2.800 Tribology
Fall 2004

- **Lecturers:**
  - Nam P. Suh
  - Nannaji Saka

- **Text book:**
  - Suh, N. P., Tribophysics, Prentice-Hall, 1986
  - Suh, N. P. and Others, Tribophysics and Design of Tribological Systems (Manuscript)

- **Mechanics**
  - Two 1 1/2 hour examination
  - Term paper
  - Homework

What is tribology?

- **Deals with friction, wear and lubrication**
- **Two aspects**
  - **Science: Basic mechanisms**
  - **Technology: Design, manufacture, maintenance**

What is tribology?

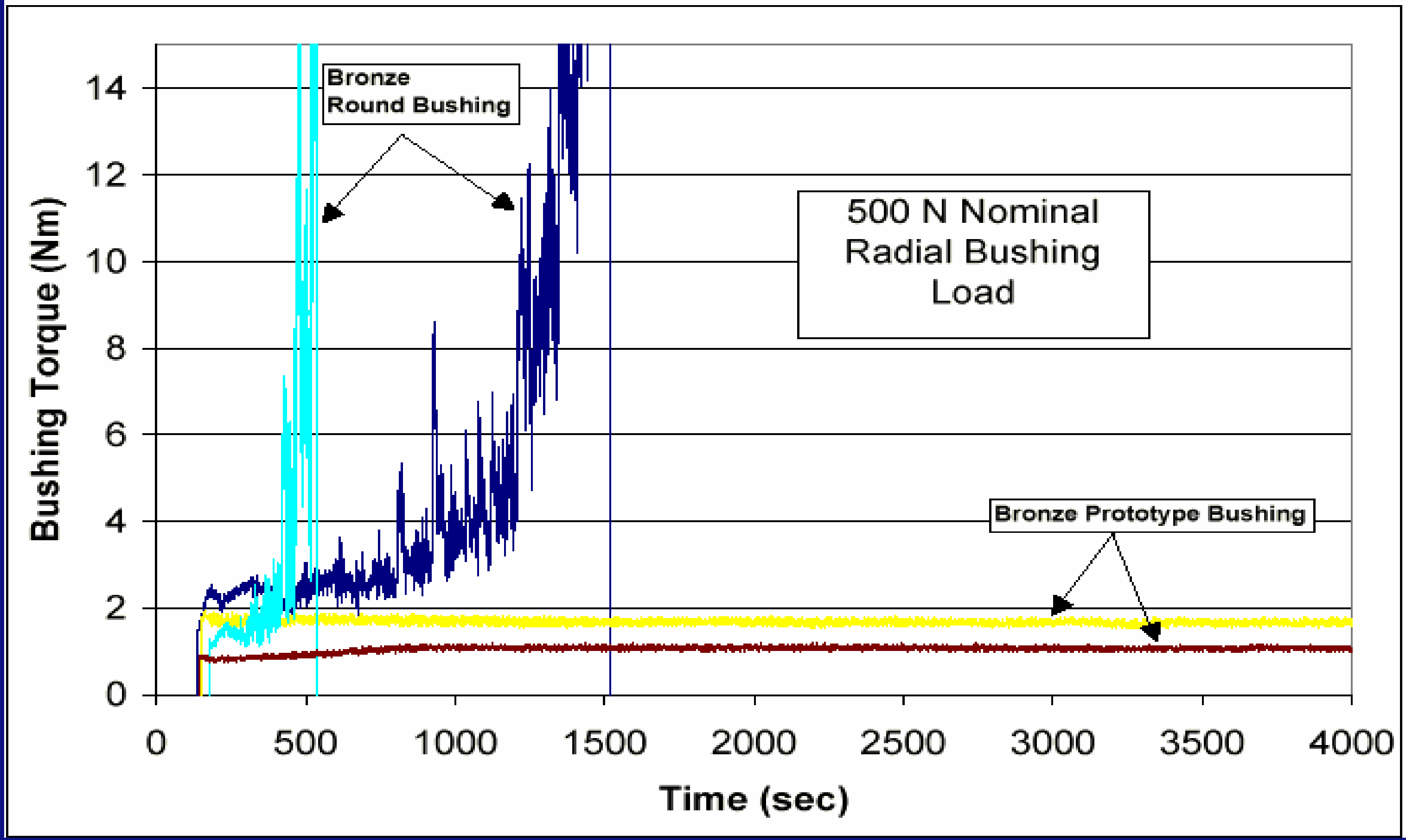
- Economically very important -- 6% GDP (Jost)
- Probably more failures are caused by tribological problems than fracture, fatigue, plastic deformation, etc.
- Tribological problems are often related to systems issues.

Examples of tribological problems

- International Space Station Beta Gimbal Assembly Failure
- Drive sprockets, idlers, rollers, Grouser shoes
- Pin Joints
- Electrical Connectors

Pin Joints -- Test Results

(Courtesy of Tribotek, Inc. Used with permission.)



Example: Electrical Connector

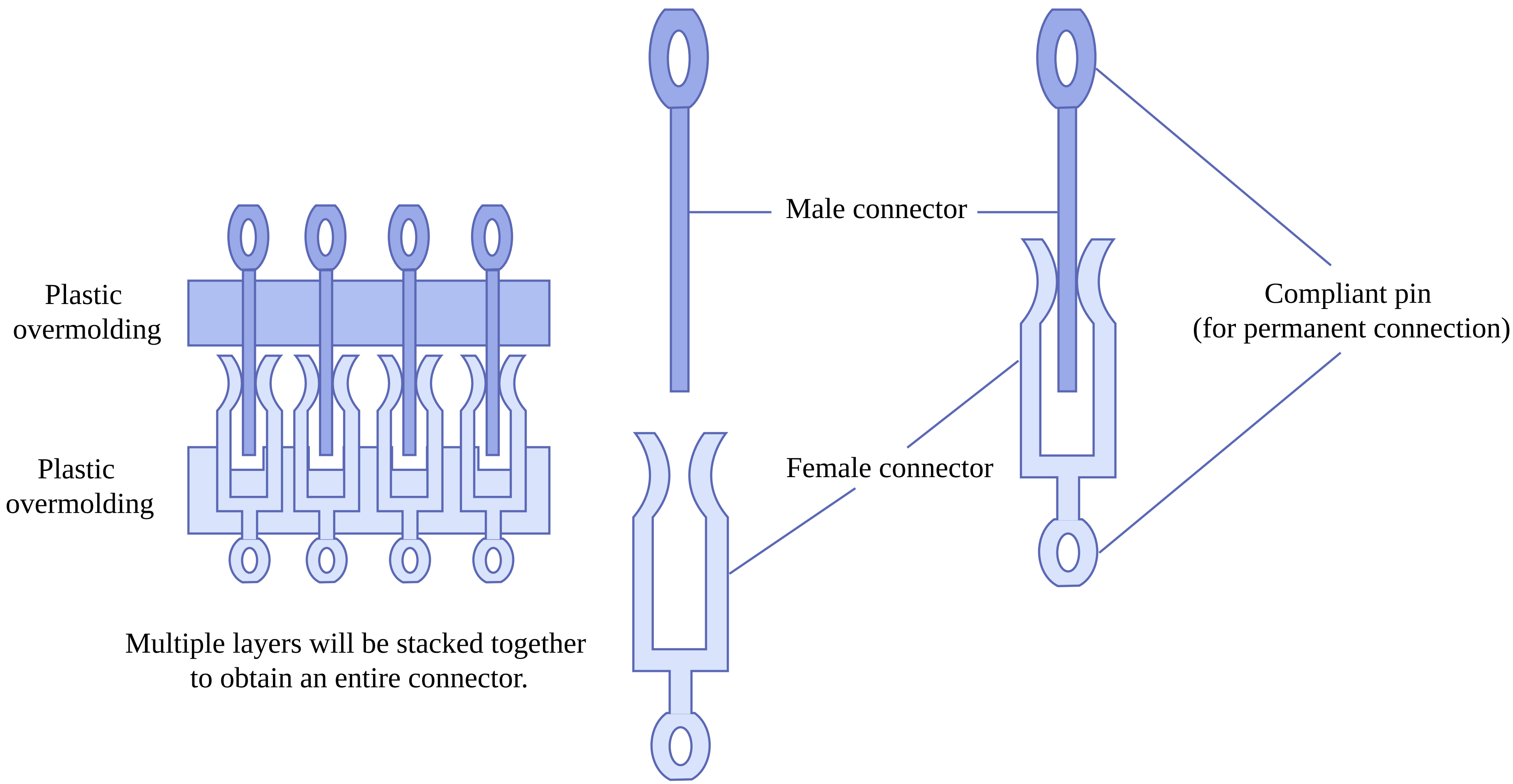


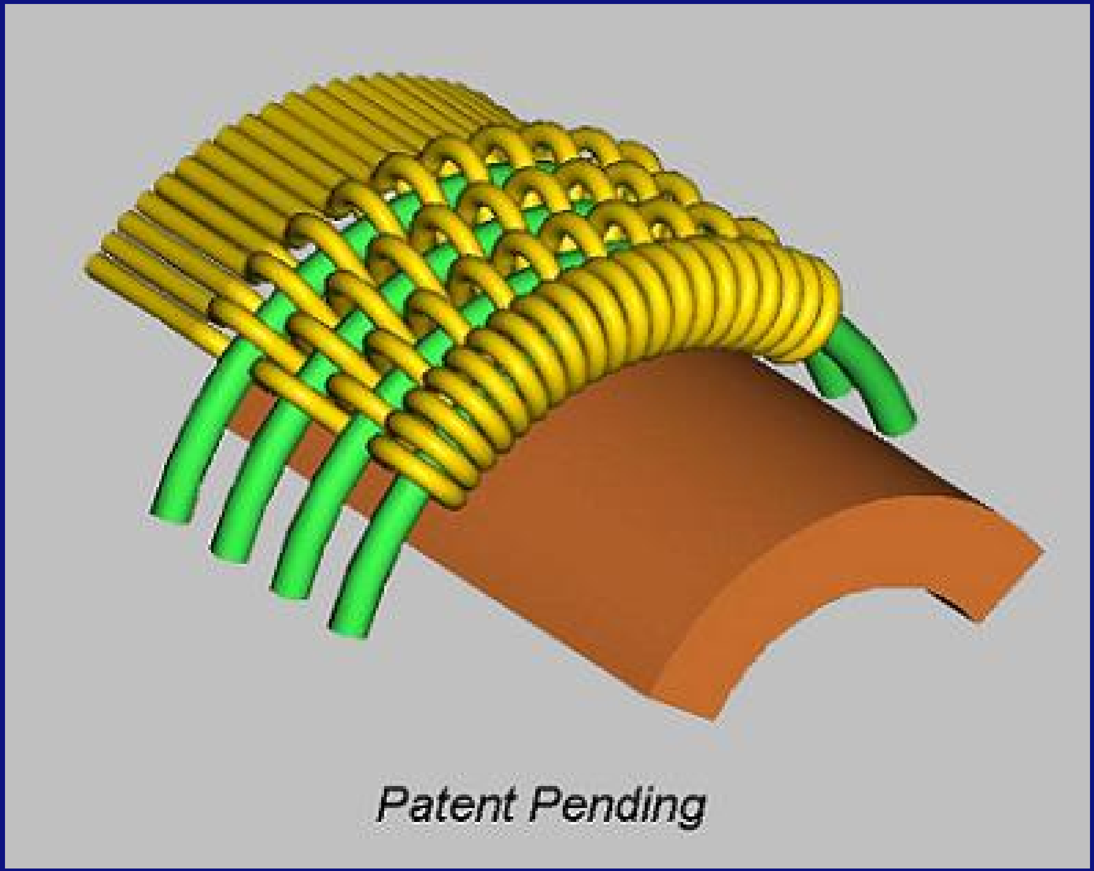
Figure by MIT OCW.

These conventional electrical connectors are coupled Design.

Coupled designs are not robust, difficult to manufacture, lack long-term stability, sensitive to slight variations, difficult to decompose, etc.

Tribotek Electrical Connectors

(Courtesy of Tribotek, Inc. Used with permission.)



