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
1. Materials – (b)

- **Loose Particles**
  - Composition
  - Hardness
  - Size distribution
  - Shape/Angularity
  - **Slurry?**
    - Concentration
  - Gas stream?
    - Concentration
    - Velocity
    - Angle of impact
1. Materials – (b)

- **Loose Particles**
  - Composition
  - Hardness
  - Size distribution
  - Shape/Angularity
  - Slurry?
    - Concentration
- **Gas stream?**
  - Concentration
  - Velocity
  - Angle of impact
1. Materials – (b)

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

![Diagram showing impact angles](image-url)
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
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
  - Lay (directionality of marks)
- **Edge conditions**
  - Sharp, as-machined edge or burr
  - Chamfer or radius
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

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)
  - 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

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:**

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

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

![Hertzian Contact Calculator](image)

**323.9 MPa**

**323.9 MPa**
Lab Set-Up
Example: Wheel-on-Rail
Application 1b: Overhead

- **Critical Tribo-Elements:**

<table>
<thead>
<tr>
<th>Materials</th>
<th>“Alloy Steel: Composition, Heat Treatment, Hardness, Case Depth (if any). Alternatively - a “Coating”</th>
</tr>
</thead>
</table>
| Contact Geometry | Flat sliding or “scrubbing”, estimate about 13 cm² 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 |
| **Environment** | 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:**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Friction Material vs. Cast Iron (or steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>Flat-on-Flat, or conformal (for drum brake)</td>
</tr>
<tr>
<td>Loading</td>
<td>From 2 MPa to 5MPa for cars, up to 7-10 MPa for HDV</td>
</tr>
<tr>
<td>Motion</td>
<td>Pure sliding, primarily unidirectional. Max Speed based on 15-20 cm diam rotor @ vehicle speed 100 kph.</td>
</tr>
<tr>
<td>Environment</td>
<td>Dry, or wet with water or contaminants. Thermal condition important.</td>
</tr>
</tbody>
</table>
Define the Tribo-Test: For material screening only – On-vehicle test required by regulators.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Friction Material vs. Cast Iron (or steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>Flat-on-Flat, probably 3-button test (more stable), minimum button size ~ 1.5 cm diameter.</td>
</tr>
<tr>
<td>Loading</td>
<td>Select between 2 MPa and 5MPa, constant load or: Varying if running constant torque tests</td>
</tr>
<tr>
<td>Motion</td>
<td>Pure unidirectional sliding Multiple “stops” from max speed to zero.</td>
</tr>
<tr>
<td>Environment</td>
<td>Dry, for screening tests. Multiple stops with Initial Brake Temperature below 38 °C.</td>
</tr>
</tbody>
</table>
Short Tutorial on Striebeck Curve
Lubrication Regimes: The Striebeck Curve

The graph shows the relationship between the coefficient of friction and the product of speed and viscosity (zn/P) divided by load. The graph has four distinct regions:

1. **Boundary**: This region is characterized by the highest friction and is observed when the fluid film is very thin or absent.
2. **Thin Film, Mixed**: This region shows a decrease in friction as the film thickness increases. It is a transition between boundary and thick film lubrication.
3. **Thick Film**: In this region, the friction is significantly lower and decreases as the film thickness increases.
4. **Absence of boundary lubricants**: This region is characterized by the highest friction and is observed when there is no fluid film between the surfaces.

The graph illustrates how the lubrication regime changes with varying load and speed/product of viscosity.
Example: Hydrodynamic Bearing
Application 3: Lubricant Viscosity Characteristics

- **Characterize the Tribo-System:**

<table>
<thead>
<tr>
<th><strong>Materials</strong></th>
<th>Steel journal (shaft), Babbit or bronze bearing</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contact Geometry</strong></td>
<td>Conformal, with converging gap. Surface roughness ~ 0.1-0.2 µm $R_a$</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td>“1-2 hundred kg” on 2 main bearings, 50 mm x 20 mm ~ 2 MPa</td>
</tr>
<tr>
<td><strong>Motion</strong></td>
<td>Unidirectional rotation of shaft. Speed varies from “zero” rpm to ~ 6000 rpm.</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Liquid lubricant, possible temperature range (automotive = -40 °C to 105 °C)</td>
</tr>
</tbody>
</table>
### Example: Hydrodynamic Bearing Application 3: Lubricant Viscosity Characteristics

- **Defining the Tribo-Test:** Strubeck 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 Strubeck 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. |
| Environment  | 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:**

<table>
<thead>
<tr>
<th></th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Materials</strong></td>
<td>Steel journal (shaft), Bronze bearing</td>
</tr>
<tr>
<td><strong>Contact Geometry</strong></td>
<td>Conformal, with converging gap.</td>
</tr>
<tr>
<td></td>
<td>Surface roughness ~ 0.2-0.4 µm Rₐ</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td>Up to 800 MPa, depending on application</td>
</tr>
<tr>
<td><strong>Motion</strong></td>
<td>1) Unidirectional rotation of shaft.</td>
</tr>
<tr>
<td></td>
<td>2) Reversing +/- 25°</td>
</tr>
<tr>
<td></td>
<td>Speed varies from “zero” rpm to ~ 1000 rpm.</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>Grease lubricant, possible temperature range</td>
</tr>
<tr>
<td></td>
<td>(Aerospace = -50 °C to 170 °C)</td>
</tr>
</tbody>
</table>
Example: Journal Bearing
Application 4: Boundary Lubricant Characteristics

