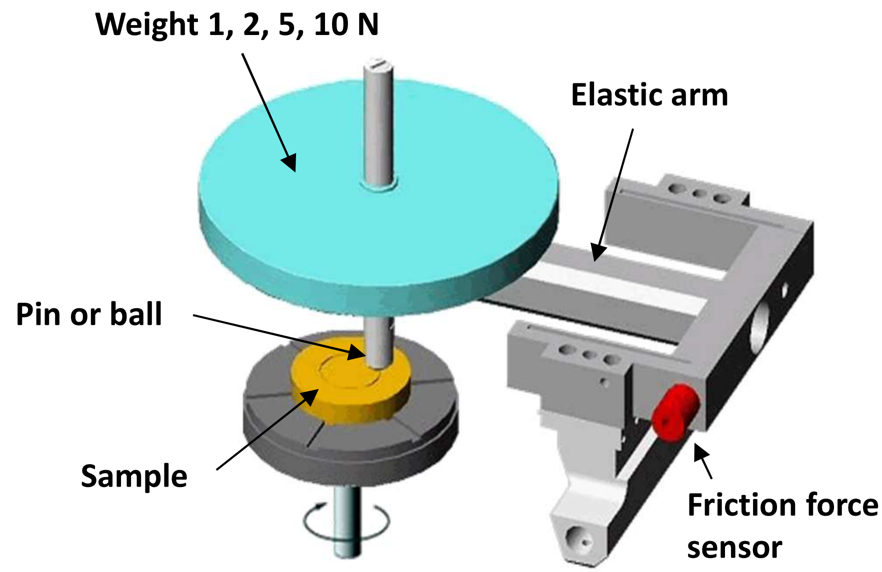
//// Pin-on-Disk Tribometer

Ball-on-disk:



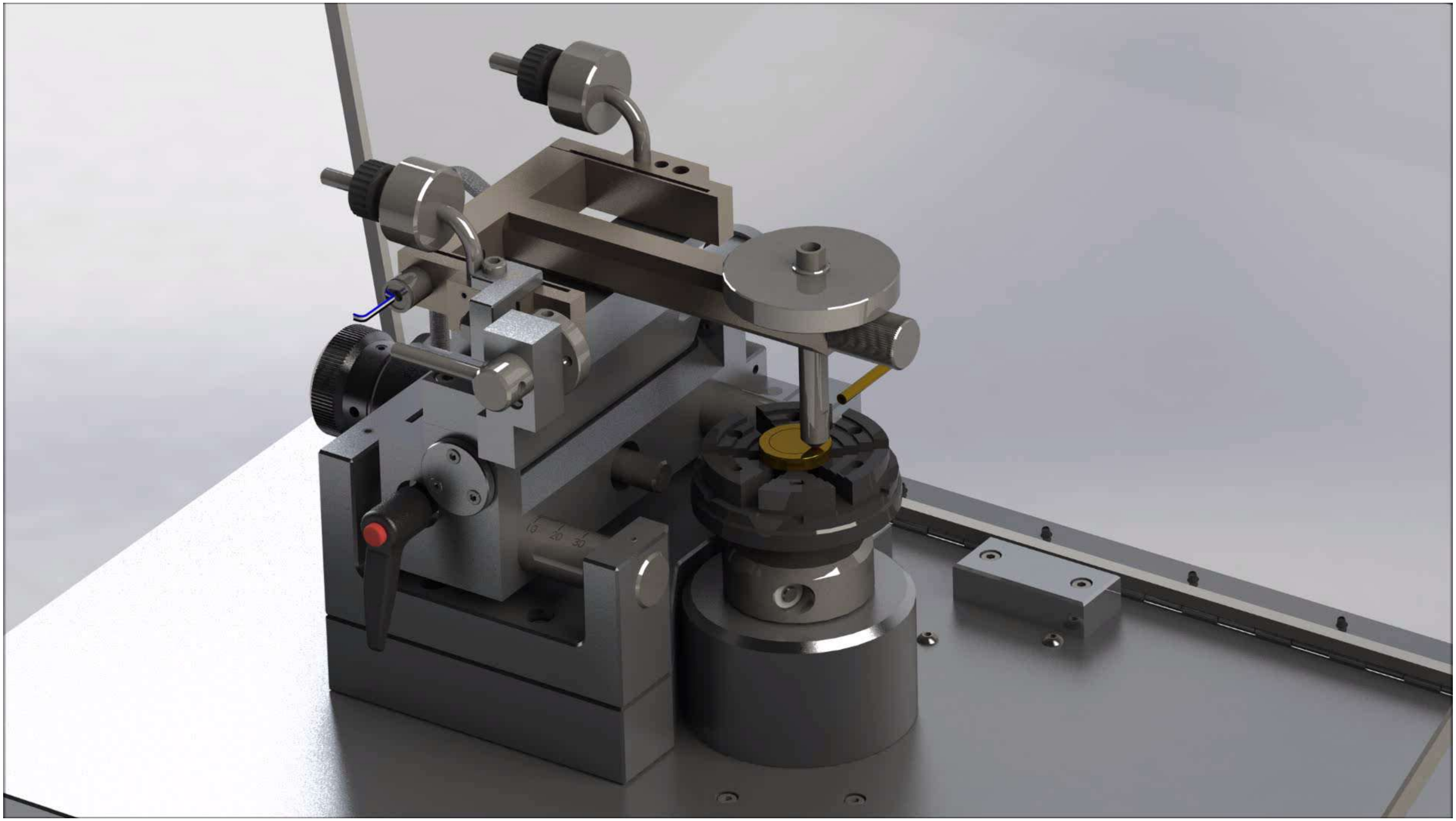
Pin-on-disk:





- Rotation speed: 0.03 – 500 rpm
- Standard loads: 1, 2, 5, 10 N (max. 60 N)
- Disk diameter: up to 60 mm
- Friction force: up to 10 N

//// Pin-on-Disk Tribometer: Rotating



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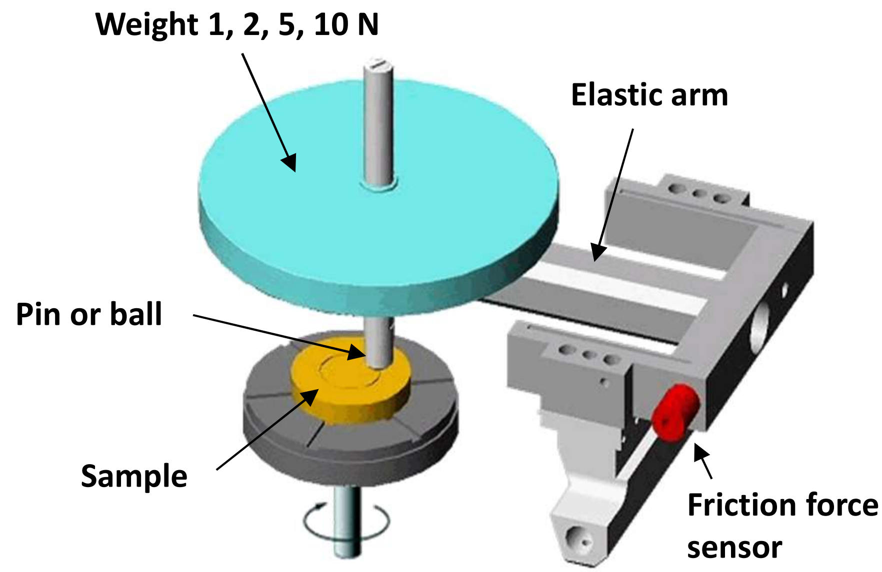
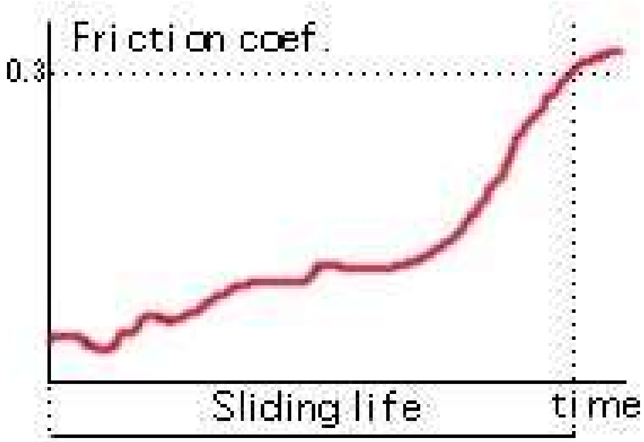
//// Pin-on-Disk Tribometer





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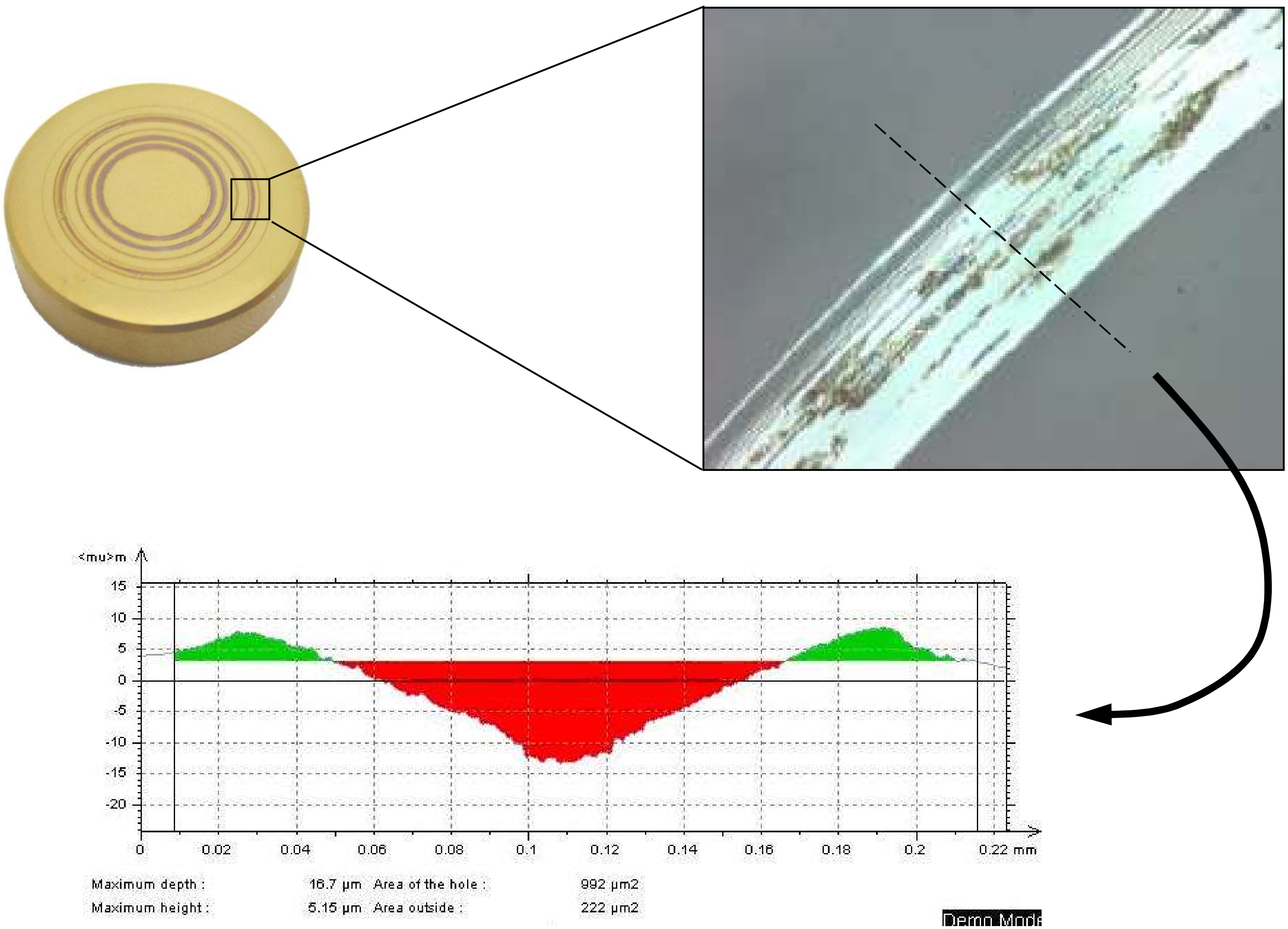

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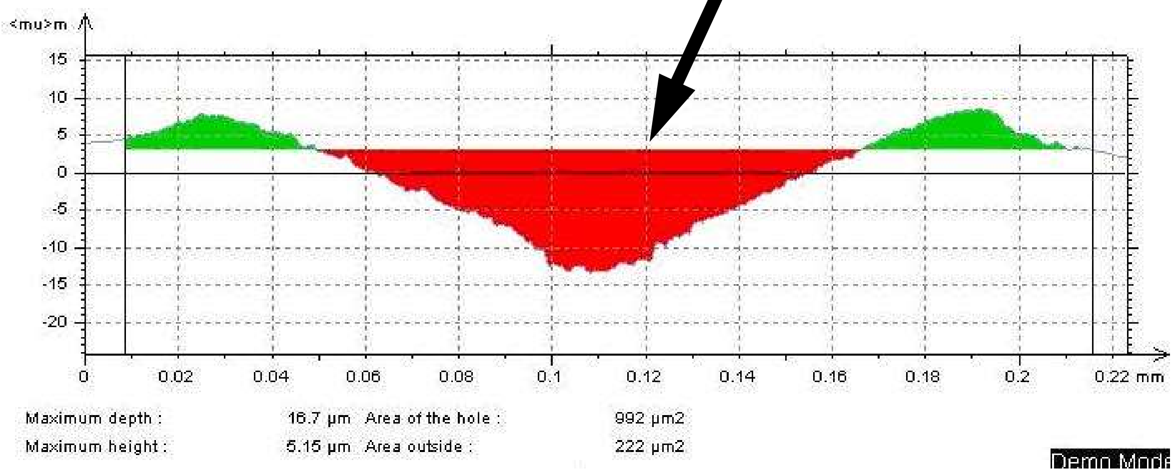
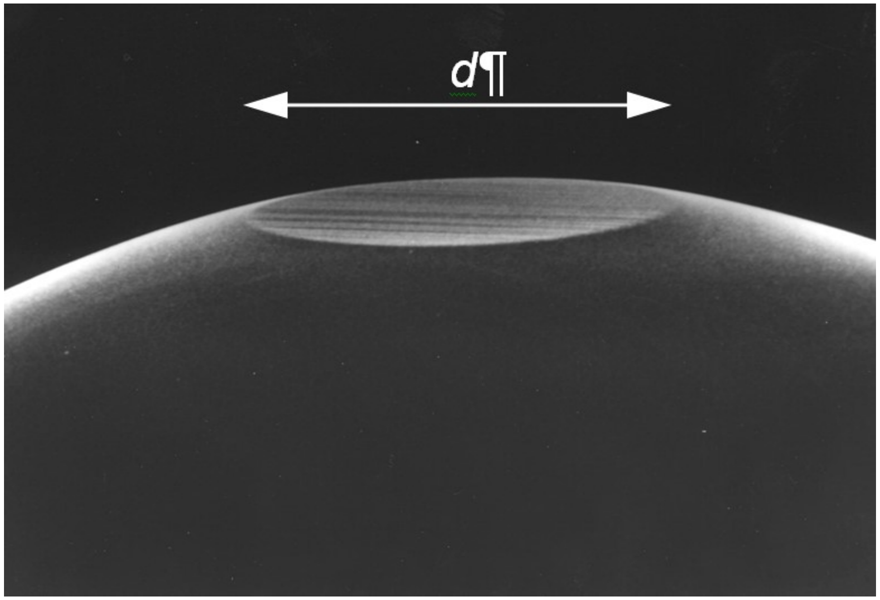
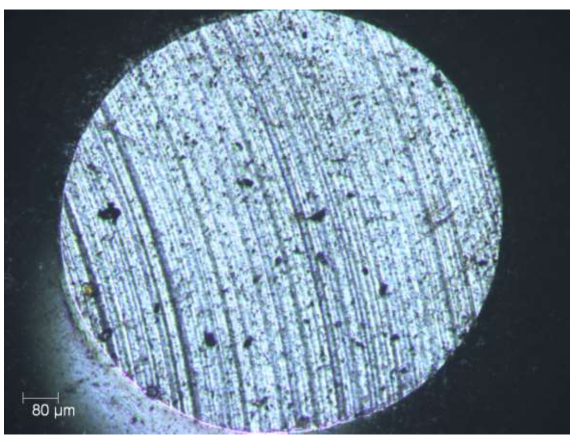
//// Pin-on-Disk Tribometer

Volume of wear debris removed, V = **<u>Worn area</u>** x wear track circumference



//// Pin-on-Disk Tribometer: Ball Wear Rate





The height, h, of the worn cap is given by:

$$h = R - \sqrt{R^2 - \frac{d^2}{4}}$$

The volume, V, of the worn cap is then:

$$V = \frac{1}{3}\pi h^2 (3R - h)$$

And the wear rate of the static partner is thus:

$$WearRate_{Partner} = \frac{V}{L.Fn}$$

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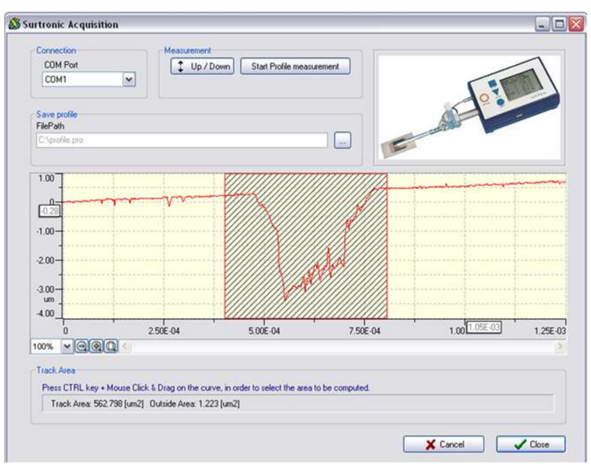
//// Pin-on-Disk Tribometer : Integrated Profilometer



> Technical specifications

> Pick-up

- Gauge range — 300 µm
- Resolution — 0.01 µm
- Accuracy — 2 % of reading + LSD µm
- Pick up type: — inductive
- Gauge force — 150-300 mg
- Diamond stylus — Tip radius 5 µm unless otherwise specified

> Instrument

- Cut off value — 0.25, 0.8, 2.5, 8mm
- Filter — 2CR or Gaussian
- Traverse Length — 0.25 – 25 mm
- Traverse speed — 1mm/sec
- Display Units — µm
- Data output — RS232
- Power — 9V Battery

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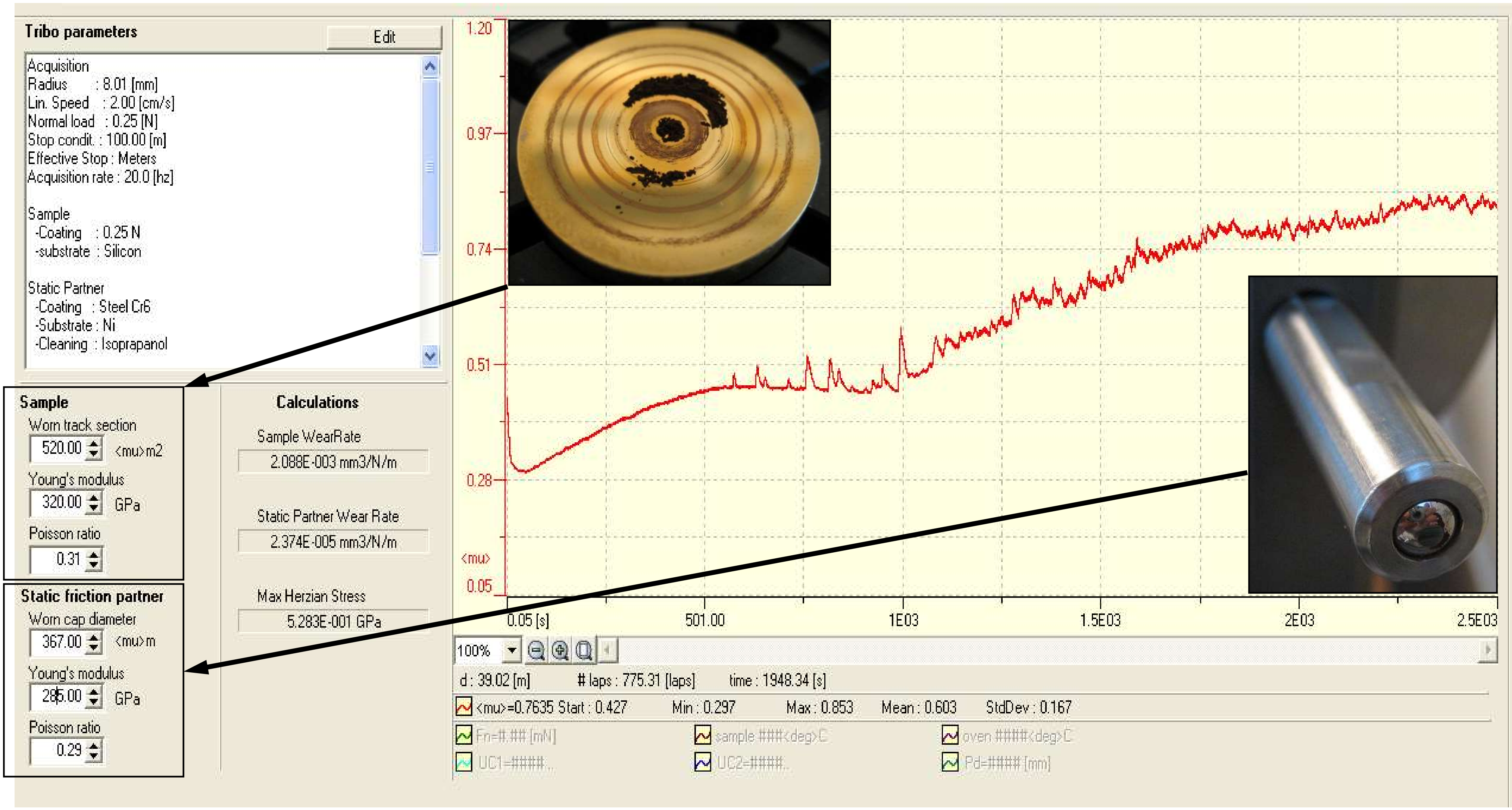
//// Pin-on-Disk Tribometer : Wear rate



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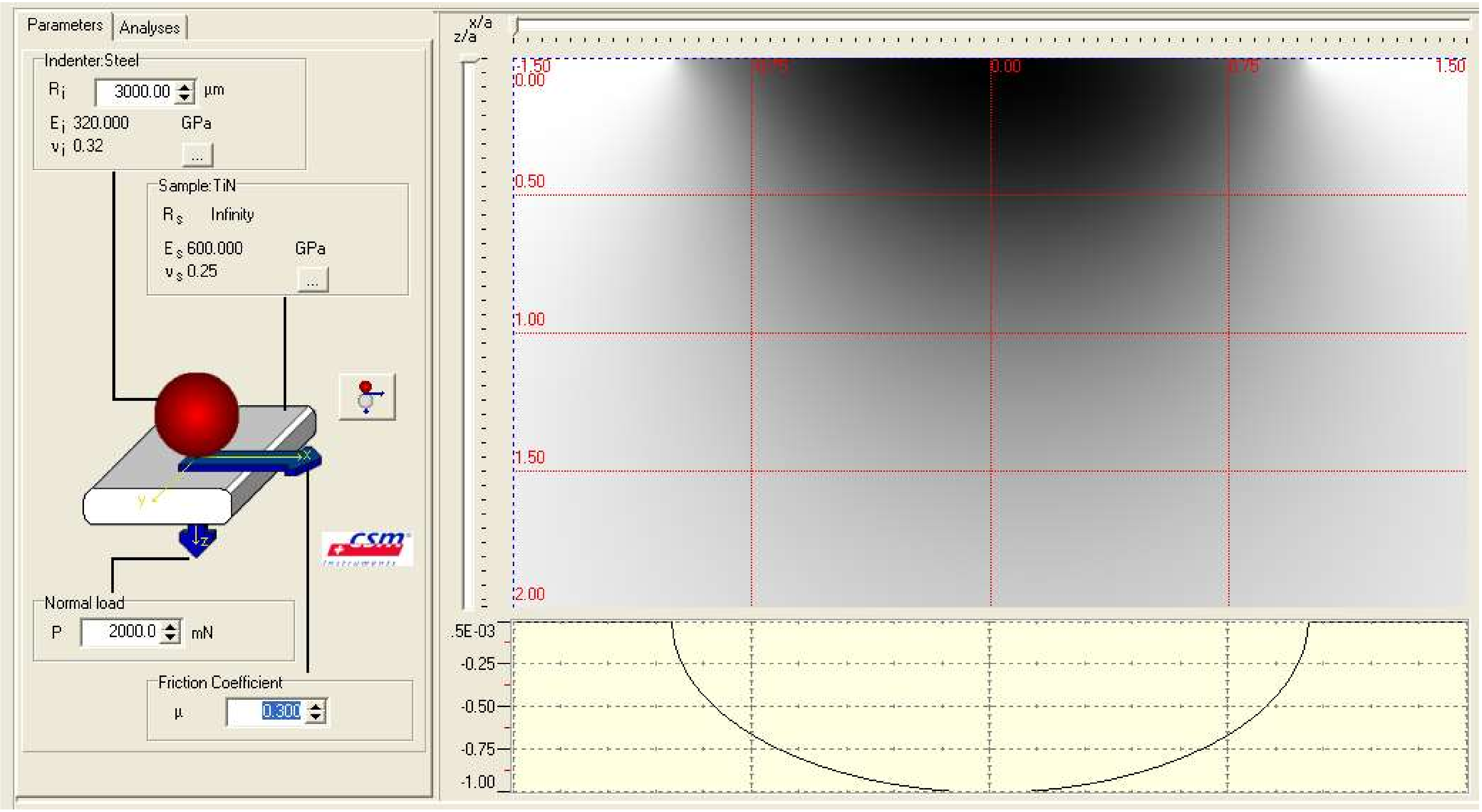
//// Pin-on-Disk Tribometer : Contact modelling



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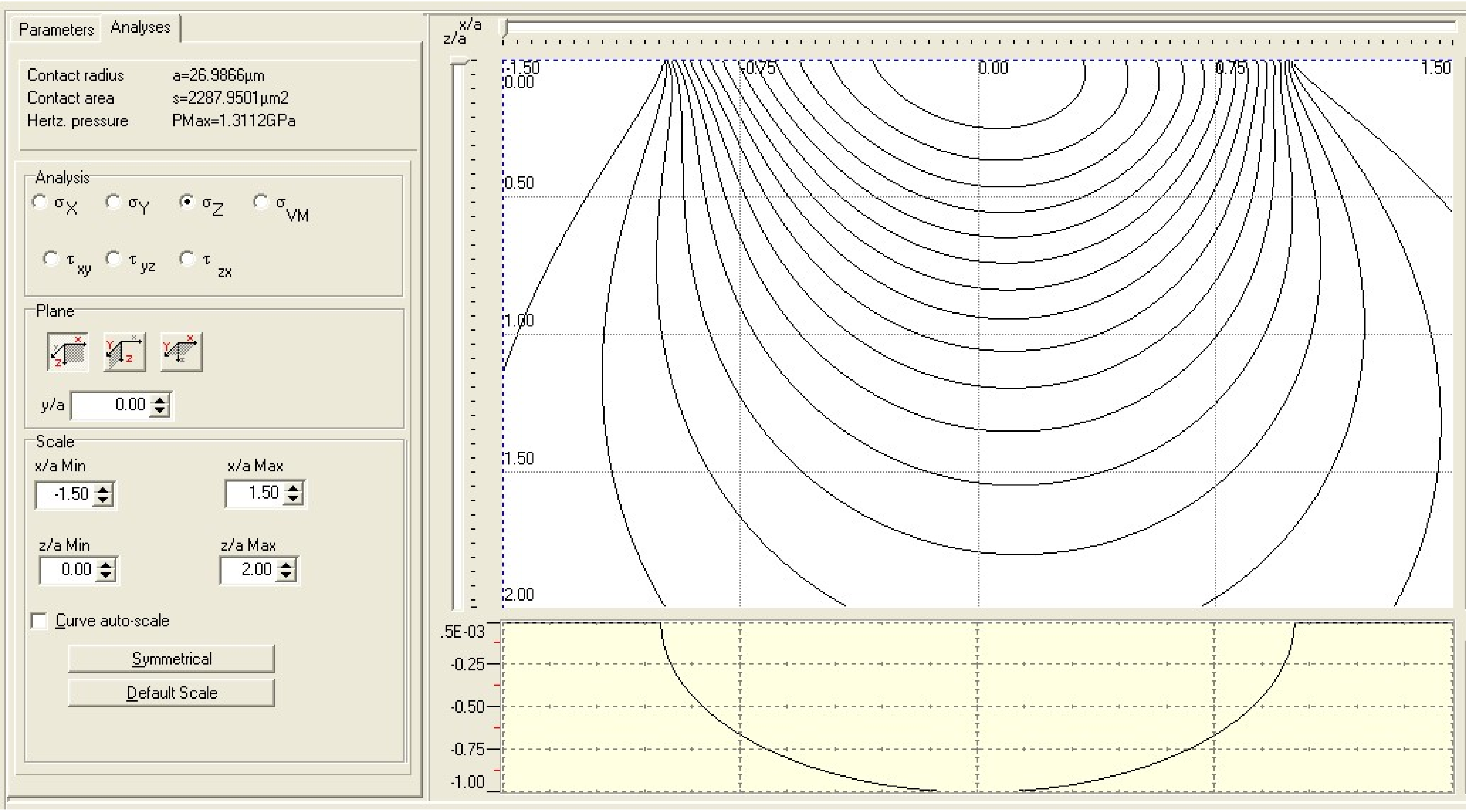

