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.
See Figure 6.1 in [Suh 1986]: Suh, N. P. *Tribophysics*. Englewood Cliffs NJ: Prentice-Hall, 1986. ISBN: 0139309837.

Fig. 6.1(a)

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

$K' = V/(L\ v\ t)$

K' --- 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 μ

$$\mu=0.09$$

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 A 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

Graphs removed for copyright reasons.
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 and0.5 m/sec

Photos removed for copyright reasons.
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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See Figure 6.6 in [Suh 1986].

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

Photos removed for copyright reasons.
See Figure 6.7 in [Suh 1986].

Crack depth as a function of friction coefficient

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See Figure 6.8 in [Suh 1986].

Figure 6.8

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.

Graphs removed for copyright reasons.
See Figure 6.11 in [Suh 1986].

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].

Fig. 6.12

(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

Graphs removed for copyright reasons.
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

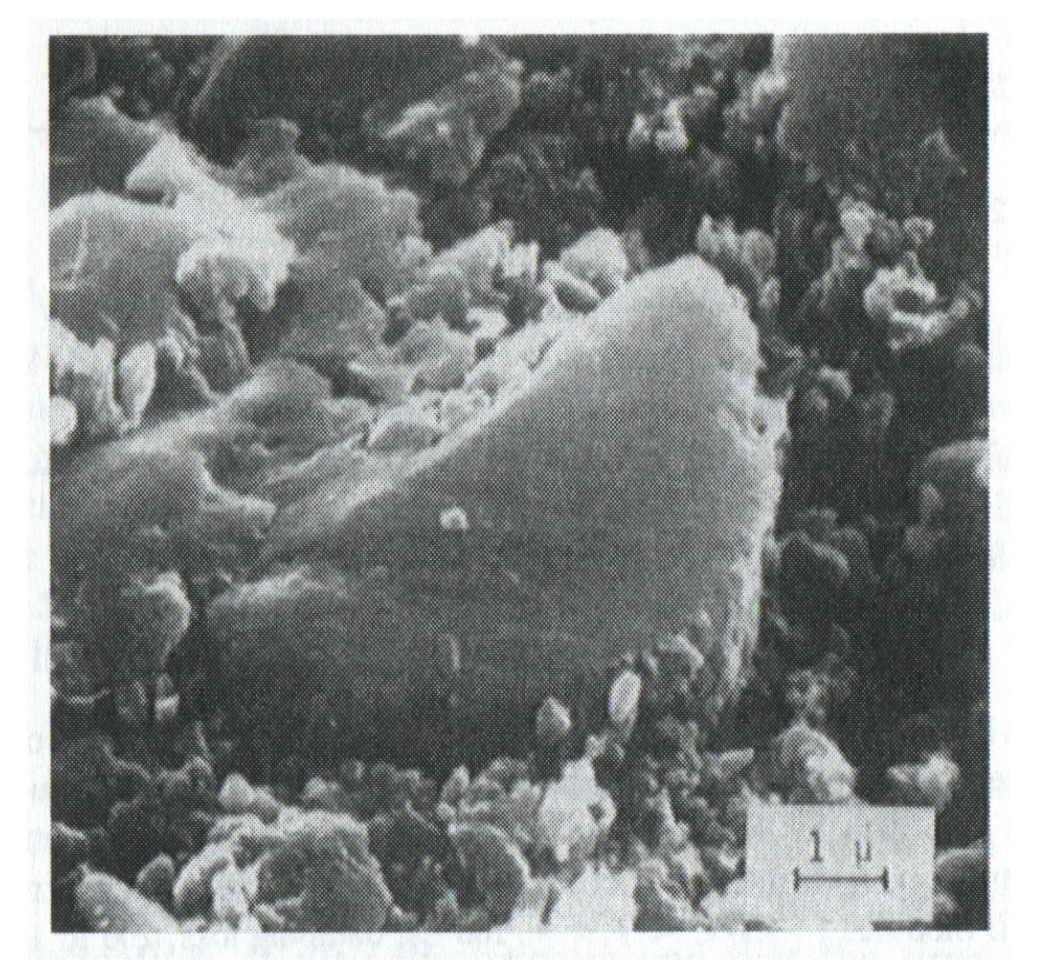
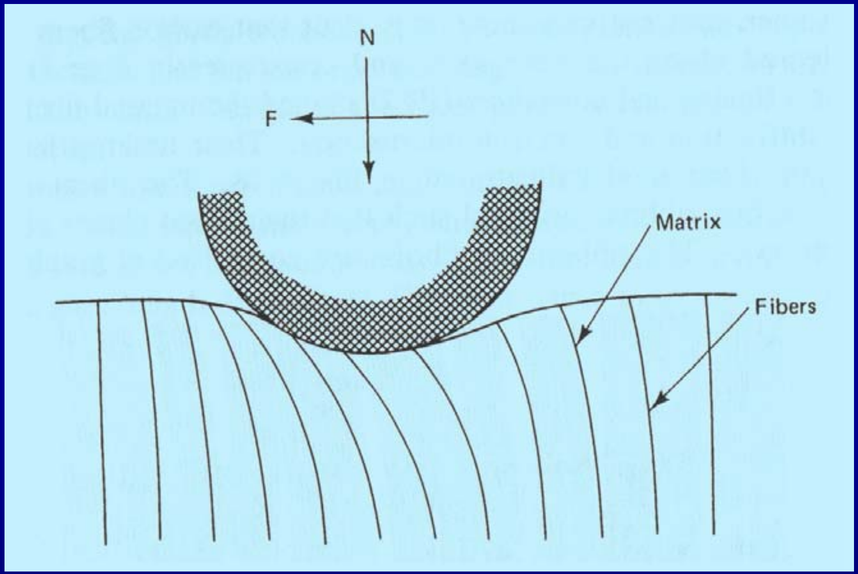