Four Elements of Tribology

- Surface interactions with its environment, including lubrication and lubricants
- Generation and transmission of forces at the interface
- Response of materials to the force generated at the interface
- Design of tribological systems

Some of the Basic Questions

- What is friction?
- How is the friction force generated?
- What is the coefficient of friction?
- How do materials wear?
- What is the effect of the applied load on friction and wear?
- What is the role of lubricant?
- How does a pin-joint seize?
- Why does it take so much force to insert electrical contacts?
- How do you lower friction?
- How should we reduce the wear rate of materials?

What is friction?

- Friction is a result of energy dissipation at the (sliding) interface.

- Friction force:

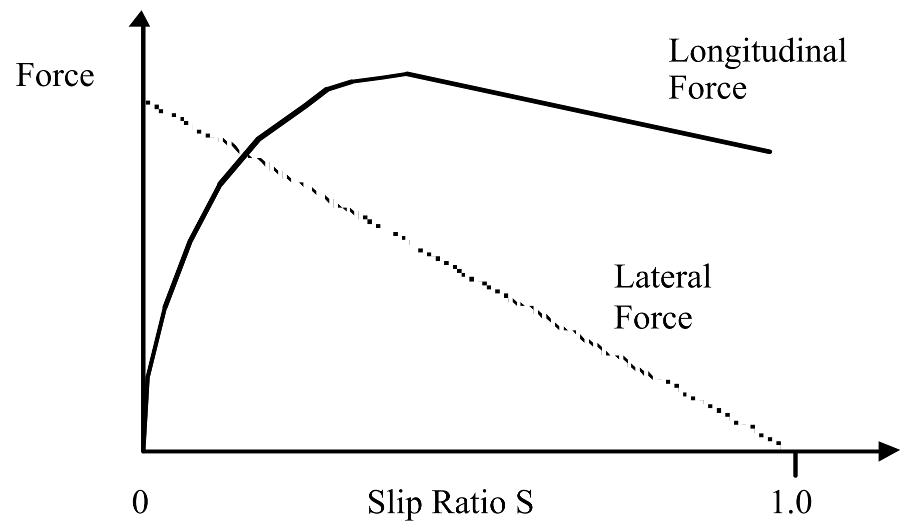
$$\mathbf{F} = \frac{\partial W}{\partial \mathbf{s}}$$

where **F** and **s** are vectors.

Friction is affected by the following:

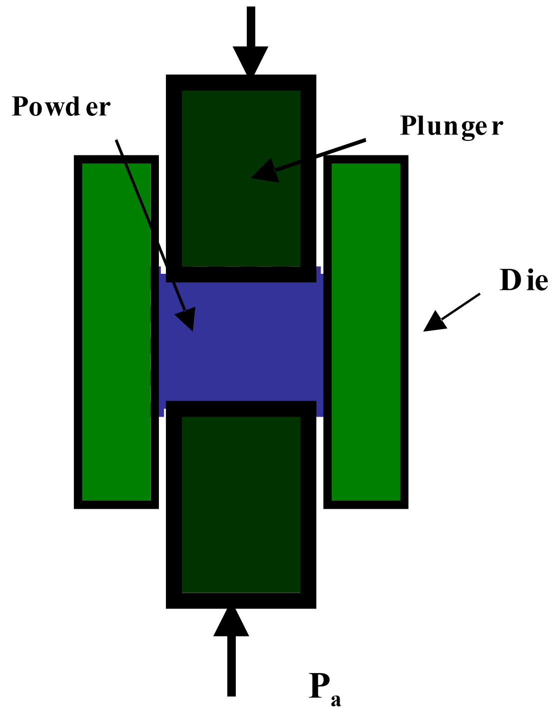
1. Presence of wear particles and externally introduced particles at the sliding interface
2. Relative hardness of the materials in contact
3. Externally applied load and/or displacement
4. Environmental conditions such as temperature and lubricants
5. Surface topography
6. Microstructure or morphology of materials
7. Apparent contact area
8. Kinematics of the surfaces in contact (i.e., the direction and the magnitude of the relative motion between the surfaces

Is the frictional force directional?



$$\text{Slip ratio} = (V_b - V_w)/V_b$$

Is the frictional force directional?



Compaction of powder

What is the coefficient of friction?

- Friction coefficient is defined as

$$\mu = \frac{\text{Tangential force}}{\text{Normal load}}$$

- Is it a material property?

What is Coulomb friction?

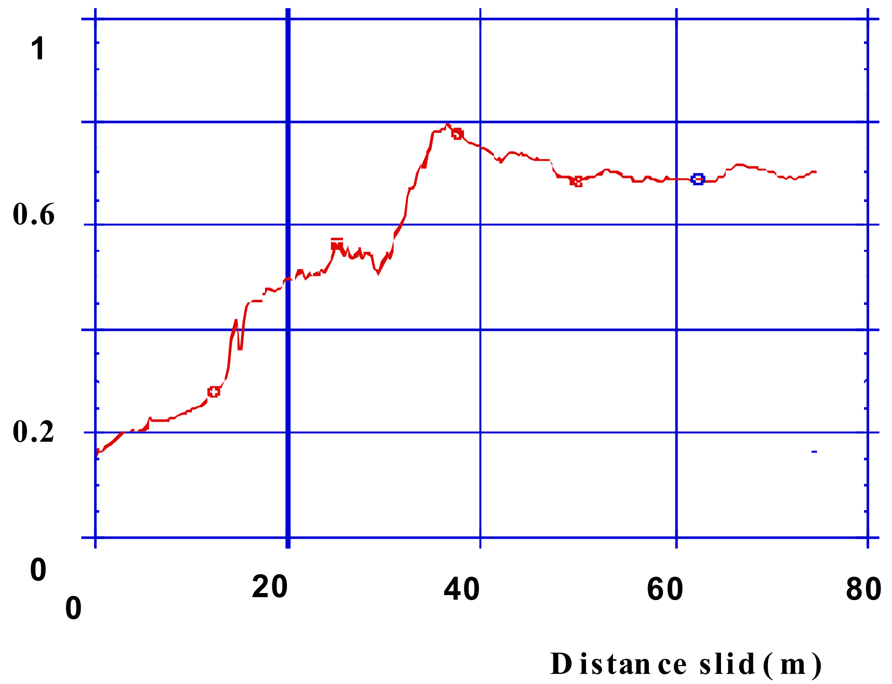
- Coulomb friction is defined as

  Friction force is proportional to normal load. That is, the coefficient of friction μ *is constant.*

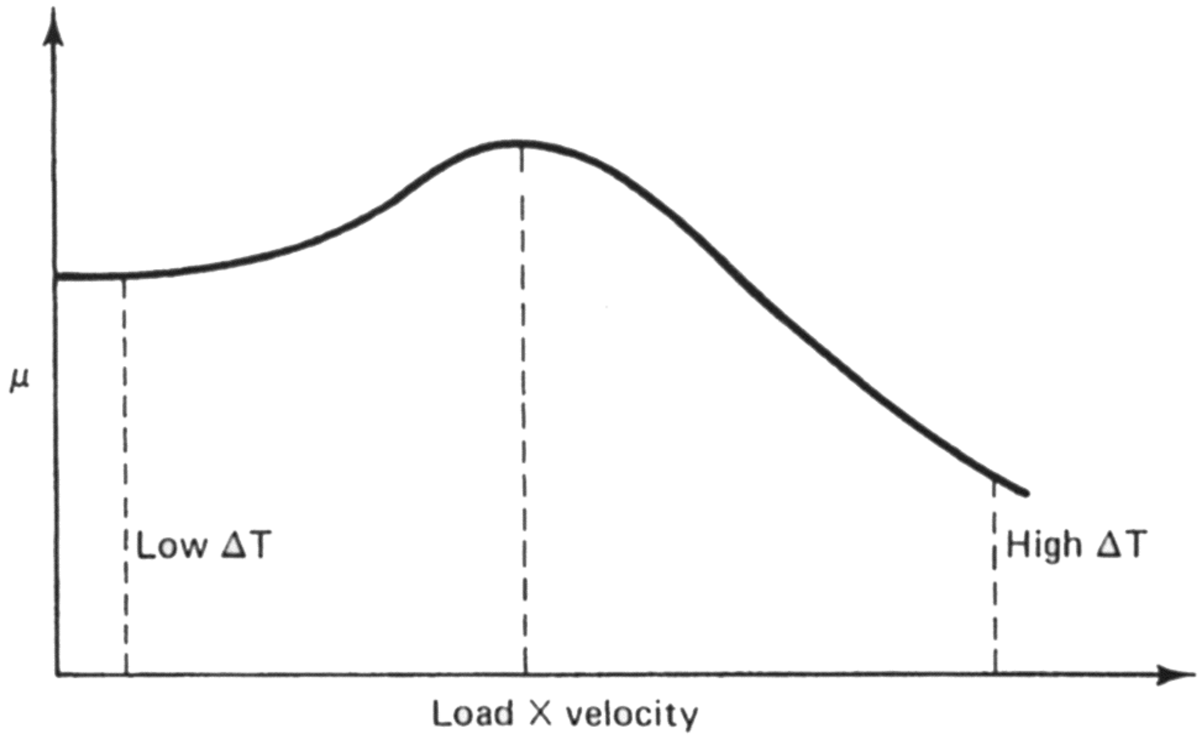
- Does the normal load always increase friction force?

- Can the friction force finite when the normal load is absent?

Is the friction coefficient constant?



Is the friction coefficient constant?



Source: Figure 1.1, Suh (1986)

Is the friction coefficient constant?

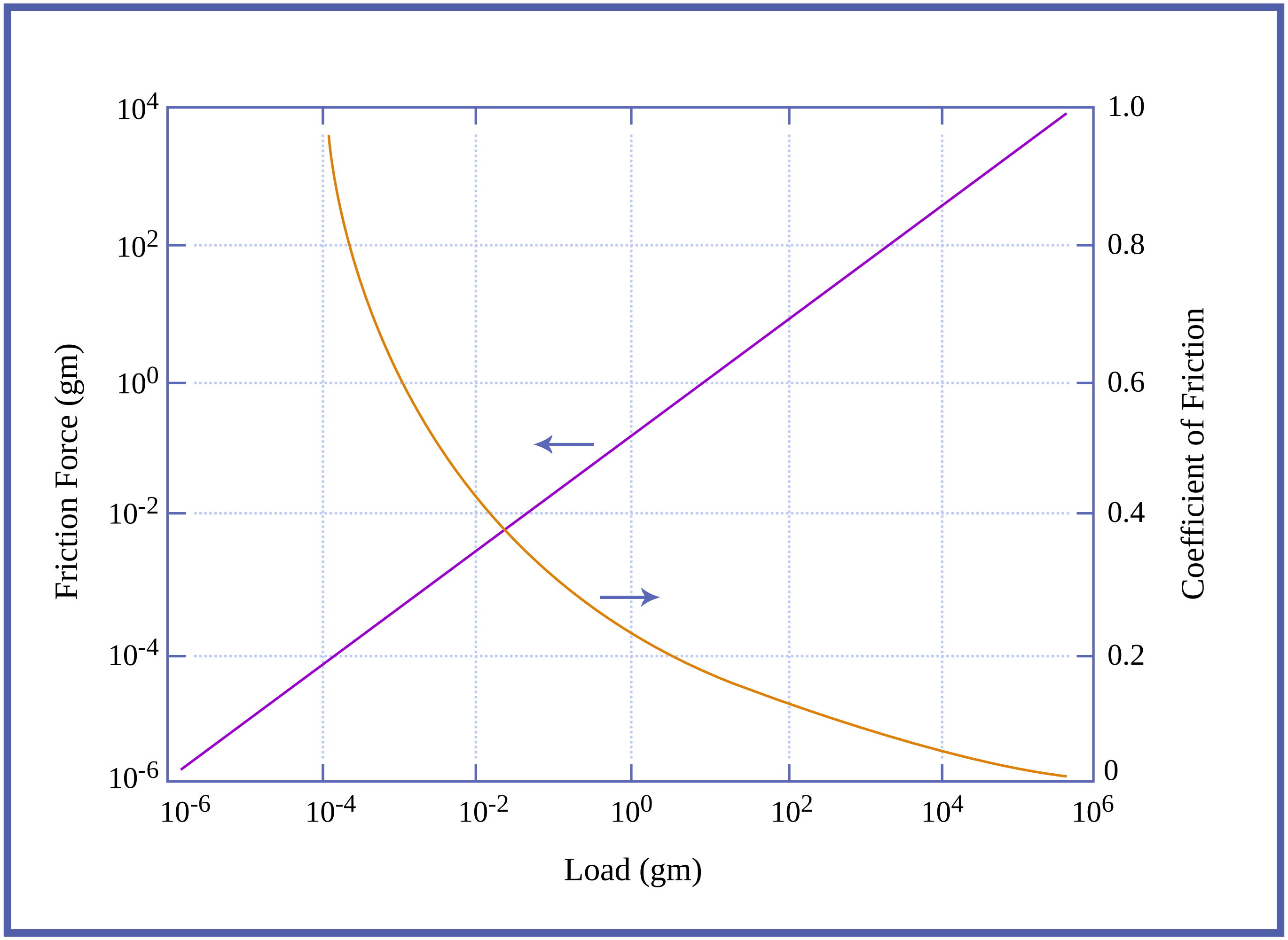


Figure by MIT OCW. After Allan, 1958.