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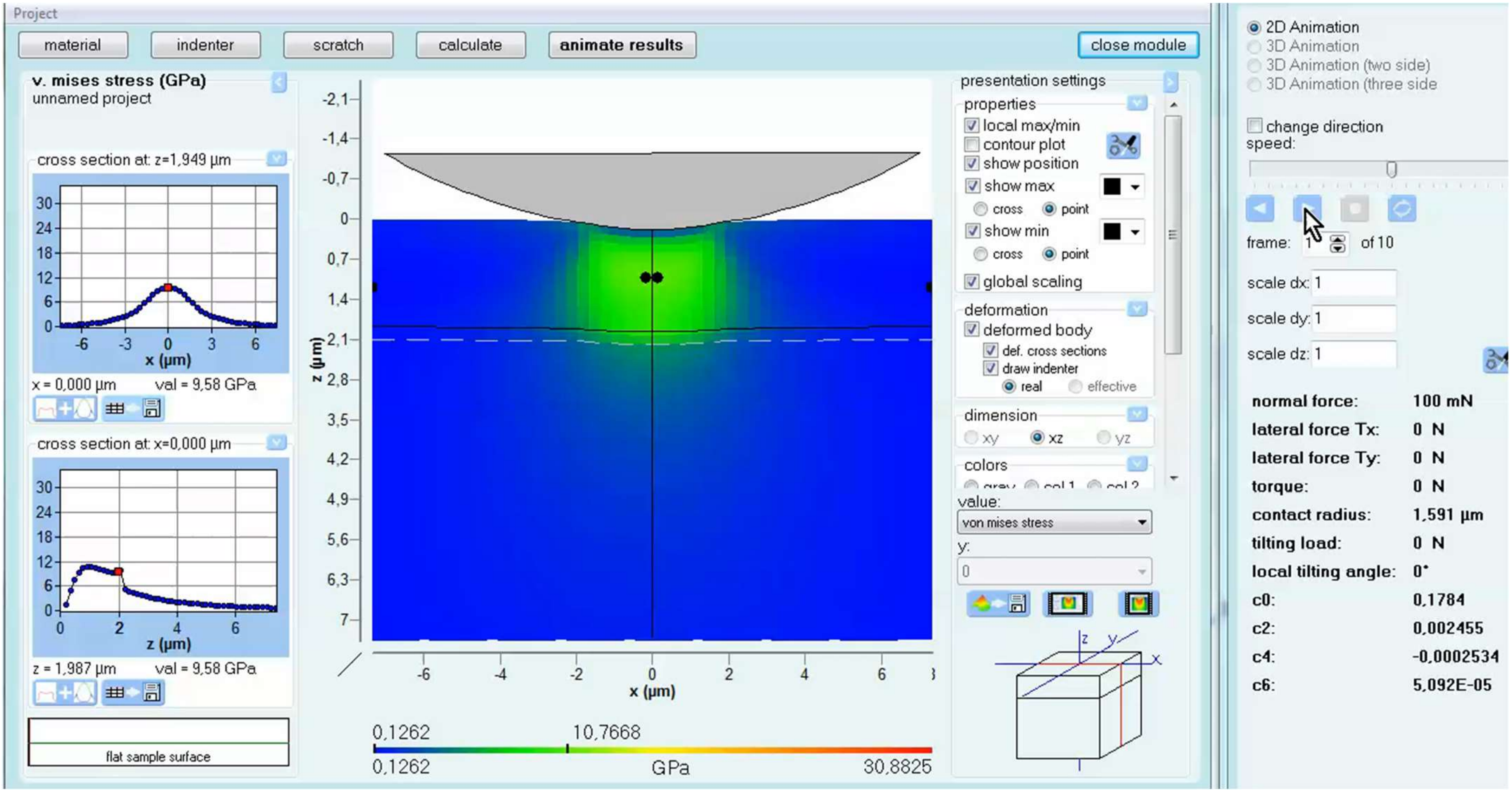
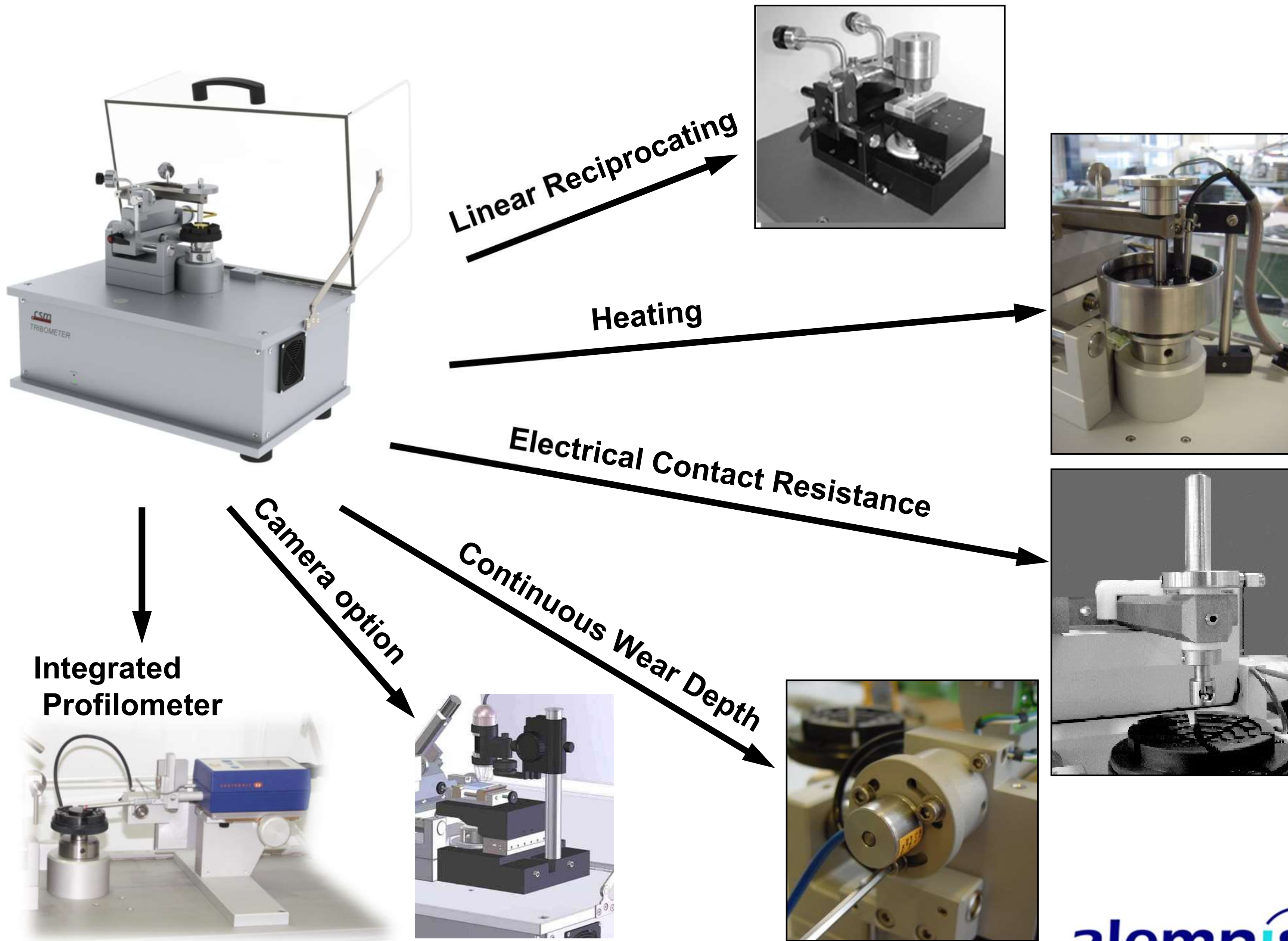
//// Pin-on-Disk Tribometer : Contact modelling



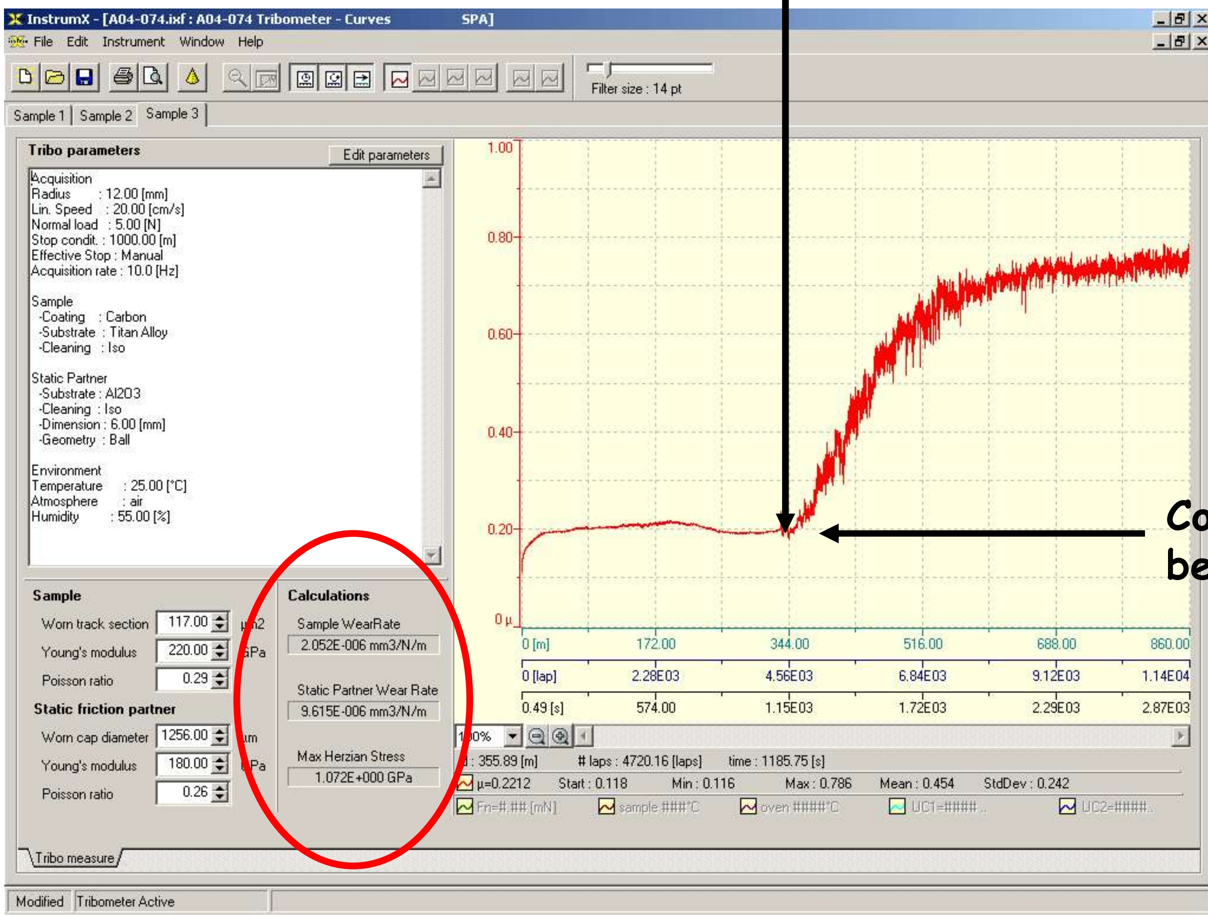
20 µm indenter applying load 100 – 1000 mN on a 2 µm thick ceramic coating on steel

//// Pin-on-Disk Tribometer Options



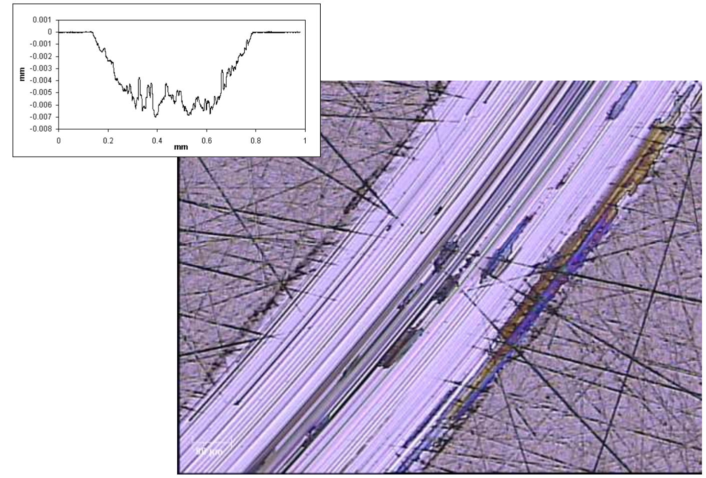
//// Pin-on-Disk Tribometer : CrN on High Speed Steel

Rupture



Friction/wear values

Cœfficient of friction of CrN/HSS pair before coating rupture



Wear track on CrN

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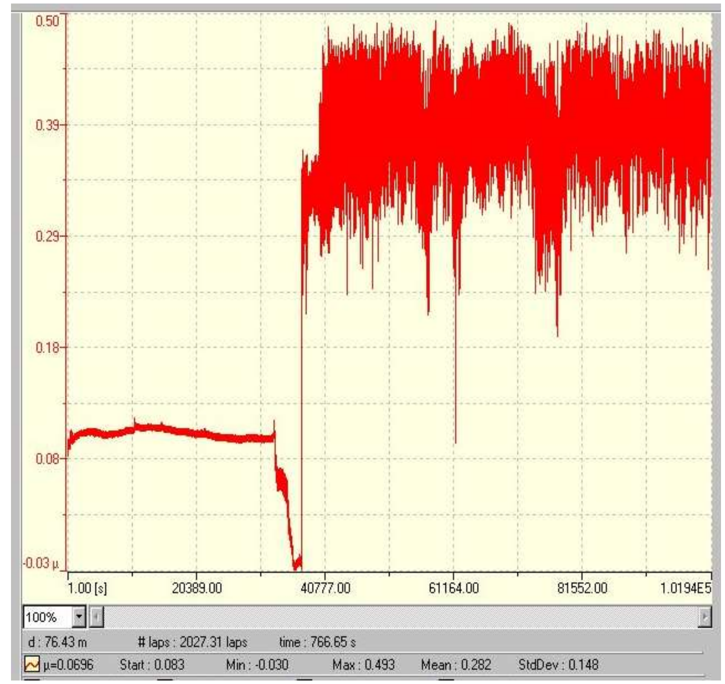
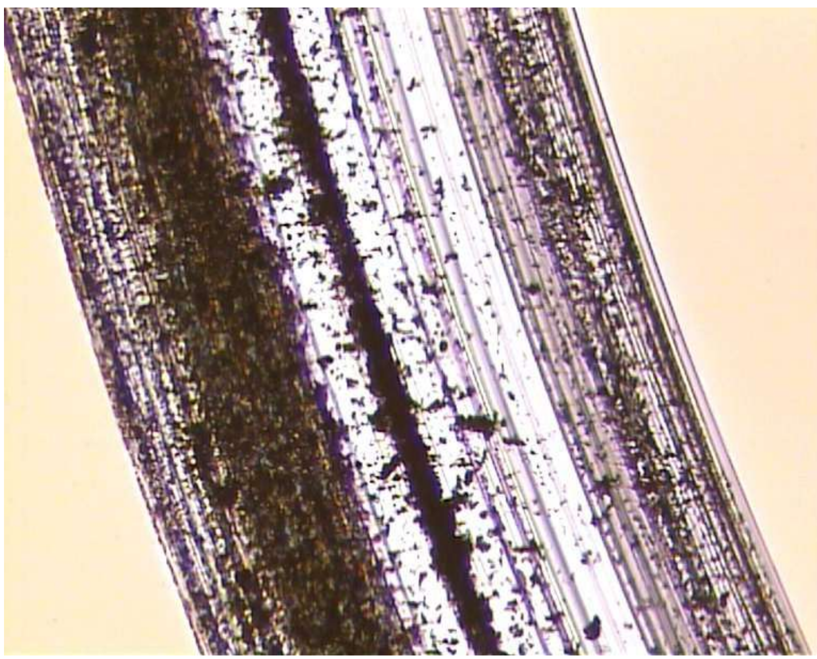
//// Pin-on-Disk Tribometer : SiO_2 Coatings



- Lifetime testing of SiO_2 surface coatings under simulated in-service conditions



- Coating failure observed by optical microscopy

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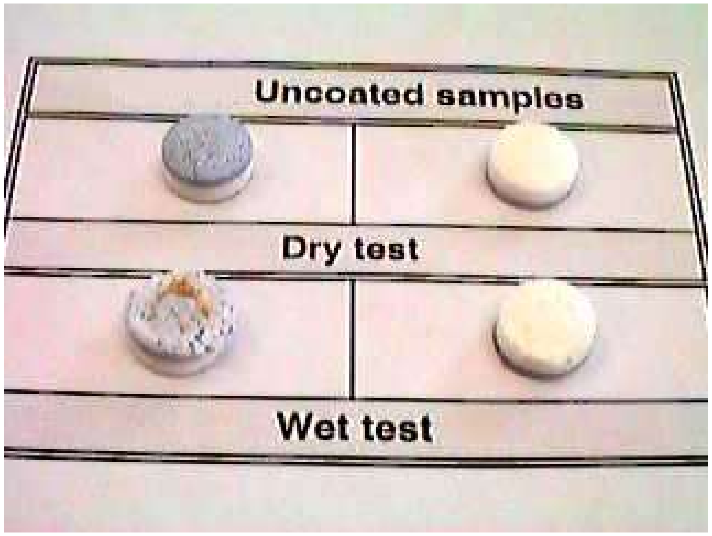
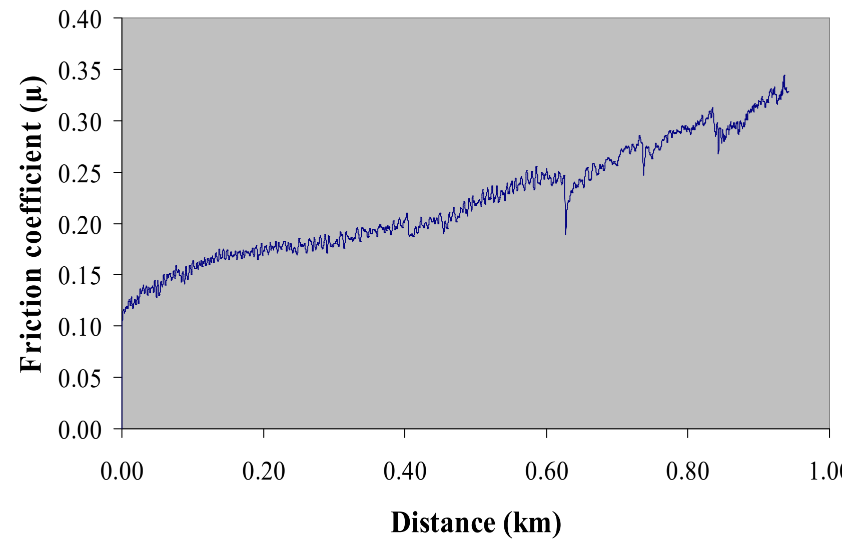
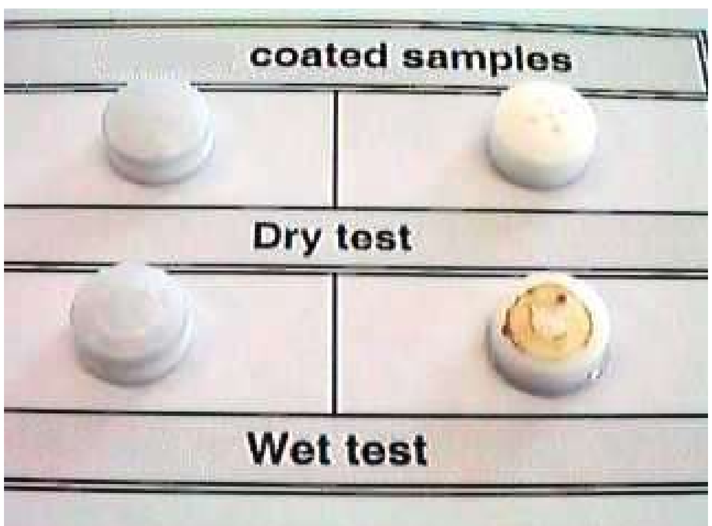
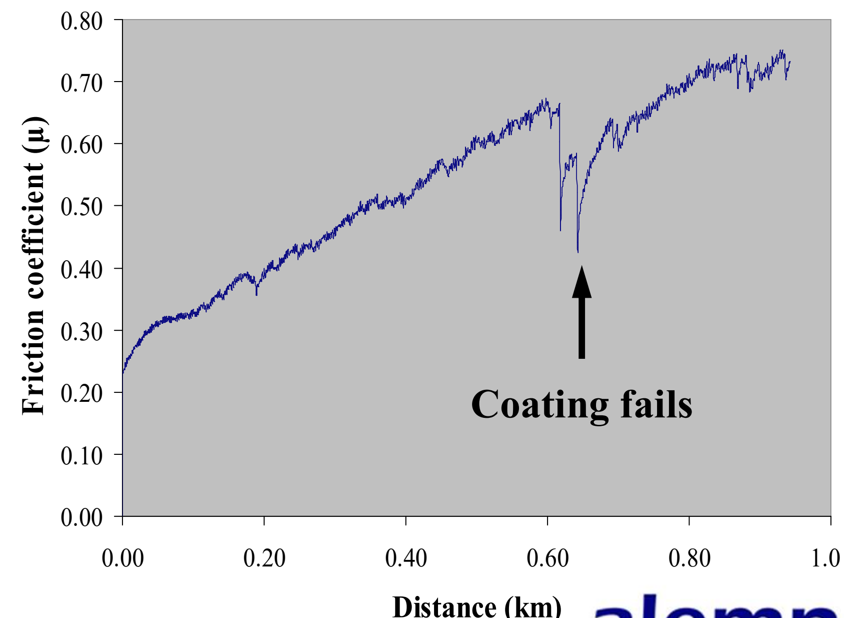
//// Pin-on-Disk Tribometer : Coatings on Pills









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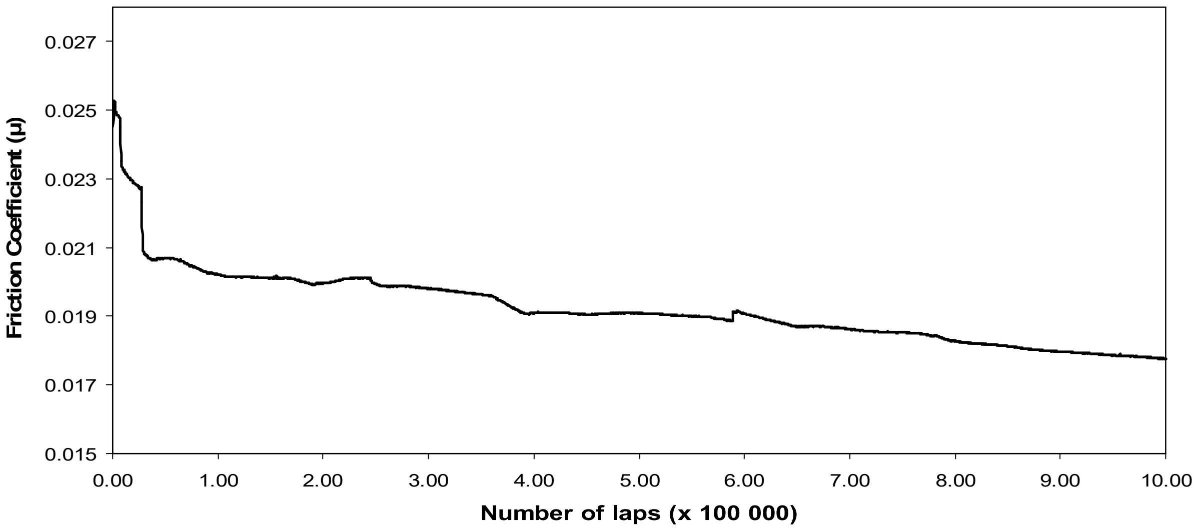
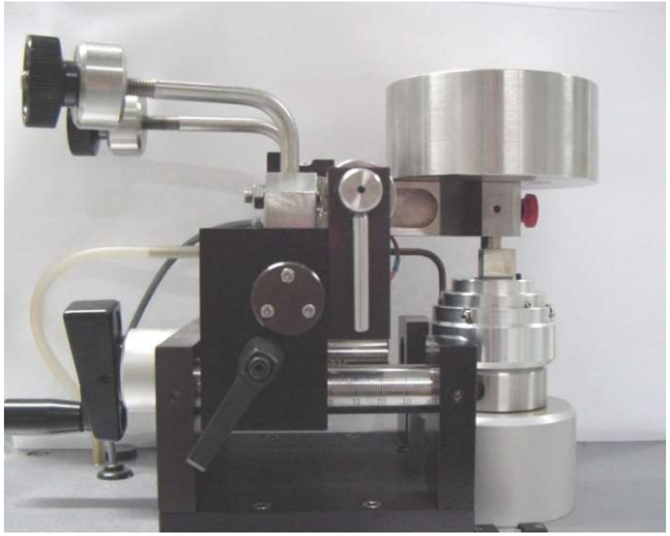
//// Pin-on-Disk Tribometer : Bearings

- Example: Single row bearing
- Applied load: 50 N (excessive)
- Speed: 28 cms^{-1}
- Steady COF not reached, even after 10,000,000 laps





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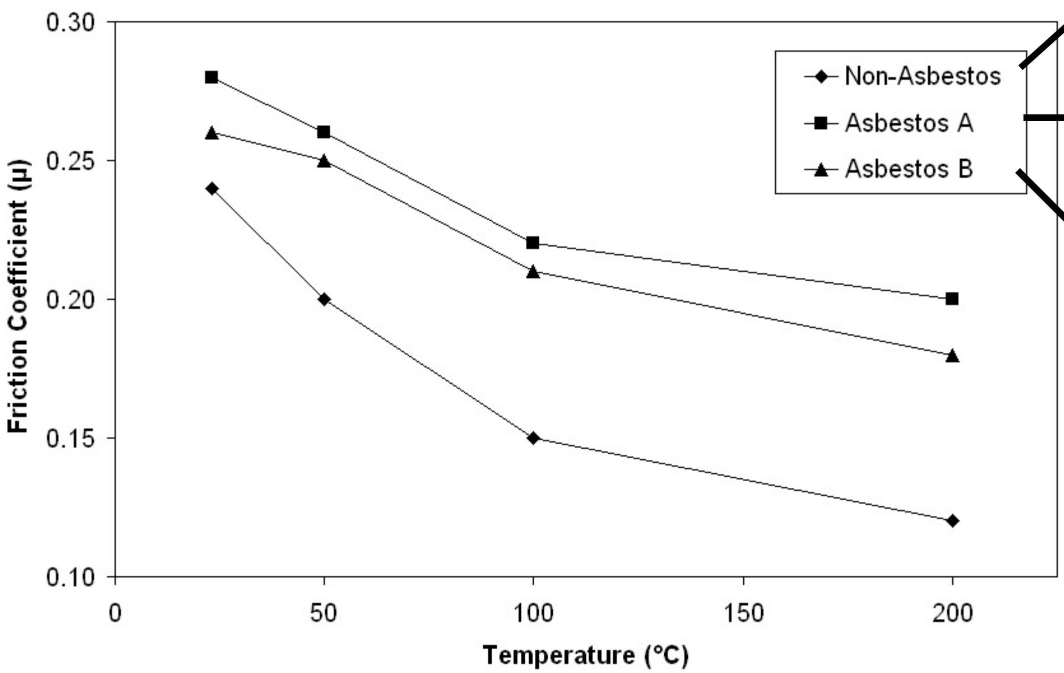
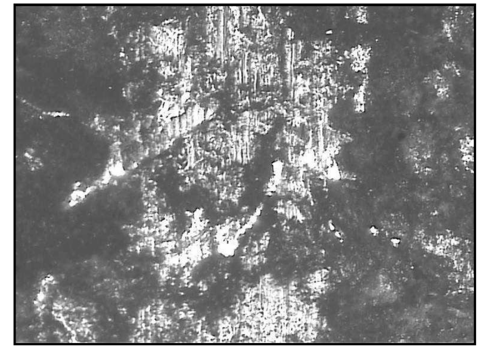
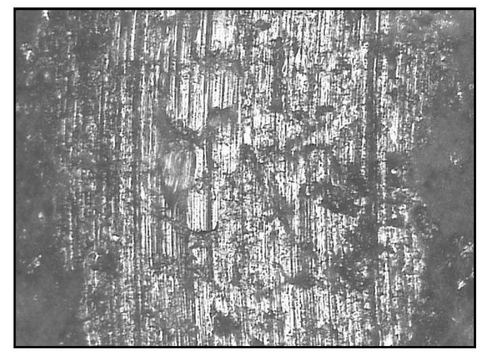
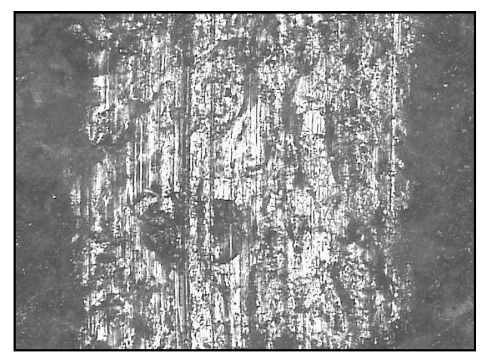
//// Pin-on-Disk Tribometer : Brake Pads

- Example: Brake pads (with and without Asbestos)
- Applied load: 5 N
- Speed: 10 cms^{-1}
- Temperature: up to 200°C