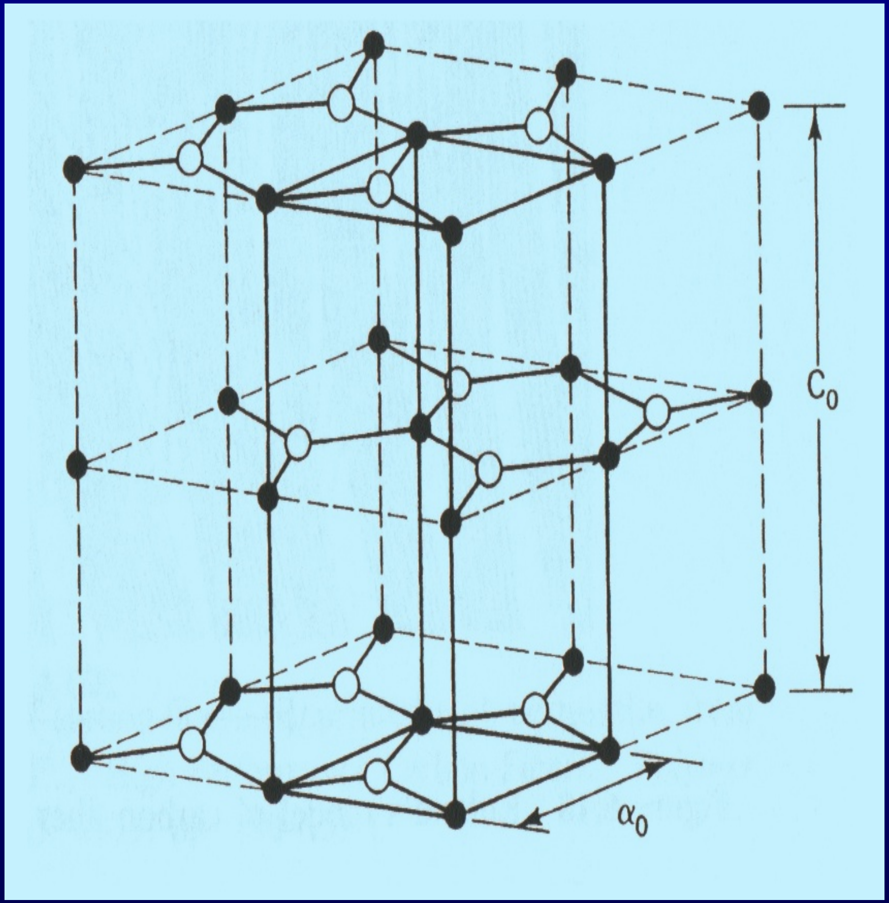
Fig. 6.15

Source: Burgess, S. M. “Friction and Wear of Composites.” S.M. Thesis, MIT, 1983.



Source: Burgess, S. M. “Friction and Wear of Composites.” S.M. Thesis, MIT, 1983.

Crystallographic structure of graphite



Models of carbon fiber structure

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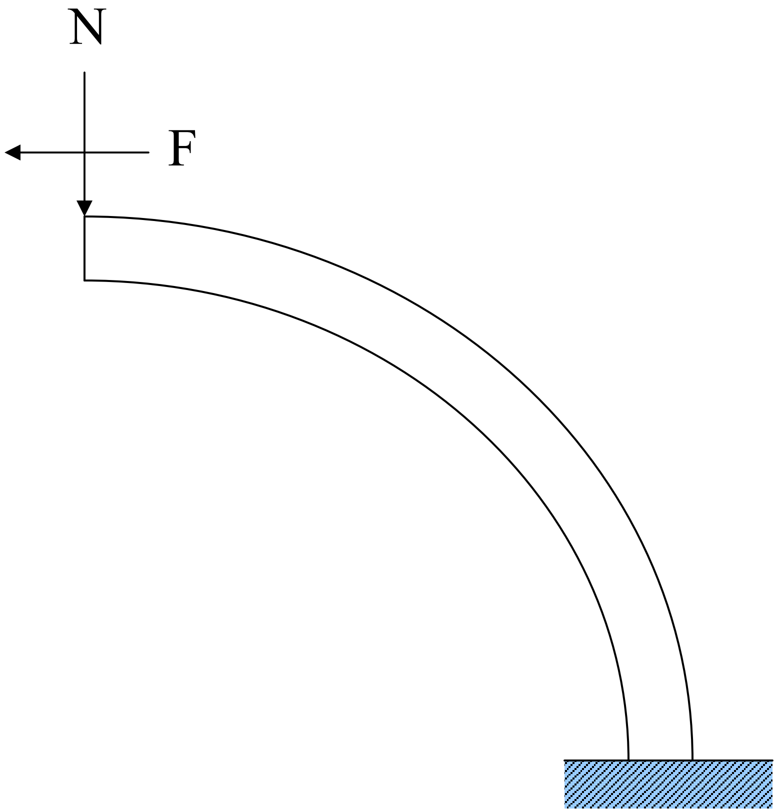
See Figure 6.18 – 6.20 in [Suh 1986].

