Tribology 101 – 2: Characterizing the Tribo-system and Defining the Tribo-test

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Elements of “The Tribosystem”

- **First Question: What is the intended application?**
  - Knowing the application helps us select the tribo-elements we need to incorporate in the tribo-test.

- **The Tribo-elements include:**

1. Materials

2. Contact Geometry

3. Loading

4. Motion

5. Environment

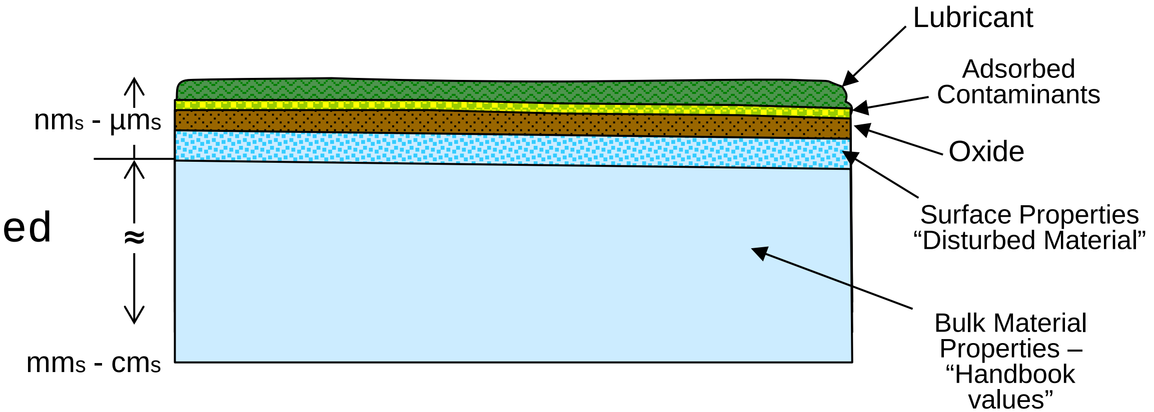
Let us examine each of these areas in more detail.

Let us try to list all the possible contributing factors which can define a tribo-system.

Elements of the Tribo-System

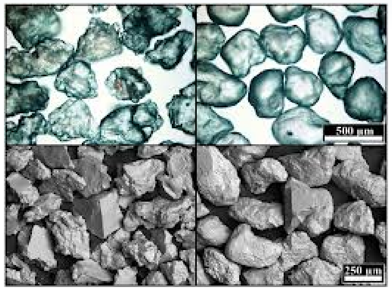
1. Materials – (a)

- **Solid bodies**
  - Bulk Materials
    - Basic Composition
    - Heat Treatment
  - Oxides
    - Thin, adherent
    - Thick, loosely bonded
  - Coatings
    - Thin
    - Thick
  - Lubricants
    - Anti-wear or EP Additives?
    - Viscosity, VI, or VP characteristics?
  - Adsorbed Layers
  - Contaminants



1. Materials – (b)

- **Loose Particles**
  - Composition
  - Hardness
  - Size distribution
  - Shape/Angularity
  - Slurry?
    - Concentration
  - Gas stream?
    - Concentration
    - Velocity
    - Angle of impact



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  - Composition
  - Hardness
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  - Shape/Angularity
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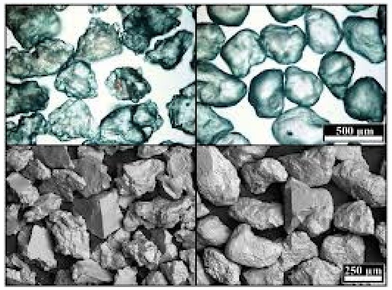
    - Concentration
    - Velocity
    - Angle of impact



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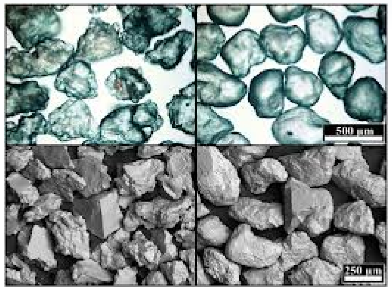

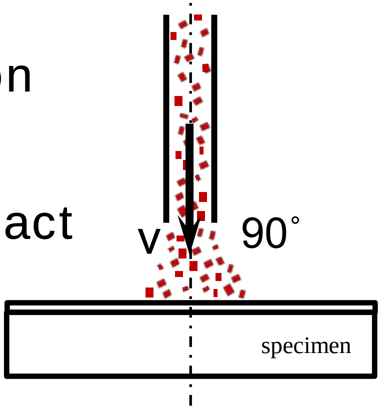

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  - Composition
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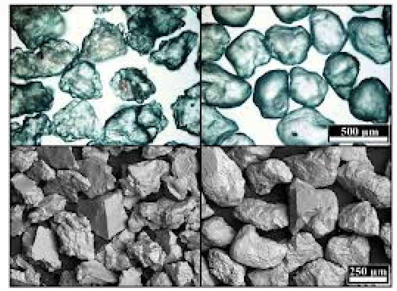
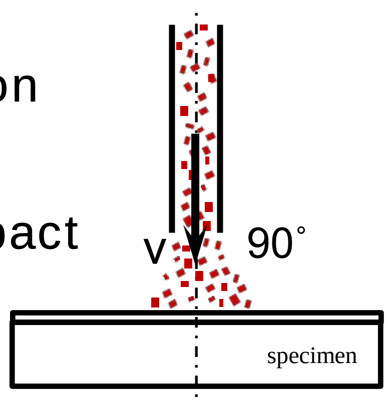
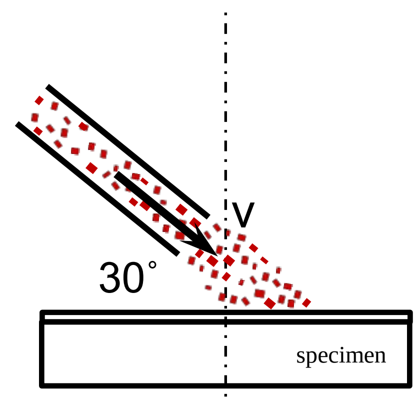
    - Velocity
    - Angle of impact