Is the friction coefficient constant?

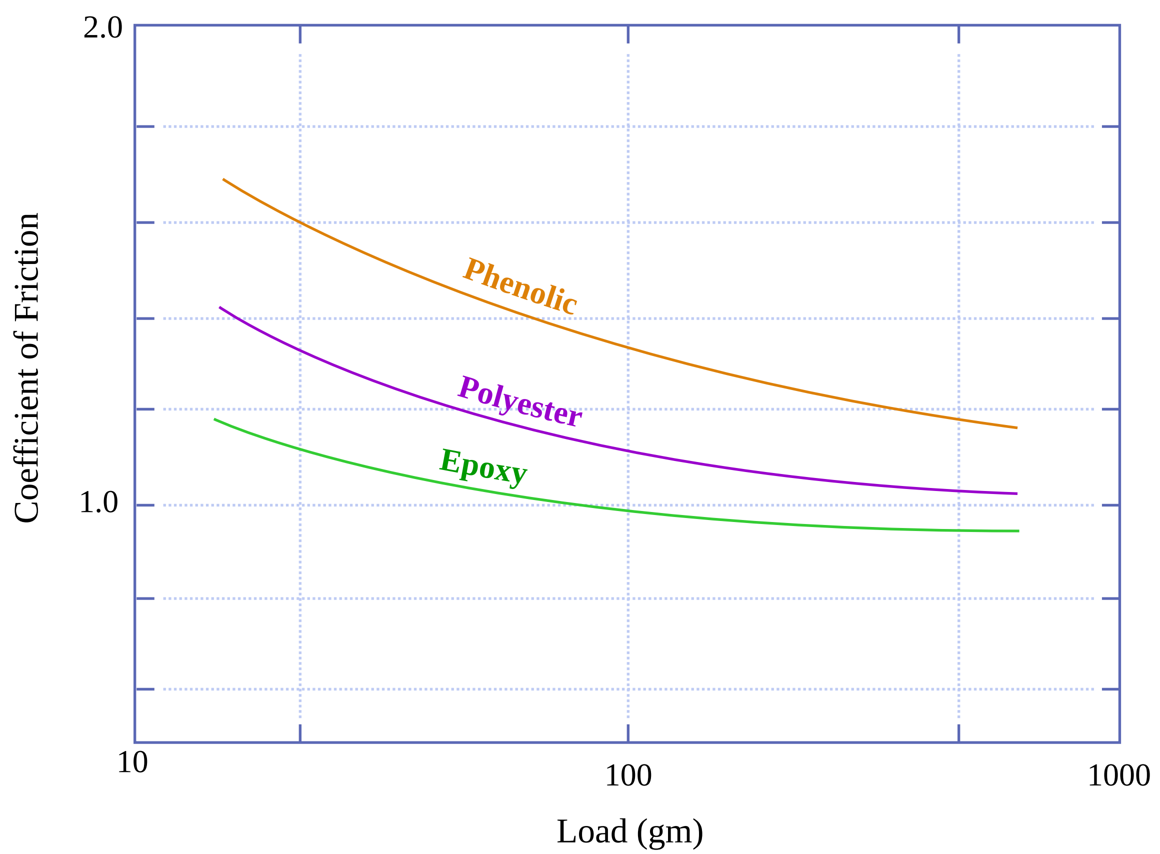


Figure by MIT OCW. After Pinchibeck, P. H. "A Review of Plastic Bearings." *Wear* 5 (1962): 85-113.

Is the friction coefficient constant?

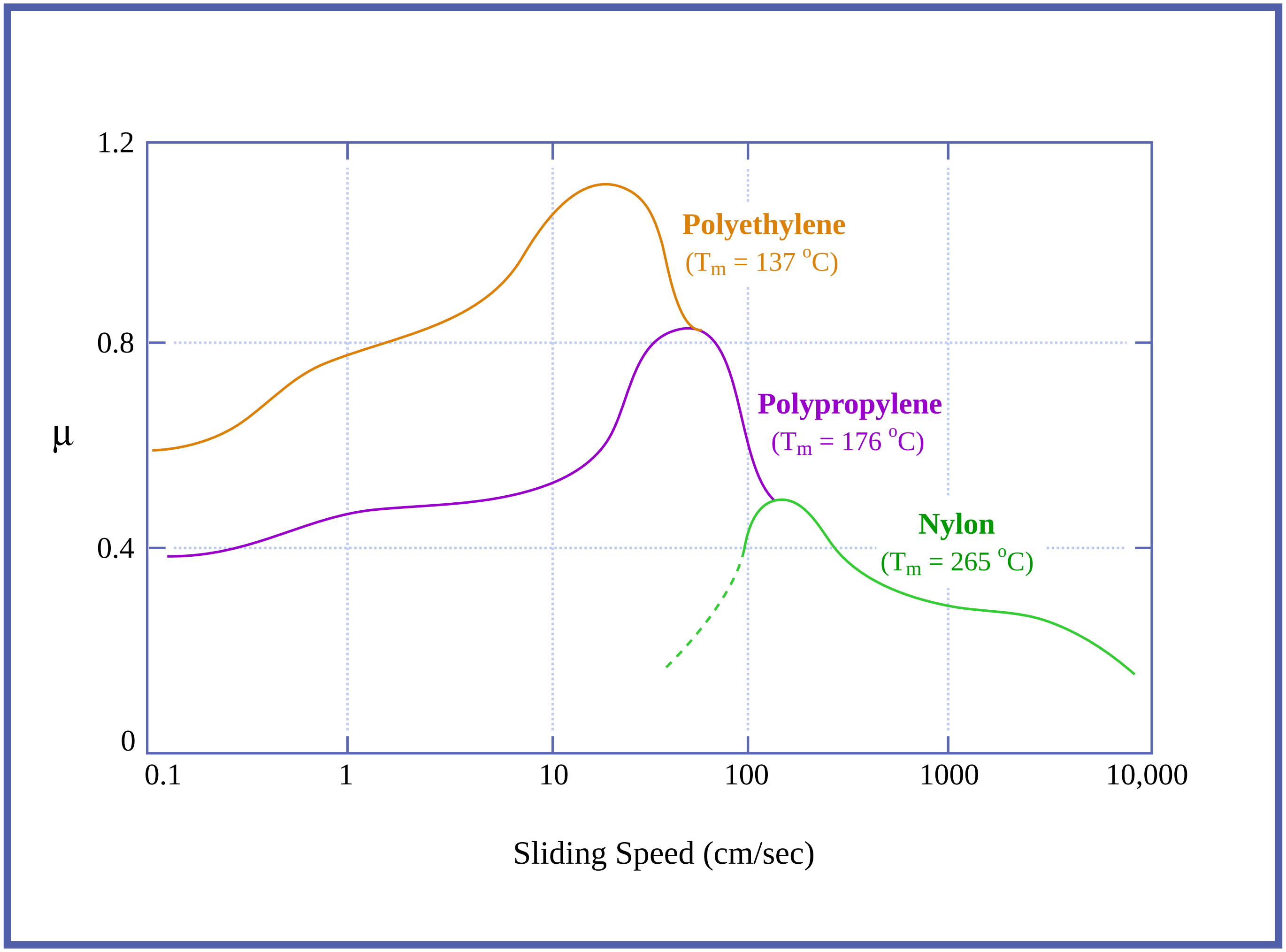


Figure by MIT OCW. After McLaren and Tabor, 1963.

Scale issues in tribology

Table 2.1 Scales in Tribology and Typical Values
(From Kim, 2000)

Scale	Range of friction Coefficient (μ) & wear coefficient (k)	Appli cations
10^{-4} m	$\mu = 0.4 \sim 1$ $k = 10^{-4} \sim 10^{-2}$	machinery brake, tools
10^{-6} m	$\mu = 0.001 \sim 0.2$ $k = 10^{-7} \sim 10^{-5}$	lubrication roller bearing
10^{-8} m	$\mu = 0.1 \sim 0.6$ $k = 10^{-7} \sim 10^{-5}$	head/d isk MEMS
10^{-10} m	$\mu = 0.001 \sim 10$ $k \sim 0$	?

How do we measure friction?

Macroscale Friction Test

Friction tester under constant normal load

Geometrically constrained system

Microscale and Nanoscale Friction Test

Atomic force microscope (AFM)

Scanning probe microscope (SPM)

etc.

Friction at Nano- and Micro-scale Contacts

- Important in hard disk

- Nanoscale contacts

  ~ 10 nm

  Interatomic forces

  $\mu \sim 0.07$ (MD simulation results)

