Friction and Wear of Polymers and Composites

• Why do we use polymeric bearings?

  Low friction
  No need to lubricate
  Bio-compatible
  Ease of manufacturing
  Low noise
  Low cost
Applications of Polymeric Bearings

• Industrial applications
  Gears
  Ball bearing cages
  Journal bearings
  Sliders
  Gyroscope gimbals
  Cams
  Seals for shafts, etc.
Tribological Applications of Polymeric “Bearings” in Medicine and Related Areas

• Bio-medical applications
  Valves
  Hip joints
  Knee joints
  Pump components
Common Plastics Used in Tribology

- Thermoplastics (with and without fibers)
  - polyethylene (PE)
  - Ultra-high molecular weight PE
  - Polyoxymethylene (POM, acetal) -- “Delrin
  - Polytetrafluoroethylene (PTFE)
  - Polyamide (nylon)
  - Polycarbonate
Structure of Some Common Polymers

Diagrams removed for copyright reasons.
Common Plastics Used in Tribology

- Thermosetting plastics (with and without fibers)
  - polyurethane
  - phenolics
  - polyester
  - phenolics
  - polyimide
Common Plastics Used in Tribology

• Elastomers (reinforced with carbon or fibers)

  - silicone rubber -- medical applications
  - natural rubber
  - polybutadiene rubber -- tires
  - nitrile rubber -- good resistance to oil
Properties of Polymers

- Viscoelasticity

  Three element model
  Deformation rate is proportional to the applied load
  Difficult to determine hardness
  Sensitive to temperature
  Low bulk hardness
  Transition temperatures
  Low melting point
Properties of Polymers

- Depending on the molecular structure
  
  Glassy polymers
  Ductile polymers
Question

• What is a typical coefficient of friction of polymers? Why?

• What is a typical wear coefficient of polymers? Why?
Properties of Polymers

- Wear Factor and Wear Equation

\[ K' = \frac{V}{(L \times v \times t)} \]

\[ K' \quad \text{--- wear factor} \]
Highly Linear Polymers

- PTFE, UHMWPE, POM
  - Structure
  - Melting point
  - Processability
PTFE

- Highly linear
- Relatively weak inter-molecular force
- Easy transfer of molecules to the counter face
- Consequently -- low $\mu$

$\mu=0.09$
Friction and Wear Mechanisms of PTFE

- **Process**

  1. Deformation of molecules near the surface due to the applied force at the surface
  2. Stretching of molecules, orienting them along the sliding direction
  3. Transfer of thin films of 50 to 200 Å thick
  4. Sliding of PTFE on PTFE
Friction and Wear Mechanisms of UHMWPE

• Process

Similar process of friction and wear is expected in UHMWPE.
Friction and Wear Mechanisms of Other Ductile Thermoplastics (LDPE, PP, PMMA)

• LDPE and PP (ductile)
  – Wear particles are thick and lumpy debris
  – Less elongation

• PMMA (brittle)
  – Cracks can develop at the surface
How Can We Prevent the Wear of Polymers?
Composite Materials to Reduce the Wear Rate

• **Reduce plastic deformation by incorporating fibers in the material**

• **Short fibers or Long fibers?**
Composite Materials
to Reduce the Wear Rate

- Short fibers or Long fibers?
Composite Materials to Reduce the Wear Rate

• Which direction?
Wear volume and friction coefficient of steel-nylon composite pairs at various sliding speeds

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See Figure 6.2 in [Suh 1986].
Worn surfaces of nylon 6/6 with fillers
(a) Worn surface topography of the specimen sliding against bronze at 0.75 m/sec, (b) Crater in the specimen sliding against bronze at 0.75 m/sec, (c) Worn surface topography of the specimen sliding against bronze at 0.75 m/sec, (d) Worn surface of steel at 05 m/sec

Photos removed for copyright reasons. See Figure 6.3 in [Suh 1986].
Worn surface of glass fiber nylon 6/6-Metal pairs
(a) Specimen surface and (b) Bronze counter face,
(c) Specimen surface and (d) Steel counterface

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See Figure 6.4 in [Suh 1986].
Crack propagation in nylon 6/6 with with 25% glass fibers. (a) sliding against steel, 5 daN and 0.5 m/sec, (b) sliding against bronze at 25 daN and 0.5 m/sec

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See Figure 6.5 in [Suh 1986].
Crack nucleation in polymeric composites sliding against bronze; (a) nylon 6/6 with fillers, (b) nylon 6/6 with 25% glass fibers (25 daN and 0.75 m/sec)

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Sheet formation in (a) nylon 6/6 with fillers, and (b) nylon 6/6 with 25% glass fibers

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Crack depth as a function of friction coefficient

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See Figure 6.8 in [Suh 1986].
Friction coefficient and wear volume as a function of sliding distance in uniaxial graphite fiber-epoxy composite. Sliding against 52100 steel with fiber orientation normal, longitudinal, and transverse to the sliding direction, (b) as a function of fiber orientation.

