Advances and Challenges in Tribology

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- Tribology as young as well as an ancient science
- Stages of development and advances
- Understanding of system approach
- Jost comission and creation of the notion
- Tribology in Russia and Belarus as a segment of global one
- Challenges of XXI century – from macro to nano, extreme conditions, tribotesting development
- Information highway in tribology
The ancient roots of tribology

First experience

Rubbing as a source of fire in the Ancient Egypt

Axle and bearing in Mesopotamia (3500 b.C)

Lubrication in the Ancient Egypt (2000 b.C)

Ancient lubrication engineer
Leonardo – first fundamentalist in tribology

- friction force is dependent on load and independent on the shape and area of nominal contact;
- friction coefficient is equal to 0.25;
- friction coefficient is dependent on the contact area
Mechanics of Friction

Amontons, 1699

friction is proportional to load

friction is not dependent on the nominal area

friction coefficient is equal to 0.3

De la Hire, 1700

Deformation of surface roughness asperities as a source of friction

Parent, 1704

angle of friction

\[ F = \tan \varphi \]
Origination of Tribology in Russia

Mikhail Lomonosov, 1752

abrasive wear tester

Leonard Euler, 1748

\[ f = \tan \alpha - \frac{2S}{gt^2 \cos \alpha} \]
Molecular Theory of Friction

Desaguliers, 1734

roughness decrease $\rightarrow$ approach of bodies $\rightarrow$ molecular forces increase $\rightarrow$ friction force increase

Coulomb, 1785

two-term friction law

\[ F = A + fN \]

$A$ – adhesion dependent on contact area

Coulomb friction tester
Theory of Lubrication

Dmitry Mendeleev, 1980s

Lubrication in watches, fundamentals of lubricant production from oil

Nikolai Petrov, 1883

\[ f = 2\pi \eta \frac{\omega R^2 L}{Wc} \]

Osborne Rainolds, 1886

\[ \frac{dp}{dx} = 6\eta V \left( \frac{h-h_0}{h^3} \right) \]
Boundary Lubrication

William Hardi, 1919

Boris Deryaguin, 1934

Two-term friction law

\[ F = f(N + p_0 A_r) \]
Dual Nature of Friction

Adhesion-deformation theory

Fillip Bowden,

Igor Kragelsky

David Tabor
Tribology Origination (1966)

Tribology – a science of solids being in relative motion

Peter H. Jost

House of Commons debates (1966)
Tribology Gold Medal Laureates

Igor Kragelsky (1975)

Georgy Vinogradov (1982)

Avtandil Chichinadze (1991)

Nikolai Bushe (2002)

Dmitry Garkunov (2005)
SCALE FACTOR IN TRIBOLOGY

<table>
<thead>
<tr>
<th>Scale</th>
<th>Factors</th>
<th>Friction Pattern</th>
<th>Wear Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>Adhesion</td>
<td></td>
<td>Fatigue</td>
</tr>
<tr>
<td>Micro</td>
<td>Topography, Heating</td>
<td>Deformation</td>
<td>Erosion</td>
</tr>
<tr>
<td>Nano</td>
<td>Mechanical Properties, Forces, Heating</td>
<td></td>
<td>Abrasion</td>
</tr>
<tr>
<td></td>
<td>Deformation</td>
<td></td>
<td>Adhesive wear</td>
</tr>
</tbody>
</table>

- Adhesion: Surface forces
- Topography: Surface properties
- Mechanical: Heating properties
- Properties: Heating forces
- Forces: Heating deformation
- Heating: Fatigue, Erosion, Abrasion, Adhesive wear
Resolution of devices used in micro/nanoscale

1- AFM, 2 – Surface Force Apparatus, 3 – scale of roughness and expected work of adhesion for real surfaces
**Atomic Force Microscope Nanotop-207M (MPRI NASB)**

