UNIT 1: Introduction to Tribology, Surfaces, Friction and Wear

Lecture by

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Plan of Talk

- Tribology, its Historical Development
- Applications
- Basic Concept of Friction
- The various types of friction, laws, modern theories.
- Know about dry sliding friction, temperature of sliding surface.
- Understand mechanism of rolling friction, friction instabilities.

Tribology

(from the Greek word 'tribos' meaning rubbing)

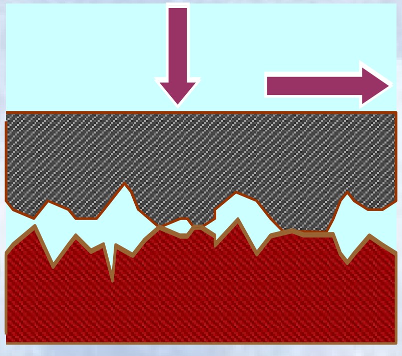
The term *'tribology'* was coined in 1966 and it is defined as *"the science and technology of interacting surfaces in relative motion"*.

It encompasses the study of:

Friction

Wear

Lubrication

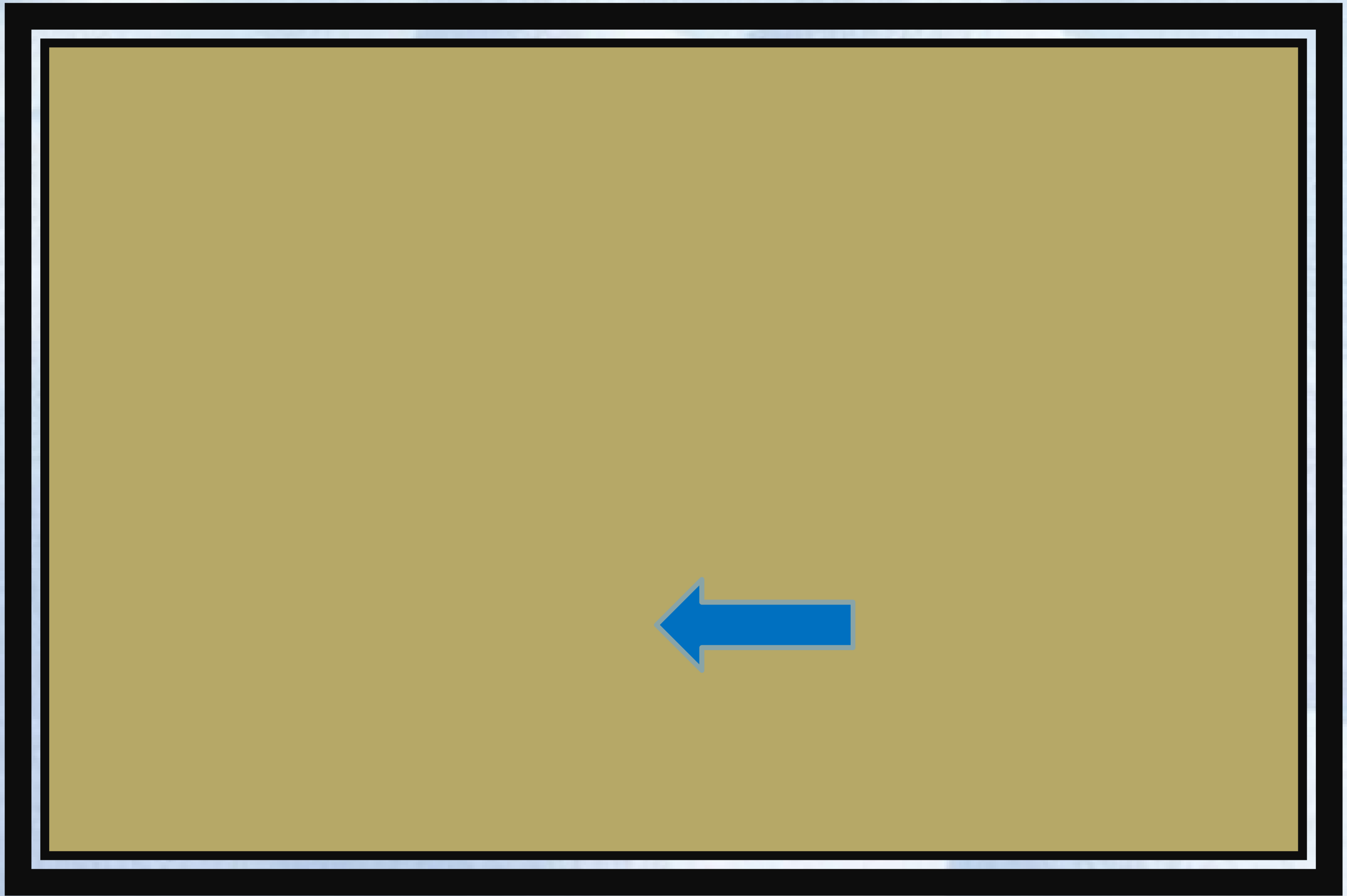


A Concise History of tribology

1880 BC	1400 – 1800 A.D	1800 – 1950 A.D	20th Century and beyond
Basic knowledge of frictional phenomena	**Studies and rules governing friction developed.**	**Scientific studies of friction and wear and advancement of other Sciences**	**1966** → **Tribology** → **Macro-tribology** / **Nano-tribology**
Archeological findings from the Ancient **Roman** and **Egyptian** Empires -water lubricated sleds	**Da Vinci** –1500 A.D -Coefficient of friction Guillaume **Amontons** -Friction force of resistance **Coulomb** 1785 A.D -Static and kinetic friction	**Industrial revolution** 1850 AD **Beauchamp Tower** 1886 -Hydrodynamic lubr. (Bearings) **Ragar Holm** 1946 -Study of wear	**1969 - 2014** Emerging of proximal probes (microscopes and the surface force apparatus), and computational techniques for simulating tip – surface interactions and interfacial properties.

In ancient times, on the order of about 500,000 B.C., early humans learned that by rubbing sticks together with great force they could create fire.

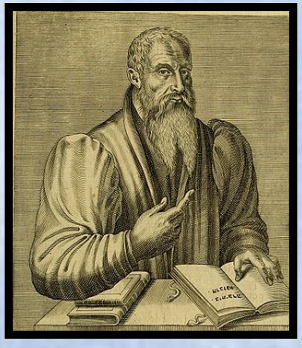
Around 3500 B.C. we learned that rolling motion required less effort than sliding, and the wheel was invented.



An Egyptian painting dating back to 1880 B.C. depicts workers dragging a sled containing a heavy statue.
One worker pours a liquid on the ground just before the runners to make the going easier.

1495-1950: Laws of friction are developed

- In 1495 **Leonardo** formulated the two basic laws of friction: Friction is independent of contact area, and friction is proportional to load. For years, he never got credit for his work, as he did not formally publish his observations.



- Some 200 years later, in 1699, **Guillaume Amontons** (1663-1705) rediscovered these two basic laws. He reasoned that friction was primarily the result of work done to lift one surface over the roughness of the other, resulting in deformation and wear of the surfaces.

- **Sir Isaac Newton** (1642-1727), in studying and creating the basic laws of motion, added that moving friction was not dependent on speed or velocity, thus formul- -ating the third law of friction. All these observations were made in the macro scale.

•In 1950, **Phillip Bowden** and **David Tabor** gave a physical explanation for the observed laws of friction. They determined that the true area of contact, which is formed by the asperities on the surface of a material, is a very small percentage of the apparent area. As the normal force increases, more asperities come into contact and the average area of each asperity contact grows.

•As our ability to analyze surface contacts at the monomolecular level has developed, we are learning that the "macro" laws don't necessarily hold and that the processes of interaction are quite complex.

•"*Amontons Laws of Friction are the first quantitative description of a tribological process. Attempts (theories, mechanisms, models) to explain these laws have been central to the development of tribology*." —**Bill Needelman**, Filtration Science Solutions.

1883-1905: Principles of hydrodynamic lubrication are elaborated

•In 1883, the elucidation of hydro-dynamic lubrication began in England, with testing done by **Beauchamp Tower**. He used a specially constructed test rig for journal bearings, simulating the conditions found in railway axle boxes.

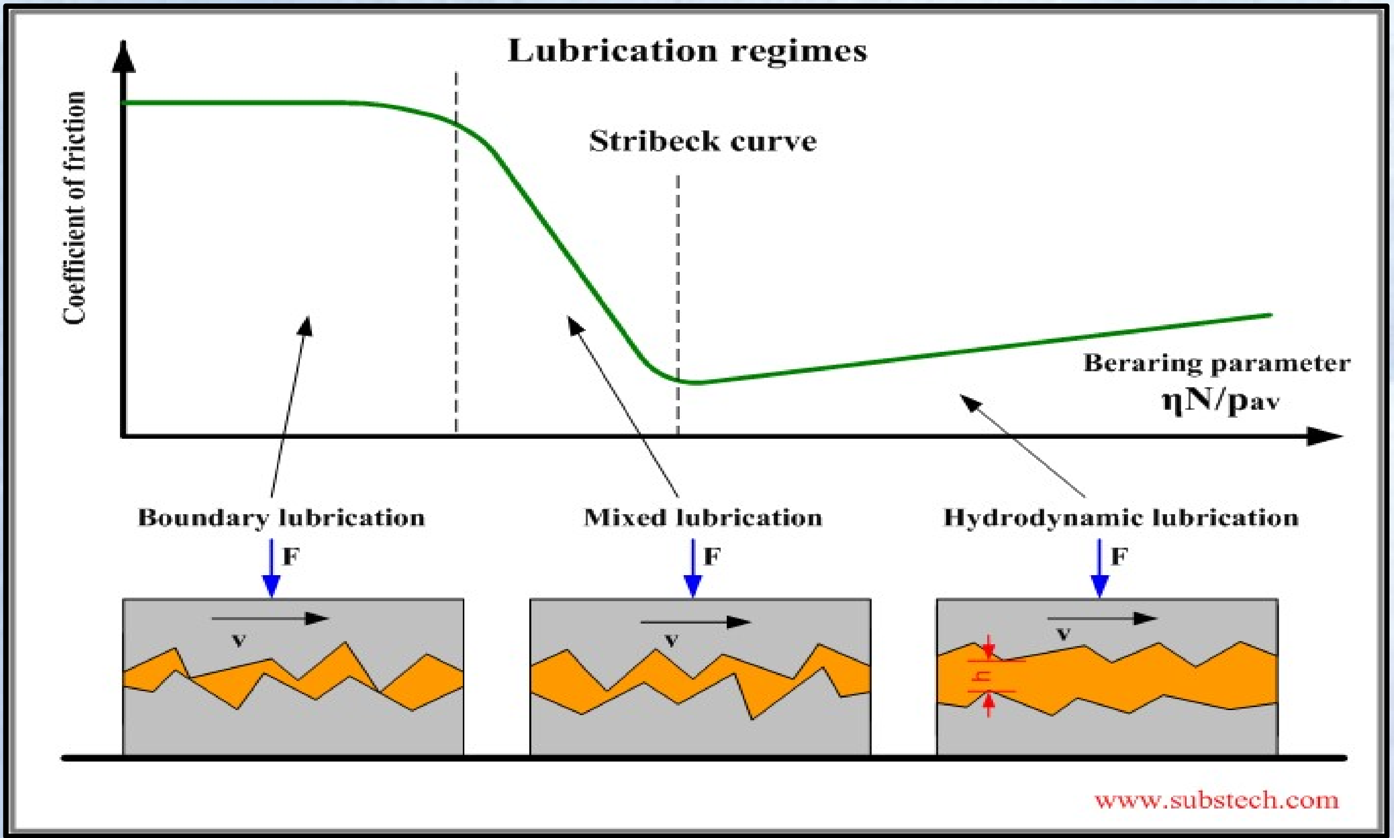
•In the final phase of his research, Tower decided to drill an oil feed hole in the bearing. The oil was found to rise upwards in the feed hole and leak over the top of the bearing cap. He then installed a pressure gauge and found it to be inadequate for measuring the high pressure levels. This result proved the existence of a fluid film that could carry significant loads.

•In 1886 **Osborne Reynolds** published a differential equation describing this pressure buildup of the oil in the narrow converging gap between journal bearing surfaces. This equation, a variation of the Navier-Stokes equations resulting in a second-order differential equation, was so complex that many years passed before it was solved for journal bearings.

•In 1902 **Richard Stribeck**, published the Stribeck curve, a plot of friction as it relates to viscosity, speed and load.

•After the work of Tower and Reynolds, **Arnold Sommerfeld** refined the work into a formal theory of hydrodynamic lubrication in about 1905.

•A surface have tiny asperities that will contact if two plates are placed together. If one of the plates were to slide over the other, then friction would increase, the asperities would break and the surfaces would wear. In hydrodynamic lubrication, a fluid film separates the surfaces, prevents wear and reduces friction.

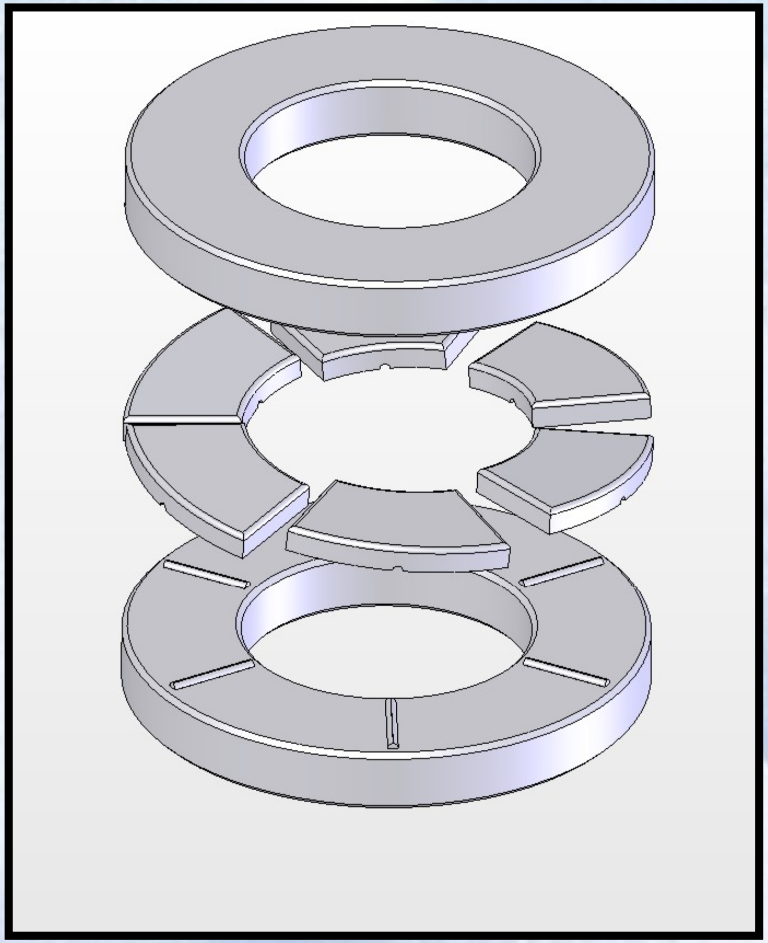


•The hydrodynamic film is formed when the geometry, surface motion and fluid viscosity combine to increase the fluid pressure enough to support the load. The increased pressure forces the surfaces apart and prevents surface contact. This is called hydrodynamic lift. Hydrodynamic bearings get load support by hydrodynamic lift.

•The most recognizable hydrodynamic bearings are slider bearings and journal bearings, both used extensively in machinery and vehicles—thanks to the development of hydrodynamic lubrication theory.

•"*The experiments of Beauchamp Tower formed the basis of modern-day hydrodynamic lubrication and inspired Osborne Reynolds to develop the Reynolds equation, which has remained at the center of fluid film lubrication to this day*." —**Martin Webster**, ExxonMobil R&E

•In 1905 fluid-film thrust bearings patented by Australian engineer **George Michell**. Michell bearings contain a number of sector-shaped pads, arranged in a circle around the shaft, and which are free to pivot. Michell's invention was notably applied to the thrust block of propellor driven ships. Their small size (one-tenth the size of old bearing designs), low friction and long life enabled the development of more powerful engines and propellers.

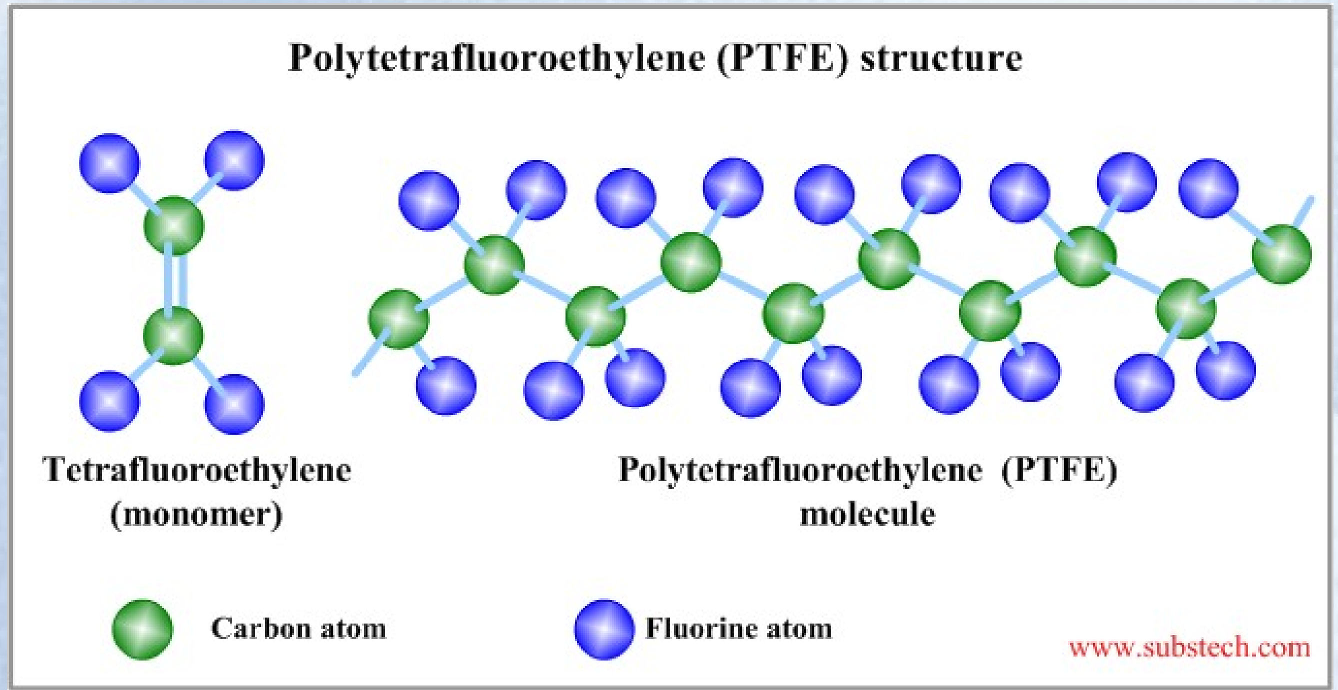


•In 1912 Dr. Albert Kingsbury invented the **hydrodynamic thrust bearing**.

•In 1922 understanding of **Boundary lubrication refined** by W.B. Hardy and I. Doubleday.

•1930s to 1940s The first **zinc dialkyldithiophosphates (ZDDPs)** began to be developed as anticorrosion agents and oxidation inhibitors. The antiwear activity of these molecules was recognized only later, in the 950s, at which point they became an integral part of many oil chemistries. To this day ZDDPs remain the backbone of antiwear additive technology.

•**PTFE**, the most famous of the self-lubricating coating materials, was discovered fortuitously during a project looking at tetrafluoroethylene as a refrigerant.



•In 1942 **Lithium grease** invented & rapidly became widely used multi-purpose grease

•In 1950 **Synthetic oils** introduced for usage in aviation.

•In 1950s **Fire Resistant Hydraulic Fluids** developed.

•In 1962 **Aluminium Complex grease** invented for high temperature applications.

•In 1960s **Multi-grade motor oils** introduced.

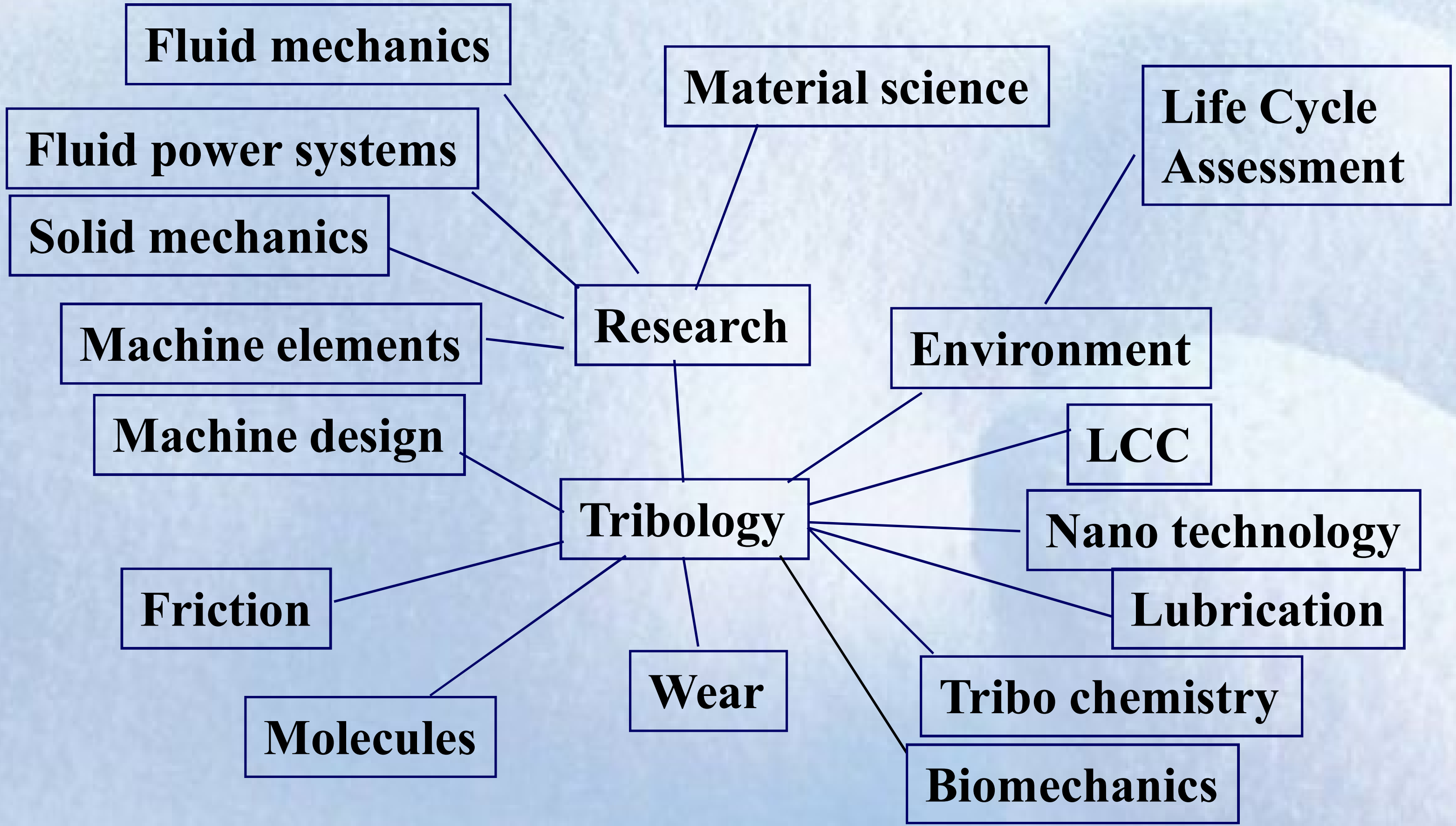
•In 1960s **Synthetic oils** used for motor oils.