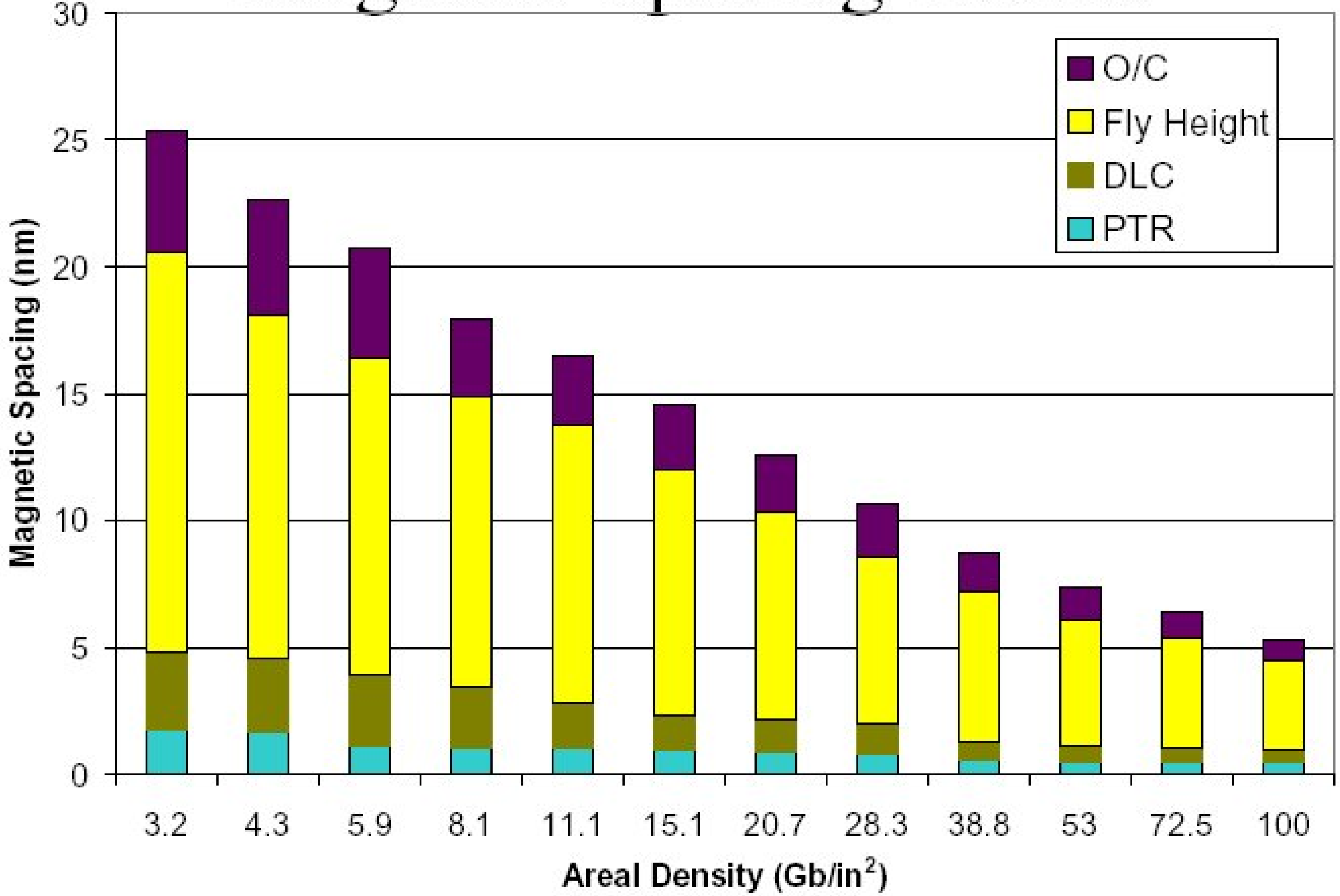
- Microscale

  ~ 10 μm

  $\mu \sim 0.7$ to 1

  Surface energy, meniscus, and adhesion at the interface

Magnetic Spacing Trends



Ref : www.tomcoughlin.com

Magnetic Spacing Requirement

Areal density (Gb/in^2)	Magnetic spacing (nm)	Disk overcoat thickness (nm)	Flying height (nm)	PTR+lube nominal value (nm)	Slider overcoat thickness (nm)
4.5	45.7	6.8	28.5	4.32	6.2
6.0	40.6	5.9	25.4	3.81	5.4
7.4	36.3	5.3	22.2	3.81	4.9
9.5	32.0	4.7	19.2	3.81	4.3
12	28.2	4.1	16.4	3.81	3.8
15	24.9	3.6	14.5	3.81	3.0
20	21.9	3.0	13.4	3.35	2.2
30	20.8	2.8	13.0	3.20	1.9
40	19.6	2.6	12.2	3.05	1.8
60	18.1	2.4	11.7	2.40	1.6
100	10.0	2.0	6.0	1.00	1.0

Ref. : A.K. Menon, "Interface tribology for 100 Gb/in^2", Tribology International, vol. 33, pp. 299–308 (2000)

Seagate has demonstrated area density demonstration of more than 100 billion data bits per square inch (100 Gigabits per square inch) using a fully integrated magnetic recording head and multi-layer antiferromagnetic coupled (AFC) disc.

The demonstration was the result of collaboration between Seagate's Recording Heads, Recording Media, Research, and Advanced Concepts organizations.

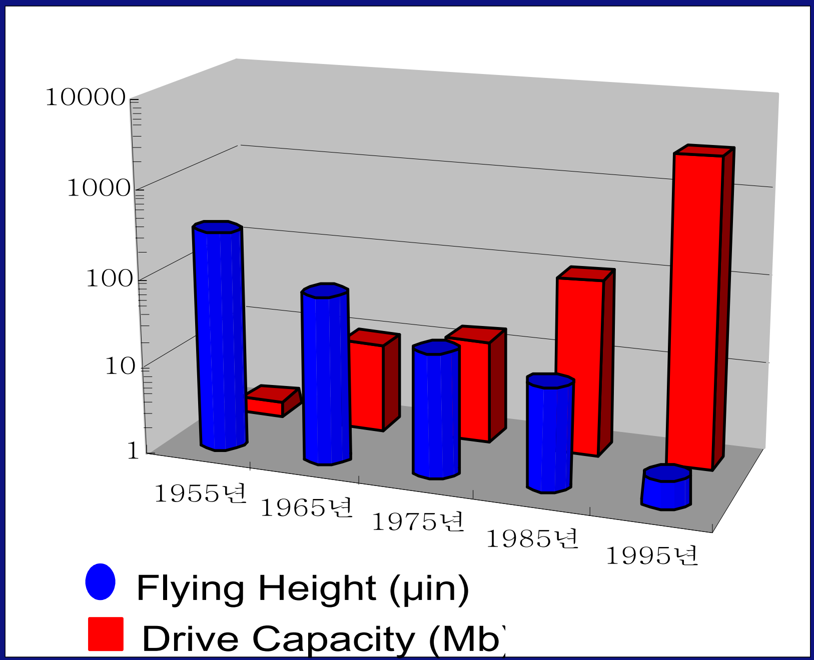
Recording components consisted of a focused ion beam (FIB) trimmed fully integrated read/write head flying at a nominal head/media separation of 0.55 microinches over an advanced AFC disc.

Technical parameters were as follows:

Areal Density:	101 Gb/in2
Track Density:	149k TPI
Bit Density:	680k BPI
Data Rate:	256 Mb/s
Bit Aspect Ratio:	4.6
On track raw error rate:	5 X 10-5
Raw error rate @ 5% squeeze and 10% OTC:	1 X 10-4

See http://www.seagate.com/newsinfo/technology/d4g.html

Challenge of HDI Technology



- **Decreasing head/disk gap**

  50nm → near-contact → contact

- **Reliability problem**

  MTBF > 1 million hours

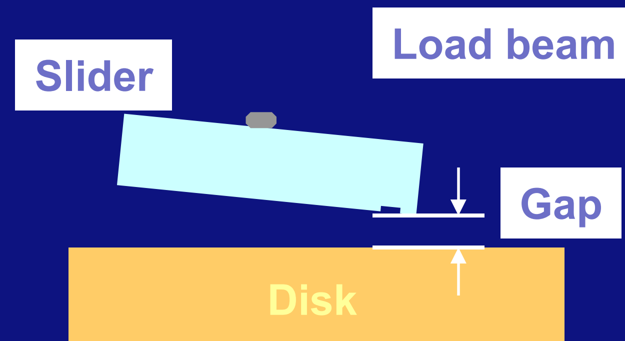
  50,000 Contact-Start-Stop cycles

Minimization of surface damage and frictional interaction ***(From Kim 2000)***

See Y.S. Park, D.H. Hwang, and D.E. Kim, "Characteristics of Head/Disk Interface Durability", Proceedings of the First Workshop on Information Storage Device, Seoul, Korea, 1999, pp. 102-109.

Microtribological Issues in HDI

High density HDD



Stiction problem
Friction problem

Surface damage
Wear particle contamination

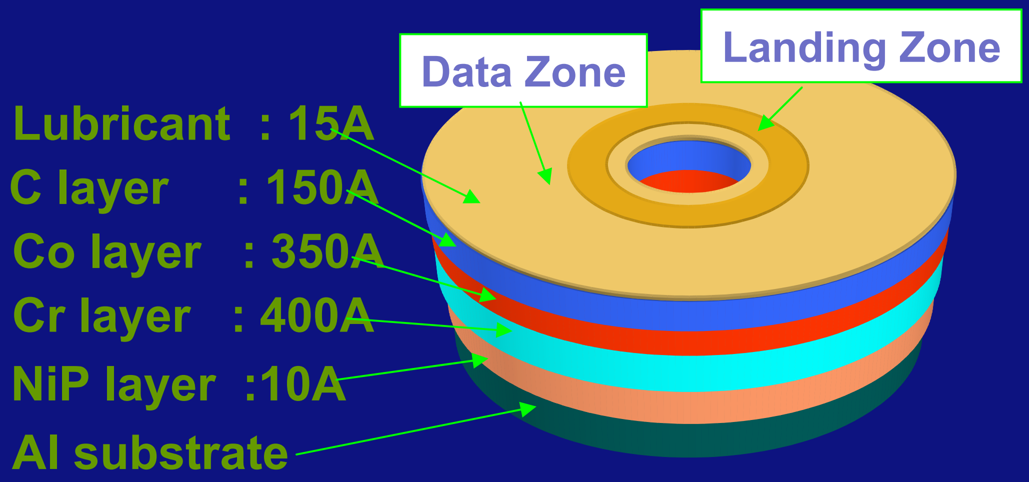
Reliability
Durability

Need to optimize the tribological characteristics of HDI

Tribological Optimization of HDI

- Design parameters:
  - Material combination
  - Coating technique (type, thickness)
  - Surface topography, shape of slider
- Operating conditions:
  - Applied load
  - Speed
  - Environment

Ra = 1nm



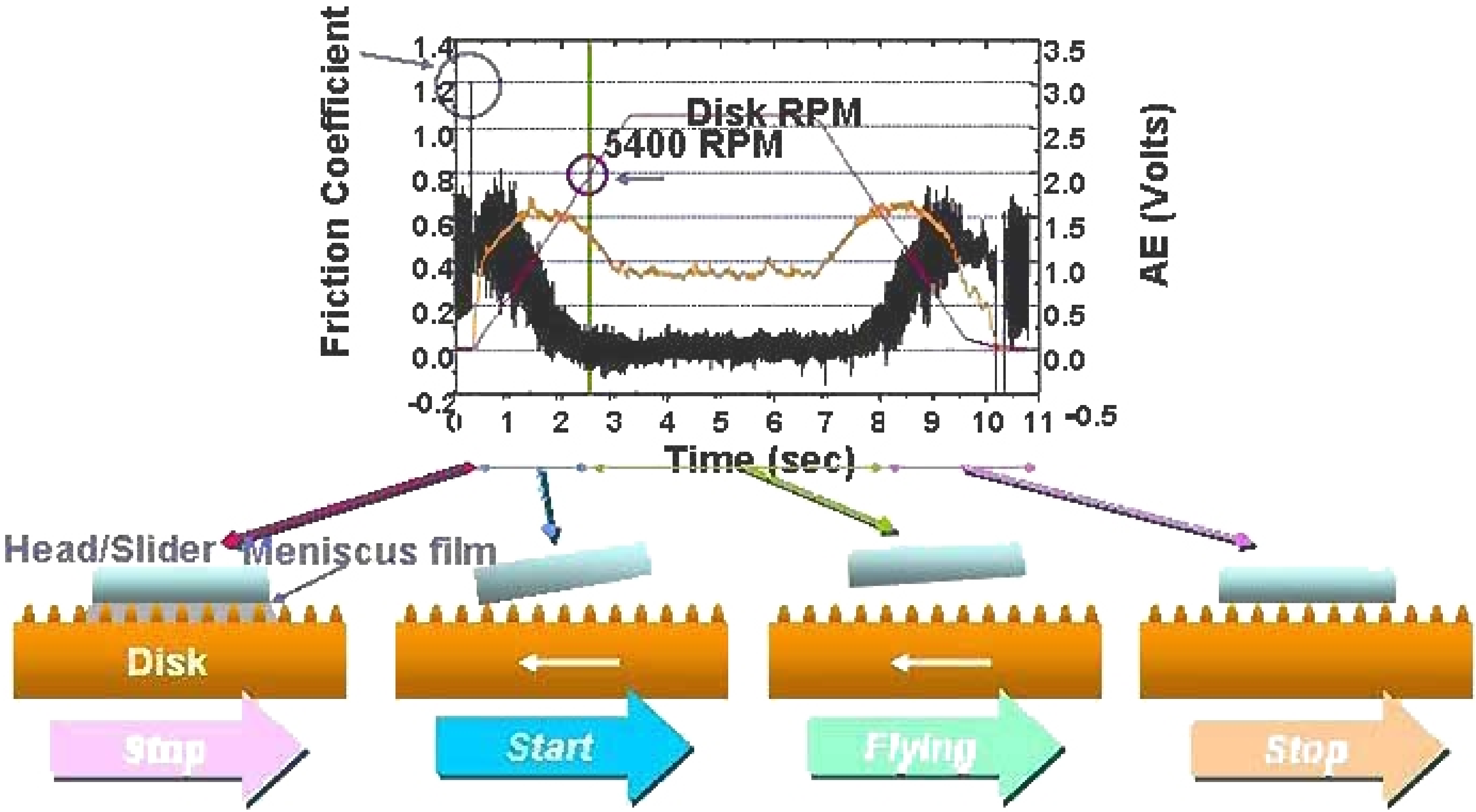
Laser Zone Textured Disk Media

Photos removed for copyright reasons.
See D.E. Kim, J.W. Park, D.K. Han, Y.S. Park, K.H. Chung, and N.Y. Park, "Strategies for Improvement of Tribological Characteristics at the Head/Disk Interface" IEEE Transactions on Magnetics, 37:2 (March 2001).