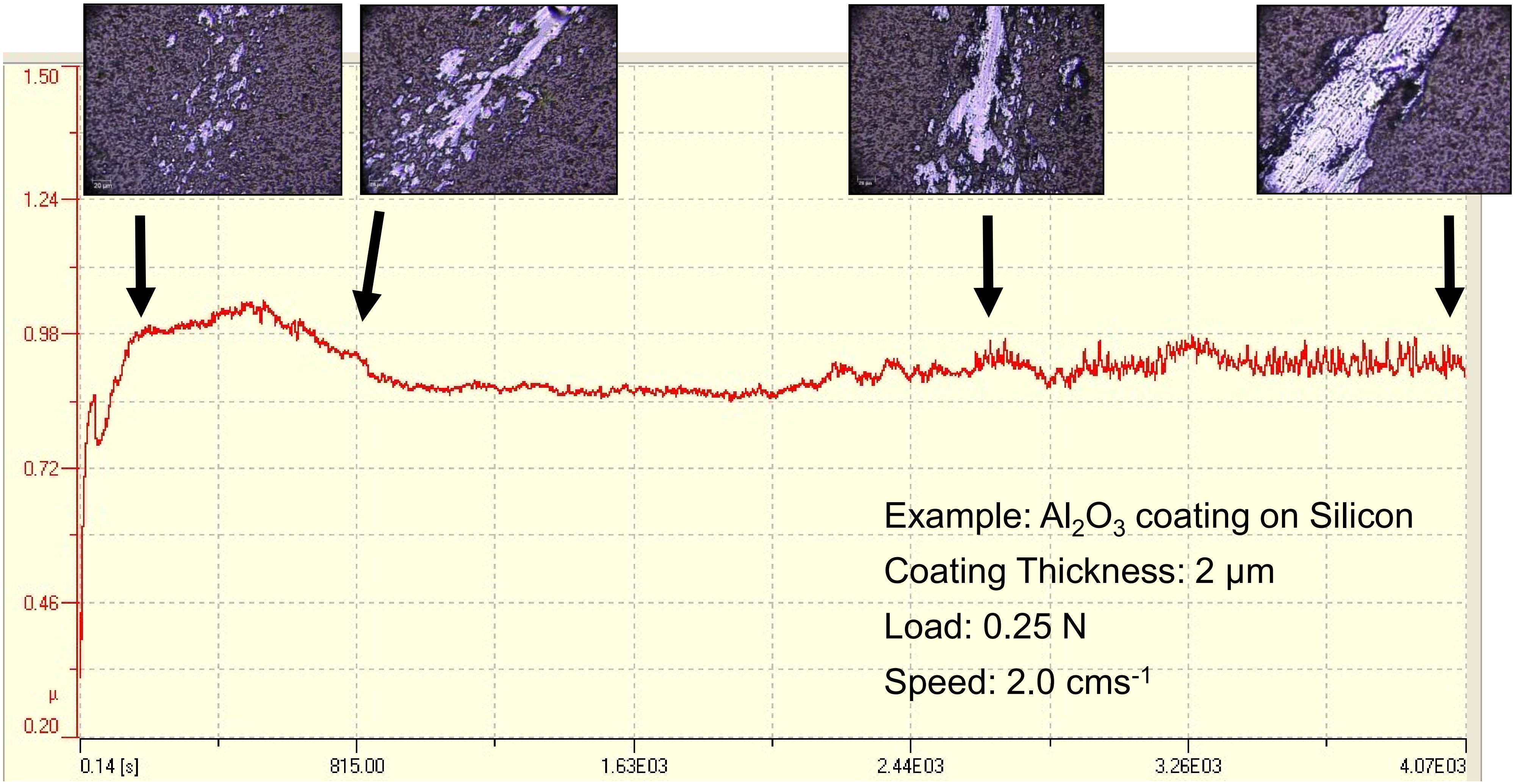








//// Pin-on-Disk Tribometer : Alumina Coating on Si



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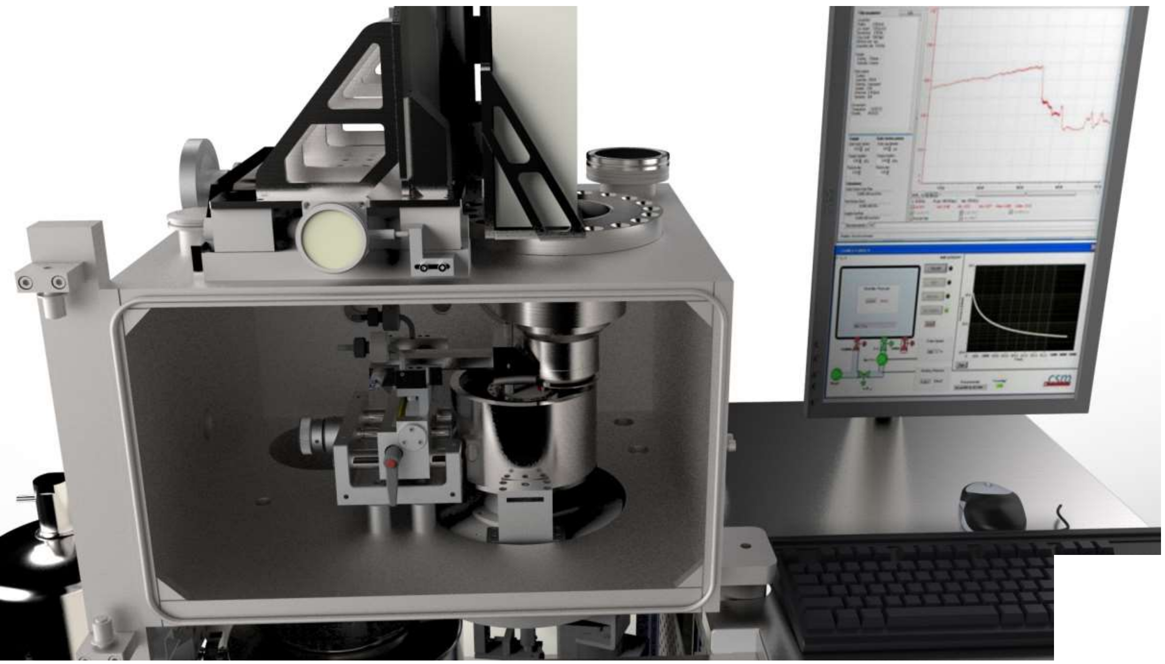
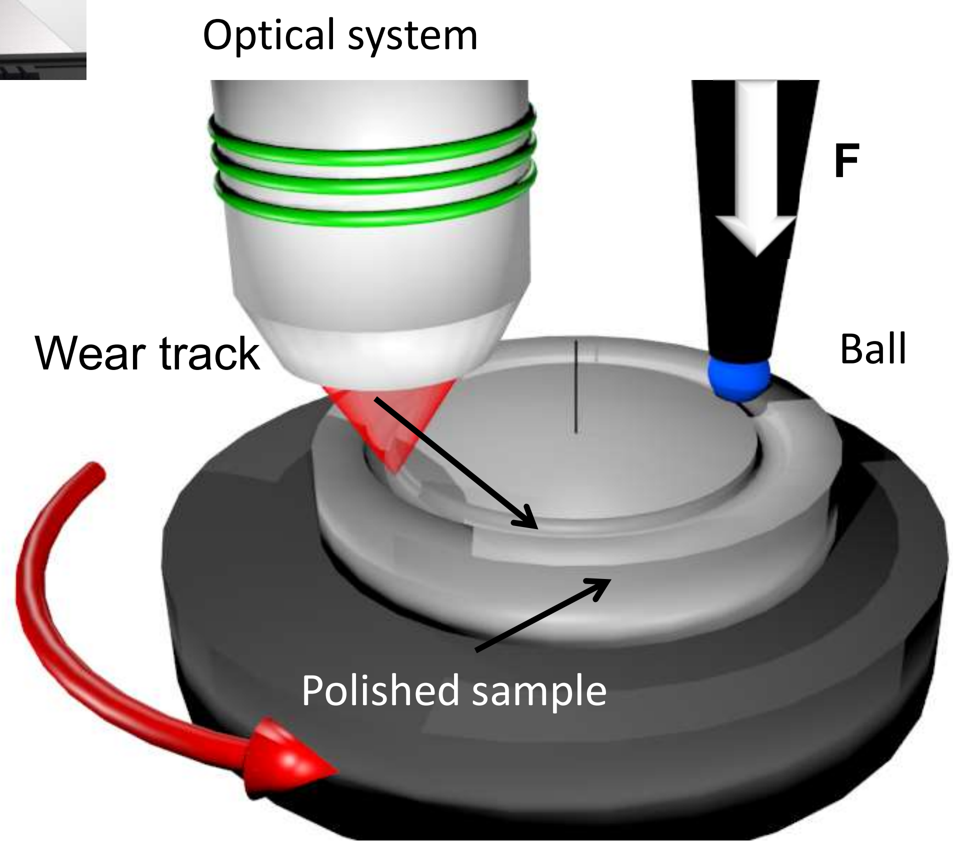
//// Pin-on-Disk Tribometer with in-Situ observation



Ball Dimension	6 mm
Load	1-20 N
Disk Diameter	Up to 50 mm
Temperature	Up to 800°C
Atmosphere	Air, Vacuum 10^{-7} mbar, or controlled flow of gas
Rotational Speed	0.3 - 500 rpm

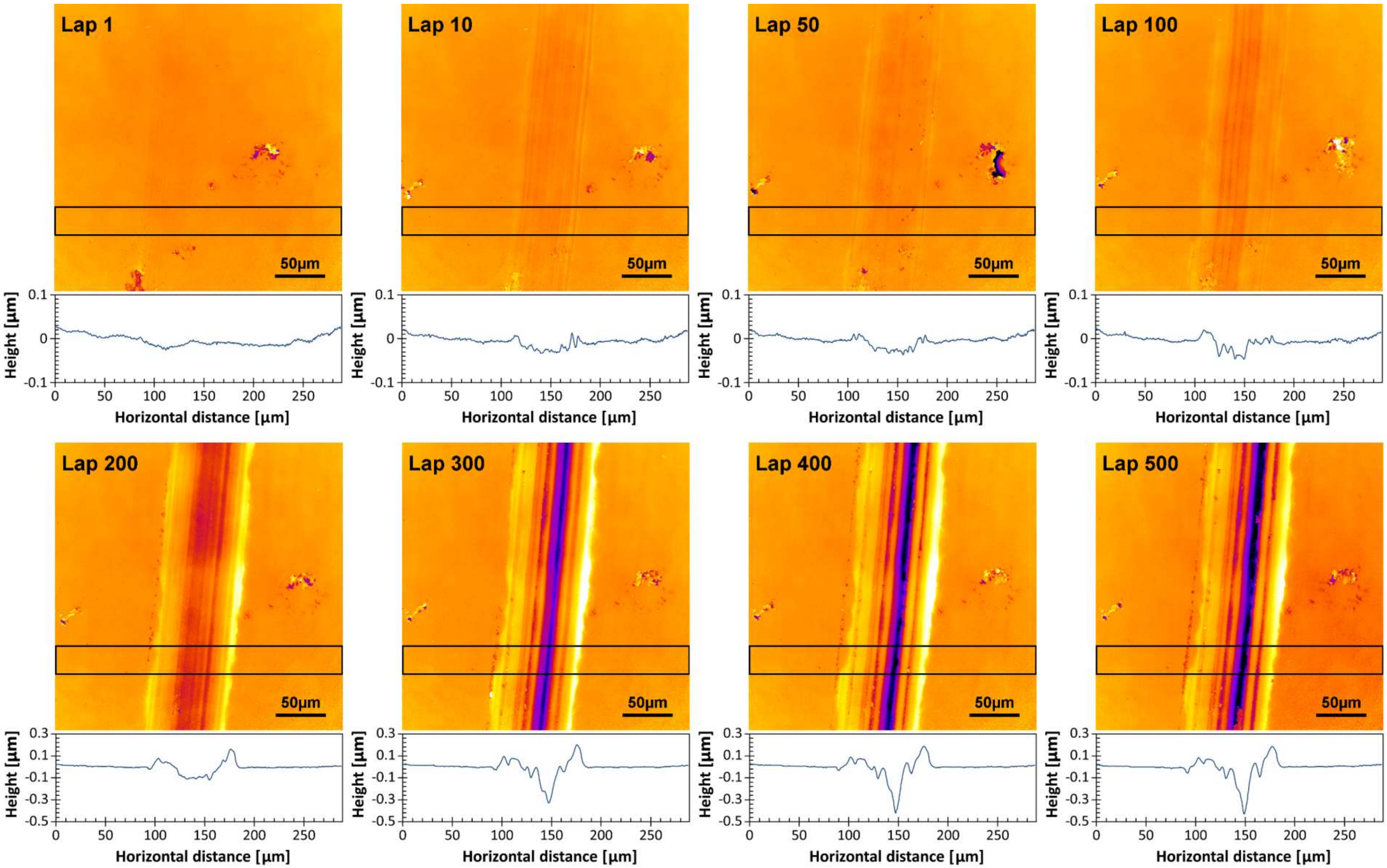


High temperature vacuum tribometer combined with Digital Holographic Microscopy (DHM) for real-time in-situ wear measurement

(Courtesy of Killian Wasmer, EMPA)

//// Pin-on-Disk Tribometer with in-Situ observation

Evolution of wear track in same position as a function of number of laps



(Courtesy of Killian Wasmer, EMPA)

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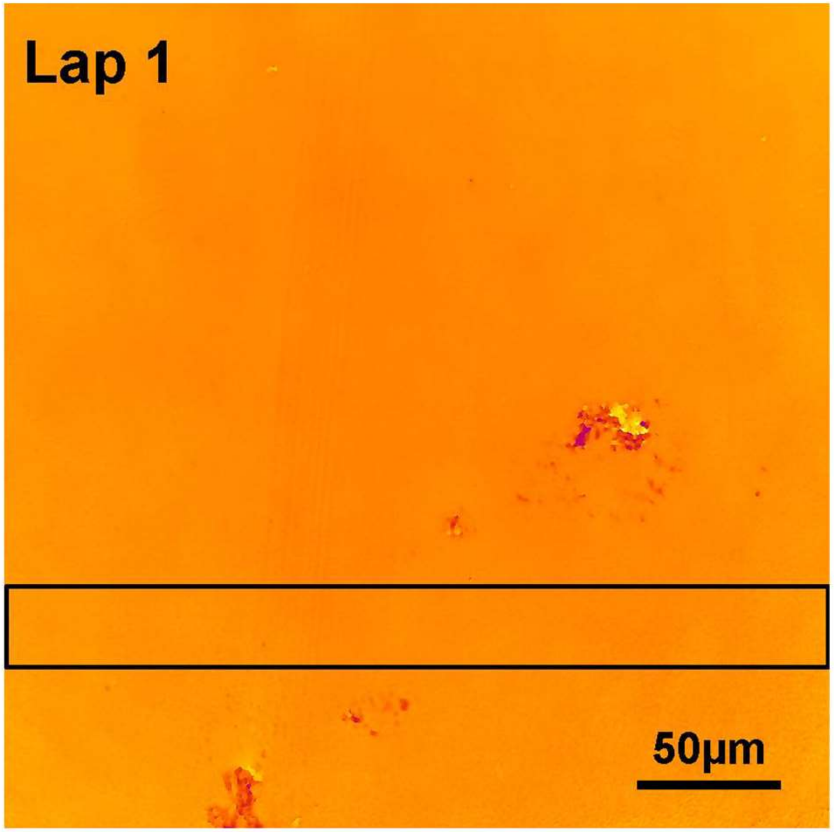
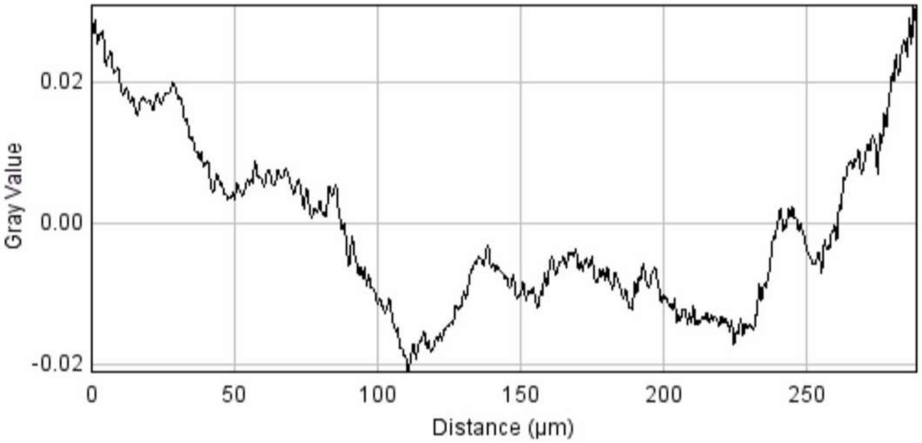
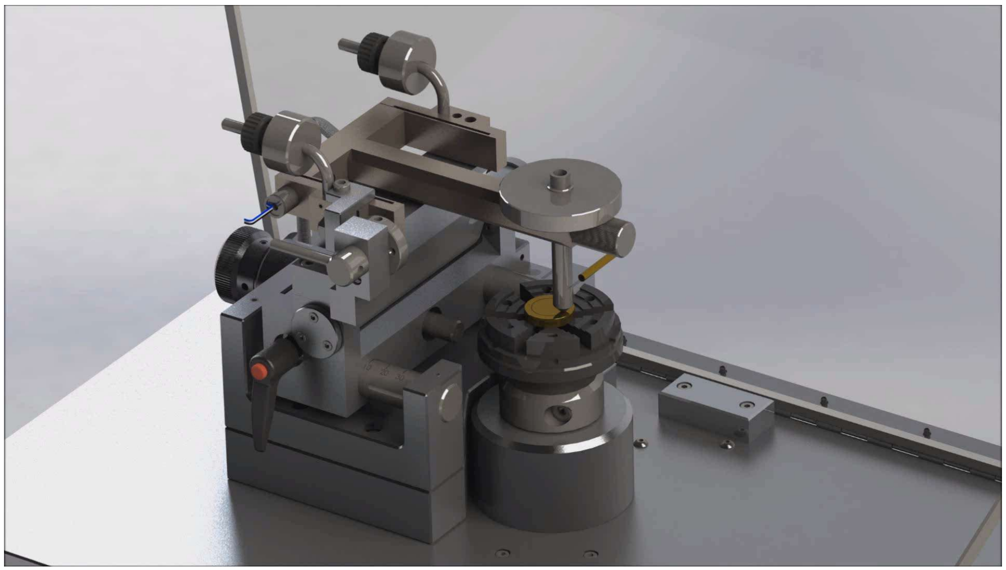
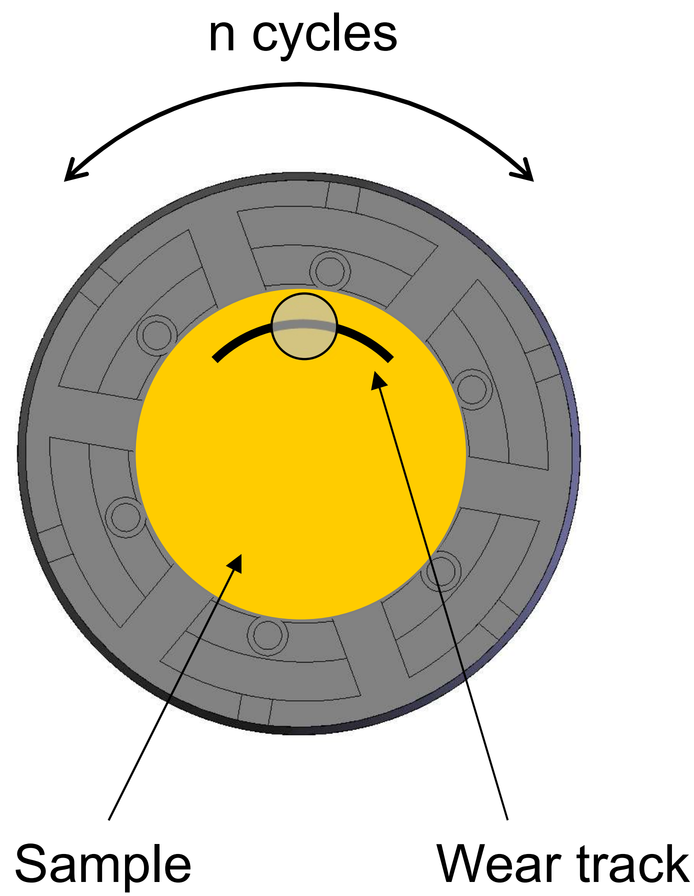




(Courtesy of Killian Wasmer, EMPA)

//// Pin-on-Disk Tribometer: Angular Reciprocating





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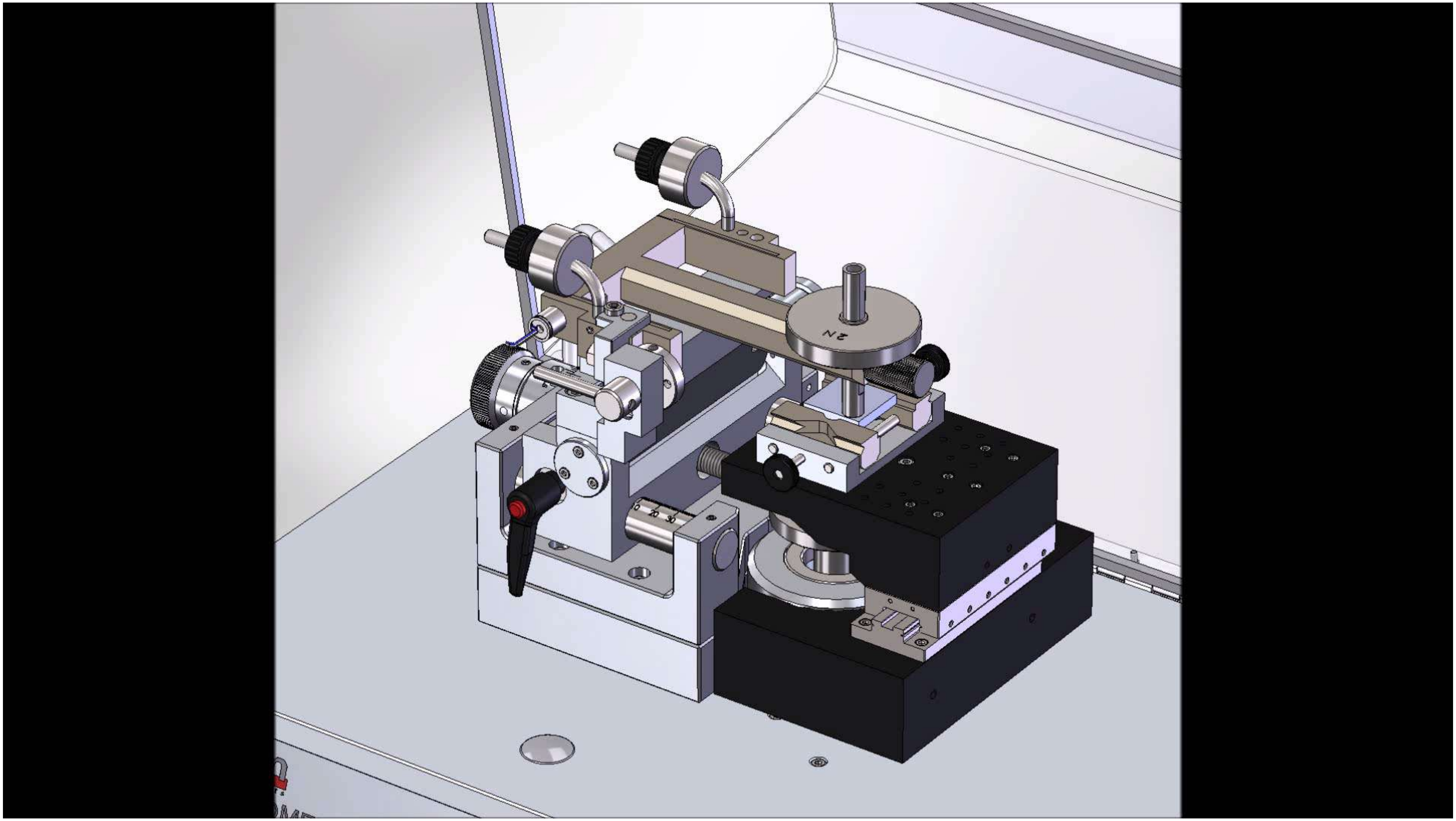
//// Pin-on-Disk Tribometer: Linear Reciprocating



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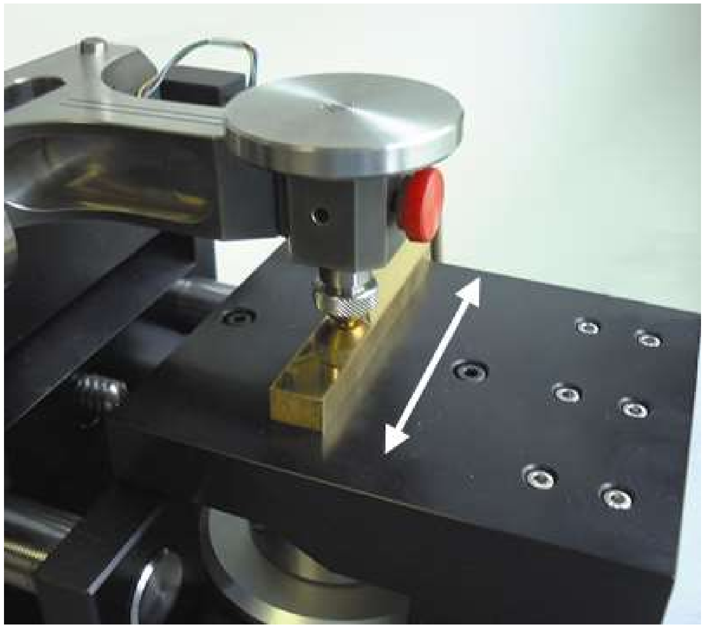
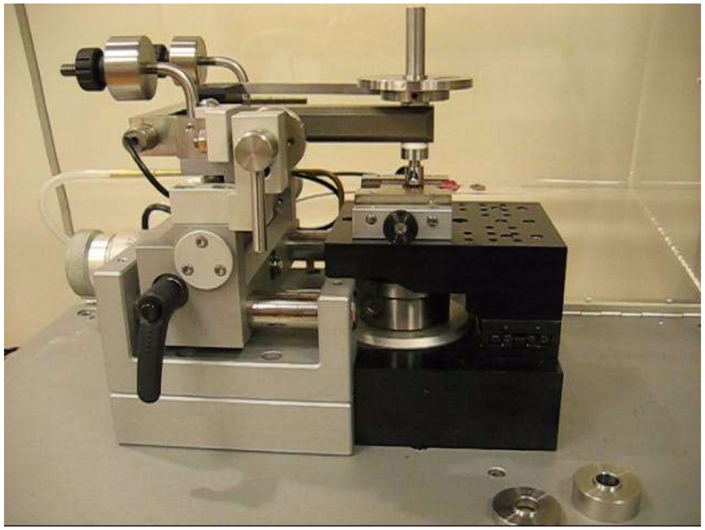
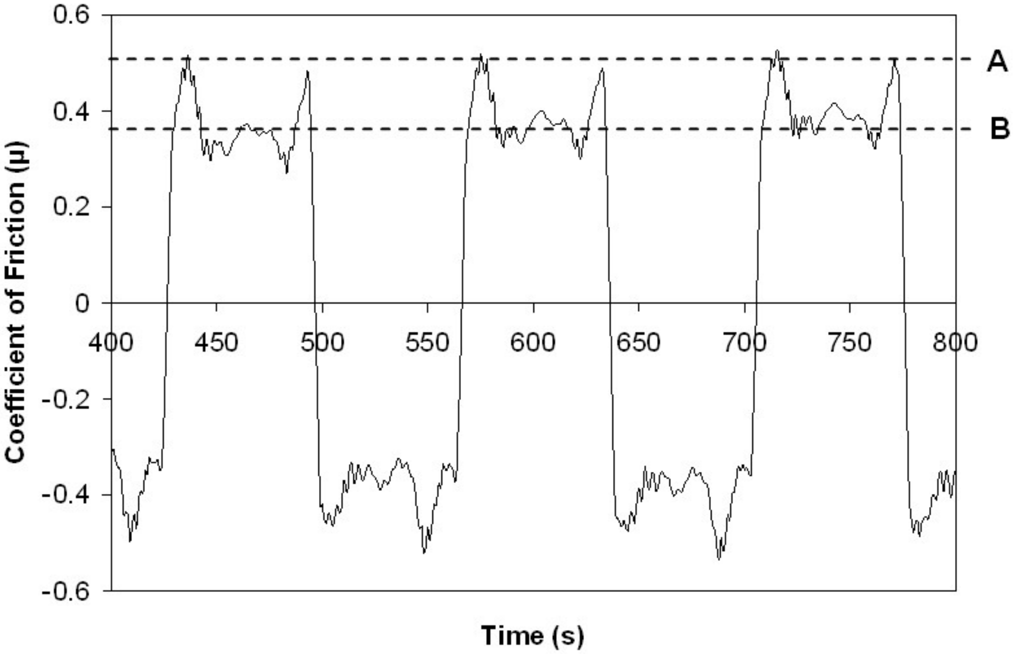
//// Pin-on-Disk Tribometer: Linear Reciprocating





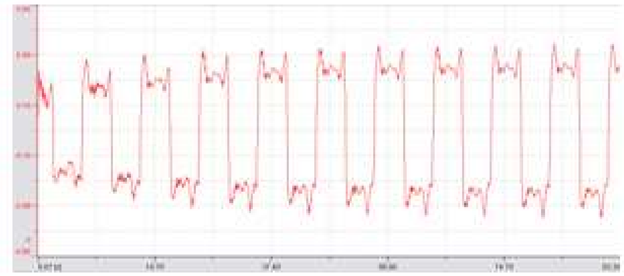
(Courtesy of CSM Instruments)