•In 1986 the development of the **Atomic Force Microscope** enabled scientists to study & understand friction at the atomic scale.

•1980 onwards **Biolubricants** developments begin.

•1990 onwards **Nanotribolgy, Biotribology** developments begin.

Tribology is a Multi-Disciplinary Subject



Tribology is Everywere- Few Examples

- Tyre-road (high friction required)
- Bearings (low friction and wear required)
- Screw joints (low friction in threading, no wear in contact)
- Ski-snow (low friction for gliding but high in the grip zone)
- Shoe-floor (medium friction for easy walking and dancing)
- Brake-disc (controlled, stable friction, not too low or too high)
- Cam-follower (no wear, low friction)
- Piston ring-cylinder (no wear, low friction)
- Chalk-board (controlled wear process)
- Pen-paper (controlled wear process)
- Artificial joints and
- Many more

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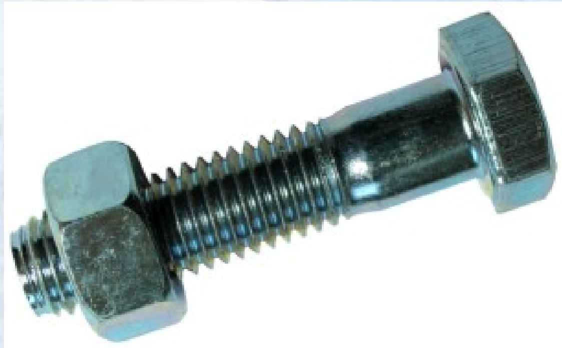
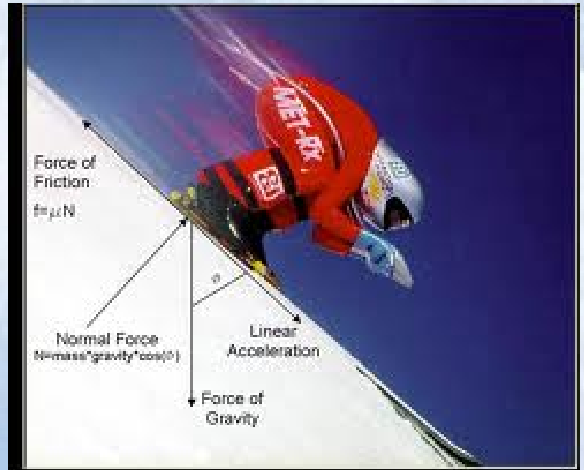


- Ski-snow (low friction for gliding but high in the grip zone)



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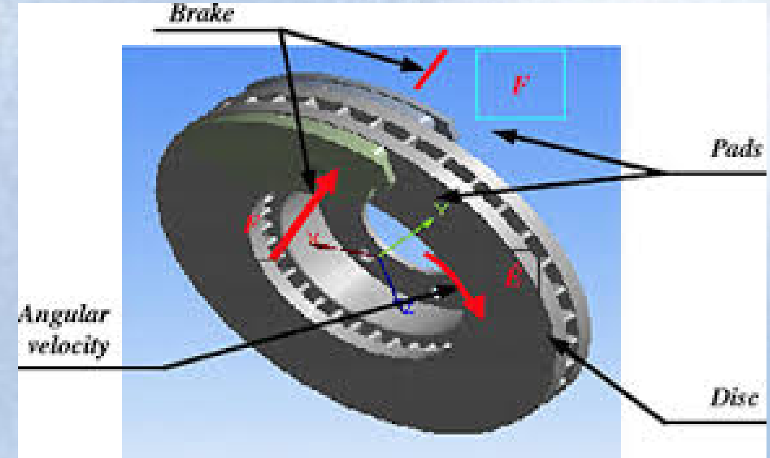


Tribology is Everywere- Few Examples

- Cam-follower (no wear, low friction)

- Piston ring-cylinder (no wear, low friction)

Tribology is Everywere- Few Examples

- Chalk-board (controlled wear process)

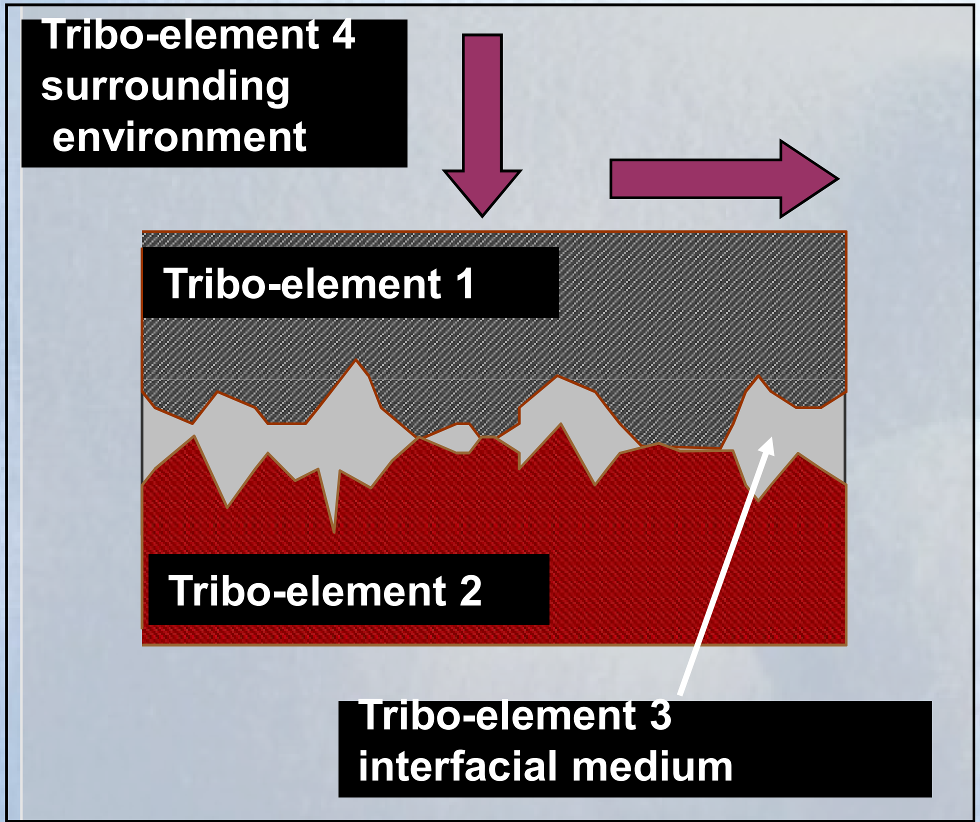
- Pen-paper (controlled wear process)

Tribology is Everywere- Few Examples

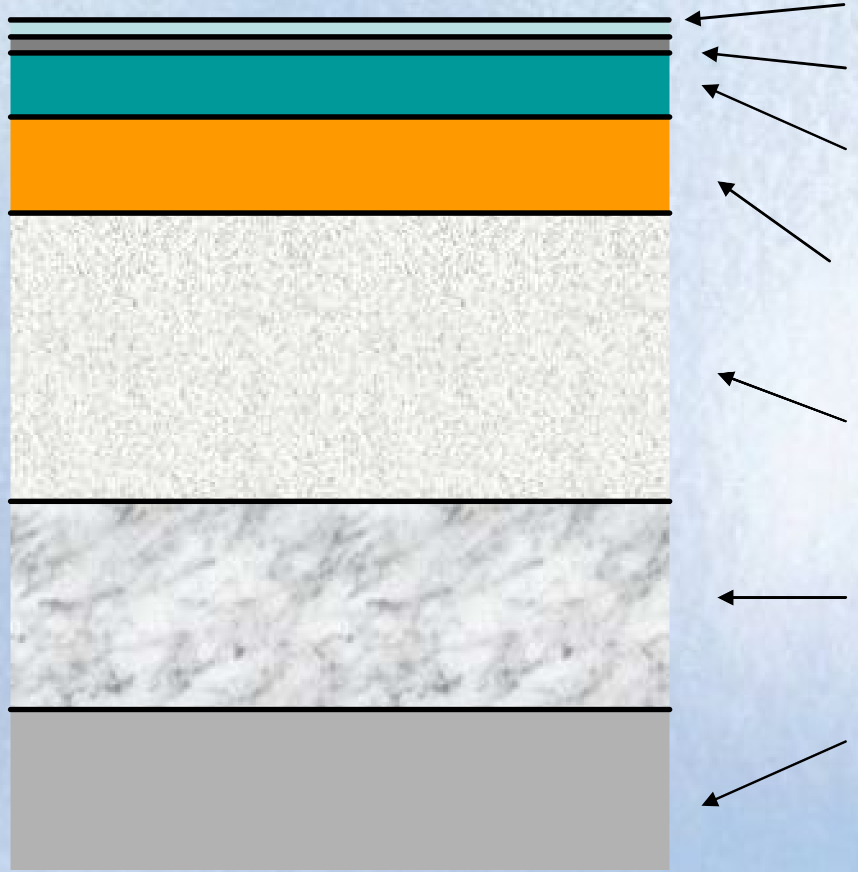
- Artificial joints

- **And Many more....**

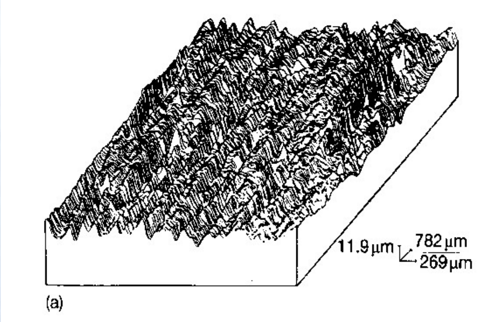
Tribo-system



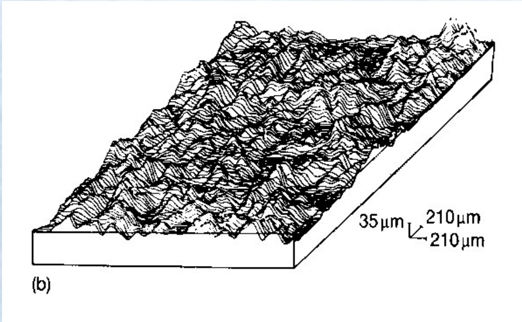
The Nature of Solid Surfaces



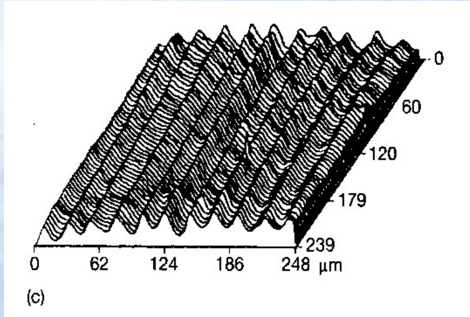
Contact of Rough Surfaces



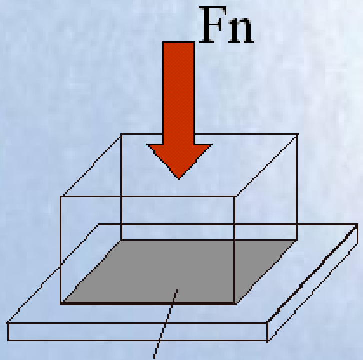
Ground steel surface

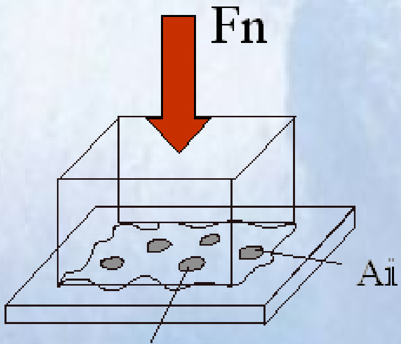


Shot-blasted steel surface



Diamond turned surface



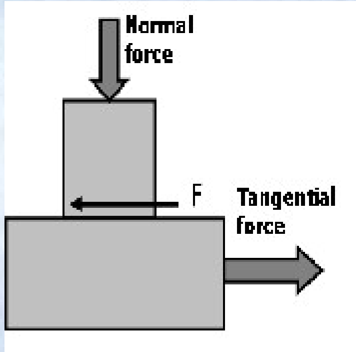


General Remarks

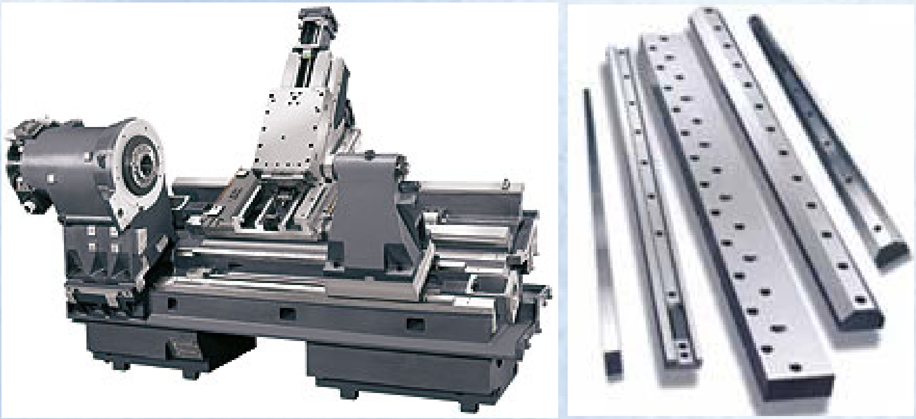
Considering the complexity of the tribological system, it may be pertinent to point out that friction and wear characteristics of materials are not their intrinsic or inherent properties but are highly system dependent.

Friction

- ***We encounter friction in all aspects of everyday lives:***
- ***Walking***
- ***Moving***
- ***Stopping or turning a car***
- ***Since the dawn of time we have been preoccupied with friction, be it:***
  - ***- the Egyptian pyramids and tombs and***
  - ***- the invention of wheel***
- ***Consequences of friction:***
  - ***Major cause of energy dissipation***
  - ***Frictional heat generation and temperature rise***

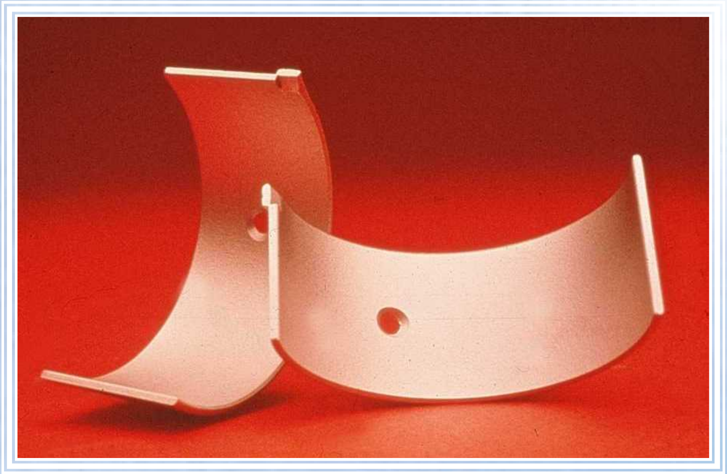


Examples of Occurrence of Sliding Friction



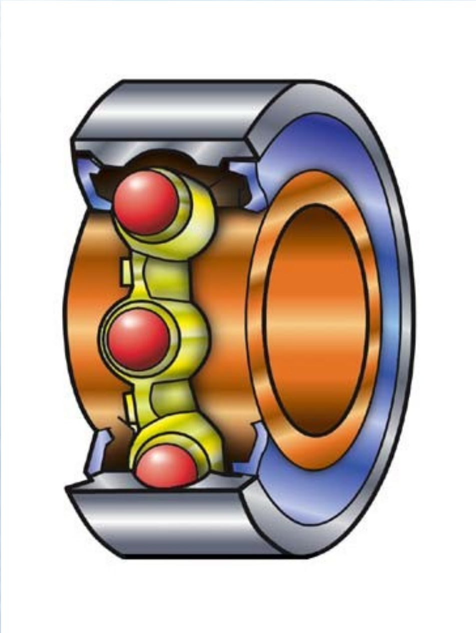
Machine tool slideways

Clutch

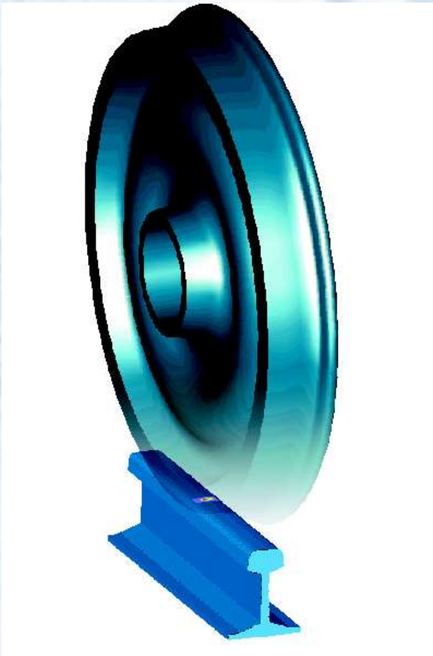


Engine bearings

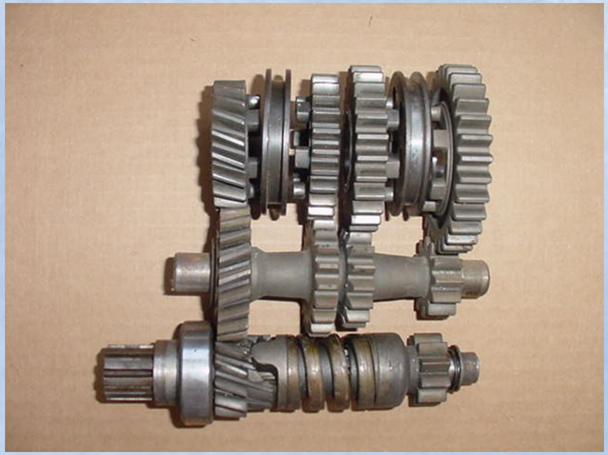
Examples of Occurrence of Rolling Friction



Ball bearing

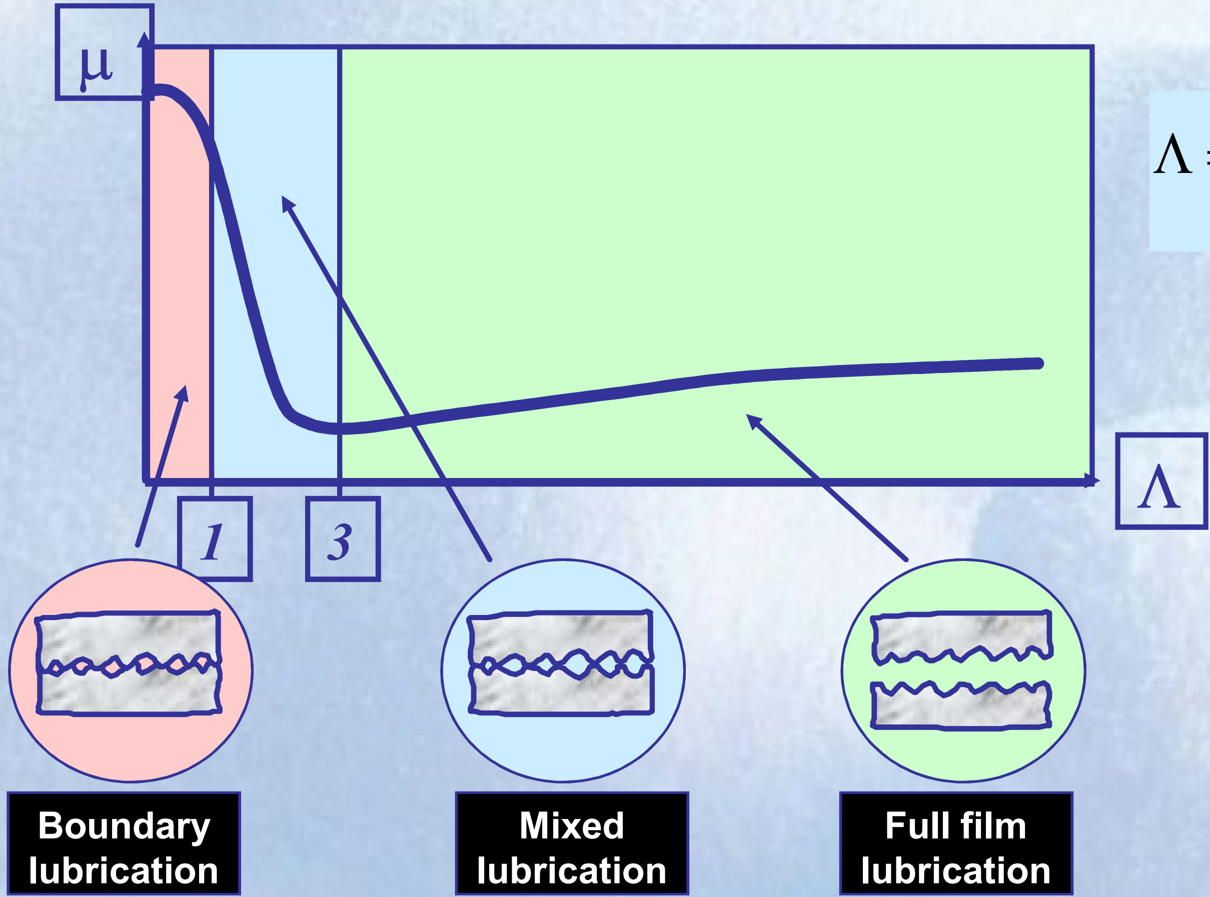


Wheel/rail



Gear transmission

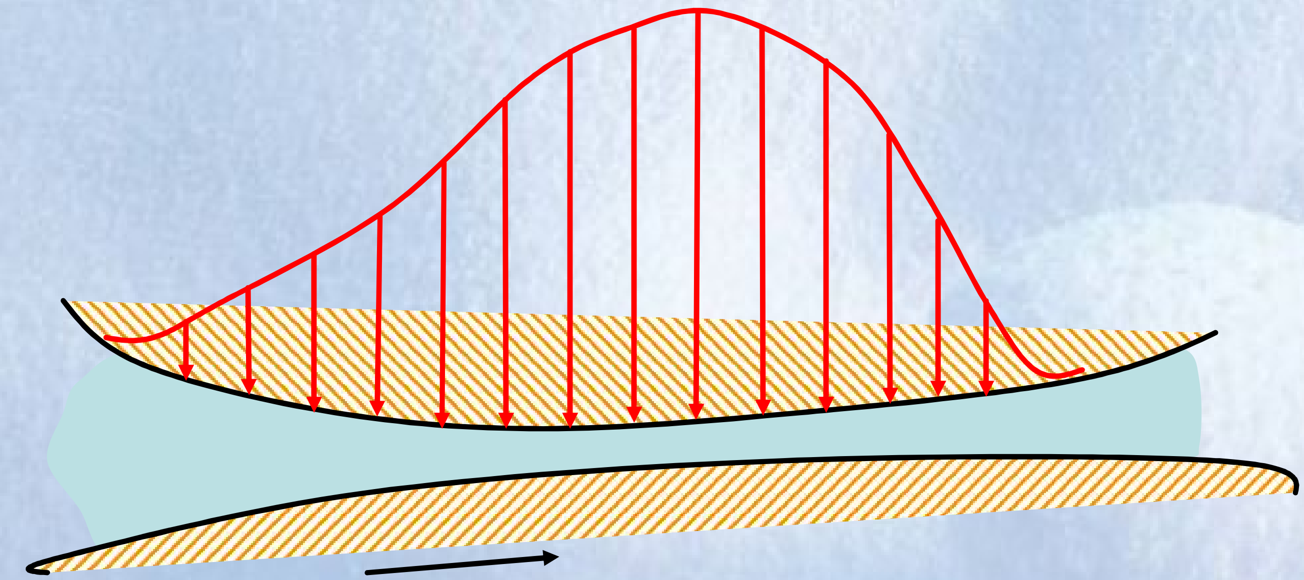
Lubricated Friction Classification



$$\Lambda = \frac{h_{min}}{\sqrt{R_{q1}^2 + R_{q2}^2}}$$

Full film lubrication: The lubricant film separates the surfaces

A hydrodynamic pressure is formed due to the converging gap → surface separation!