$$f_b = \frac{v}{s}$$

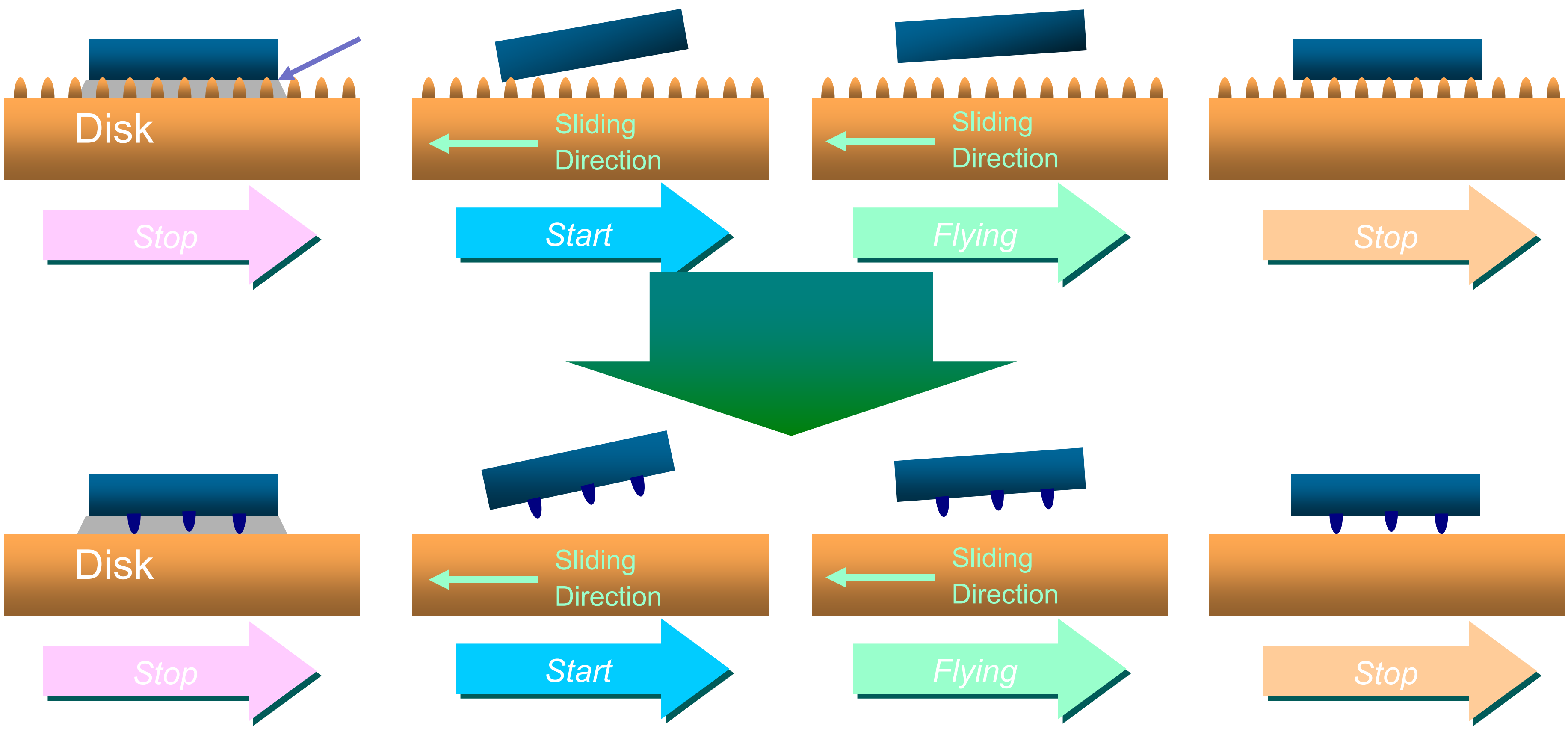
(f_b : frequency due to bump pattern, v : disk vel., s : track direction between bumps

Contact-Start-Stop Test



See Chung, K. H., Han, D. K., Park, J. W., Lee, S. C., Kim, D. E., "Feasible Method for Accelerated Testing of HDI Tribological Behavior", 11th Annual Symposium on Information Storage and Processing Systems, Santa Clara, USA, June 23, 2000.

Principle of Stiction Free Slider



CSS Test Result for Stiction Free Slider (From Kim 2000)

Slider without mechanical bump on data zone

Graphs removed for copyright reasons.
See D.E. Kim, J.W. Park, D.K. Han, Y.S. Park, K.H. Chung, and N.Y. Park, "Strategies for Improvement of Tribological Characteristics at the Head/Disk Interface" IEEE Transactions on Magnetics, Vol. 37, No. 2, Mar, 2001.

High stiction force due to large contact area

CSS Test Result for Stiction Free Slider

(From Kim 2000)

Slider with mechanical bump on data zone (3.5 gf preload)

Graphs removed for copyright reasons.
See D.E. Kim, J.W. Park, D.K. Han, Y.S. Park, K.H. Chung, and N.Y. Park, "Strategies for Improvement of Tribological Characteristics at the Head/Disk Interface" IEEE Transactions on Magnetics, Vol. 37, No. 2, Mar, 2001.

Low stiction force due to small contact area

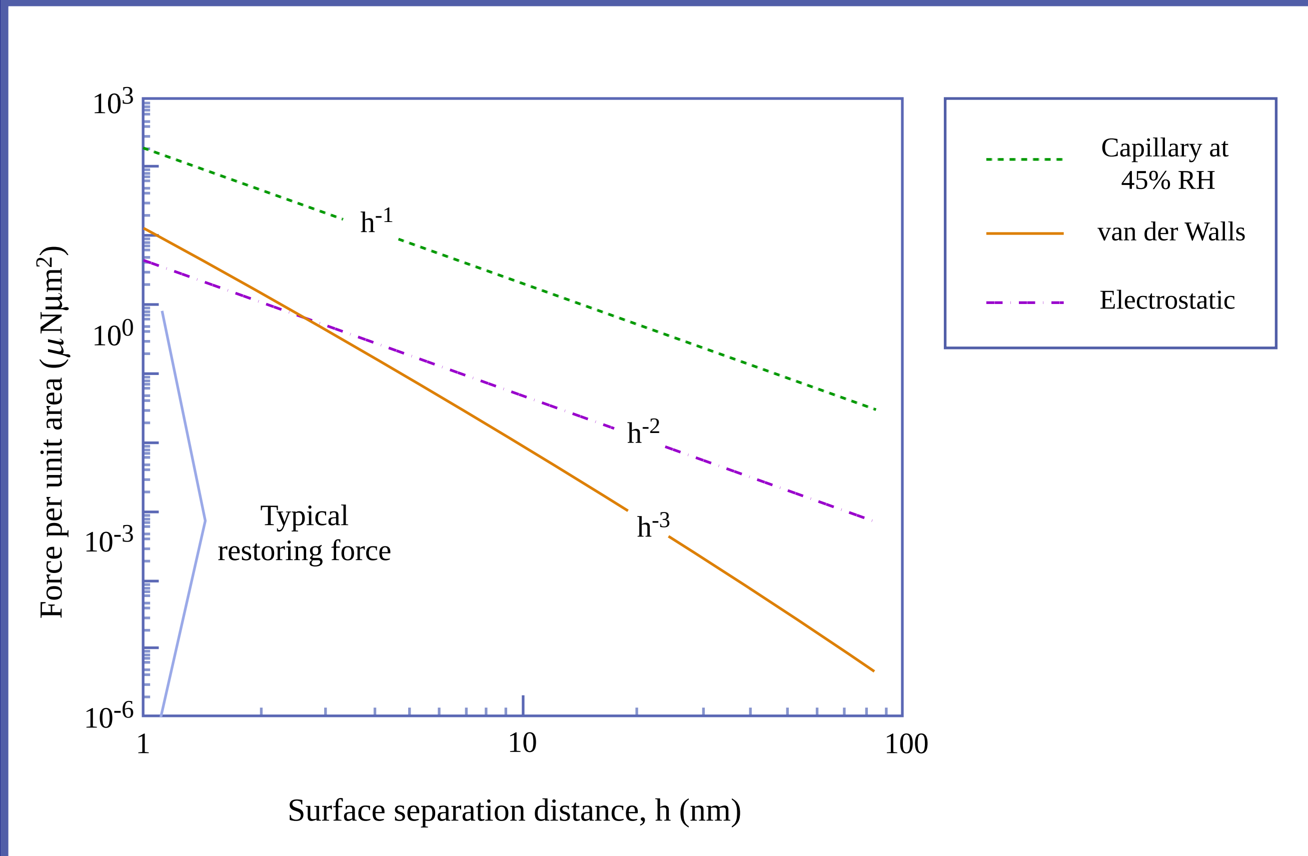
MEMS (Micro-Electro-Mechanical System) (From Komvopoulos 1996)

• **Attractive forces act on atomically flat surfaces**

Attractive forces - Capillary, Electrostatic, van der Waals

• **Capillary force**
- strongest attraction

• **Restoring force**
- much smaller than attractive force



Adhesion (stiction) reduction is very important in MEMS

Tibological issues in MEMS

Attractive forces act on interfaces - Capillary, Electrostatic, van der Waals

a. Release stiction

- **micromachine stiction during release etch process in fabrication**
- **hydrogen bridging**

b. In-use stiction

- **caused by operation and environmental condition**

c. Sliding wear and contact fatigue

- **caused by intermittent contact due to small clearance**

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 Macro-scale Sliding Contacts

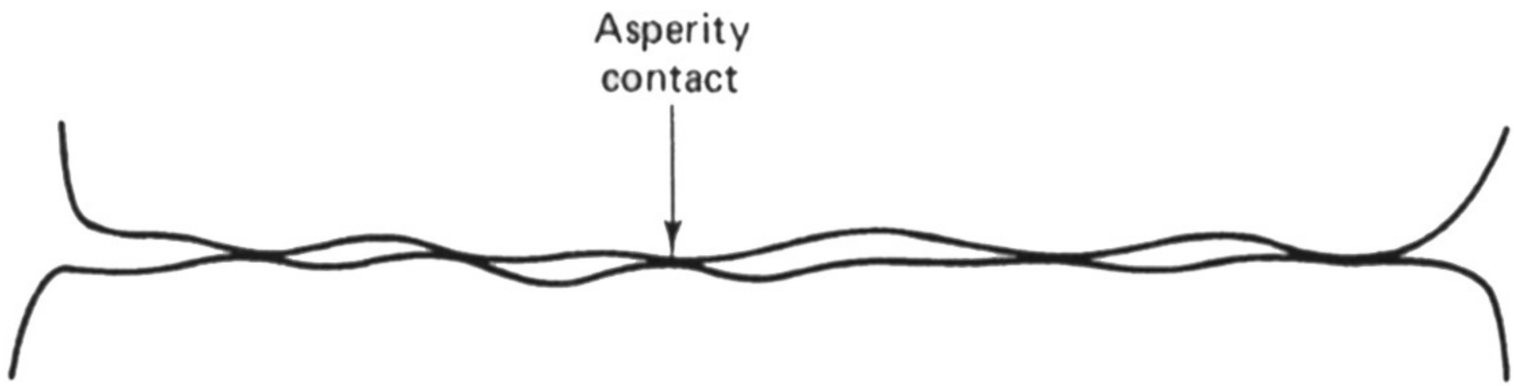
Macroscale

>100 μm

$\mu \sim 0.4$ to 0.7

Plastic deformation

Friction at Macro-scale Sliding Contacts
Adhesion Model



Source: Figure 1.4, Suh (1986)