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

<table>
<thead>
<tr>
<th>Materials</th>
<th>Steel journal (shaft) vs Bronze bushing, or Steel Pin vs Bronze Disc (or vice versa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>Conformal journal bearing. Or cylinder-on-disc or conformal block-on-ring Surface roughness ~ 0.2-0.4 µm Rₐ</td>
</tr>
<tr>
<td>Loading</td>
<td>Up to 150 MPa, step-wise for PV evaluation, or steady for wear</td>
</tr>
<tr>
<td>Motion</td>
<td>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</td>
</tr>
<tr>
<td>Environment</td>
<td>Grease lubricant, possible temperature influence (e.g. Aerospace = -50 °C to 170 °C)</td>
</tr>
</tbody>
</table>
- **Characterize the Tribo-System:**

<table>
<thead>
<tr>
<th>Material</th>
<th>DLC, &lt; 10 µm thick on SiO₂ vs. “dust” or other hard particles or objects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>“Sharp” radius or angular point versus Flat; Elastic/Hertzian contact</td>
</tr>
<tr>
<td></td>
<td>Surface roughness ~ 0.05-0.1 µm Rₐ</td>
</tr>
<tr>
<td>Loading</td>
<td>Unknown contact stress, could be as high as 15 GPa</td>
</tr>
<tr>
<td>Motion</td>
<td>Linear sliding contact, short sliding distance, likely unidirectional</td>
</tr>
<tr>
<td>Environment</td>
<td>Ambient</td>
</tr>
</tbody>
</table>
Example: Abrasion-Resistant Coating
Application 5: Anti-Scratch coating for glass

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

<table>
<thead>
<tr>
<th>Materials</th>
<th>DLC, &lt; 10 µm thick on SiO$_2$ vs. diamond indenter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>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.</td>
</tr>
<tr>
<td>Loading</td>
<td>Linearly Increasing load until coating failure</td>
</tr>
<tr>
<td>Motion</td>
<td>Linear sliding contact, short sliding distance, Unidirectional, unless sample size and load gradient dictate alternate method, e.g. zig-zag scratch</td>
</tr>
<tr>
<td>Environment</td>
<td>Ambient</td>
</tr>
</tbody>
</table>

Example: Abrasion-Resistant Coating
Application 5: Anti-Scratch coating for glass
Example: Low Friction Coating Application 6: Action Components for Lubricant-Free Machine Gun

- **Characterize the Tribo-System:**

<table>
<thead>
<tr>
<th>Materials</th>
<th>Coating, up to 30 µm thick, or Surface Treatment, on High Strength Steel (AISI 4340), Self-mated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contact Geometry</td>
<td>Cylinder-on-flat, cylinder on flat edge, flat-on-flat Surface roughness ~ 0.4-0.8 µm $R_a$</td>
</tr>
<tr>
<td>Loading</td>
<td>Up to 100 MPa (Hertzian calculated)</td>
</tr>
<tr>
<td>Motion</td>
<td>Linear reciprocating sliding, 40 mm sliding distance, total sliding distance 6,500 m, speed up to 350 cm/sec</td>
</tr>
<tr>
<td>Environment</td>
<td>Ambient, up to 150 °C, No lubrication</td>
</tr>
</tbody>
</table>
Key Critical Interface: Pin-in-Spiral Cam Slot

Rotational Motion

Linear Motion

Spiral Cam Slot

Pin
Example: Low Friction Coating
Application 7: Action Components for Lubricant-Free Machine Gun

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

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

<table>
<thead>
<tr>
<th>Materials</th>
<th>$\text{Al}_2\text{O}_3$, $\text{Zr}_2\text{O}_3$ or $\text{CoCrMo}$ vs. UHMWPE</th>
</tr>
</thead>
</table>
| Contact Geometry | Conformal – Ball-in-hemisphere  
Surface roughness $\sim 0.2$-$0.4$ 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:**

<table>
<thead>
<tr>
<th><strong>Materials</strong></th>
<th>Al₂O₃, Zr₂O₃ or CoCrMo vs. UHMWPE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Contact Geometry</strong></td>
<td>Conformal or Non-Conformal for screening Surface roughness ~ 0.2-0.4 µm Rₐ</td>
</tr>
<tr>
<td><strong>Loading</strong></td>
<td>Variable, including unloading</td>
</tr>
<tr>
<td><strong>Motion</strong></td>
<td>Non-Linear, reciprocating sliding with cross sliding/rotating. Stroke length approximately 1-3 cm.</td>
</tr>
<tr>
<td><strong>Environment</strong></td>
<td>For Screening, 37 °C Saline Solution or Bovine Serum</td>
</tr>
</tbody>
</table>
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)