Genesis of Friction between Macroscale contacts

- Reference: Chapter 3 of the text books

What is friction?

$$\overline{F} = \frac{\partial W}{\partial s}$$

What is friction coefficient?

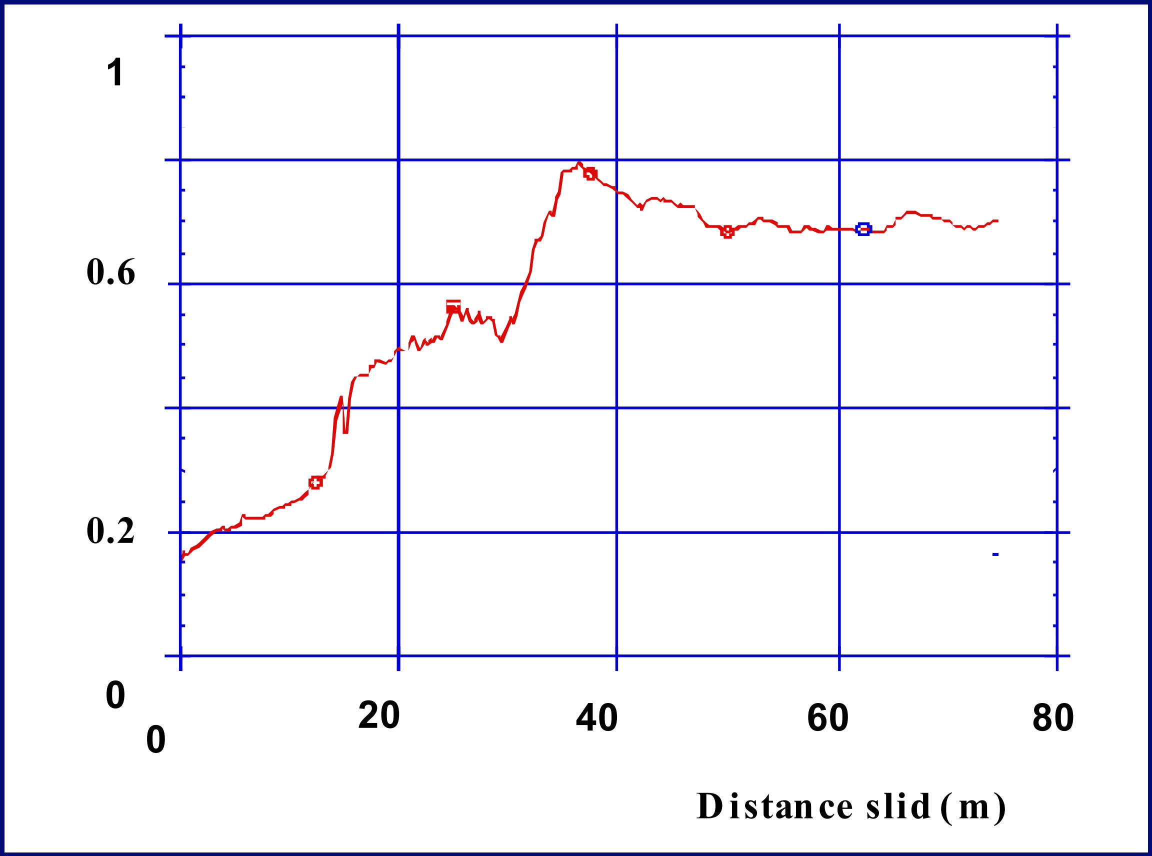
- Definition

$$\mu = \frac{\text{Friction force}}{\text{Normal load}} = \frac{F}{L}$$

- Coulomb friction

$$\mu = \text{constant}$$

μ varies as a function of the sliding distance.



Scale issues in tribology

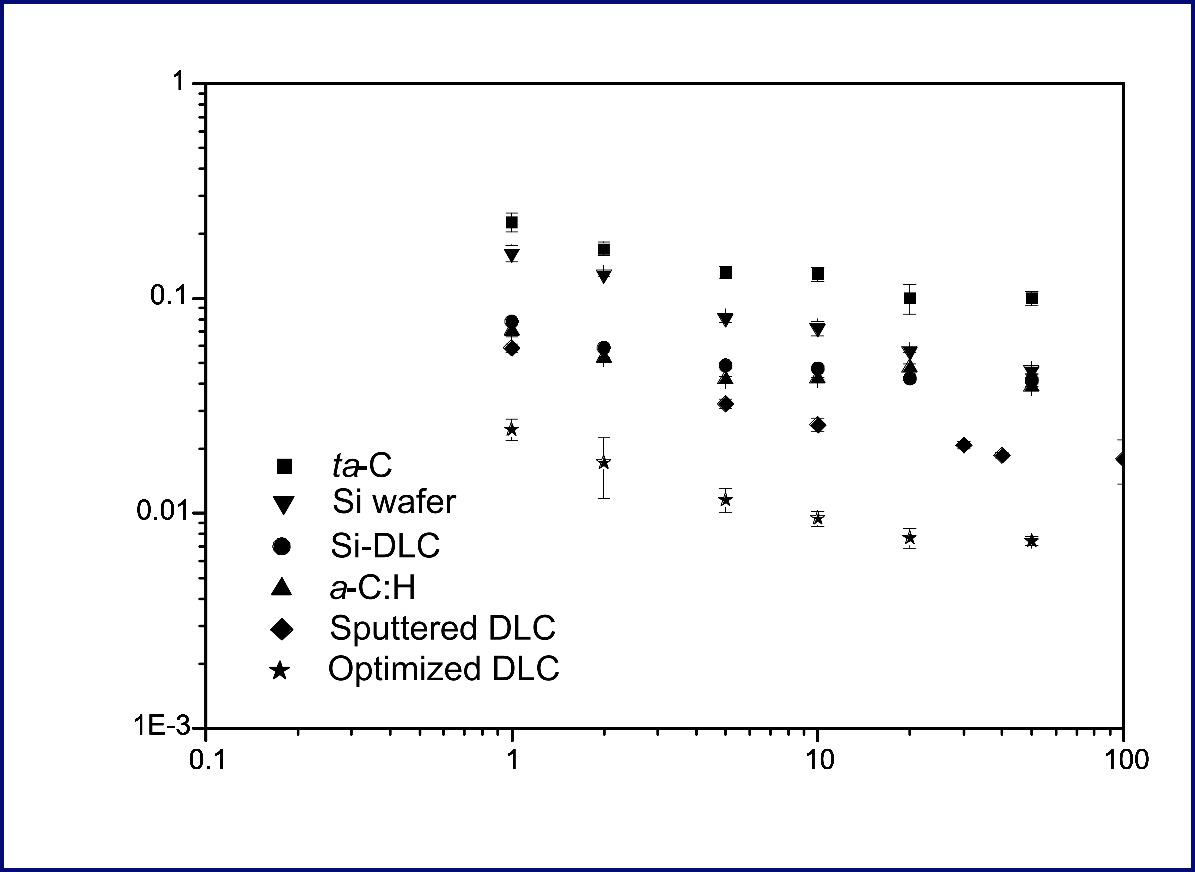
Table 3.1 Scales in Tribology and Typical Values
(Adapted from Kim, 2000)

Scale	Range of friction coefficient (μ) & wear coefficient (k)	Applications
10^{-4} m	$\mu = 0.1 \sim 1$ $k = 10^{-5} \sim 10^{-2}$	machinery brake, tools
10^{-6} m	$\mu = 0.001 \sim 0.2$ $k = 10^{-7} \sim 10^{-5}$	lubrication roller bearing
10^{-8} m	$\mu = 0.01 \sim 0.6$ $k = 10^{-8} \sim 10^{-5}$	head/ disk MEMS
10^{-10} m	$\mu = 0.001 \sim 0.6$ $k \sim 0$	AFM lithography

Friction Measurement Lab

- Wednesday, September 22, 2004
- Please report to the Tribology Lab
- Dr. Nannaji Saka

Microscale friction as a function of coating
(various carbon film -- 250 nm thick -- on Si wafer, diamond tip of r=0.2 mm)



Relative friction forces in MEMS of two flat and smooth surfaces as functions of the distance between the two surfaces