Friction at Macro-scale Sliding Contacts
Adhesion Model

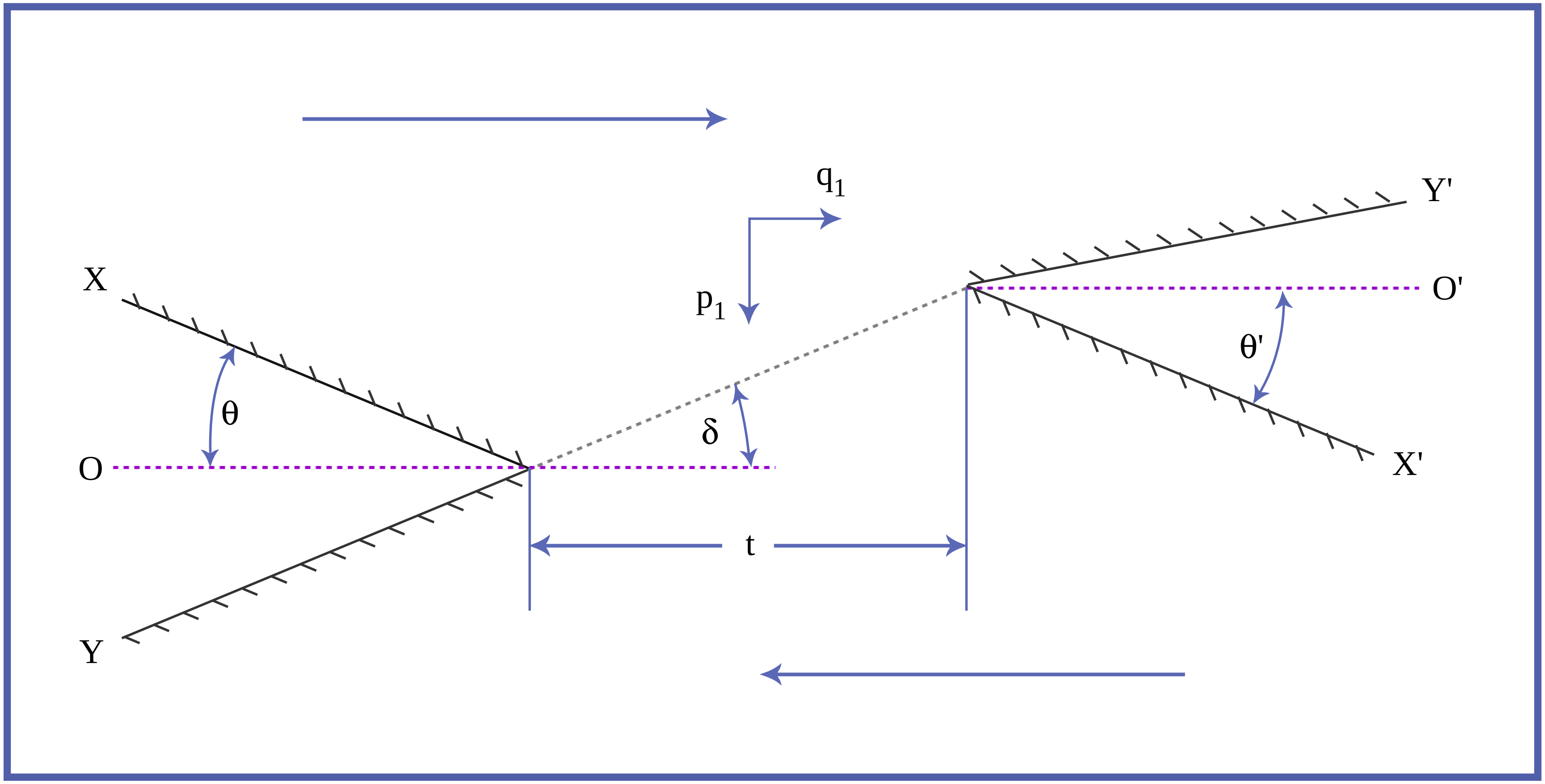


Figure by MIT OCW. After Green, A. P. "The Plastic Yielding of Metal Junctions due to Combined Shear and Pressure." *Journal of the Mechanics and Physics of Solids* 2 (1955).

Friction at Macro-scale Sliding Contacts
Adhesion Model

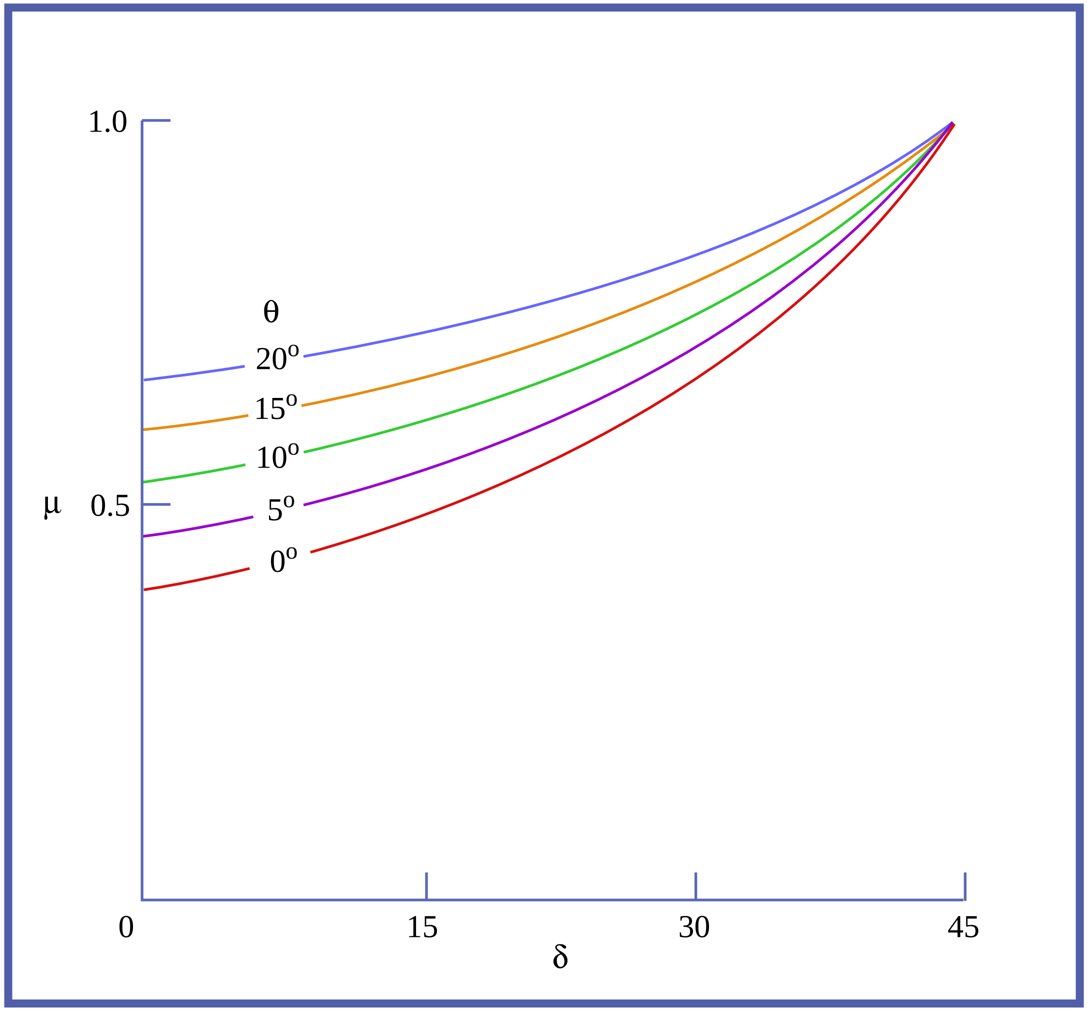
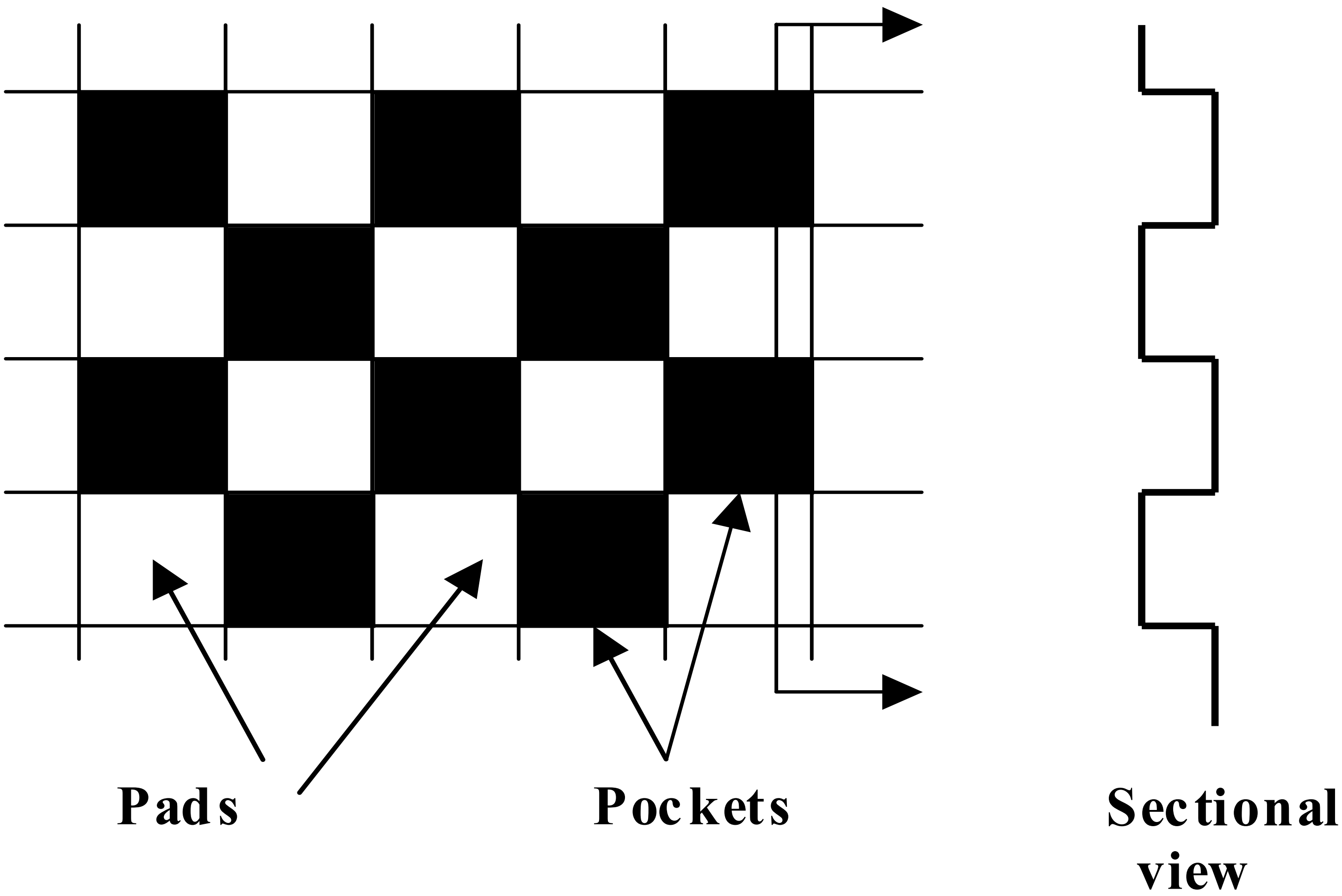


Figure by MIT OCW. After Suh, N. P., and H. C. Sin. "The Genesis of Friction." *Wear* 69 (1981): 91-114.

