Tribology – *At a Glance*

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Introduction

- Tribology is derived from the Greek word “Tribos”. Meaning of Tribos is Rubbing.

- Tribological knowledge helps *to improve service life, safety and reliability* of interacting machine components; and yields substantial economic benefits.
- Tribology is the science and technology of interacting surfaces in relative motion (and the practices related thereto), including the subject of *friction, wear* and *lubrication*.

- BEARINGS –

  Minimal friction & Minimal wear
- BRAKES –

  Maximum friction & Minimal wear
- MACHINING –

  Minimal friction & Maximum wear

Lubrication….? ? ?

Tribological Examples

- Left hand side is photograph of centrally grooved engine *journal bearing.*
- It appears that bearing is worn out due to foreign particles.

- Right hand side is a photograph of an *aluminum bearing* subjected to heavy load,
- Which causes shaft surface to run over bearing inner surface.

Tribological Examples

- Deep cracks which breaks outer ring in number of pieces. Such failure occurs due to faulty manufacturing and wrong assembly of *roller bearing*.
- Tribological relations help estimating increase in contact stresses due to misalignment of shaft and improper mounting of bearing surfaces.
- Hence an approximate reduction in service life can be estimated.

- A pit on the surface of *gear tooth* is shown in Fig. The pit generally occurs due to excessive contact stress.
- Understanding the effect of contact stress helps in developing an equation for estimation of perspective gear life.

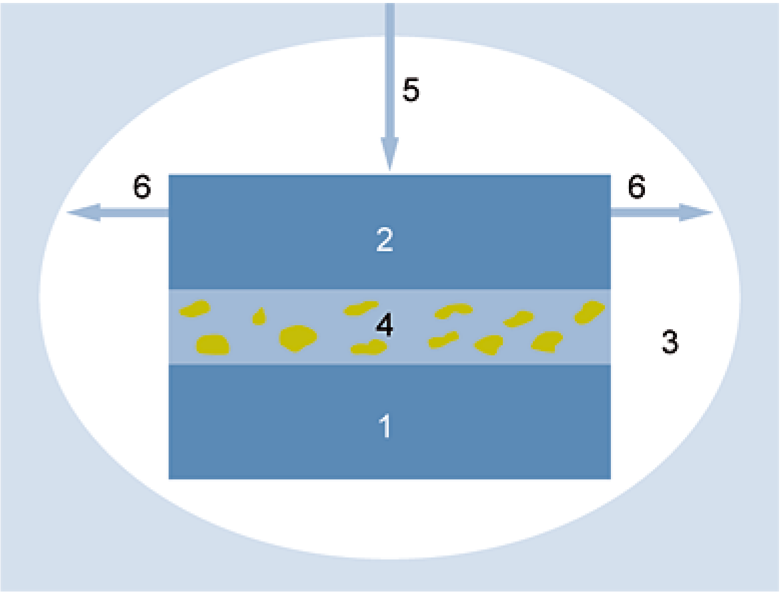
Tribological Examples

Why… Tribology…?

- Friction, wear and lubrication have been taught in many science and engineering classes at basic level. It means *empirically derived trends* (friction force is proportional to loading force, static friction is greater than kinetic friction, viscous friction in a fluid is proportional to the normal contact force, etc.) are often used as the only *predictive tools* over a limited range of parameters, so one does not even know which are the important parameters and at what range the observed trends are valid. This poor predictive power has led the field of tribology important to learn.
- Most tribological phenomenon are inherently *complicated and interconnected*, making it necessary to understand the concepts of Tribology in detail.
- *Integration of knowledge* from multi-disciplines (solid mechanics, fluid mechanics, material science, chemistry etc) is essential and therefore a separate subject is required.

Tribological System

- A tribological system consists of the surfaces of two components that are in moving contact with one another and their surroundings. The type, progress and extent of wear are determined by the materials and finishes of the components, any intermediate materials, surrounding influences and operating conditions



1 Base object
2 Opponent body
3 Surrounding influences: Temperature, relative humidity, pressure
4 Intermediate material: Oil, grease, water, Particles, contaminants
5 Load
6 Motion

Surface Phenomenon

- In tribology, motion under load induces stresses, which leads; elastic bending, breakage or ploughing of soft surface by asperities. It appears that *surface roughness* plays an important role in tribological phenomena.

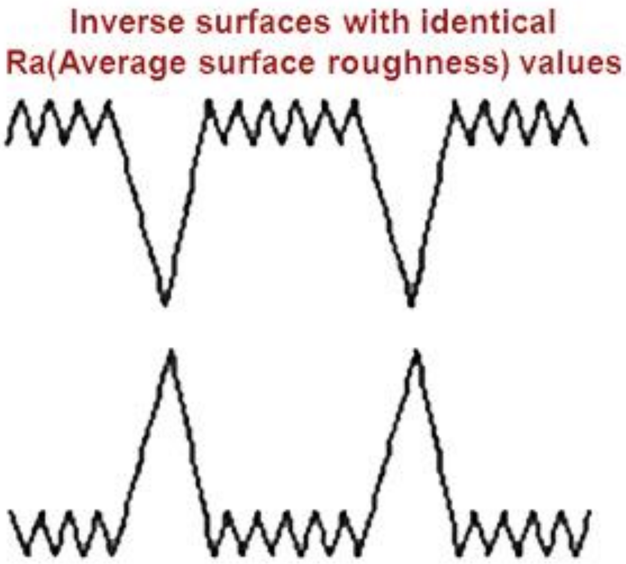
- *Failure rate* of any tribo pair (two machine components in relative sliding motion) depends on the surface roughness of machine components

- As two surfaces are brought together, surface roughness causes contact to occur at discrete contact spots. *Elastic and plastic deformations* occur in the region of contact spots, establishing stresses which oppose the applied load. When a elastic solid (completely reversible stresses and strains) is slide against a slider, it experiences cyclic loading.

Continue…

- Due to positive deviations (roughness above the nominal surface), the contact between solids confines to a very small fraction of nominally area (δA), and as a result estimated contact stress on rough surface = $F/\delta A$ are much higher in magnitude compared to nominal stresses as expressed by following equation : Stress on smooth surface = F/A

- Based on this understanding it can be stated that following two surfaces are *least preferred* from tribology point of view :



Inverse surfaces with identical Ra(Average surface roughness) values

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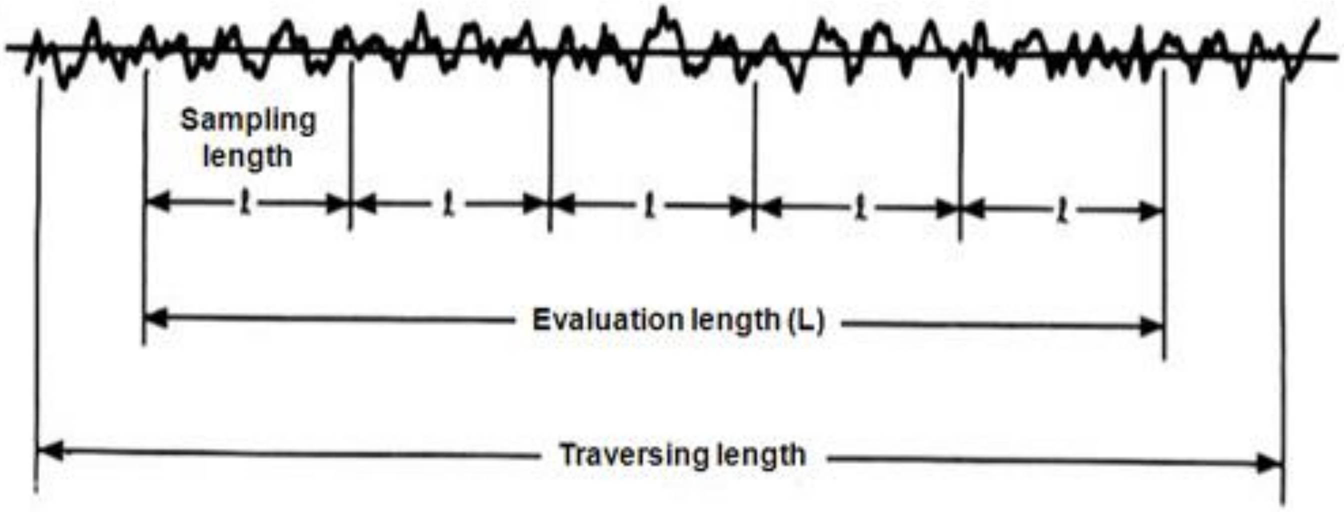
- Surface roughness is defined by short wavelength vertical deviations from nominal surface. Larger the deviations, rougher the surface. Fig. shows three different length: *Sampling length, evaluation length and traversing length*.

- This figure shows that traversing length is greater than evaluation length. This means we collect more sampling data and reject few data collected at the start and end of stylus. Further, to find statistically reliable surface roughness, averaging of roughness data over five sampling lengths is performed. Often roughness is quantified as average (R_a) and root mean square (R_q) roughness.



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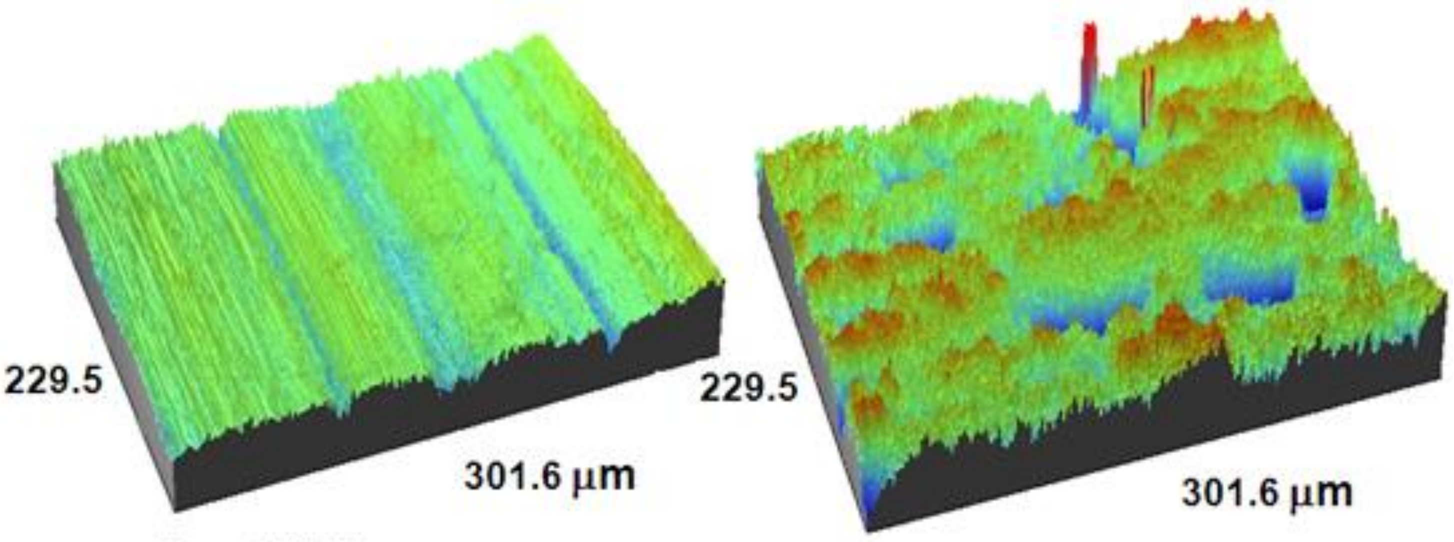
- Fig. shows too tribo-surfaces. If we compare R_a and R_q values of two images as shown in (a) and (b) respectively, we find *better performance* of (a) compared (b).
- In other words rough surfaces usually wear *more quickly* and have *higher friction coefficients* than smoother surface.



R_a : 451.61 nm
R_q : 597.96 nm

(a) Good Surface

R_a : 1.25 µm
R_q : 1.80 µm

(b) Bad Surface

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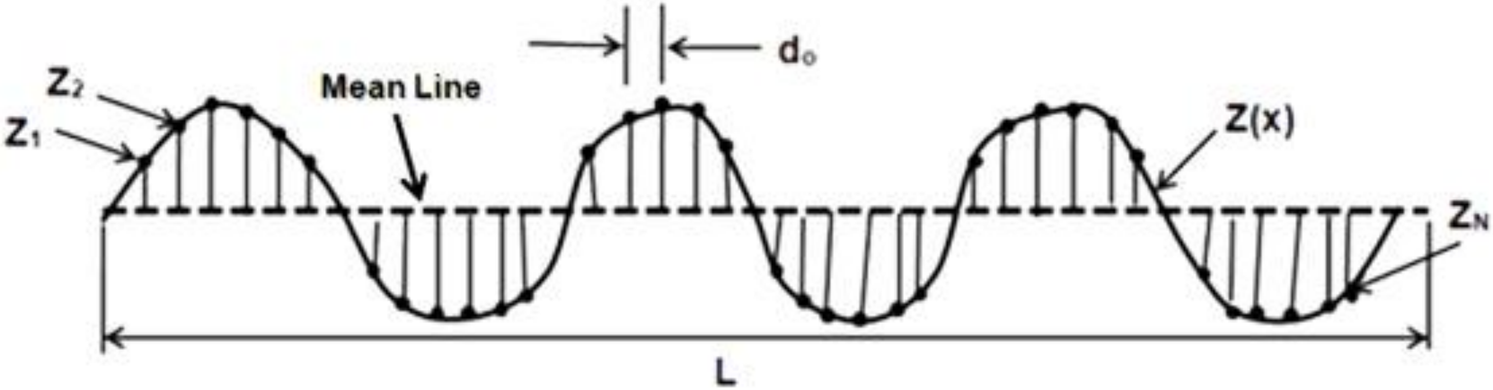
- Surface roughness is quantified by R_a and R_q values which can be calculated by *discrediting surfaces* as shown in Fig. in number of points.

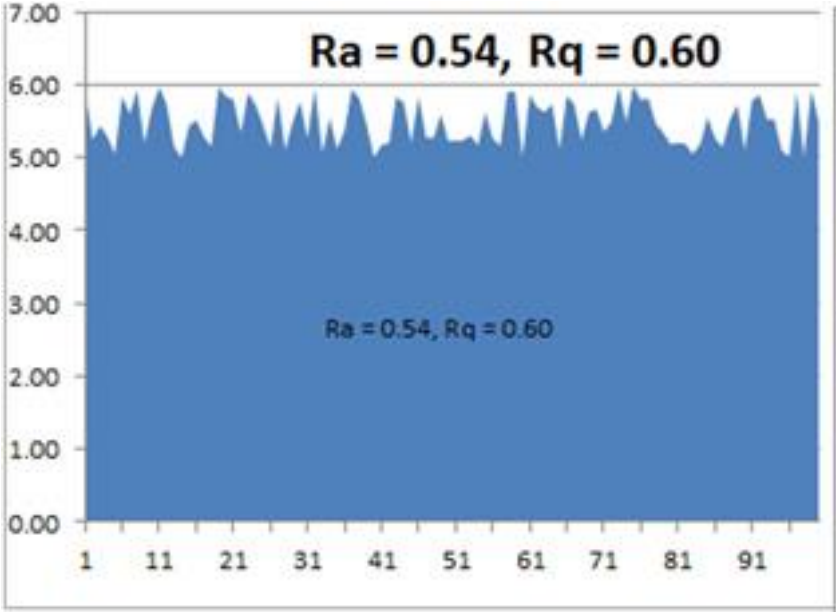


$$R_a = \left(|z_1| + |z_2| + \ldots |z_{N-1}| + |z_N|\right) / N$$

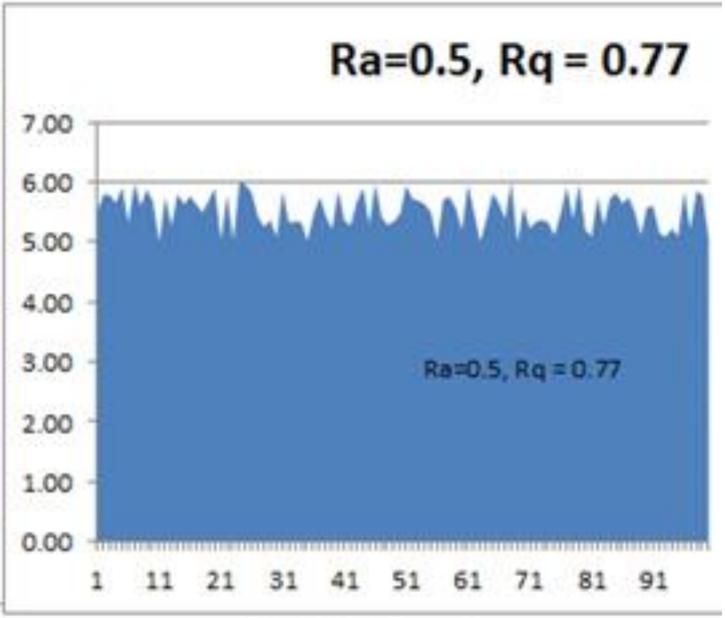
$$R_q = \sqrt{\left(\frac{z_1^2 + z_2^2 + \ldots z_{N-1}^2 + z_N^2}{N}\right)}$$

Continue…

- From Tribology point of view R_q(root mean square) roughness is *preferred* over R_a(Average) roughness. Fig. (a) surface is treated as a good surface compared to surface shown in Fig. (b) due to lower value of R_q .
- This feature is often missed on comparing R_a value of two surfaces that is why comparing R_q values is *more important* than R_a values.