2. Contact Geometry (a)

- **Macroscopic Geometry of Contact**
  - **Flat-on-Flat** (disk brake or gate valve)
  - Conformal
  - Non-Conformal
    - Point, line, ellipse
- Surface Finish or Roughness
  - R_a, R_q
  - Bearing Area
  - Peak shape
  - Valley volume
  - Lay (directionality of marks)
- Edge conditions
  - Sharp, as-machined edge or burr
  - Chamfer or radius

2. Contact Geometry (a)

- **Macroscopic Geometry of Contact**
  - Flat-on-Flat
  - **Conformal** (drum brake, plug valve or journal bearing)
  - Non-Conformal
    - Point, line, ellipse
- Surface Finish or Roughness
  - R_a, R_q
  - Bearing Area
  - Peak shape
  - Valley volume
  - Lay (directionality of marks)
- Edge conditions
  - Sharp, as-machined edge or burr
  - Chamfer or radius

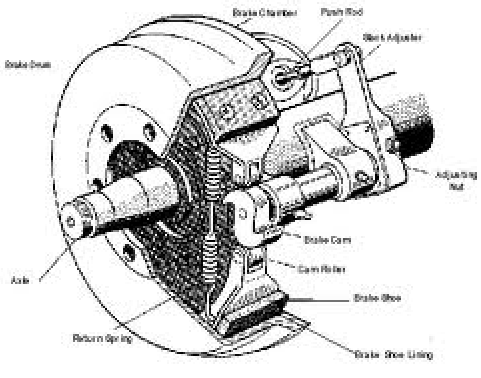


Figure 5-2 S-cam Air Brake

2. Contact Geometry (a)

- **Macroscopic Geometry of Contact**
  - Flat-on-Flat (disk brake)
  - Conformal (drum brake)
  - **Non-Conformal**
    - Point, line, ellipse
- Surface Finish or Roughness
  - R_a, R_q
  - Bearing Area
  - Peak shape
  - Valley volume
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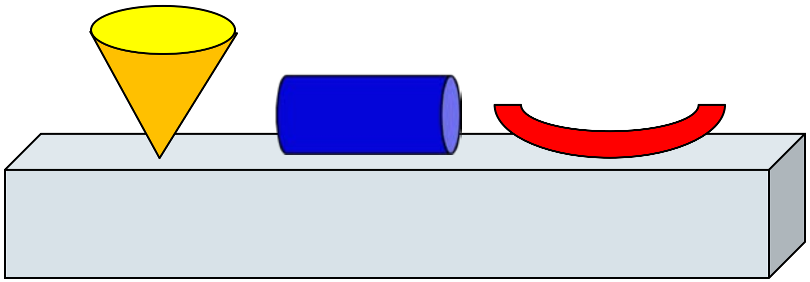
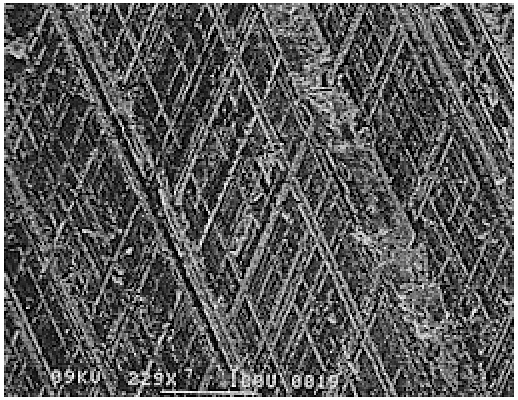


2. Contact Geometry (b)

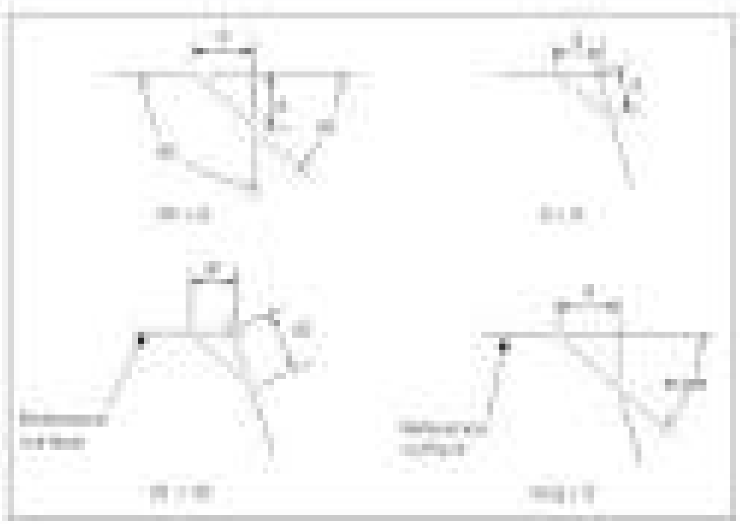
- Macroscopic Geometry of Contact
  - Flat-on-Flat (disk brake)
  - Conformal (drum brake)
  - Non-Conformal
    - Point, line, ellipse
- **Surface Finish or Roughness**
  - R_a, R_q
  - Bearing Area
  - Peak shape
  - Valley volume
  - Lay (directionality of marks)
- Edge conditions
  - Sharp, as-machined edge or burr
  - Chamfer or radius



Cross-honed Cylinder

2. Contact Geometry (c)

- Macroscopic Geometry of Contact
  - Flat-on-Flat (disk brake)
  - Conformal (drum brake)
  - Non-Conformal
    - Point, line, ellipse
- Surface Finish or Roughness
  - R_a, R_q
  - Bearing Area
  - Peak shape
  - Valley volume
  - Lay (directionality of marks)
- **Edge conditions**
  - Sharp, as-machined or stamped edge or burr
  - Chamfer or radius

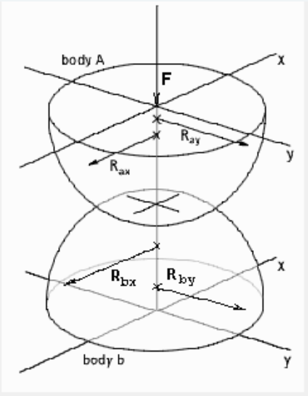


Edge Machining Instructions

To the extent possible, the samples should be finished in the same manner as the real-life components.