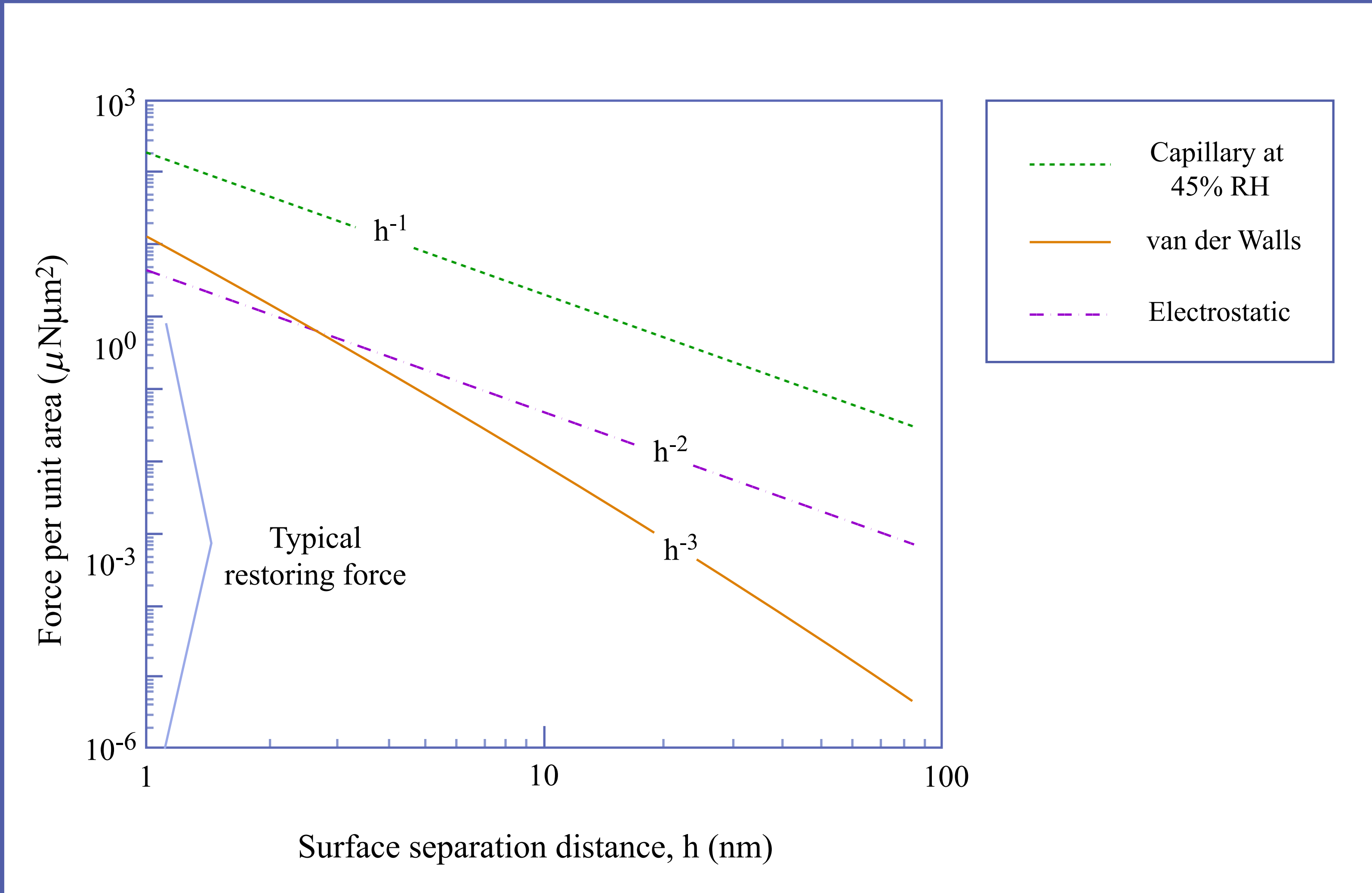


Figure by MIT OCW. After Komvopoulous, K. "Surface engineering and microtribology for microelectromechanical systems." *Wear* 200 (Dec 1996): 305-327.

Attractive forces in MEMS devices: (a) Stiction of two surfaces created by etching of silicon. (b) In use stiction caused by operational and atmospheric conditions. (c) Friction in sliding contacts due to intermittent contacts, wear, and fatigue

Diagram removed for copyright reasons. See Komvopoulous, K. "Surface engineering and microtribology for microelectromechanical systems", Wear, Vol. 200, pp. 305-327, Dec, 1996.

Friction at Macroscale Sliding Contacts

(a) What is the controlling mechanism for observed friction?

(b) Is the friction due to adhesion?

(c) What is the role of wear particles in determining the coefficient of friction?

(d) Why do different material combinations give arise to different friction coefficient?

(e) What is the effect of environment?

Friction at Dry Sliding Interface
Basic Mechanisms for Friction

(a) Plowing of the surface by wear debris and other particles
(b) Removal of asperities by asperity interactions at the interface
(c) Adhesion of the sliding interface

Experimental results show that of these three mechanisms, the most important mechanism for friction at the interface of metals and many plastics is the plastic deformation of the surface by wear particles, which plow the surface.

SEM micrographs of the surfaces of worn slider

(a) to (d) -- Iron on iron, 1020, 1045, and 1095 steel

(e) to (h) -- 1020 steel on iron, 1020, 1045, and 1095 steel

(I) to (l) -- 1045 steel on iron, 1020, 1045, and 1095 steel

(m) to (p) -- 1095 steel on iron, 1020, 1045, and 1095 steel

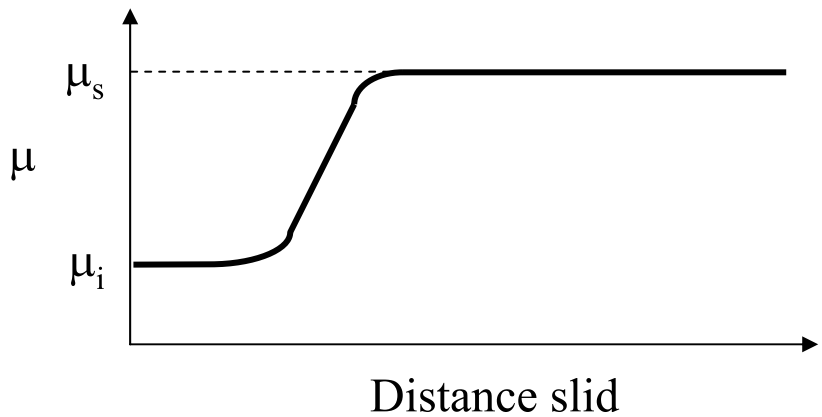
See Figure 3.1 in [Suh 1986]: Suh, N. P. *Tribophysics*. Englewood Cliffs NJ: Prentice-Hall, 1986. ISBN: 0139309837.

SEM micrographs of the surfaces of worn specimen

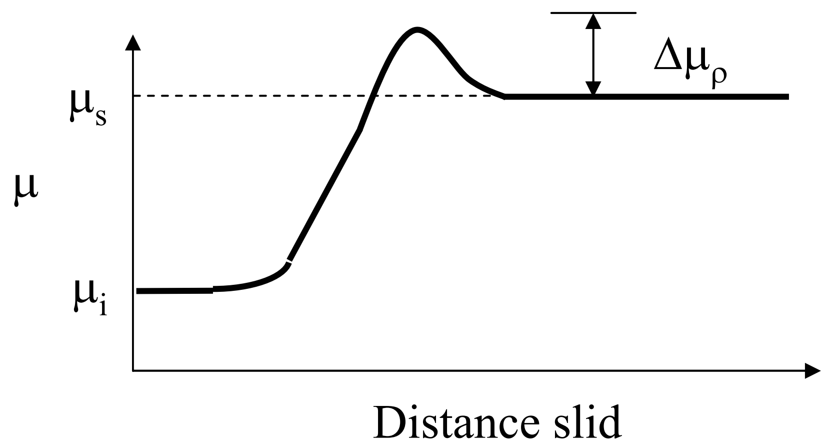
(a), (e), (I), (m) -- Iron on iron, 1020, 1045, and 1095 steel
(b), (f), (j), (n) -- 1020 steel on iron, 1020, 1045, and 1095 steel
(c), (g), (k), (o) -- 1045 steel on iron, 1020, 1045, and 1095 steel
(d), (h), (l), (p) -- 1095 steel on iron, 1020, 1045, and 1095 steel

Photos removed for copyright reasons.
See Figure 3.2 in [Suh 1986].

Coefficient of friction versus sliding distance

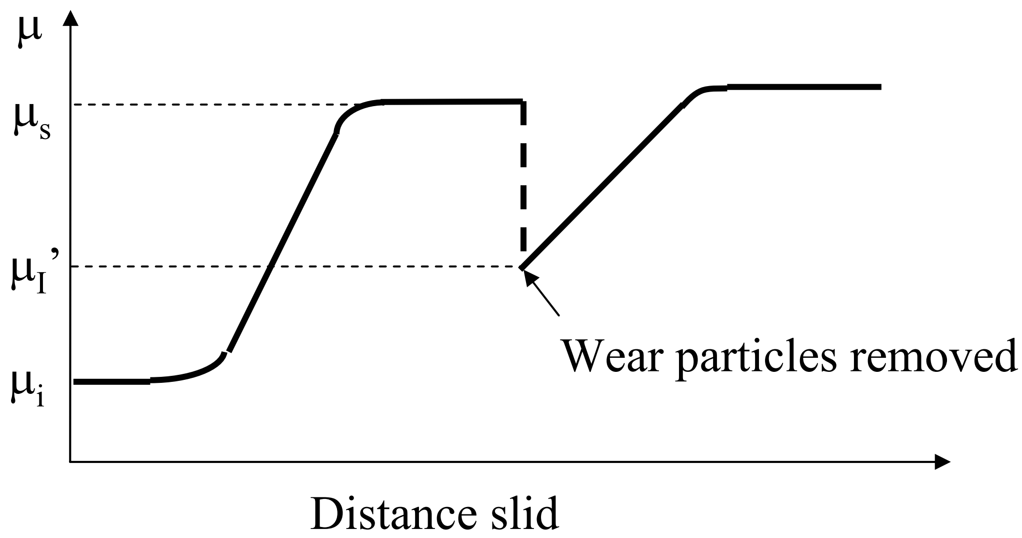


(a)



(b)