EHL - What is that?

Elastohydrodynamic lubrication (EHL)

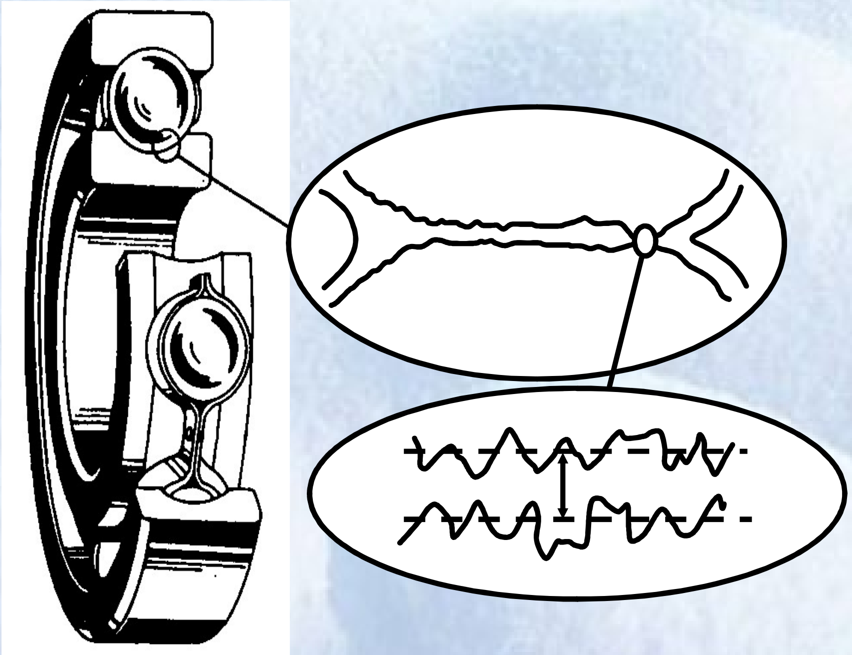
Non-conformal surfaces → small contact region

High contact pressures, 1-3 GPa (1000-3000 N/mm^2)

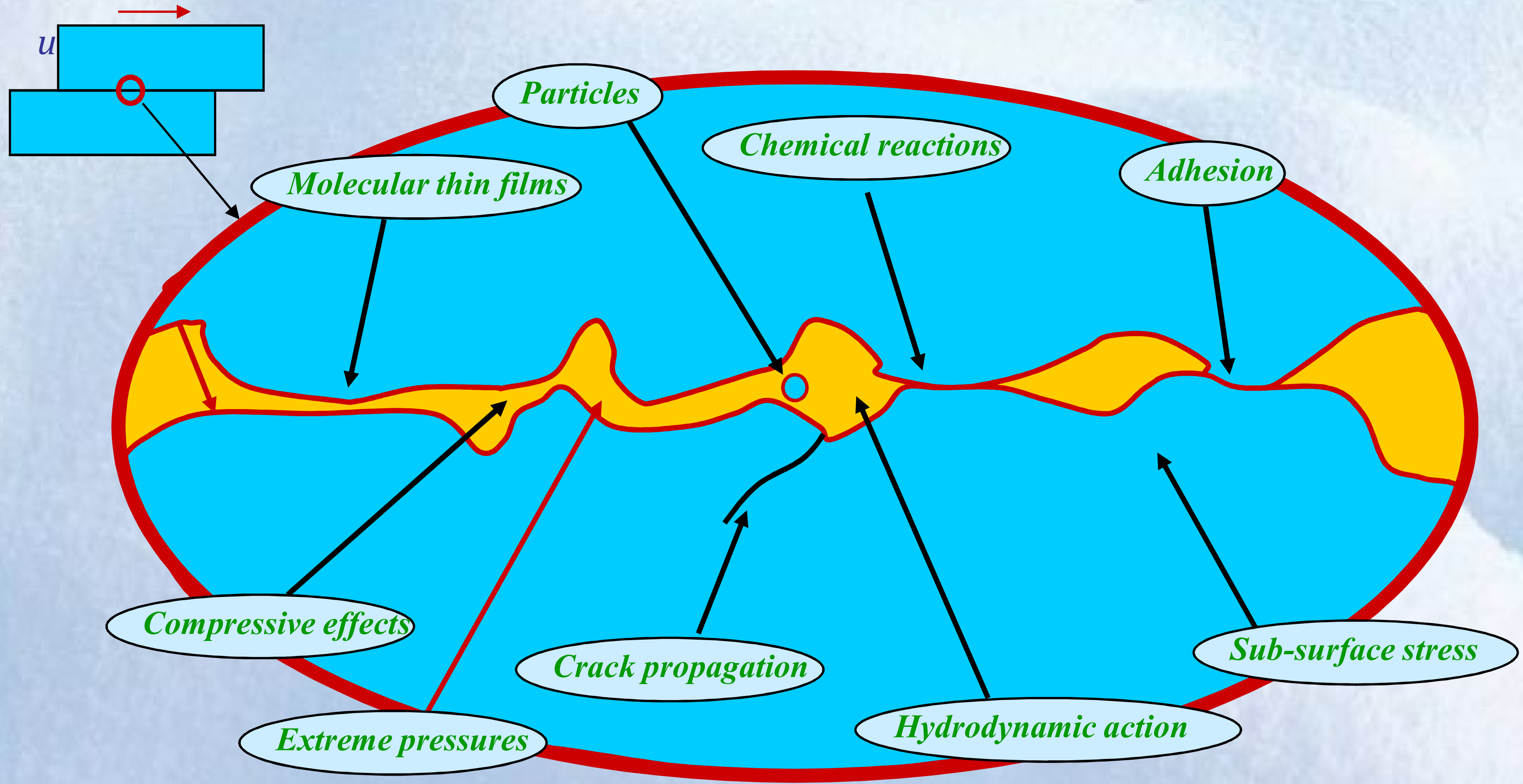
The surfaces are deformed

Thin lubricant films <1μm

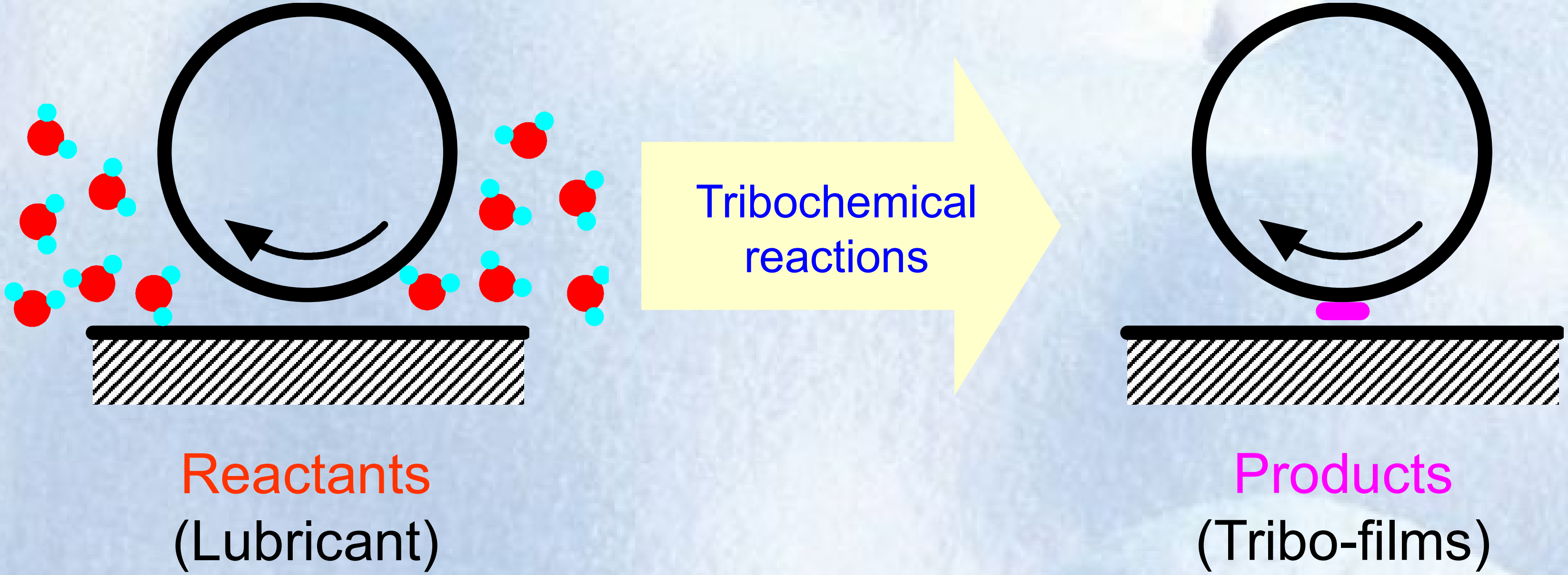
Example: the ball bearing

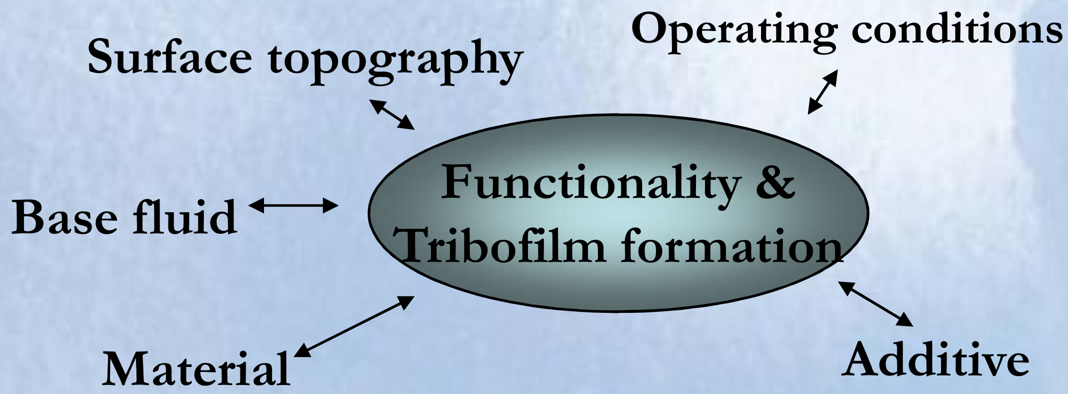


Lubricated Contacting Surfaces



Boundary Lubrication



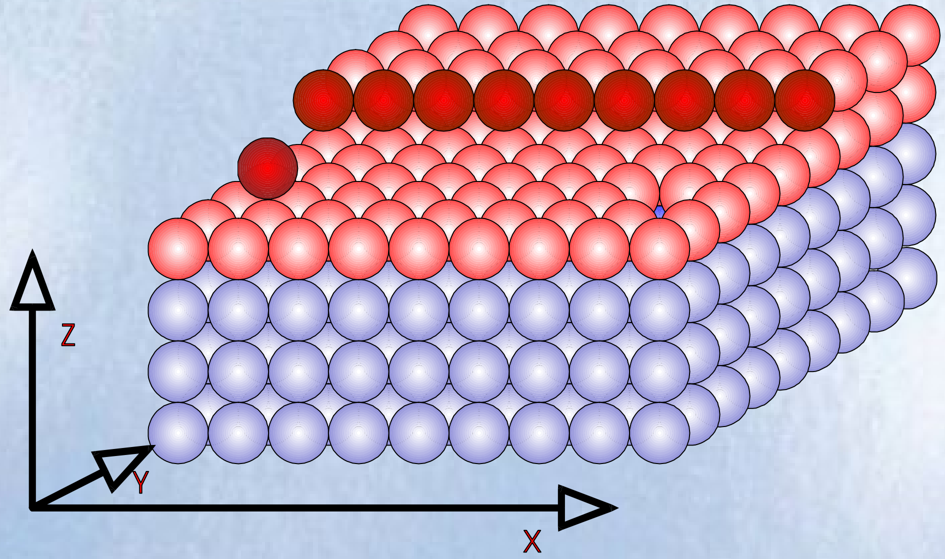


Future challenges in tribology

- Light weight machines/high power densities
- Lubricants for extreme operating temperature (low and high temp.)
- Environmental protection
- Predictability
- Controllability
- Profitability
- Sustainability

Surfaces

A surface is made by a sudden termination of the bulk structure. The bonding that was involved in the bulk lattice (for a solid) or liquid is severed to produce the interface.



Since it requires energy to terminate the bonding, the surface is **energetically** less stable than the bulk.

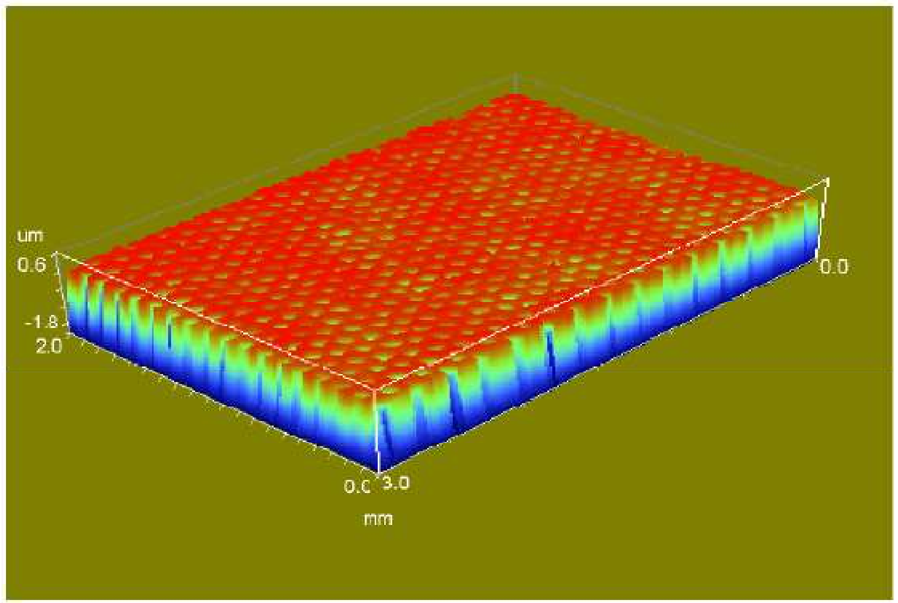
This energy is known as the **surface free energy**. In the case of liquid interfaces, this energy is called **surface tension**.

Why Surfaces?

- Properties different from that of the bulk
- Have major impact on several areas including semiconductors, corrosion, detergent, and *TRIBOLOGY*
- Specialised techniques required to study topography, composition and chemistry of surfaces

Significance of Surfaces in Tribology

- friction
- wear
- effectiveness of lubricants
- surface defects and initiation of cracks
- thermal and electrical conductivities



Ra= 0.1987 µm, Rq= 0.304 µ m, Rz= 10.04 µ m

Surface Defects Caused During Manufacturing

- Crack
  internal/external
- Craters
- Folds/Seams/Laps
- Heat Affected Zone
  thermal cycling w/o melting
- Inclusions
- Residual stresses
- Splatter
- Intergranular attack
- Metallurgical transformations
  temp., press., cycling
- Plastic deformation
  worn tools
- Pits
  shallow surface depressions

Surface Characterisation

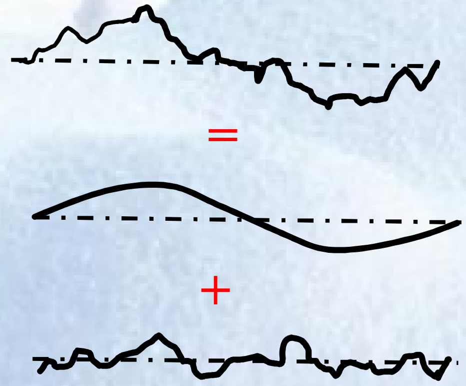
- General features of surface
  - Appearance
  - Shape of surface
  - – Anisotropy ?
- Mechanical properties
  - Modulus
  - Yield Strength
  - Hardness
  - Toughness....
  - Stresses and strains
- Chemistry of surface
  - Elements present
  - Phase distribution

- **Localised defects**
  - Any local changes in
    - Shape
    - Mechanical properties
    - Chemistry
  - Cracks

The Origin of Surface Irregularities

- The production process
  - Turning
  - Grinding
  - Polishing
- The material structure
  - Brittleness
  - Atomic structure
- The use of the surfaces
  - Wear
  - Running-in
  - Corrosion

The Spectrum of Wavelengths

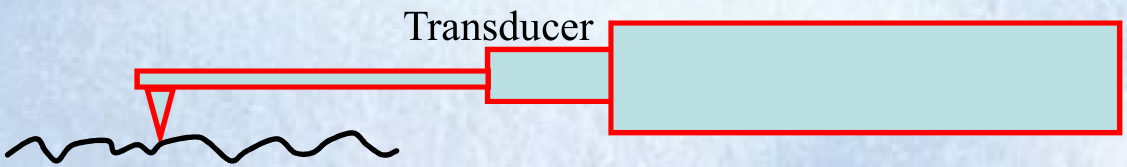


- Form
  - long wavelengths
  - >1000 times its amplitude
- Waviness
  - intermediate wavelengths
  - ratio between wavelength and its amplitude 100:1 - 1000:1
- Roughness
  - Short wavelengths

There is no clear limit between waviness and roughness – it depends on the measurement's sampling length and the filtering technique!

Surface Topography Measurement Methods

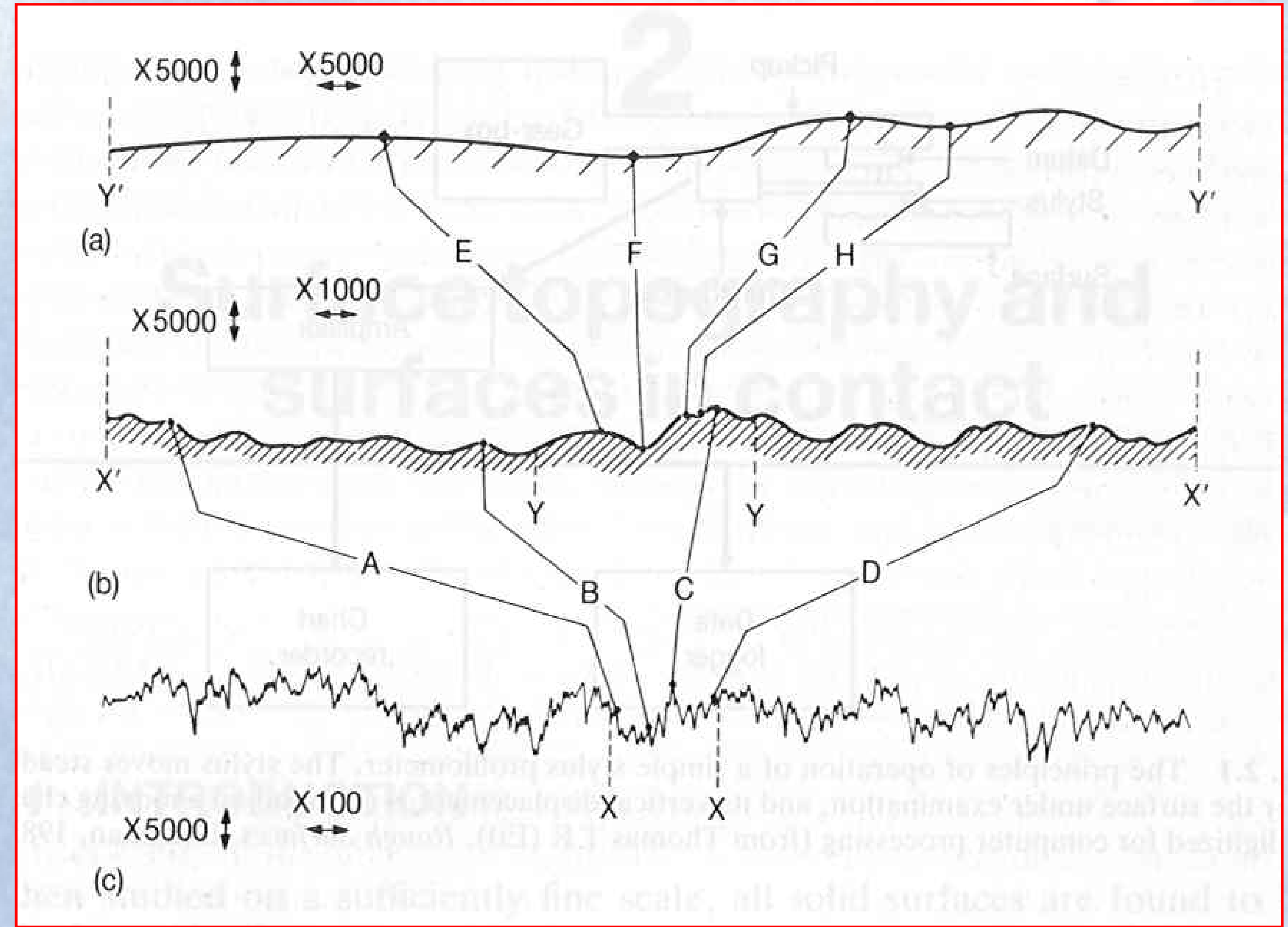
- Stylus profilometers (2D+1D)



- Optical methods (3D)
  - Interferrometry
- Scanning probe microscopy (2D+1D)
  - Scanning tunneling microscopy (STM)
  - Atomic force microscopy (AFM)

Surface topography measurements are never exact. All different Techniques give different answers. Even the use of the same technique at different laboratories!