<table>
<thead>
<tr>
<th>Modes</th>
<th>Non-contact, tapping, contact modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image</td>
<td>Topography and friction force</td>
</tr>
<tr>
<td>Scanning area</td>
<td>35 x 35 µm</td>
</tr>
<tr>
<td>Plane resolution</td>
<td>2nm on the damping table</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>0.1-0.2 nm</td>
</tr>
<tr>
<td>Specimen size</td>
<td>30/30/8 mm</td>
</tr>
</tbody>
</table>
AFM applicaton for roughn contact simulation

AFM image separation: A = B + C, where A – initial image, B – long-wave components of roughness, C – nanoscale roughness

Visualization of contact spots: a – AFM image (15×15 mcm); b – microscale contact spot; c – real contact at nanoscale
Contact Adhesion Meter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force, mN</td>
<td>0.01 - 10</td>
</tr>
<tr>
<td>Distance, nm</td>
<td>10 -- 10000</td>
</tr>
<tr>
<td>Sample size, mm</td>
<td>20x20x5</td>
</tr>
<tr>
<td>Probe size, mm</td>
<td>0.2 -- 5</td>
</tr>
</tbody>
</table>

1 - rotating frame; 2 - spring suspension; 3 - ball holder; 4 - movable EM coil; 5 - mirror; 6 - laser; 7 - optical base expander; 8, 11 - photodetectors; 9 - EM coil; 10 - specimen; 12 - stepping motor; 13 - piezodrive; 14 - DS; 15 - PC.
Model of contact adhesion

Formation of contact: A – moment of surface forces origination; B – moment of point contact formation; C – moment of sphere contact with non-deformed surface of plate; D – moment of equilibrium of attraction and elastic reaction of plate

Force—distance curve: \( h_{AC} \) – effective radius of surface forces; \( h_{BC} \) – elastic deformation of surface; \( h_{CD} \) – elastic penetration with the account of adhesion
Contact Adhesion Meter ADM.

Si plate – steel sphere: 1 – approach; 2 – separation.

TiOx

OTS
**UNIVERSAL MICROTRIBOMETER**

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Load, mN</strong></td>
<td>10 - 1000</td>
</tr>
<tr>
<td><strong>Friction force, mN</strong></td>
<td>0.01 - 2</td>
</tr>
<tr>
<td><strong>Velocity, mm/s</strong></td>
<td>0.1 - 10</td>
</tr>
<tr>
<td><strong>Stroke, mm</strong></td>
<td>5</td>
</tr>
<tr>
<td><strong>Ball radius, mm</strong></td>
<td>1 - 5</td>
</tr>
</tbody>
</table>

1 — drive electromagnets, 2 — flexible guides, 3 — stage for specimens, 4, 9, 13 — position, load, and friction force transducers, 5 — AE transducer, 6 — stepping drive, 7 — loading electromagnet, 8 — lever, 10 — head, 11 — balancing weights, 12 — optic coupler
Scale factor in friction

Steel ball against DLC

<table>
<thead>
<tr>
<th>Coating</th>
<th>Thickness, nm</th>
<th>Friction coefficient</th>
<th>Failure cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>1.2</td>
<td>0.12</td>
<td>20 000</td>
</tr>
<tr>
<td>DDPO₄</td>
<td>1.67</td>
<td>0.08</td>
<td>250</td>
</tr>
<tr>
<td>ODPO₄</td>
<td>2.2</td>
<td>0.09</td>
<td>350</td>
</tr>
<tr>
<td>OTS</td>
<td>2.6</td>
<td>0.08</td>
<td>20 000</td>
</tr>
<tr>
<td>SEBS</td>
<td>8</td>
<td>0.09</td>
<td>20 000</td>
</tr>
</tbody>
</table>