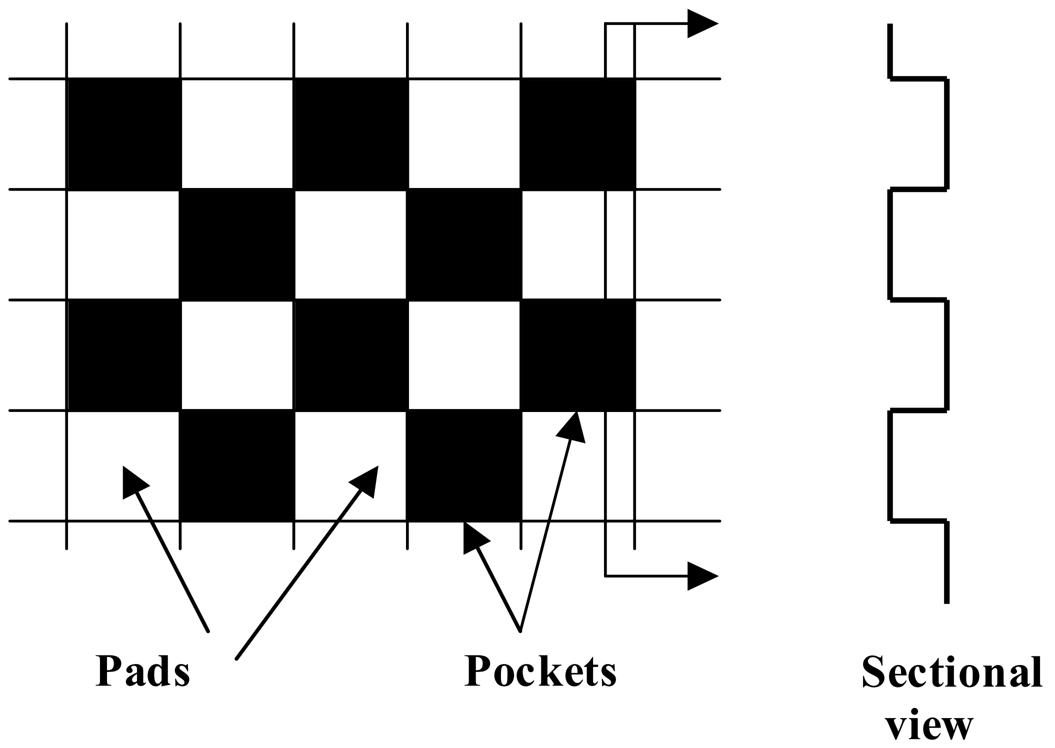
Effect of removing wear particles for an Armco iron slider sliding against an Armco iron specimen



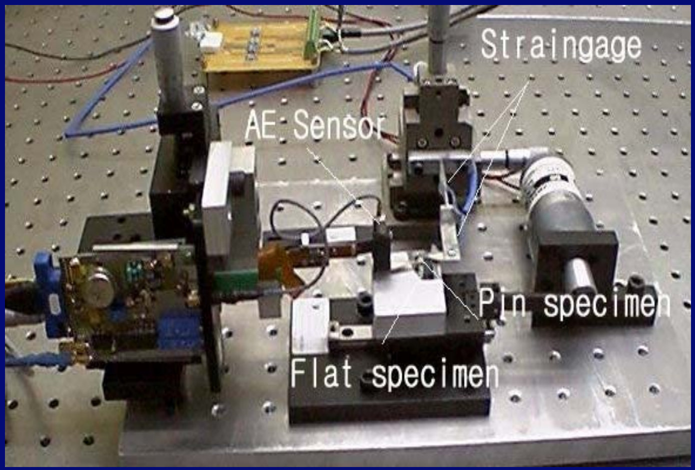
Friction at Dry Sliding Interface

- **Plowing Mechanism**
- **Particle Agglomeration**
- **Height of Agglomerated Particles**
- **Friction Coefficient and the Number of Agglomerated Particles**
- **Reduction of Friction by Elimination of Particles**

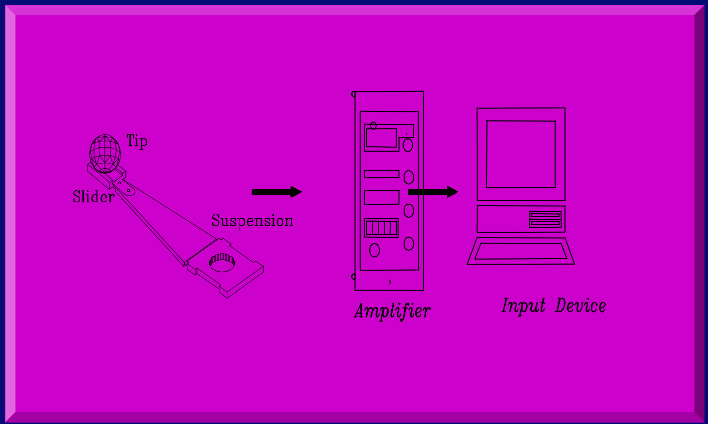
Friction at Dry Sliding Interface
Undulated Surface for Elimination of Particles



Experimental Setup



Pin-on-reciprocator tester



Experimental setup

Experimental conditions

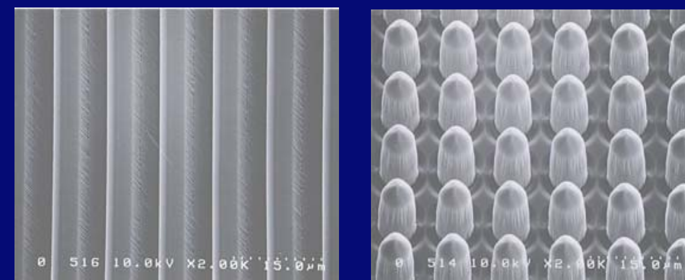
Speed	1 mm/sec
Normal load	1, 5 gf
Temperature	25±2 ℃
Humidity	35, 50, 70 %
Distance	2.4 m

Specimens

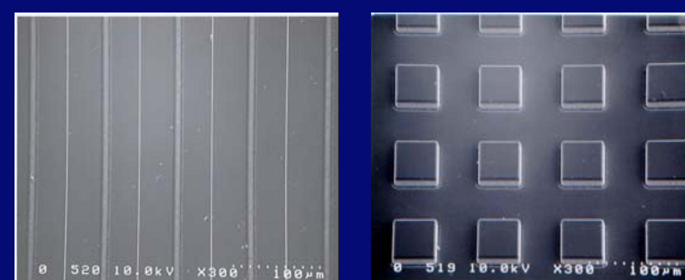
- Pin specimens
  - Bearing ball (1/16”)
  - Slider (Nano type)
- Flat specimens
  - μ-structured Si(coated)

    : Linear and square

    : 5, 10, 20, 50㎛ width

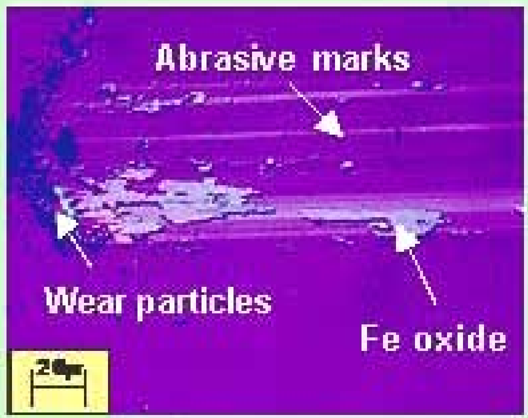


5μm spacing μ-structured Si

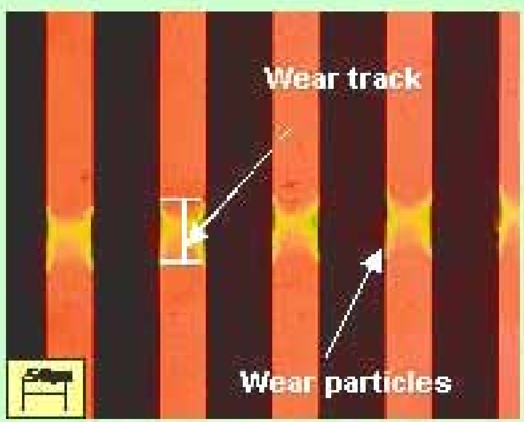


50μm spacing μ-structured Si

Wear Track of Si_3N_4 Coated Flat and μ-structured Surface (ball pin, 5gf, RH 35%)