(a) Good Surface

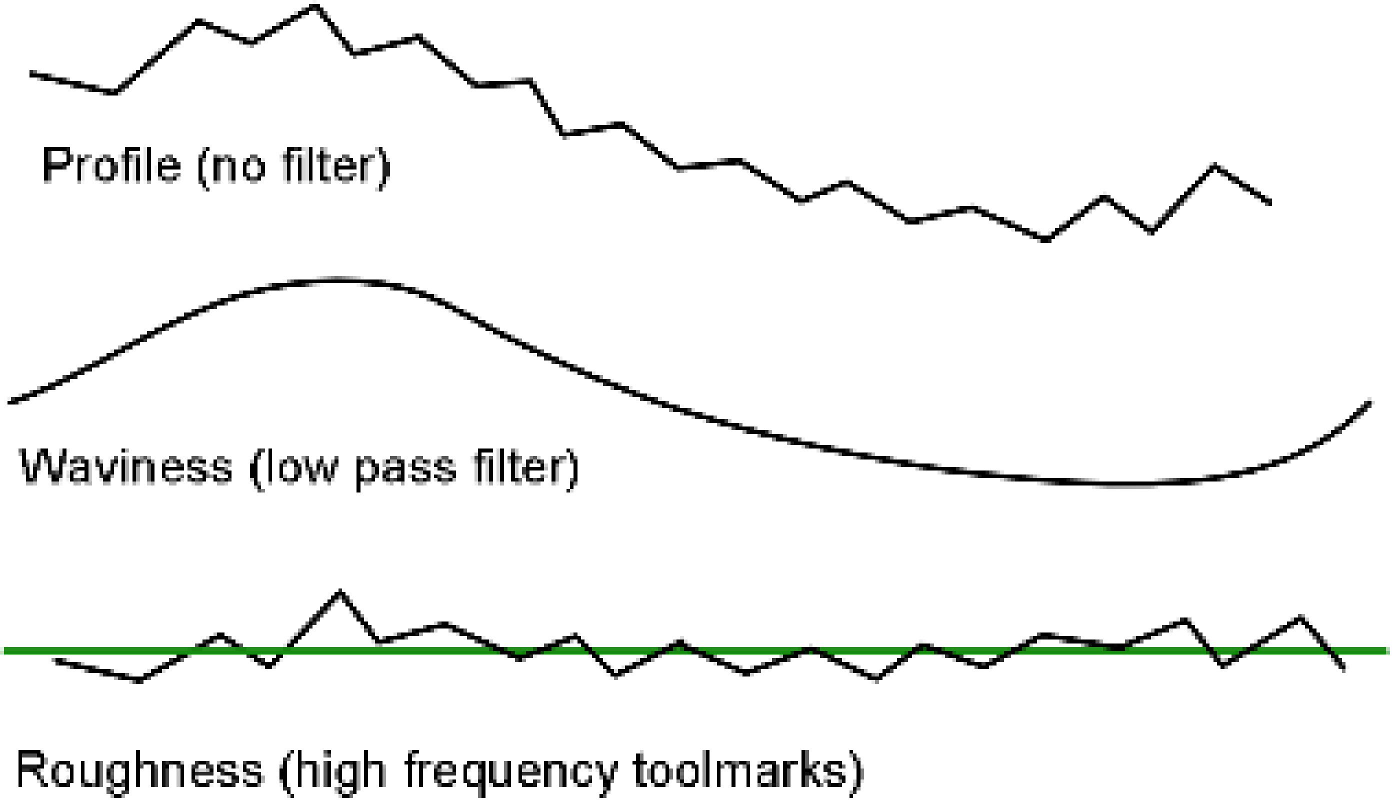


(b) Bad Surface

Numerical

- Take actual reading and calculate RA and RMS value of three different kind of surface of actual machine components.

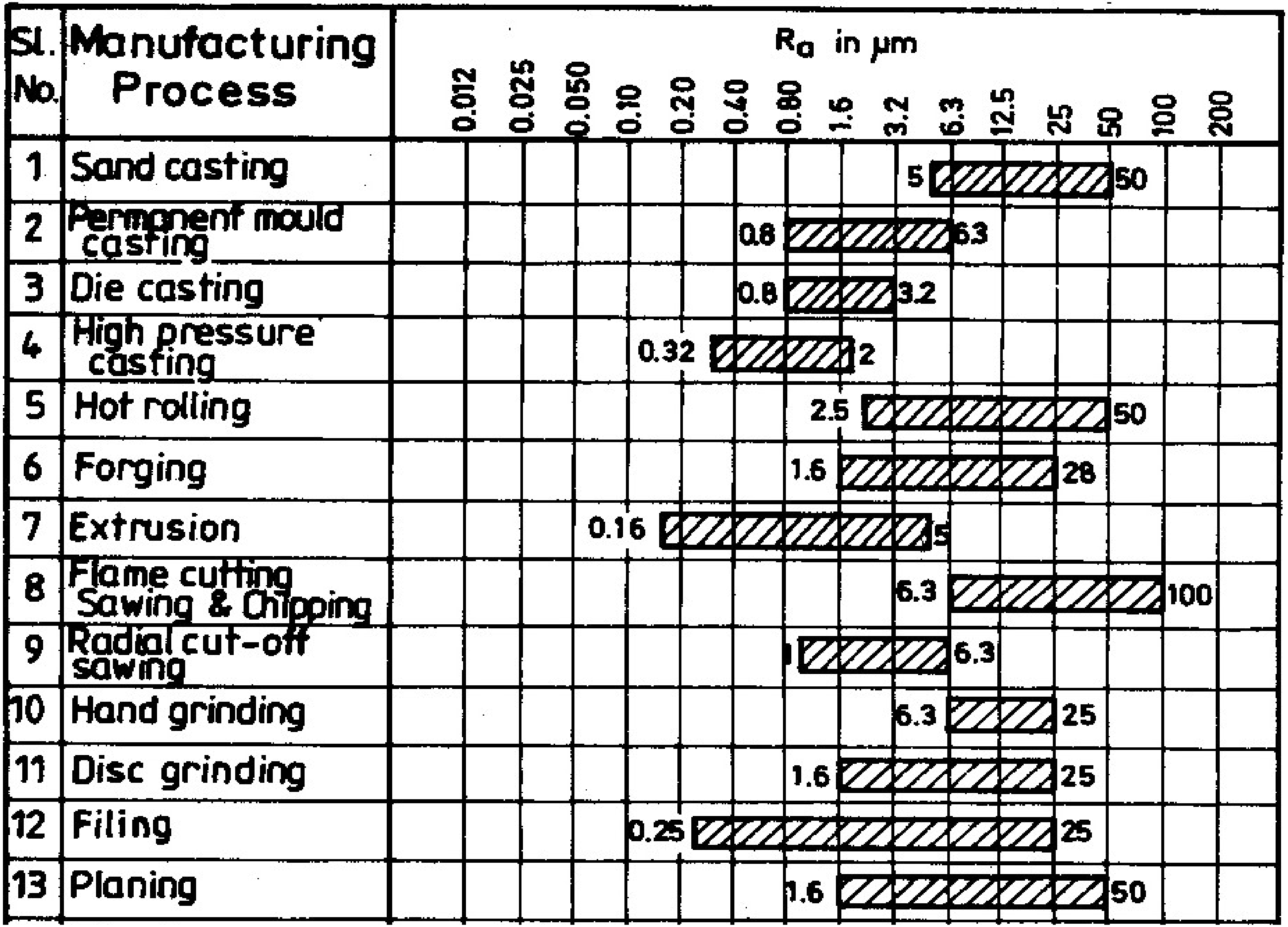
Surface Irregularities

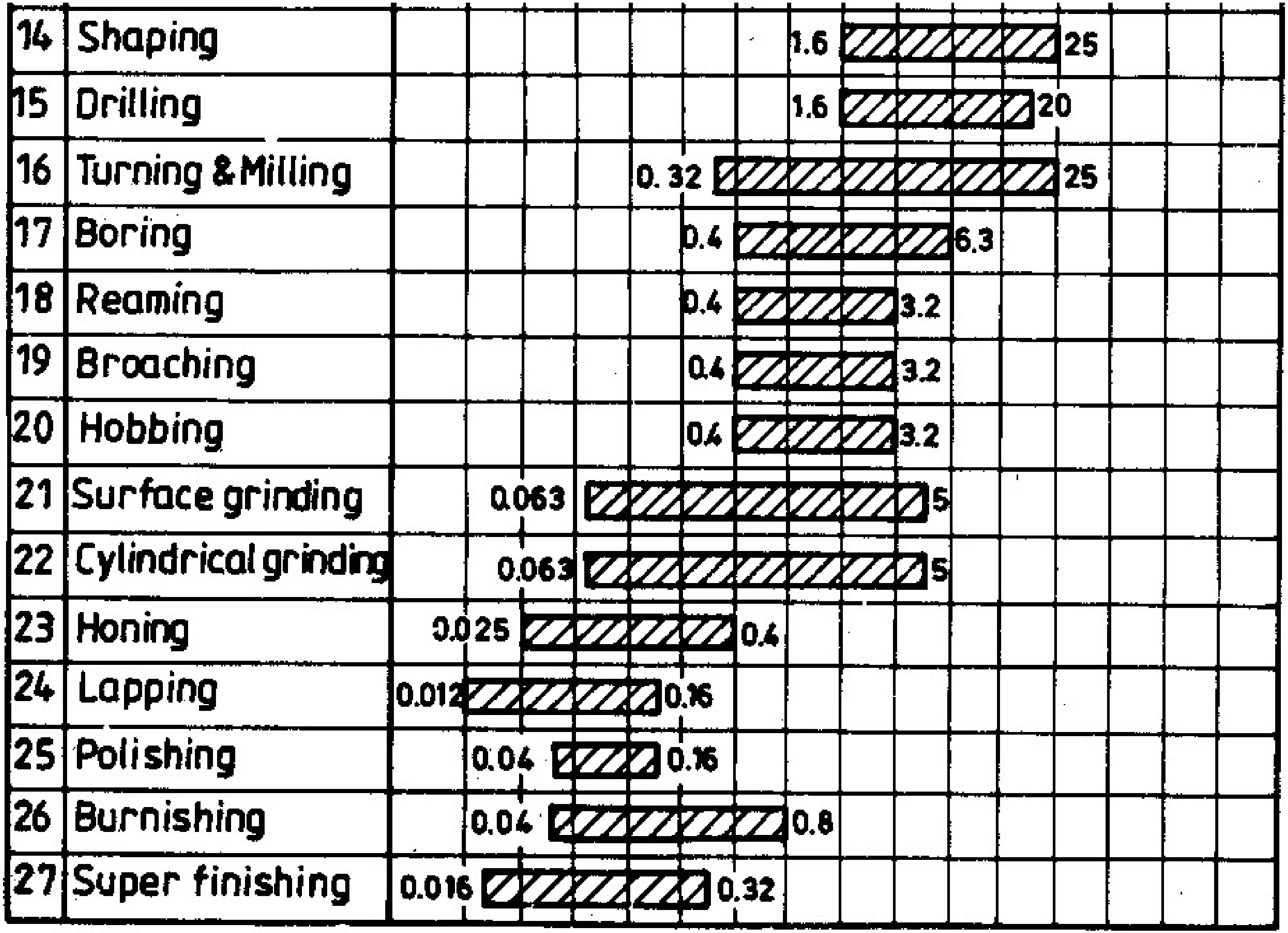


Profile (no filter)

Waviness (low pass filter)

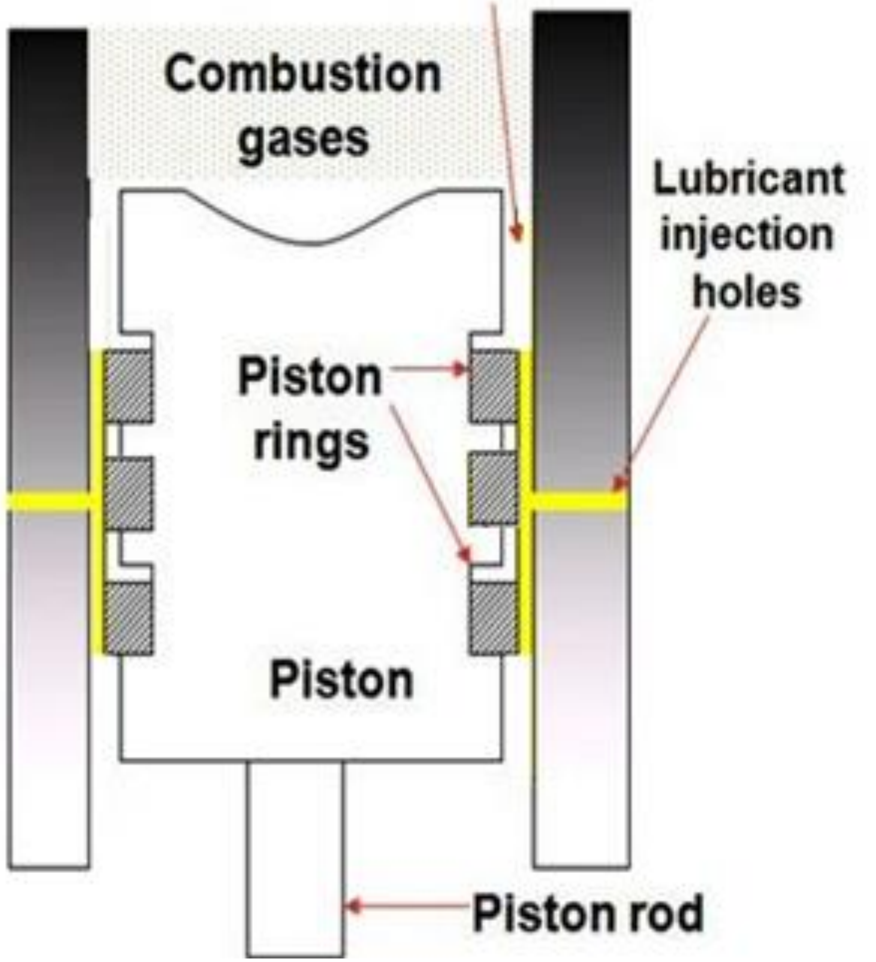
Roughness (high frequency toolmarks)


Sl. No.
Manufacturing Process
Ra in µm
0.012
0.025
0.050
0.10
0.20
0.40
0.80
1.6
3.2
6.3
12.5
25
50
100
200
1 Sand casting 5 50
2 Permanent mould casting 0.8 63
3 Die casting 0.8 3.2
4 High pressure casting 0.32 2
5 Hot rolling 2.5 50
6 Forging 1.6 28
7 Extrusion 0.16 5
8 Flame cutting Sawing & Chipping 6.3 100
9 Radial cut-off sawing 1 6.3
10 Hand grinding 6.3 25
11 Disc grinding 1.6 25
12 Filing 0.25 25
13 Planing 1.6 50


14 Shaping 1.6 25
15 Drilling 1.6 20
16 Turning & Milling 0. 32 25
17 Boring 0.4 6.3
18 Reaming 0.4 3.2
19 Broaching 0.4 3.2
20 Hobbing 0.4 3.2
21 Surface grinding 0.063 5
22 Cylindrical grinding 0.063 5
23 Honing 0.025 0.4
24 Lapping 0.012 0.16
25 Polishing 0.04 0.16
26 Burnishing 0.04 0.8
27 Super finishing 0.016 0.32

Economic Benefits

- There are more than 700 million vehicles in world. Average power of engine is estimated as 30 BHP and with tribological knowledge this can be increased by 2 to 5%. If we assume 2% improvement in BHP, then 420 million HP can be saved.