3. Loading

- **Contact Stress**
  - **Elastic**/Hertzian (usually from rolling contact)
  - Plastic (usually from sliding contact)
- Steady, Increasing, Decreasing Load
- Variable Load
- Fixed Load Direction
- Oscillating Load



3. Loading

- Contact Stress
  - Elastic/Hertzian (usually from rolling contact)
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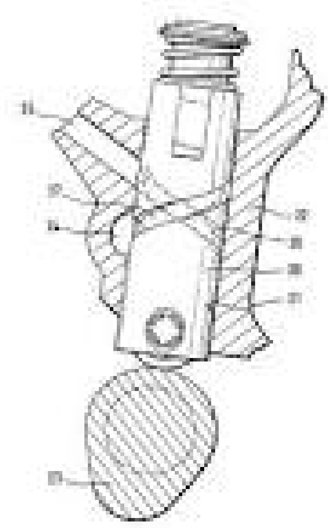
- **Steady, Increasing or Decreasing Load**
- Variable Load
- Fixed Load Direction
- Oscillating Load

Gate Valve

3. Loading

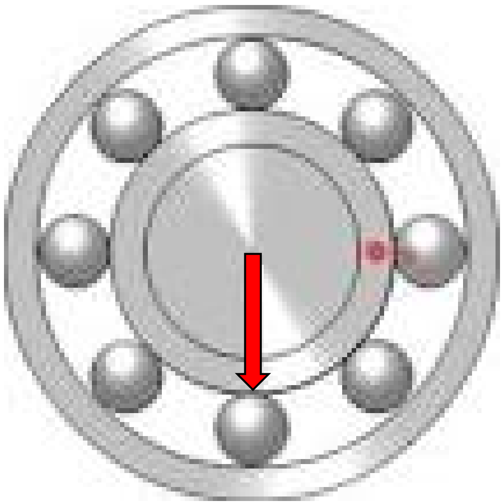
- Contact Stress
  - Elastic/Hertzian (usually from rolling contact)
  - Plastic (usually from sliding contact)
- Steady, Increasing or Decreasing Load
- **Variable Load**
- Fixed Load Direction
- Oscillating Load



Cam Follower

3. Loading

- Contact Stress
  - Elastic/Hertzian (usually from rolling contact)
  - Plastic (usually from sliding contact)
- Steady, Increasing or Decreasing Load
- Variable Load
- **Fixed Load Direction**
- Oscillating Load



3. Loading

- Contact Stress
  - Elastic/Hertzian (usually from rolling contact)
  - Plastic (usually from sliding contact)
- Steady, Increasing or Decreasing Load
- Variable Load
- Fixed Load Direction
- **Oscillating Load**

Pendulum

4. Motion

- Continuous
- Stop/Start
  - Unidirectional
  - Reciprocating
- Duty Cycle
  - Dwell Time between sliding events

5. Environment

- Temperature
- Humidity
- Pressure
  - Ambient
  - Vacuum
  - High Pressure
- Liquid
- Electrolyte

Defining the Tribo-Test

Defining the Tribotest

- Always begin with: **What is the intended application?**
- Then determine: **What are the important parameters in specific areas of?**
    1. Materials
    2. Contact Geometry
    3. Loading
    4. Motion
    5. Environment

Defining the Tribotest

- Remember, **not everything is going to have an important or measurable effect**.
- So we can be pragmatic and thorough at the same time.

Defining the Tribotest: Material Example - "steel".

- Do we need the exact heat treatment?
  - If it is an **abrasive wear** situation, and our abradant's hardness is near that of the steel in its heat treated condition, then we had better use the same heat treatment on our samples.
  - If it is a situation in which we are running **fully hydrodynamic,** then the heat treatment doesn't really matter, but replicating the surface finish is important.

A Few Examples

Examples

- Wheel on Rail (rolling, sliding)
- Brakes/Clutches
- Journal Bearing - Hydrodynamic
- Sleeve Bearing – Boundary
- Abrasion-Resistant Material or Coating
- Low Friction Material or Coating
- Prosthetic Hip Joint
- Gate Valve in High Temp Steam System

Example: Wheel-on-Rail

Application 1a: Railroad

- **Critical Tribo-Elements:**

Materials	Alloy Steel: Composition, Heat Treatment, Hardness, Case Depth (if any)
Contact Geometry	Non-Conformal Line Contact, Disk Edge-on-Flat, 0.5 m radius, 75 mm contact width Surface roughness , below a maximum value, is unimportant (becomes polished due to mild abrasion and plastic deformation of the asperities)
Loading	“25 Tons per axle”, Hertzian Contact, (111,000 N = 322 MPa)
Motion	Rolling Contact (possibly some side slip), primarily unidirectional. Speed based on 1 m diam wheel @ 200 kph
Environment	Dry, or wet with water or contaminants. Oxides are probably unimportant. Ambient outdoor temperature range.