Graphs removed for copyright reasons. See Figure 6.9 in [Suh 1986].
Friction coefficient and wear volume as a function of sliding distance in uniaxial Kevlar 49-epoxy composite sliding against 52100 steel (three different orientation of the fiber)

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See Figure 6.10 in [Suh 1986].
Friction coefficients and wear volume as a function of sliding distance in biaxially oriented glass microfiber-MoS2-PTFE composite, sliding against 52100 steel with sliding planes normal to three orthogonal directions x, y, and z.

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Basic Mechanism of Friction in Polymers

- Viscoelastic-plastic deformation at the sliding interface
- Plowing
- Asperity deformation
- Wear particle deformation
Friction coefficient and tangential stress on the LDPE sliding against steel as a function of temp.

Graphs removed for copyright reasons. See Figure 6.12 in [Suh 1986].
(a) Rolling friction of 3/16 steel ball over the surface of a nylon copolymer as a function temperature; (b) Low-frequency viscoelastic loss data for the same polymer

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See Figure 6.14 in [Suh 1986].
Model for Graphite Fiber Reinforced Composite

- Brittle matrix and single fiber (e.g., glass fiber)
- Ductile matrix with graphite fiber
Smooth appearance of a worn graphite-fiber tip

Crystallographic structure of graphite
Models of carbon fiber structure

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See Figure 6.18 – 6.20 in [Suh 1986].
Single deflected fiber (From Burgess, 1983)

Tangential load borne by a fibril

Figure 6.22 Surface traction on fiber tip

Figure 6.23 Tangential load borne by a fibril (From Burgess, 1983)

Minimization of Wear of Composites

- Introduced voids into polyurethane/graphite fiber composites

Minimization of Wear of Composites

• Void size distribution

Minimization of Wear of Composites

- Friction coefficient

Minimization of Wear of Composites

• Wear products

Minimization of Wear of Composites

- Wear products

Wear Particles of UHMWPE measured with AFM
Wear particle distribution by weight

Wear Particle Size (nm)

Percent (%)

Total 2.29 %
Total 67.95 %
Total 29.76 %
Wear mass as a function of the number of cycles

![Graph showing wear mass as a function of cycles. The graph includes data points for retrieved particle data, interpolated profilometry data, and interpolated weight measurement data. Each data type is represented by different markers and line styles.](chart_url)
Effect of Different Sterilization of UHMWPE on its Wear Rate

- Pin-on-disk experiment
- UHMWPE on Co-Cr femoral heads, 22 mm diameter
- Roughness: ball = 0.01 µm, disk = 0.5 µm
- Test condition:
  - $1 \times 10^6$ cycles, 15 cm/s, Max Hertzian pressure = 12.5 MPa
- UHMWPE sterilized
  - Irradiated at 2.5 MRad in air
  - Ethylene oxide gas for 12 hours
  - Plasma gas (peracetic acid vapor, H$_2$ and O$_2$)
Effect of Different Sterilization of UHMWPE on its Wear Rate

![Bar graph showing wear mass (mg) for control, gamma irradiated, ETO, and gas plasma sterilization methods. The graph indicates that gamma irradiation results in the highest wear mass, followed by control, ETO, and gas plasma sterilization methods.]
Effect of Different Sterilization of UHMWPE on its Wear Rate

• Irradiated samples showed subsurface cracks.
Minimization of Wear of Polymers by Plasma Treatment

- Crystalline polymers: HDPE, POM
- Amorphous polymers: PMMA, PC
- CASING (Cross-linking by activated species of inert gases)
- Helium plasma (1 torr, 13.56 MHz, 100 Watts, Room temp.) for 500 and 1000 seconds
- Pin-on-disk, Normal load = 4.4 N, speed = 3.3 cm/s
- Film thickness measurement:
  - HDPE: p-xylene, PMMA: toluene, POM: aniline, PC: ethylene dichloride
Minimization of Wear of Polymers by Plasma Treatment

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Other Treat Techniques for Low Friction and Wear

• Fluorination of polyethylene surfaces
• PTFE in porous brass
• PTFE and graphite fibers
• Polybutadiene rubber with carbon black