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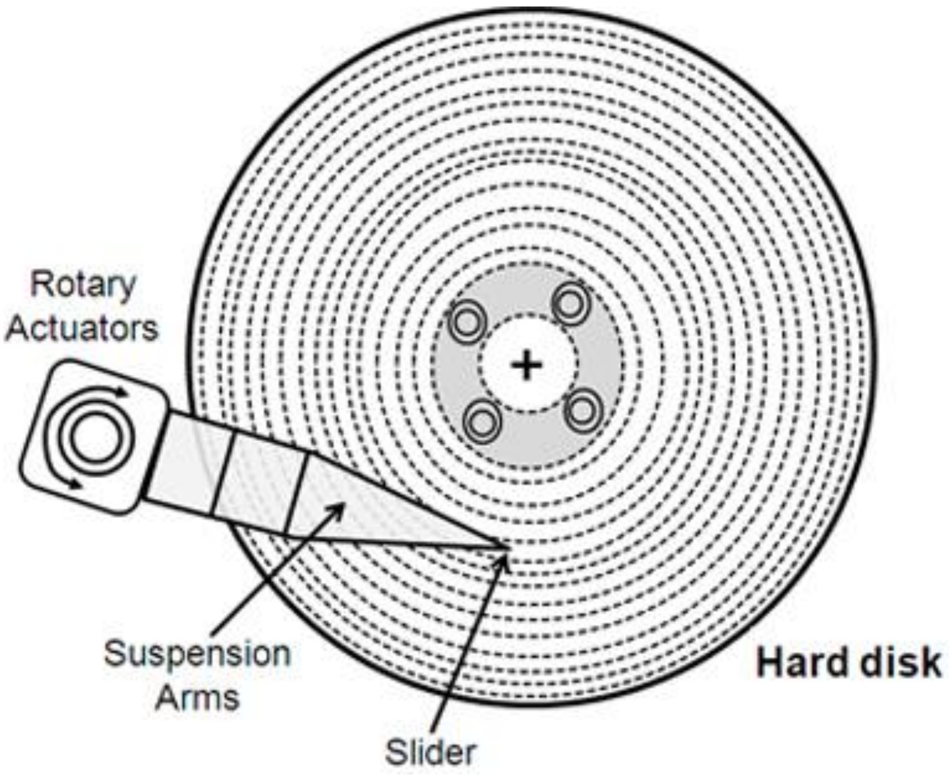
- Reduction in spacing between head sensor & magnetic medium by implementing tribological guidelines, increases the areal density and larger data can be stored in relatively smaller space.



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- Average Iron and Steel industry allots Rs. 3-5 million for maintenance / Replacement of bearings. A rough estimation indicates that 10% percent of bearing life can be improved by better lubricant, lubricant additive, proper bearing installation Implementation of tribological knowledge in iron and steel industries of India can save 3 to 5 million rupees per year.

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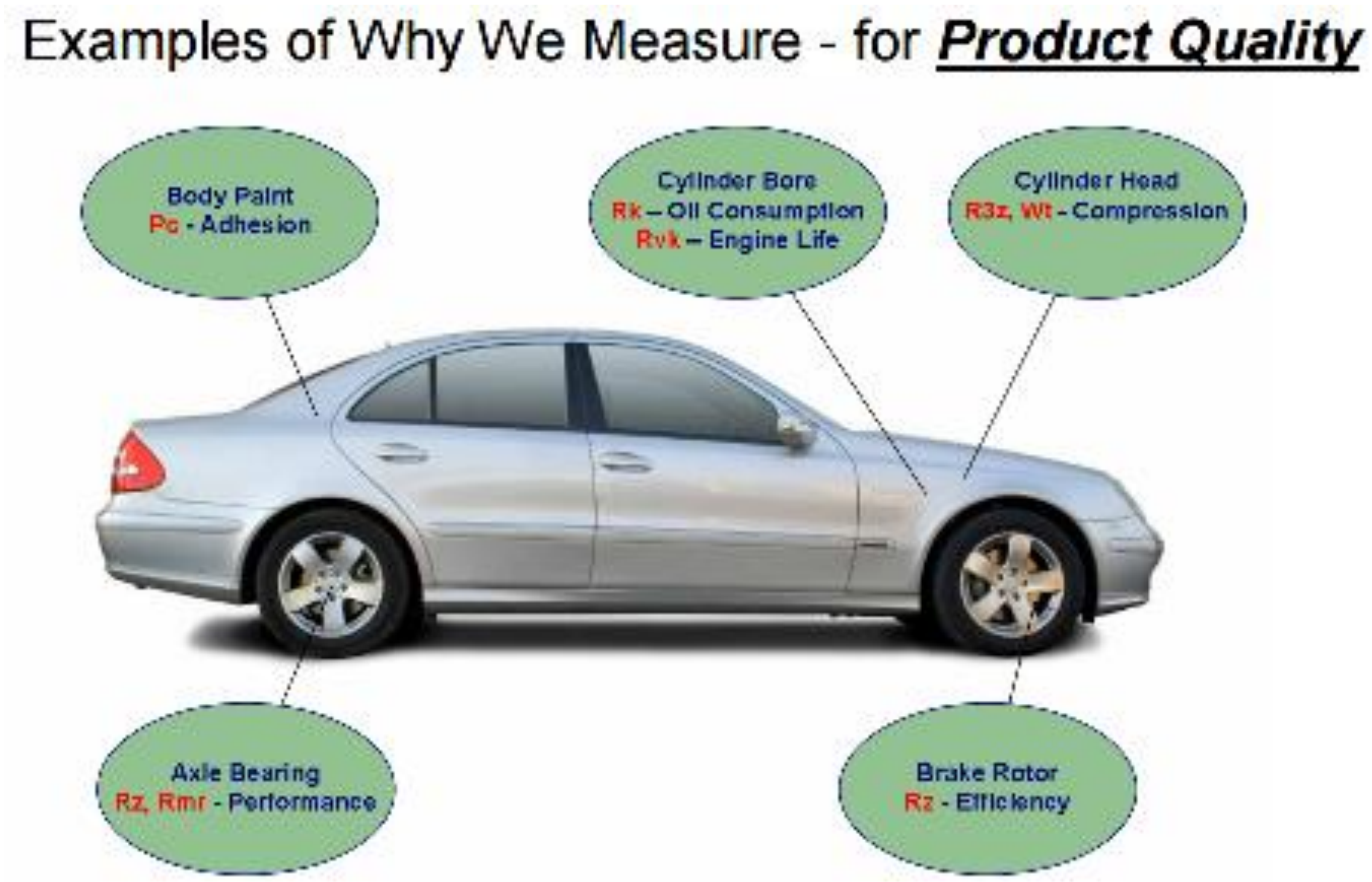

Examples of Why We Measure - for ***Product Quality***

Body Paint
Pc - Adhesion

Cylinder Bore
Rk – Oil Consumption
Rvk – Engine Life

Cylinder Head
R3z, Wt - Compression

Axle Bearing
Rz, Rmr - Performance

Brake Rotor
Rz - Efficiency

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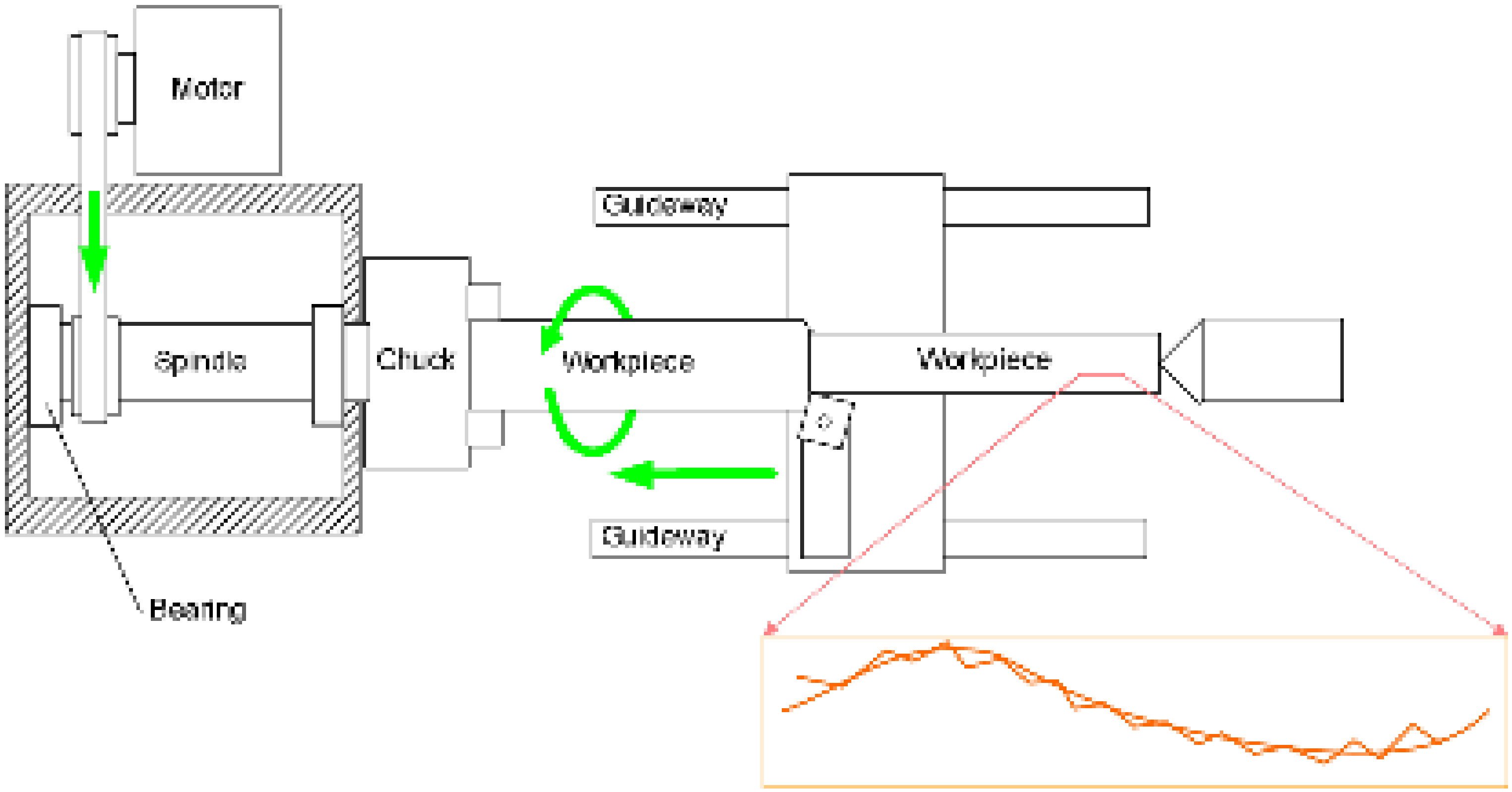
Examples of Why We Measure - for ***Process Control***



- Surface data has different wavelengths and amplitudes

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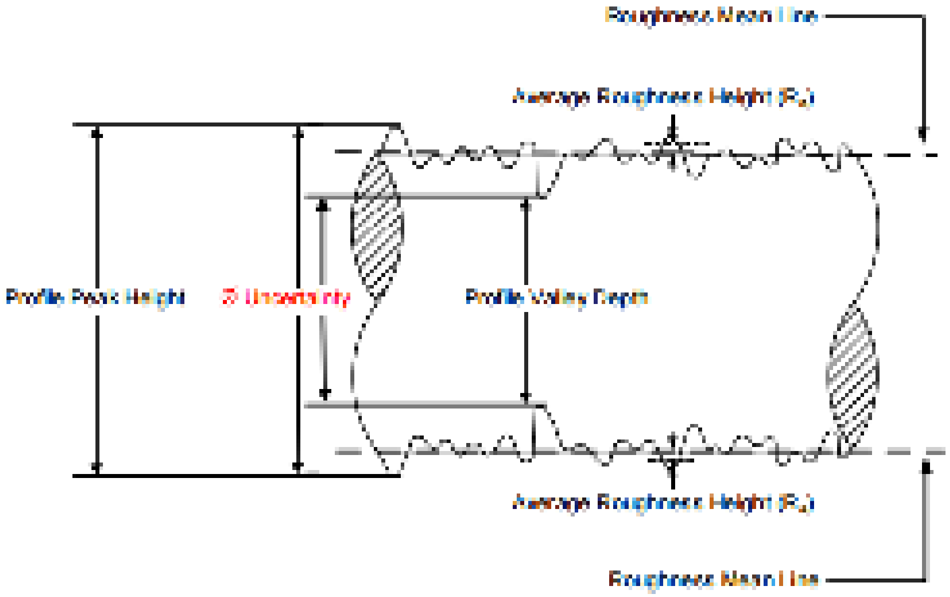
Examples of Why We Measure – for ***Size Control***



- Roughness peak to valley can be >4 times R_a
- Surface texture specification should be in appropriate for diameter tolerance

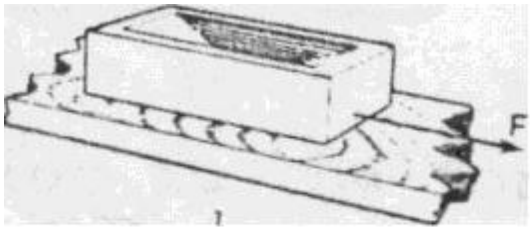
Friction

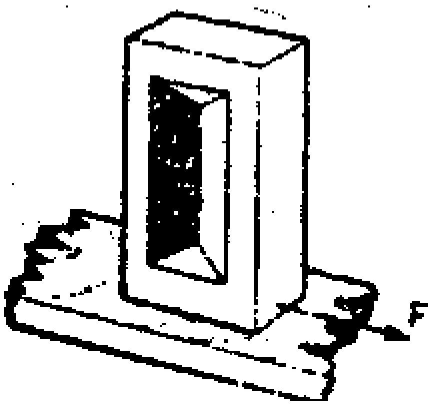
Introduction

- When one solid body is slide over another there is a resistance to the motion which is called friction.
- Considering friction as a nuisance, attempts are made to eliminate it or to diminish it to as small a value as possible.
- Considerable loss of power is caused by friction (e.g. about 20% in motor cars, 9% in airplane piston engine and (1 ½ -2)% in turbojet engines) but more important aspect is the damage that is done by friction – the WEAR of some vital parts of machines.
- This factor limits the design and shortens the effective working life of the machines.

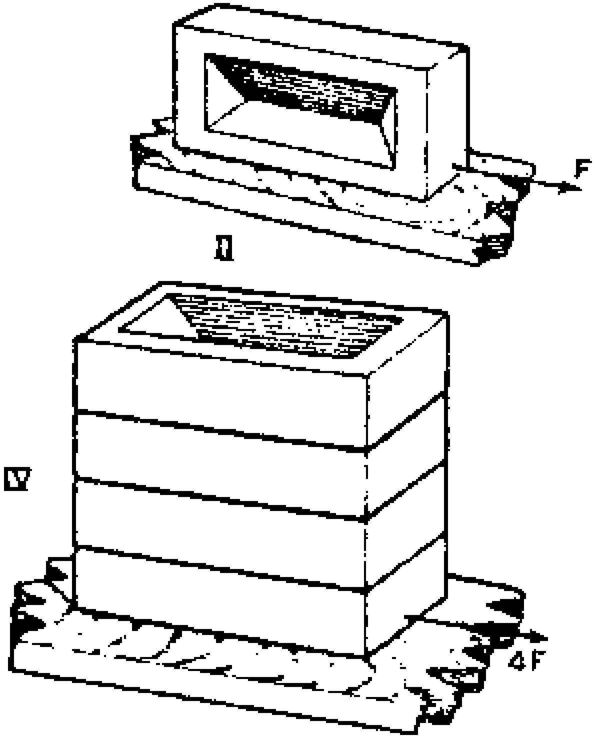
Laws of Friction

- First Law: The friction is independent of the area of contact between the solids .
- For example; if one pulls a brick along a table, the friction is same whether the brick is lying flat, or on its side, or standing on its end





- Second Law: The friction is proportional to the load between the surfaces
- e.g. if the load is doubled by putting a second brick on top of first, the force required to cause sliding is twice as great. If a pile of four bricks is used, the friction would be four times as great, and so on



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- Hence for any particular pair of surfaces, the ratio of Friction / Load is constant, and this constant is called the coefficient of friction (µ).

  where;;

  µ = Friction / Load

- It may be noted that µ varies widely for different solids.

- **Example:** For a case of a brick sliding over a clean wooden table µ = 0.5, i.e. force equal to one-half of the weight of the brick is required to pull it along.

  For ice sliding on ice, µ = 0.02 – 0.03 & For copper sliding over copper, µ = 0.8 to 1.0,

Static and Kinetic Friction

- Static friction is the force required to start sliding.
- kinetic friction is the force required to maintain it.
- It is known that kinetic friction is less than the static friction and kinetic friction is nearly independent of the speed of sliding.

Measurement of Friction

- To measure the friction, the basic requirements are simply a means of applying a normal load W and a means of measuring a tangential force F.