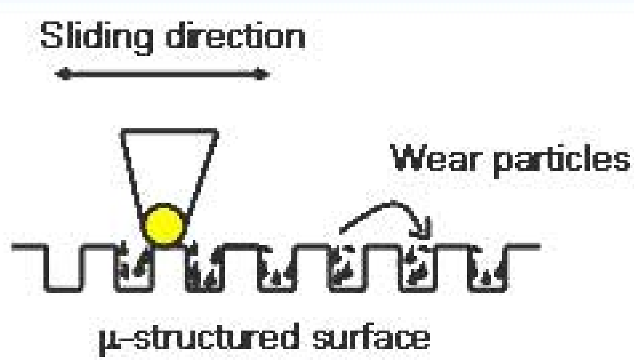


Flat surface

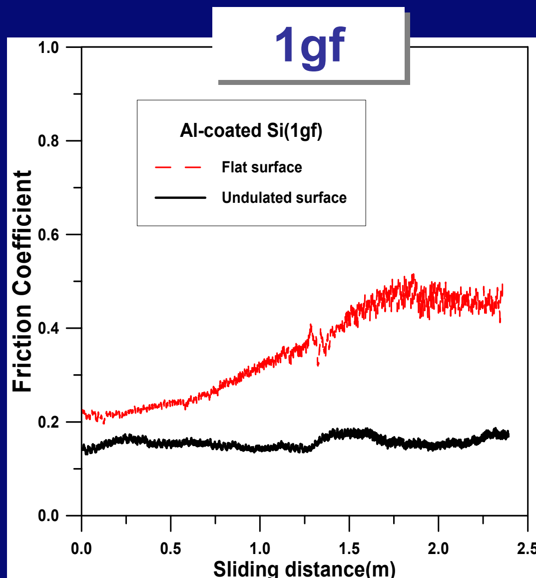


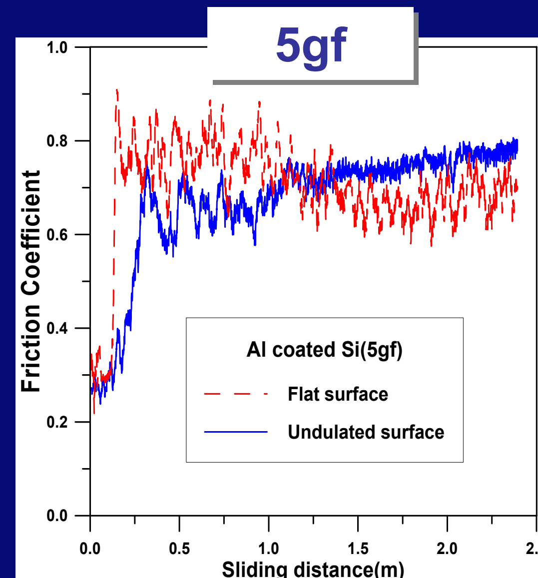
μ-structured surface

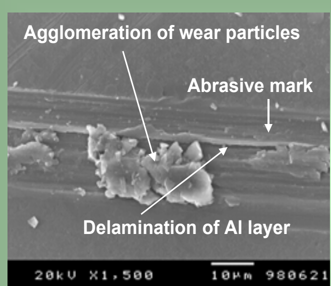
- **Flat surface**
  - Severe wear scar - abrasion, adhesion, ...
  - Many wear particles in wear track
- **μ-structured surface**
  - No severe wear marks
  - Little wear particles in wear track



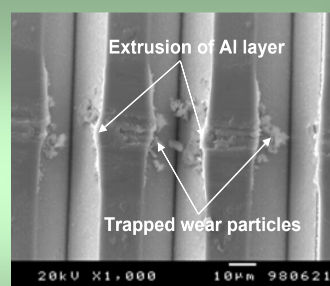
Wear Track of Al Coated Flat and μ-structured Surface (ball pin, RH 35%)



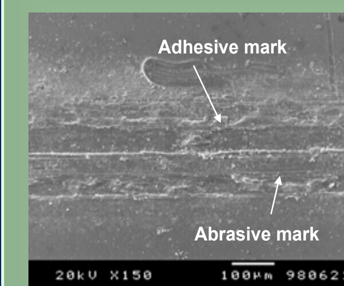




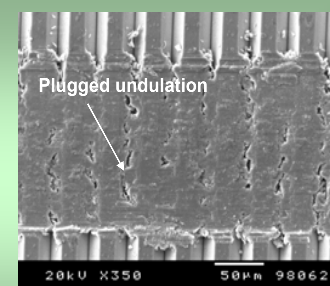
Flat surface



μ structured surface

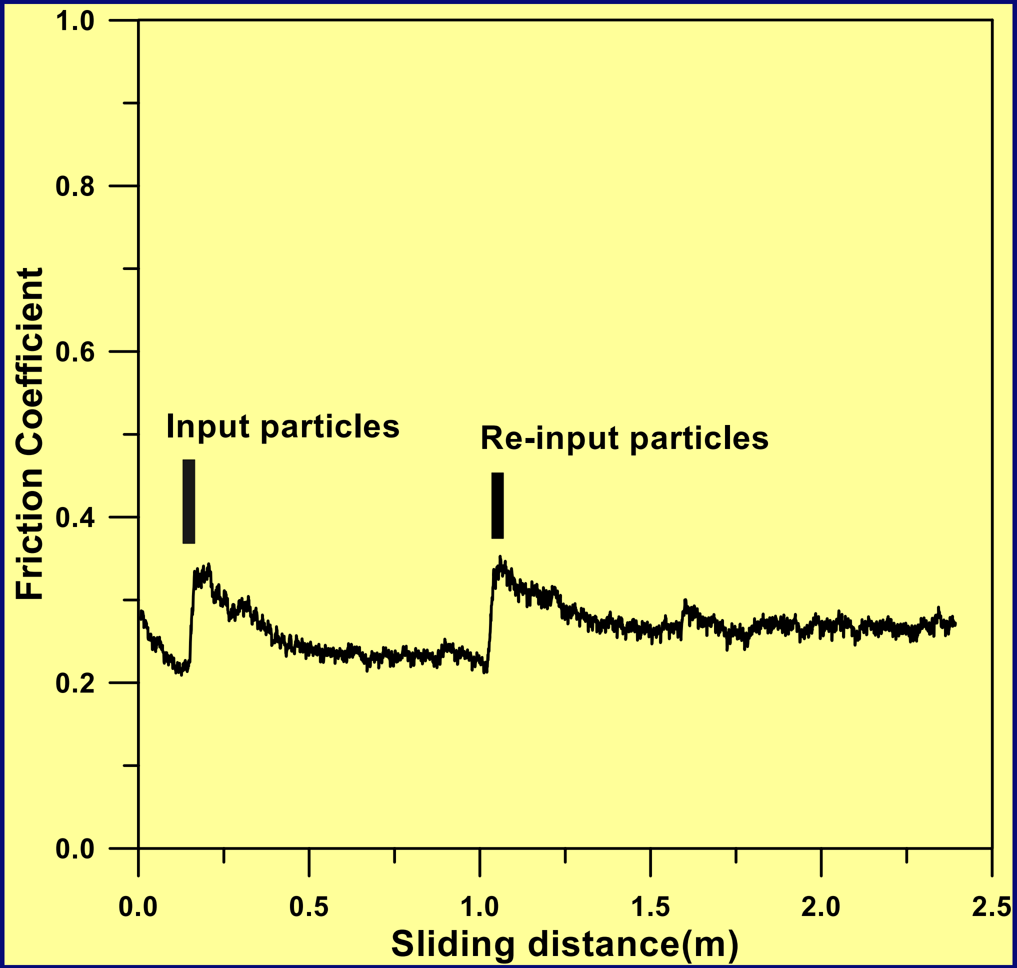


Flat surface



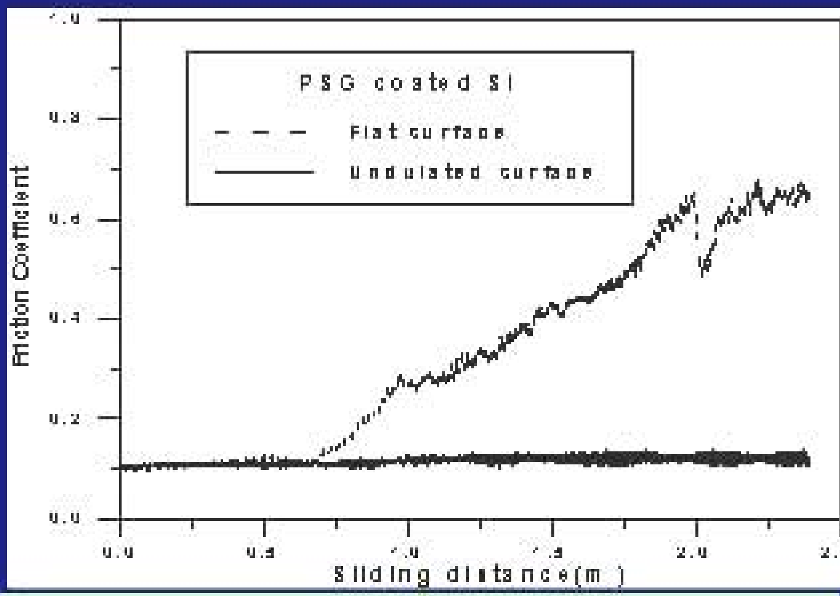
μ structured surface

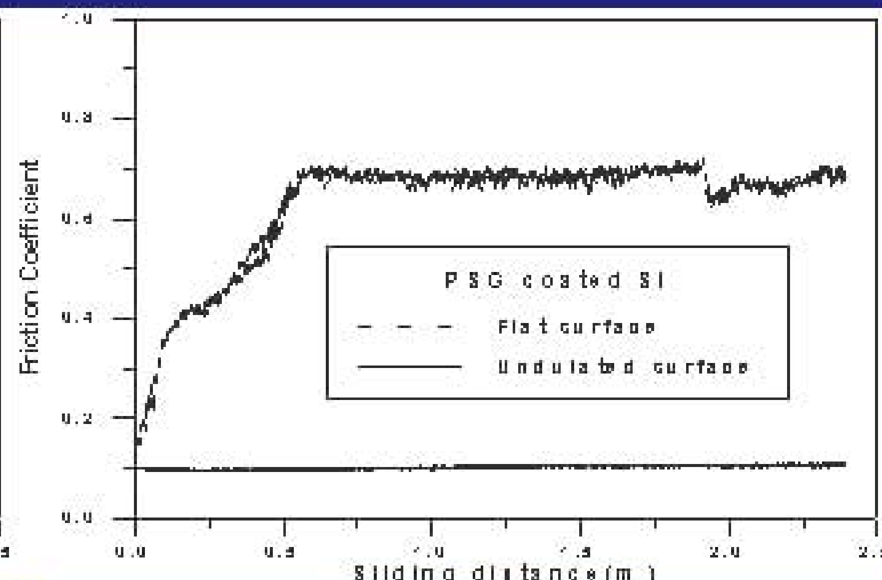
Particle (SiC) Insertion into Al Coated μ-structured Surface (ball pin, 1gf)



1. Contact area reduction
2. Wear particle trapping

Wear Track of PSG coated Flat and μ-structured Surface (ball pin, RH 35%)