Surfaces are Flatter Than One Expect

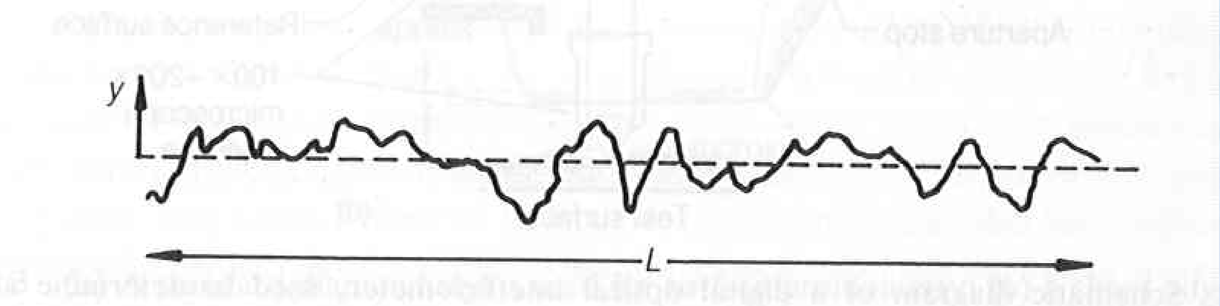


Asperity slopes are rarely steeper than 10°

Problems Encountered in Surface Topography Measurements

- **Stylus profilometers**
  - The tip radius (a few μm) is too large to resolve very fine irregularities
  - Might damage the surface (replication might be the solution)
- **Optical methods**
  - Expensive equipment
  - Thin films on the surface might cause errors
- **Scanning probe microscopy**
  - Expensive and sensitive equipment
  - Measurement on very small areas might lead to mis-interpretations

Average Roughness Parameters



- Average roughness, R_a:

$$R_a = \frac{1}{L}\int_0^L |y(x)|dx$$

- R.M.S roughness, R_q:

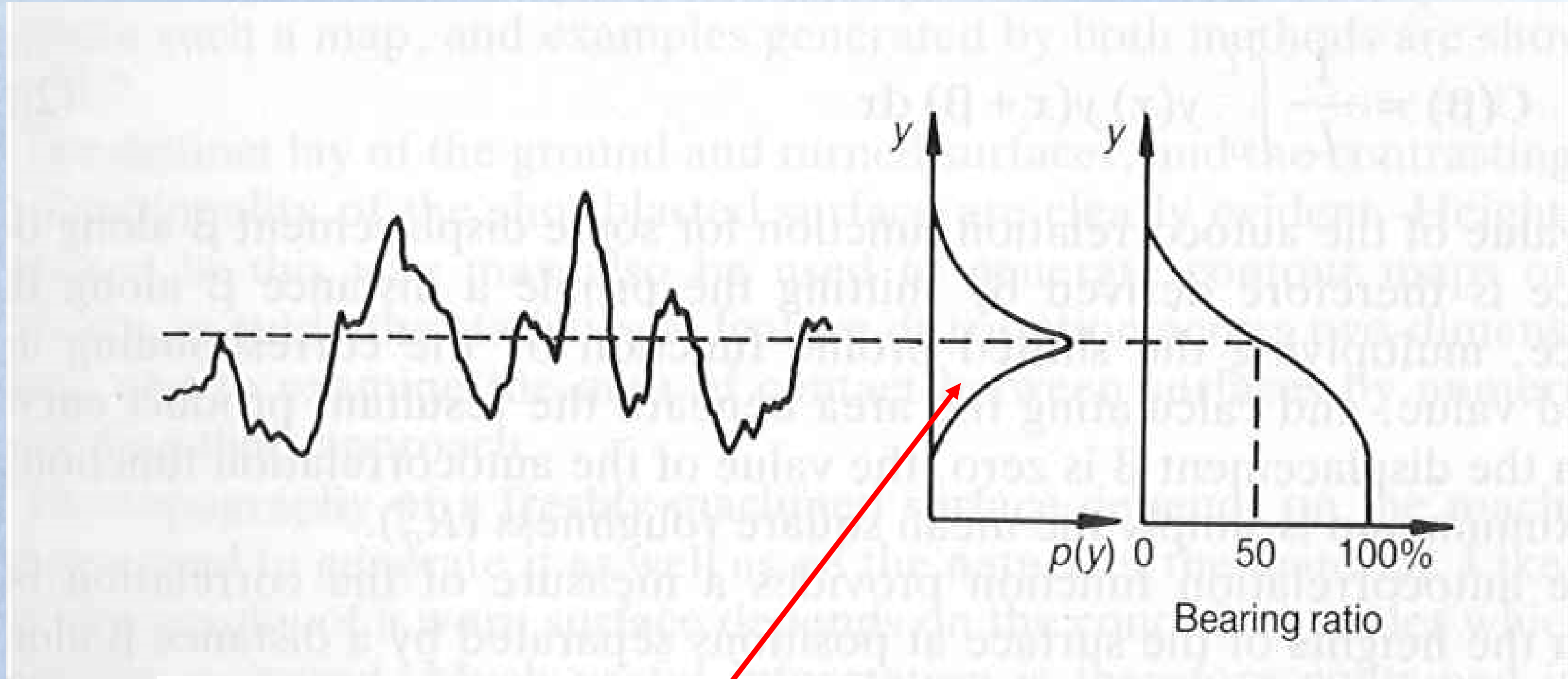
$$R_q = \sqrt{\frac{1}{L}\int_0^L y(x)^2 dx}$$

- R.M.S slope, Δ_q:

$$\Delta_q = \sqrt{\frac{1}{L}\int_0^L \left(\theta(x) - \bar{\theta}\right)^2 dx} \qquad \bar{\theta} = \frac{1}{L}\int_0^L \theta(x)dx$$

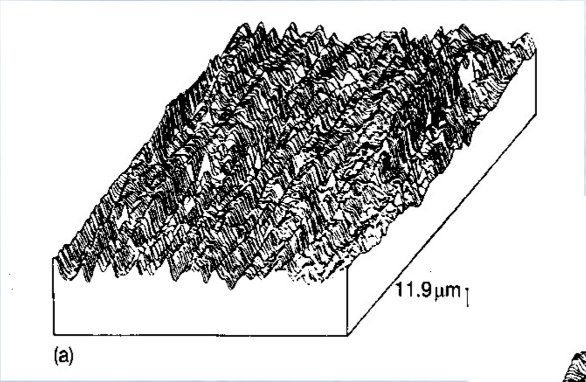
The Amplitude Density Function

Describes the probability to find a point on the surface at height '*y*' above the mean line

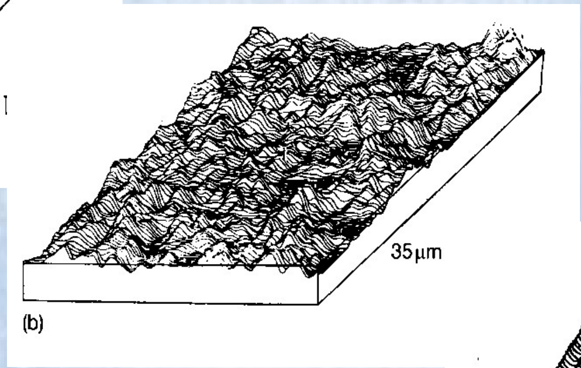


(Gaussian distribution)

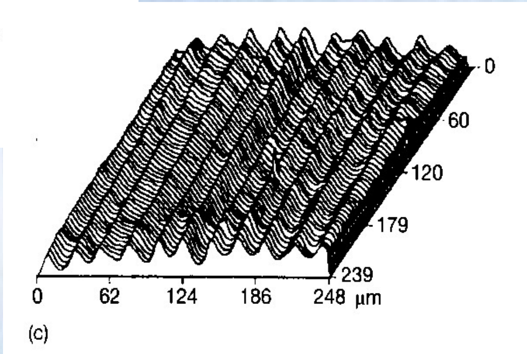
The topography of Engineering Surfaces



Ground steel surface



Shot-blasted steel surface



Diamond turned surface

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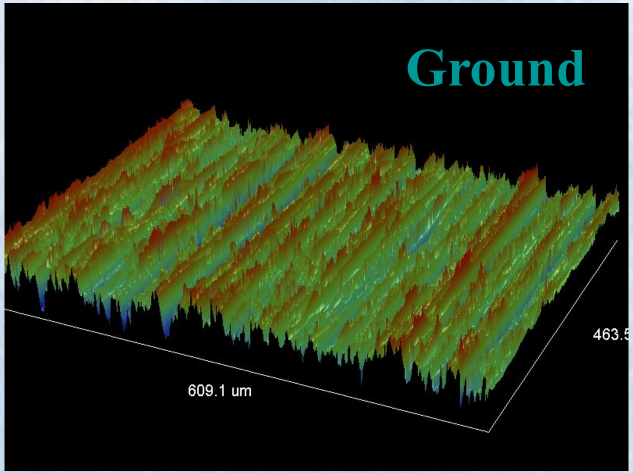
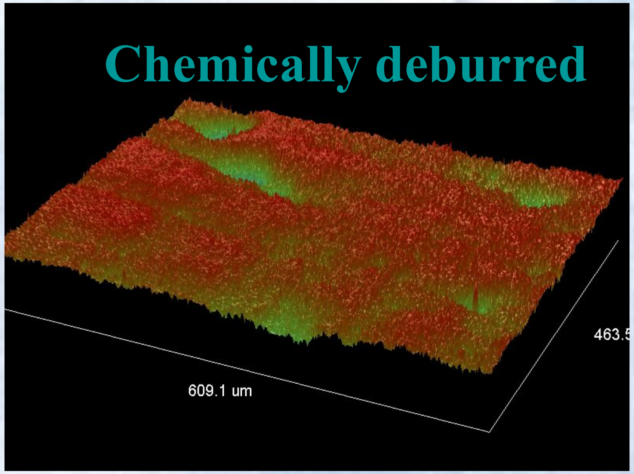
Typical Ra values for Engineering Surfaces

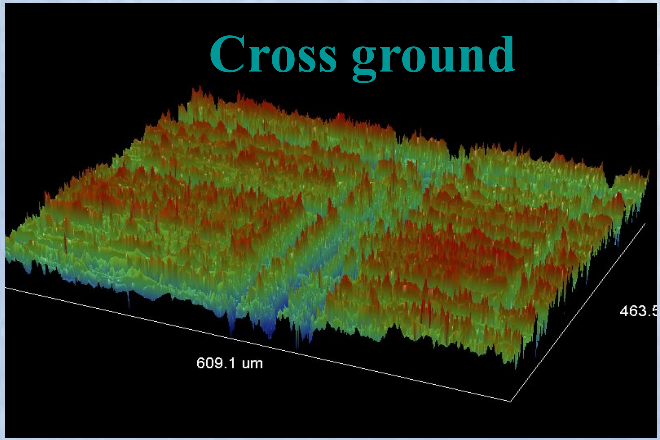
Process	Ra (μm)
Planing, shaping	*1-25*
Milling	*1-6*
Drawing, extrusion	*1-3*
Turning, boring	*0.4-6*
Grinding	*0.1-2*
Honing	*0.1-1*
Polishing	*0.1-0.4*
Lapping	*0.05-0.4*

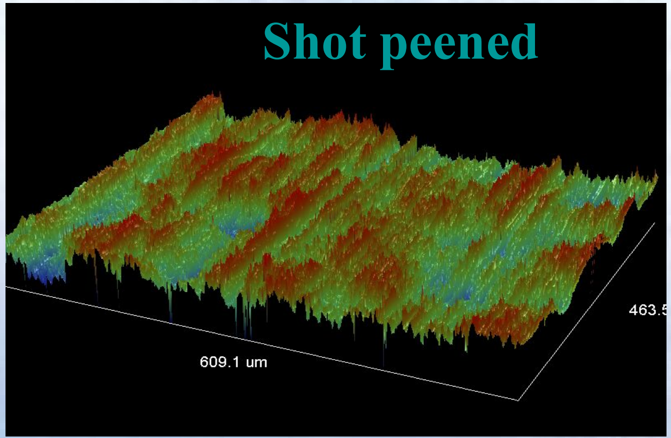
(I.M. Hutchings)

Surfaces Manufactured in Different Ways









Source: John Lord, LTU

Some Remarks about Surface Topography

- Surface topography plays an important role in determining the performance of various tribological machine components.
- There is a need to establish a correlation between surface topography and tribological performance in order to establish optimal surface topography specifications for different moving machine components.

As someone has said:

"The surfaces should be as smooth as possible but as rough as necessary".

It is, of course easier said than done.

Future challenges are to produce the surfaces having specified topographical parameters for optimal tribological performance.

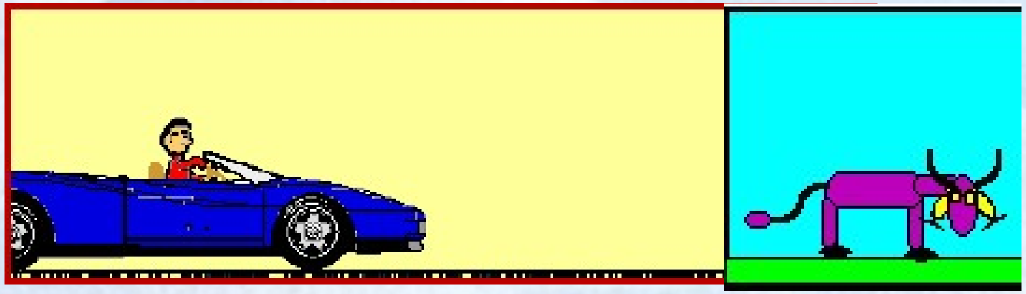
Basic Concept of Friction

INTRODUCTION

- Friction is the resistance to motion during sliding or rolling that is experienced when one solid body moves tangentially over another with which it is in contact .The occurrence of friction is a part of everyday life.

- It is needed so that we have control on our walking.

The Lucky Cow…



- **In this animation, the driver of the car applies the brakes to avoid hitting the cow.**
- **But how does this cause the car to slow down and stop?**
- **The brakes cause the wheels to stop turning and to slide on the road surface.**
- This action produces a force that resists the forward movement of the car.
- This force is called **Friction**

Friction is a force…

- **<u>that acts to resist the motion of one object sliding over another</u>**.
- You may be used to seeing moving objects slow down and stop once the force pushing or pulling the objects is removed.
- For example a wagon will stop moving once you stop pulling it.
- A ball will stop moving once it is caught.

Friction is a force…

- What you may not realize is that there are many forces acting upon objects that affect movement.
- Friction is one of these.
- Friction occurs when two objects are rubbed together.
- The bumps of one surface catch and hook into the bumps of the other surface.

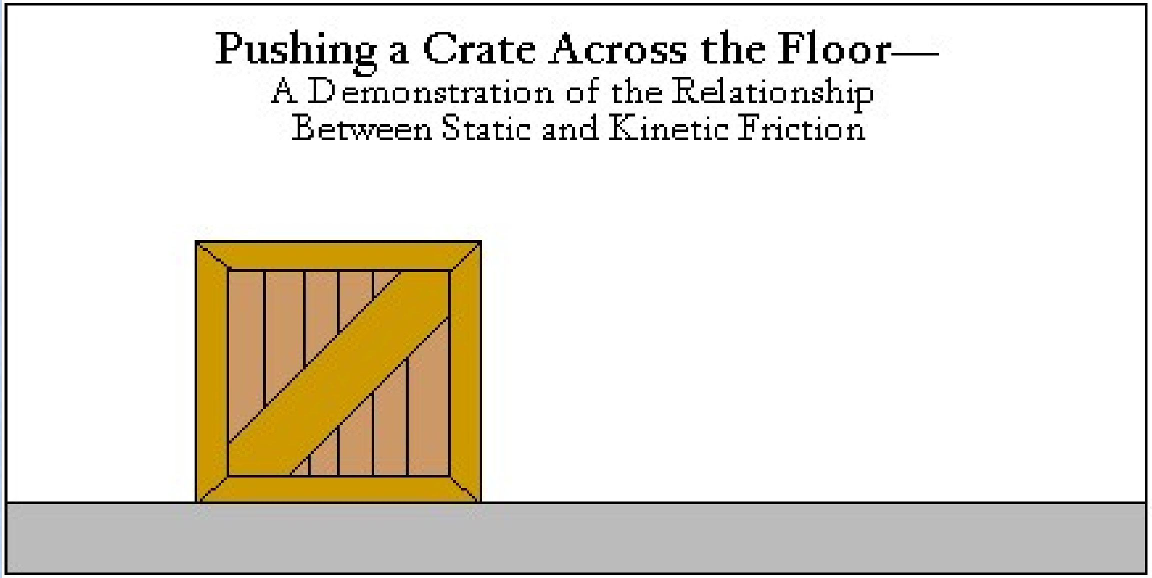
- When the surfaces stick together, the motion between the objects slows down and stops.

- Frictional forces make it possible for us to walk, hold balls, open jars, and ride bikes.

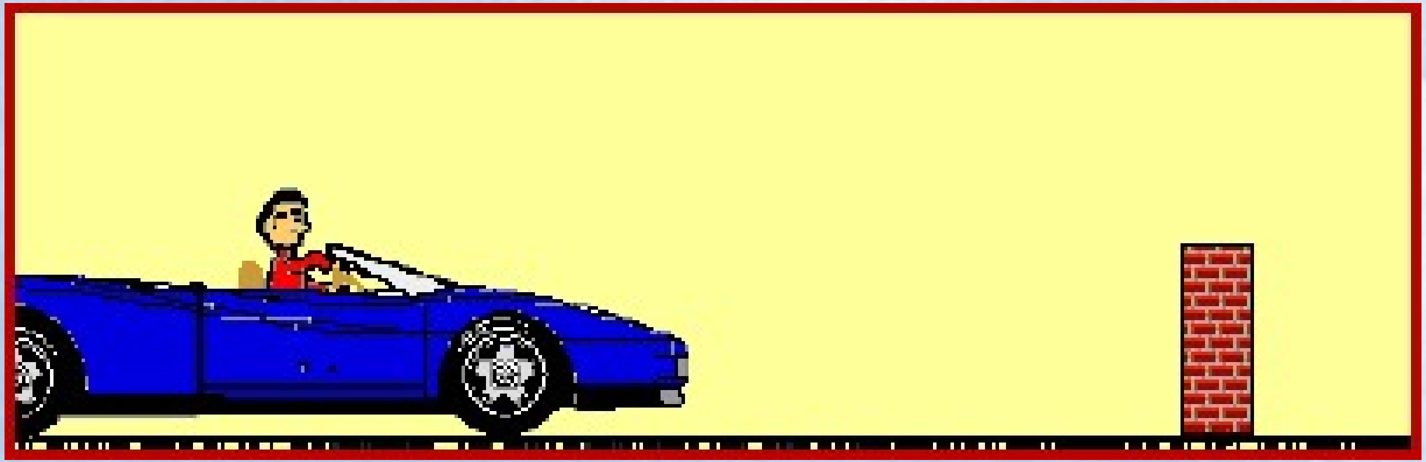
- Lots of friction helps **<u>keep things in place</u>** (cleats on soccer shoes help the shoes grip the ground),
- while little friction **<u>can make motion easy</u>** (moving over a smooth surface like a slide).

- Most motion on earth involves friction.
- A ball rolling on a level floor will eventually stop because the floor pushes against the ball and creates friction.
- When you play baseball and slide into a base, you stop because of friction between you and the earth.
- If there were no friction you would slide right on over the base.

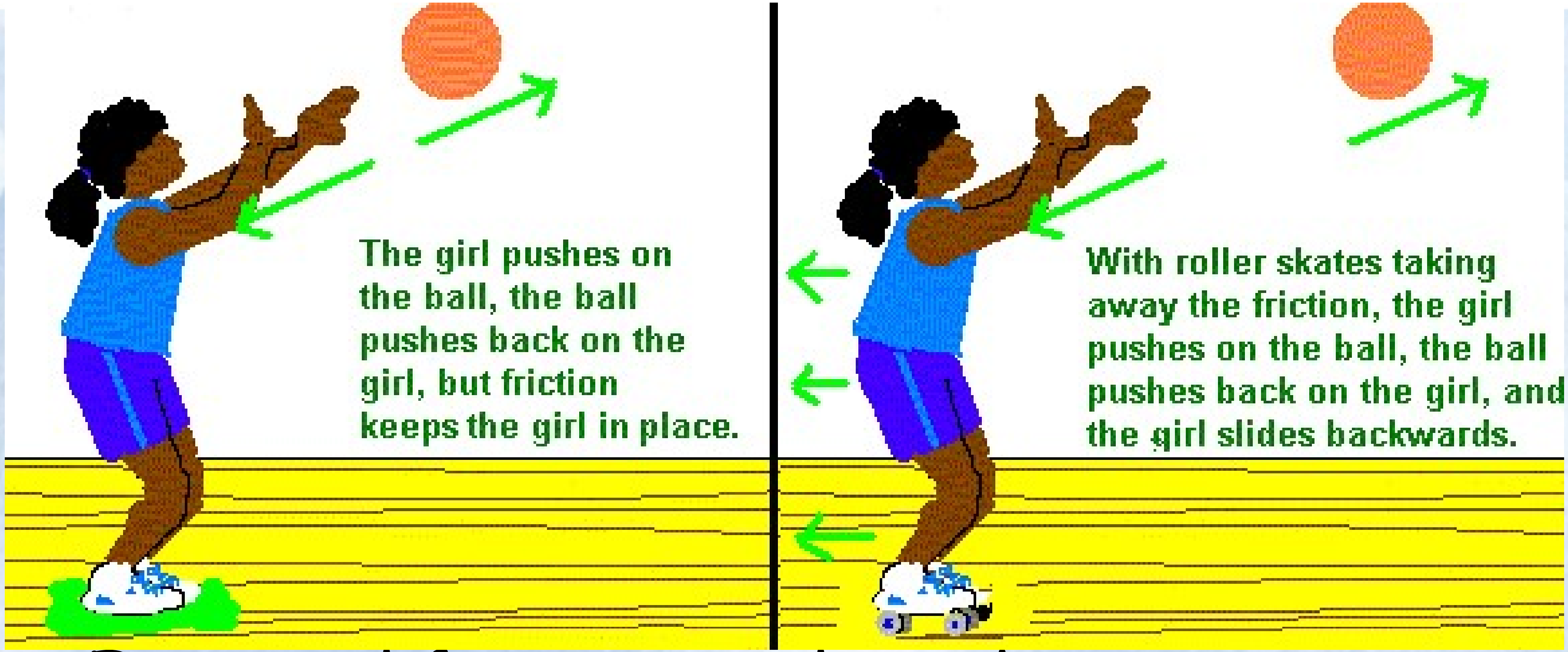
- It is the force of friction that **opposes an object moving**.
- Many people think that it is a nuisance because it has causes us to apply a greater force to move an object.
- But in fact, it is of great help to us.



- **If there is no friction, then cars cannot move on the road and we can hardly even walk.**



- Imagine when you go skiing, is it very hard to walk on ice?
- How about those penguins?

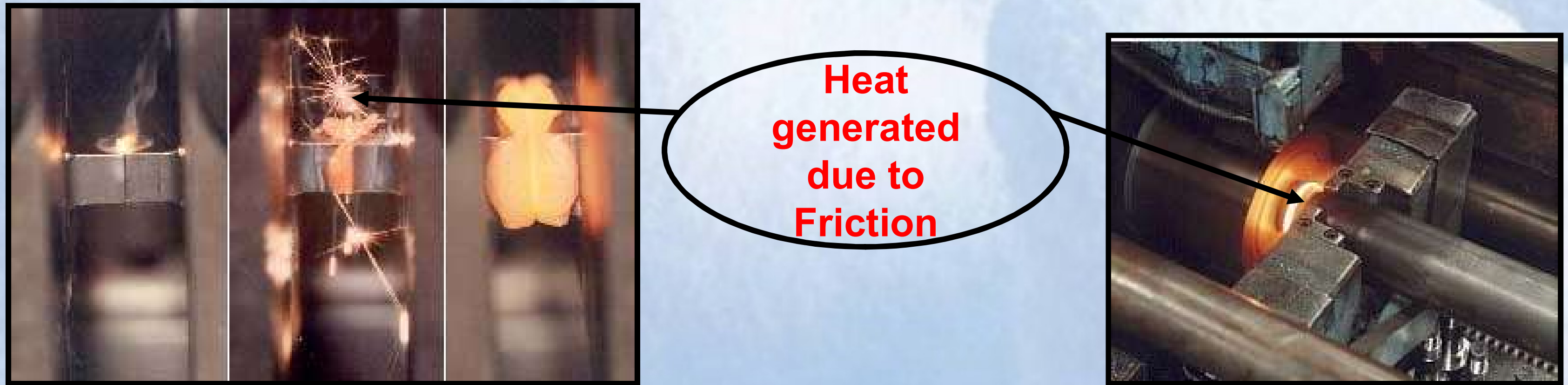


- Frictional forces act along the common surfaces between two bodies in contact so as to resist the relative motion of the two bodies.
- The frictions involved form an **action-reaction pair.**

Friction

INTRODUCTION…..(Cont…)

- On the other hand, in most of running machines friction is undesirable (energy loss, leading to wear of vital parts, deteriorating performance due to heat generation) and all sorts of attempts (i.e. using low friction materials, lubricating surfaces with oil or greases, changing design so that sliding can be reduced) have been made to reduce it.