Stress Calculation

Railroad Wheel on Rail

500 mm

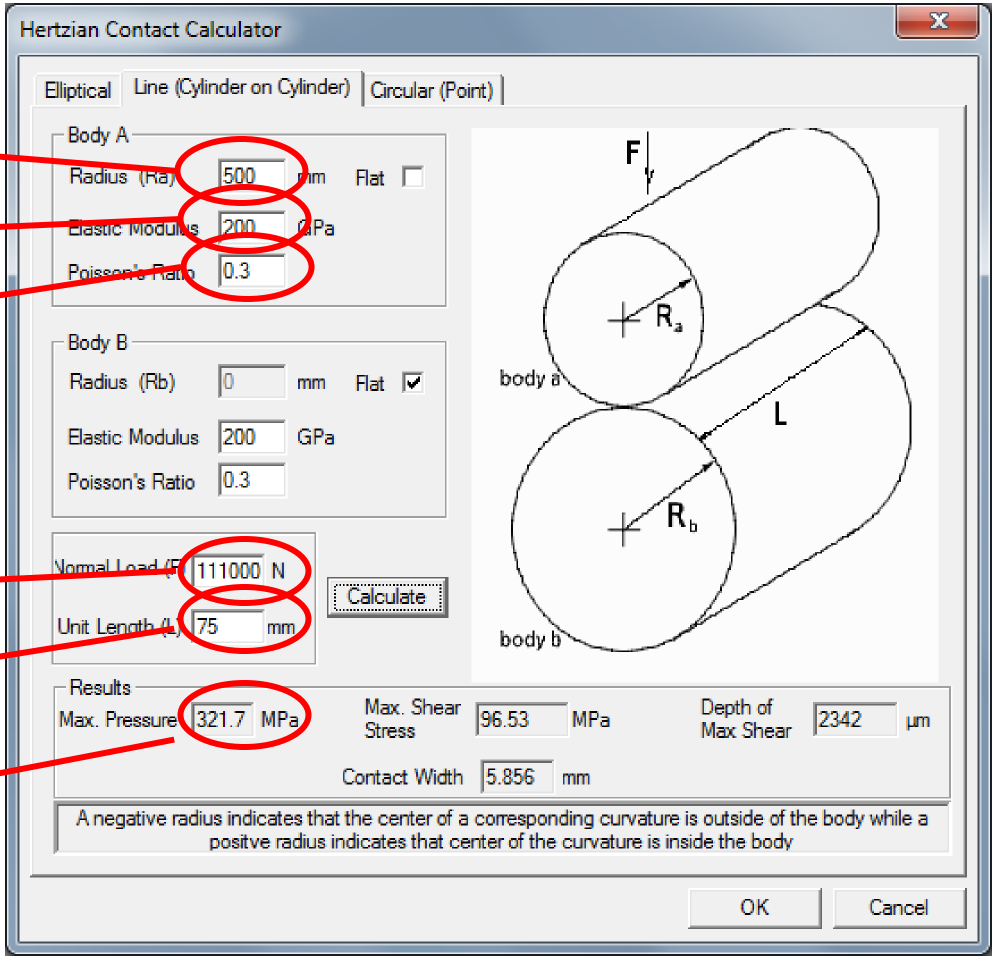
200 GPa

0.3

111,000 N

75 mm

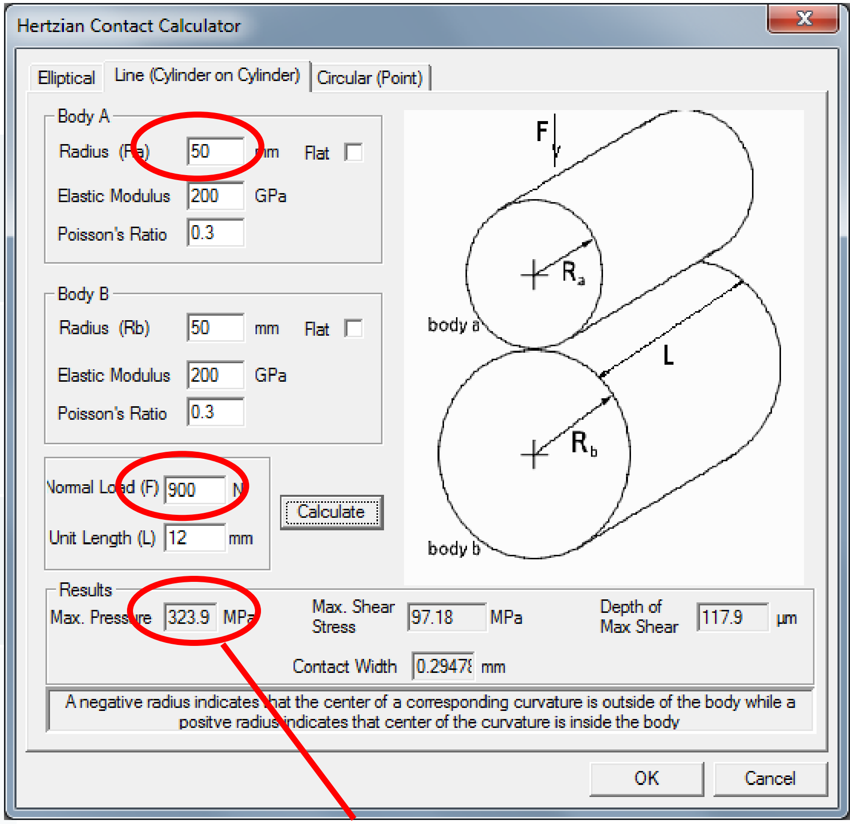
321.7 MPa



Example: Wheel-on-Rail Application 1a: Railroad

- **Defining the Tribo-Test:** COF, rolling contact fatigue, slip

Materials	Alloy Steel: Same Composition, Heat Treatment, Hardness, Case Depth (if any)
Contact Geometry	Non-Conformal Line Contact, Roller-on-Roller
Loading	Hertzian Contact – 100 mm x 12 mm vs. 100 mm x 12 mm. = 324 MPa
Motion	Rolling Contact (can add slip) Speed required = 10,600 rpm
Environ-ment	Dry, or wet with water or contaminants. Ambient outdoor temperature range may not matter.