Single Deflected Fiber



Single deflected fiber (From Burgess, 1983)

Source: Burgess, S. M. “Friction and Wear of Composites.” S.M. Thesis, MIT, 1983.

Tangential load borne by a fibril

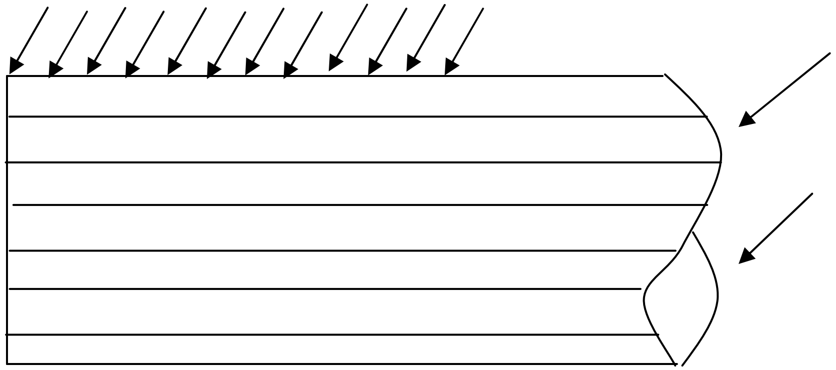


Figure 6.22 Surface traction on fiber tip

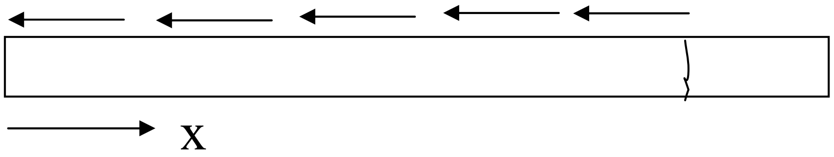
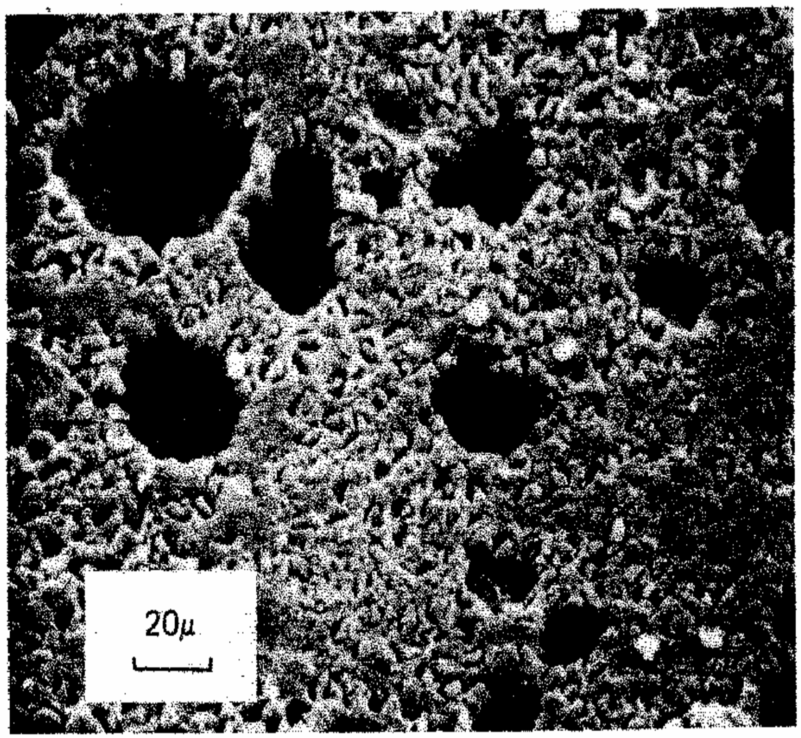


Figure 6.23 Tangential load borne by a fibril (From Burgess, 1983)

Source: Burgess, S. M. "Friction and Wear of Composites." S.M. Thesis, MIT, 1983.