Friction

INTRODUCTION…..(Cont..)

- Often coefficient of friction(μ) is considered a constant value for a pair of material. In addition, the value of μ is accounted much lesser than 1.0. In practice μ greater than 1.0, as shown in Table, has been observed. Generally coefficients of friction depend on parameters such as temperature, surface roughness and hardness.

Table : Coefficient of friction for various metals sliding on themselves.

Aluminum	1.5
Copper	1.5
Gold	2.5
Iron	1.2
Platinum	3
Silver	1.5

Fig. 2.1 indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.

Friction

INTRODUCTION…..(Cont..)

❖ Fig. indicates that under dry lubricant conditions, μ ranges between 0.1 to 1.0 for most of the materials. Very thin lubrication reduces coefficient by 10 times.

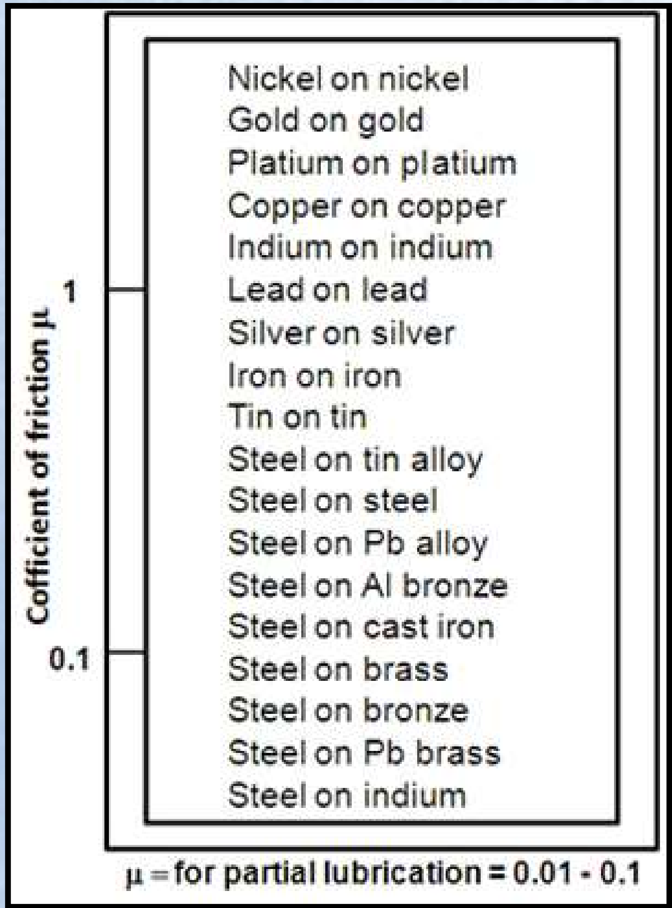


Fig. : Coefficient of friction for various metals.

Friction

INTRODUCTION…..(Cont..)

- Generally, adhesion (ref. Fig.) increases the friction. So, while selecting metal pairs, low adhesion metal pairs must be selected to reduce friction force. Similar material pair must be avoided as similar materials have higher tendency of adhesion.

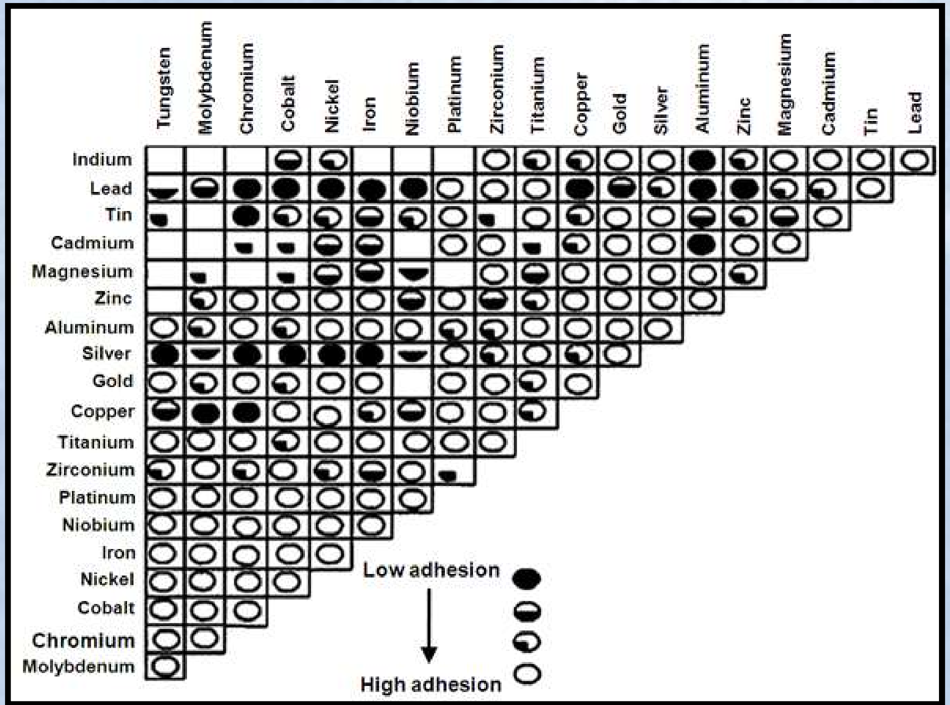


Fig. : Adhesive Friction among various materials

Types of Friction

- Static
- Sliding
- Rolling
- Fluid

Static & Kinetic Frictions

- Before starting friction mechanisms, it is necessary to define static and kinetic friction.
- Let us consider a block on the surface getting pushed by a tangential force F.
- On application of 20 N load, block does not move.
- This second point on the graph(Fig.) shows that on application of 40 N, still block does not move.
- There is static force equilibrium between application force and friction force. On application of 50 N load, block just start sliding. At this point of load application friction force remains equal to 50 N, but friction resistance decreases subsequently to 40 N.

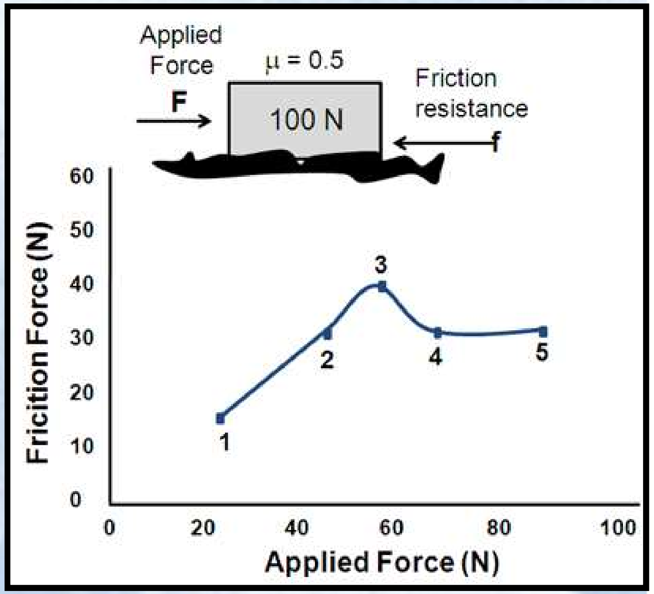


Fig.: Difference between the static and kinetic friction may initiate 'stick-slip'.

Static & Kinetic Frictions (Cont..)

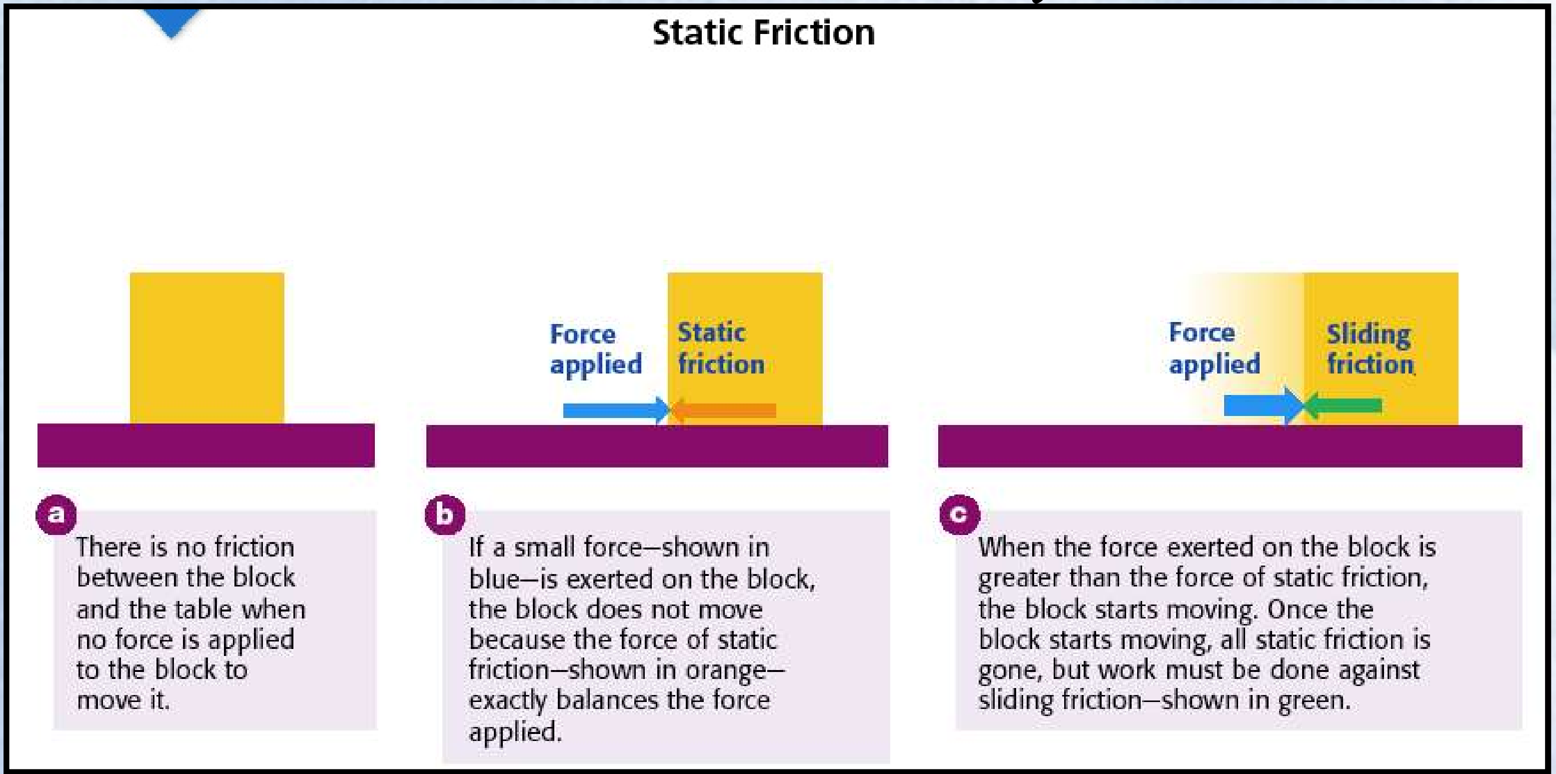
- In other words, static friction is higher than kinetic friction.
- Table shows few published results of static/kinetic coefficient of friction.
- This table indicates that coefficient of friction is statistical parameter.
- It is difficult to obtain same value under various laboratory conditions.
- Further, there is a possibility of substantial decrease in kinetic friction relative to static friction.
- Stick-slip is a phenomenon where the instantaneous sliding speed of an object does not remain close to the average sliding speed.
- Stick-slip is a type of friction instability.

Table: μ for wood-on-wood reported in various articles.

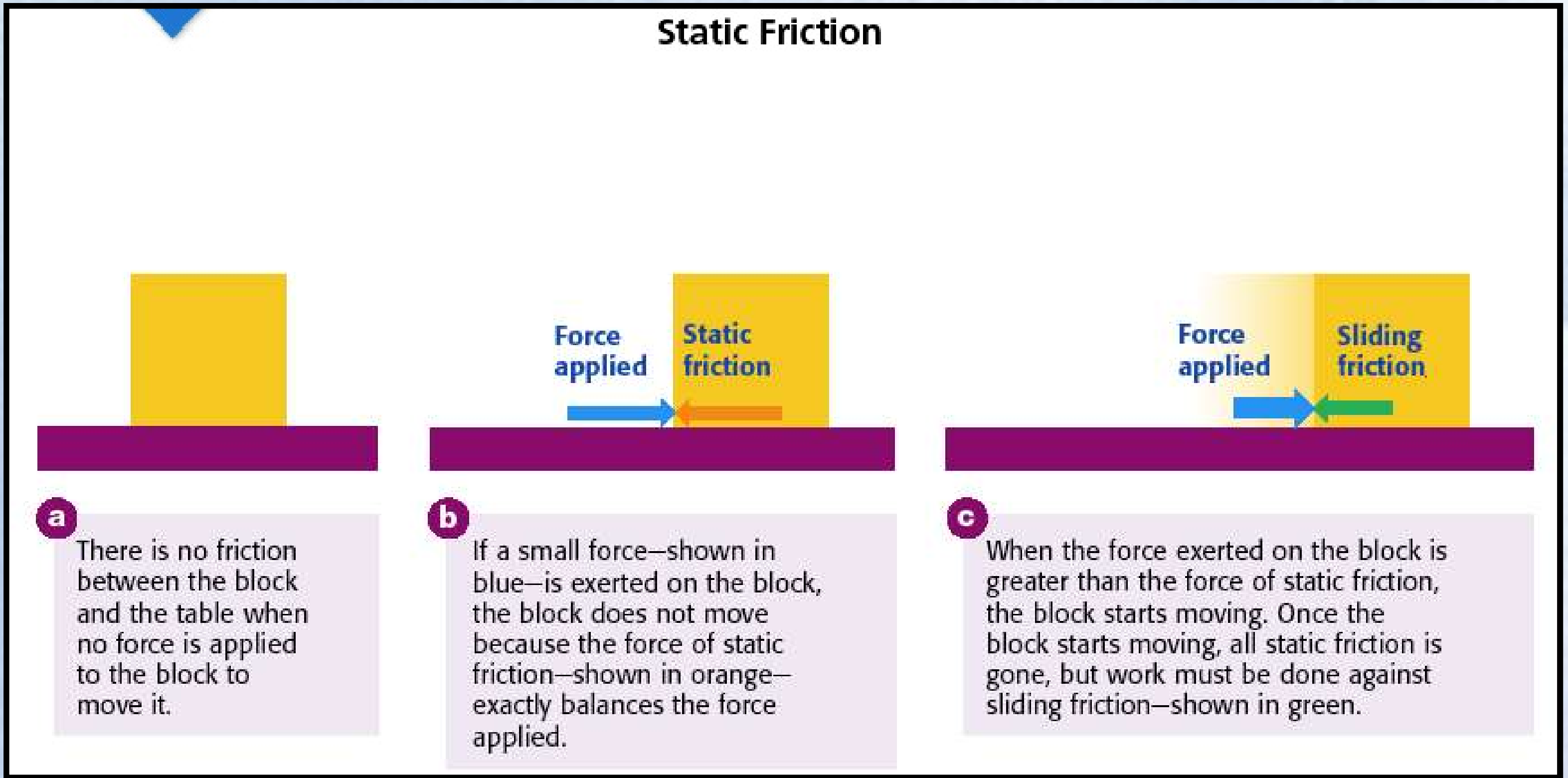
Listed material combination	μ_s	μ_k
Wood on wood	0.25 – 0.5	0.19
Wood on wood (dry)	0.25 – 0.5	0.38
Wood on wood	0.30 – 0.70	---
Wood on wood	0.6	0.32
Wood on wood	0.6	0.5
Wood on wood	0.4	0.2
Oak on oak (para. to grain)	0.62	---
Oak on oak(perp. To grain)	0.54	0.48
Oak on oak(fibers parallel)	0.62	0.48
Oak on oak(fibers crossed)	0.54	0.34
Oak on oak(fibers perpendicular)	0.43	0.19

Static Friction

- In this figure, a horizontal force is applied to a body with an intention to move it to the right-side. (note: if the force applied is too small the "static friction is greater and the block will not move.)



- **As long as the body is at rest, the frictional force is equal to the applied force and directs to the left-side (opposite direction of motion) resisting the motion.**
- **The friction is <u>static as there is no motion</u>.**



Greater Mass Creates More Friction

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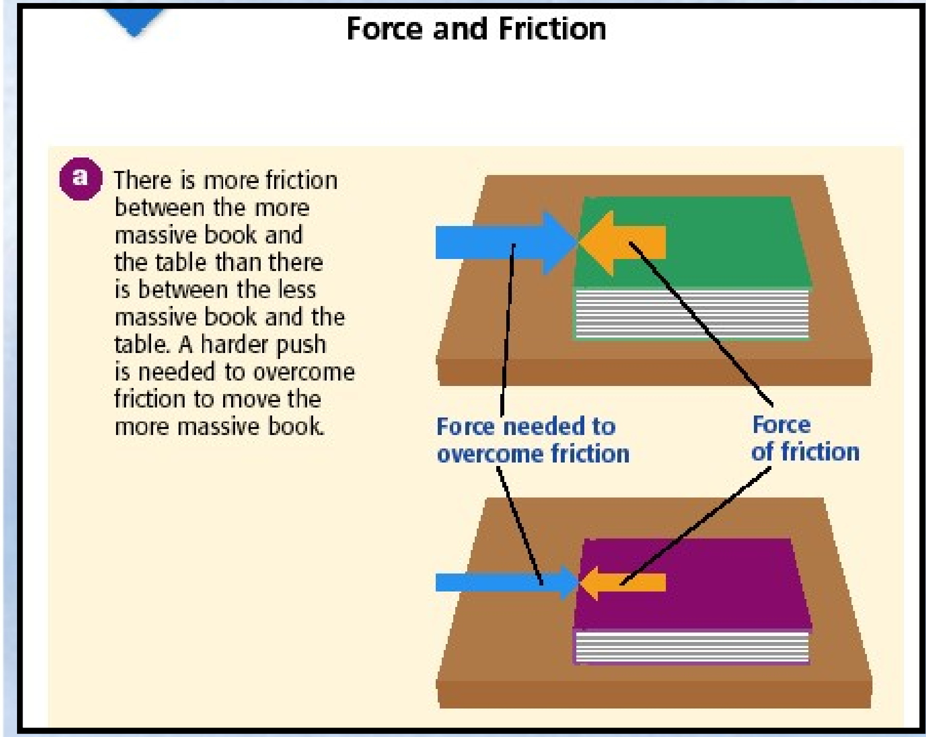
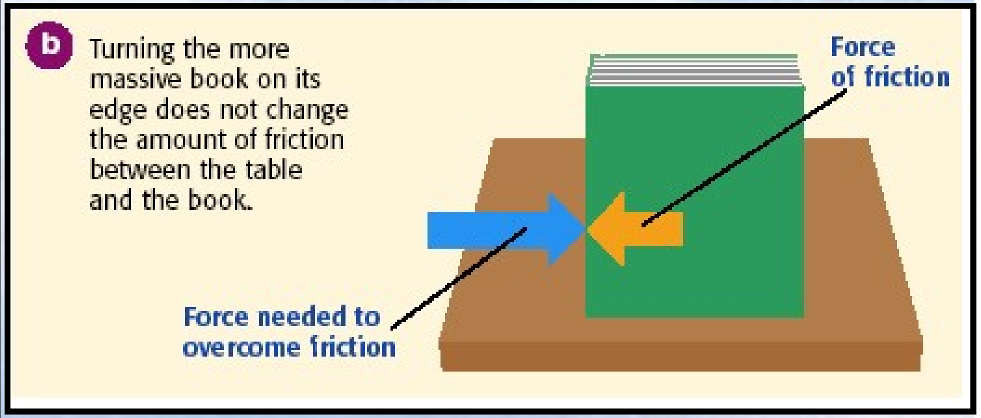
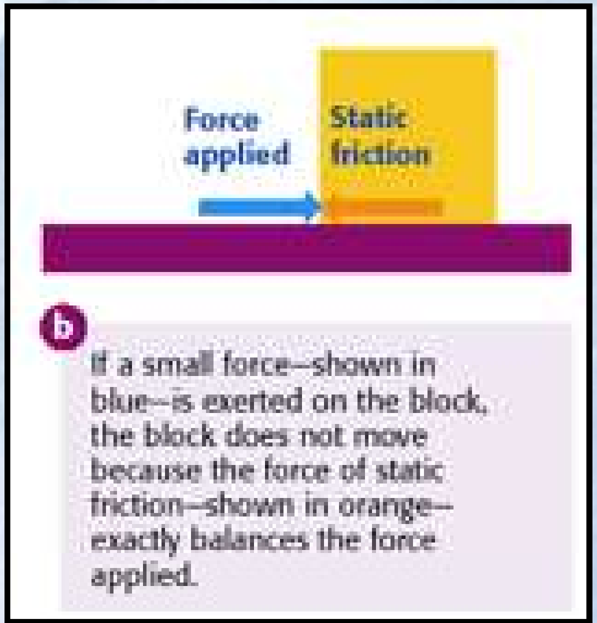
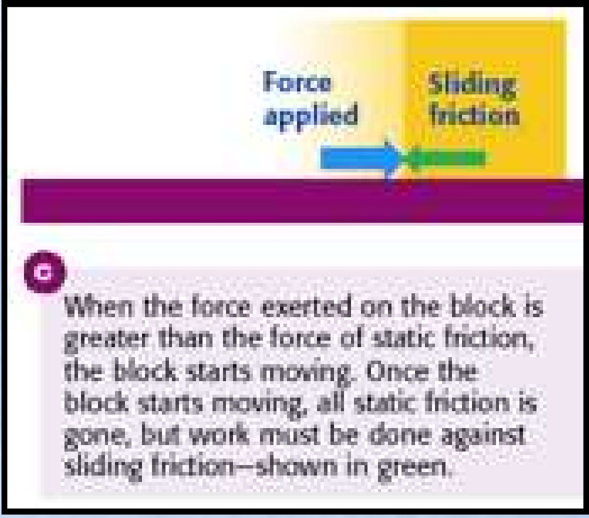
A greater push is needed to overcome the greater mass which has greater (static) friction





Static Friction



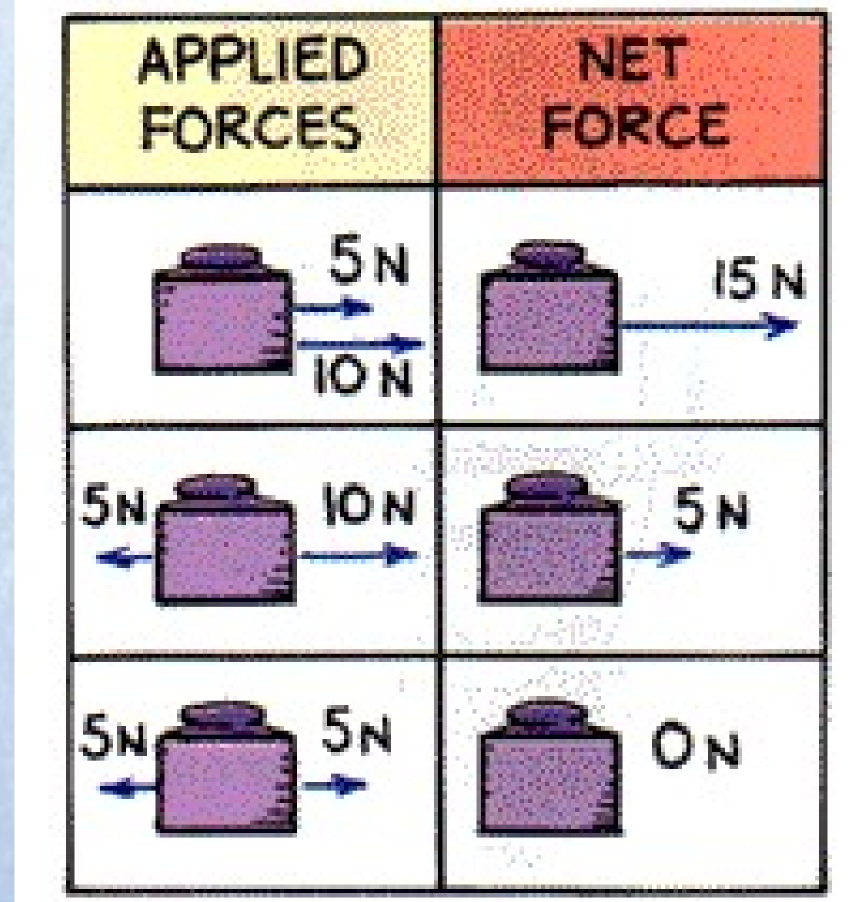


- If applied force is increased, the frictional force will also increase until it reaches the
- **limiting frictional force**.
- As the applied force increases further, the body will begin to move.
- The limiting frictional force is independent of the applied force but depends on the nature of the surfaces and the normal contact force.