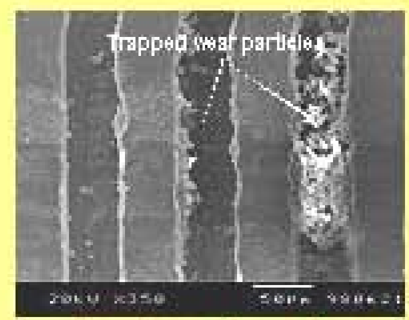




Flat surface

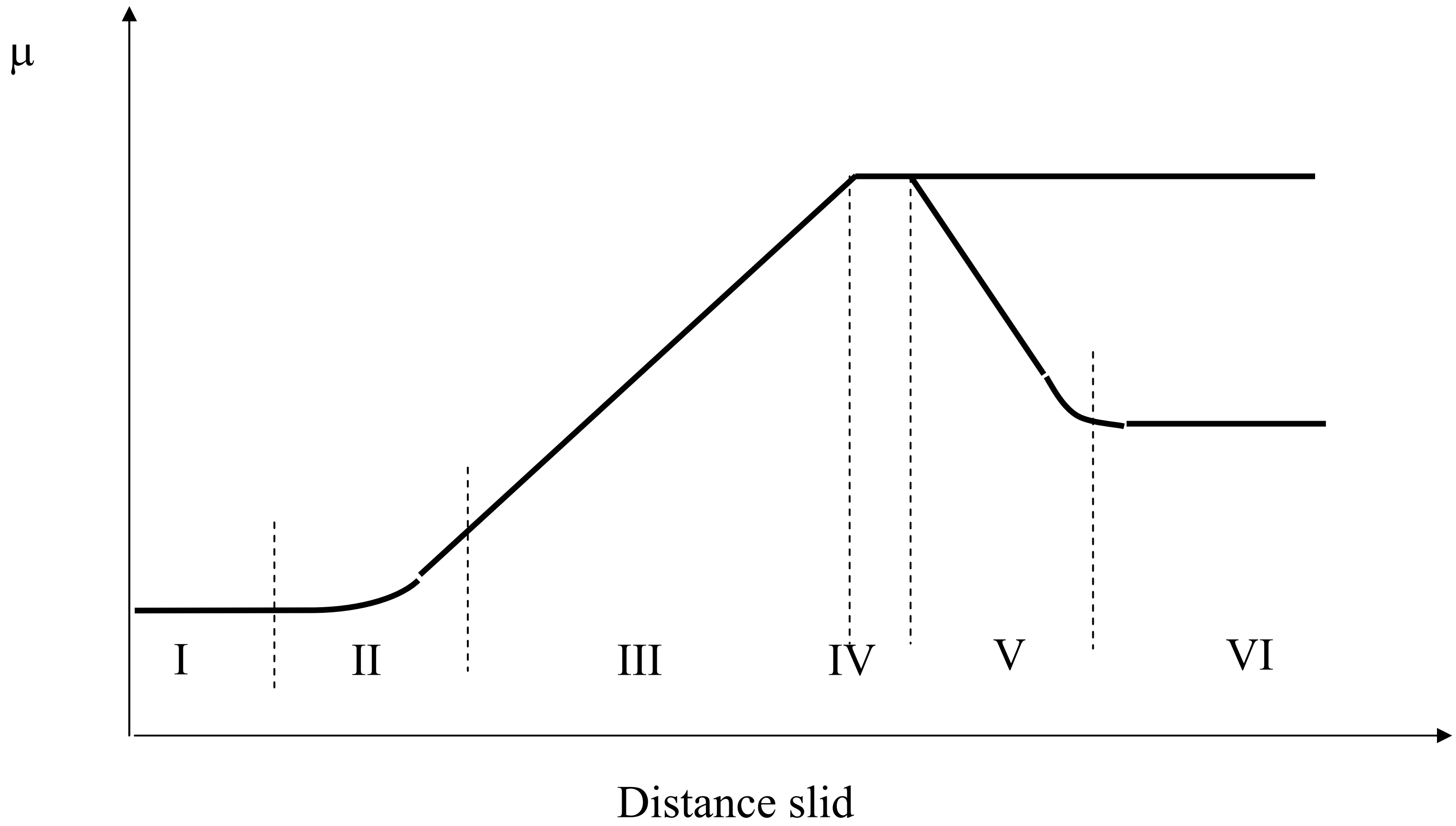
μ-structured surface

Flat surface

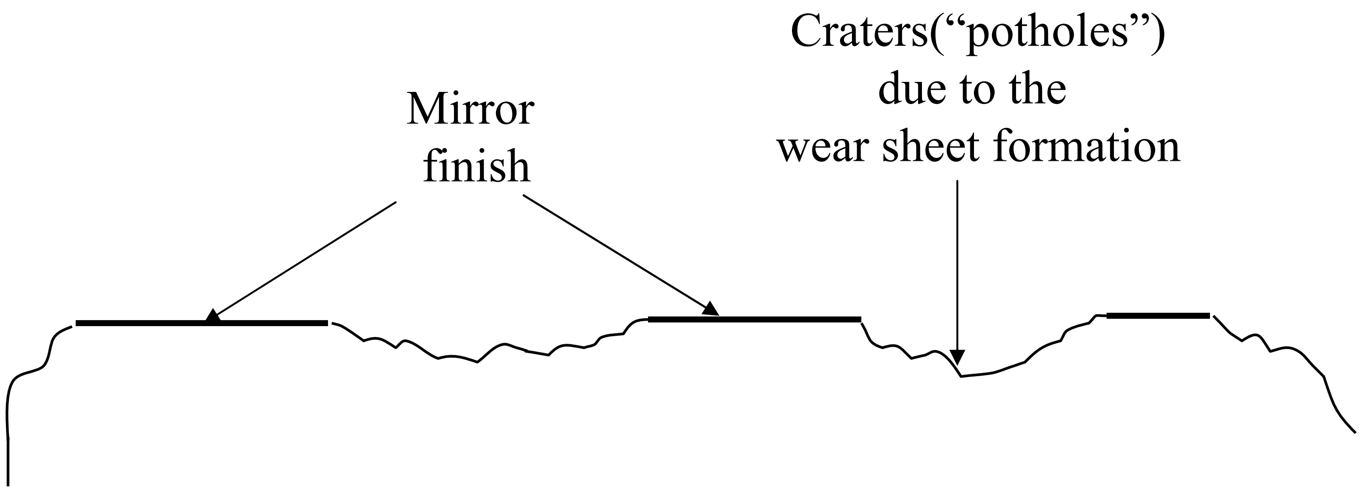


μ-structured surface

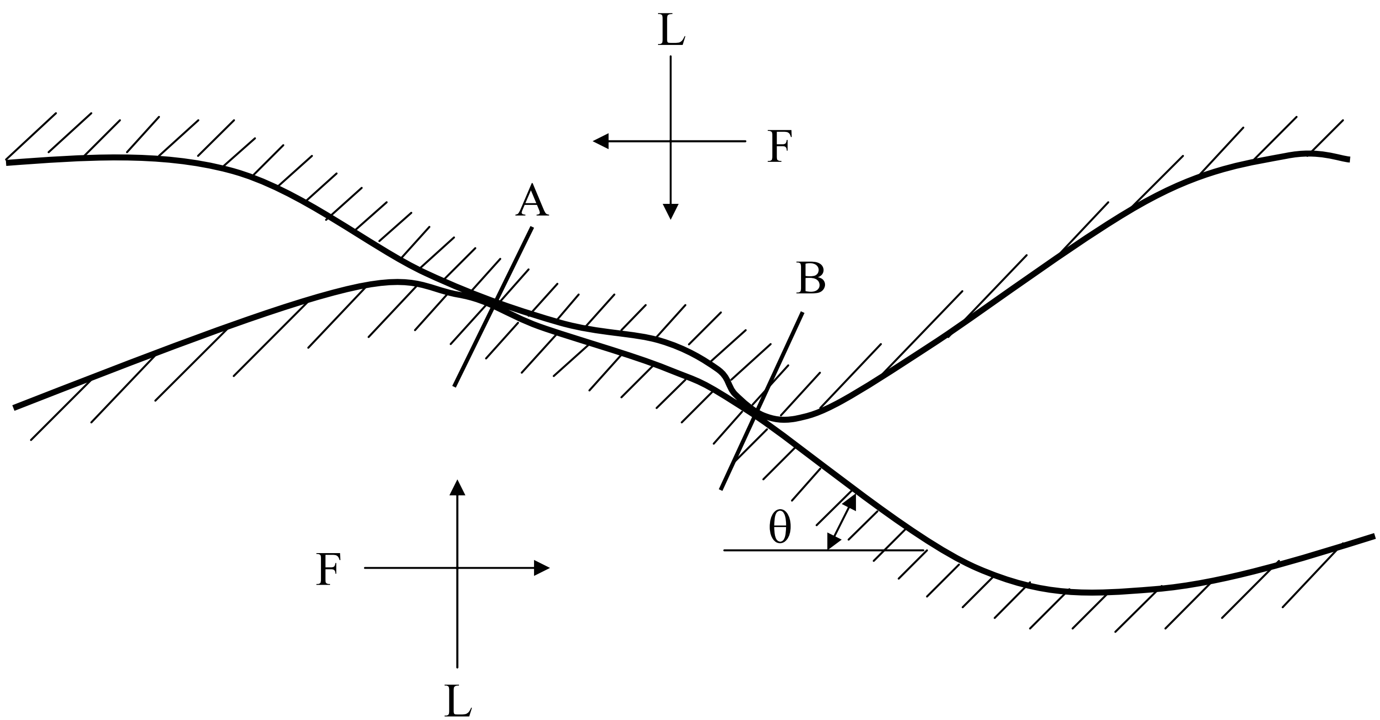
Six stages in the frictional force versus distance slid relationship