1- friction coefficient, 2- number of acoustic emission pulses
<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>Substrate</td>
</tr>
<tr>
<td>Ti</td>
<td>Ti coating (100 nm) on Si substrate</td>
</tr>
<tr>
<td>TiO_x</td>
<td>TiOx coating (20 nm) on Si substrate</td>
</tr>
<tr>
<td>DLC</td>
<td>Diamond like carbon (~200 nm) on Si substrate</td>
</tr>
<tr>
<td>Ti-ODPO_4</td>
<td>Octadecylphosphoric acid ester (2.2 nm) on Ti covered Si substrate</td>
</tr>
<tr>
<td>TiOx-ODPO_4</td>
<td>Octadecylphosphoric acid ester on TiOx covered Si substrate</td>
</tr>
<tr>
<td>TiOx-DDPO_4</td>
<td>dodecylphosphoric acid ester on TiOx covered Si substrate</td>
</tr>
<tr>
<td>OTS</td>
<td>Octadecyltrichlorsilane (2.6 nm) on Si substrate</td>
</tr>
<tr>
<td>SEBS</td>
<td>Poly[styrene – b - (ethylene-co-butylene) - b- styrene] (1.67 nm) on Si substrate</td>
</tr>
<tr>
<td>Epoxilane</td>
<td>SAM (~1 nm) with epoxy surface groups on Si substrate</td>
</tr>
</tbody>
</table>
Friction and adhesion forces

a – friction coefficient (LFM), b – adhesion (contact adhesion meter) and separation force (AFM) normalized by tip radius
Tribology in Space Exploration

The history of space exploration started from first Sputnik has required the immediate solutions of friction, wear and lubrication problems.

Failures of tribological origin:

Soyuz-1 (1967), high friction in the bushing of parachute, death of cosmonaut.

Docking of Soyuz-10 with Salyut (1970) failed due to seizure.


EXPERIENCE OF TRIBOTEST IN SPACE
(Luna-22 spacecraft, 30 years ago)

Tests were done in a ground laboratory, at the launching position, and at the Moon orbit. There were 2 testers - ground and space ones. The latter was installed on the surface of the spacecraft. Tester consisted of three units with a total mass of 7 kg and spent in Space 1.5 years during the whole flight.
Tribometer for the International Space Lab – ground prototype in MPRI NASB
“Smart” Magnetic Nanofluid

MNF-stable magnetic colloids with particle size of about 10 nm

1 – particle
2 – SAC molecule

Free surface of MNF above the magnet

magnetic force:

\[ f_m = \mu_0 m \nabla H, \]

\( \mu_0 \) – magnetic constant, \( m \) – magnetic moment of particle, \( \nabla H \) – field intensity gradient

1 – no field
2 – field is present
MNF Applications

- Space
- Vacuum
- Power engineering
- Biotechnology
- Information technologies
- Chemistry
Space technologies

- Sealing of shafts up to 250mm.
- Peripheral velocity up to 10 m/s.
- Temperature -50 to +50°C.
- Pressure drop to 0.2 MPa.
- Leakage lower than $5 \times 10^{-11} \text{m}^3\text{Pa/s}$.
- Service life 15 years.

MF seals and sensors were used in spacecrafts “Buran”, Phobos”, “Mars”, “Mir” (11 years) and now at ISL.
Variety of monitoring systems are available, their applications depend on task and complexity of tribosystem.
Optical magnetic detector

1 – detector, 2– electronic unit, 3— analog-to-digital converter, 4 – input-output unit, 5 – PC, 6 – vacuum pump, 7 – test oil
Applications of Condition Monitoring

(POSCO Iron&Steel Co). OMD monitoring of gear box and bearings of large air compressor (7 tons of oil). Data for 30 days of control before failure of gear box.
Superlubricity

Illustration of graphite superlubricity at dry friction

Superlubricity of DLC at 40 at.% of hydrogen when rubbing in nitrogen at room temperature
Polymer nanocomposites

Polymer melt modified by organic clays and surface active agent

Tracktor (1–3) and automotive (4, 5) components made of nanocomposites with polyamide matrix
Information in tribology
Information in tribology
Modern trends in tribology

• Contact problems solved at micro/nanolevel
• Evolution of new tribotesting equipment
• Tribosystems for extreme conditions
• New coatings and lubricants
• Nanocomposites
• Condition monitoring and predictive maintenance
• Global information exchange
THANKS