A: Static Coefficient of Friction

B: Dynamic (Sliding) Friction

//// Pin-on-Disk Tribometer: Linear Reciprocating



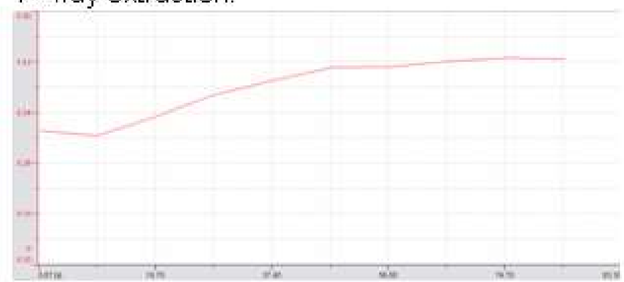
<u>Data Extraction</u>

Forward Direction: 1st Way Extraction

Reverse Direction: 2nd Way Extraction

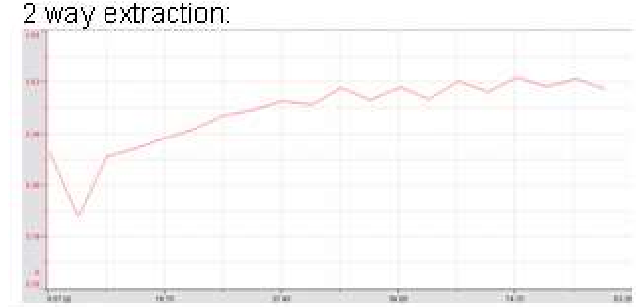
Average of both: 2 Way Extraction

1st way extraction:

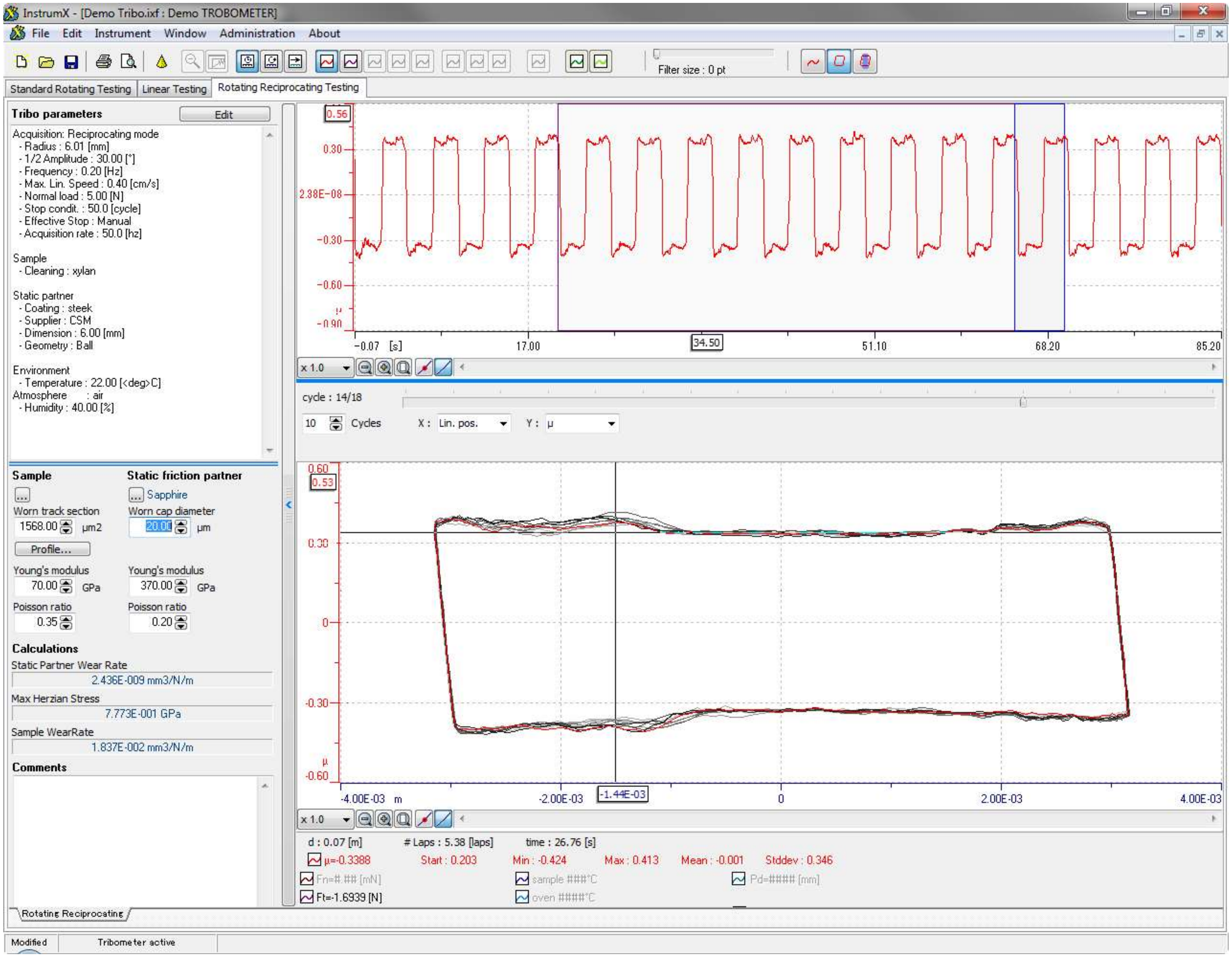


2nd way extraction:

2 way extraction:



//// Pin-on-Disk Tribometer: Linear Reciprocating



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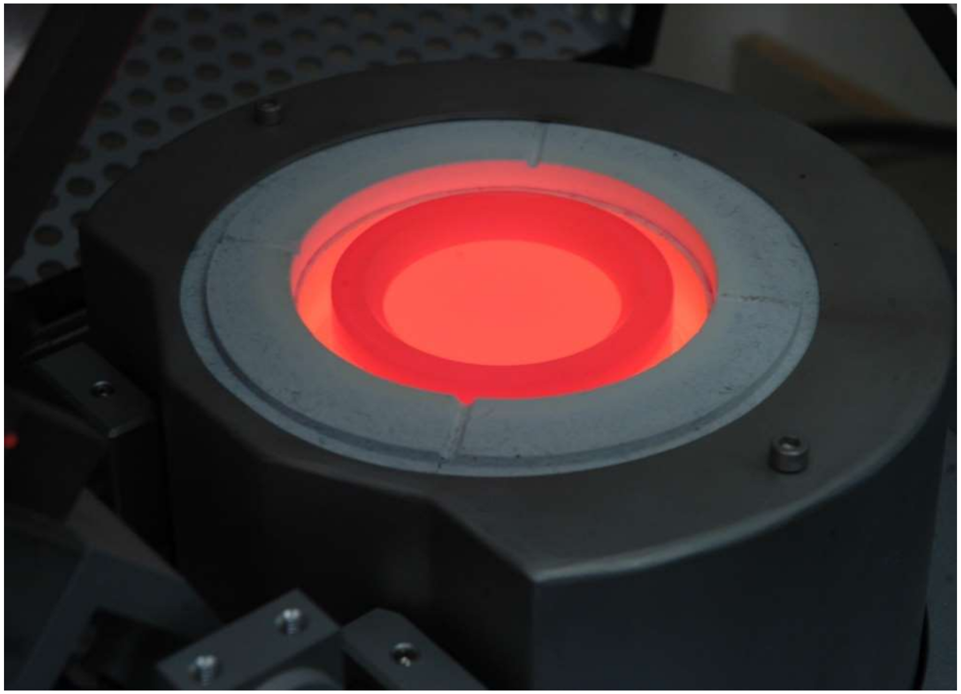
//// Pin-on-Disk High Temperature Tribometer

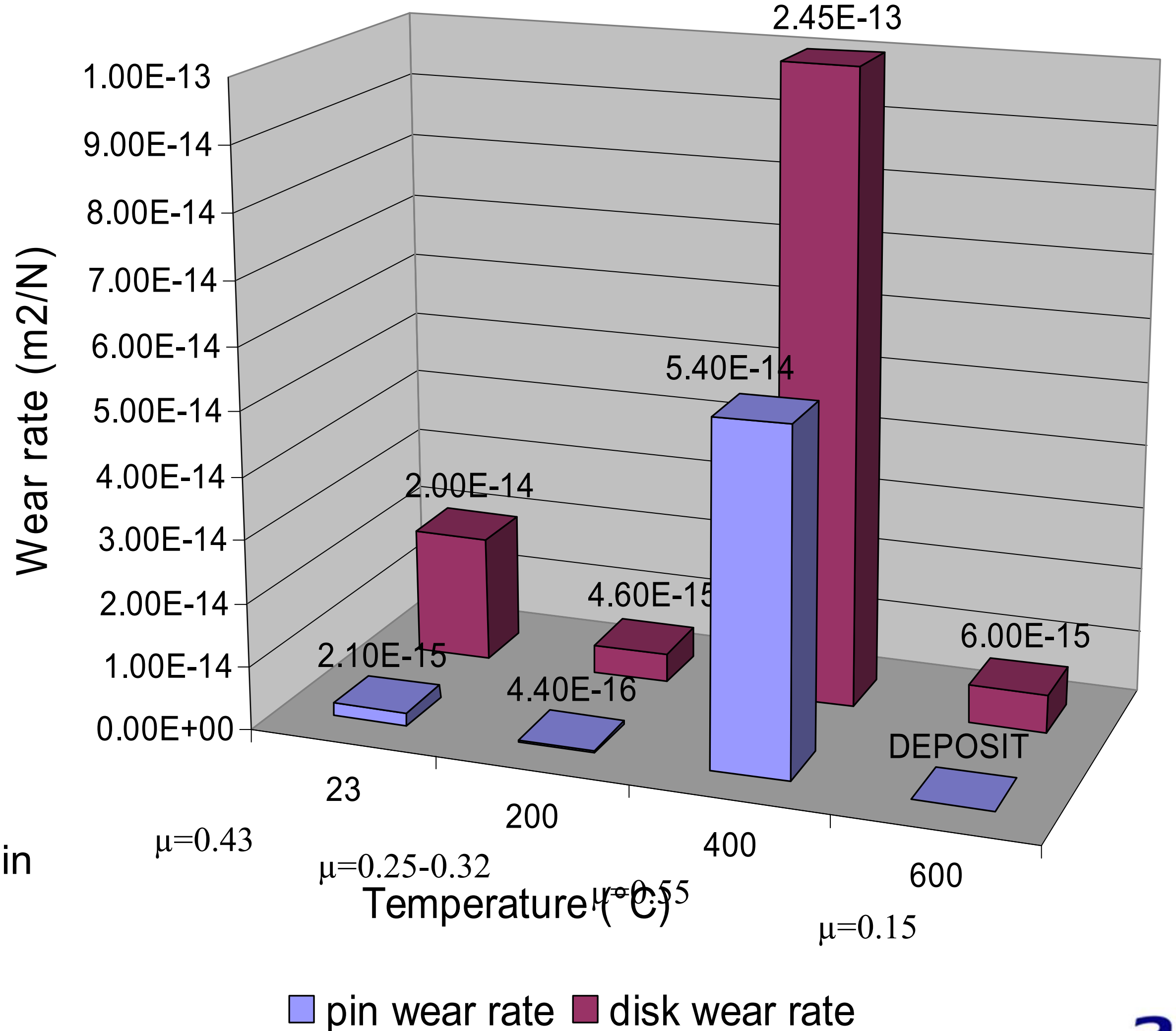


From 20°C to 1000 °C

(Courtesy of CSM Instruments)

//// Pin-on-Disk High Temperature Tribometer

TiN+Ag layers studied with the high temperature tribometer



Load: 5N
Sliding speed: 10 cm/s Pin
material: Hayness 25

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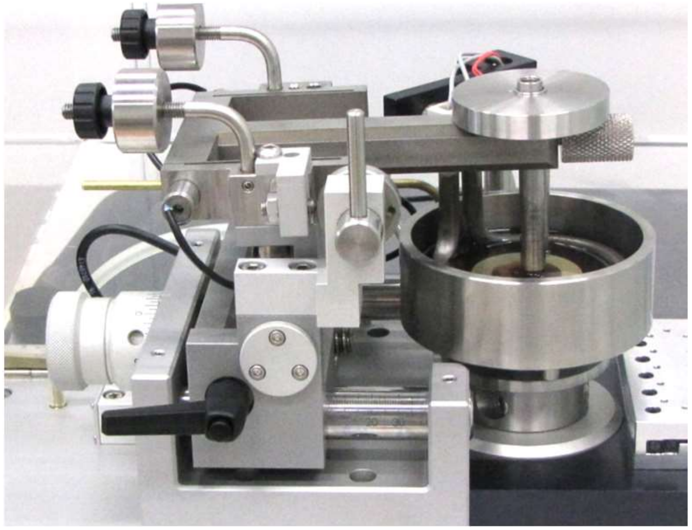
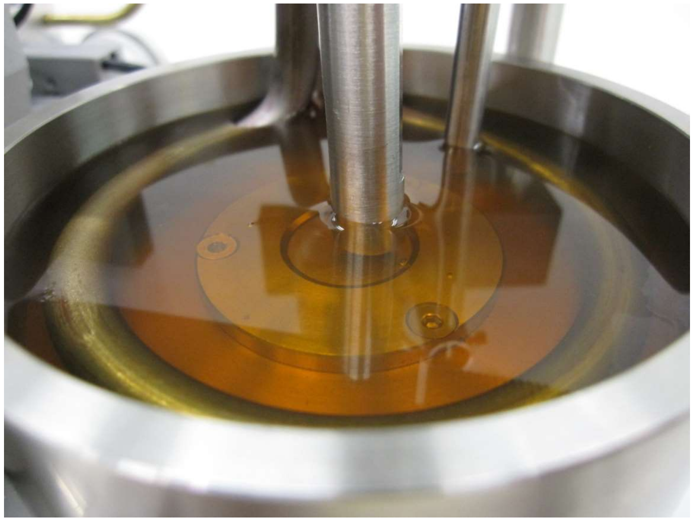
//// Pin-on-Disk Tribometer: Liquid Heating

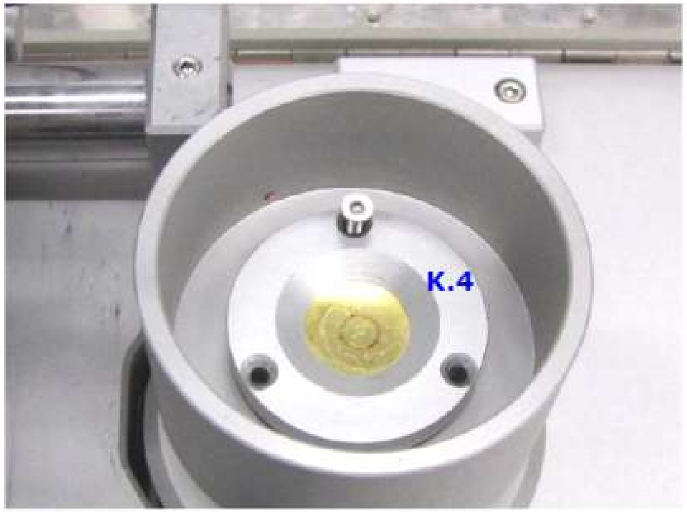
Temperature up to 150°C (0.1°C precision)
Sample size 20- and 30- mm diameter

The heating module uses a liquid to heat the sample and to run the test under lubricated conditions.





Bovine Serum at 37 °C



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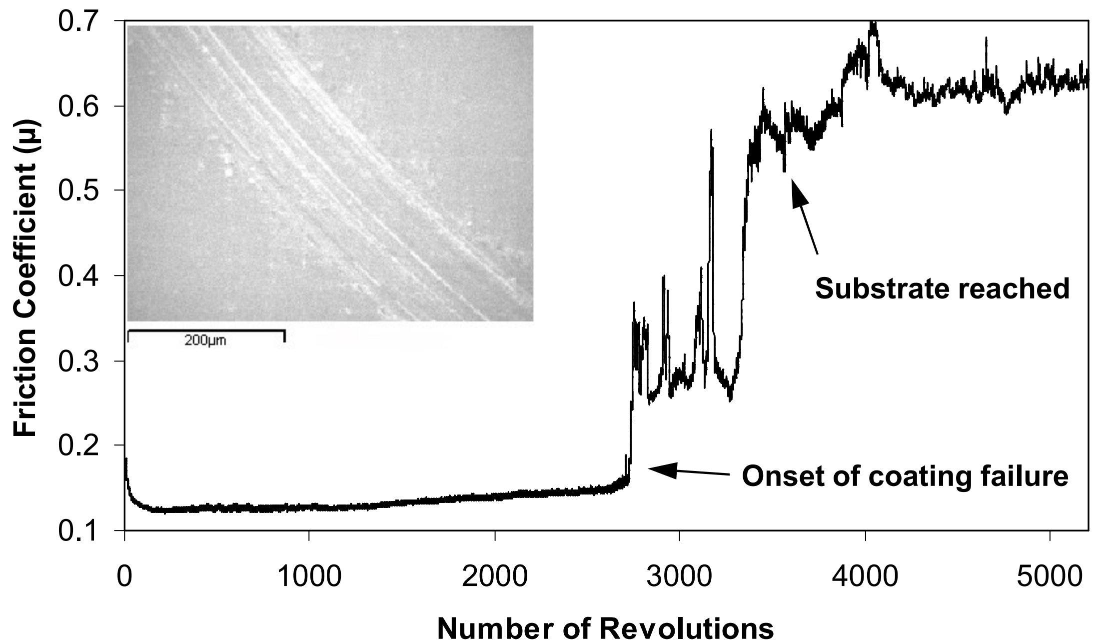
//// Pin-on-Disk Tribometer: Liquid Heating

Example: Tin Oxide coatings for biomedical

Substrate: 316L stainless steel

Liquid: Body Mimicking Fluid (BMF)

Temp: 37°C (body temperature)



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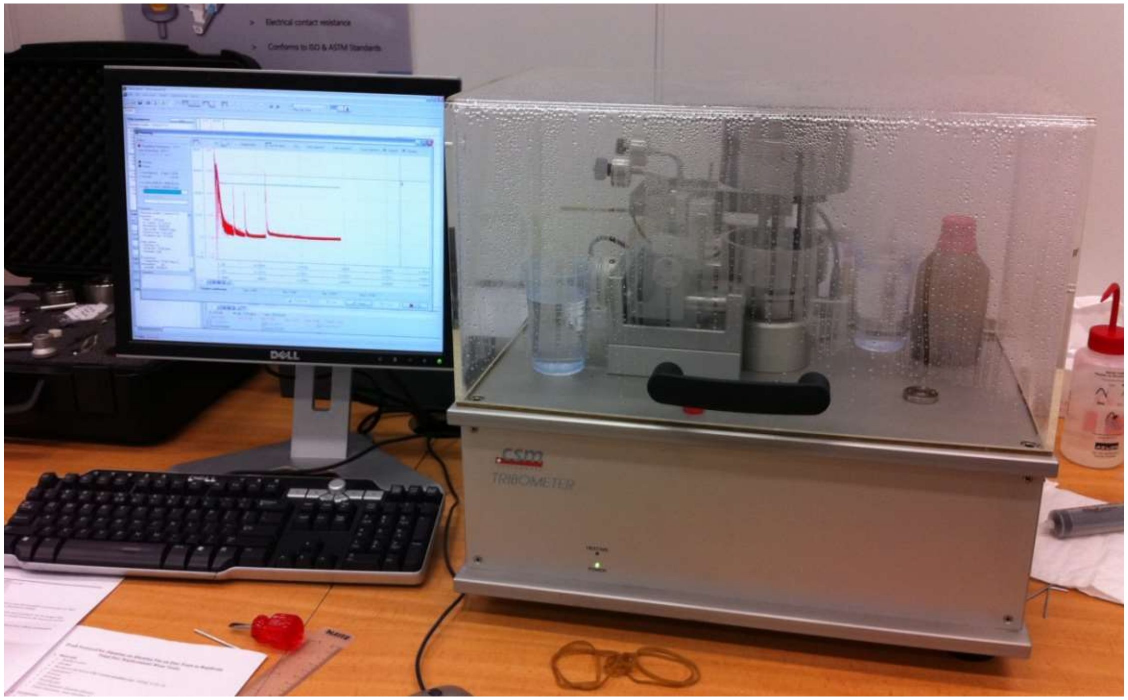
//// Pin-on-Disk Tribometer: Liquid Heating

Biotribological simulation of prosthetic joint

•Lubricant: Newborn Calf Serum (see www.seralab.co.uk)
•Static partner: 14mm dia. Alumina ball
•Dynamic partner: Alumina disks
•Applied load: 50 N
•Temperature: 37ºC
•Linear velocity: 0.044 m/s
•Rotational velocity: 70 rpm
•Duration: 1 million cycles
•Pause at 250k, 500, 750k to measure wear volume



Bovine Serum with protein concentration of 20 g/l
For long duration tests (>24h), sodium azide is added to stabilize serum

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//// Pin-on-Disk Tribometer: Liquid Heating

Biotribological simulation of prosthetic joint

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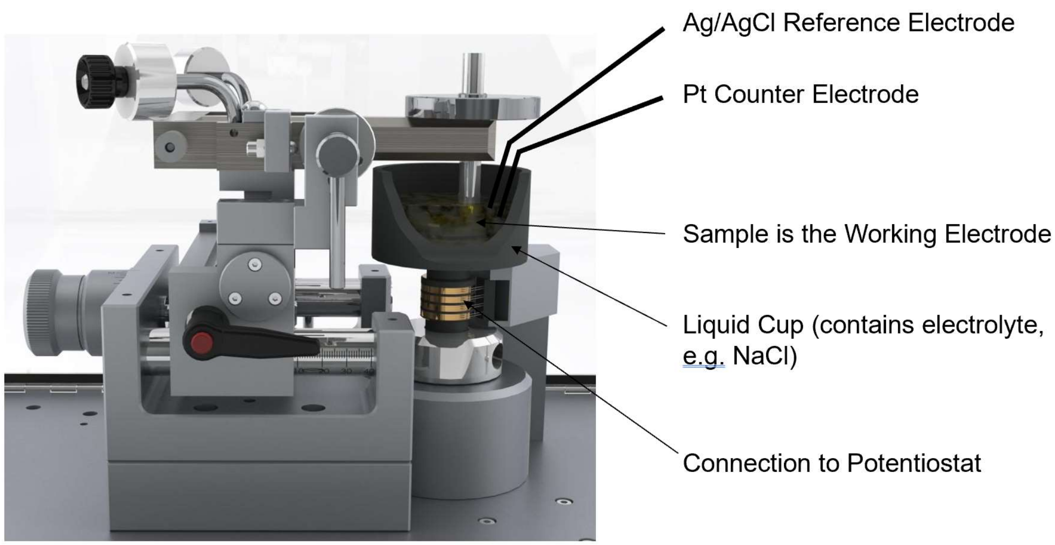
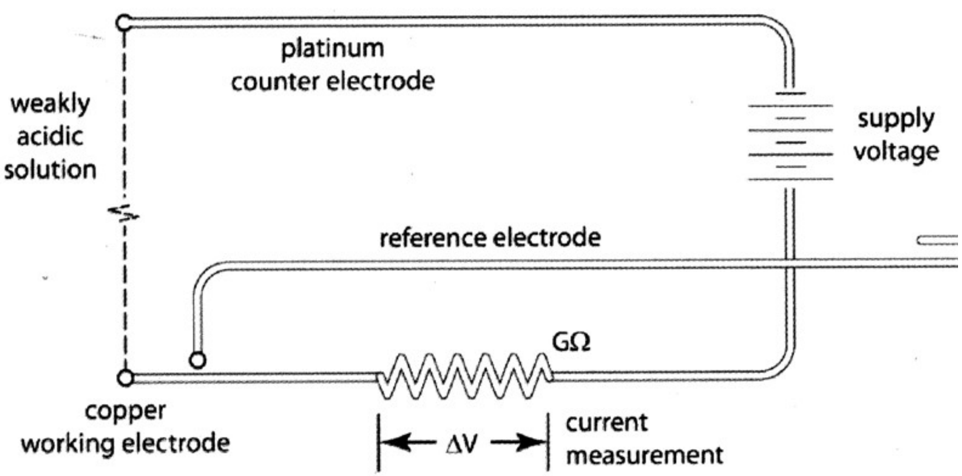
//// Pin-on-Disk Tribometer: Tribo Corrosion





- Sample (disk): this can be the working electrode, or a separate electrode can be placed in the liquid bath.
- Static partner (ball): typically of ceramic (Al_2O_3 or Si_3N_4) in order to be unreactive in a corrosive electrochemical environment
- Ag/AgCl reference electrode
- Pt counter electrode (provides stable potential and is corrosion resistant)
- Electrolyte solution (NaCl or body-mimicking fluid)
- Heating coil and thermostat if a stable temperature is required (e.g. body temperature)

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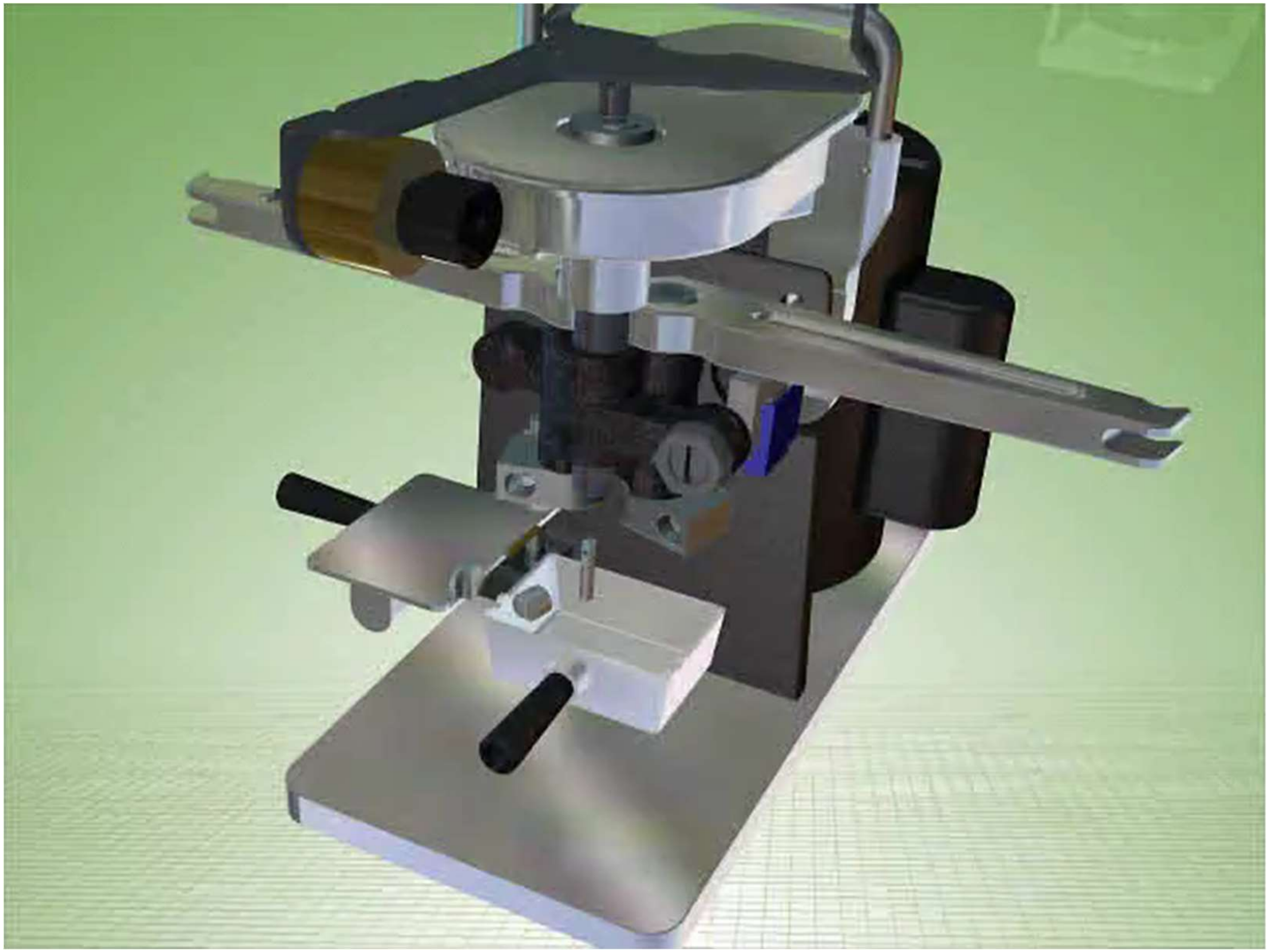
//// Pin and Vee Block Test



(Courtesy of Falex)

//// Pin and Vee Block Test

GENERAL USE: Measures friction, wear and extreme pressure properties of lubricants and materials under a wide variety of test conditions. Widely used for metalworking, industrial, automotive and bonded solid lubricants.
CONTACT: Line (V Block), Area (C Block)
MOTION: Sliding
SPEEDS: 290 ± 10 rpm, 60-3600 rpm
LOADS: 0 to 3000 Lb. direct load
TEMPERATURES: Ambient to 150°C
ENVIRONMENTS: Liquid, Semi-liquid, Dry, Pressurized test chamber
ASTM TEST METHODS: D2625, D2670, D3233, D5620

(Courtesy of Falex)