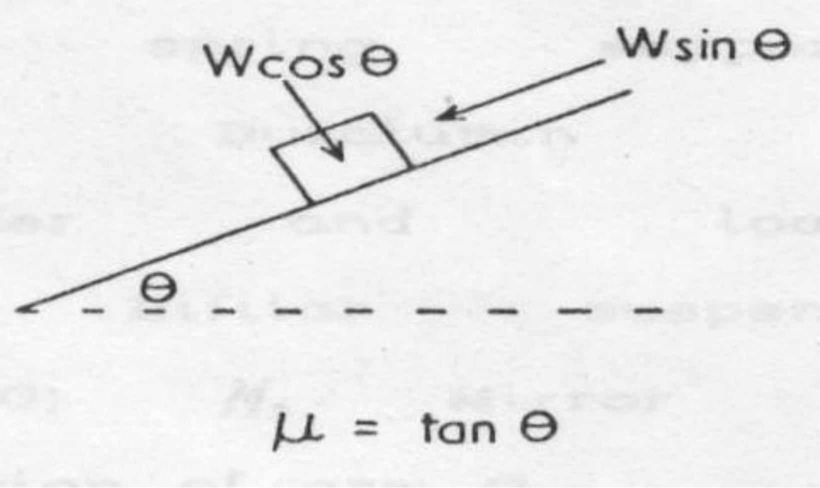
Continue…

- Method -1:

  If the lower surface is flat, the simplest method is to use the gravity loading and to tilt the lower surface until sliding begins

  If θ is the angle at which sliding begins, then, normal force = w cos θ, and tangential force = w sinθ,

  so that, μ = tan θ.



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- It is a convenient quick rough method to determine μ, but the vibration during the tilting may produce error.
- Generally, once sliding is started at an angle θ, the upper body accelerates down the slope.
- This is because the friction to start sliding (the static coefficient of friction μs) is generally greater than the friction which arises during sliding (the coefficient of kinetic friction μk).

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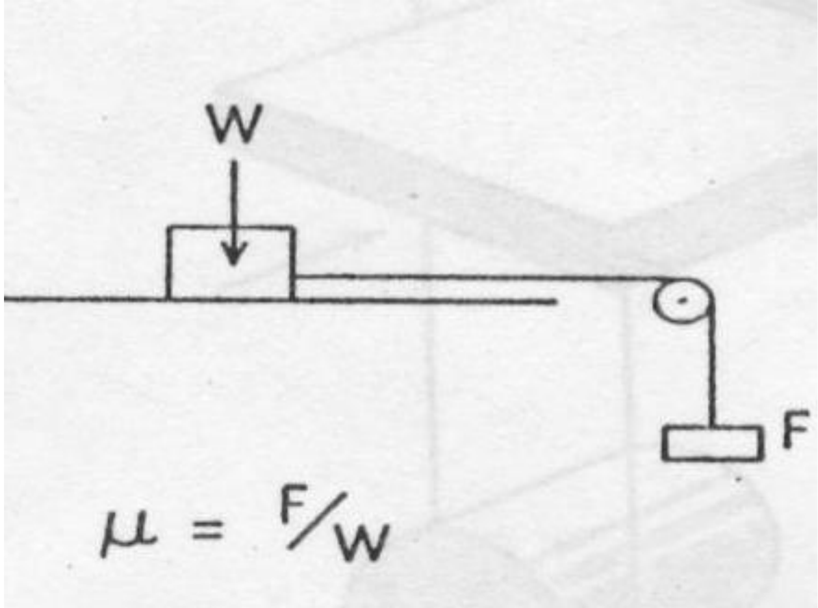
- The second method also uses the gravity loading but the lower surface is kept horizontal and the tangential loading is applied by means of dead load over pulley and μ = F/W.



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- Both the methods are however, defective because of the inertia of the moving parts they cannot readily detect fluctuations which occur during sliding. For this reason, it is often more fruitful to use a device of high natural frequency. On the basis of this approach various sophisticated apparatus have been developed.

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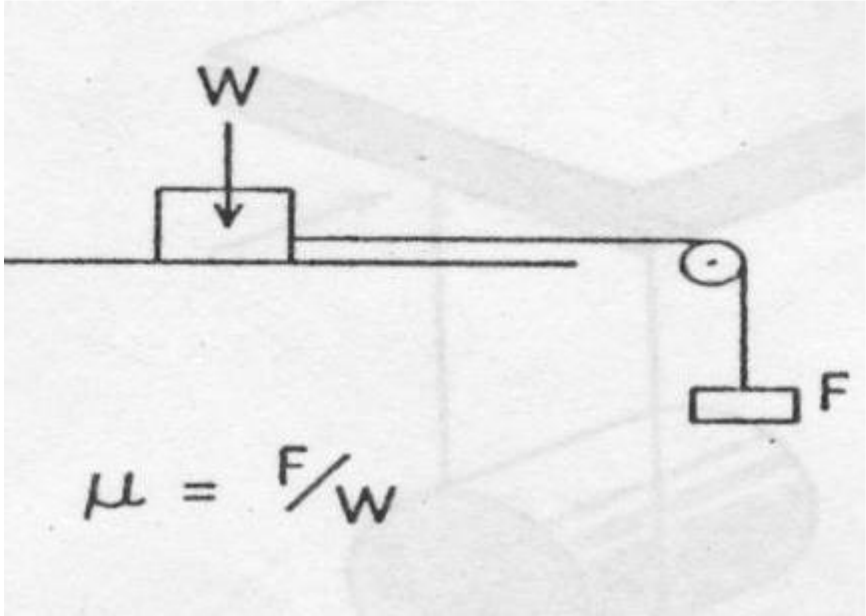

Continue…

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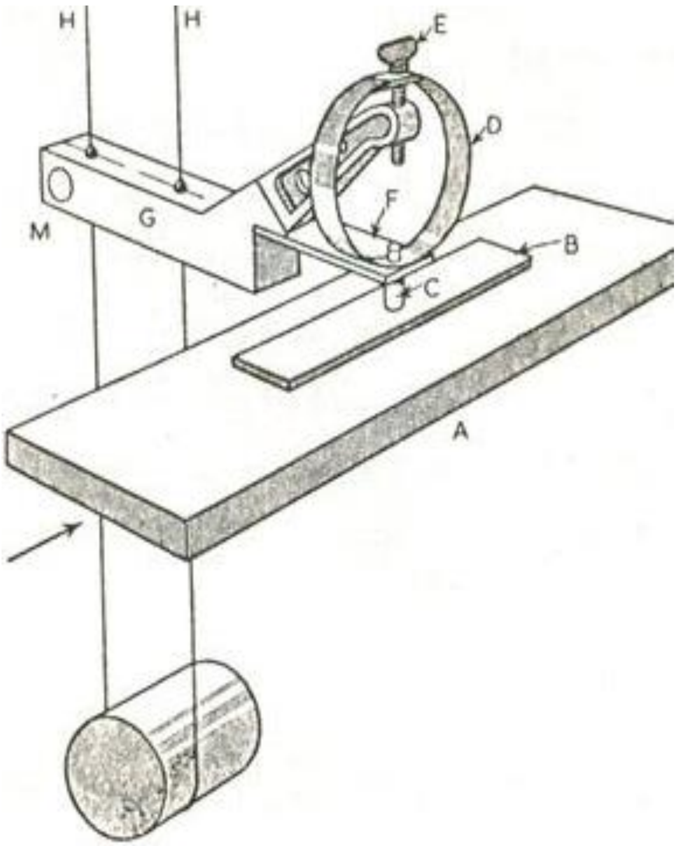
Continue…

- Apparatus-1 with high natural Frequency for determining friction between sliding solids. A, carriage holding lower surface (and heating element): B, Lower surface in form of finely abraded flat surface: C. Upper surface or slider, usually hemispherical in shape: D, E. spring and screw for applying normal load; F, Stiffening spring supporting slider; G, Duralumin arm holding slider and loading spring; H, Bifilar suspension holding arm G; M, Mirror for recording deflexion of arm G.



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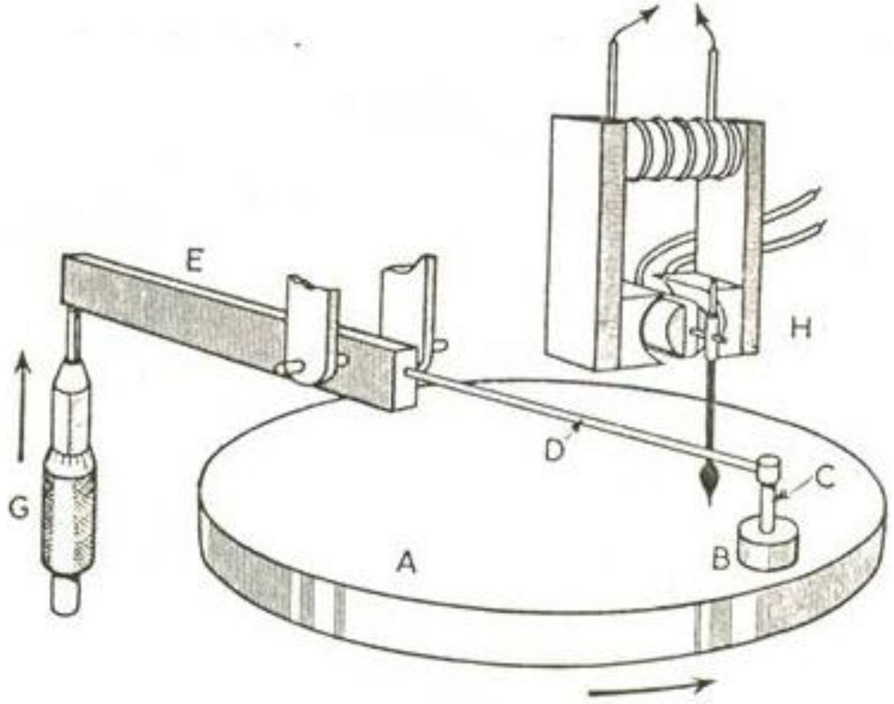
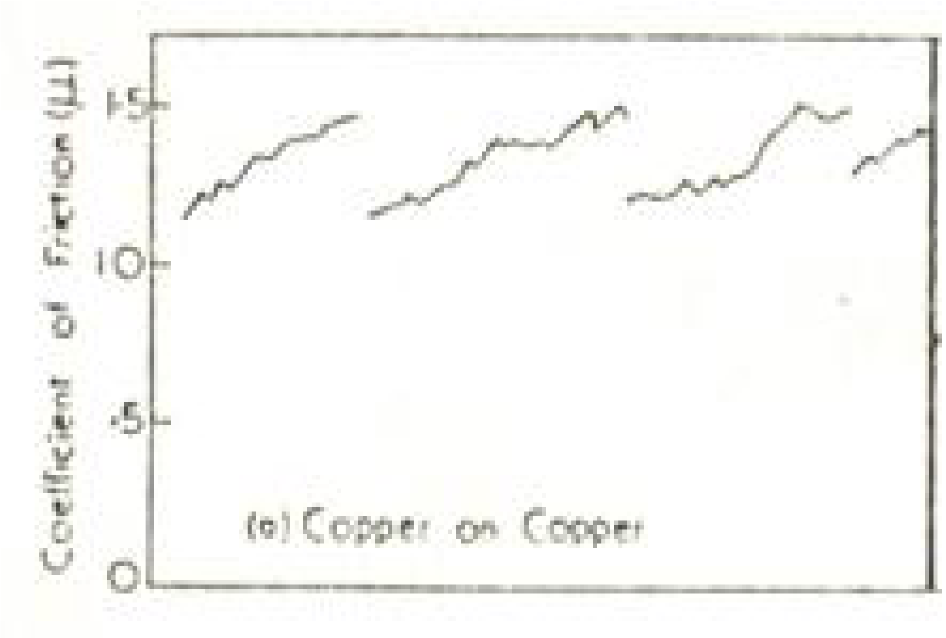
- Apparatus-2 for measuring friction between surfaces over a wide load range. A, Turntable carrying lower specimen: B; C, Upper surface or slider; D, Cylindrical beam supporting slider; E, Lever arm holding beam D; G, Micrometer for raising or lowering end of lever arm and so flexing beam in vertical plane; H, Galvanometer elements for recording flexing of beam in horizontal direction. By using wires of various thicknesses for the beam D a practical load range from about 5 milligrams to 100 grams may be obtained.



Frictional Characteristics

- For two clean specimens of the same metal sliding together in air, the friction is high (μ = 1 to 1.5) and some what irregular and the track shows very heavy damage and tearing



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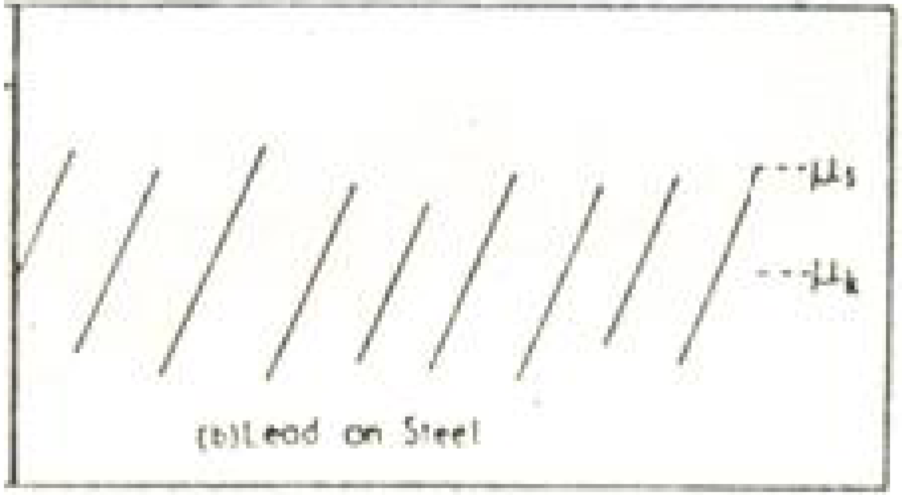
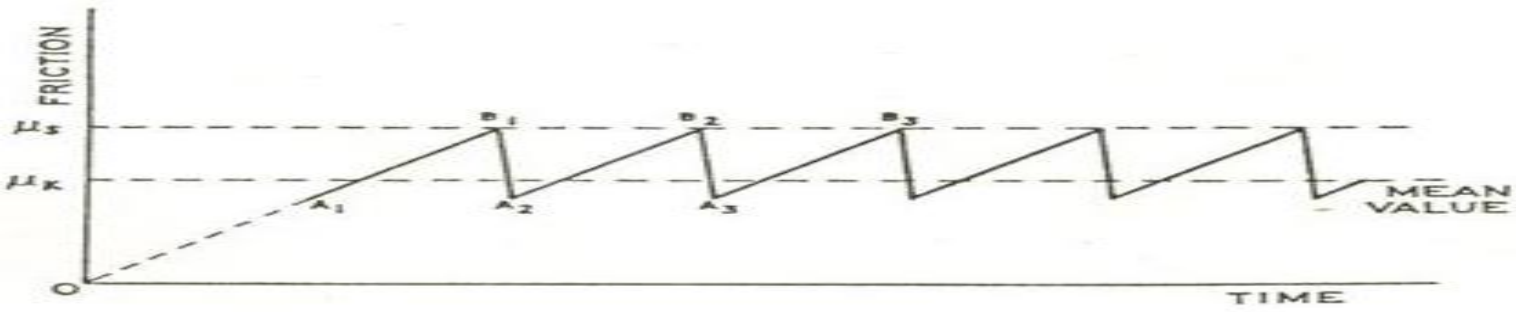
- When a soft metal slides on a harder metal the friction is of the same order but generally shows a regular intermittent motion of a “stick-slip” nature



(b)Lead on Steel

“stick-slip” Phenomenon

- During the “stick” the upper surface moves with the lower surface until the restoring force is sufficient to initiate sliding.
- A rapid “ slip” then occurs and continues until the upper surface becomes again firmly attached to the lower surface.
- For hard metals sliding on soft metals the sliding is often smooth, and corresponding to this the friction track consists of a well defined uniform groove in the lower surface. In other cases the motion is intermittent and the friction track is in the form of irregular groove.