323.9 MPa

Lab Set-Up

Example: Wheel-on-Rail

Application 1b: Overhead

- **Critical Tribo-Elements:**

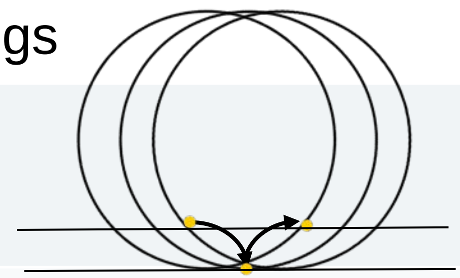
Materials	"Alloy Steel: Composition, Heat Treatment, Hardness, Case Depth (if any). Alternatively - a "Coating"
Contact Geometry	Flat sliding or "scrubbing", estimate about 13 cm^2 area Surface roughness , unimportant - becomes worn due to moderate abrasion or adhesion
Loading	Stress is Unknown. Best estimate is based on contact area and estimated load of 10 kN to 45 kN (~7.5 - 35 MPa)
Motion	Sliding Contact, bidirectional. Speed based on 300 mm radius wheel at 1 m/sec rolling
Environment	Dry, Oxides are probably unimportant. Maybe "mill dust"? Ambient shop temperature range.

Example: Wheel-on-Rail

Application 1b: Overhead Crane - Wear of Flange

- **Defining the Tribo-Test:** Sliding wear (abrasive/adhesive)

Materials	Various heat treatments for steel. Various coatings – thick overlays, hardfacings
Contact Geometry	Flat on flat sliding
Loading	Run tests in range of estimated service stress of: 15-70 MPa
Motion	Reciprocating Sliding Contact ~ 40 mm stroke Sliding distance based on service life estimate of 5 traverses per day of full rail length (200 m), for one year. Speed ~ 25 mm/sec
Environ-ment	Dry. Can add “mill dust” if important. Normal Ambient shop range ~ normal lab temperature.



Example: Brake and Clutch Materials

Application 2: COF and Wear

- **Critical Tribo-Elements:**

Materials	Friction Material vs. Cast Iron (or steel)
Contact Geometry	Flat-on-Flat, or conformal (for drum brake)
Loading	From 2 MPa to 5MPa for cars, up to 7-10 MPa for HDV
Motion	Pure sliding, primarily unidirectional. Max Speed based on 15-20 cm diam rotor @ vehicle speed 100 kph.
Environment	Dry, or wet with water or contaminants. Thermal condition important.

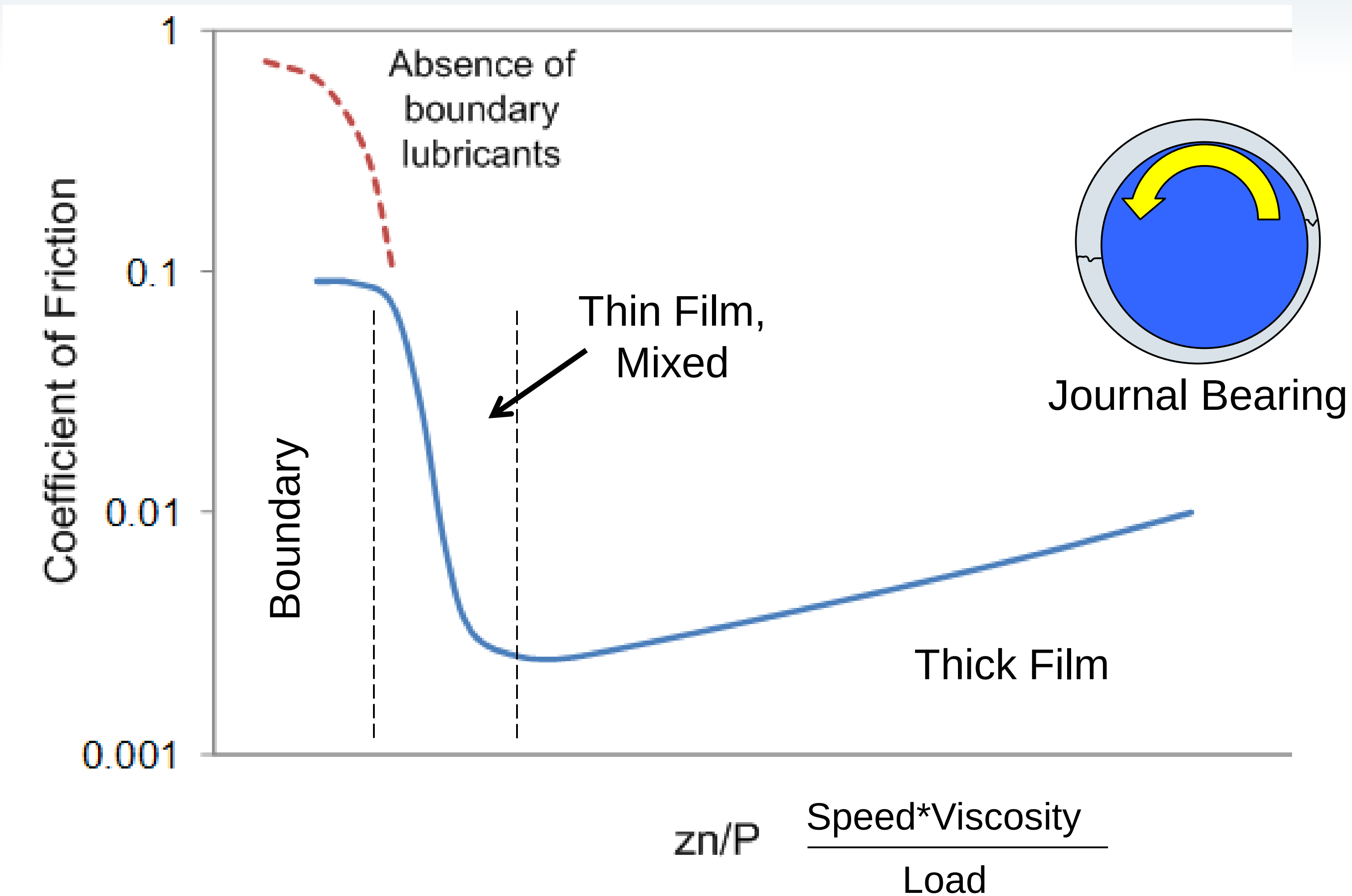
Example: Brake and Clutch Materials Application 2: COF and Wear

- **Define the Tribo-Test:** For material screening only – On-vehicle test required by regulators.