Friction at Dry Sliding Interface
Undulated Surface for Elimination of Particles



Friction at Macro-scale Sliding Contacts
Surface Topography and contacts

- Roughness, waviness, etc.
- Important in well lubricated interfaces with little wear
- Manufacturing operations -- acceptable quality of machined surfaces
- Not important when wear takes place or when particles are present

Friction at Macro-scale Sliding Contacts
Surface Topography and contacts

- Surface must be *designed* to achieve certain functional requirements

- Important to know the relationship between functions and surface topography (only limited understanding)

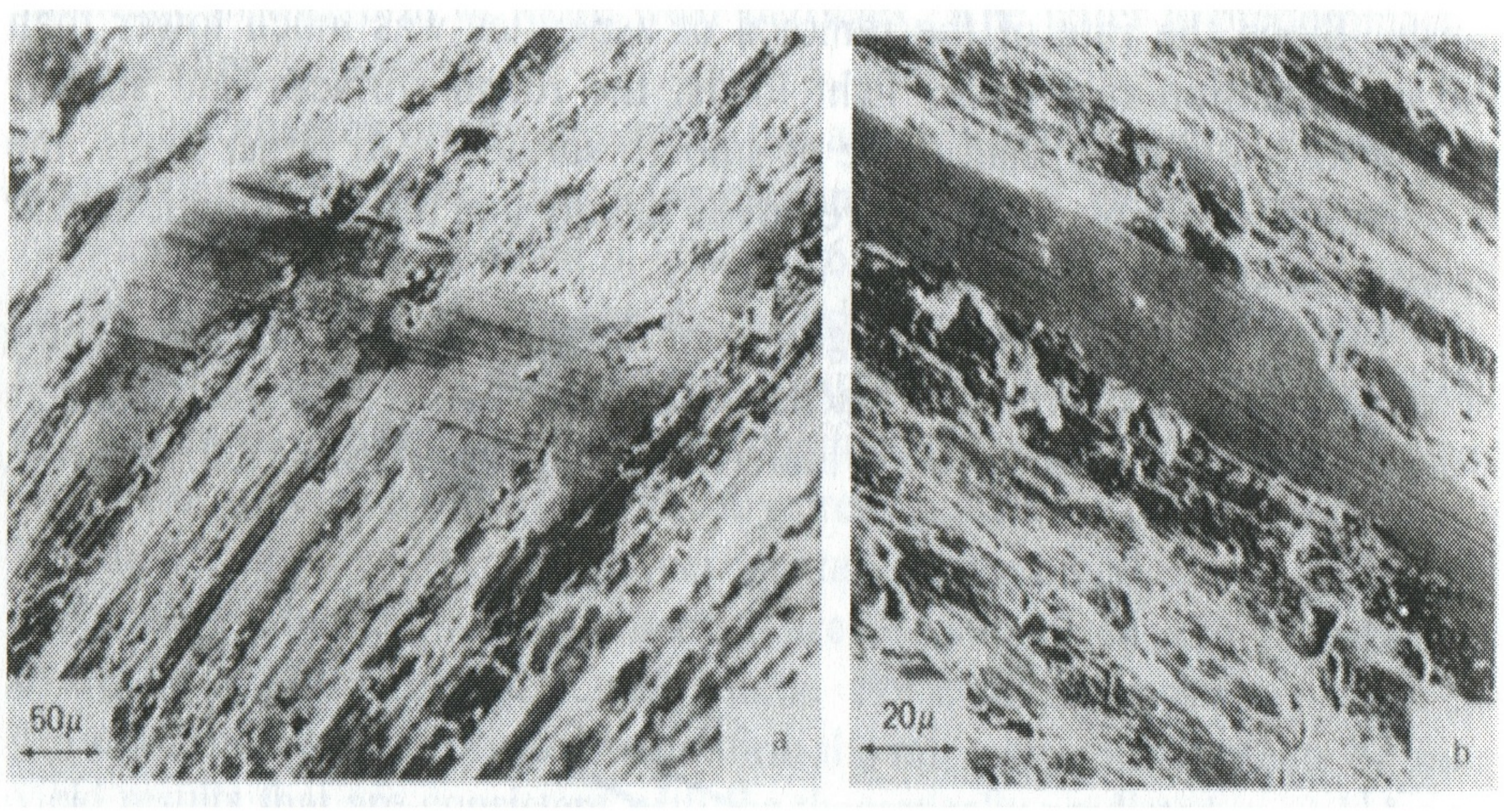
Friction at Macro-scale Sliding Contacts

Surface Topography and contacts

- Asperity contacts and particles

- Topography may change during sliding

Plastic deformation of the original asperities on machined AISI 1018 steel during cylinder-on-cylinder wear tests



Weight loss of AISI 1018 steel as a function of sliding distance and normal load

Load = 75g

Load = 300g

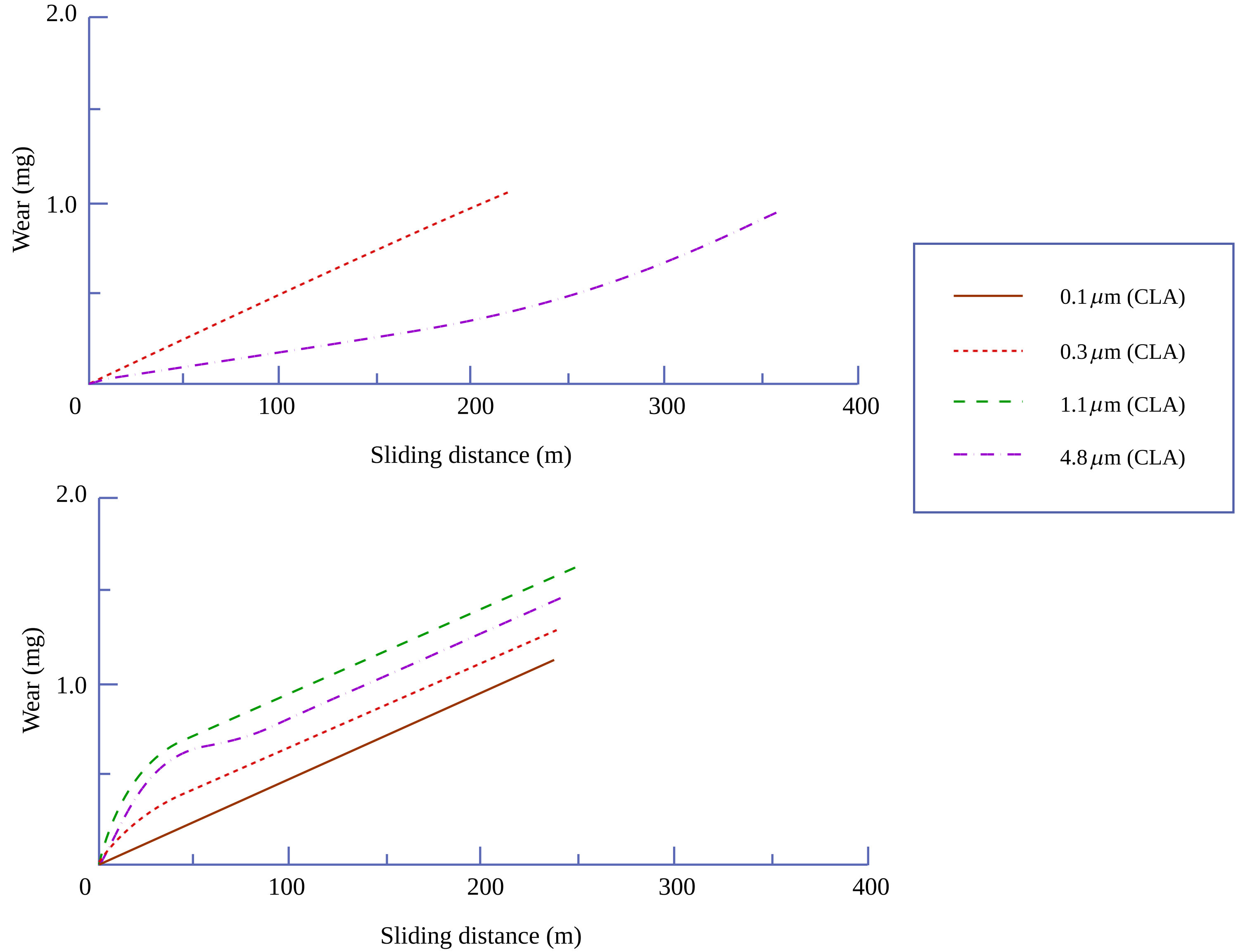


Figure by MIT OCW. After Abrahamson et al., 1975.

Surface Topography and contacts

- Difference between the case of constant normal load and the geometrically constrained case

Surface Topography and contacts

- Number of asperity contacts:

$$n = \left(\frac{N}{H}\right)\frac{1}{A_a} = \left(\frac{N}{3\sigma_y}\right)\frac{1}{A_a}$$

Friction at Macro-scale Sliding Contacts
Surface Topography and contacts

- What happens to n when the load increases?

$$N = \text{normal load} = \sum n\ A_i\ H$$

Abrasive Wear Model

$$K = \frac{3VH}{LS}$$

Sliding Wear Model

$$K = \frac{3VH}{LS} = \frac{V}{A_p S} = \frac{\text{Worn volume}}{\text{volume of the plastically drormed zone}}$$

Fretting Wear

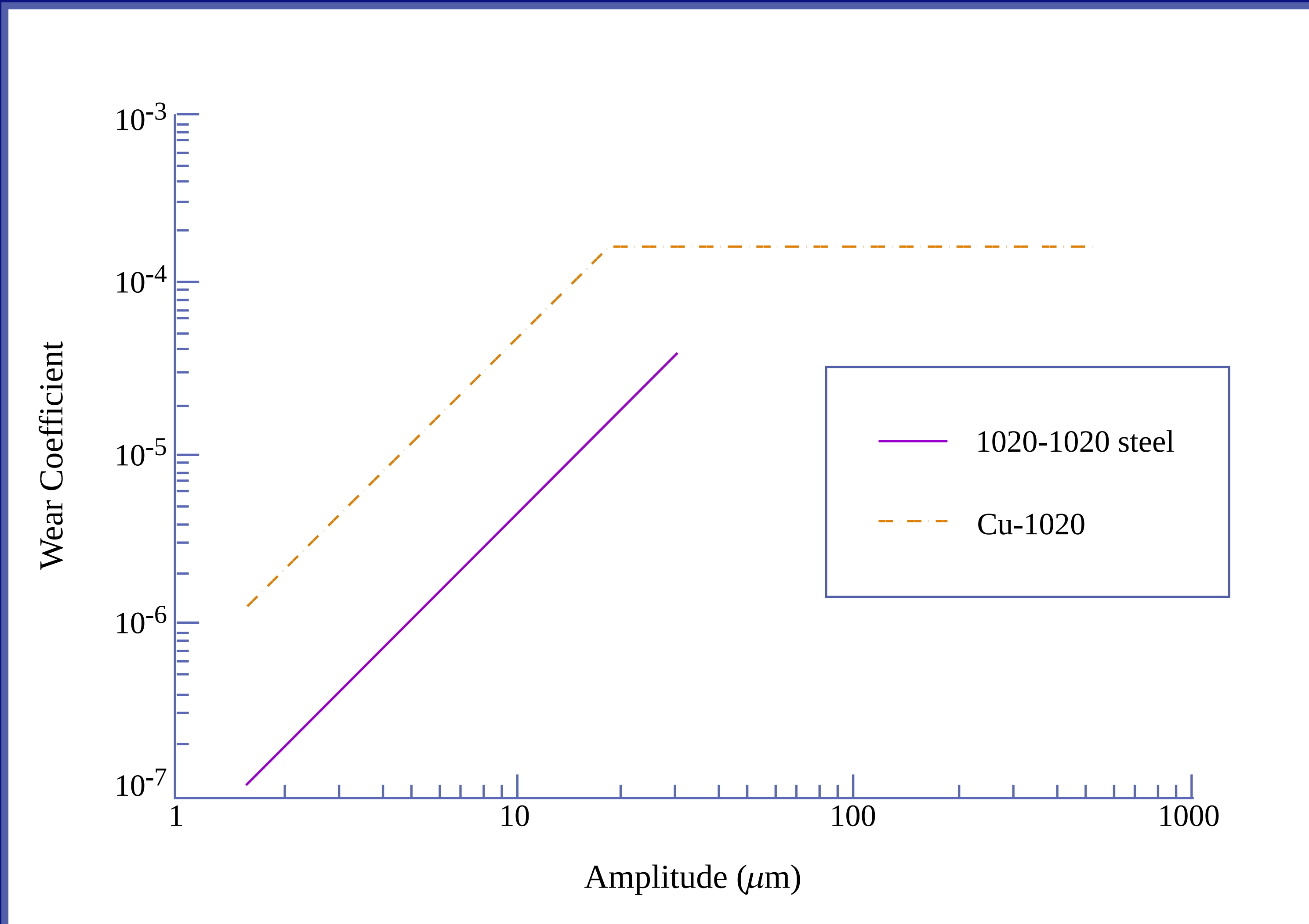


Figure by MIT OCW. After Stowers, 1974.