12 April 2020

What is Net force?

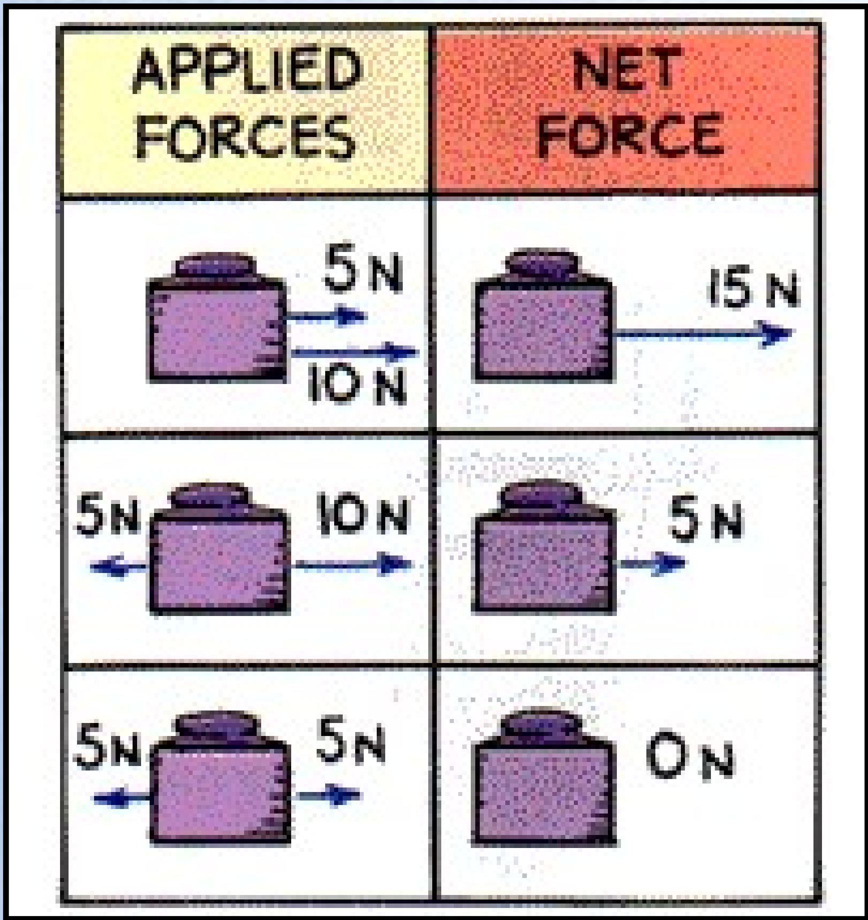
- Combining all forces exerted on an object



Draw this at the bottom
Of the page!

Calculating net force: Combining all forces exerted on an object

- Forces in the **same** direction
- **Add** forces together

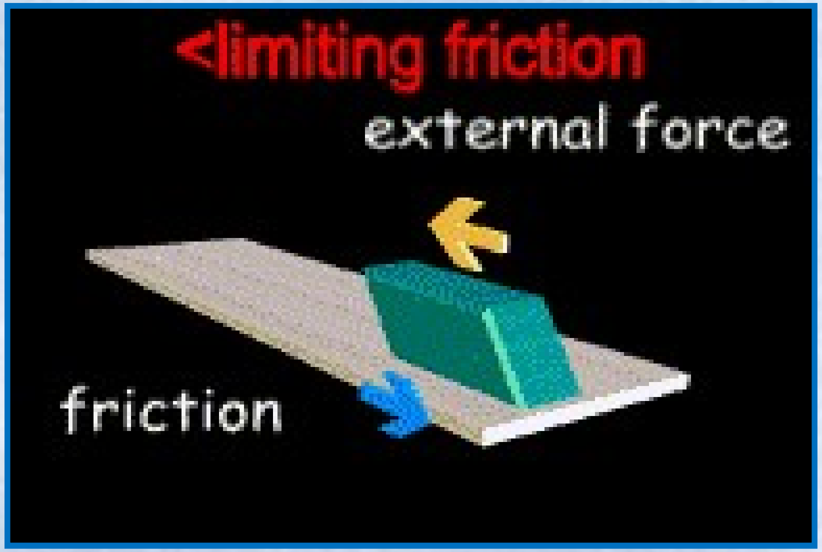


- Forces in the **opposite** direction
- **Subtract** smaller force from the larger force

Static Friction

- This figure shows that object begin to move if the applied force is larger than the limiting friction.
- Before that, the frictional force increased with the applied force.

Static Friction continued



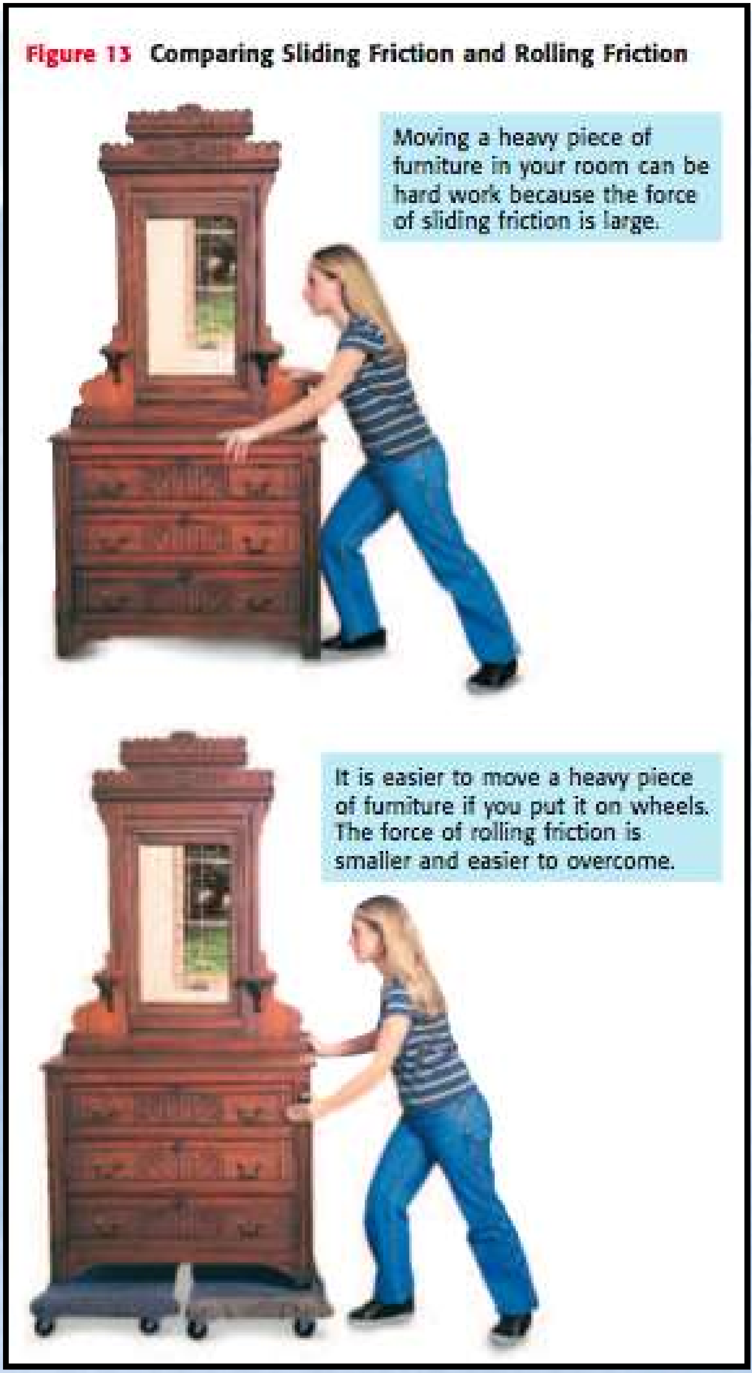
- Once the body starts to move, the frictional force would fall to a smaller value compare with the static frictional force.
- This frictional force remains constant even though the applied force is increased further.

A plane and it's friction experience with "Sliding Friction"

Sliding friction = HEAT

Rolling Friction

- The friction between the wheels and the ground is an example of rolling friction.
- The force of rolling friction is usually less than the force of sliding friction



Rolling Friction

Fluid Friction

- **<u>Fluid friction</u> opposes the motion of objects traveling through a fluid**

- **Remember that fluids <u>include liquids & gases</u>, water, milk and air are ALL fluids**

Figure 14 *Swimming provides a good workout because you must exert force to overcome fluid friction.*

Theories on Friction

- A friction is statistical parameter depends on a number of variable. There is a need to understand science of friction.
- To understand the effect of material pair, role of lubrication, and environmental factors let us start with dry friction.
- The dry friction is also known as solid body friction and it means that there is no coherent liquid or gas lubricant film between the two solid body surfaces.
- Four theories given by Leonardo da Vinci, Amonton, Coulomb and Tomlison for dry lubrication are explained in following slides.

Theories on Friction (Cont..)

- ***Leonardo da vinci(Earliest experimenter, 1452-1519) :***

  As per Leonardo, “Friction made by same weight will be of equal resistance at the beginning of movement, although contact may be of different breadths or length”.

  “Friction produces the double the amount of effort if weight be doubled”.

  In other words, F α W.

Theories on Friction (Cont..)

- ***G. Amontons, 1699 :*** The friction force is independent of the nominal area (F ≠ A) of contact between two solid surfaces. The friction force is directly proportional F α N to the normal component of the load. He considered three cases (Fig.) and showed that friction force will vary as per the angle of application of load. As per Amontons μ = 0.3 for most of materials.

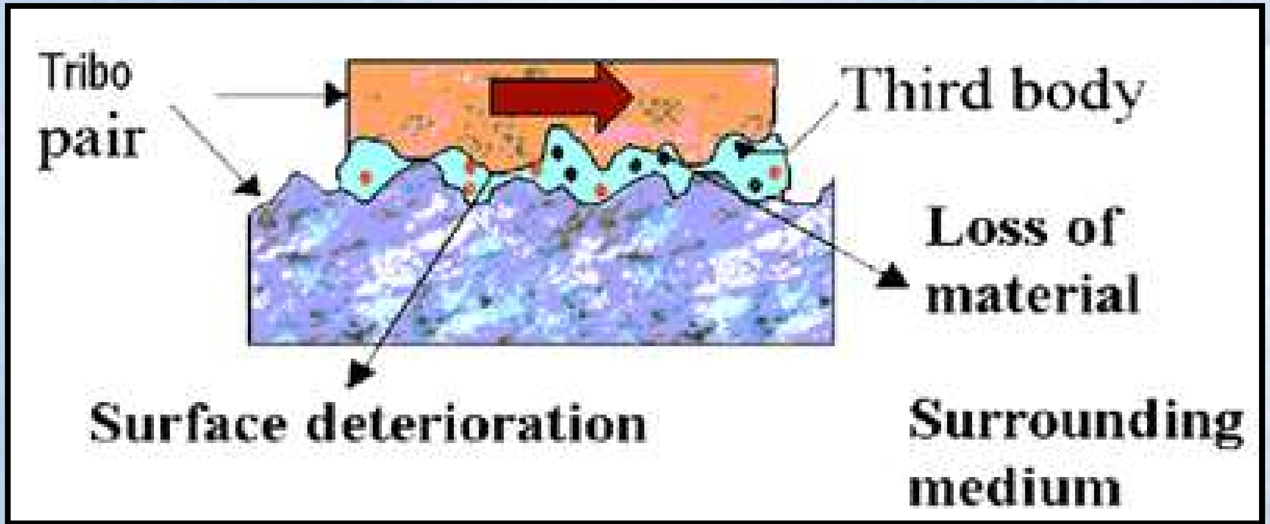


Fig. : Amonton`s work.

Theories on Friction (Cont..)

❖ ***C.A. Coulomb 1781 (1736-1806) :***

✓ Clearly distinguished between static & kinetic frictions. Friction due to interlocking of rough surfaces.

Contact at discrete points μstatic ≥ μkinetic.

f ≠ func(A).

f ≠ func(v).

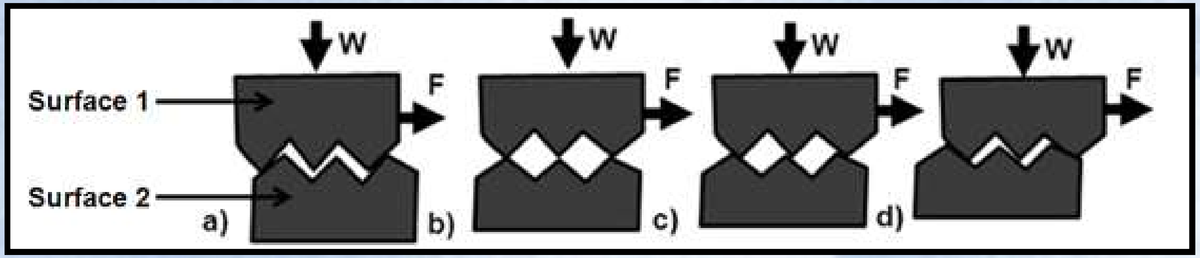


Fig. : Coulomb friction model.

✓ As per coulomb friction force is independent of sliding speed. But this law applies only approximately to dry surfaces for a reasonable low range of sliding speeds, which depends on heat dissipation capabilities of tribo-pairs.

Theories on Friction (Cont..)

❖ ***TOMLINSON's Theory of Molecular attraction, 1929 :***

Tomlison based on experimental study provided relation between friction coefficient & elastic properties of material involved.

- As per Tomlison due to molecular attraction between metal, cold weld junctions are formed. Generally load on bearing surface is carried on just a few points. These are subjected to heavy unit pressure, and so probably weld together. Adhesion force developed at real area of contact.

$$f = 1.07 * [\theta_I + \theta_{II}]^{2/3}$$

where E is young modulus, Mpsi

Where θ is

$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

Clean Steel E = 30 Mpsi, G=12 Mpsi → 0.6558
Aluminum E = 10 Mpsi, G=3.6 Mpsi → 0.742
Titanium E = 15.5 Mpsi, G=6.5 Mpsi → 0.5039

Fig. : Examples on Tomlison formula.

- Fig. provides illustration related to Tomlison`s friction formula. This figure indicates f = 0.6558 for clean steel and aluminium, f = 0.742 for aluminium and titanium, and f = 0.5039 for clean steel and titanium.

Theories on Friction (Cont..)

❖ ***Scientific Explanation of Dry Friction :***

- There are two main friction sources: ***Adhesion and Deformation***. Force needed to plough asperities of harder surface through softer.
- In lubricated tribo-pair case, friction due to adhesion will be negligible, while for smoother surfaces under light load conditions deformation component of friction will be negligible.
- Fig. demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction.

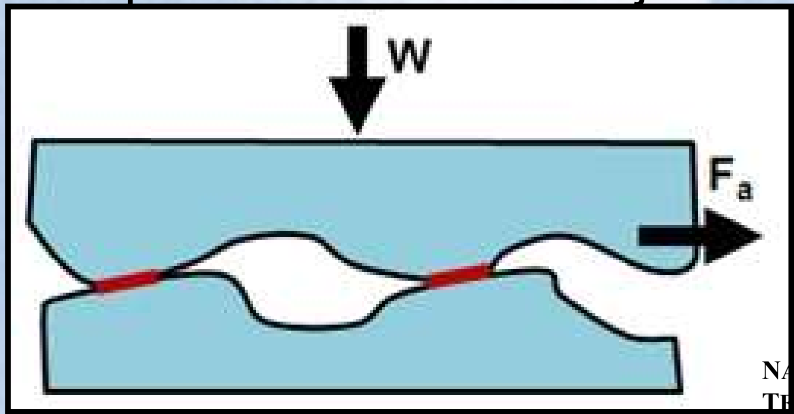


Fig. : Adhesion

Theories on Friction (Cont..)

❖ ***Scientific Explanation of Dry Friction :***

➢ Fig. demonstrates the deformation process. It shows a conical asperity approaching to a softer surface. To move upper surface relative to lower surface some force is required.

✓ Two friction sources: Deformation and Adhesion.

✓ Resulting friction force (F) is sum of two contributing (F_a & F_d) terms.

✓ Lubricated tribo-pair case -- negligible adhesion.

✓ Smoother surfaces under light load conditions – Negligible deformation.

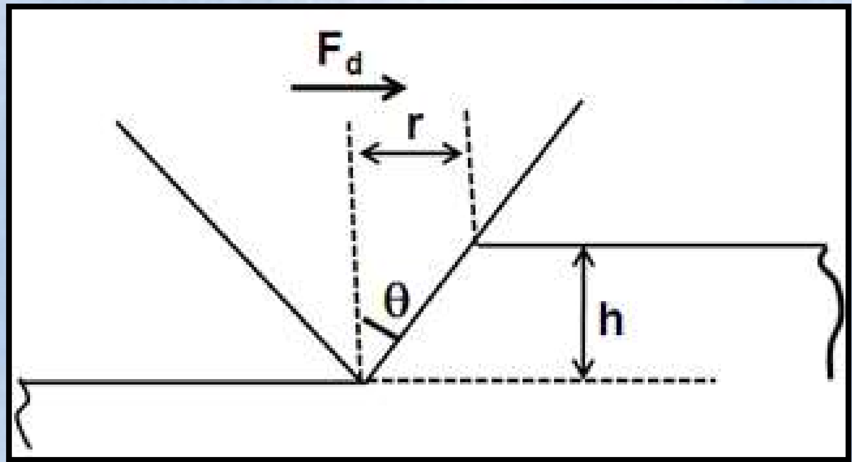


Fig.: Abrasion (Deformation)

Adhesion and Ploughing in Friction

- This theory is based on the fact that all surfaces are made of atoms.
- All atoms attract order one another by attractive force.
- For examples, if we press steel piece over indium piece (as shown in Fig.) they will bind across the region of contact.
- This process is sometimes called "cold welding," since the surfaces stick together strongly without the application of heat.

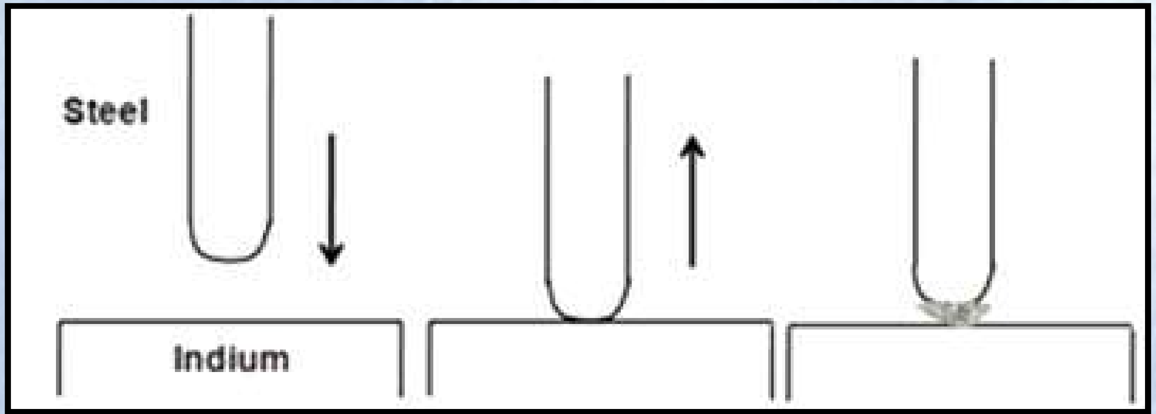


Fig. : Cold welding in steel and indium

Adhesion and Ploughing in Friction (Cont..)

- It requires some force to separate the two surfaces.
- If we now apply a sideways force to one of surfaces the junctions formed at the regions of real contact will have to be sheared if sliding is to take place.
- The force to do this is the frictional force. Fig. shows carbon graphite material adhered to stainless steel shaft.

Fig. : Carbon graphite and stainless steel.

THEORY OF ADHESIVE FRICTION

- Bowden and Tabor developed theory of adhesive friction.
- As per this theory on application of W, initial contact at some of higher asperity tips occurs.
- Due to high stress those asperities suffer plastic deformation, which permits strong adhesive bonds among asperities.
- Such cold formed junctions are responsible for the adhesive friction.
- The real area of contact, A can be estimated by applied load W and hardness of the soft material, H.
- If s is shear stress of softer material, then force F_a required to break these bonds can be estimated by Equation $F_a = A_s$.
- The coefficient of friction due to adhesive friction is given by ratio of friction force to applied load W.

THEORY OF ADHESIVE FRICTION (Cont..)

- Fig. shows the formulation and breakage of cold junctions. •
  - ✓ Two surfaces are pressed together under load W.
  - ✓ Material deforms until area of contact (A) is sufficient to support load W, A = W/H.
  - ✓ To move the surface sideway, it must overcome shear strength of junctions with force Fa.
  - ✓ $\mu = Fa/W = s/H$.
  - ✓ In other words shear strength(s) and hardness(H) of soft material decides the value of μ.
  - ✓ This means whatever properties of the other harder pairing material, μ would not change.

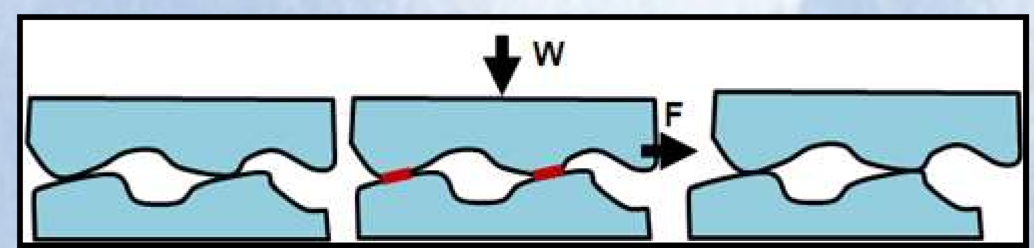


Fig. : Adhesion theory

THEORY OF ADHESIVE FRICTION (Cont..)