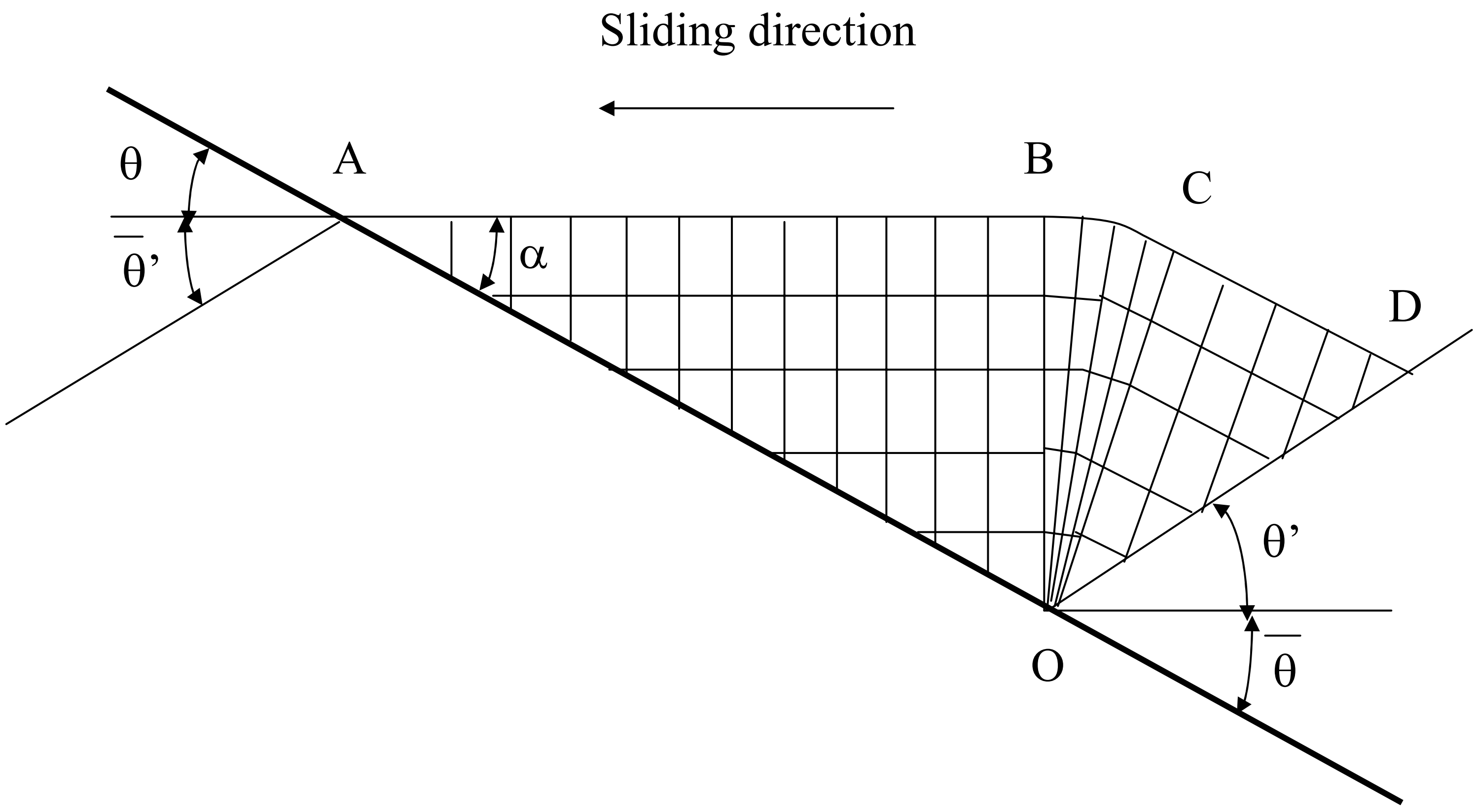
Hard stationary surface polished by a soft surface



Two interacting surface asperities



Geometrically compatible slip-line field.