Minimization of Wear of Composites

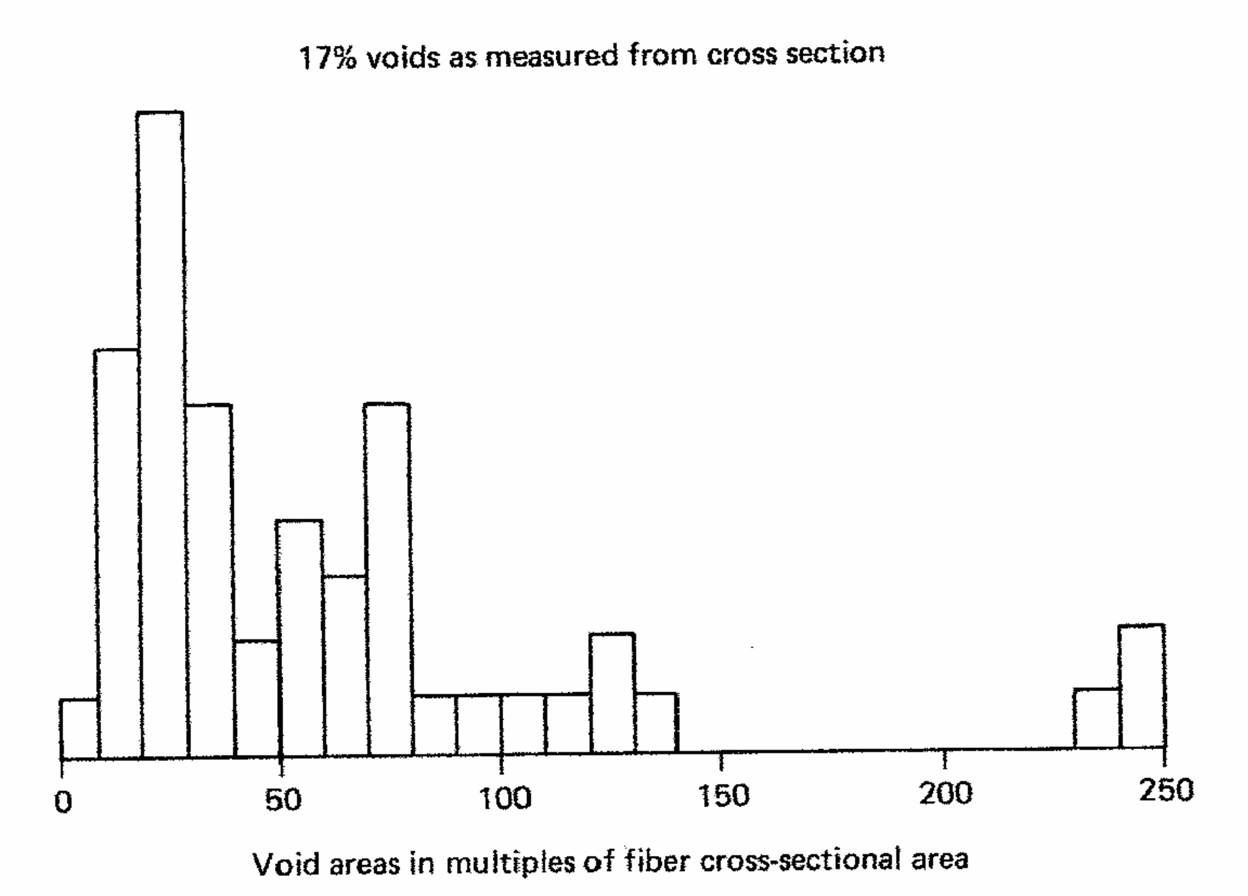
- Introduced voids into polyurethane/graphite fiber composites



Source: Burgess, S. M. “Friction and Wear of Composites.” S.M. Thesis, MIT, 1983.