- For most of untreated materials H = 3 σy & s = σy/1.7321.
- Expected value of μ = 0.2, as μ = s ⁄ H.
- But for most of the material pair(shown in Fig.) μ is greater than 0.2.
- There is a huge difference between measured values of friction coefficient and estimated by theory of adhesion.
- Theory is unable to estimate different μ for steel on indium and steel on lead alloy. Theory related to deformation needs to be explored.

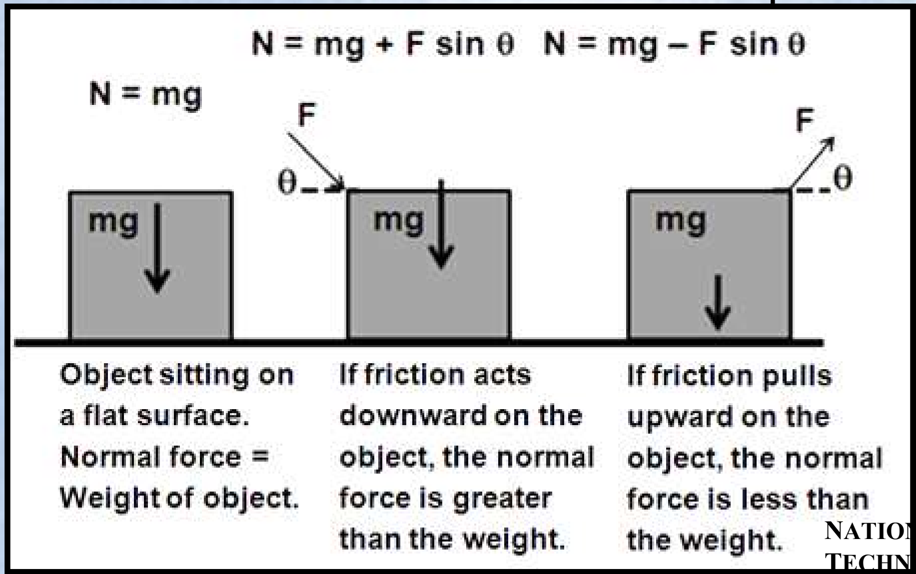


Fig.:Friction coefficients for various material pairs.

FRICTION DUE TO DEFORMATION

- This theory is based on the fact that contact between tribo-pairs only occurs at discrete points, where the asperities on one surface touch the other.
- The slope of asperities governs the friction force.
- Sharp edges cause more friction compared to rounded edges.
- Expression for coefficient of friction can be derived based on the ploughing effect.
- Ploughing occurs when two bodies in contact have different hardness.
- The asperities on the harder surface may penetrate into the softer surface and produce grooves on it, if there is relative motion.

FRICTION DUE TO DEFORMATION (Cont..)

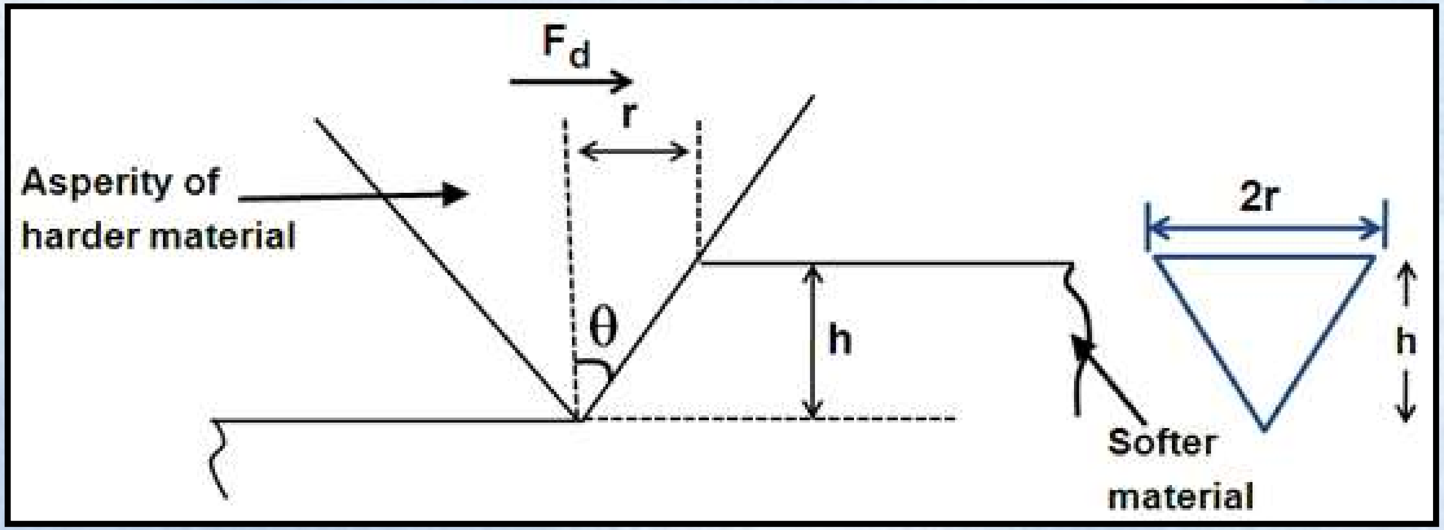


Fig. : Deformation theory[1].

- Contact between tribo-pairs only occurs at discrete points. Assume n conical asperities of hard metal in contact with flat soft metal, vertically project area of contact.

$$W = n(0.5 * \pi r^2)H$$

$$A = n\left(0.5 * \pi r^2\right)$$

$$F = n(rh)H$$

[1]. J Halling, Principles of Tribology, The Macmillan Press Ltd, London, 1975.

FRICTION DUE TO DEFORMATION (Cont..)

- μd = (F/W), substituting the equations of F and W, we get μd = (2/π)cot θ : This relation shows important of cone angle, θ.
- Table lists the μd for various θ values.
- In practice slopes of real surfaces are lesser than 100 (i.e. θ > 800), therefore μd = 0.1. If we add this value(μd = 0.1), total μ, should not exceed 0.3. Total μ, representing contribution for both ploughing and adhesion terms.

Table

θ	μ
5	7.271
10	3.608
20	1.748
30	1.102
40	0.758
50	0.534
60	0.367
70	0.231
80	0.112
85	0.055

PLOUGHING BY SPHERICAL ASPERITY

- If we consider asperities on solid surfaces are spherical, vertical projected area of contact:

$$A = n\left(0.5 * \pi r^2\right)$$

$$or\ A = n\left(0.5 * \pi (0.5\ d)^2\right)$$

$$or\ A = n\ \frac{\pi\, d^2}{8}$$

$$W = n\frac{\pi\, d^2}{8}H$$

$$F = n\ \frac{2hd}{3}H$$

$$\mu_d = \frac{2hd8}{3\pi d^2} = \frac{16}{3\pi}\frac{h}{d} = \frac{16}{3\pi}\frac{h}{\sqrt{8hR}} = 0.6\sqrt{\frac{h}{R}}$$

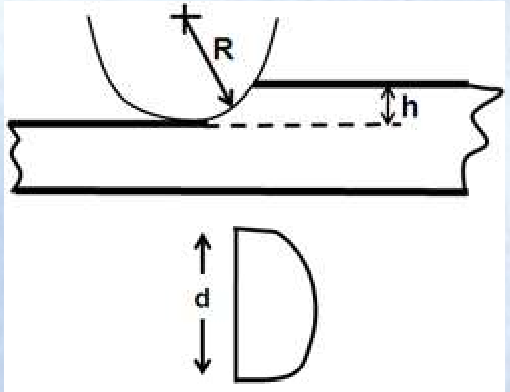


Fig. : Spherical asperity.

- Generally h << R, therefore μd Ξ 0.1. This means total μ, should not exceed 0.3. Summary of theories related to adhesion and ploughing effects.

PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Adhesion, $\mu_a = \frac{s}{H}$

Deformation by Conical Asperities:

$$\mu_d = \frac{2}{\pi}\cot\theta = 0.64\frac{h}{r}$$

Deformation by Spherical Asperities:

$$\mu_d = 0.6\sqrt{\frac{h}{R}}$$

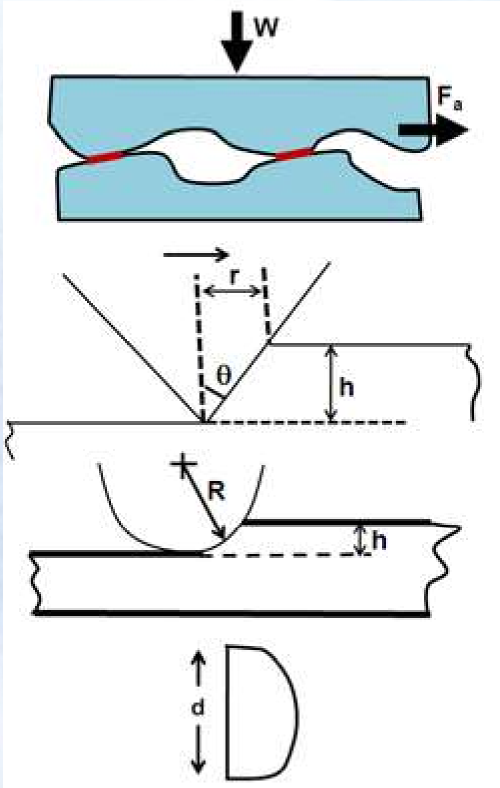


Fig.: Summary of adhesion and ploughing.

PLOUGHING BY SPHERICAL ASPERITY (Cont..)

Three frictional theories were discussed :

- In first expression it is shown that friction depends on the lowest shear strength of the contact tribo-pair. Reducing shear strength and increasing the hardness reduces the coefficient of friction.
- Second expression shows the dependence of coefficient of friction on the angle of conical asperity.
- Third expression indicates lesser sensitivity of coefficient of friction compared to that of conical asperity.
- ✓ None of these expression provides reliable estimation of coefficient of friction which we observe during laboratory tests. Bowden and tabor improved that theory of adhesion and incorporated the limiting shear stress concept.

JUNCTION GROWTH

- Bowden and Tabor were motivated to think that contact area(shown in Fig.) might become much enlarged under the additional shear force and they proposed junction growth theory.
- They considered two rough surfaces subjected to normal load W and friction force at the interface.
- To explain their hypothesis they considered two dimensional stress system(Eq.(1)). If W force is in y-direction and force in x-direction is zero, then principle stresses can be expressed by Eq.(2) and Eq.(3).

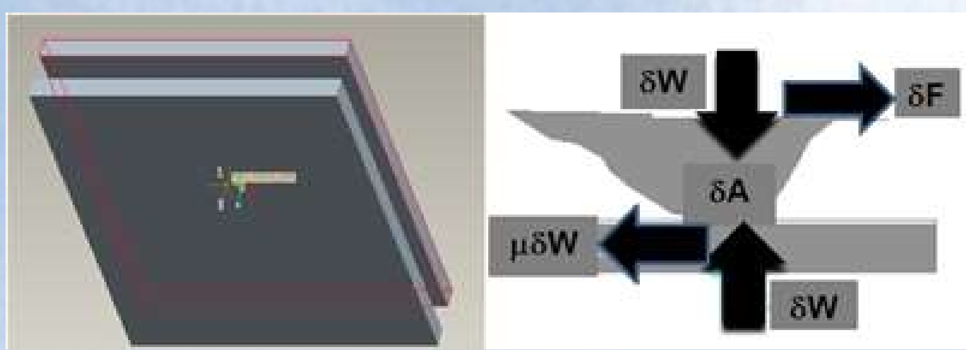


Fig. : Two contacting surfaces.

"WEAR"

Lecture by

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Instructional Objectives

After studying this unit, you should be able to understand:

- Classification of Wear, Theories of adhesive, abrasive, surface fatigue and corrosives wear, erosive, cavitation and fretting wear.
- Wear models, wear of miscellaneous machine components such as gears, plain bearings and rolling element bearings.
- ASTM standards for wear measurement.
- Wear resistant materials & Wear resistant components.

Wear

INTRODUCTION

- Wear is defined as the undesirable but inevitable removal of material from the rubbing surfaces.
- Though the removal of material from the surface is small, it leads to a reduction in operating efficiency.
- The more frequent replacement or repair of worn components and overhauling of the machinery may cost enormously in terms of labour, machine down-time and energy in the manufacture of spares.
- The term wear is used to describe the progressive deterioration of the surface with loss of shape often accompanied by loss of weight and the creation of debris. Through, at the outset wear appears to be simple, the actual process of removal of material is very complex.
- This is because of a large number of factors which influence wear.

Wear (Cont..)

INTRODUCTION

- ❖ The major factors influencing wear are given below:
- ➢ Variable connected with metallurgy.
  - ✓ Hardness.
  - ✓ Toughness.
  - ✓ Constitution and structure.
  - ✓ Chemical composition.
- ➢ Variables connected with service.
  - ✓ Contacting materials.
  - ✓ Pressure.
  - ✓ Speed.
  - ✓ Temperature.
- ➢ Other contributing factors.
  - ✓ Lubrication.
  - ✓ Corrosion.

Wear (Cont..)

INTRODUCTION

- Wear is a process of gradual removal of a material from surfaces of solids subject to contact and sliding.
- Damages of contact surfaces are results of wear.
- They can have various patterns (abrasion, fatigue, ploughing, corrugation, erosion and cavitation).
- The results of abrasive wear are identified as irreversible changes in body contours and as evolutions of gaps between contacting solids.
- The wear depth can be estimated with the aid of wear laws.

Wear (Cont..)

INTRODUCTION

- Further, the wear which occurs in practice is usually a combination of one or more elementary forms.
- Hence, no single empirical relations connecting wear with the operating parameters such as load, speed and material constants for all situations is available.
- In fact the search for such a single relation is somewhat meaningless since several quite distinct phenomena are lumped in a single word Wear.

Wear (Cont..)

INTRODUCTION

- Therefore, to combat wear, it is essential to understand the mechanism of the various elementary forms of wear given below.
  - ✓ Adhesive.
  - ✓ Abrasive.
  - ✓ Surface fatigue.
  - ✓ Corrosive.
- Through the knowledge of elementary forms of wear it is easy to understand the special forms of wear such as:
  - ✓ Oxidative.
  - ✓ Fretting.
  - ✓ Erosion.
  - ✓ Cavitation.

Wear (Cont..)

INTRODUCTION

- Survey carried out on wear encountered in industry has revealed the following contributions:
  - ✓ Abrasive 50%
  - ✓ Adhesive 15%
  - ✓ Erosive 8%
  - ✓ Fretting 8%
  - ✓ Chemical 5%
- There are many situations in which wear can change from one type to another. Adhesive wear may be responsible for generating hard wear debris which then leads to abrasive wear. Two types of wear may operate concurrently; eg: abrasive wear and chemical wear operate together in marine diesel engine cylinder liners

Wear: Basic Concept

- Wear is damage to a solid surface generally involving progressive loss of material, due to relative motion between that surface and a contacting substance or substances.
- This includes topography without loss of materials, as well as the more usual case of material removal.
- The wear processes common in machines in which one surface slid or rolls against another, either with or without the presence of deliberately applied lubricant and the more specialized types of wear which occur when the surface is abraded by hard particles moving across it, or is eroded by solid particles or liquid drops striking it or by the collapse of cavitation bubbles in a liquid.
- The difficulties involved in fully describing and then in formulating models for, the behaviour of a wearing surface are not just associated with the extreme local conditions.

Wear: Basic Concept (Cont..)

- The problem is much more complex than that, for at least three more reasons.
- First, the process of wear itself changes the composition and properties of the surfaces and near surface regions; the material which separates two sliding surfaces can be treated as distinct ‘third- body’ with its own evolutionary history and properties and these properties will often change during the life time of the system.
- Second, the removal or displacement of material during wear leads to change in surface topology.
- Third, the mechanism by which wear occurs are often complex and can involve a mixture of mechanical and chemical processes; for example, in the unlubricated sliding of two steel surfaces, material may be removed by mechanical means after oxidation, while under conditions of boundary lubrication the source of wear is often the mechanical removal of the products of chemical reaction between the steel surface and the lubricant additives.

Classification of Wear Mechanism

- Mechanism of wear are the succession of events whereby atoms, products of chemical conversion, fragments, et al., are induced to leave the system (perhaps after some circulation) and are identified in a manner that embodies or immediately suggests solutions.
- These solutions may include choice of materials, choice of lubricants, choice of contact condition, choice of the manner of operation of the mechanical system, etc.
- The classification of wear parameters, along with descriptive terms of the wear mechanisms, is shown in Table.

Classification of Wear Mechanism

Class	Parameter						
Friction type	Rolling	Rolling–sliding	Sliding	Fretting	Impact		
Contact shape	Sphere/ sphere	Cylinder/ cylinder	Flat/ flat	Sphere/ flat	Cylinder/ flat	Punch/ Flat	
Contact pressure level	Elastic	Elasto-plastic	Plastic				
Sliding speed or loading speed	Low	Medium	High				
Flash temperature	Low	Medium	High				
Mating contact material	Same	Harder	Softer	Compatible	Incompatible		
Environment	Vacuum	Gas	Liquid	Slurry			
Contact cycle	Low (single)	Medium	High				
Contact distance	Short	Medium	Long				
Phase of wear	Solid	Liquid	Gas	Atom	Ion		
Structure of wear particle	Original	Mechanically mixed	Tribochemically formed				
Freedom of wear particle	Free	Trapped	Embedded	Agglomerated			
Unit size of wear	mm scale	µm scale	nm scale				
Elemental physics and chemistry in wear	Physical adsorption, chemical adsorption, tribochemical activation and tribofilm formation, oxidation and delamination, oxidation and dissolution, oxidation and gas formation, phase transition, recrystallization, crack nucleation and propagation, adhesive transfer and retransfer						
Elemental system dynamics related to wear	Vertical vibration	Horizontal vibration	Self-excited vibration	Harmonic vibration	Stick-slip motion		
Dominant wear process	Fracture (ductile or brittle)	Plastic flow	Melt flow	Dissolution	Oxidation	Evaporation	
Wear mode	Abrasive	Adhesive	Flow	Fatigue	Corrosive	Melt	Diffusive
Wear type	Mechanical	Chemical	Thermal				

Classification of Wear Mechanism

- Wear processes can be usefully classified into three broad groups:
  - ✓ Wear by hard particles or liquids.
  - ✓ Wear by sliding and rolling contact.
  - ✓ Chemically assisted wear.
- A brief introduction to the most common wear mechanisms in these categories are:
- ***Wear By Hard Particles or Liquids.***
  - ✓ Well-known wear processes which fall into this category include abrasion, adhesion, corrosion, solid and liquid droplet erosion and cavitation erosion. Collectively, these account for nearly 80 % of all wear-related costs in industry.

Classification of Wear Mechanism

❖ ***Abrasive Wear***

- ✓ This is the form of wear which occurs when a rough hard surface, or a soft surface containing hard particles, slides on a softer surface, and ploughs a series of grooves in it.
- ✓ The material from the grooves is displaced in the form of wear particles, generally loose ones.
- ✓ Abrasive wear can also take place whenever hard foreign particles such as metal grit, metallic oxides, and dust and grit from the environment, are present between the metal and then tear off the metallic particles.
- ✓ The former type is called two body abrasion and the latter three body abrasion (Fig. a and Fig. b).

Classification of Wear Mechanism

❖ ***Abrasive Wear***

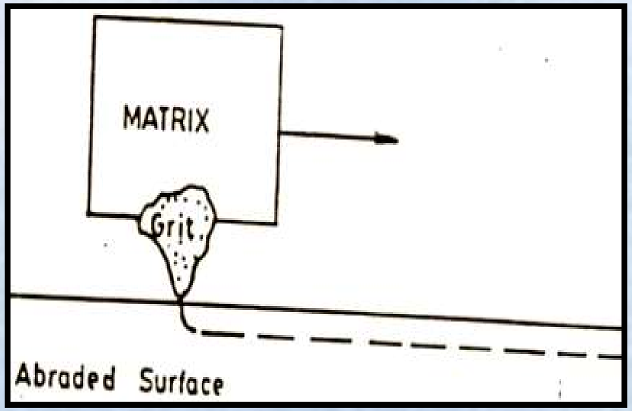

Figure a: Schematic View of 2-Body Abrasive Wear Mechanism .

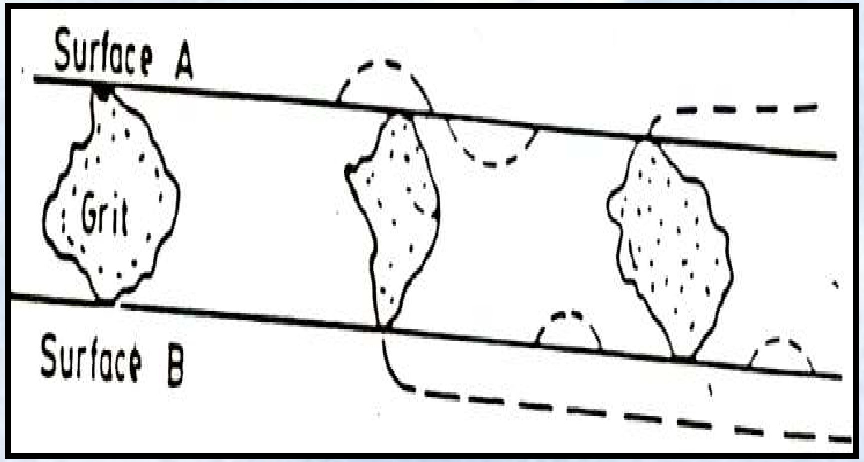

Figure b Schematic View of 3-Body Abrasive Wear Mechanism .

❖ Depending on the severity, abrasive wear is classified into gouging, grinding and scratching abrasion.

❖ Abrasive wear is one of the most common types of wear encountered in engineering practice, and it is probably the highest single cause of wear in many machine applications.

Classification of Wear Mechanism

❖ ***Adhesive Wear***

- ✓ This is the form of wear which occurs when two smooth bodies are slid over each other, and fragments are pulled off one surface to adhere to the other (Fig.).
- ✓ Later, these fragments may come off the surface on which they are formed and be transformed back to the original surface, or else form loose wear particles.

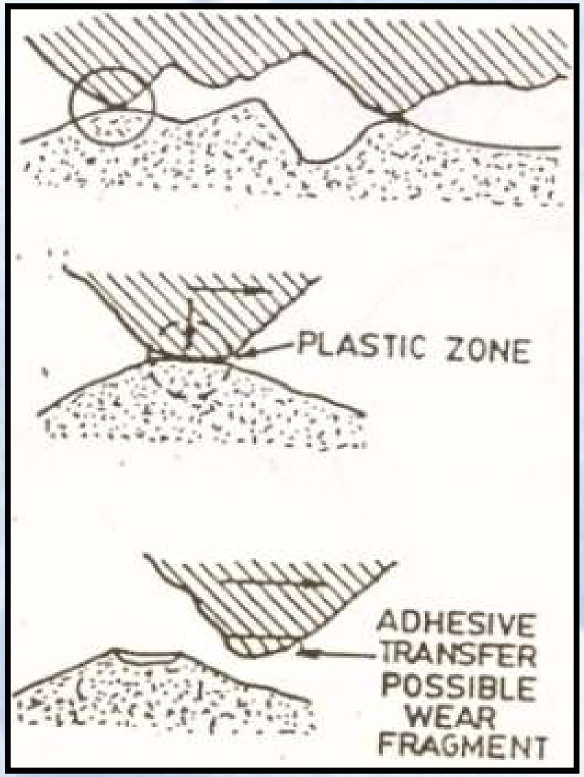

Figure 1.27 Schematic View of Adhesive Wear Mechanism [11].