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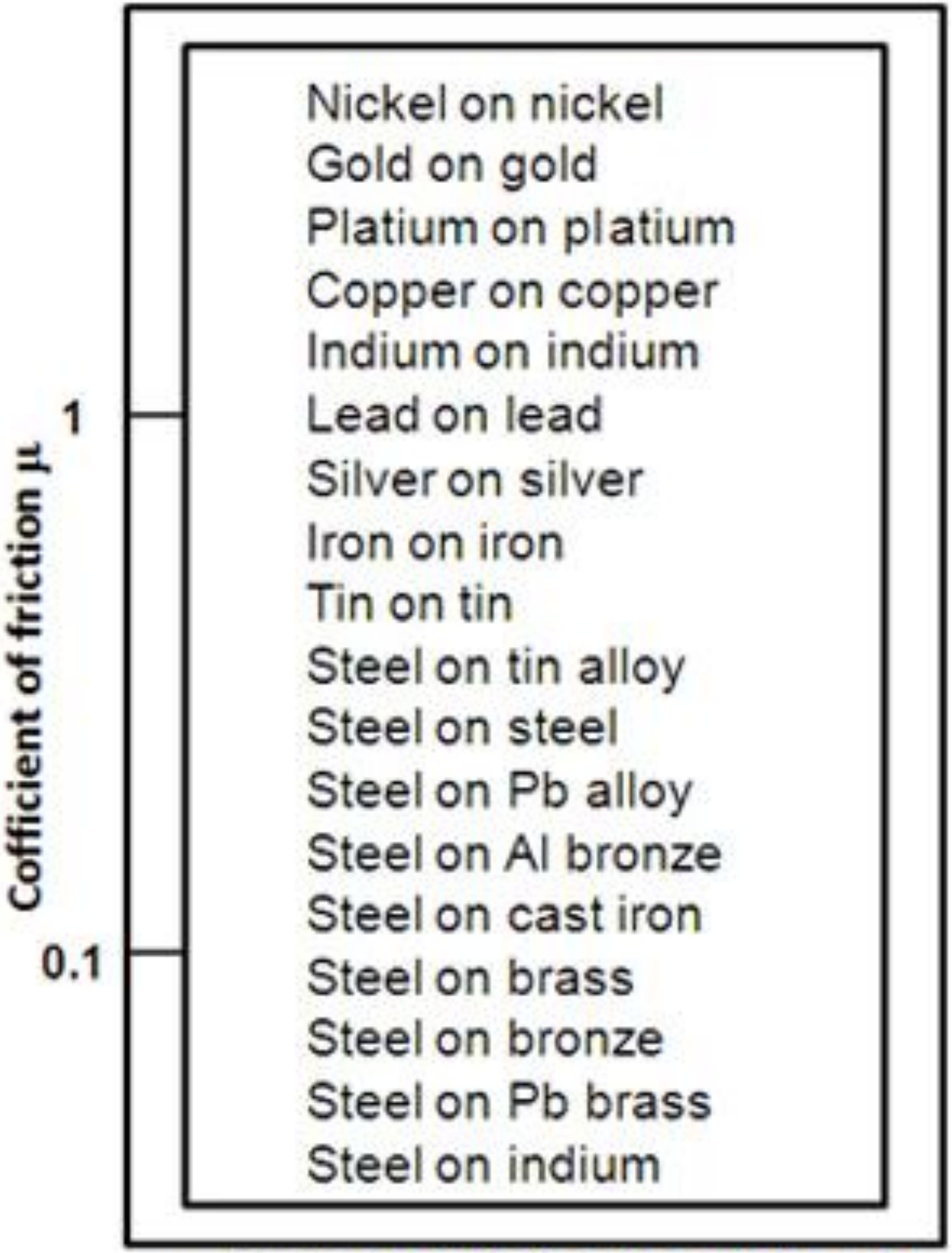
Possible reasons for stick-slip phenomenon :

- Interlocking of asperities during stick phenomenon but separation during sliding.
- Adhesion during stick action and breakage of weld joint during sliding.
- Electrostatic charge during stick event.

To avoid this phenomenon either :

- Increase operating speed or
- Reduce the difference between μ_s and μ_k.

Overall stick-slip behavior of systems depends on stiffness, inertia, damping and magnitude of unbalanced force.



μ = for partial lubrication = 0.01 - 0.1

Mechanism of Friction

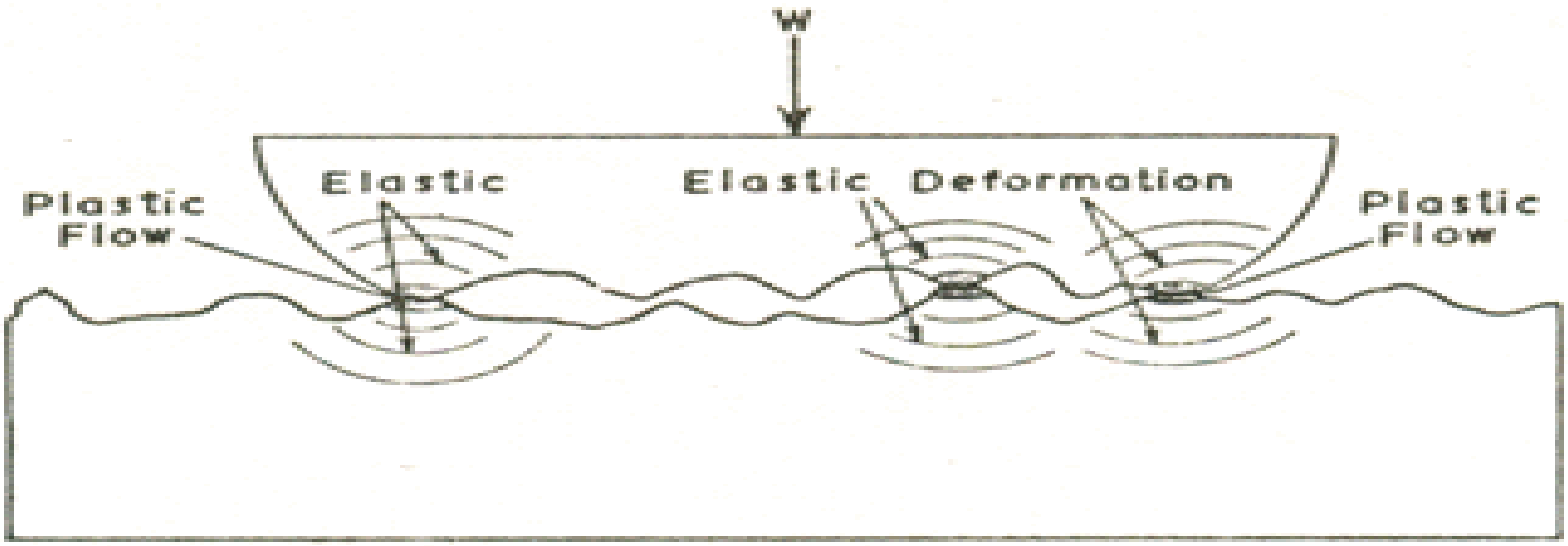
- If the material that has to be sheared has a mean shear strength “S” then F=AxS, where A is the real area of contact and is proportional to the load and independent of the size of the bodies, and

$$\mu = \frac{F}{W} = \frac{AxS}{AxS} = \frac{S}{P} = \frac{Share\ Strength}{Yield\ Pressure}$$

- Where, P is the yield pressure and is defined as the stress at which a substantial amount of plastic deformation takes place under load (also known as yield point). Experimentally, S is almost equal to the bulk shear strength of the softer metal of the sliding pair.
- In practice, the value of μ may be modified by small amounts of surface contamination (impurity due to mixing of other materials).

Continue…

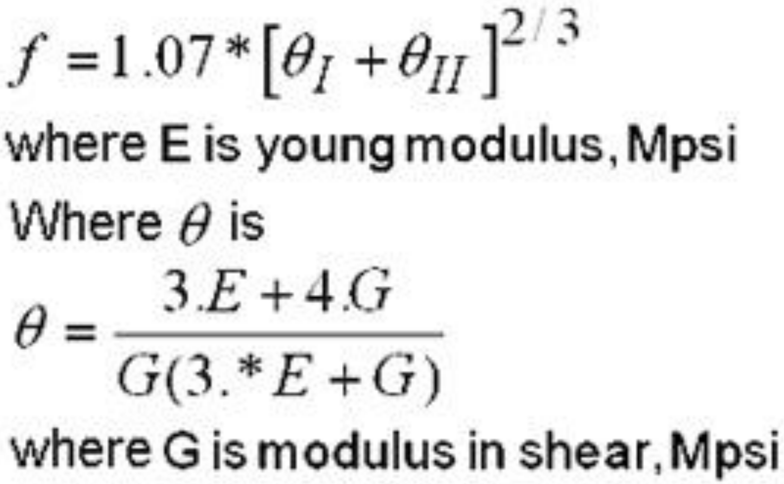
- Sketch showing plastic deformation at the points of real contact. At these regions junctions are formed and surrounding regions are deformed elastically so that when the load is removed these elastic stresses are released, and the junctions are broken.
- With metals this process may be referred as ***Cold Welding (Adhesion mechanism of friction).***



TOMLINSON’s Theory of Molecular attraction

- 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.

  Equation 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



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

where E is young modulus, Mpsi

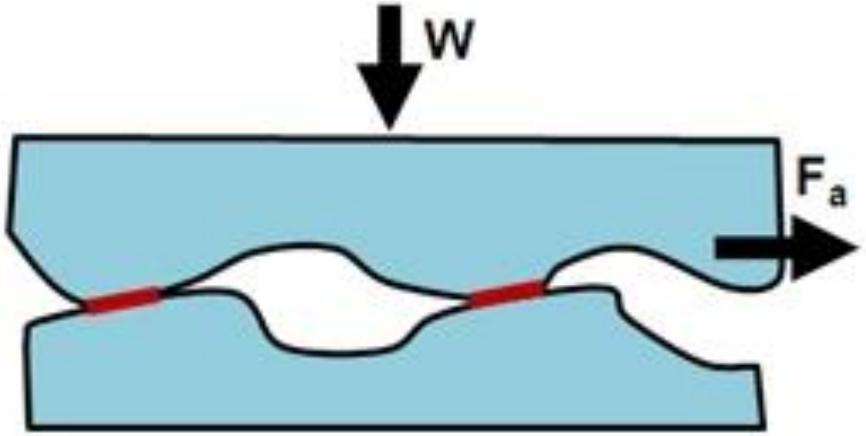
Where θ is

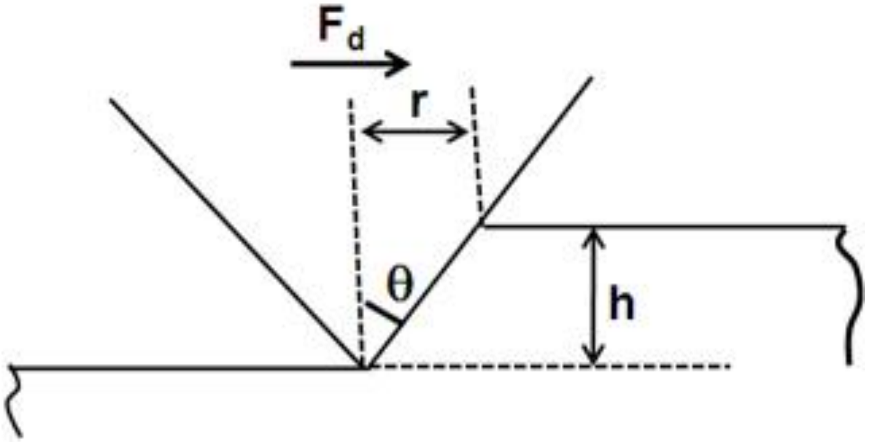
$$\theta = \frac{3.E + 4.G}{G(3.*E + G)}$$

where G is modulus in shear, Mpsi

Friction Sources

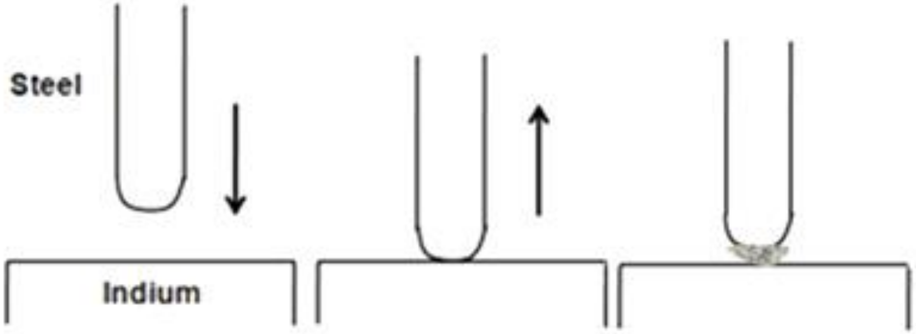
- There are two main friction sources: Adhesion and Deformation. Force needed to plough asperities of harder surface through softer.
- Fig. demonstrates the adhesion (cold weld) between two surfaces. Some force, F_a, is required to tear the cold junction.
- Fig. demonstrates the deformation process. It shows a conical asperity approaching to a softer surface. To move upper surface relative to lower surface some force is required.
- 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.

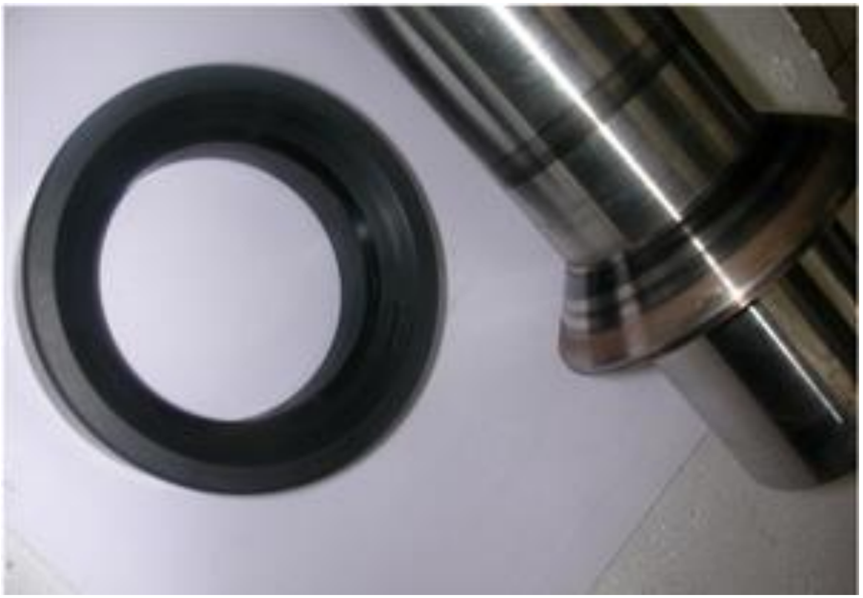




Adhesion Theory

- This theory is based on the fact that all surfaces are made of atoms.
- 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.
- 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.





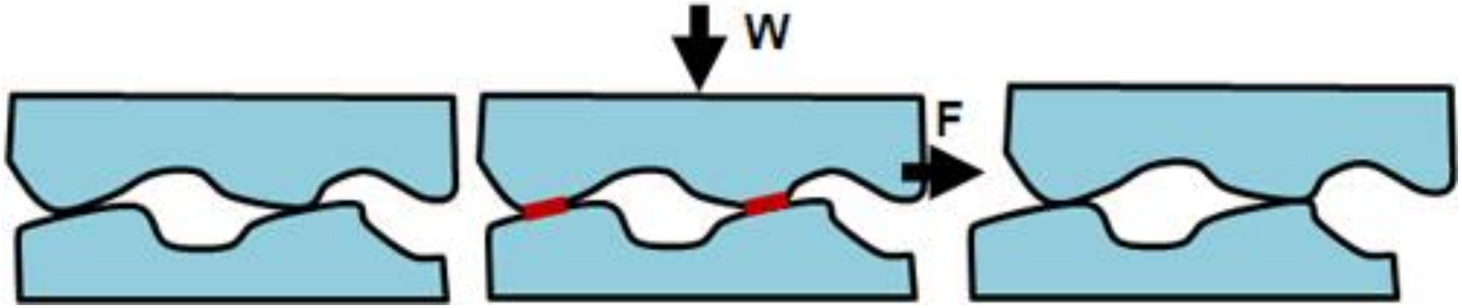
Bowden and Tabor - Theory of Adhesive Friction

- 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 $F_a = As$. The coefficient of friction due to adhesive friction is given by ratio of friction force to applied load W. 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 F_a.

  $\mu = F_a / W = s / H$.

  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.