Minimization of Wear of Composites

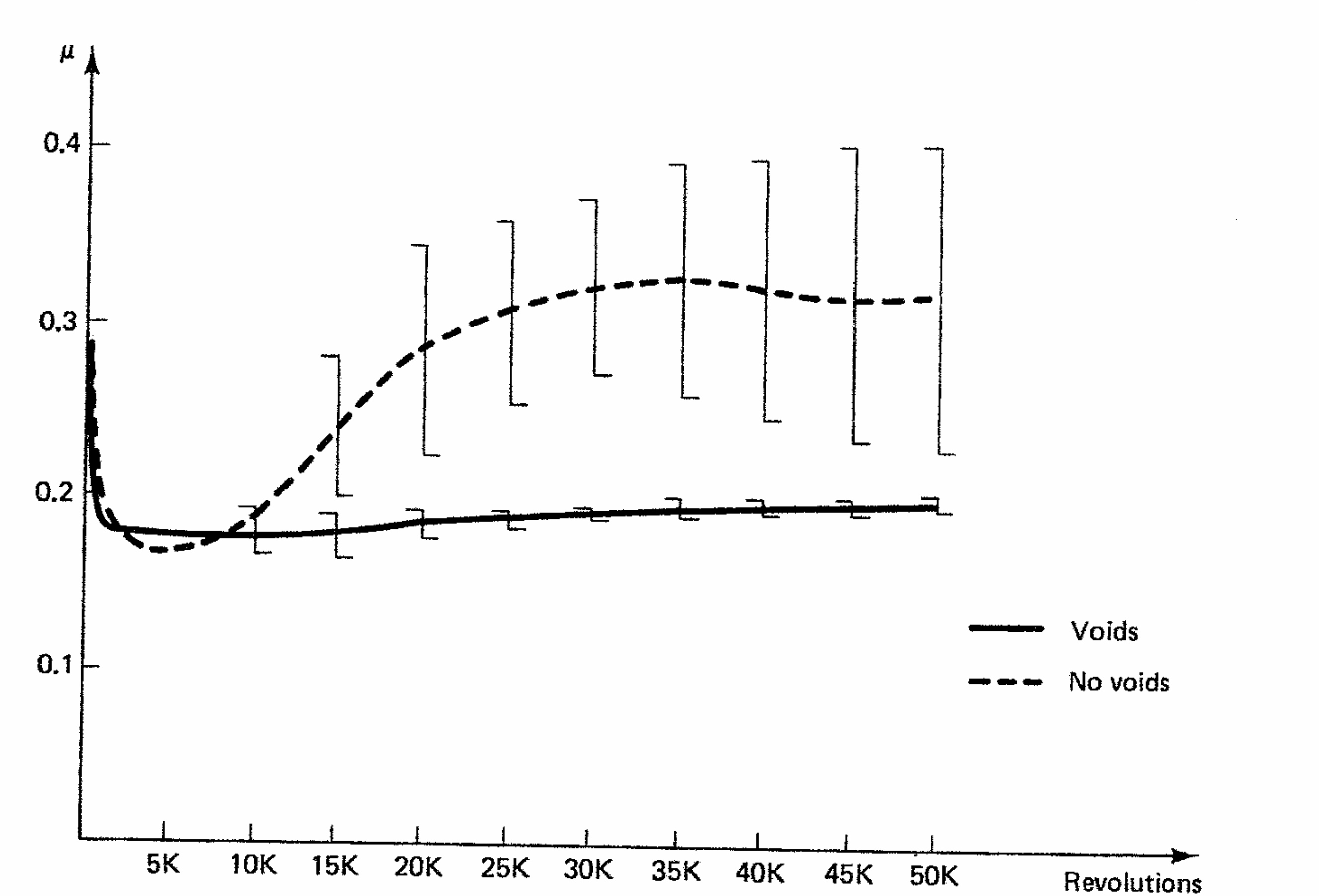
- Void size distribution



Source: Burgess, S. M. “Friction and Wear of Composites.” S.M. Thesis, MIT, 1983.

Minimization of Wear of Composites

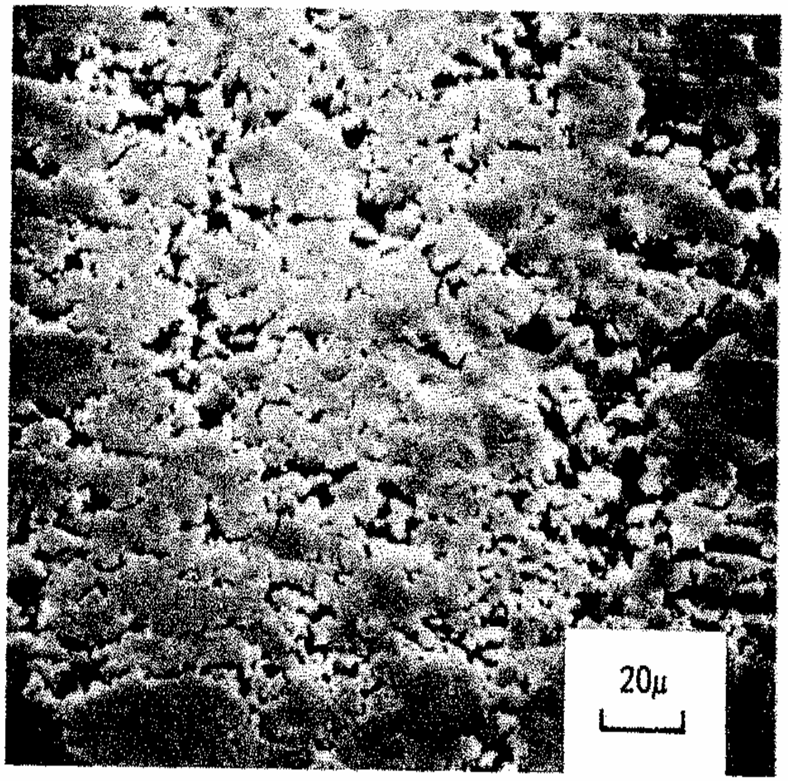
- Friction coefficient



Source: Burgess, S. M. "Friction and Wear of Composites." S.M. Thesis, MIT, 1983.