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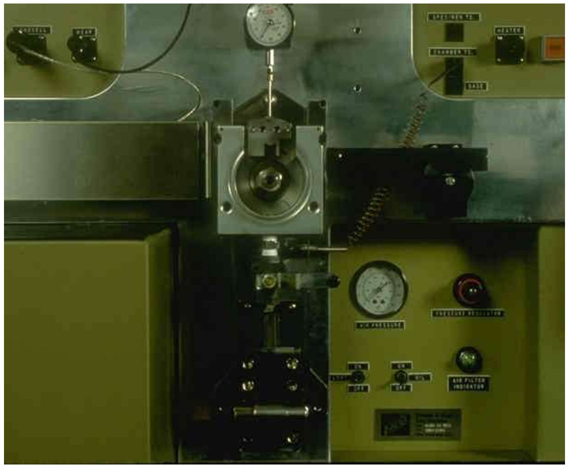
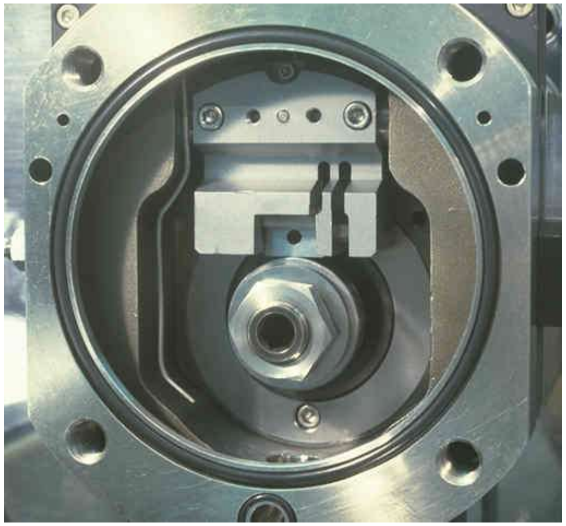
//// Block on RingTest

GENERAL USE: Measures friction, wear and extreme pressure properties of lubricants and materials under a wide variety of test conditions
CONTACT: Point, Line, Area
MOTION: Sliding, Oscillation
SPEEDS: 60-3600 rpm, 1/2 -7200 rpm,
LOADS: 10 to 1,300 Lb.
TEMPERATURES: Ambient to 250°C
ENVIRONMENTS: Liquid, Semi-liquid, Dry, Humidified, Pressurized test chamber
ASTM TEST METHODS: D2714, D2981, D3704, G75





(Courtesy of Falex)

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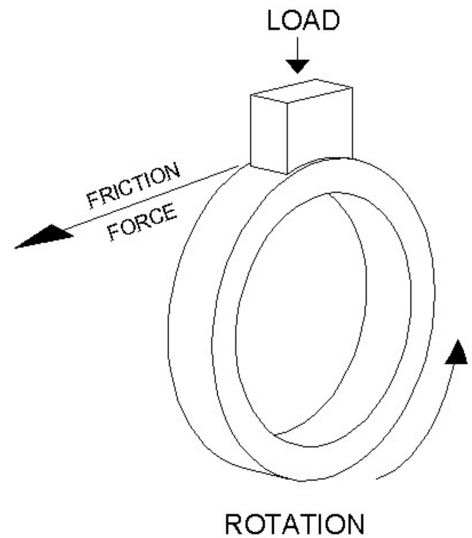

(Courtesy of Falex)

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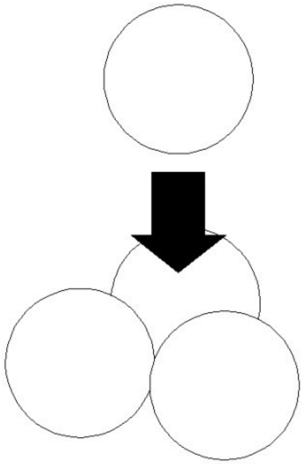
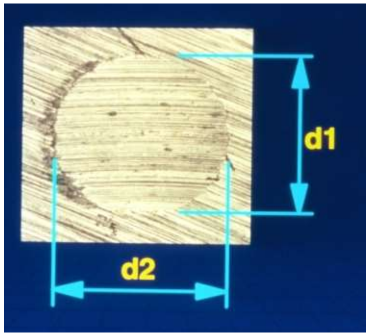
//// Four Ball Wear Test

GENERAL USE: Measures friction and wear properties of lubricants and materials. Widely used for gear oils, greases, engine oils, bonded solid films and diesel fuels
CONTACT: Three Point Contact
MOTION: Sliding, Rolling
SPEEDS: 600,1200,1800; 1/2 -10,000 rpm,
LOADS: 5 to 50 kg, 5-180 kg
TEMPERATURES: Ambient to 235°C (450°F)
ENVIRONMENTS: Liquid, Semi-liquid, Dry,Atmospheric Environment Chamber,
ASTM TEST METHODS: D2266, D4172, D5183



Wear from scar diameter



(Courtesy of Falex)

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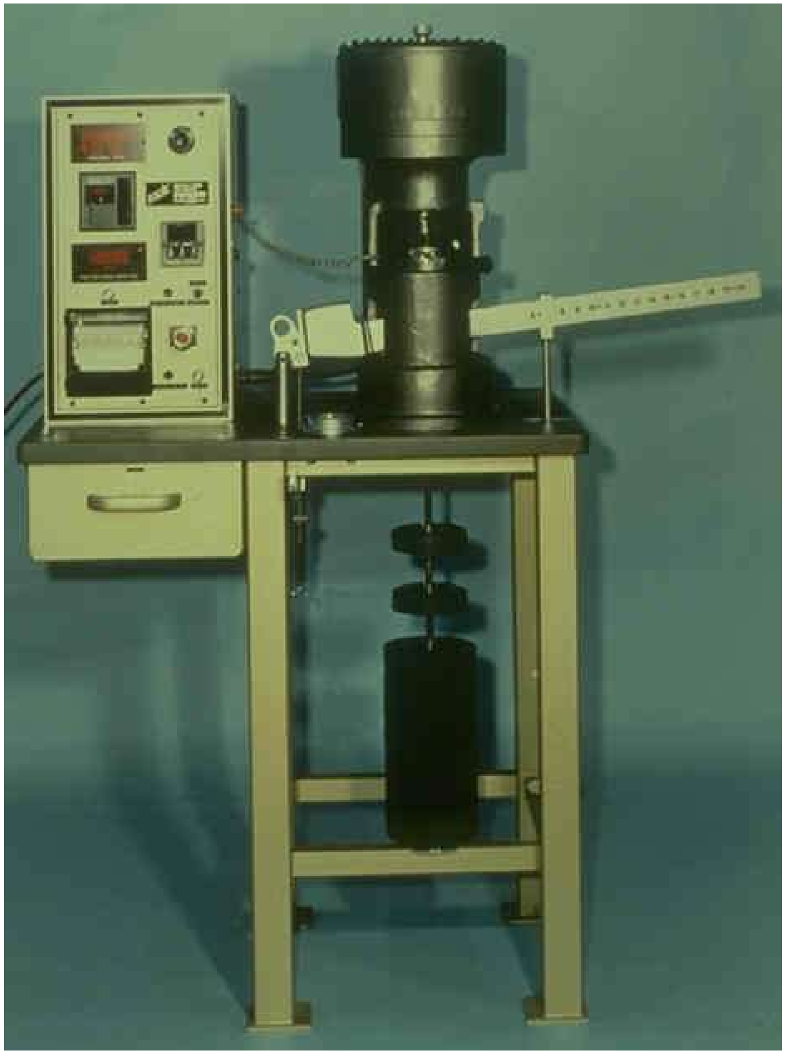

(Courtesy of Falex)

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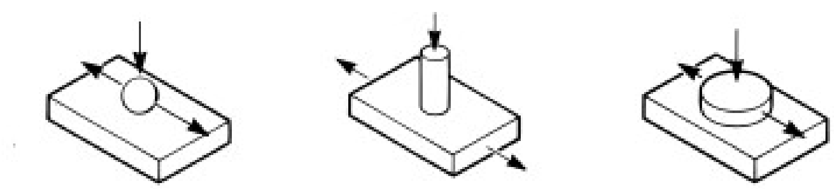
//// Fretting (SRV) Test

GENERAL USE: Determines wear and extreme pressure properties of greases where high-speed vibration or start-stop motions are present with high Hertzian point contacts
CONTACT: Point, line, area
MOTION: Reciprocating
SPEEDS: 50 Hz
LOADS: 50 - 1400 N
TEMPERATURES: Ambient- 80°
ASTM TEST METHODS:
D5706 - "Determining Extreme Pressure Properties of Lubricating Greases Using a High-Frequency, Linear Oscillation (SRV) test machine"
D5707 - "Measuring Friction and Wear Properties of Lubricating Grease Using a High-Frequency, Linear Oscillation (SRV)Test Machine"



(Courtesy of SRV)

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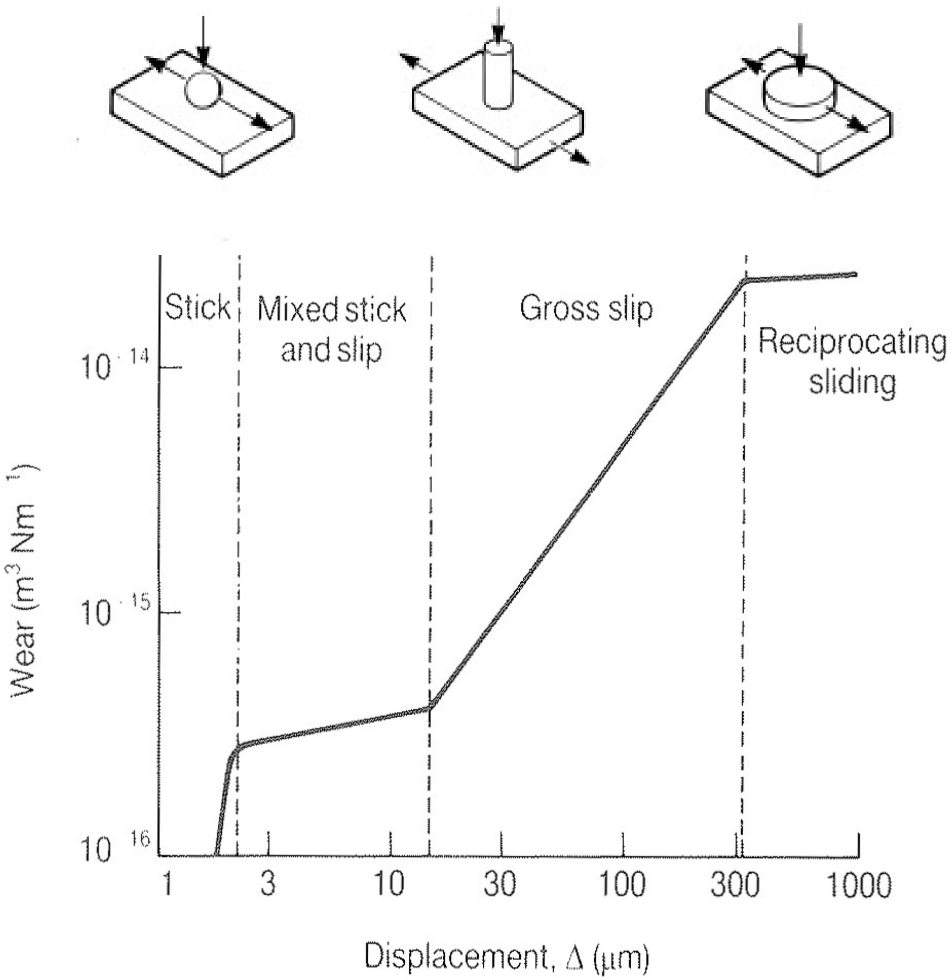
//// Tribological Testing: Fretting



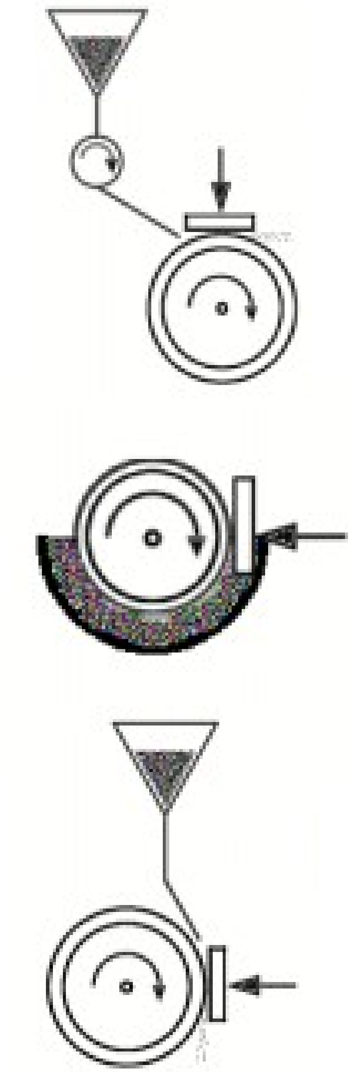
•'Fretting' denotes a small oscillatory movement between 2 surfaces in contact

•Fretting can be regarded as reciprocating sliding wear but the displacements are often very small

•Fretting is often associated with 'stick-slip' sliding and wear rate will depend highly on amplitude of displacement

•Stick-slip and fretting often occur in MEMS where small oscillations are common

//// Tribological Testing: Abrasion/Erosion testing



•Loose grit or sand of well-defined size

•Abrasive paper bonded to a substrate

•Parameters:
- Choice of particle
- Sharpness or angularity of particle
- Particle flow rate
- Counterface material
- Contact load

•Limitations:
- Controlling rate of supply of abrasive
- Condition of abrasive
- Clogging

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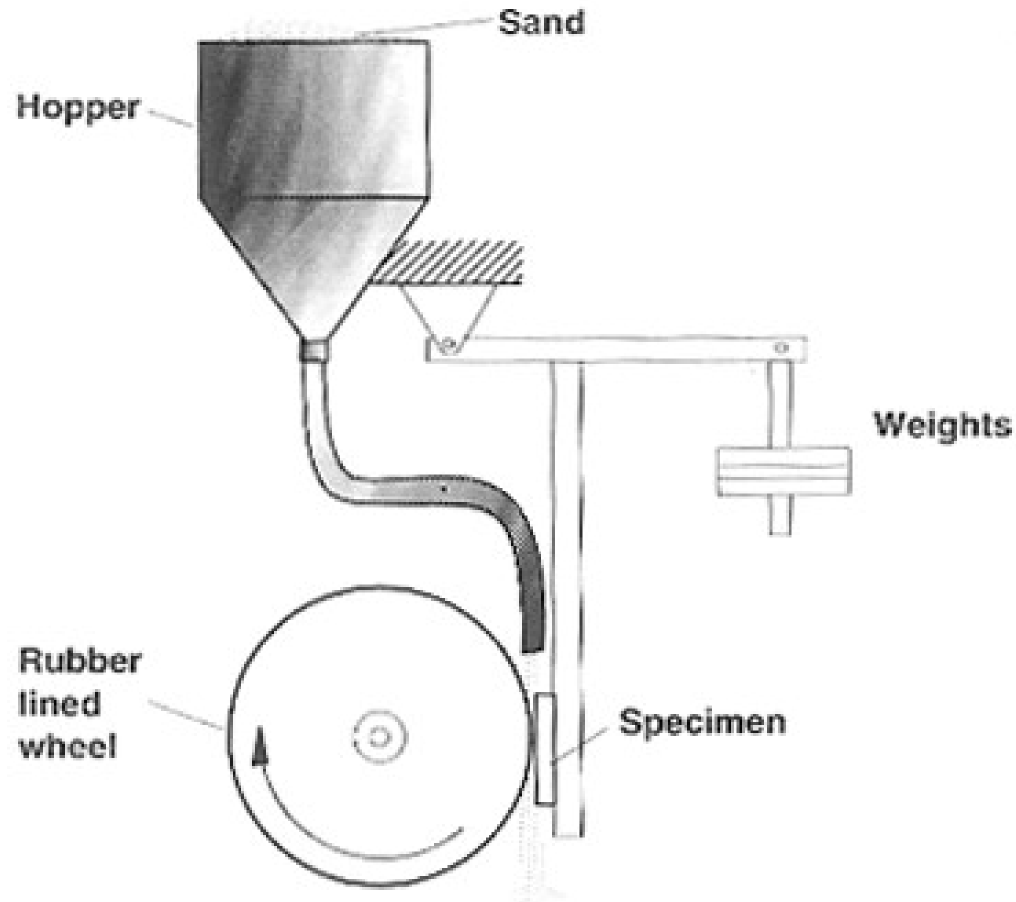
//// Dry sand/rubber wheel erosion test

•Typical abrasive is sand (ASTM G65)

•Applied dry or in a water slurry

•Quick test (few minutes)

•Wear measured by profilometry of region or by weight loss



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//// Dry sand/rubber wheel erosion test

GENERAL USE: Determines wear resistance of materials to third-body abrasion
CONTACT: Point, line, area
MEDIA: Dry sand particles or sand in wet slurry
SPEEDS: 2000 rpm
LOADS: <150 N
TEMPERATURES: Ambient
ASTM TEST METHODS: G65

(Courtesy of TribSys)

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//// Taber Abraser

- Different abrasive wheels available
- Commonly known as “Taber Test”
- Conforms to ASTM D6037, F510, D4712

- Taber Wear Index,

$$I = \frac{(A - B) \times 1000}{C}$$

A = weight of sample before abrasion
B = weight of sample after abrasion
C = number of cycles

(Courtesy Taber Industries)

//// Taber Abraser

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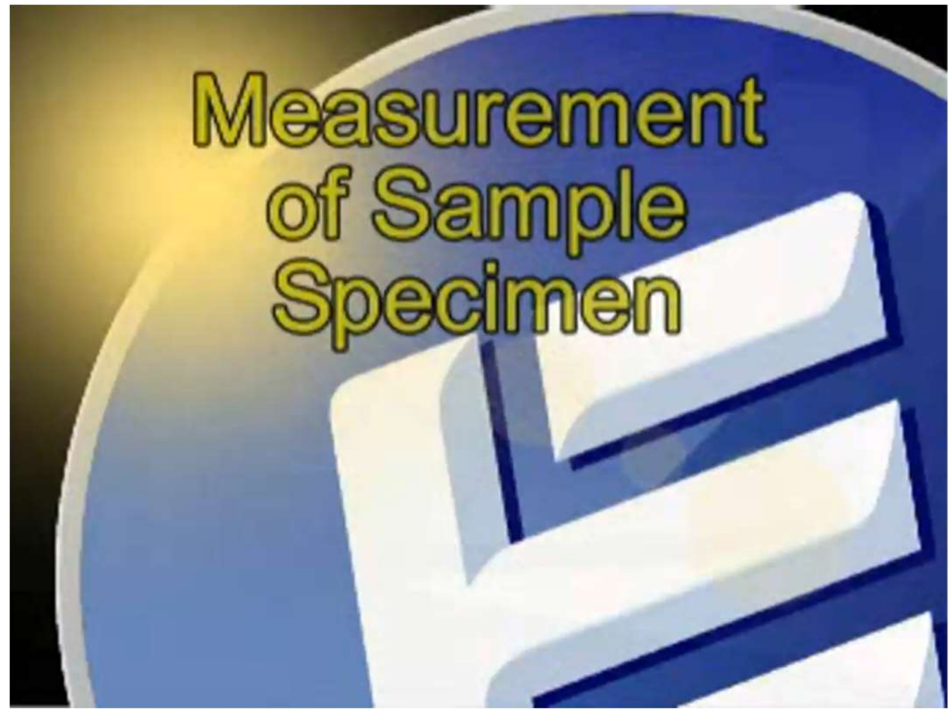

(Courtesy Taber Industries)

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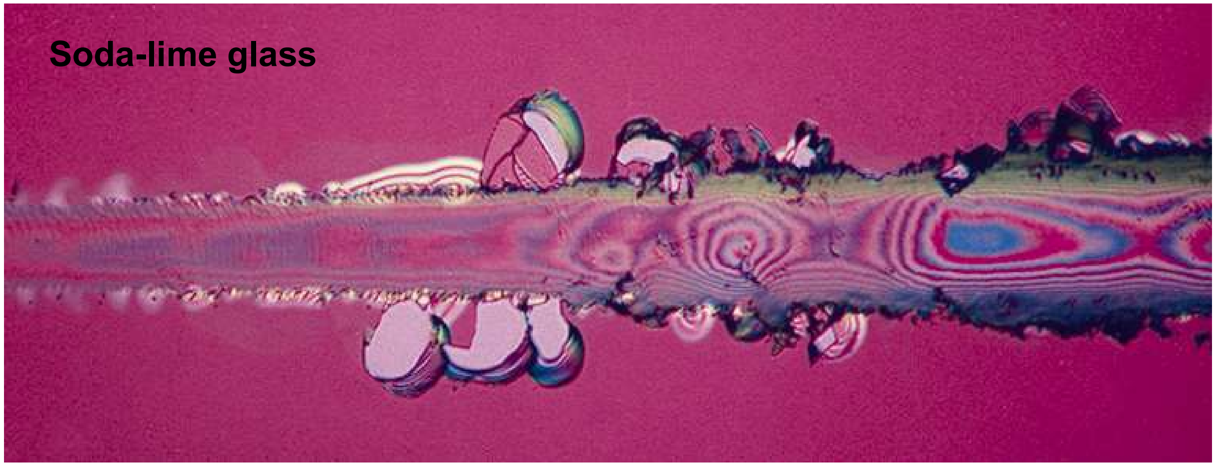
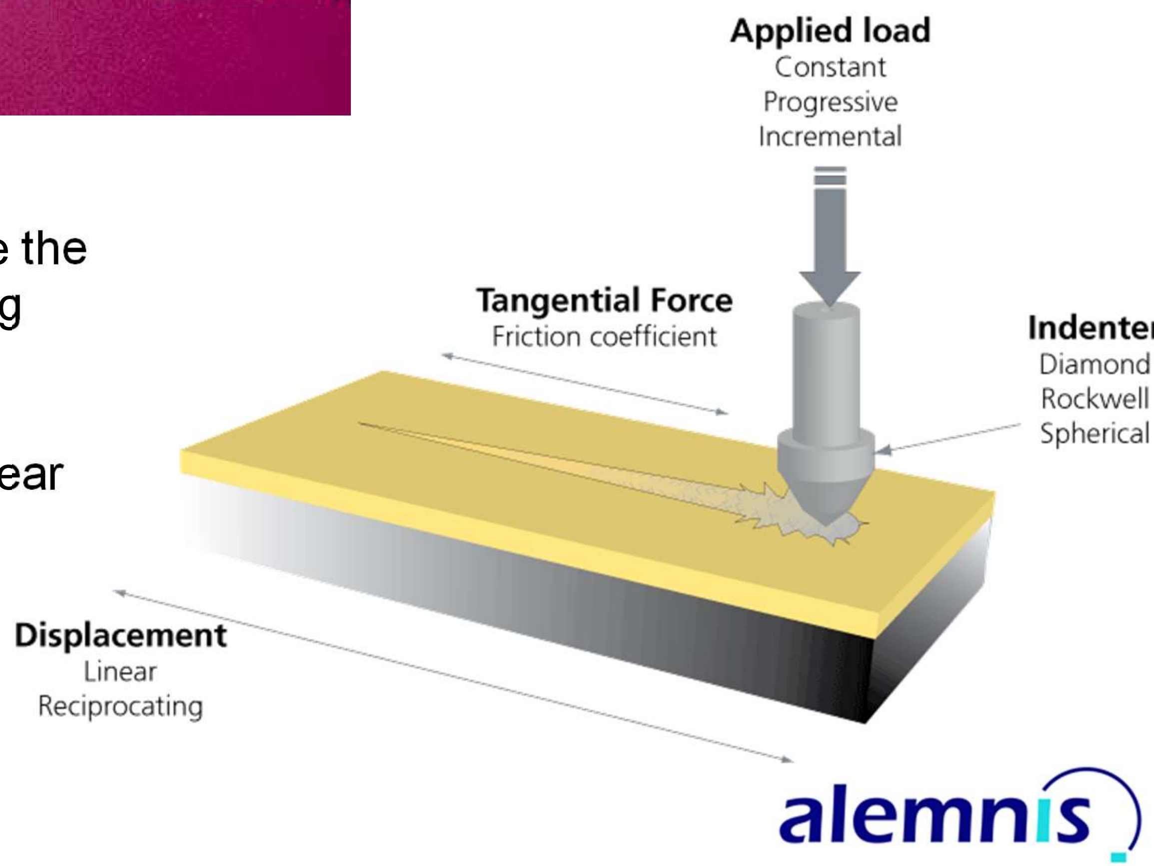
//// Scratch Test

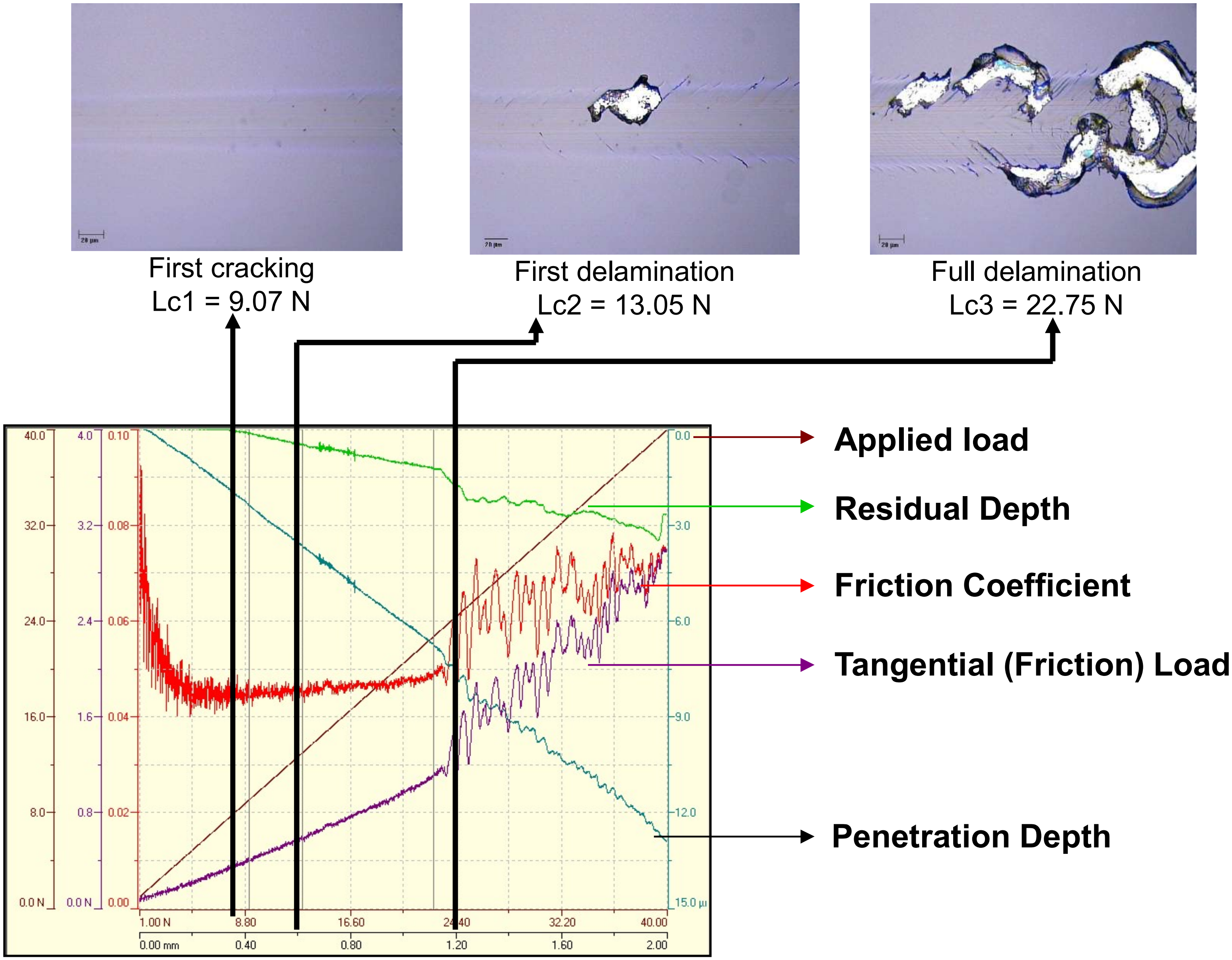


•Scratch testing can be used to determine the applied contact pressure at which cracking commences

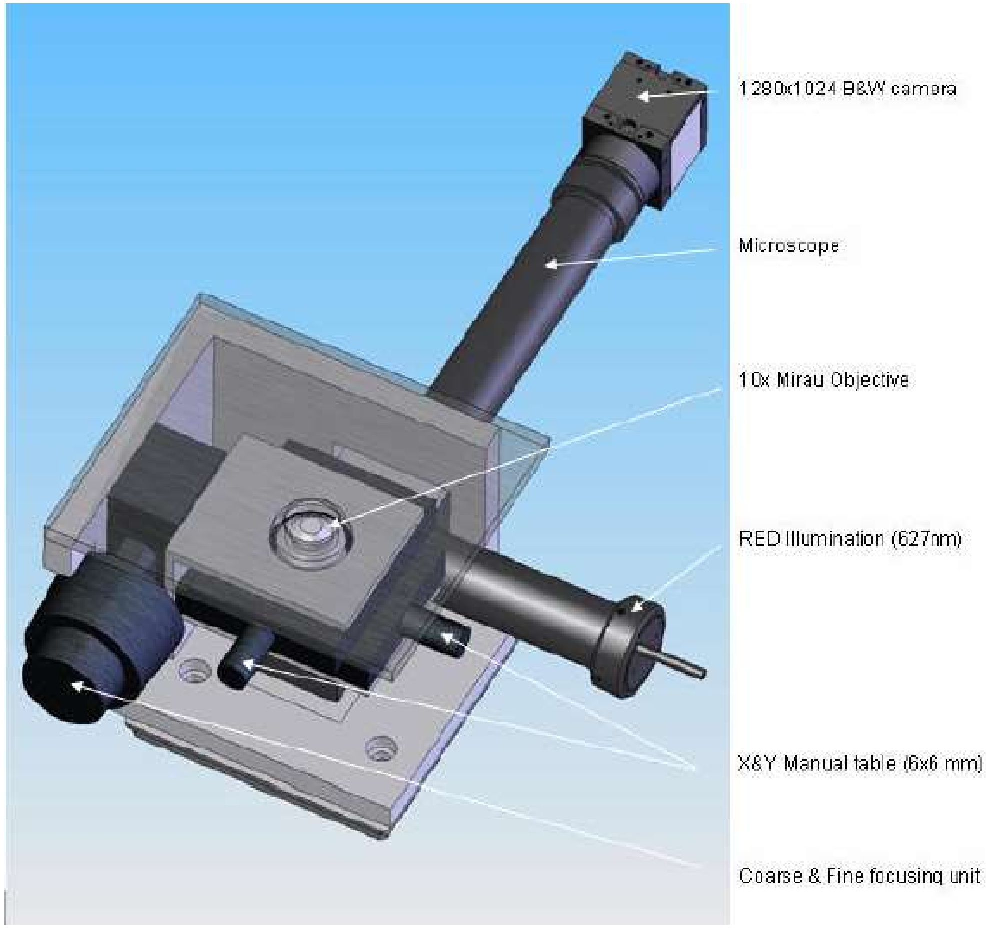
•The indenter tip simulates an abrasive wear particle