Slip-line field solution for friction as a function of the slope of asperities

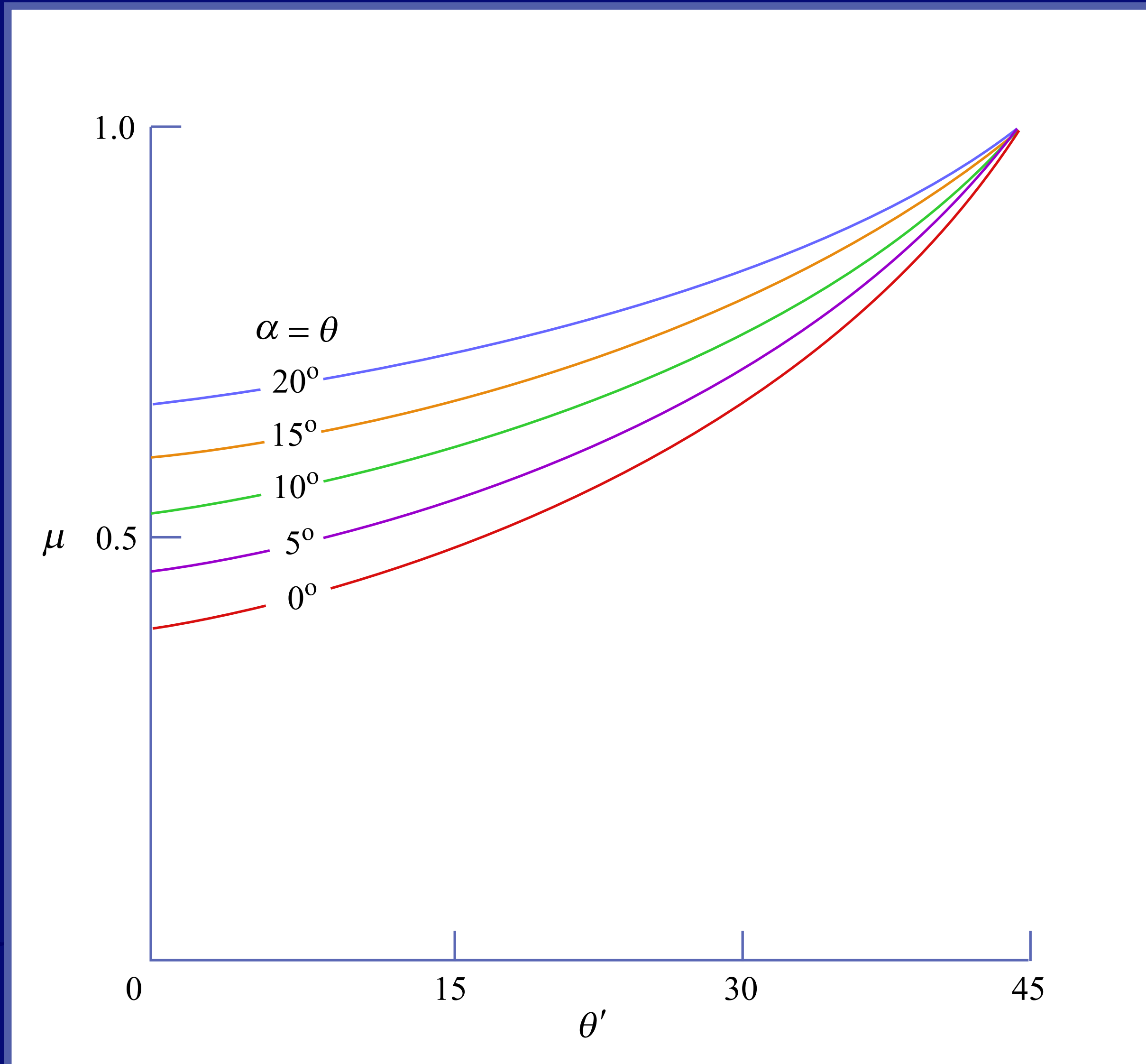


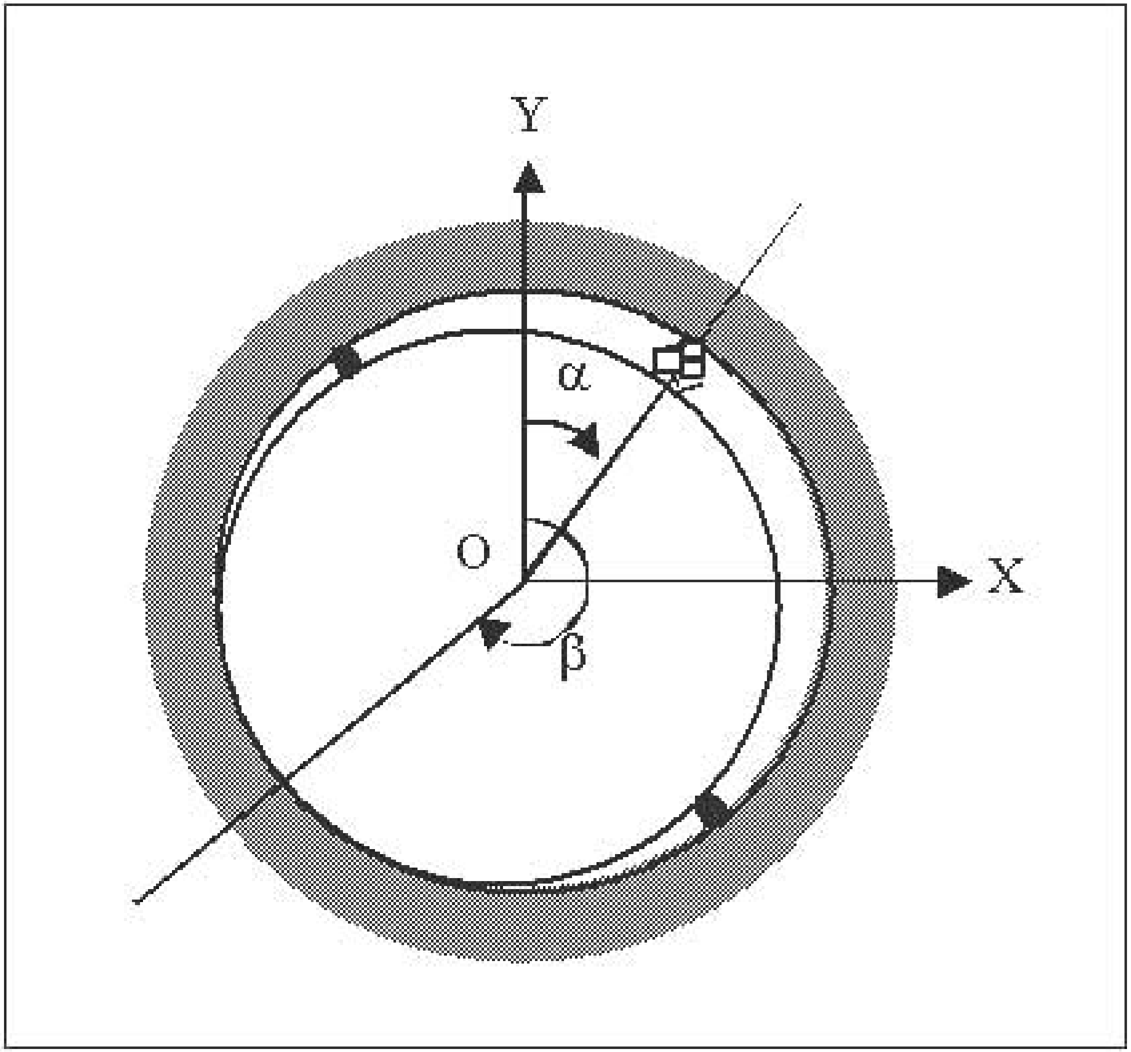
Figure by MIT OCW. After Suh, N. P., and H. C. Sin. "The Genesis of Friction." *Wear* 69 (1981): 91-114.

Effect of Boundary Lubrication

~ μ ~ 0.1

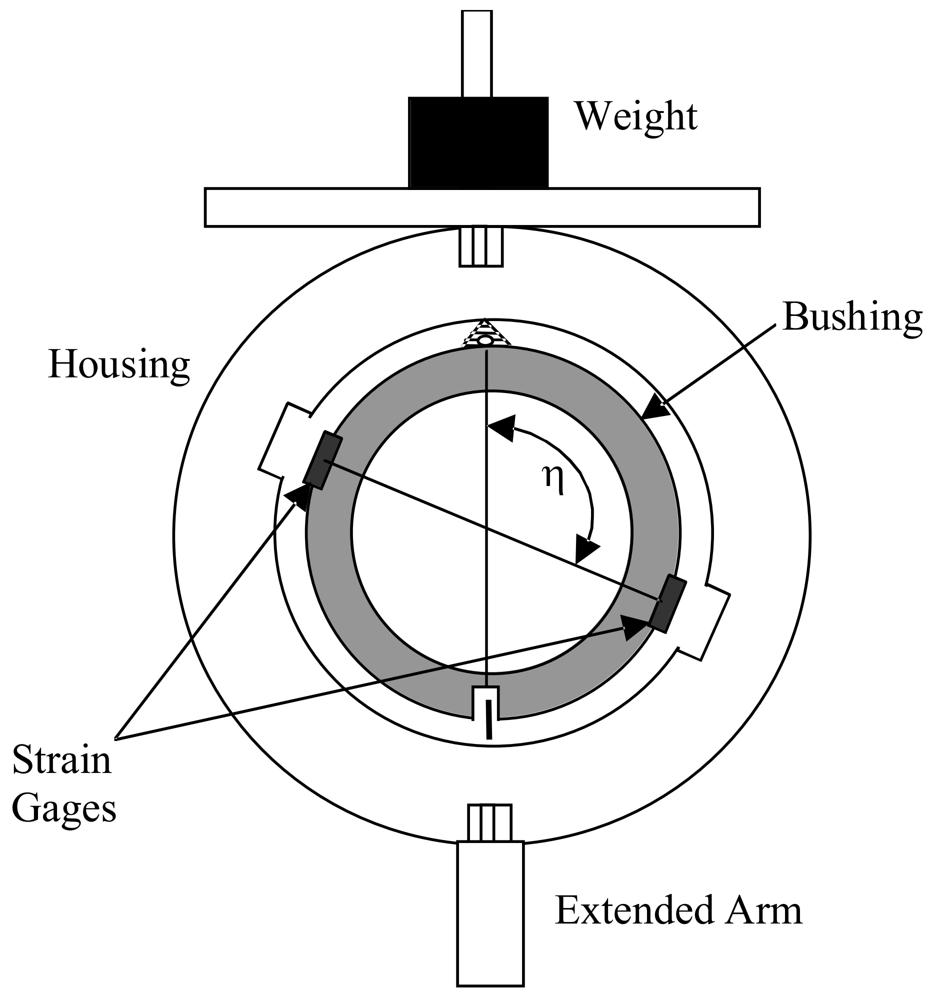
- Cause?
  - Plowing
- What is the role of a lubricant?
  - Lower shear stress
  - Transport particles
  - Prevent particle agglomeration
  - Prevent adhesion