Minimization of Wear of Composites

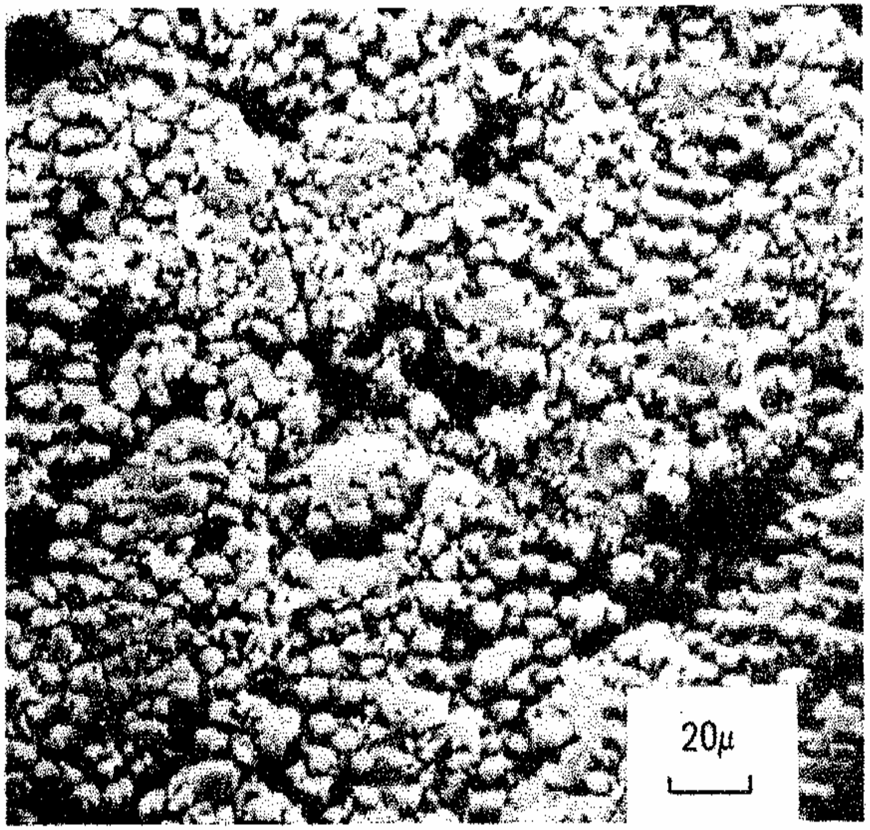
- Wear products



Source: Burgess, S. M. "Friction and Wear of Composites." S.M. Thesis, MIT, 1983.