Materials	Friction Material vs. Cast Iron (or steel)
Contact Geometry	Flat-on-Flat, probably 3-button test (more stable), minimum button size ~ 1.5 cm diameter.
Loading	Select between 2 MPa and 5MPa, constant load or: Varying if running constant torque tests
Motion	Pure unidirectional sliding Multiple "stops" from max speed to zero.
Environment	Dry, for screening tests. Multiple stops with Initial Brake Temperature below 38 ˚C.

Short Tutorial on Stribeck Curve

Lubrication Regimes:
The Stribeck Curve



Example: Hydrodynamic Bearing

Application 3: Lubricant Viscosity Characteristics

- **Characterize the Tribo-System:**

Materials	Steel journal (shaft), Babbit or bronze bearing
Contact Geometry	Conformal, with converging gap. Surface roughness ~ 0.1-0.2 µm R_a
Loading	“1-2 hundred kg” on 2 main bearings, 50 mm x 20 mm ~ 2 MPa
Motion	Unidirectional rotation of shaft. Speed varies from “zero” rpm to ~ 6000 rpm.
Environ-ment	Liquid lubricant, possible temperature range (automotive = -40 ˚C to 105 ˚C)

Example: Hydrodynamic Bearing

Application 3: Lubricant Viscosity Characteristics

- **Defining the Tribo-Test:** Stribeck Curve – Right hand Side

Materials	Steel journal, babbit or bronze bearing (Steel likely OK, as long as surface roughness is replicated)
Contact Geometry	Converging gap. Can use cylinder-on-side versus flat disk. Surface roughness replicated 0.1-0.2 µm R_a
Loading	As needed to develop Stribeck Curve, depending on sample size and geometry, and relative speed of interface.
Motion	Unidirectional rotation of shaft. Speed varies from “low” rpm to “liftoff speed ~1000-2000 rpm.
Environ-ment	Liquid lubricant of choice, controlled temperature range if needed for VI and VT work. (probably not to exceed -40 ˚C to 105 ˚C)

Example: Journal Bearing

Application 4: Boundary Lubricant Characteristics

- **Characterize the Tribo-System:**

Materials	Steel journal (shaft), Bronze bearing
Contact Geometry	Conformal, with converging gap. Surface roughness ~ 0.2-0.4 µm R_a
Loading	Up to 800 MPa, depending on application
Motion	1) Unidirectional rotation of shaft. 2) Reversing +/- 25˚ Speed varies from “zero” rpm to ~ 1000 rpm.
Environ-ment	Grease lubricant, possible temperature range (Aerospace = -50 ˚C to 170 ˚C)

Example: Journal Bearing

Application 4: Boundary Lubricant Characteristics

- **Define the Tribo-Test:** Stribeck Curve – Left Hand Side COF, or PV Characteristics, or Wear Rate

Materials	Steel journal (shaft) vs Bronze bushing, or Steel Pin vs Bronze Disc (or vice versa)
Contact Geometry	Conformal journal bearing. Or cylinder-on-disc or conformal block-on-ring Surface roughness ~ 0.2-0.4 µm R_a
Loading	Up to 150 MPa, step-wise for PV evaluation, or steady for wear
Motion	1) Unidirectional rotation of shaft for PV and COF. 2) Reversing +/- 25˚ for wear and “static” or breakaway COF Speed can vary from 0.01 to 2-3 m/s, to simulate application
Environ-ment	Grease lubricant, possible temperature influence (e.g. Aerospace = -50 ˚C to 170 ˚C)

Example: Abrasion-Resistant Coating

Application 5: Anti-Scratch coating for glass

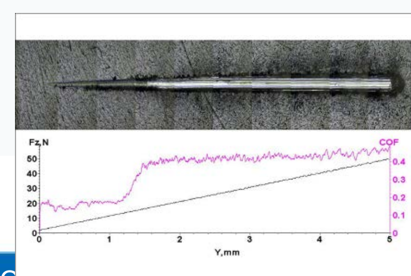
- **Characterize the Tribo-System:**

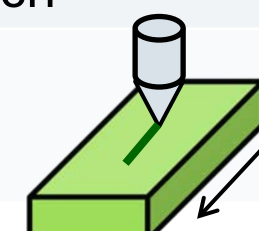
Materials	DLC, < 10 µm thick on SiO_2 vs. "dust" or other hard particles or objects
Contact Geometry	"Sharp" radius or angular point versus Flat; Elastic/Hertzian contact Surface roughness ~ 0.05-0.1 µm R_a
Loading	Unknown contact stress, could be as high as 15 GPa
Motion	Linear sliding contact, short sliding distance, likely unidirectional
Environment	Ambient

Example: Abrasion-Resistant Coating
Application 5: Anti-Scratch coating for glass

- **Define the Tribo-Test: Scratch Test**

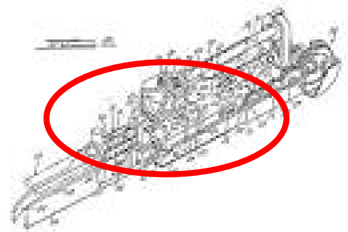
Materials	DLC, < 10 µm thick on SiO_2 vs. diamond indenter
Contact Geometry	Sharp, hard tip (e.g. 2.5, 12.5, 200 µm radius tip), depending on coating thickness Surface roughness ~ 0.05-0.1 µm R_a, per application
Loading	Linearly Increasing load until coating failure
Motion	Linear sliding contact, short sliding distance, Unidirectional, unless sample size and load gradient dictate alternate method, e.g. zig-zag scratch
Environment	Ambient