ROLLING FRICTION

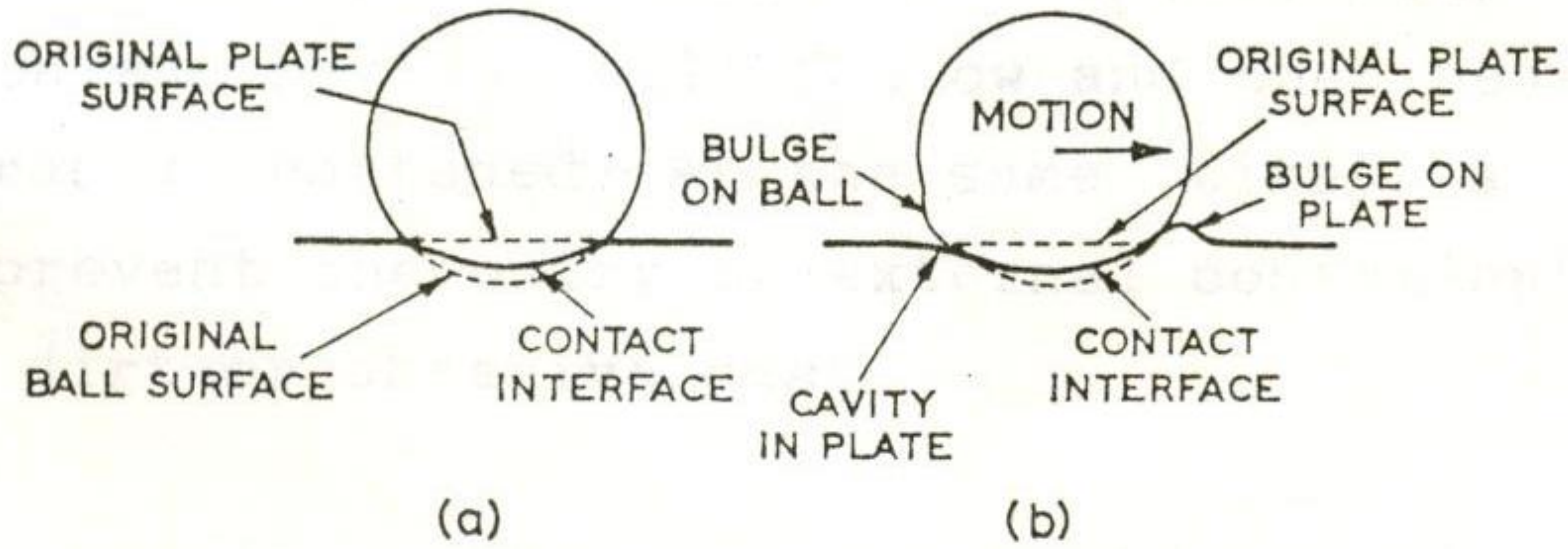
- Other than sliding, an other way in which surfaces can move over one another is rolling, and it is much easier to roll surfaces along than to slide them.

Types of Rolling :

- The first type of rolling occurs when a car wheel is driven over a road or a train wheel over a rail. Here considerable tangential forces are involved in pulling the vehicle along, and the conventional frictional grip between the wheel and the surface is of great importance.
- The other type of rolling involves only a minute tangential traction i.e. the rolling that occurs when a ball or cylinder rolls freely over another surface called free rolling which is most commonly applied in ball bearings and roller bearings. The resistance in these cases is phenomenally low (≤ 0.001).

Mechanism of Rolling

- Fig shows a steel ball resting on a flat steel plate; the actual arc of contact is exaggerated in order to show the form of elastic deformation. As the ball rolls in the direction of the arrow, the elastic deformation will assume a shape similar to that as shown in Fig . A form of bulge will be pushed up from the plate surface in front of the ball and a cavity will follow a similar bulge on the trailing edge of the ball. This type of deformation occurs when the ball and plate are both made of material having similar elastic properties. The plate surface over which the ball moves will undergo stretching and contraction as the ball pushes a minute bow-wave of metal along in front of it. Similarly, the ball surface itself will undergo cyclic stretching and contraction as it continually modifies its original spherical shape.



Mechanism of Rolling Friction:-
(a) Elastic ball and plate at rest
(b) Elastic ball rolling on plate

Friction of a Complete Rolling Contact Bearing

- Friction in rolling contact bearing is largely due to elastic-hysteresis means that its magnitude will be influenced by all the factors which normally cause variation in hysteresis effects. In the case of the rolling elements alone, these would be the elastic properties of the materials, the speed of rolling and the temperature. Additional factors which may influence the frictional behavior of complete rolling contact bearing are the condition, shape and relative positions of the surfaces, the magnitude and direction of the load, the friction between the cage and the rolling elements, the friction between the cage and the rings and the conditions of lubrication.

Introduction

- *Undesirable removal of material from operating solid surface is known as **wear**.*

(1) **Zero wear :** Removal of material which causes polishing of material surfaces may be known as "Zero wear". It may increase performance. It is for betterment, so it is not undesirable

(2) **Measurable wear :** Removal of material from surface that increases vibration; noise or surface roughness may be treated an "Measureable wear". Often we measure wear in volume/mass reduction. Undesirable removal of material occurs in measurable wear.

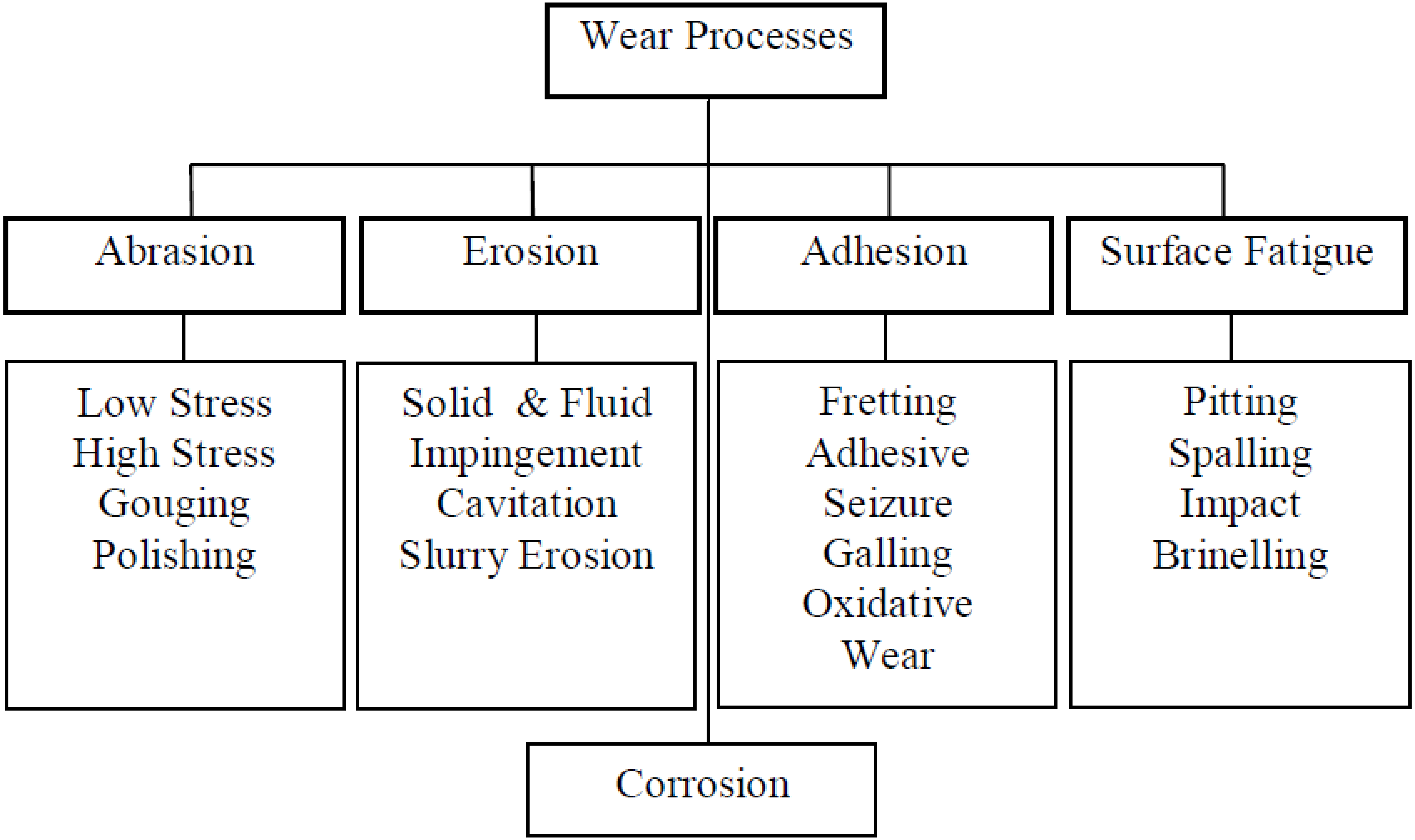
Continue…

Occurrence of Wear depends on

- Geometry of the surface
- Applied load
- The rolling and sliding velocities
- Environmental conditions
- Mechanical, Thermal, Chemical and Metallurgical properties
- Physical, Thermal and Chemical properties of the lubricant

Continue…

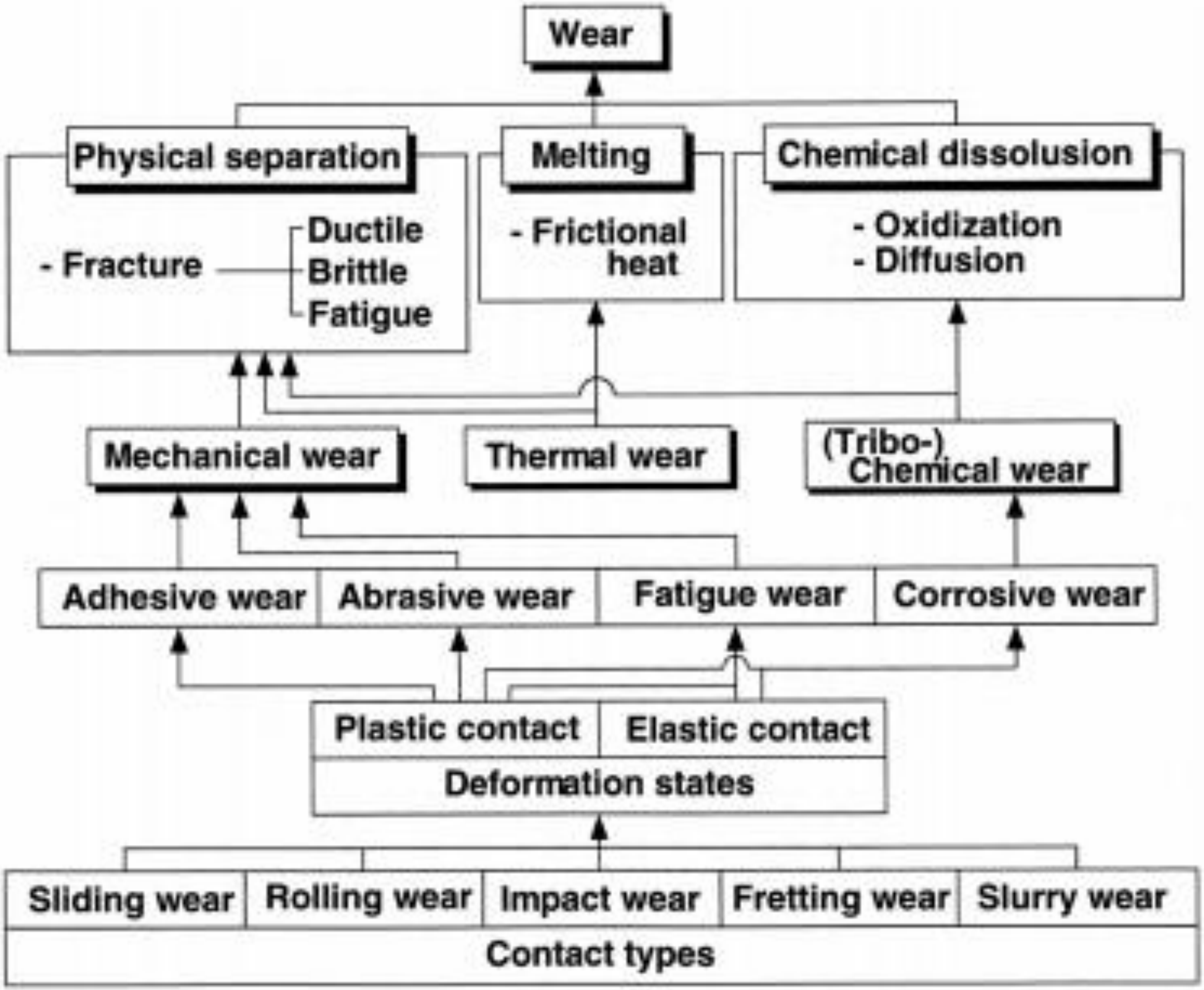
Types of wear process



Wear Processes

- Abrasion
  - Low Stress
  - High Stress
  - Gouging
  - Polishing
- Erosion
  - Solid & Fluid Impingement
  - Cavitation
  - Slurry Erosion
- Adhesion
  - Fretting
  - Adhesive
  - Seizure
  - Galling
  - Oxidative Wear
- Surface Fatigue
  - Pitting
  - Spalling
  - Impact
  - Brinelling
- Corrosion

Continue…

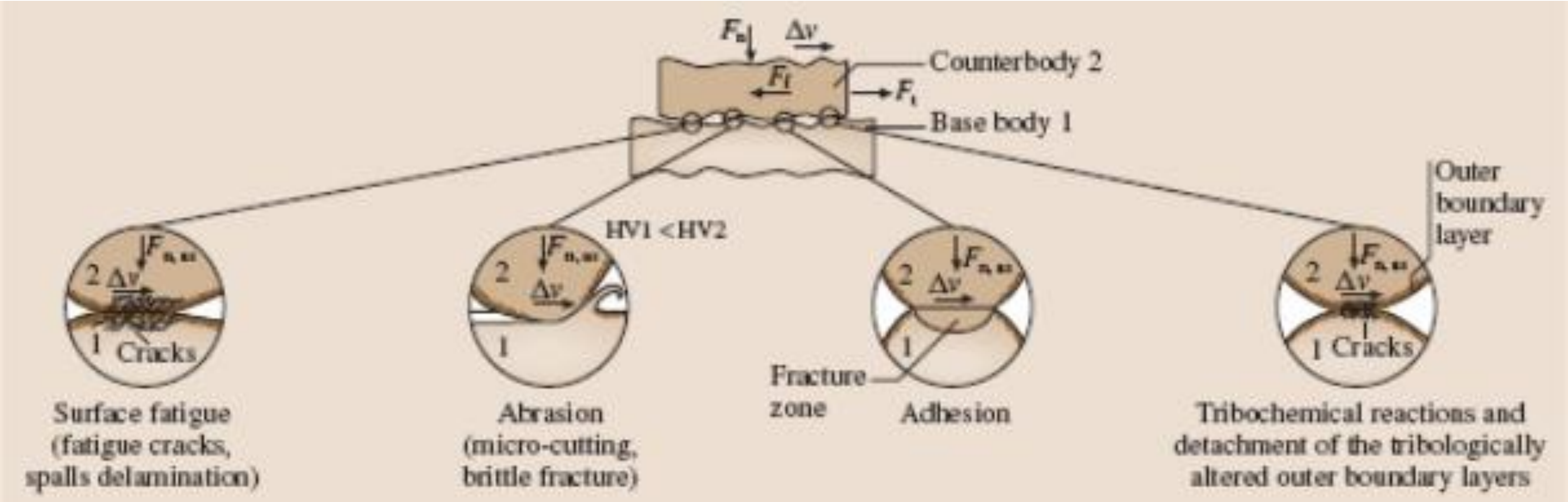

Wear
Physical separation
- Fracture
Ductile
Brittle
Fatigue
Melting
- Frictional heat
Chemical dissolusion
- Oxidization
- Diffusion
Mechanical wear
Thermal wear
(Tribo-) Chemical wear
Adhesive wear
Abrasive wear
Fatigue wear
Corrosive wear
Plastic contact
Elastic contact
Deformation states
Sliding wear
Rolling wear
Impact wear
Fretting wear
Slurry wear
Contact types

Wear Mechanisms

- Wear can be classified based on the ways that the frictional junctions are broken, that is, elastic displacement, plastic displacement, cutting, destruction of surface films and destruction of bulk material. There are many types of wear mechanisms, but we shall discuss about common wear mechanisms, which are:

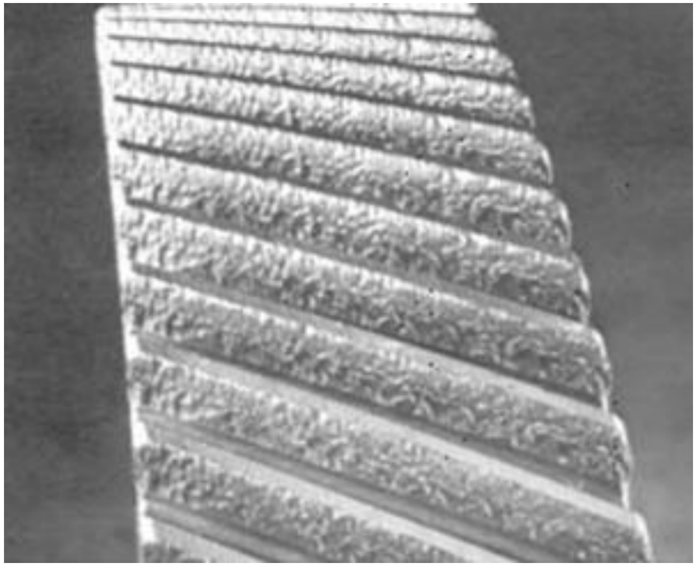
  - Abrasive Wear : polishing, scouring, scratching, grinding, gouging.
  - Adhesive Wear : galling, scuffing, scoring.
  - Cavitation (interaction with fluid).
  - Corrosive Wear (Chemical nature).
  - Erosive Wear.
  - Fatigue : delamination.
  - Fretting Wear.