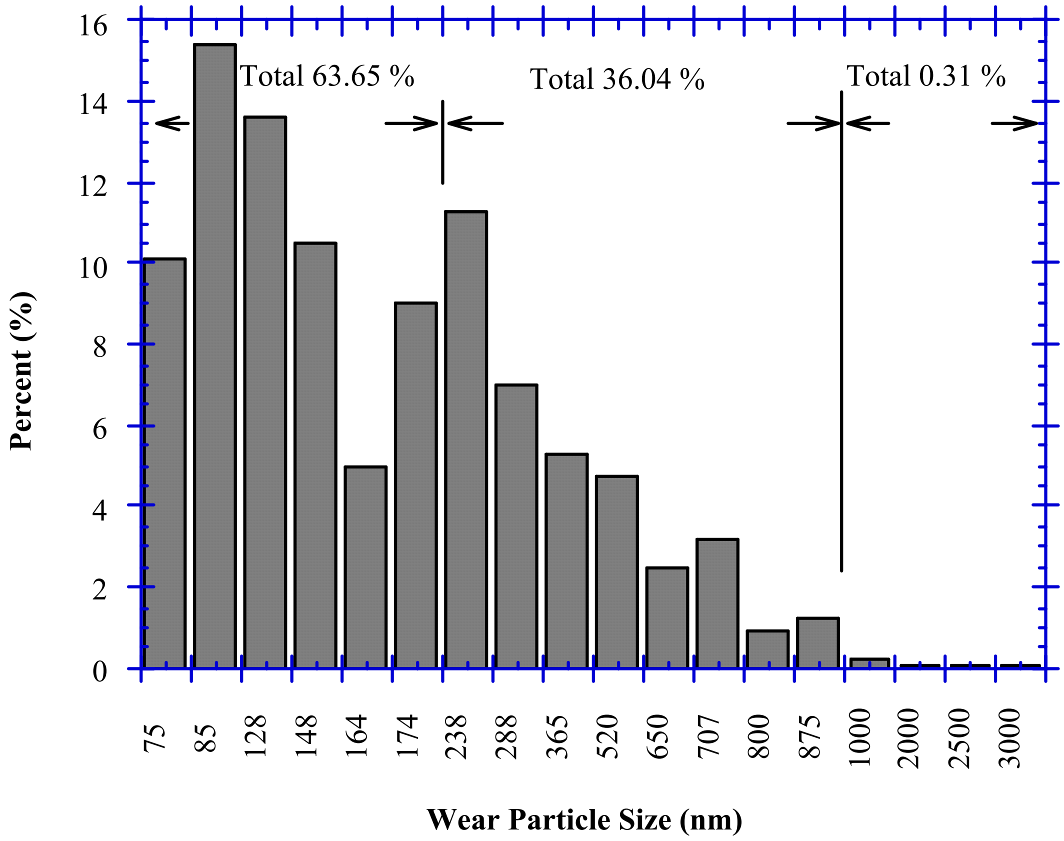
Minimization of Wear of Composites

- Wear products

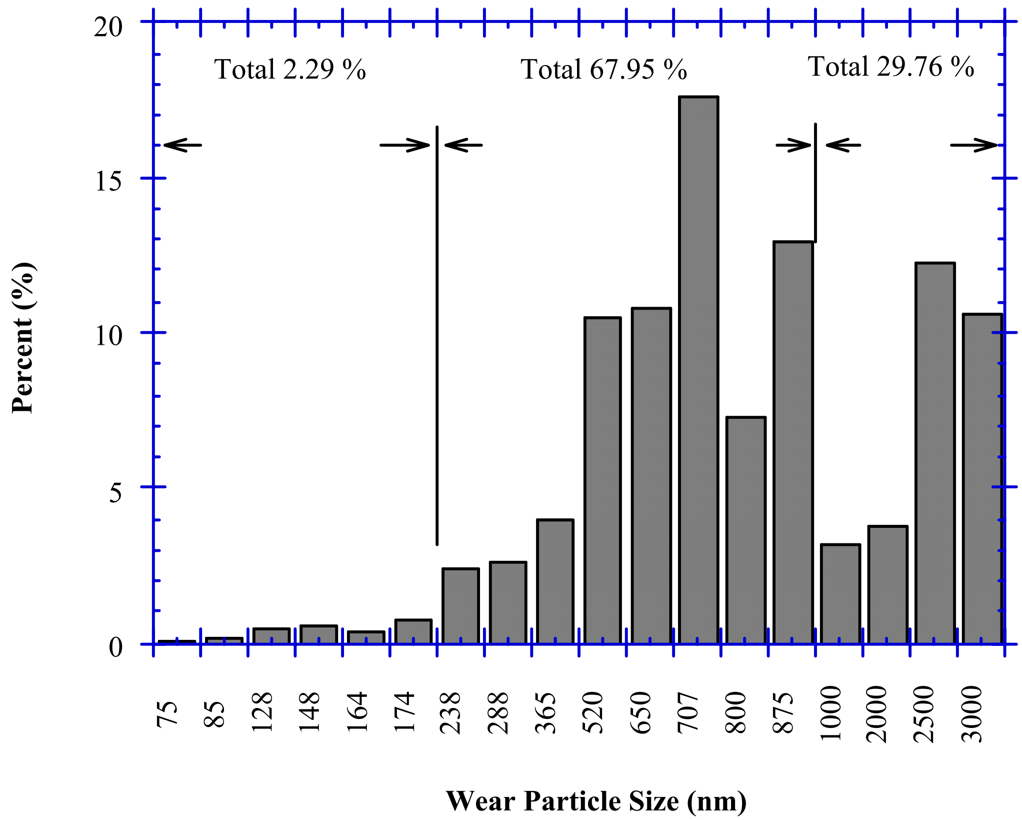


Source: Burgess, S. M. "Friction and Wear of Composites." S.M. Thesis, MIT, 1983.

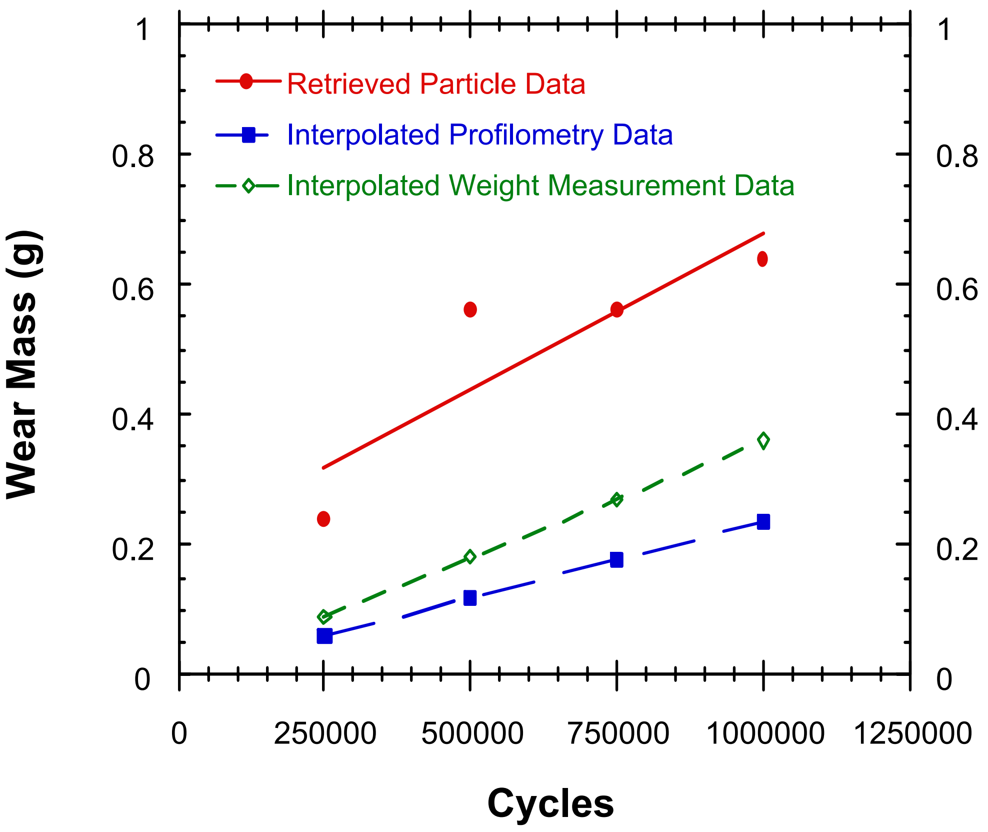
Wear Particles of UHMWPE measured with AFM