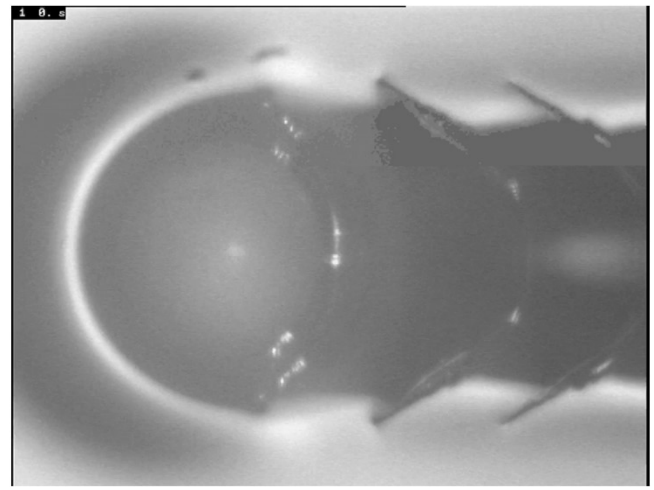


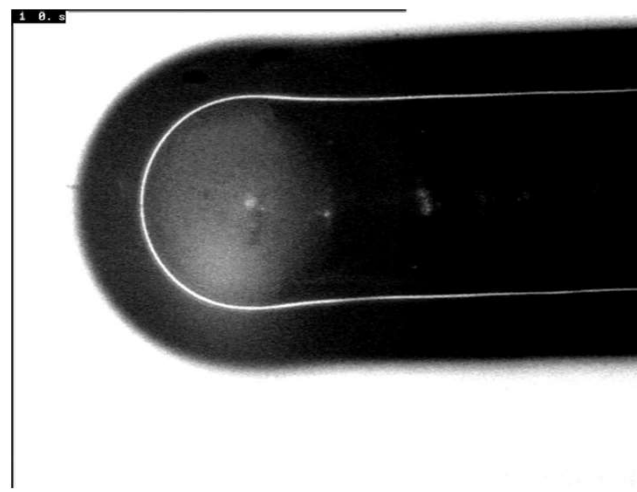
//// Scratch Test



//// Integrated Mirau Interferometer



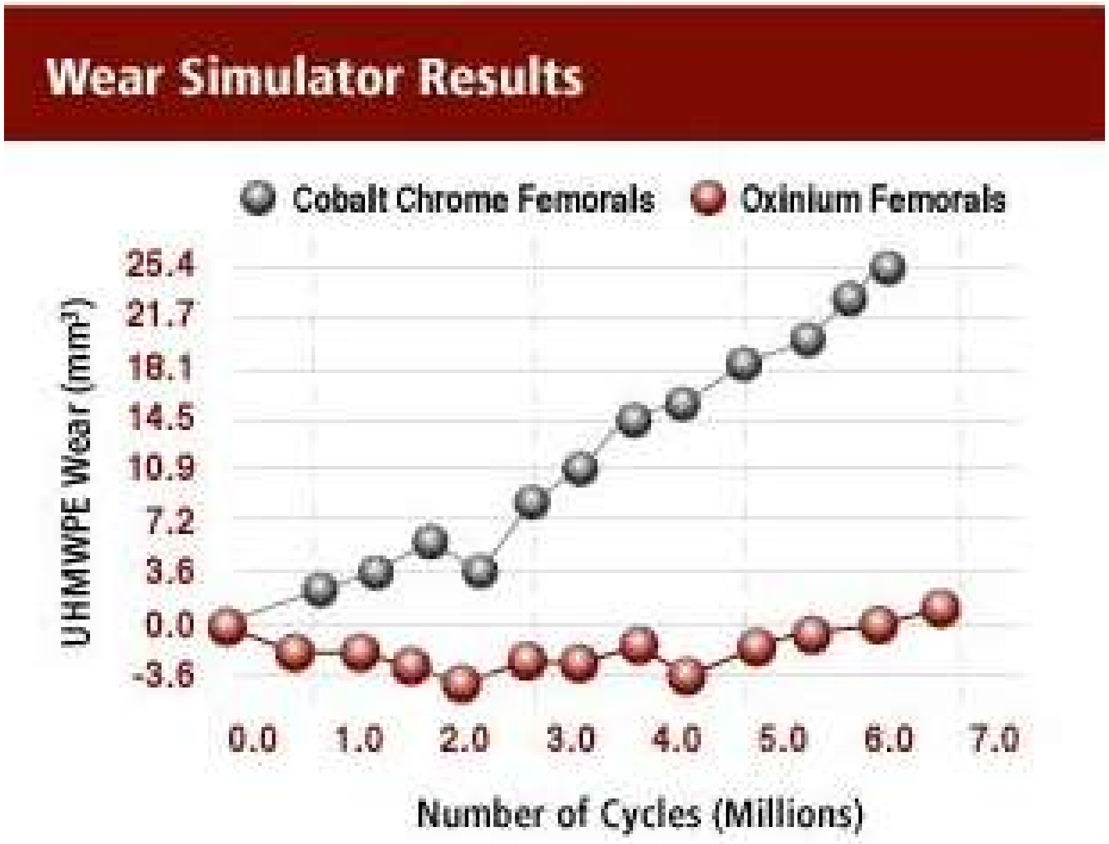




Allows in-situ visualisation of true contact area

//// Dedicated Tribological Testing

Cobalt Chrome and Oxinium femorals tested against polyethylene tibials using 3-axis simulator



(Courtesy of Oxinium Implants)

//// Dedicated Tribological Testing

- Hip joint simulator
- Joints materials tested *in-situ* in sinovial fluid

(Courtesy of Oxinium Implants)

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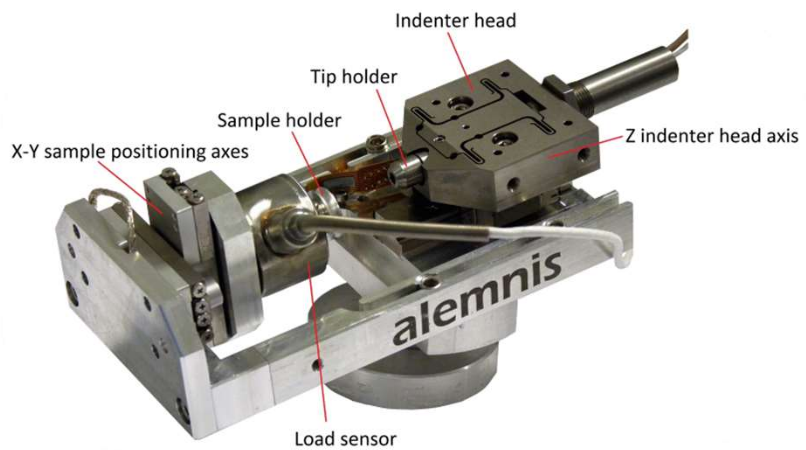
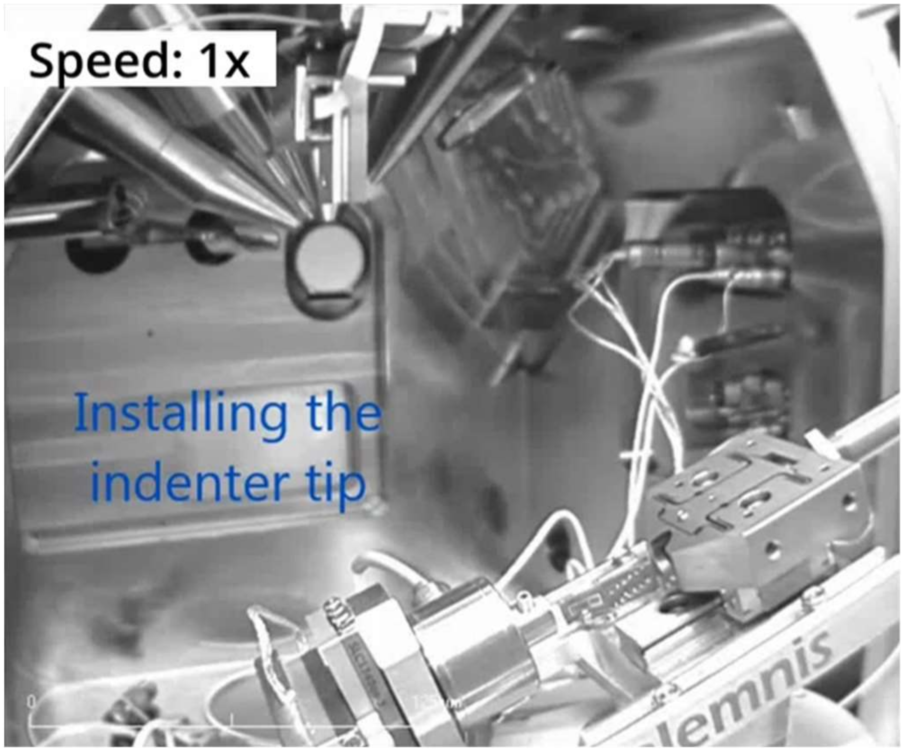
//// Custom *In-Situ* Tribology Tests





Short video showing an experimental overview of in-situ testing in a scanning electron microscope (speed 5x).

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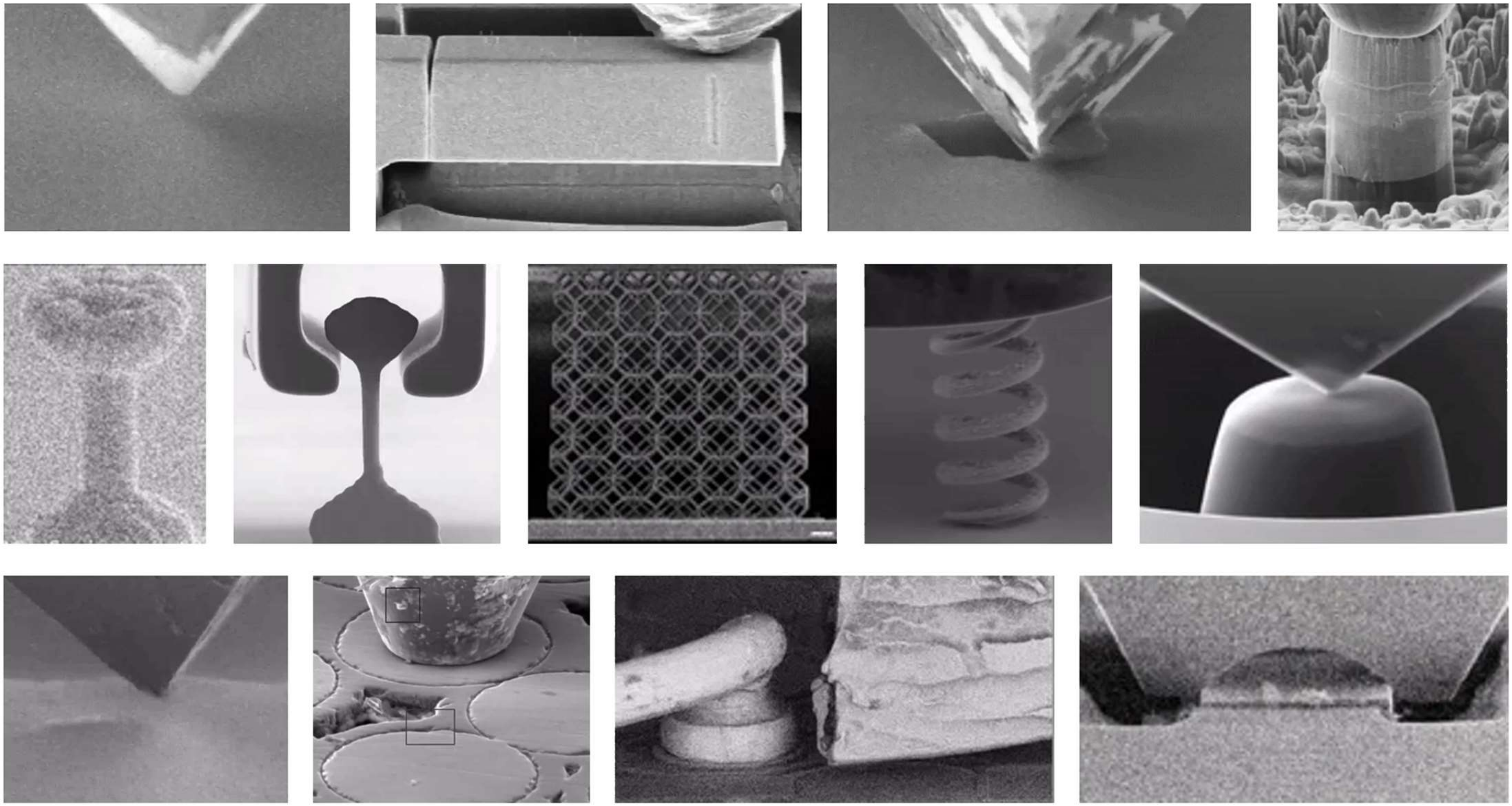
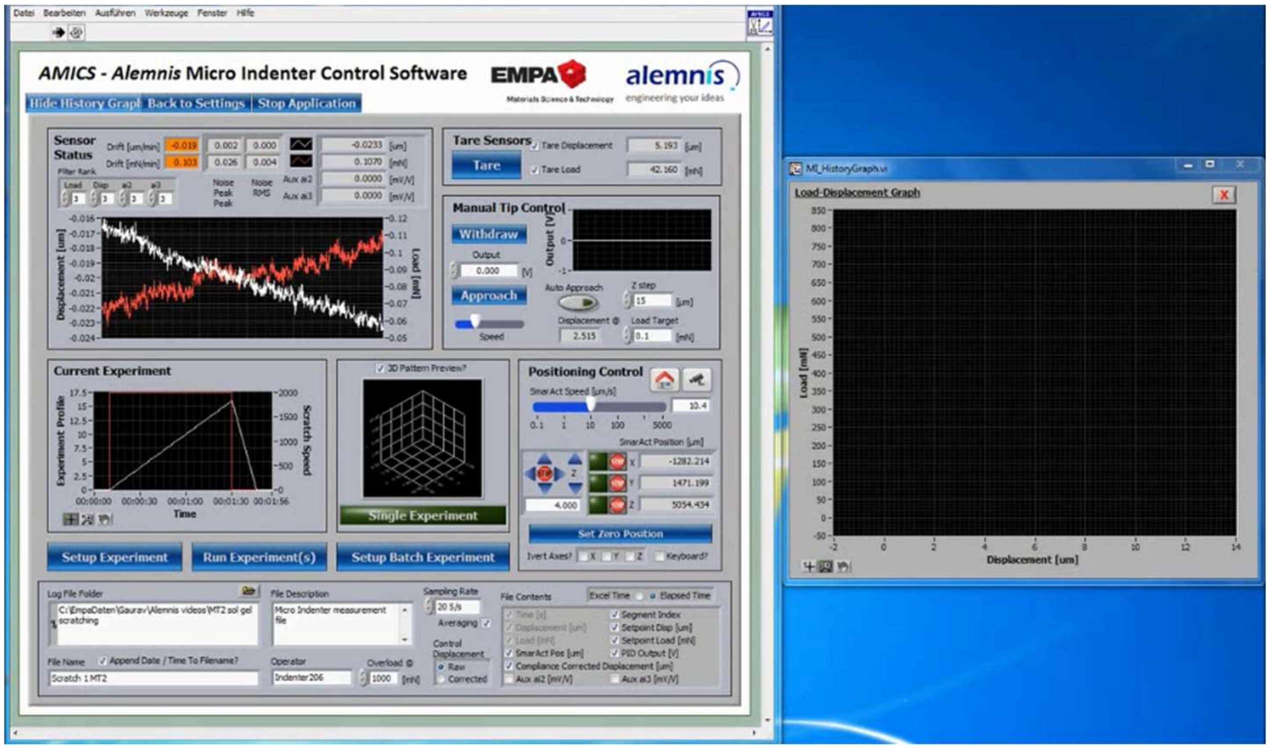
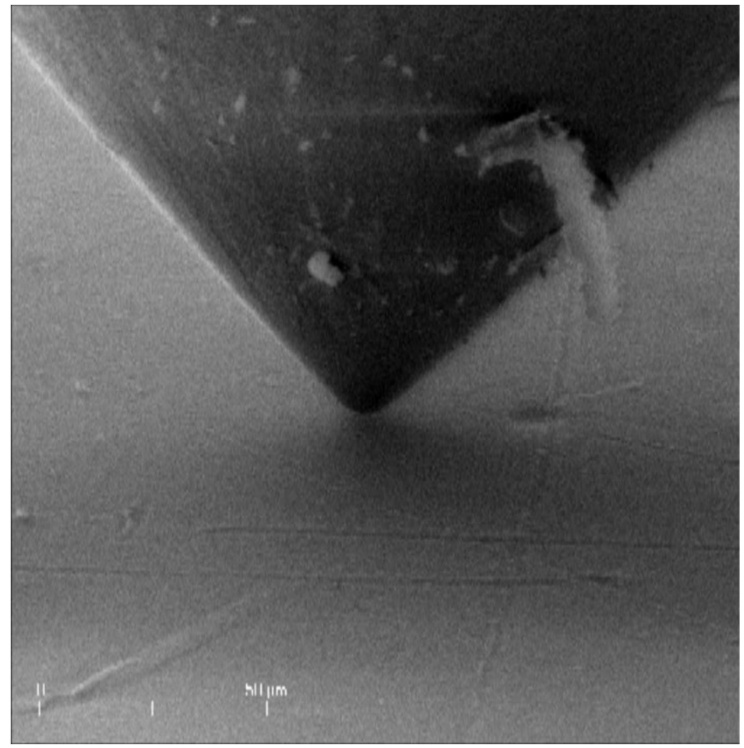
//// Custom *In-Situ* Tribology Tests



//// Custom *In-Situ* Tribology Tests





Periodic conical cracks can be seen on scratching with a cono-spherical indenter tip (Silica SolGel)

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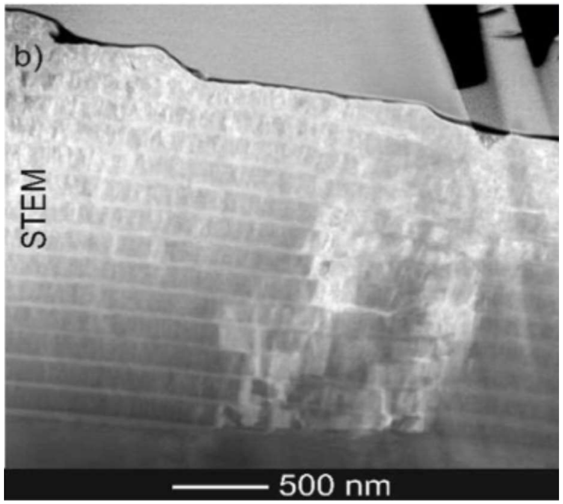
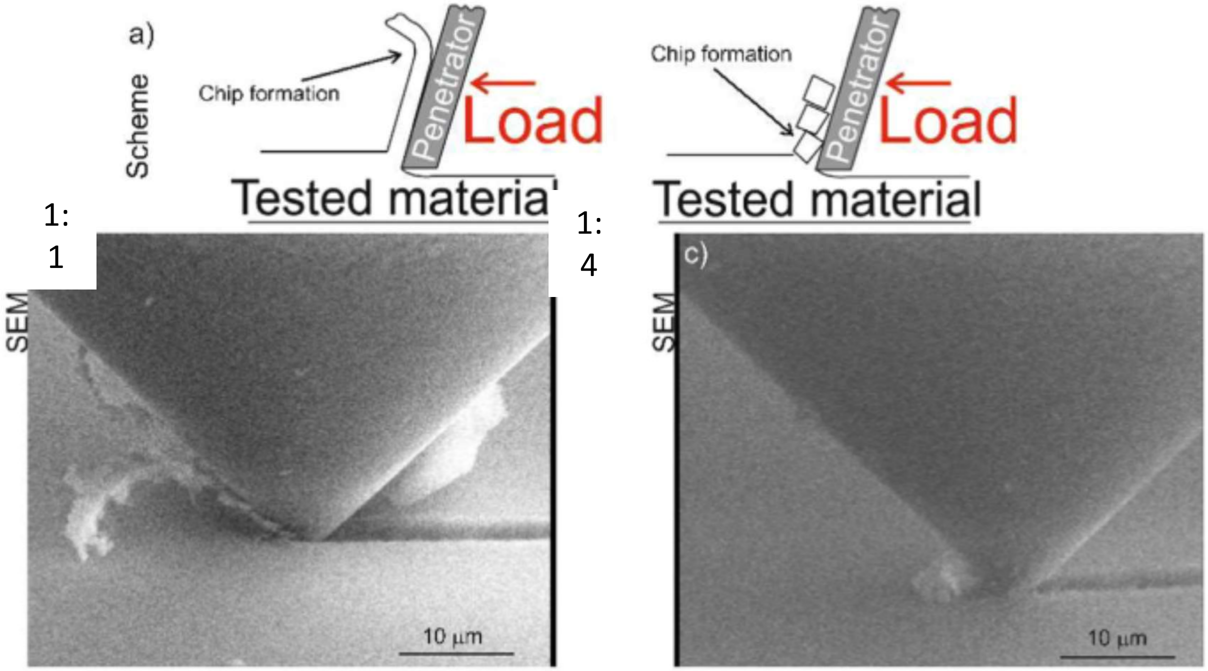
//// Custom *In-Situ* Tribology Tests

Wear Mechanism of Zr/Zr_2N Coatings

Correlation between chip formation and coating multilayer structure (1:1 and 1:4 ratios tested)

Zr/Zr_2N with 1:1 ratio:

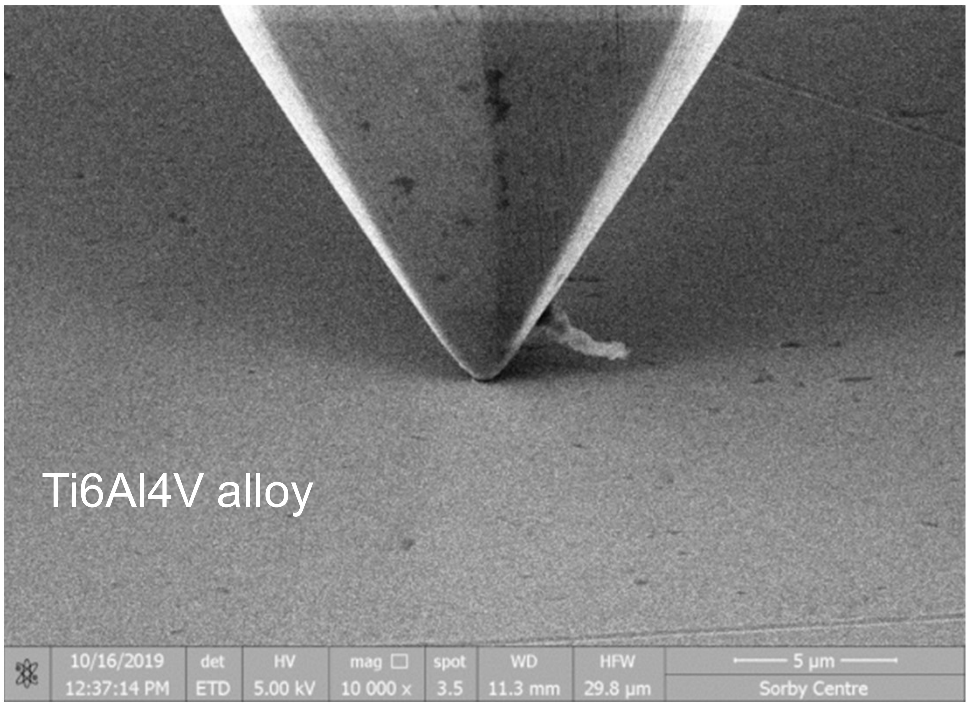


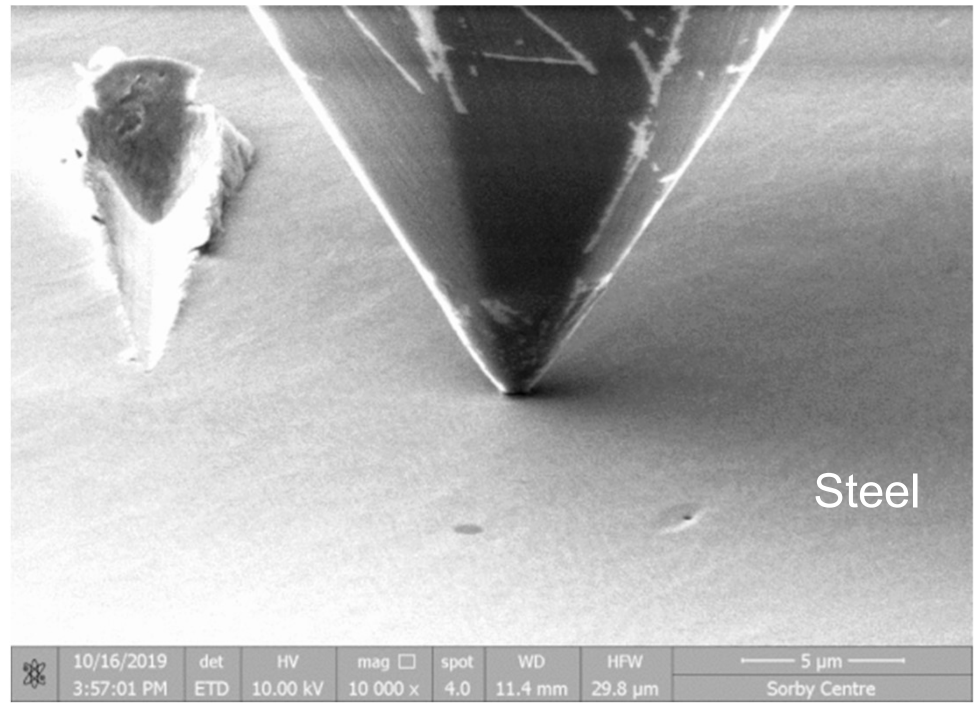


L. Major, R. Major, M. Kot, J. M. Lackner and B. Major, *Ex situ and in situ nanoscale wear mechanisms characterization of Zr/Zr_xN tribological coatings*, Wear 404-405 (2018) 82-91

//// Custom *In-Situ* Tribology Tests

Chip formation in metals:





(Courtesy of University of Sheffield, UK)