Continue…


F_n
Δv
F_t
Counterbody 2
F_t
Base body 1
$F_{n,m}$
2
Δv
1
Cracks
Surface fatigue (fatigue cracks, spalls delamination)
HV1 <HV2
Abrasion (micro-cutting, brittle fracture)
Fracture zone
Adhesion
Outer boundary layer
Tribochemical reactions and detachment of the tribologically altered outer boundary layers

Abrasive Wear

- Abrasive wear, sometimes called cutting wear, occurs when hard particles slide and roll under pressure, across the tooth surface.
- Hard particle sources are: dirt in the housing, sand or scale from castings, metal wear particles, and particles introduced into housing when filling with lube oil.
- Scratching is a form of abrasive wear, characterized by short scratch-like lines in the direction of sliding. This type of damage is usually light and can be stopped by removing the contaminants that caused it. Fig. shows abrasive wear of a hardened gear.



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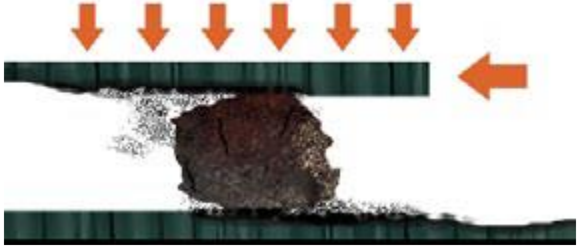
Types of abrasive wear

Gouging abrasion
- Large particles
- High compression loads



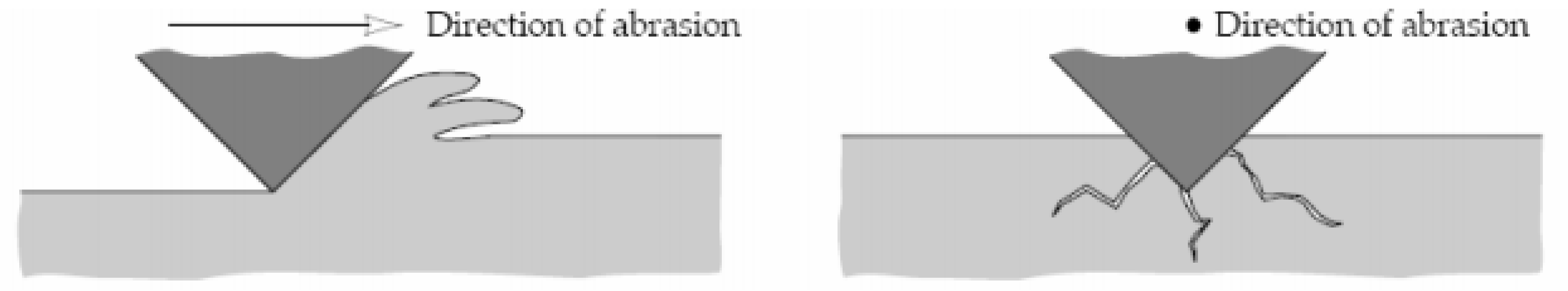
High stress or grinding abrasion
- Smaller particles
- High compression load

Low stress or scratching abrasion
- No compression load
- Scratching abrasion while material is sliding

Polishing abrasion

Ref.: www. mesto.com

Mechanism of Abrasive Wear



a) Cutting

b) Fracture

c) Fatigue by repeated ploughing

d) Grain pull-out

Fig. *Mechanisms of abrasive wear: microcutting, fracture, fatigue and grain pull-out*

Modes of Abrasive Wear

- The way the grits pass over the worn surface determines the nature of abrasive wear.
- The literature denotes two basic modes of abrasive wear:
  - *two-body and*
  - *three-body abrasive wear.*
- Two-body abrasive wear is exemplified by the action of sand paper on a surface. Hard asperities or rigidly held grits pass over the surface like a cutting tool.
- In three-body abrasive wear the grits are free to roll as well as slide over the surface, since they are not held rigidly.

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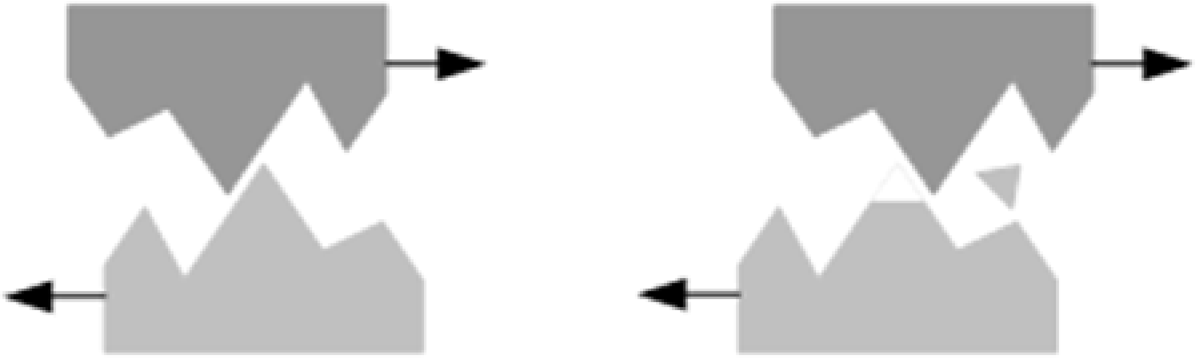
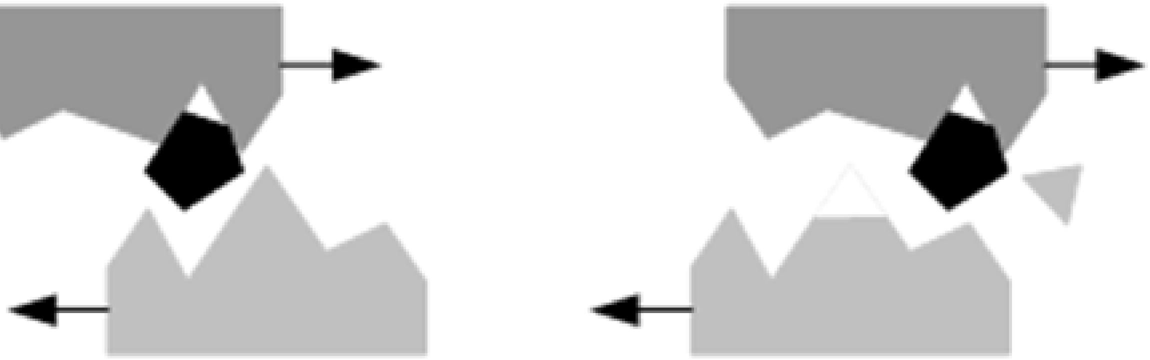
Abrasive wear

Abrasive wear occurs when a harder material is rubbing against a softer material

Two body wear



Three body wear



Ref.: www.substech.com

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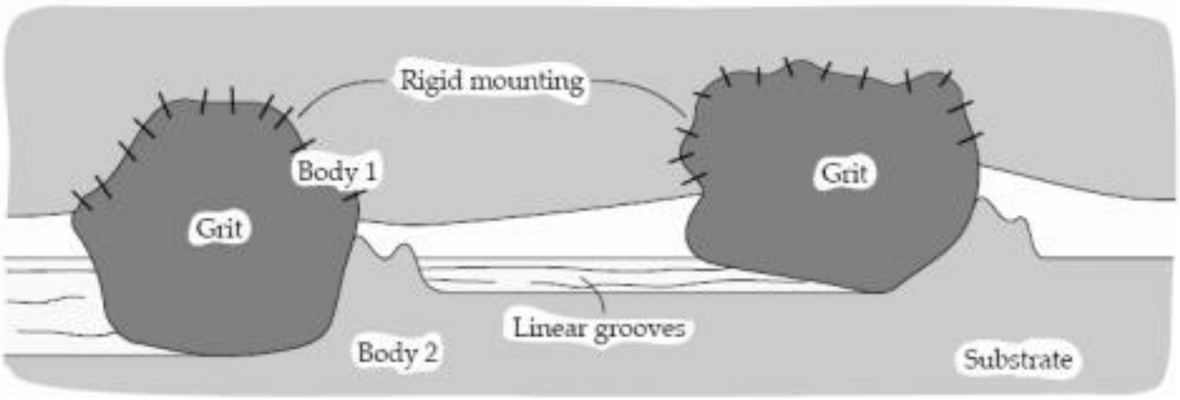
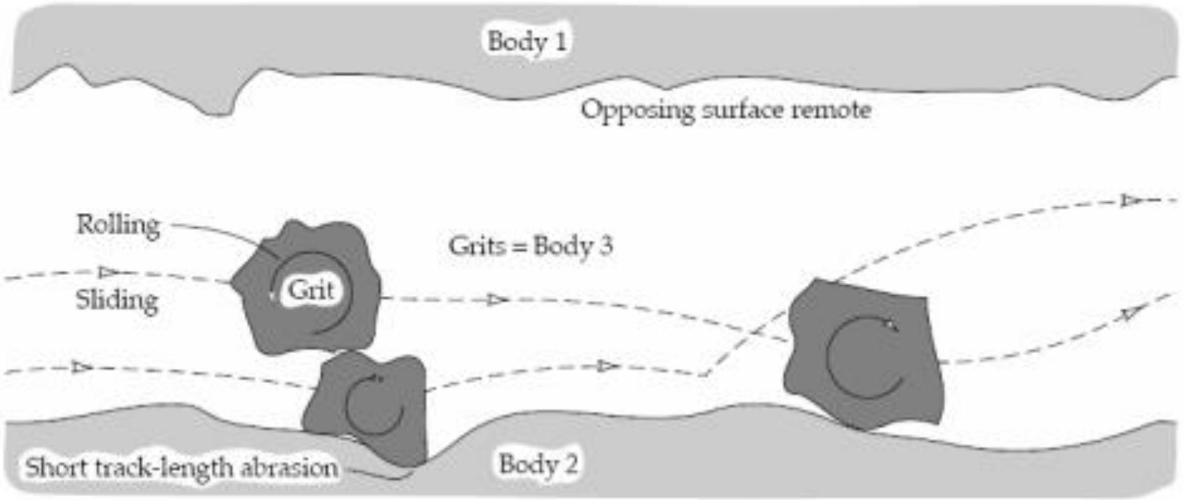


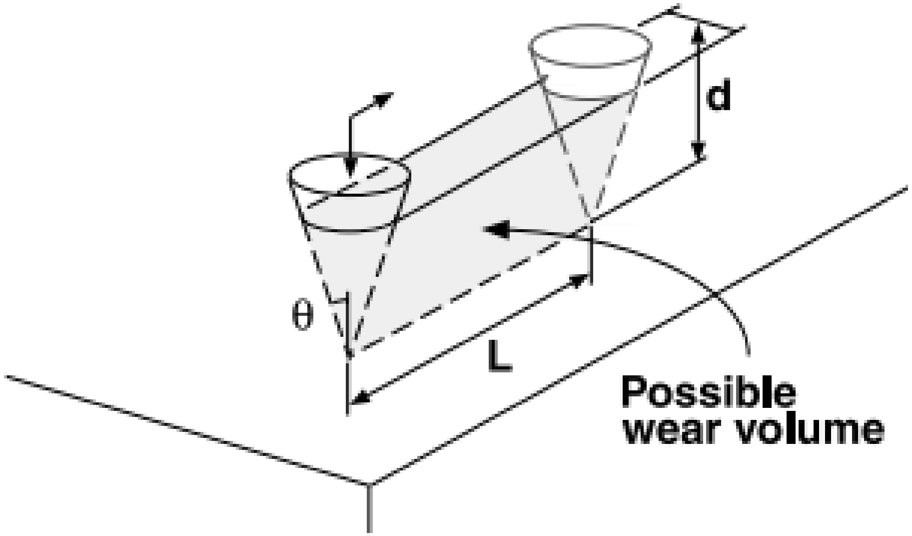
Two-body mode



Three-body mode

Fig. *Two and three-body modes of abrasive wear*

Estimation of Abrasive wear Volume



$$V = \frac{2}{\pi \cdot \tan\theta} \cdot \frac{WL}{H_v}$$

Typical model of abrasive wear by a conical indentor.

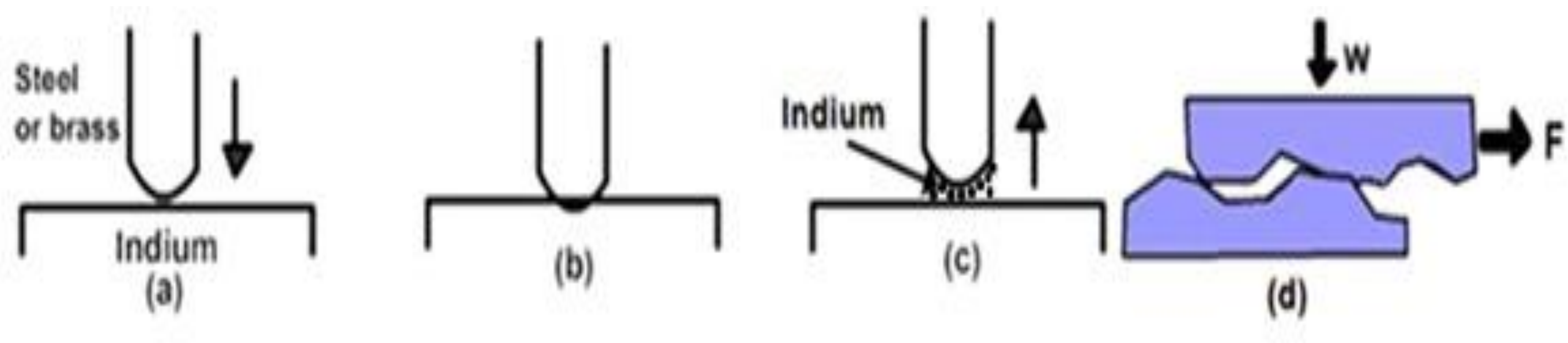
Based on Sliding Velocity

$V = K\,(WV_s/3\,\sigma_s)$

Where
V = wear volume, Vs = sliding velocity
W = applied load, σs = surface strength
K = wear coefficient

Adhesion Wear

- Adhesive wear is very common in metals. It is heavily dependent on the mutual affinity between the materials. Let us take example of steel and indium.
- When steel pin under load is pushed [Fig. 3.5(b)] in indium block, and subsequently retracted, a thin layer of indium transferred on the steel pin.