Wear particle distribution by weight



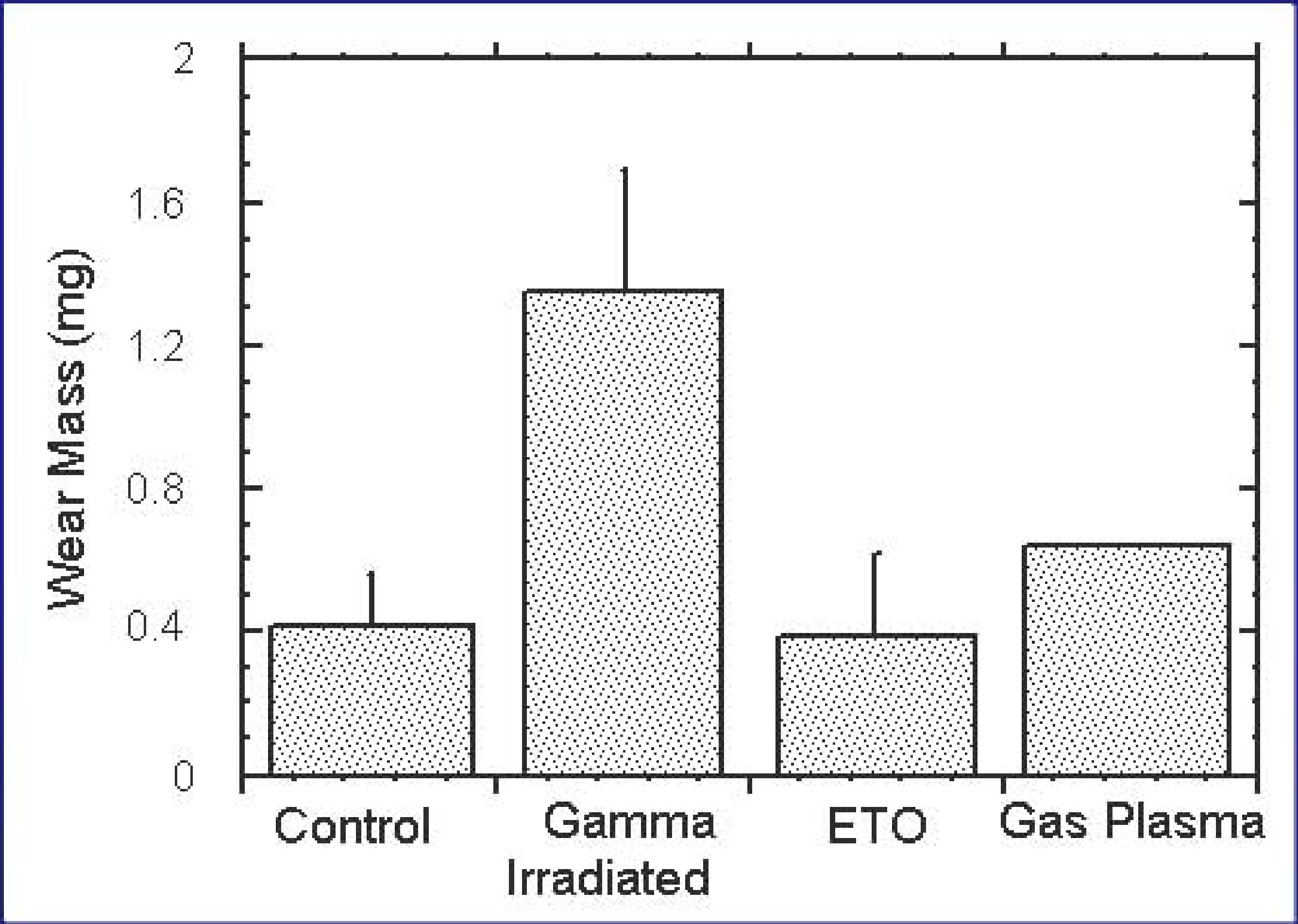
Wear mass as a function of the number of cycles



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:
  - 1×10^6 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



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

Graphs removed for copyright reasons.
See Youn, J.R., and N.P. Suh. "Tribological Characteristics of Surface Treated Polymer." Proceedings of the Society of Plastics Engineers, 39th ANTEC, Boston MA. May 1981.

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