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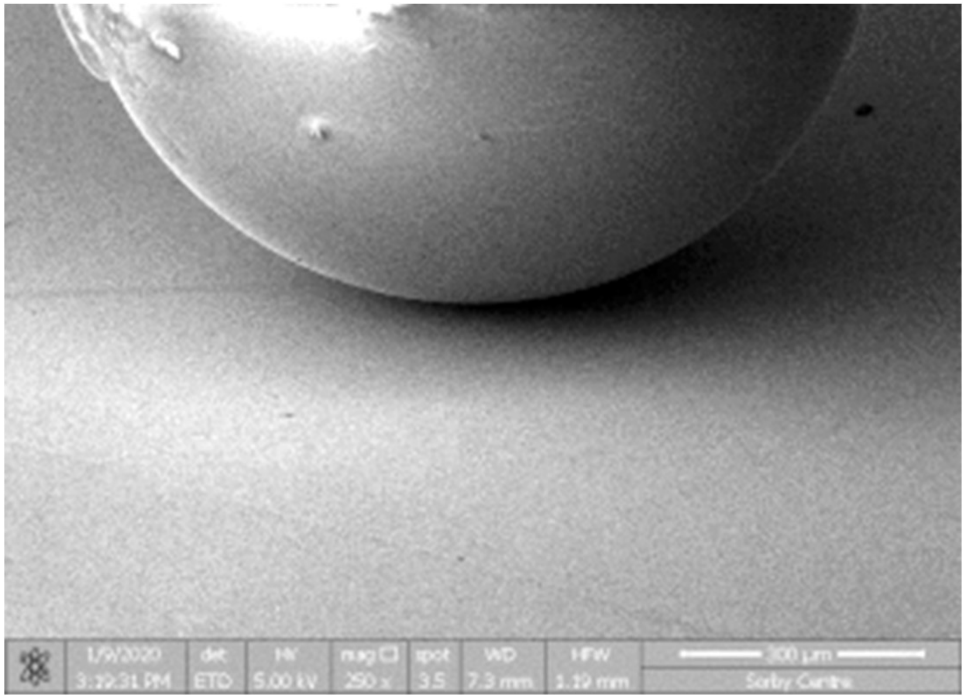
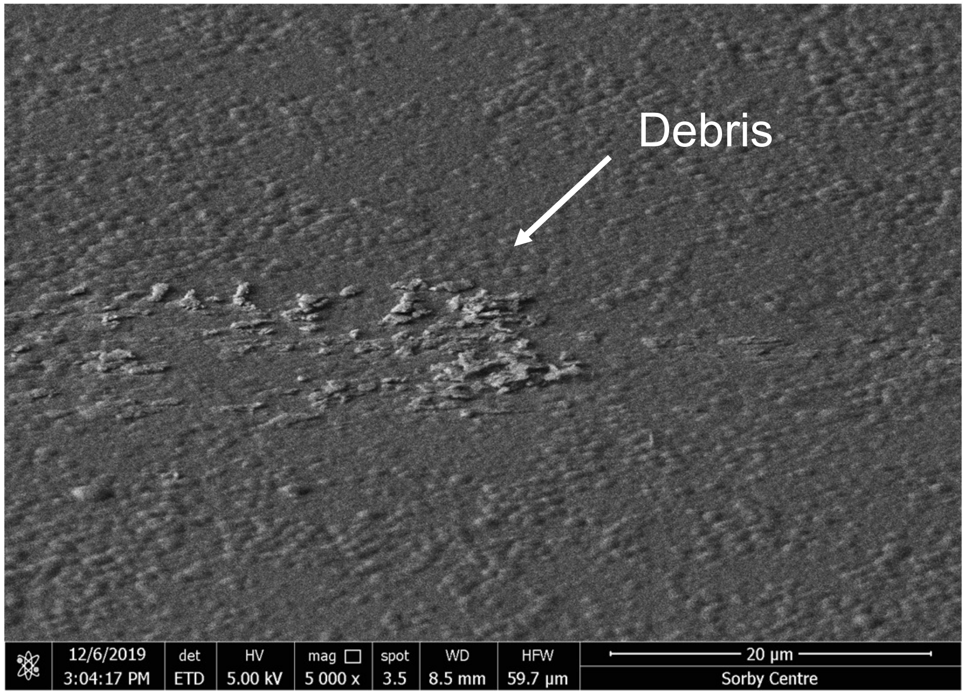
//// Custom *In-Situ* Tribology Tests

Sapphire ball (Φ 1mm) on Silicon doped Diamond-like Carbon thin film



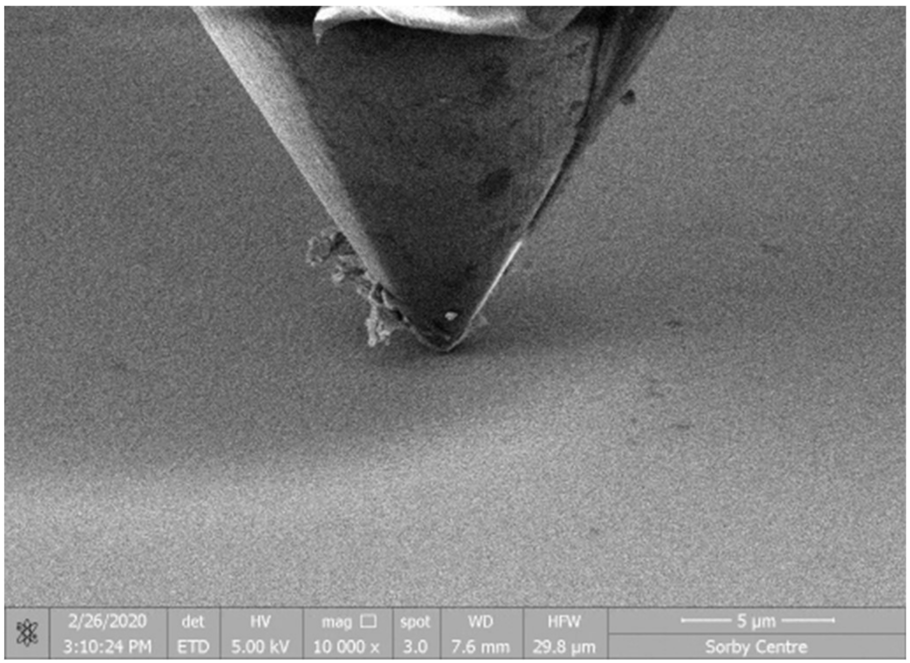


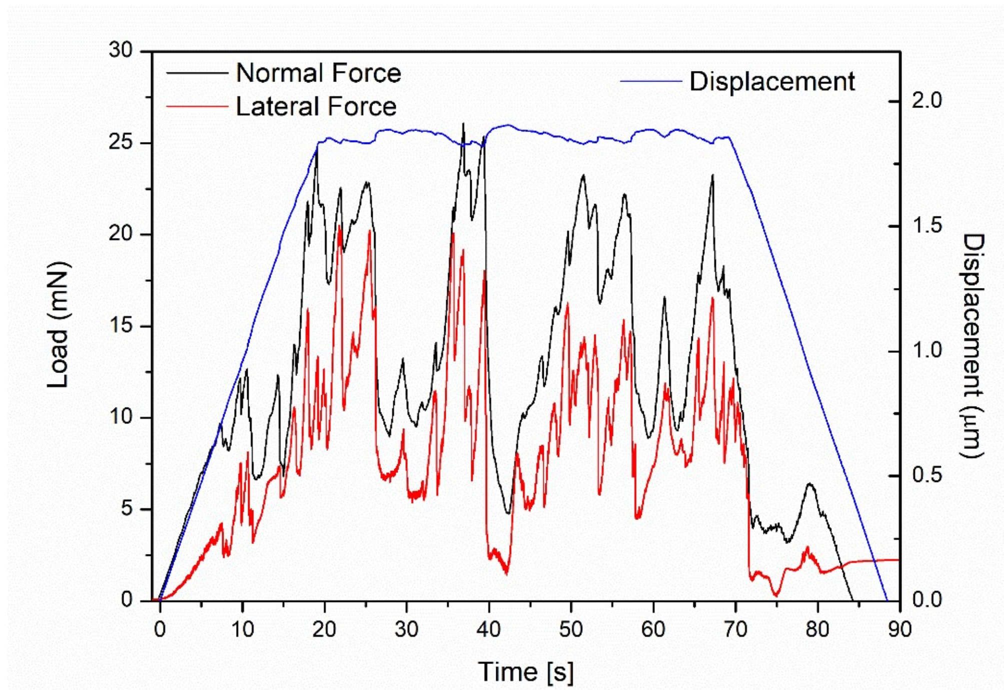
(Courtesy of University of Sheffield, UK)

//// Custom *In-Situ* Tribology Tests

In-situ self-healing effect

STEP 1: Scratch test on WS_2/DLC to create defined damage:





(Courtesy of University of Sheffield, UK)

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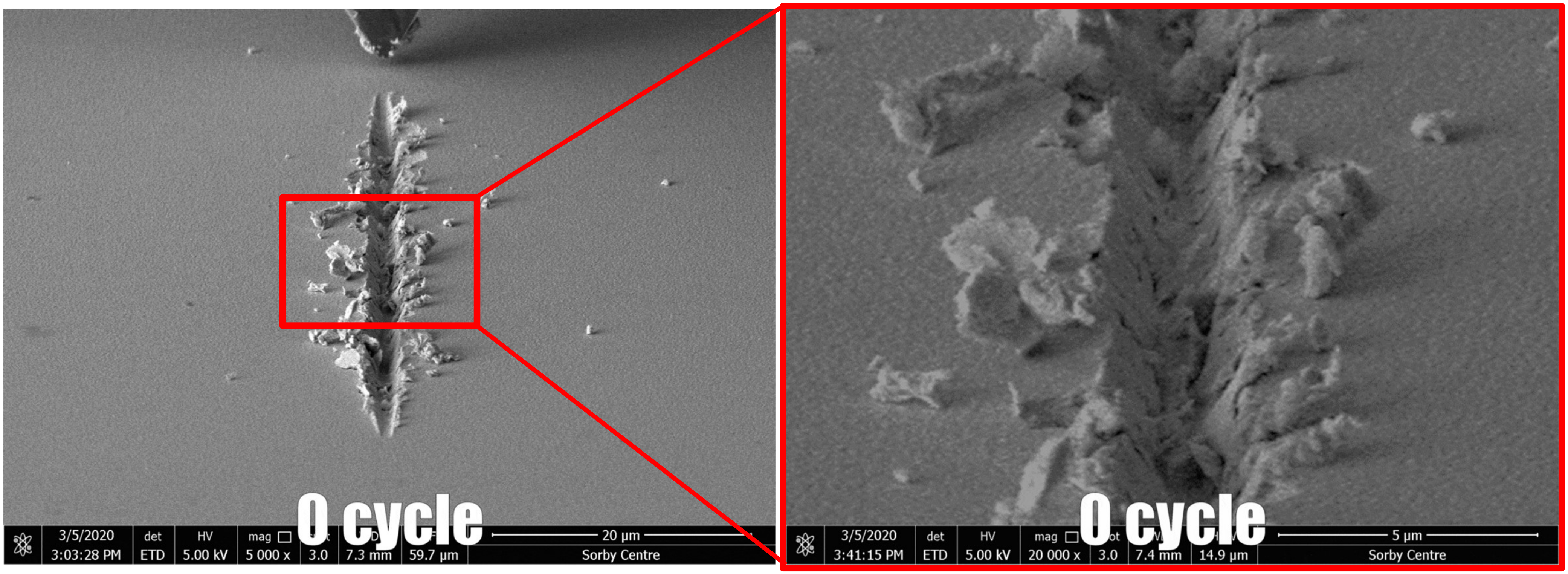
//// Custom *In-Situ* Tribology Tests

In-situ self-healing effect

STEP 2: Reciprocating wear test over damage with SiC ball (Φ 800 µm):



Applied load 500 mN, length 100 µm, speed 100 µm/s

(Courtesy of University of Sheffield, UK)

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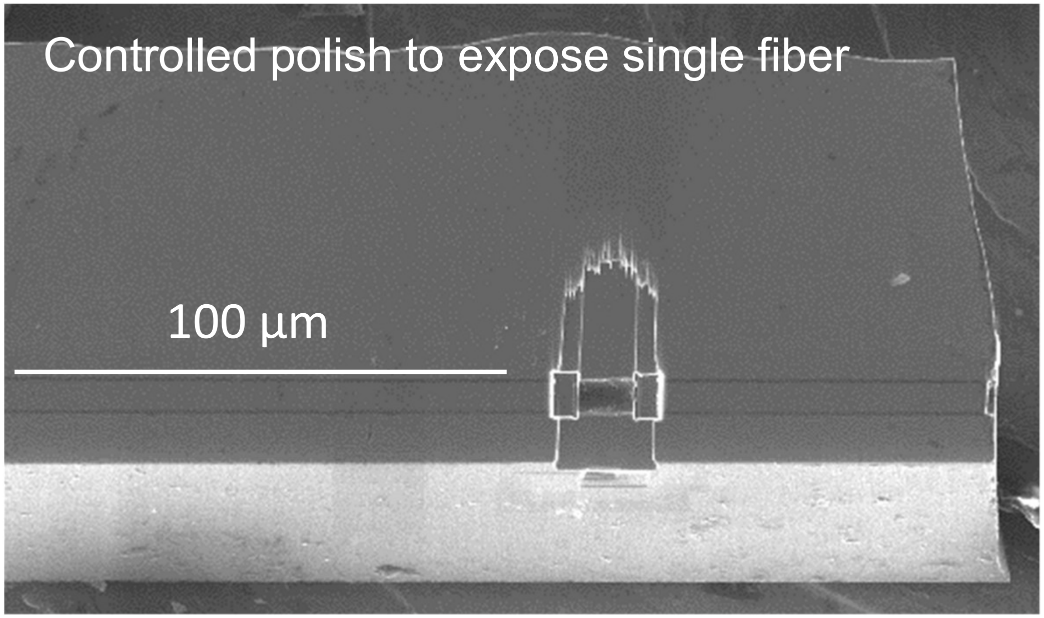
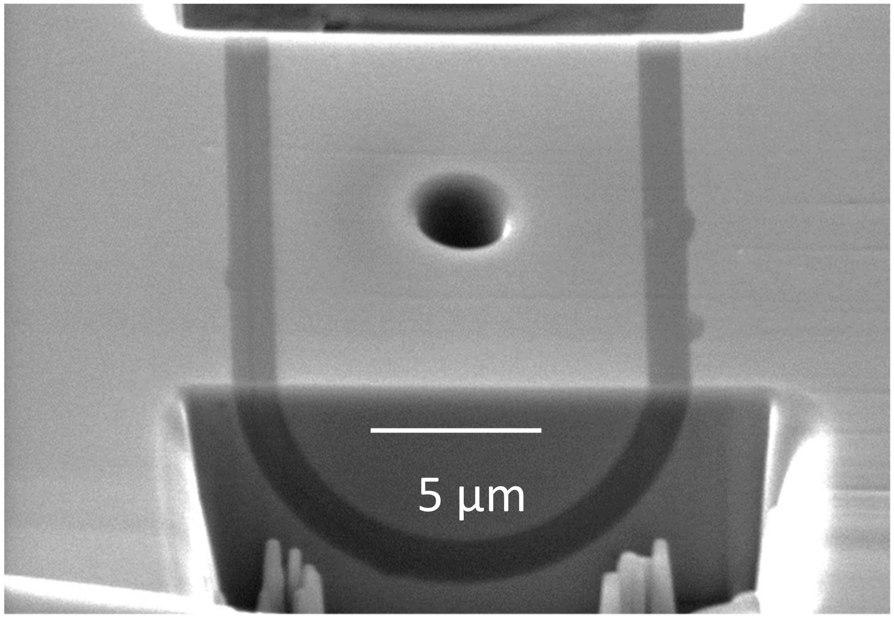
//// Custom *In-Situ* Tribology Tests

Objective: measure interfacial shear strength and wear properties in SiC fiber/pyrolytic carbon/SiC matrix composites





(Courtesy of J. Kabel, UC Berkeley, USA)

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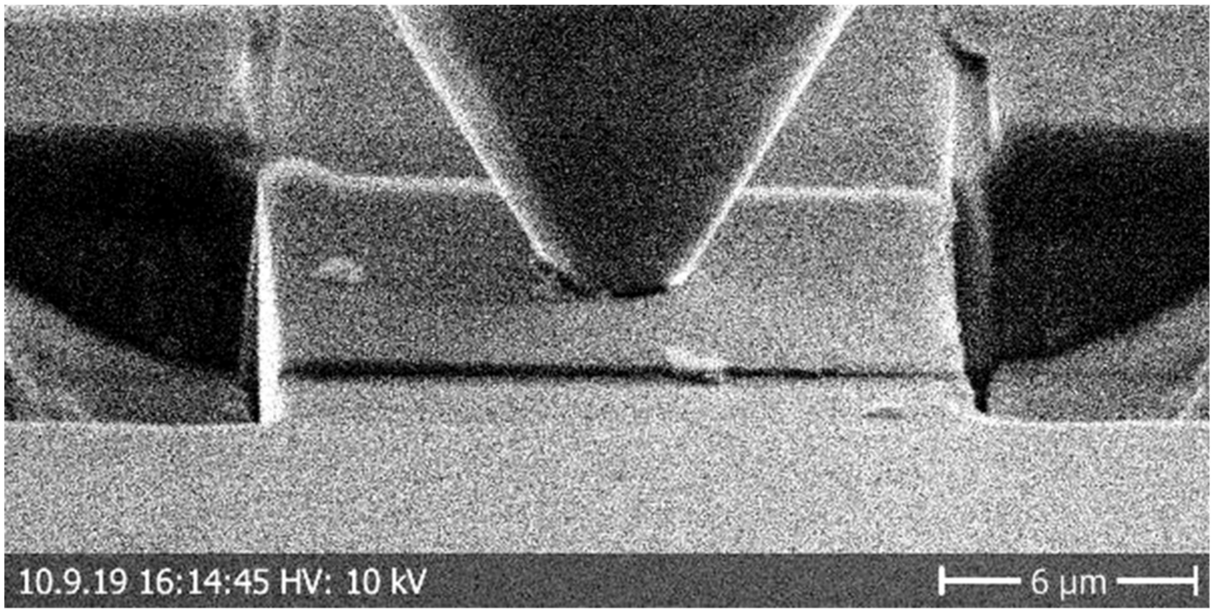
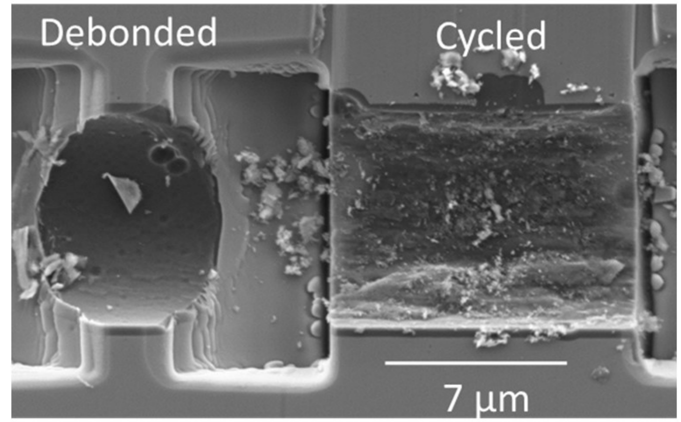
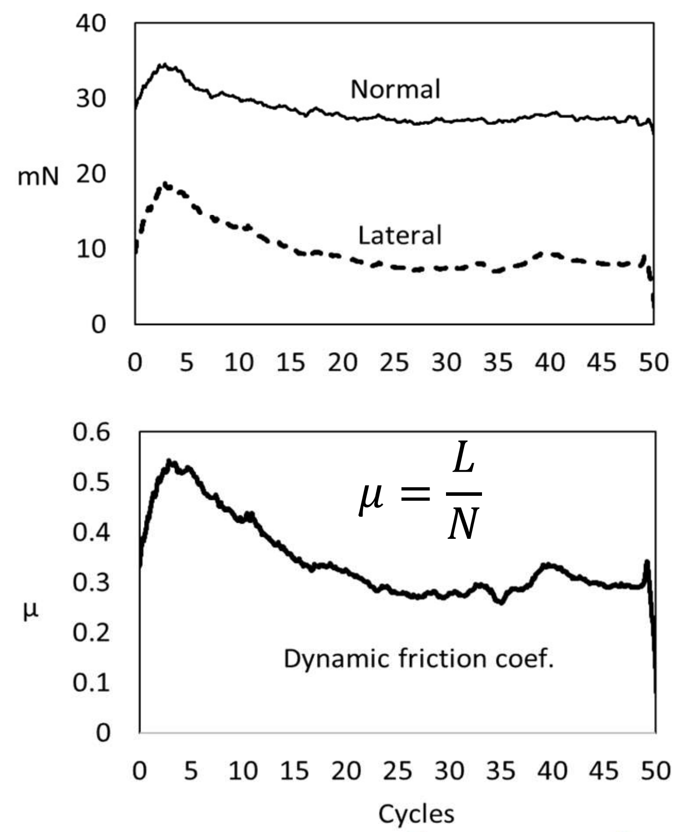
//// Custom *In-Situ* Tribology Tests

Results: Cyclic sliding with speed of 3 µm/s



(Courtesy of J. Kabel, UC Berkeley, USA)





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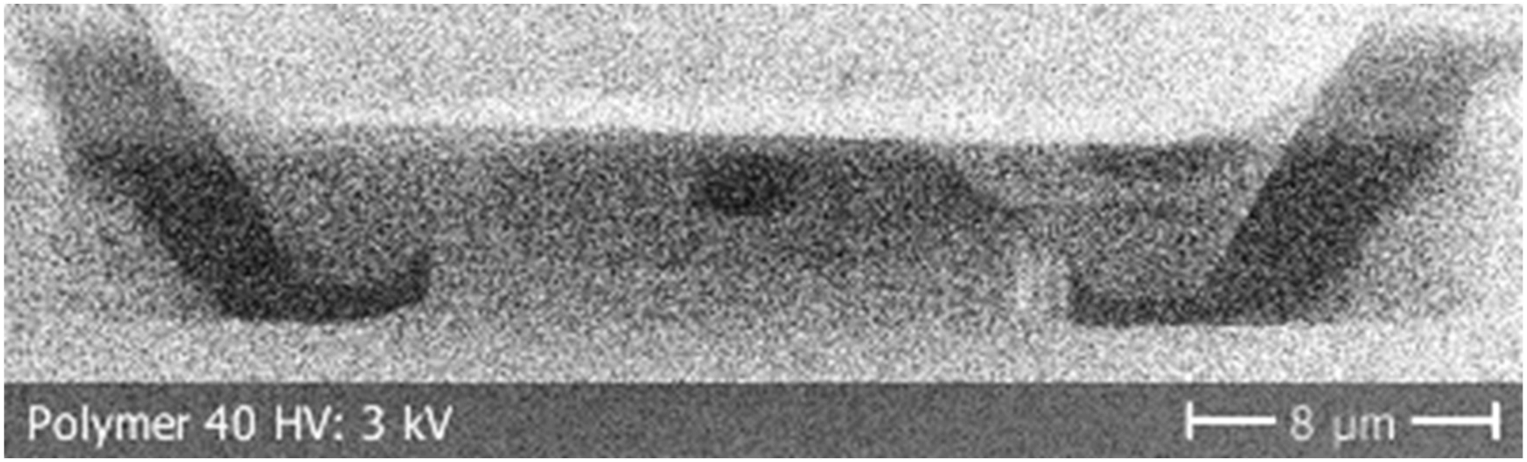
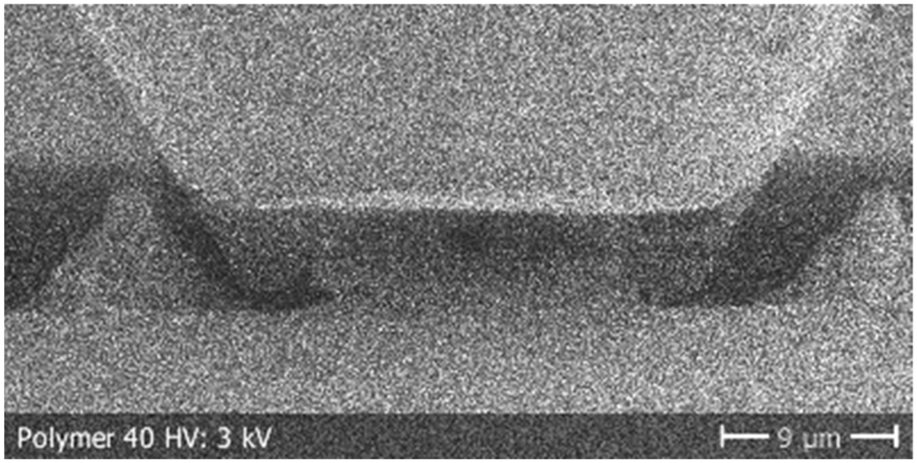
//// Custom *In-Situ* Tribology Tests

Results: Improved diamond double-prong indenter and cyclic sliding with different frequencies

1 Hz, 15 mN (Fn)



5 Hz, 15 mN (Fn)



(Courtesy of J. Kabel, UC Berkeley, USA)

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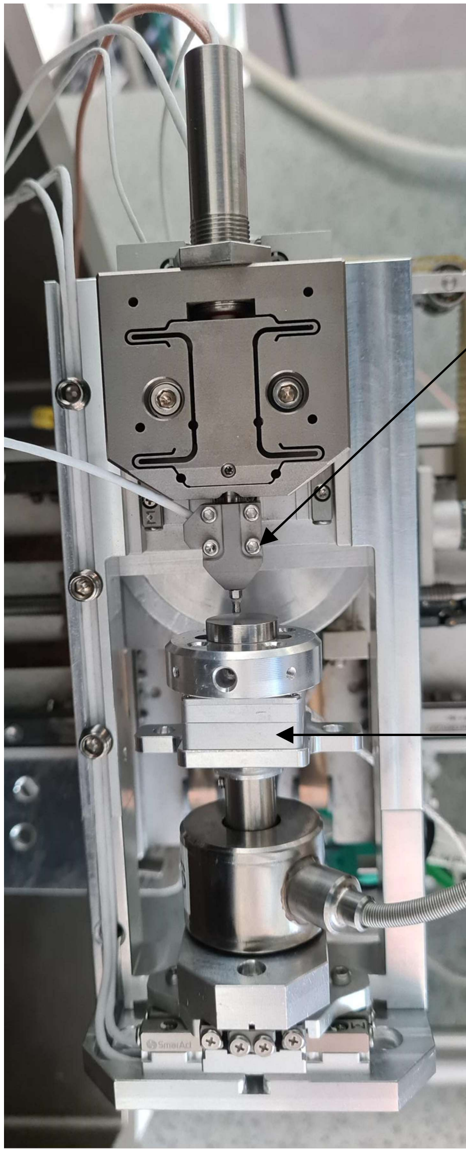
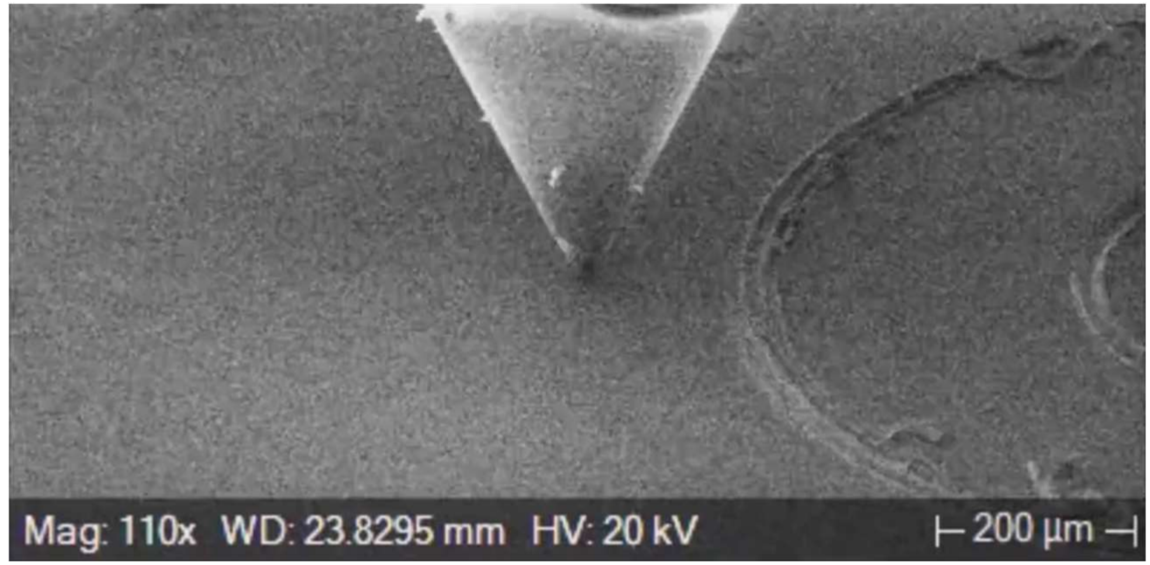
//// *In-Situ* Pin-on-Disk

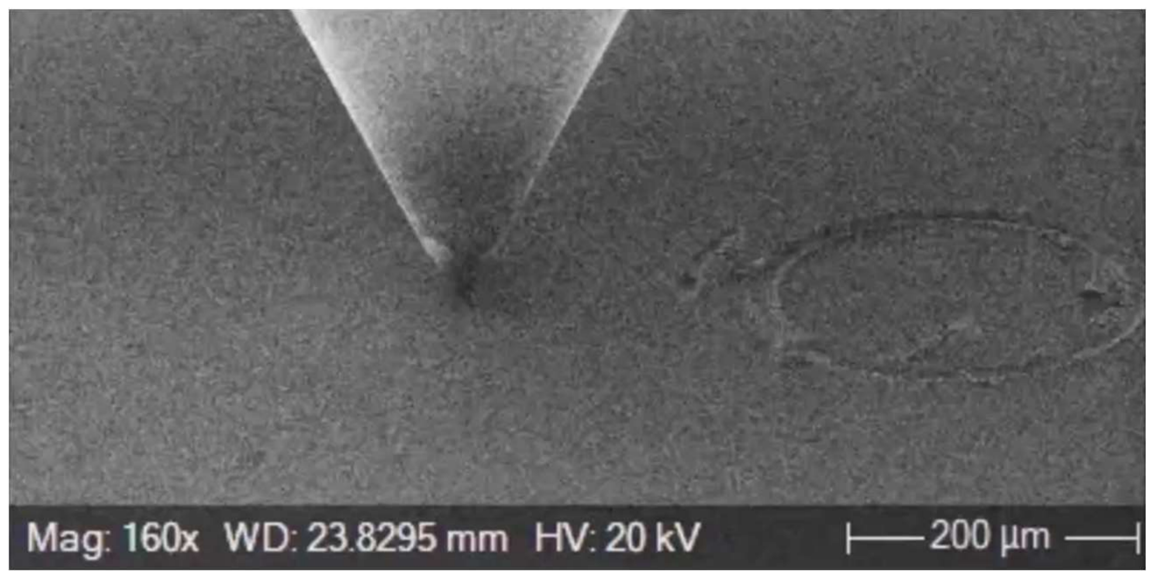


Lateral force sensor (LFS)

Rotation Stage

Diamond spherical indenter (radius 10 µm), Cu sample (Video 8x)