Friction in Geometrically Confined Space

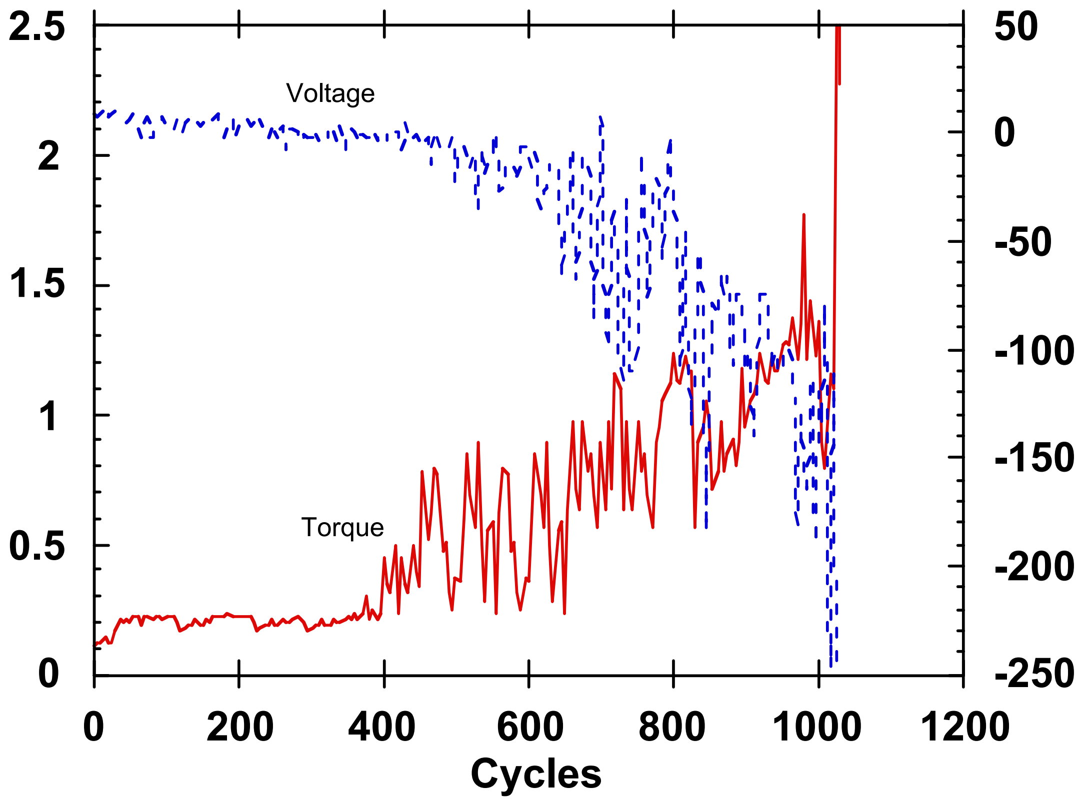


Friction in Geometrically Confined Space

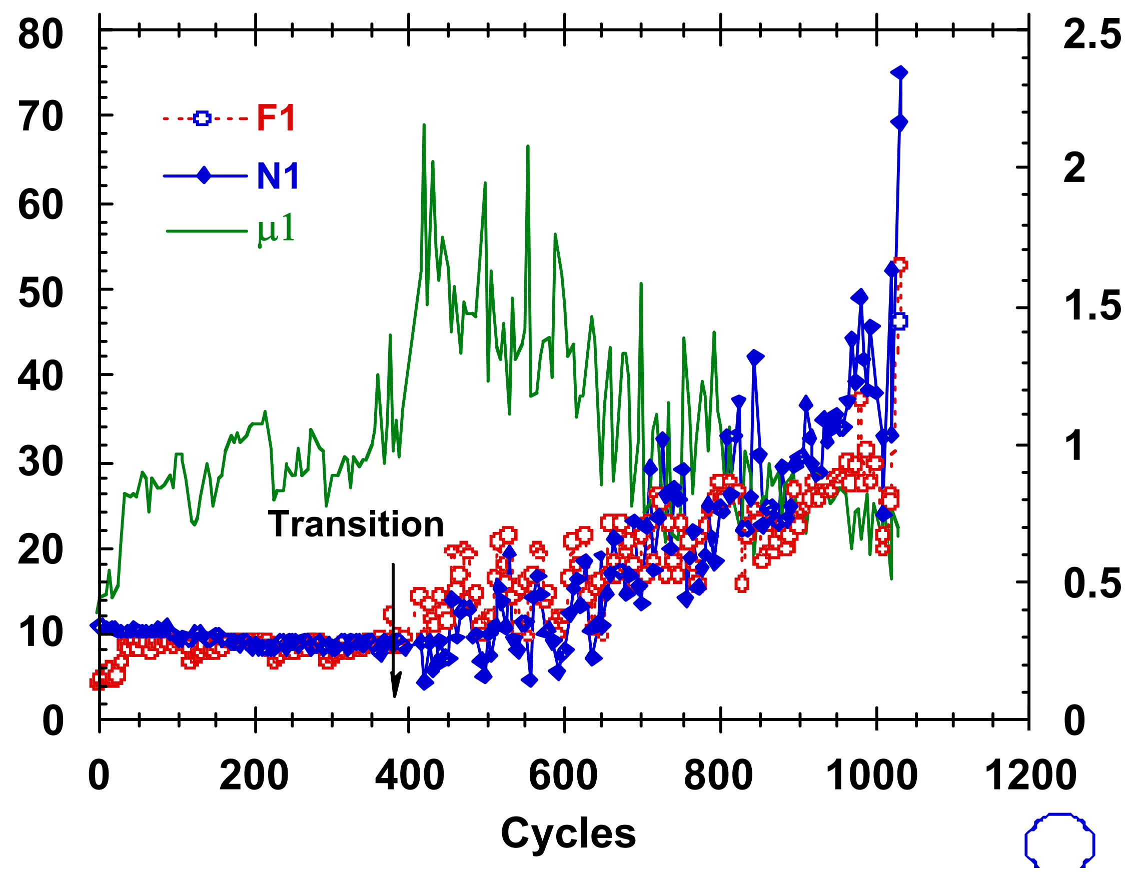
Experimental Arrangement



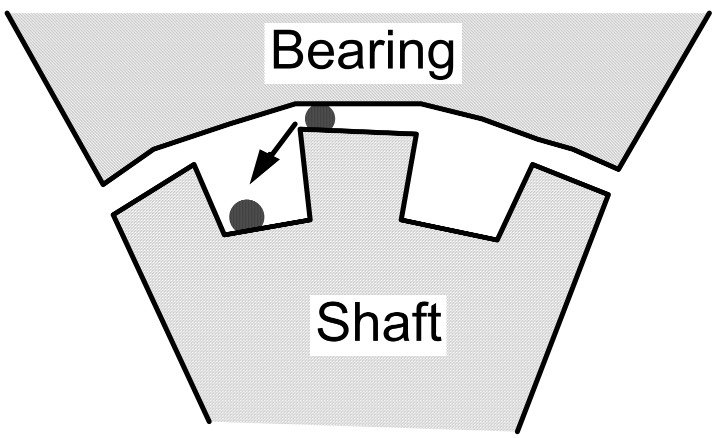
Friction in Geometrically Confined Space

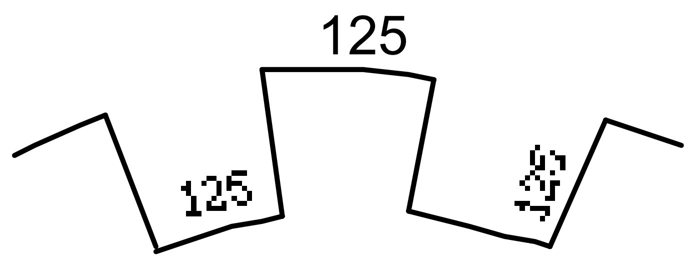


Friction in Geometrically Confined Space



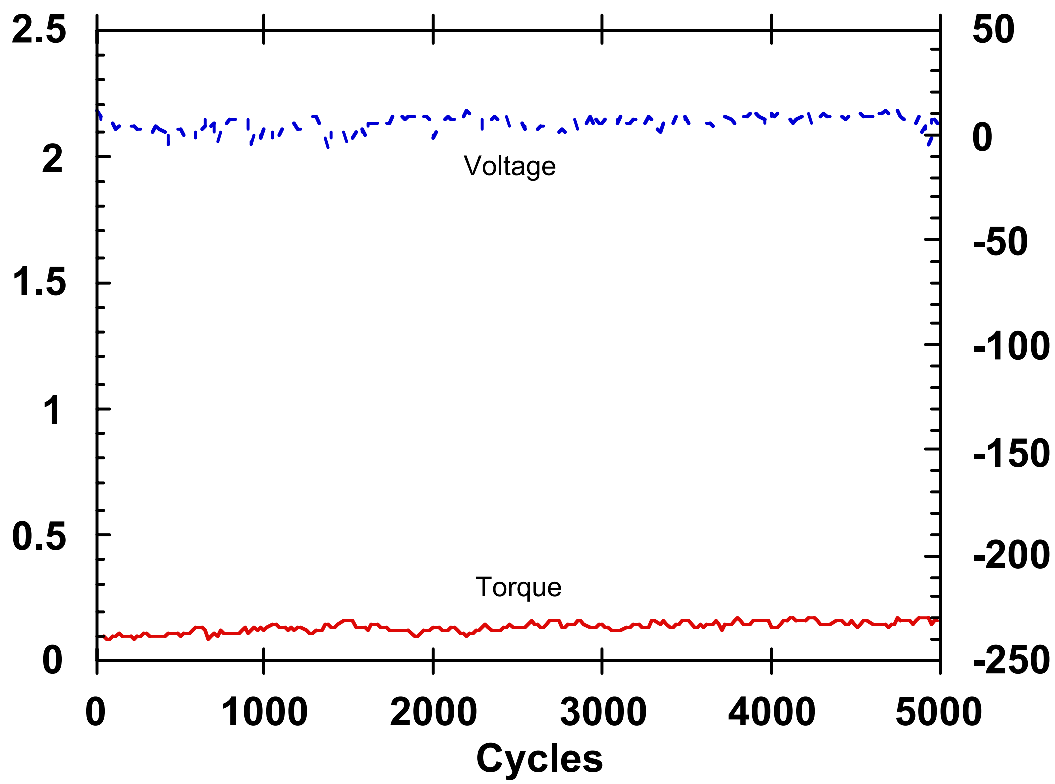
Friction in Geometrically Confined Space





Dimensions in μm

Friction in Geometrically Confined Space



Friction at Boundary Lubricated Interface

Typical wear track of Al^+ implanted Fe disk shows shallow grooves. The test was done in mineral oil. (From Shepard and Suh, 1982)

Photo removed for copyright reasons.

Friction at Polymeric Interfaces

- Thermoplastics
  - Highly linear semicrystalline polymers: HDPE, PTFE
  - Linear semicrystalline polymers
  - Polymers with large pendant groups (amorphous polymers)
- Thermosetting plastics
  - Epoxy, phenolics, polyesters, polyurethane
  - Glass fiber reinforced or filler
- Elastomers
  - Thermoplastic elastomers
  - Polybutadiene rubber

Structure of some thermoplastics

Diagrams removed for copyright reasons.
See Figure 6.1 in [Suh 1986].

Friction Coefficient of Low Density Polyethylene (LDPE)

Graphs removed for copyright reasons.
See Figure 6.12 in [Suh 1986].

(a) μ as a function of the sliding velocity at various temperatures of acrylonitrile-butadiene rubber on wavy glass
(b) Master curve (Reference temperature = 20C)
(c) Shift factor a(T) vs (T-T_s)

Graphs removed for copyright reasons.
See Figure 6.13 in [Suh 1986].

(a) Rolling friction of 3/16 inch steel ball over the surface of a nylon copolymer as a function of temperature (load 1050 g). (b) Low -frequency vicoelastic loss data for the same polymer as a function temperature.

Frictional Behavior of Composites

- Fiber orientation
- Continuous vs. chopped fibers
- Example: Brake lining, carbon/carbon composites, teflon/graphite fiber composites

Effect of Coatings on Friction

- Hard coatings on metals
  - TiN, DLC, TiC, Al_2O_3-13TiO_2, etc.

- Soft coatings on metals (primarily to reduce wear)
  - Ni/Au/Steel, Cd/Steel, Au/steel, etc.

- Polymeric coatings on metals
  - Polyurethane, Fluorocarbon polymers, etc.

Conclusions

1. Friction is a manifestation of the energy consumed when two surfaces in contact slide relative to each other -- with and without the normal load.

2. Because friction is caused by plowing, adhesion and asperity removal, it is best represented by "Friction Space".

3. In a majority of engineering applications that involve a metal surface sliding against another, the friction force is generated by plowing of the surfaces by wear particles. The friction force is also generated by the work done to shear asperities and in some rare cases, by the adhesion between the two contacting surfaces.

Conclusions

4. Friction is not an inherent material property. It depends on the relative hardness of materials that are sliding against each other. The friction is the highest when the two surfaces have exactly the same hardness.

5. Removal of wear particles by the use of undulated surface reduces the coefficient of friction to a level of boundary lubricated cases with boundary lubricants.

6. Boundary lubricants lower the friction coefficient by preventing wear particle agglomeration and plowing, but still there is a metal-to-metal contact, which leads to plowing and the observed coefficient of friction of about 0.1.

Conclusions

7. Polymers are used extensively in diverse applications because of their unique tribological properties. For instance, highly linear polymers have low coefficients of friction.

8. Composites can be made with polymeric materials and fibers or fillers to satisfy a specific set of functional requirements.