Classification of Wear Mechanism

- ***Adhesive Wear***
- ✓ Depending on the severity of action adhesive wear is further classified as galling, scuffing, scoring, and seizing wear.
- ✓ This is probably the most basic type of wear.
- ✓ It is caused by a shearing action of microwelds formed between the surface asperities that actually carry the load between two mating surfaces.
- ✓ In turn, film failure is caused by high temperatures, pressures, and sliding velocities.

Classification of Wear Mechanism

❖ ***Corrosive Wear***

- ✓ This form of wear occurs when sliding takes place in a corrosive environment.
- ✓ In the absence of sliding, the products of the corrosion would form a film on the surfaces, which would tend to slow down or even arrest the corrosion, but the sliding action wears the film away, so that the corrosive attack can continue (Fig.).
- ✓ It is not easy to find a good illustration of corrosive wear, but an example of it is the IC engine cylinder surface wear.

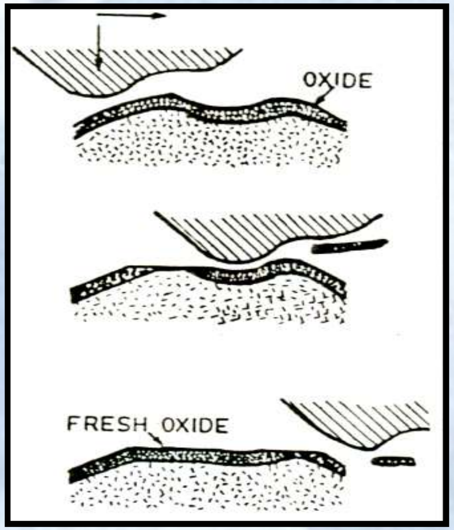

Figure: Schematic View of Oxidative Wear Mechanism .

Classification of Wear Mechanism

❖ ***Surface Fatigue Wear***

✓ This form of wear is observed during repeated sliding or rolling over a track. The repeated loading and unloading cycles to which the materials are exposed may induce the formation of surface or subsurface crack, which eventually will result in the break-up of the surface with the formation of large fragments, large pits in the surface (Fig.).

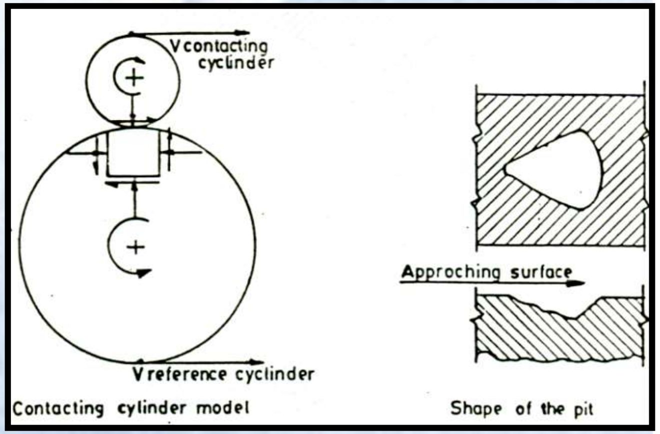

Figure: Schematic View of Surface Fatigue Wear Mechanism .

✓ This form of wear is also known as pitting, pitting corrosion, spalling and cause crushing. It is normally encountered in a pair of gears, ball and a race or cam and the follower.

Classification of Wear Mechanism

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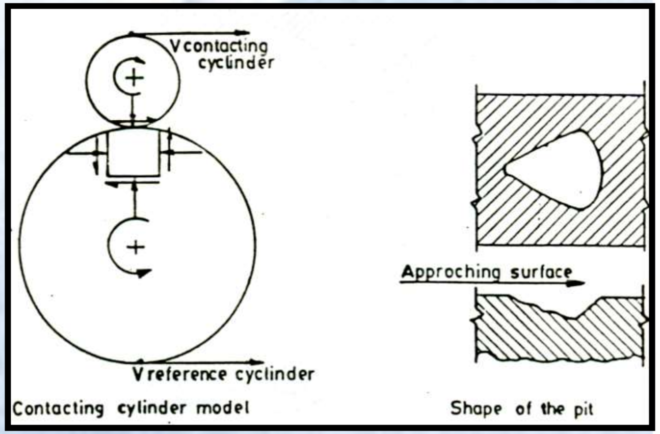

Figure: Schematic View of Surface Fatigue Wear Mechanism .

✓ This form of wear is also known as pitting, pitting corrosion, spalling and cause crushing. It is normally encountered in a pair of gears, ball and a race or cam and the follower.

Classification of Wear Mechanism

- ***Surface Fatigue Wear***
- ✓ The surface fatigue wear is further classified into two groups.
- ✓ Incipient pitting which is taking place when two virgin surfaces make the repeated sliding contacting.
- ✓ This may continue till the surfaces bed-in and will not progress thereafter.
- ✓ Destructive pitting sets in if the corrective action associated with the incipient pitting at the beginning of operation is insufficient to halt the pit formation.
- ✓ This is characterized as being progressive and leads to disintegration of the surface.

Classification of Wear Mechanism

- ***Special Forms Of Wear***

These are either another form of the basic types of wear arising out of changed situation or combination of the basic types of wear. Among these oxidation fretting, erosion and cavitation are the predominant types of wear encountered in Engineering field.

- ***Oxidative Wear***

- ✓ This is another form of adhesive wear.
- ✓ Metallic surfaces exposed to any atmosphere bearing oxygen will get oxidized and thin oxide film will be formed on the surface.
- ✓ This oxide film diminishes the adhesive wear and result in mild wear. However, during sliding it gets ruptured if not adherent to the surface and results in wear debris predominantly oxide in nature.

Classification of Wear Mechanism

- ***Special Forms Of Wear***
  - ***Fretting Wear***

- This type of wear is also known by several names viz. Frottage, fretting corrosion, false brinelling, wear oxidation, friction oxidation and chafing fatigue.
- It is a combination of adhesive, corrosive and abrasive wear.
- This form of wear arises when contacting surfaces undergo oscillatory tangential displacement of small amplitude.
- A typical example would be a splined out of line shaft coupling, in which the steel teeth undergo one small tangential to and fro movement per shaft revolution.

Classification of Wear Mechanism

- ***Special Forms Of Wear***
  - ***Fretting Wear***

✓ This type of partial movements also occurs in press-fitted assemblies.

✓ Damage may vary from discolouration of the mating surfaces to the wearing away of 1.5mm of material.

✓ In addition, the surface may show the formation of a great deal of corroded material or may have a heavily galled appearance with little oxide.

✓ It is presumed that the oscillatory motion breaks down any natural protective film on the surface, causing the metal to adhere and break away at each oscillation.

✓ Fretting damage is found in automobile front wheel bearings, kingpins, rocker arms, variable pitch propellers, landing wheels, cam followers in textile machinery, and electrical contacts.

Classification of Wear Mechanism

❖ ***Special Forms Of Wear***

➢ ***Fretting Wear***

✓ Then the debris may be converted into an abrasive oxide which causes the severe damage (Fig.).

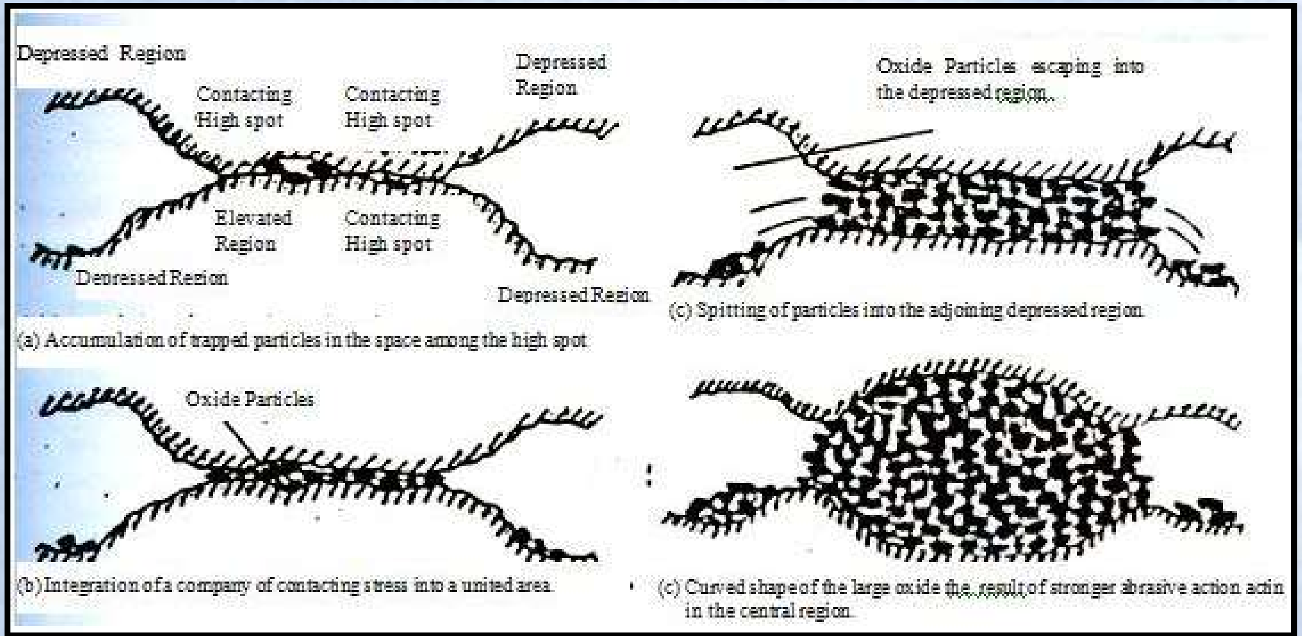

Figure: Schematic View of Fretting Wear Mechanism.

Classification of Wear Mechanism

❖ ***Special Forms Of Wear***

➢ ***Erosion***

- ✓ The damage produced by sharp particles impinging on an object is closely analogous to that produced by abrasion.
- ✓ The main difference is that in erosion the surface roughness produced may become relatively greater, because an impinging particle may readily remove material from a low point on the surface (Fig.).

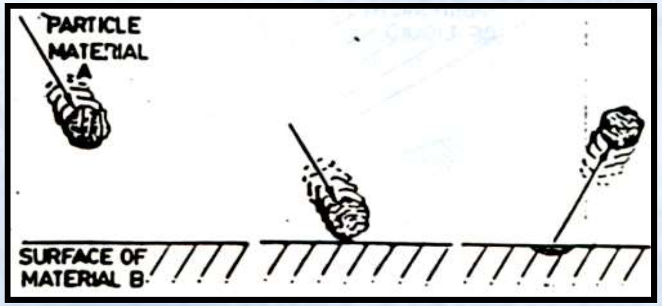

Figure: Schematic View of Fretting Wear Mechanism.

Classification of Wear Mechanism

❖ ***Special Forms Of Wear***

➢ ***Cavitation***

✓ This is a process of surface damage and material removal caused by a liquid or gas without the presence of a second surface. In industrial practice the most common type of erosion is cavitation erosion (Fig.).

✓ It occurs in propeller blades, diesel engine cylinder liners, turbines and pumps. Cavitation is caused by high relative motions between the metal and the liquid.

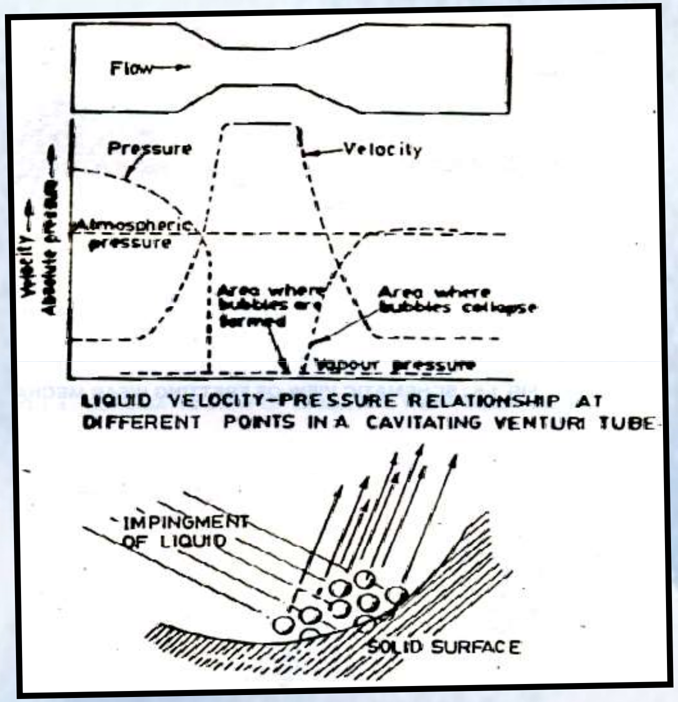

Figure: Schematic View of Cavitation Wear Mechanism.

Classification of Wear Mechanism

- ***Special Forms Of Wear***
  - ***Cavitation (Cont...)***
- ✓ At such motions, the local pressure on the liquid is reduced, the liquid temperature reaches the boiling point, and the cavities of the vapour are formed. When the pressure returns to normal, implosion occurs and the cavity collapses.
- ✓ This produces high impact forces on the metal, causing work- hardening, fatigue, and formation of cavitation pits.
- ✓ This action is purely mechanical, but often it exists in the presence of galvanic corrosion.

Classification of Wear Mechanism

❖ ***Wear By Sliding and Rolling Contact***

➢ ***Sliding Wear***

✓ Sliding wear is due to two solid surfaces sliding over each other under some applied load. In most engineering applications, such as plain bearings or bushings, the surfaces are lubricated in which case any wear that occurs is termed lubricated wear.

✓ Sliding wear is often also called adhesive wear, which is somewhat misleading since adhesion between the sliding surfaces represents but one aspect of sliding wear.

✓ Nevertheless, adhesion is evident in the well-known phenomena of scuffing and galling, which occur under conditions of high applied loads and/or poor lubrication.

Classification of Wear Mechanism

❖ ***Wear By Sliding and Rolling Contact***

➢ ***Sliding Wear (Cont...)***

✓ A characteristic feature of the sliding wear of metals is the occurrence of transitions in the rate of material loss as a function of sliding speed, applied load, and ambient temperature.

✓ In the mild (oxidational) wear regime, the sliding metals are separated by thin oxide films and direct metallic contact occurs only occasionally.

✓ Wear rates are low and the debris formed by the wear process is typically finely divided and consists of a mixture of metallic oxides.

✓ Mild wear is generally associated with the low loads and sliding speeds, although a severe form of oxidational wear can occur at high speeds and low loads where high interfacial temperatures result in rapid oxide film growth.

Classification of Wear Mechanism

❖ ***Wear By Sliding and Rolling Contact***

➢ ***Sliding Wear (Cont...)***

✓ With increasing loads and speeds, transitions occurs from mild to severe wear as a result of a change in the nature of the contact.

✓ The severe wear regime is characterised by penetration of the oxide films and direct metallic contact.

✓ Friction stresses tend to be high as a result of adhesion between the sliding metals and metallic wear debris is formed by material transfer and/or subsurface cracking and delamination.

✓ The wear rates experienced in the severe wear regime are two to three orders of magnitude higher than in the mild wear regime and are unacceptable in engineering applications.

Classification of Wear Mechanism

❖ ***Wear By Sliding and Rolling Contact***

➢ ***Rolling Contact Wear***

- ✓ Rolling contact wear occurs as a result of the repeated application of mechanical stresses to the surface of one body rolling on another body.
- ✓ It is most commonly found in components such as rolling element bearings and gears and is characterised by pitting due to surface fatigue.
- ✓ For this reason, the wear process is also often called rolling contact fatigue.
- ✓ The fatigue process is exacerbated by sliding (slip) which often accompanies the rolling motion, particularly in gears, and applies additional friction stresses on the surfaces.
- ✓ It is therefore important to ensure adequate lubrication of rolling systems in order to minimise the influence of slip.

Classification of Wear Mechanism

❖ ***Wear By Sliding and Rolling Contact***

➢ ***Chemically Assisted Wear***

✓ Chemically assisted wear refers to material damage which is caused by the combined influence of wear and environmental attack (corrosion).

✓ It is widely encountered in industrial systems such as slurry handling equipment and power generation plant.

✓ The rate of material loss associated with chemically assisted wear is often considerably higher than the sum of the material loss rates due to wear and corrosion alone (i.e. these mechanisms act synergistically).

✓ This is not unexpected since wear can accelerate corrosion by removing protective oxide films and exposing fresh, reactive metal surfaces.

✓ A special case of chemically assisted wear is fretting wear or fretting corrosion which is caused by small amplitude oscillations of contacting surfaces which are normally at rest.

Laws of wear

❖ **ARCHARD'S LAW OF ABRASIVE WEAR**

- ✓ Friction and wear depend as much on sliding conditions (the normal pressure and the sliding velocity) as on properties of materials concerned.
- ✓ The normal pressure and the sliding action are necessary for wear, i.e. mechanical wear is a result of the mechanical action.
- ✓ Therefore, the wear process depends first of all on the rubbing process.
- ✓ The earliest contributions to the wear constitutive equations were made by Holm (1946).
- ✓ Holm established a relationship for the volume of the material removed by wear (W) in the sliding distance (s) and related it to the true area of contact.

Laws of wear

❖ **ARCHARD'S LAW OF ABRASIVE WEAR**

- ✓ Archard (1953) formulated the wear equation of the form: the volume of the material removed (W) is directly proportional to the sliding distance (s), the normal pressure (pn) and the dimensionless wear coefficient (k), and inversely proportional to the hardness of the surface being worn away (H), i.e.,

$$W = k\frac{p_n s}{H}$$

- ✓ Nowadays, it is generally recognized that wear is related to the wear coefficient, the pressure and the sliding distance.
- ✓ Pin-on-disc test experiments can be used to determine how wear is acted by the pressure and the sliding distance.

Role of wear debris in modifying friction and wear

- ✓ The friction phenomenon is very sensitive to changes of sliding conditions.
- ✓ Experimental studies demonstrate that wear particles entrapped between sliding surfaces can affect frictional and wear behaviour very signicantly.
- ✓ The presence of the debris implies modifications of the friction coefficient and the wear rate, see Kuwahara and Masumoto (1980).
- ✓ Circulation of wear particles is reflected by the friction coefficient, which increases when the particles are accumulated and decreases when the particles are removed from the sliding interface.
- ✓ According to Suh and Sin (1980), the kinetic coefficient of friction for metals is in the neighbourhood of 0.1 to 0.2 (but mostly in the range of 0.12 to 0.17) regardless of materials tested, i.e. gold on gold, steel on steel, brass on steel, etc.

Role of wear debris in modifying friction and wear

- Wear particles entrapped between sliding surfaces affect frictional behaviour increasing the friction coefficient to 0.5-0.7.
- Variations in the friction coefficient show evolution of the amount of debris in the contact; a stability of the friction coefficient indicates a constant amount of debris in the contact interface.
- In some experiment study, a steady value of the friction coefficient was reached when the number of newly formed wear particles was equal to the number of particles leaving the contact interface (= 0.28 initial value, = 0.63 steady value).
- The steady-state wear rate may be larger for some sliding conditions where wear particles cannot be removed from the contact and act as abrasive particles.

Role of wear debris in modifying friction and wear

- ✓ There is a number of reports in the literature that spherical and cylindrical wear particles roll over each other with resulting low friction.
- ✓ It has also been reported that, as a result of the roll formation, the coefficient of friction undergoes transition to lower values by a factor of three, and the wear decreases by several orders of magnitude.
- ✓ The coefficient of friction in the presence of rolls usually ranges from 0.1 to 0.4 (Zanoria et al., 1995).
- ✓ It has been suggested that cylindrical debris can act as miniature roller bearings or "solid lubricants", so that sliding friction can be reduced.

Models of Wear

- Bahadur (1978) presented 13 analytical expressions for the prediction of wear published in the years 1937-1974.
- Earlier relationships connected the volume of the removed material with hardness only.
- Meng and Ludema (1995) found more than 300 equations of wear published during the period 1955-1995.
- The great number of independent variables that influence the wear rate was used in those equations, namely 625 variables.
- Meng and Ludema (1995) classified three general stages of deriving wear equations: empirical equations, phenomenological equations, equations based on materials failure mechanisms.

Models of Wear

- ✓ Ludema (1996) classified the variables of wear equations as follows: variables from fluid mechanics, variables from solid mechanics, variables from material sciences, variables from chemistry.
- ✓ In spite of that, at present, Archard's law is a quantitatively simple calculation procedure of wear, see Rabinowicz (1995), Ravikiran (2000), Kato (2002).
- ✓ Some researchers try to define the so called wear criterion. They define a place in the body boundary where the wear process is initiated.
- ✓ Usually it depends on the existence and development of the sub-surface plastic zones.
- ✓ Kennedy and Ling (1974) assumed that the wear criterion is a modified criterion for plastic zone.

Models of Wear

- If the second invariant J2 of the stress deviator equals or exceeds the critical value W (i.e. the yield stress of the material) then wear will occur

$$J_2 \geqslant \overline{W}$$

  where, the second invariant of the deviatoric part of the stress tensor and the critical value are given by

$$J_2 = \frac{1}{2}\operatorname{tr} S^2 \qquad S = \sigma - \frac{1}{3}(\operatorname{tr}\sigma)\mathbf{1} \qquad \overline{W} = \overline{k}^2$$

  where, k^{-2} is the yield stress of the softer material. If J2 < W no wear will occur.

- It is assumed that when the accumulated strain energy reaches the critical value at which the yielding occurs, most of this energy is transformed into production of wear particles.
- In such a place, the amount of wear is calculated, i.e. the volume of the removed material or the wear depth.

Models of Wear

- ✓ Yang et al. (1993) assumed that wear is first expected to take place at the point with the maximum critical stress.
- ✓ The wear equation can be derived from the maximum stress principle criterion (e.g. von Mises criterion) and yield strength.
- ✓ According to Ting and Winer (1988), wear is assumed to result from the yielding of materials. The yielding condition is governed by the temperature dependent yield strength and the stress field of a material.
- ✓ The stress field is combined from the isothermal stress field generated by surface traction and the thermal stress field induced by frictional heating.
- ✓ Ohmae and Tsukizoe (1980) simulated numerically large wear particle formation (so called delamination wear) using the finite element method and theory of elastic-plastic deformations.

Models of Wear

- Ohmae and Tsukizoe (1980) divided the contact surface into very small finite elements.
- It was assumed that each element represented a dislocation cell.
- The typical cell size was found to be 0.5 m.
- When the equivalent stress of the element exceeds the failure stress (i.e. the fracture stress), a void of failure is generated.
- From these voids, cracks are propagated along directions of maximum plastic stresses.
- Penetrating into the bulk of the body, the cracks cause generation of wear particles.
- Ohmae (1987) recognized that large plastic deformations that lead to the void nucleation can only be dealt with properly used theory of large strains and displacements.

Models of Wear

- Furthermore, Ohmae (1987) discussed different wear criteria used by various researchers: stress intensity factor, J-integral (proposed by Rice), etc.
- Dierent approaches to modelling of wear are present in the literature.
- In the opinion of some researchers, wear laws should not be accepted as postulates, but as a consequence of both a geometry of surface micro-regions (asperities) and elastic-plastic deformations of interlocking surface asperities, Kopalinsky and Oxely (1995), Torrance (1996).

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Thank You