Example: Low Friction Coating

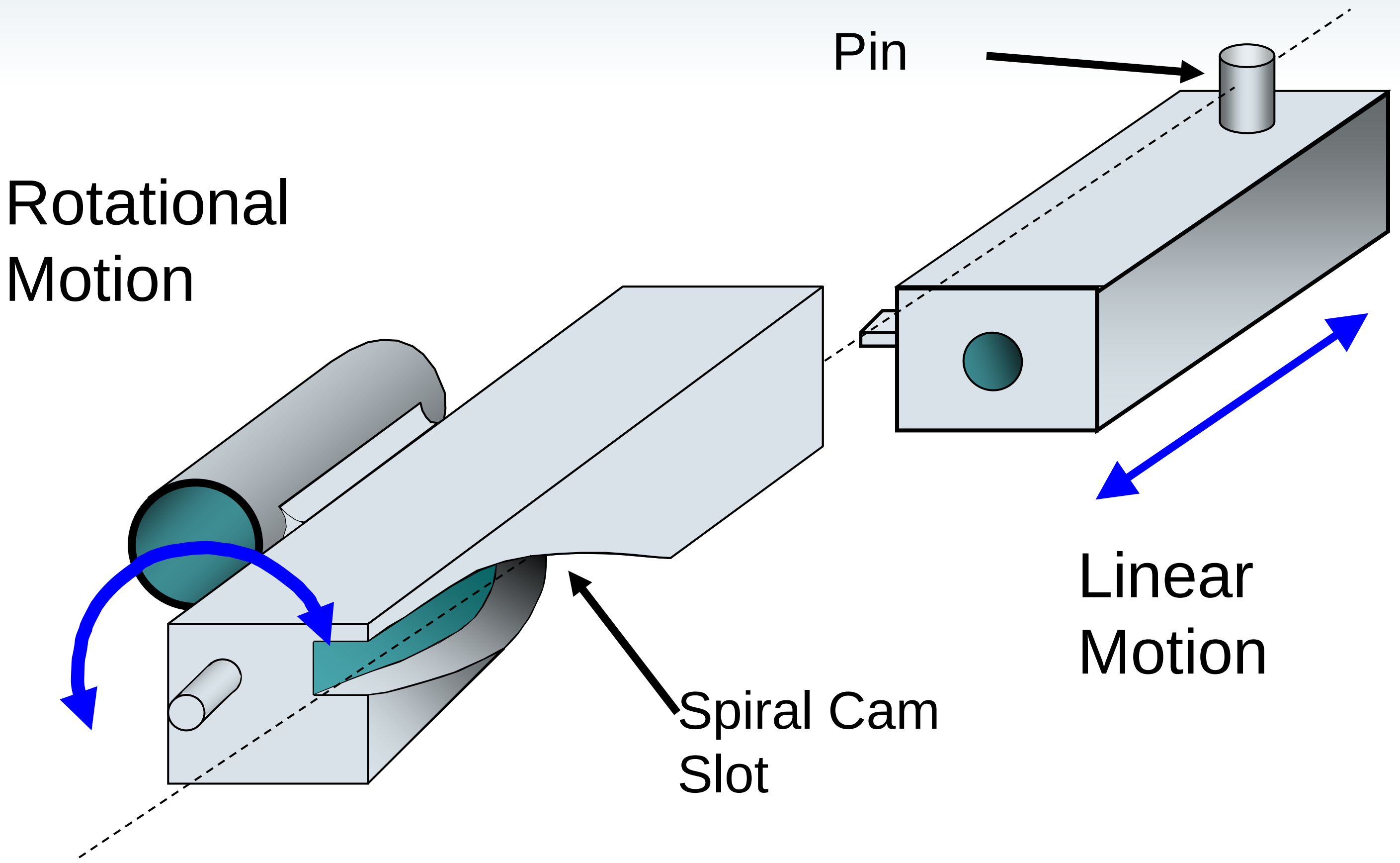
Application 6: Action Components for Lubricant-Free Machine Gun



- **Characterize the Tribo-System:**

Materials	Coating, up to 30 µm thick, or Surface Treatment, on High Strength Steel (AISI 4340), Self-mated
Contact Geometry	Cylinder-on-flat, cylinder on flat edge, flat-on-flat Surface roughness ~ 0.4-0.8 µm R_a
Loading	Up to 100 MPa (Hertzian calculated)
Motion	Linear reciprocating sliding, 40 mm sliding distance, total sliding distance 6,500 m, speed up to 350 cm/sec
Environment	Ambient, up to 150 ˚C, No lubrication

Key Critical Interface: Pin-in-Spiral Cam Slot



Example: Low Friction Coating

Application 7: Action Components for Lubricant-Free Machine Gun

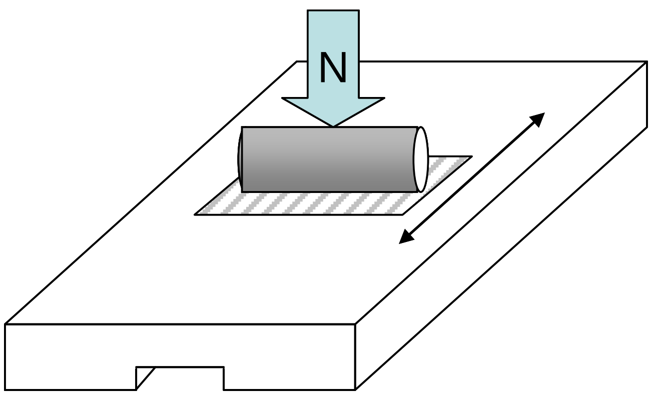
- **Define the Tribo-Test:** Sliding wear and COF