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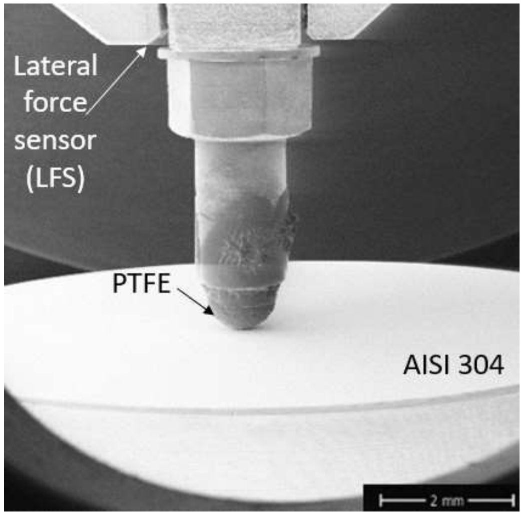
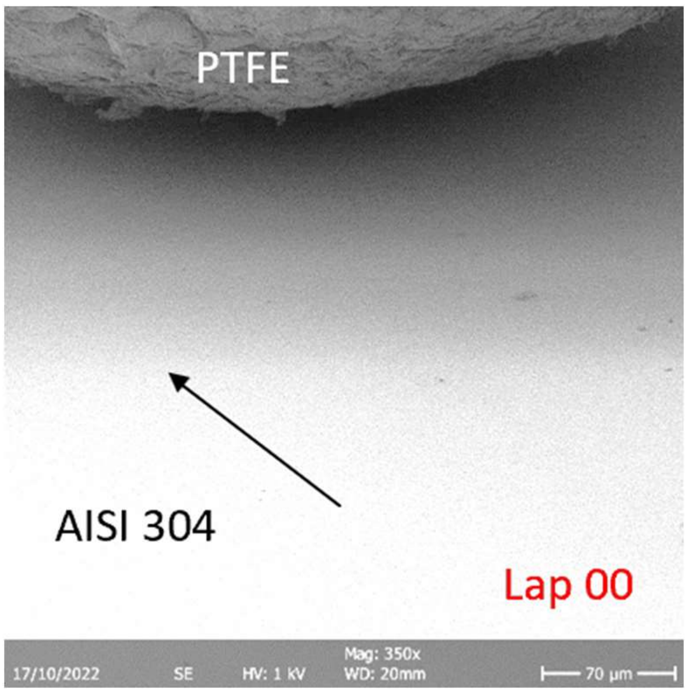
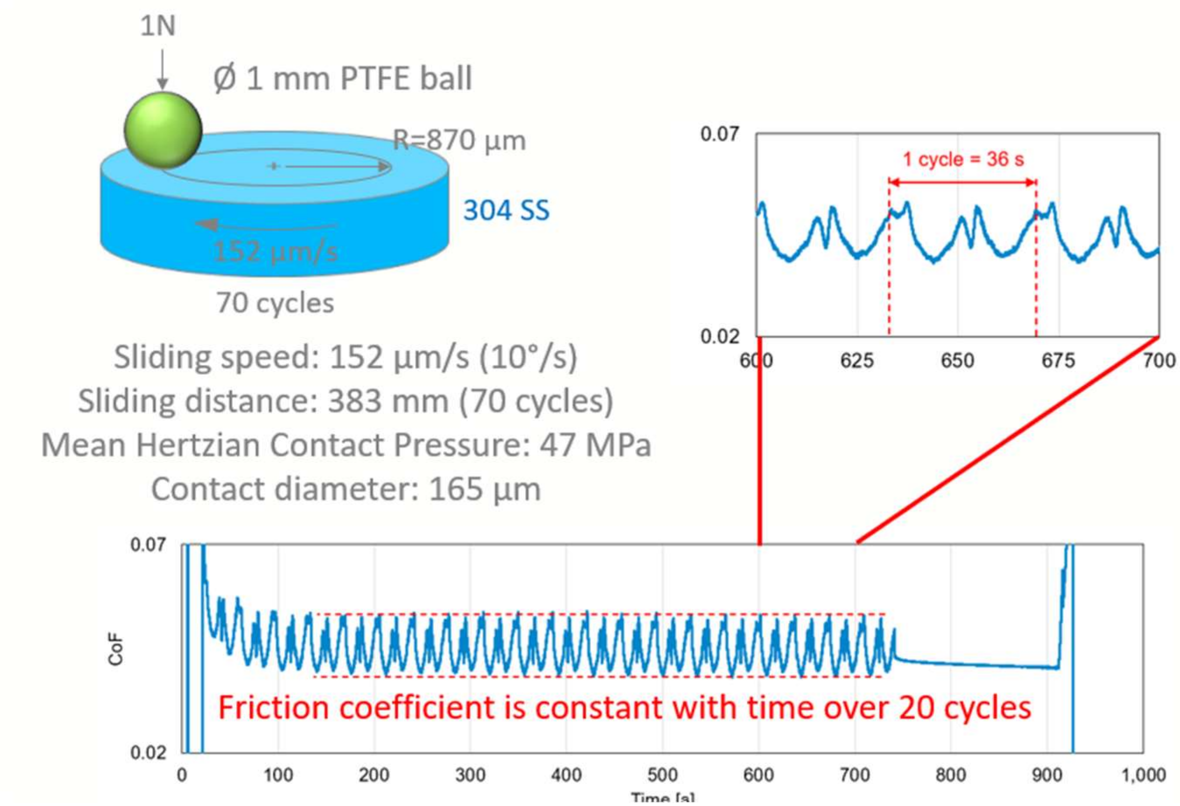
//// *In-Situ* Pin-on-disk for PTFE transfer film investigation







(Courtesy of Imperial College London, UK)

//// Insect Foot Tribology

– The „sample“ must live during testing - as the tribochemical nature of their „pads“ does require an active metabolism
– However the „sample fixation“ is not so easy as freedom is a biological priority
➔ the animal must be tied

Double cantilever

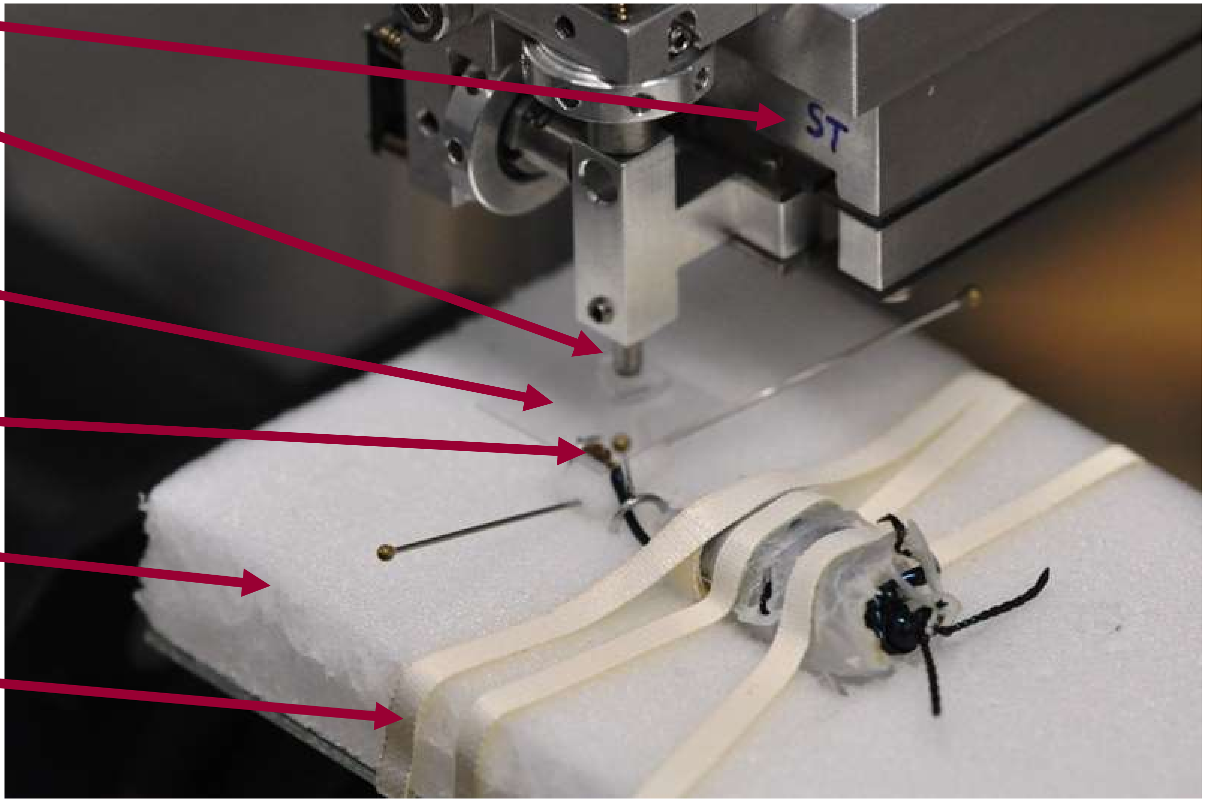
2 mm standard pin connector interface

„**Pin**“ = glass counterpart (glued on 2 mm pin)

„**Disc**“ = pad of animal foot (1 foot is separately fixed)

Ergonomically shaped bug bed

Adhesive tape strips for tieing



//// Insect Foot Tribology

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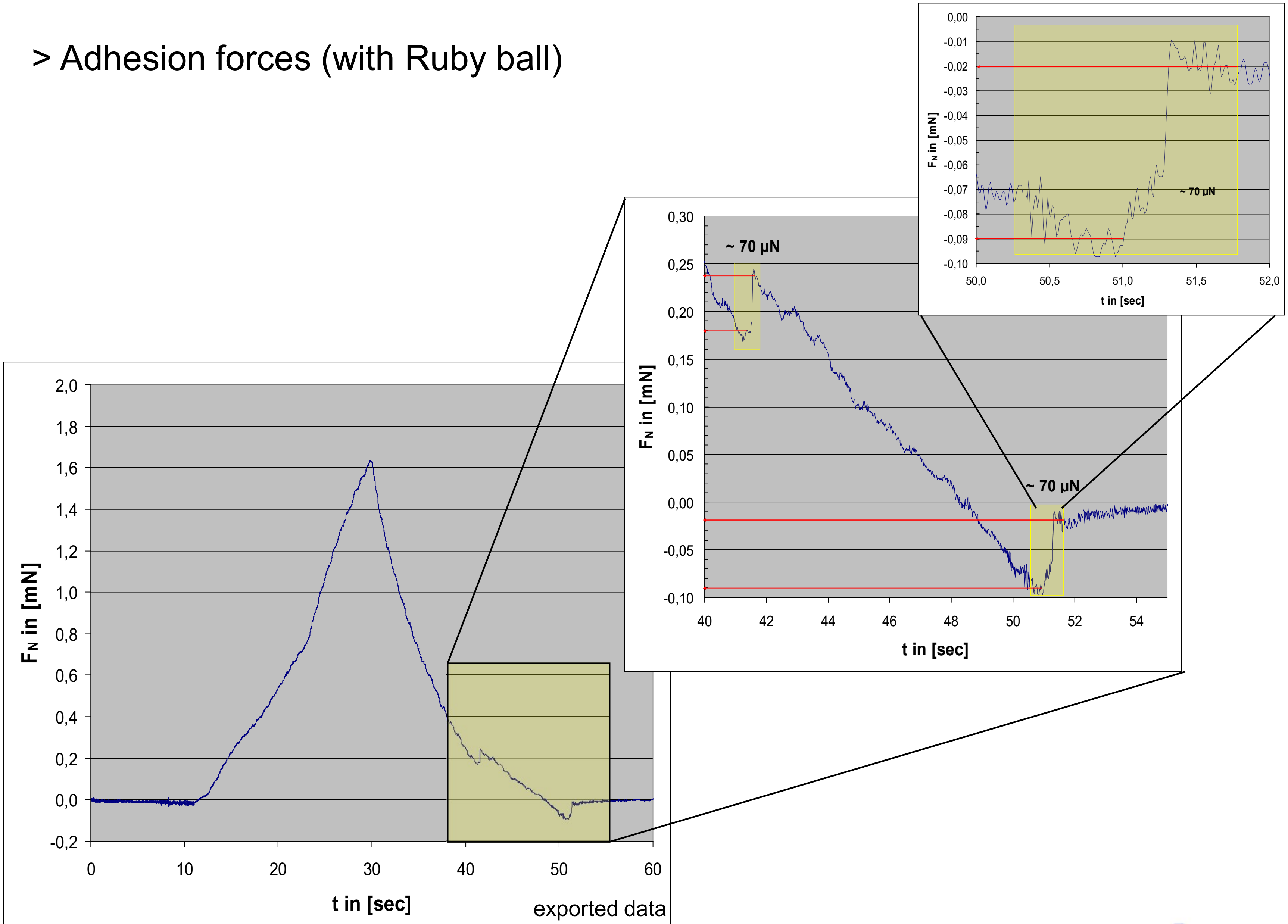
NANOTRIBOMETER: INSECT FOOT ADHESION/FRICTION

> Adhesion forces (with Ruby ball)



Courtesy of Prof. Dr. Oliver BETZ; Eberhard-Karls-Universitaet; Tuebingen

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//// Tribological Testing

When designing an experiment:

- Get the tribological principles right first
- Remember that friction and wear are system properties
- Have a sense of proportion and scale
- Ignore temperature and thermal effects at your peril
- Get the mechanics right, both static and dynamic
- Avoid unnecessary complexity
- Choose the right test machine for the job

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USEFUL REFERENCES

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2. K. Ludema, *Friction, Wear, Lubrication: A Textbook in Tribology*, CRC Press (1996)

3. F. Ling and C. Pan, *Approaches to modeling of friction and wear: proceedings of the Workshop on the Use of Surface Deformation Models to Predict Tribology Behavior*, Columbia University, New York, (1986)

4. R. Bayer and A. Ruff, *Tribology Wear Test Selection for Design and Application*, ASTM International (1993)

5. C. Yust and R. Bayer, Selection and Use of Wear Tests for Ceramics, ASTM International (1988)

6. K. Ludema and R. Bayer, Tribological Modeling for Mechanical Designers, ASTM International (1991)

7. M. Hutchings, Tribology: Friction and Wear of Engineering Materials, Arnold, London (1995)

8. J. A. Williams, Engineering Tribology, Oxford University Press (1994)

9. R. Bayer, Selection and Use of Wear Tests for Coatings, ASTM International (1982)

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APPENDIX 1: Tribological Testing Methods

APPENDIX 2: Tribological Testing Standards

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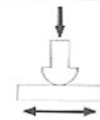
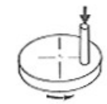
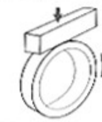
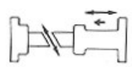
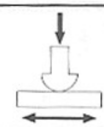
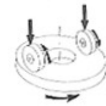
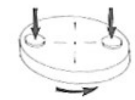
//// Summary of Tribological Testing methods

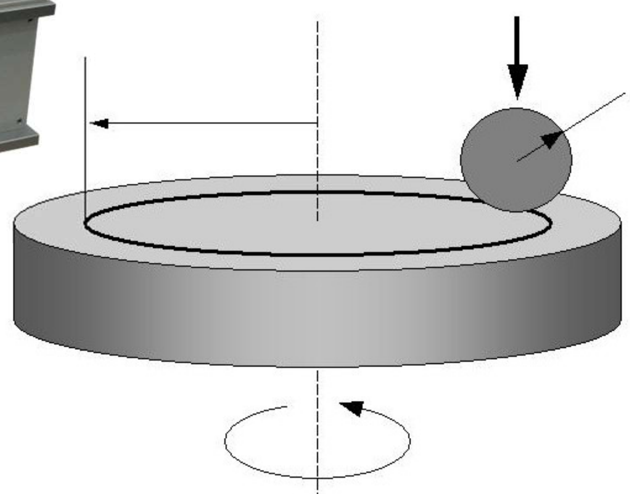
	BLOCK-ON-PIN (FALEX)	TWIN DISC (AMSLER)	PIN-ON-FLAT (ASTM)	PIN-ON-DISC (VAMAS)	BLOCK-ON-RING (ASTM)
TEST CONFIGURATION					
TEST PURPOSE	Determination of wear rate, load carrying capacity and friction coefficient for sliding contacts.	Determination of sliding or rolling wear rate of test materials, treatments or coatings.	Determination of wear rate and coefficient of friction at low loads and speeds and with small specimens.	Determination of sliding wear rate and coefficient of friction.	Determination of adhesive wear rate of materials.
SPECIMENS	A 6.35 mm diameter cylindrical journal is rotated within two loaded stationary V-blocks to give a 4-line contact.	Normally two discs 40 mm diameter and 10 mm thick. Alternatively the discs may be 30 and 50 mm in diameter.	A pin or ball rubbing against a plate.	A pin or a ball rubbing on a rotating plate.	A steel ring is rotated against a stationary block.
TEST CONDITIONS	Journal speed 290 rev/min. Sliding velocity 0.1 m/s. Load (constant or increasing) 89-20000 N. Hertz stress 242-3450 MN/m^2. Specimens can be immersed in oil or other fluid.	Lower disc speed 0-400 rev/min. Upper disc speed 440 rev/min. Load 200 - 2000 N. Dry or lubricated.	Reciprocating sliding frequency 5 Hz. Stroke length 10 mm. Load 25 N. Temperature 18-23°C. Humidity 40-60 %RH Specimen can be dry or fully immersed in lubricant.	Sliding speed 0.1 m/s. Load 10 N. Sliding distance 1 km. Temperature 23°C. Humidity 50 %RH.	Ring speed (max) 7000 rev/min. Load (max) 6000 N. Duration 5400-24000 cycles. Specimen can be dry or immersed in oil or other fluid.
MEASUREMENTS	Journal driving torque. Progressing wear depth. Wear life. Seizure failure load. Final specimen weights.	Individual disc weight loss or profile. Total disc weight loss. Wear life.	Weight loss of disc. Height loss of pin. Wear track profilometry. Ball wear area measurement. Friction force.	Height loss of pin. Wear track profilometry. Ball wear area measurement. Friction force.	Test block weight loss. Scar width. Ring weight loss. Friction force. Lubricant film load currying capacity.
WEAR TYPES/ COMMENTS	Mild and severe adhesive wear. Scuffing.	Mild and severe adhesive wear. Rolling contact fatigue (pitting).	Mild adhesive wear suitable for tribological coating evaluation.	Mild and severe adhesive wear. Suitable for tribological coating evaluation.	Mild and severe adhesive wear. Lubricated wear.

//// Summary of Tribological Testing methods

	HAMMER WEAR	FRETTING	RUBBER WHEEL ABRASION (ASTM)	DRY ABRASION (TABER)	WET SLURRY ABRASION
TEST CONFIGURATION					
TEST PURPOSE	Determination of cohesion and adhesion qualities of coatings and also their wear characteristics under arduous vibrating conditions.	Determination of wear rate and friction in small amplitude oscillating contacts.	Determination of wear resistance of materials to third body-scratching abrasion.	Determination of the abrasive wear rate and the Taber wear index of material surfaces.	Determination of the abrasive wear rate and the abrasion resistance of materials and treatments.
SPECIMENS	Obliquely cut specimens of 23 mm² contact area.	Ball or pin against a flat plate.	Flat (coated) pad is loaded against a rotating rubber wheel. The abrasive particles are a rounded quartz grain sand as typified.	Flat face of the disc abraded by two rubber bonded abrasive wheels (CS-10).	Two specimen pads loaded against a rotating circular plate.
TEST CONDITIONS	Combined impact and sliding. Sliding distance 0.76 mm. Impact frequency 60-70 Hz. Impact load 60-223 N. Temperature 600°C. Duration 6-10 h.	Sliding amplitude 0.02-0.4 mm. Sliding frequency 5-20 Hz. Load 2-50 N. Temperature 22°C. Specimen can be dry or fully immersed in lubricant.	Wheel speed 2000 rev/min. Load 130 N. The abrasive media is dry sand particles or sand particles in wet slurry.	Load 9.81 N. Wheels cleaned with abrasive paper every 1000 revolutions. Test is run without lubricant.	Load 112 N. Runs in bath of abrasive slurry.
MEASUREMENTS	Volume loss. Fretting resistance.	Volume loss by wear scar measurements. Friction force.	Weight loss or wear scar depth by profilometry.	Weight loss. Taber Wear Index = weight loss/1000 revs (mg).	Volume loss.
WEAR TYPES/ COMMENTS	Adhesive wear. Fatigue wear. Fretting.	Fretting wear.	Dry or wet low stress abrasion.	Low stress abrasion.	High stress grinding abrasion. Low stress abrasion.

//// Tribology Testing Standards

Instrument	Standard No.	Standard Title	Comments
TRB/THT	ASTM G99	Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus	Calculation of wear
	ASTM G133	Standard Test Method for Linearly Reciprocating Ball-on-Flat Sliding Wear	Calculation of wear
	DIN 50324	Testing of Friction and Wear	



Pin volume loss = $(\pi h/6)[3d2/4 + h2]$

where $h = r - [r2 - d2/4]1/2$ (height of material removed)
d = wear scar diameter
r = ball radius

Assuming no significant pin wear, the volume loss of the disk is given by:

Disk volume loss = $2\pi R[r2 \sin-1 (d/2r) - (d/4)(4r2 - d2)1/2]$

where R = wear track radius
d = wear track width

//// Tribology Testing Standards

Instrument	Standard No.	Standard Title	Comments
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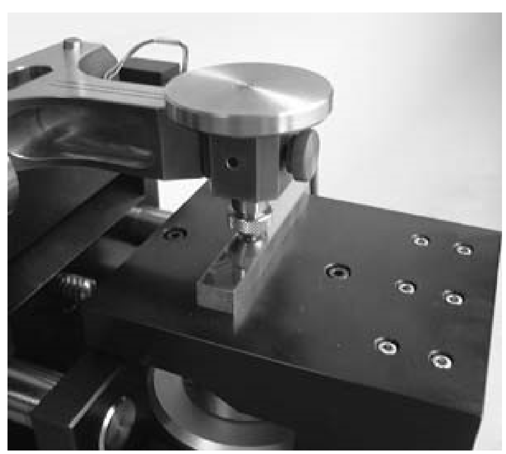
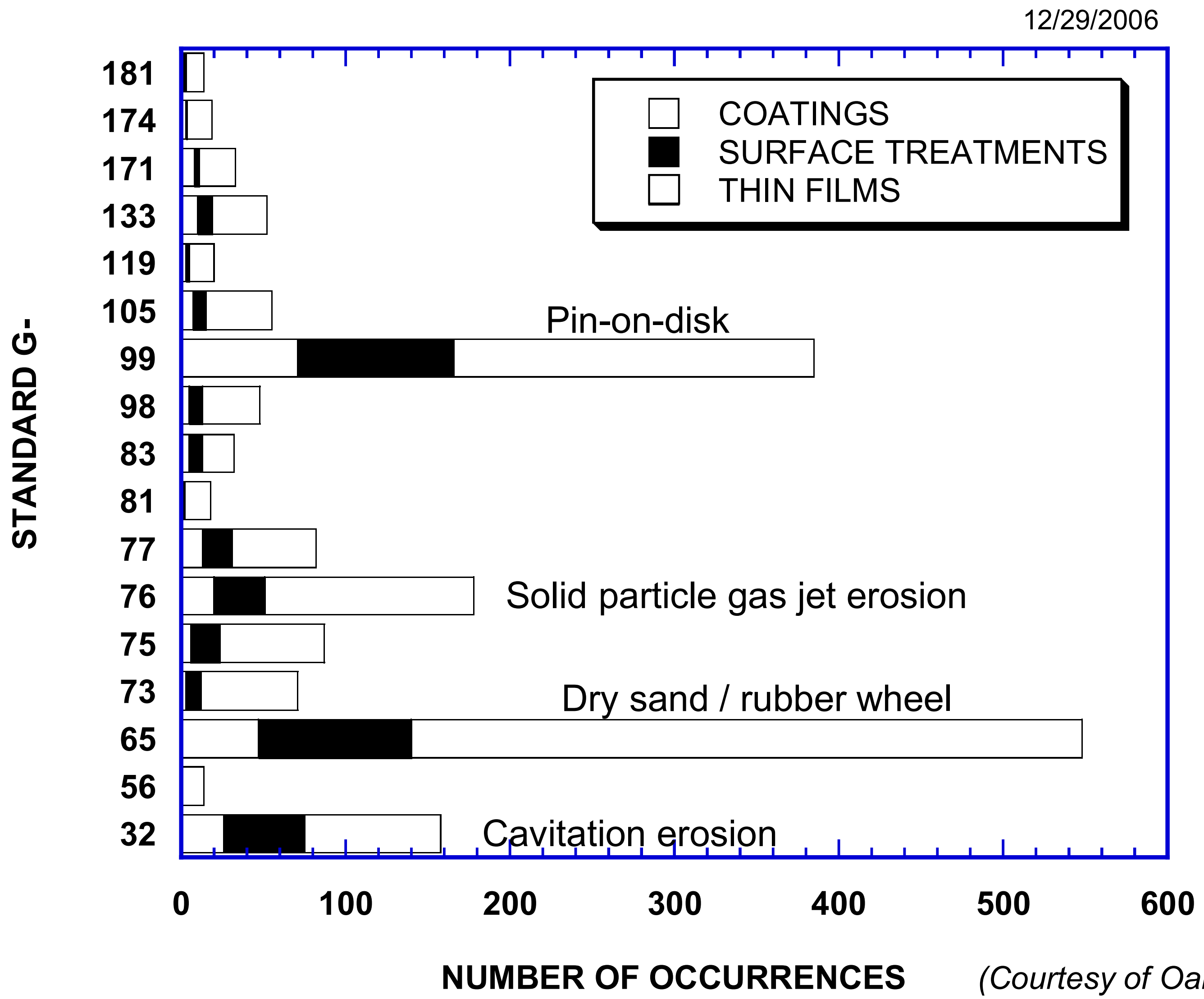


$$V_{track} = A \times L$$

where A **= average cross-sectional area of the track**
L **= length of the stroke**

//// Tribological Testing Standards

Popularity of standards (No. of Google "hits" for each standard):



(Courtesy of Oak Ridge Nat Labs)

//// Summary of Tribological Testing Standards

	Title*	Materials in the Scope Statement	Wear Criteria
C501	STM for relative resistance to Wear of Unglazed Ceramic Tile	ceramic tile	mass loss
C1624	STM for Adhesion Strength and Mechanical Failure Modes of Ceramic Coatings by Quantitative Single Point Scratch Testing	ceramic coatings on metal or ceramic substrates	critical load for coating failure, by friction, acoustic emission, or observation
D968	STM for Abrasion Resistance of Organic Coatings by Falling Abrasive	organic coatings on panels	relative ranking of materials
D1044	STM for Resistance of Transparent Plastics to Surface Abrasion	transparent plastics	luminous transmittance and haze observed after abrasion
D4060	STM for Abrasion Resistance of Organic Coatings by the Taber Abraser	organic coatings (paint) on panels	loss in weight or number of cycles to remove a unit of coating thickness
D7027	STM for Evaluation of Scratch Resistance of Polymeric Coatings and Plastics Using an Instrumented Scratch Machine	polymers	observations of scratch damage as well as friction force
F1978	STM for Measuring Abrasion Resistance of Metallic Thermal Spray Coatings by Using the Taber™ Abraser	thermally-sprayed metallic coatings intended for use in implants	mass loss

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//// Summary of Tribological Testing Standards

	Title*	Materials in the Scope Statement	Wear Criteria
G32	STM for Cavitation Erosion Using Vibratory Apparatus	non-specific materials	mass loss
G56	STM for Abrasiveness of Ink-Impregnated Fabric Printer Ribbons	abrasion of hardened AISI 52100 steel by fabric printer ribbons	left to the user's discretion
G65	STM for Measuring Abrasion Using the Dry Sand/Rubber Wheel Apparatus	metallic materials (a coating could qualify)	mass loss
G73	SP for Liquid Impingement Erosion Testing	solid materials or coatings (especially thin film coatings on window materials)	mass loss ("or other damage manifestation")
G75	STM for Determination of Slurry Abrasivity (Miller Number) and Slurry Abrasion Response of Materials (SAR Number)	any material with the exception of thin hard coatings (0.051-0.127 mm thick) that cannot be surface finished	mass loss
G76	STM for Conducting Erosion Tests by Solid Particle Impingement Using Gas Jets	non-specific materials	mass loss
G77	STM for Ranking Resistance of Materials to Sliding Wear using Block-on-Ring Wear Test	any material(s) that can be fabricated into blocks and rings	block scar width and block weight loss (optional), converted to wear volume
G81	STM for Jaw Crusher Gouging Abrasion Test	materials homogeneous in structure and properties, but allows for surface-treated and composite materials	mass loss

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//// Summary of Tribological Testing Standards

	Title*	Materials in the Scope Statement	Wear Criteria
G83	STM for Wear Testing Using a Crossed Cylinder Apparatus	metallic couples (but does not exclude coatings)	mass loss converted to volume
G98	STM for Galling Resistance of Materials	metals, alloys, non-metallics, coatings, and surface-modified alloys	visual examination
G99	STM for Wear Testing with a Pin-on-Disk Apparatus	non-specific materials (but does not exclude coatings)	specimen dimensions or weight loss converted to volume
G105	STM for Conducting Wet Sand/Rubber Wheel Abrasion Tests	metallic materials	mass loss converted to wear volume
G119	SG for Determining Synergism Between Wear and Corrosion	metallic materials	volume loss per unit area
G132	STM for Pin Abrasion Testing	non-specific materials	mass loss converted to volume
G133	STM for Linearly Reciprocating Ball-on-Flat Sliding Wear	ceramics, metals, and other wear-resistant materials	ball wear diameter, cross-sectional area of wear track
G134	STM for Erosion of Solid Materials by a Cavitating Liquid Jet	solid materials	mass loss
G171	STM for Scratch Hardness of Materials using a Diamond Stylus	metals, ceramics, polymers, and coated surfaces	scratch width converted to a hardness number
G174	STM for Measuring Abrasion Resistance of Materials by Abrasive Loop Contact	metals and coatings applied to metals	scar width or mass loss

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