Abrasive Wear Model

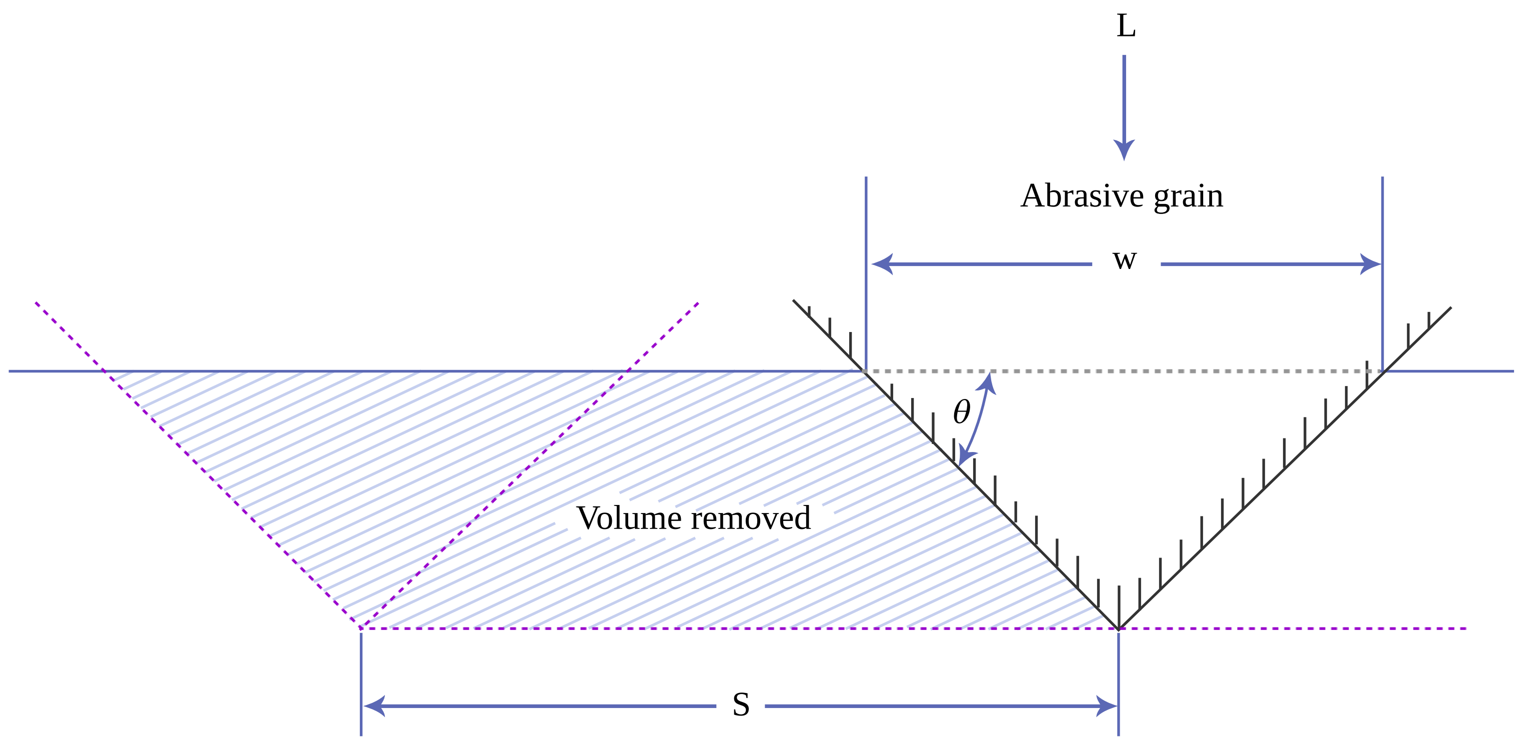


Figure by MIT OCW. After Rabinowicz, 1965.

Ductility vs. Abrasive Wear Rates

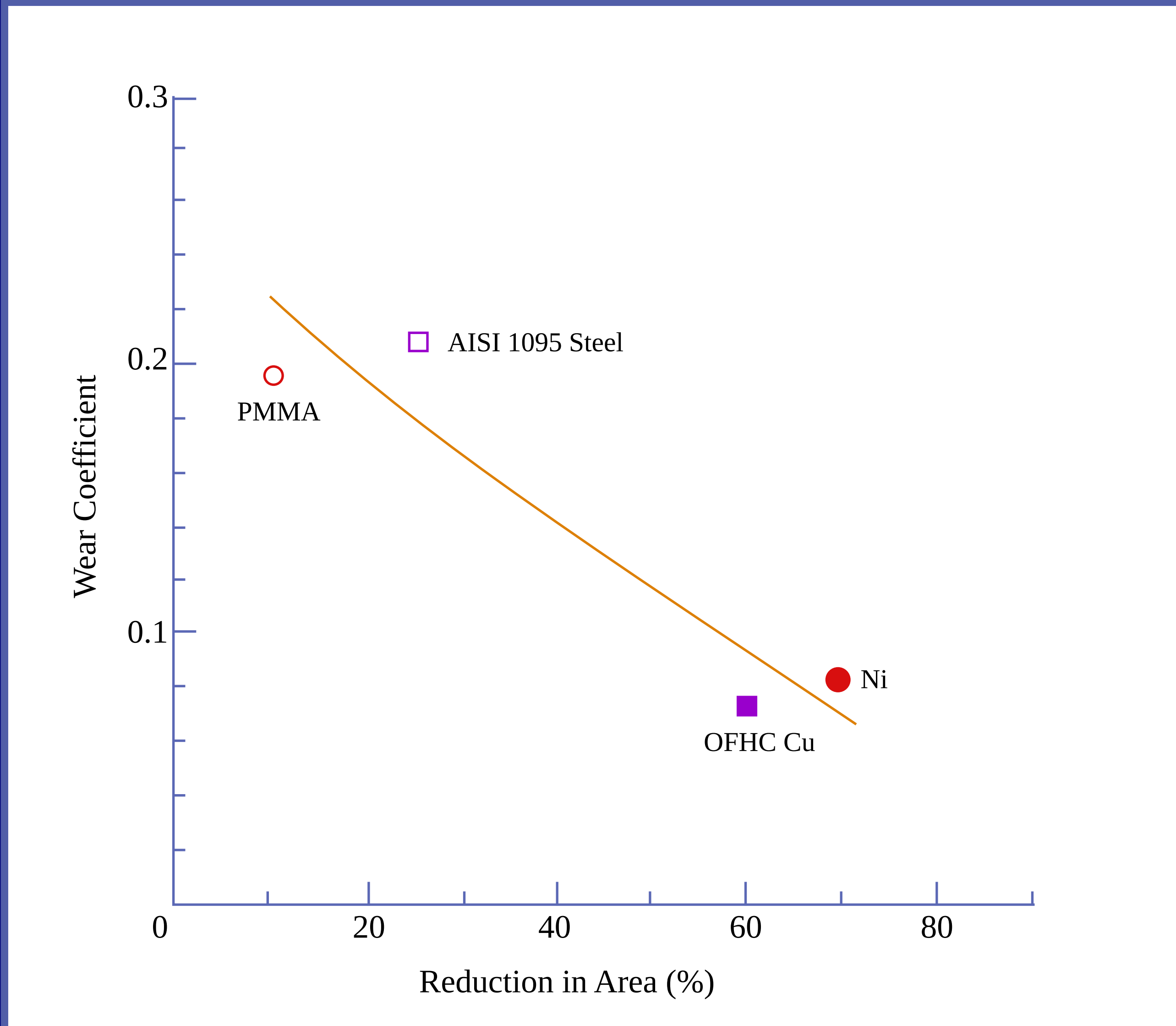


Figure by MIT OCW. After Sin et al. "Abrasive Wear Mechanisms and the Grit Size Effect." *Wear* 55 (1979): 163-190.

Wear Coefficient of Abrasive Wear

$$K = \frac{3\mu VH}{\mu LS} = 3\mu \frac{Vu}{FS} \approx \frac{Vu}{FS} \approx \frac{\text{work done to create abrasive wear particles by cutting}}{\text{external work done}}$$

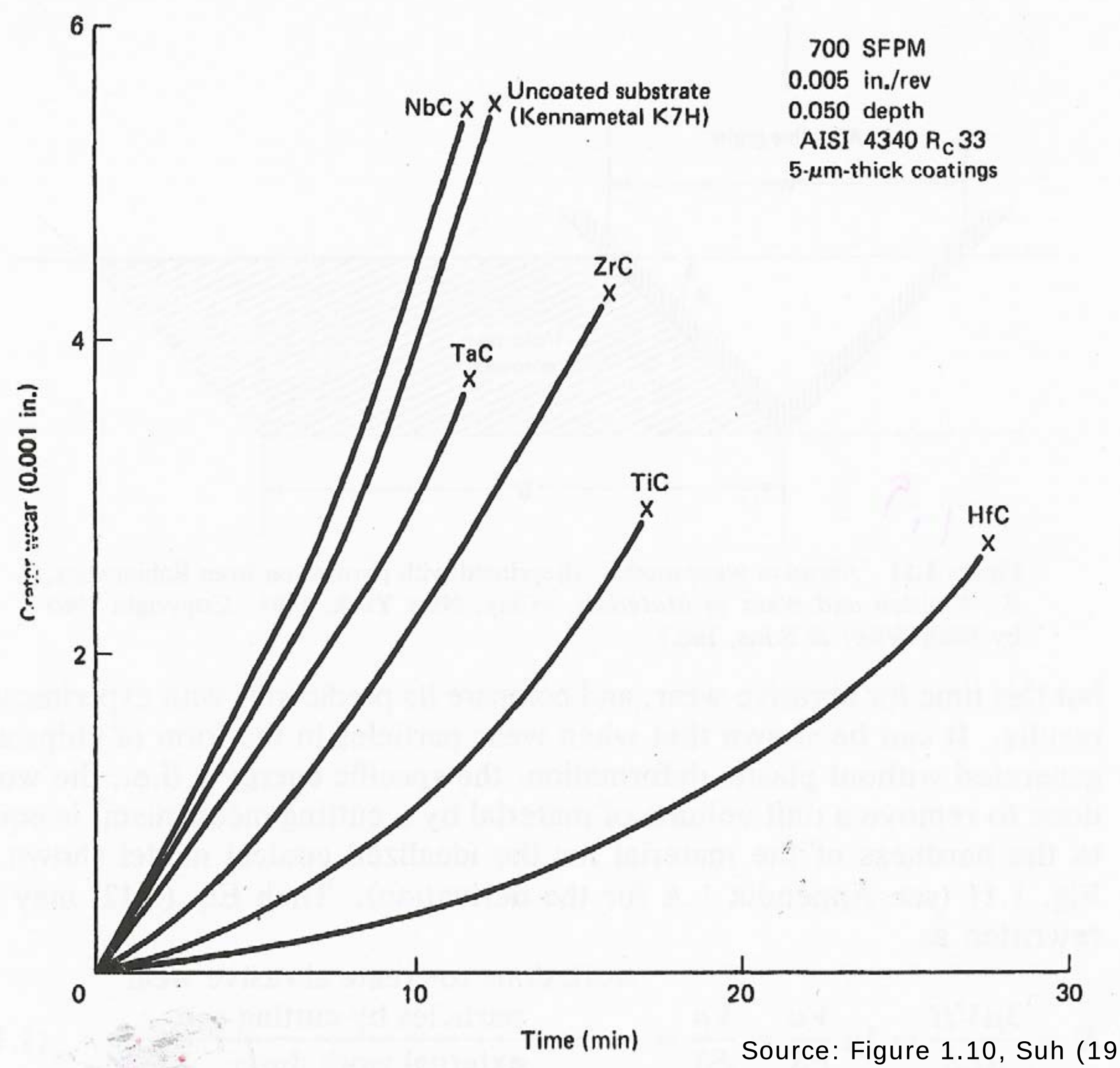
Thin Film structure

(Bhushan, et al., 1995; Yoshizawa, et al, 1993, Klein, et al., 1994)

Image removed due to copyright reasons.

Carbide Tools Cutting 4340 Steel

Rc 33 at 700 fpm



Source: Figure 1.10, Suh (1986)