Materials	Various Coatings, on High Strength Steel (AISI 4340), Self-mated
Contact Geometry	Cylinder-on-flat, cylinder on flat edge, flat-on-flat (3-button) Surface roughness ~ 0.4-0.8 µm R_a, per application
Loading	Multiple lower loads for screening, up to 100 MPa stress
Motion	Linear reciprocating sliding, 40 mm stroke length Unidirectional to achieve tot. sliding distance > 6,500 m, Speed up to 350 cm/sec
Environment	Ambient for screening, 150 ˚C for final testing

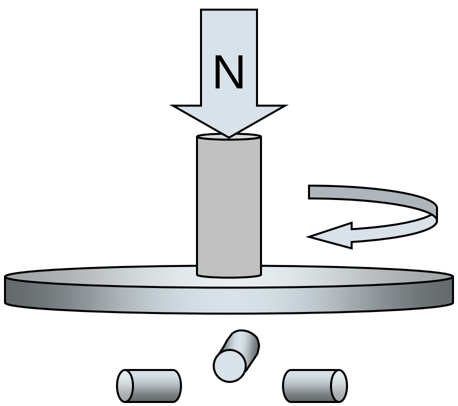
Tribology Experiments: Basic Rig & Sample Design

Reciprocating Tests

Unidirectional Tests



Pin-on-Side

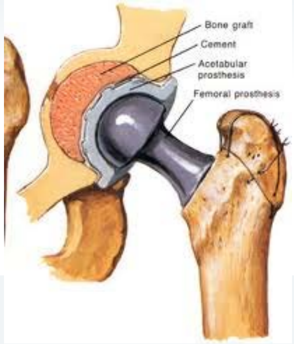


3-Button

Example: Prosthetic Hip

Application 7 – Wear Rate and COF

- **Characterize the Tribo-System:**



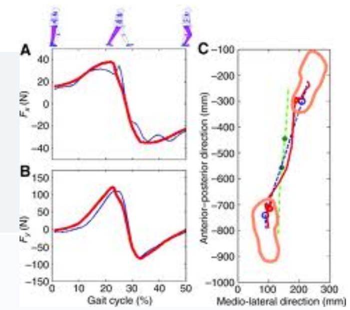
Materials	Al_2O_3, Zr_2O_3 or CoCrMo vs. UHMWPE
Contact Geometry	Conformal – Ball-in-hemisphere Surface roughness ~ 0.2-0.4 µm R_a
Loading	Variable, including unloading
Motion	Non-Linear, reciprocating sliding with cross sliding/rotating. Stroke length approximately 1-3 cm.
Environment	37 ˚C, Synovial Fluid lubrication

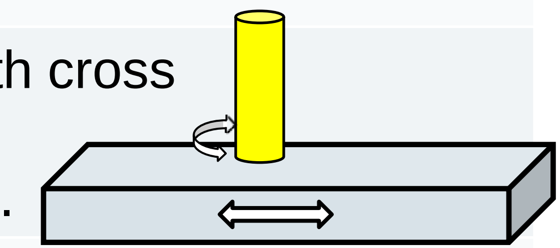
Example: Prosthetic Hip

Application 7 – Wear Rate and COF

- **Define the Tribo-Test:**

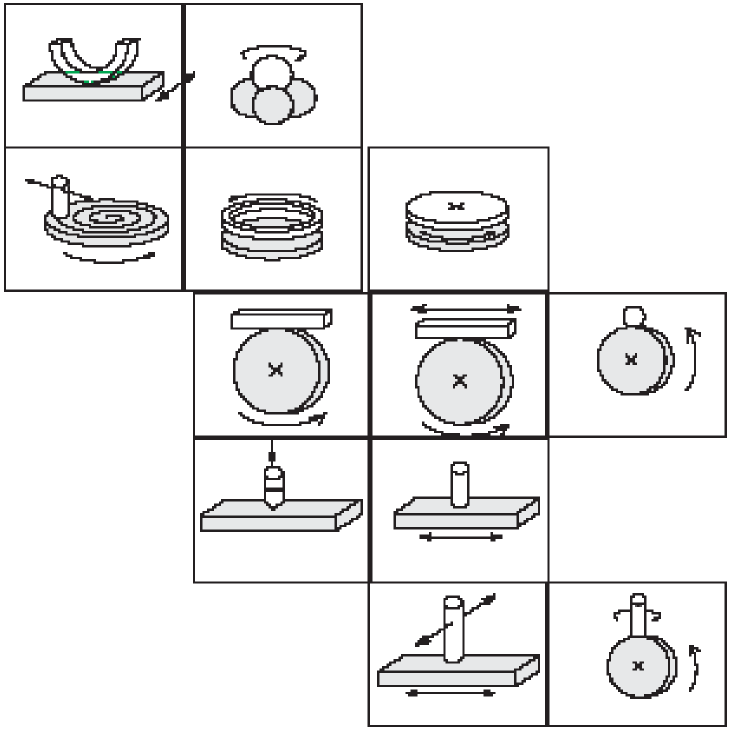
Materials	Al_2O_3, Zr_2O_3 or CoCrMo vs. UHMWPE
Contact Geometry	Conformal or Non-Conformal for screening Surface roughness ~ 0.2-0.4 µm R_a
Loading	Variable, including unloading
Motion	Non-Linear, reciprocating sliding with cross sliding/rotating. Stroke length approximately 1-3 cm.
Environment	For Screening, 37 ˚C Saline Solution or Bovine Serum





Tribology & Mechanical Testing (TMT)

- Universal platform for Tribology studies: Wear, Friction,.. when 2 surfaces meet.



- Large load range
- Wide variety of environments (corrosion, HT, liquid)
- Wide variety of configurations (rotating & translating motions)

www.bruker.com

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