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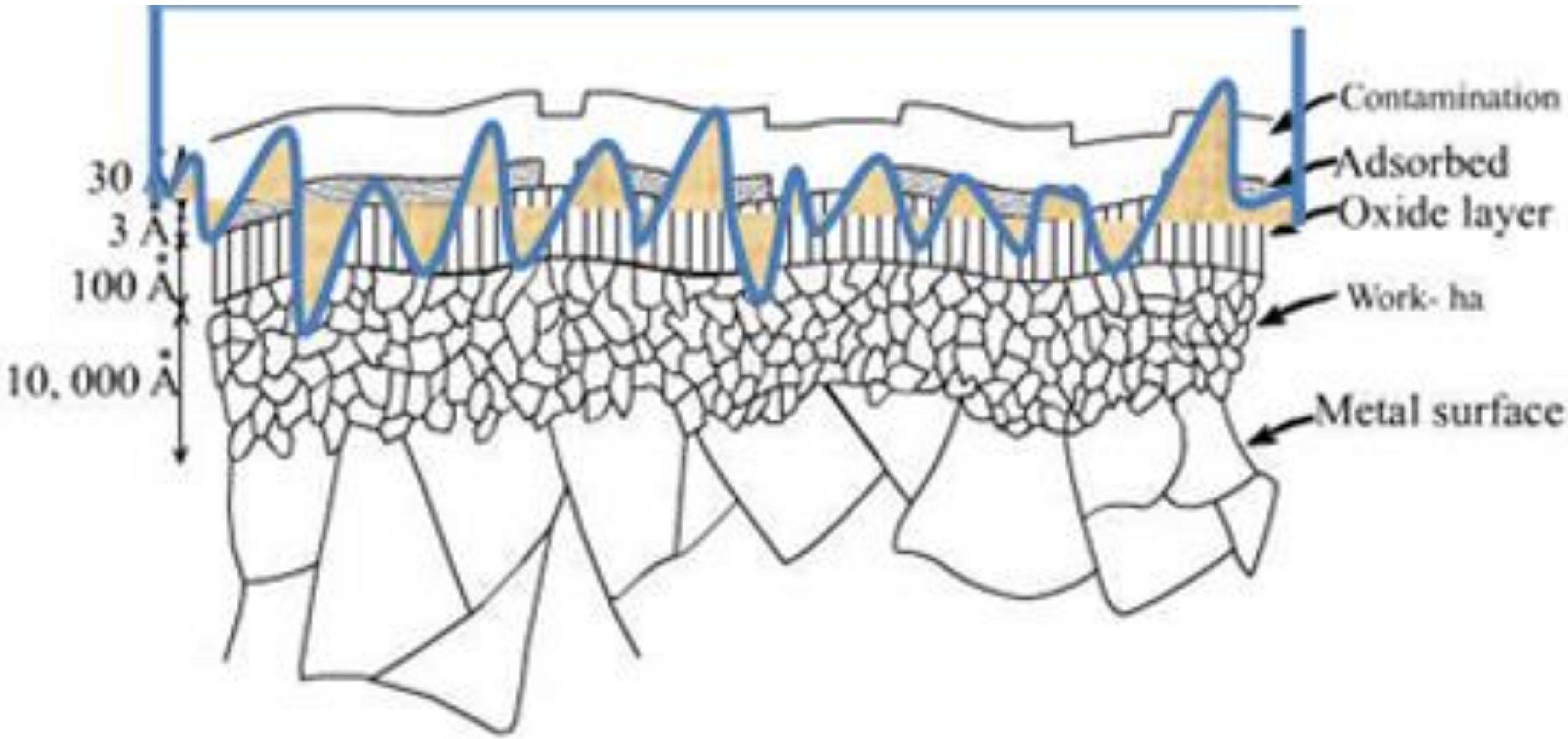
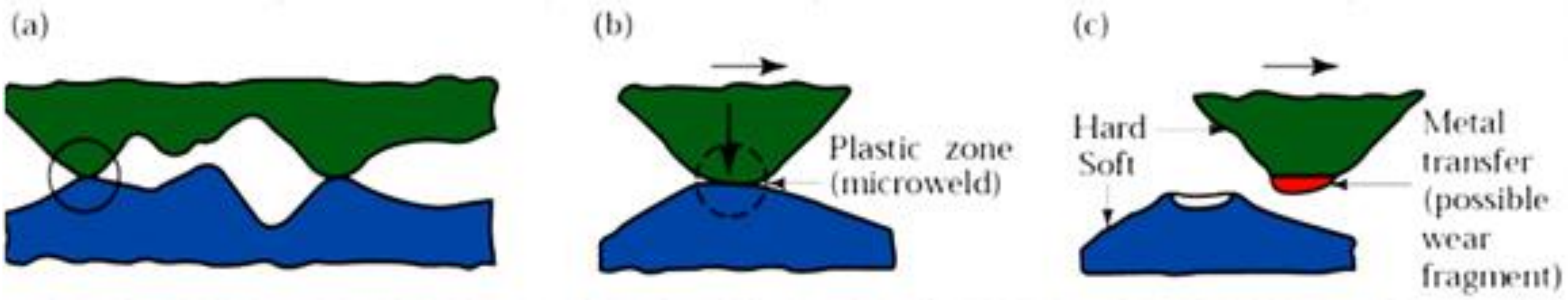

30 Å
3 Å
100 Å
10, 000 Å
Contamination
Adsorbed
Oxide layer
Work- ha
Metal surface

Steps in Adhesion Wear

Steps can be summarized as follows:

1. Deformation of contacting asperities
2. Removal (abrasion) of protective oxide surface film.
3. Formation of adhesive junctions
4. Failure of junction by pulling out large lumps and transfer of materials



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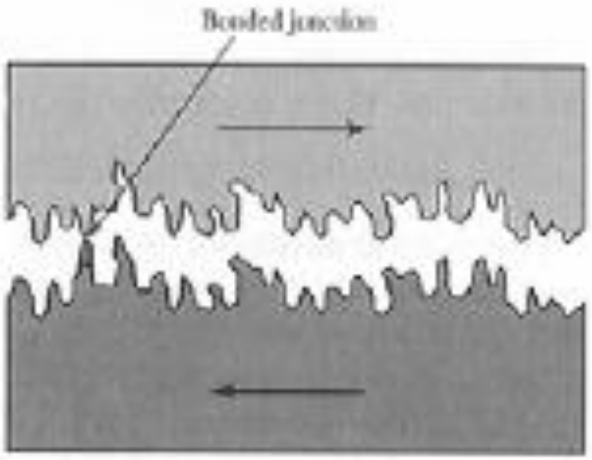
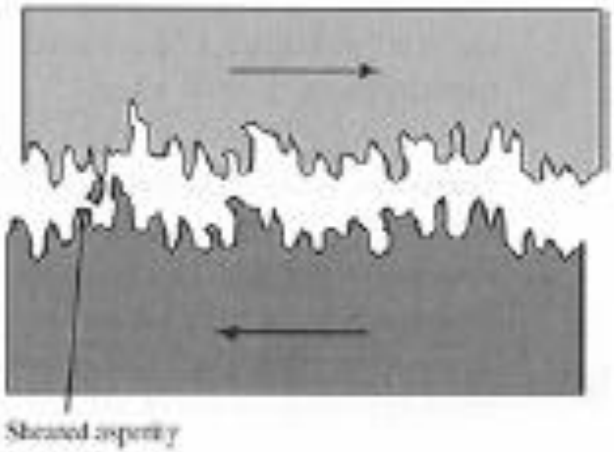
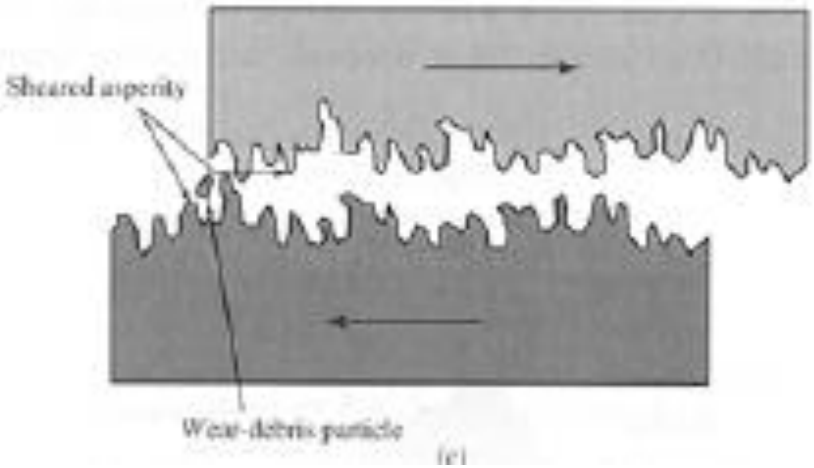
The sequence of steps occurring during adhesive wear:



(*a)* High local stresses plastically deform the material in the vicinity of the contact points, resulting in the formation of atomic bonds across the interface.



(b) As the force causing the relative sliding motion is increased, the shear stress in the joined region increases until it exceeds the shear strength of one of the solids.



(c) Subsequently, material is lost into the region between the two solids.

Laws of Adhesive Wear

1. Wear Volume proportional to sliding distance of travel (L)
   - *True for wide range of conditions except where back transfer occurs.*
2. Wear Volume proportional to the load (W)
   - *Dramatic increase beyond critical load.*
3. Wear volume inversely proportional to hardness(H) of softer material

Archer’s Adhesion Wear Model

As per adhesion wear laws, wear volume is given by **$V = K_1WL/3H$**. This equation is known as **Archard’s Wear** Equation.

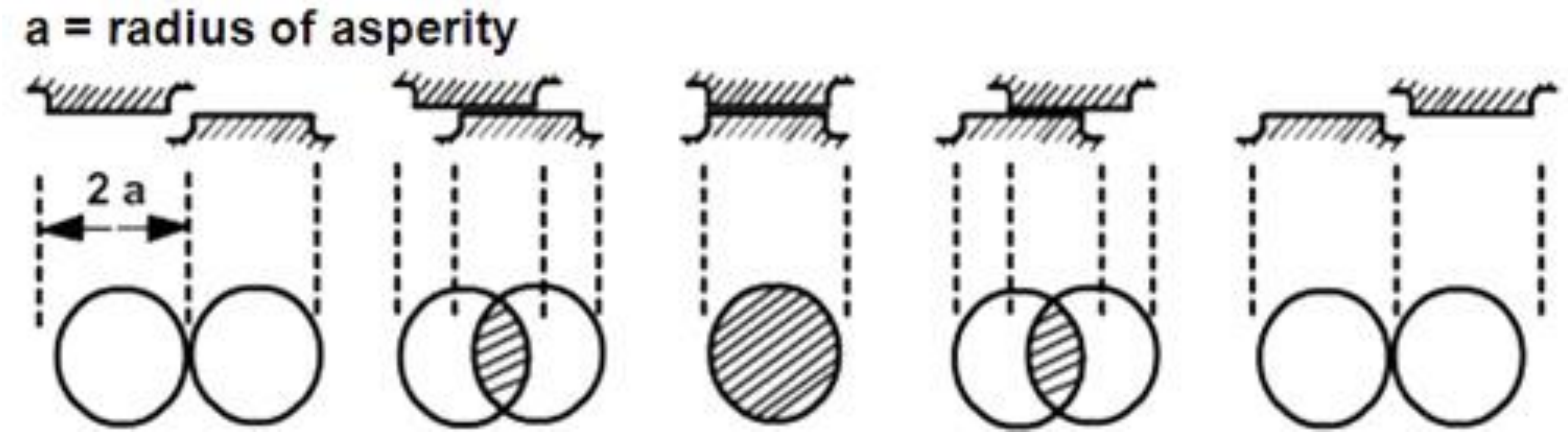
The value of k_1 depends on;

- *elastic-plastic contacts,*
- *shearing of those contacts,*
- *effect of environment,*
- *mode of lubrication, etc.*

This expression of wear volume is a simple expression, as it does not require to estimate constant n($A = (W/H)^n$), individual shear strength of elastic and plastic junctions, effect of lubricant thickness, roughness, etc.

Continue…

- Archard assumed that the contact between tribo-pair involve formation and breakage of junctions. In other words, contacts occurs only at asperities.
- The real area of contact of contacting surfaces, as distinguished from the apparent or geometric area of contact, is the instantaneous sum of the areas of all junctions.
- The Archard model is demonstrated in Fig., where cross section of asperities after plastic deformation is assumed to be circular. First sketch demonstrates the approach of junction forming asperities.
- Area of contact increases with sliding distance and subsequently decreases. But this process is continuous and happens among number of asperities. On average, it is assumed that n asperities will be in contact at any frame of time.

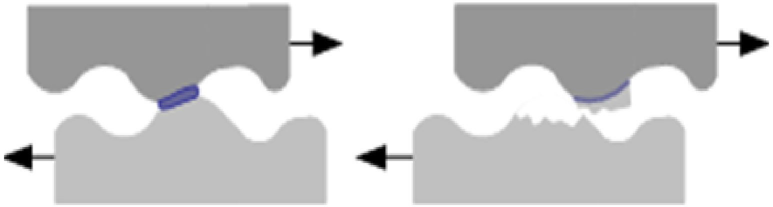


Frictional wear / adhesive wear

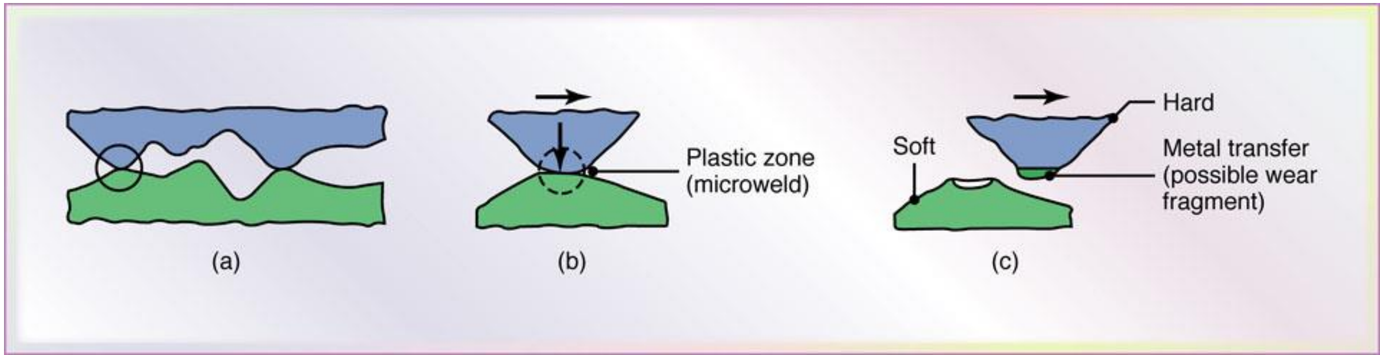
Two bodies sliding over or pressed into each other which promote the material transfer from one to another.

$$\frac{V}{L} = K\frac{P}{3\sigma y}$$

Where
V = wear volume
L = sliding velocity
P = applied load
σy = yield stress of softer material
K = wear coefficient

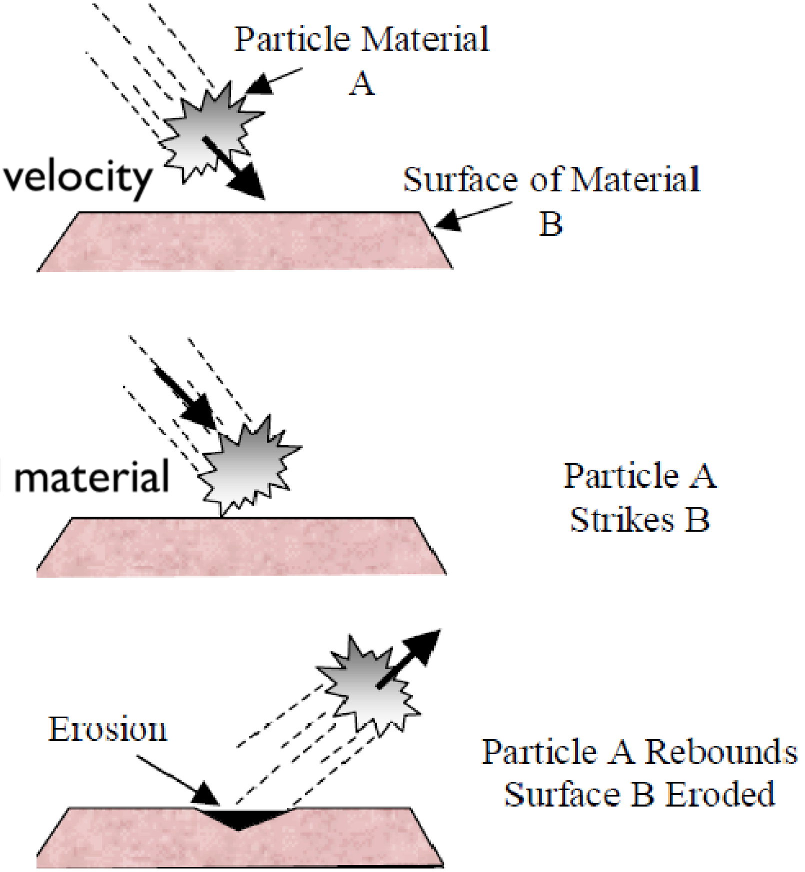


Ref.: www.substech.com



Erosive wear

The impingement of solid particles, or small drops of liquid or gas on the solid surface cause wear what is known as erosion of materials and components.



Pressure generated due to change in velocity

$$P = \Delta V \sqrt{E \rho}$$

P = Impact pressure
E = Modulus of elasticity of impacted material
ρ = Density of the fluid
V = Velocity

Advantages

- Cutting, drilling and polishing of brittle material

Ref.: dcu.ie/~stokesjt/Thermal Spraying/Book/Chapter1

Types of erosion

Solid particle erosion

Surface wear by impingement of solid particles carried by a gas or fluid.

e.g. Wear of helicopter blade leading edges in dusty environments.

- **Liquid drop erosion**

  Surface wear by impingement of liquid drops.

e.g. Wear of centrifugal gas compressor blades by condensate droplets.

- **Cavitation erosion**

  Surface wear in a flowing liquid by the generation and implosive collapse of gas bubbles.

e.g. Fluid-handling machines as marine propellers, dam slipways, gates, and all other hydraulic turbines.

Erosive wear rate(V_e) is function of :

1. Particles velocity (K.E.)

2. Impact angle and

3. Size of abrasive.

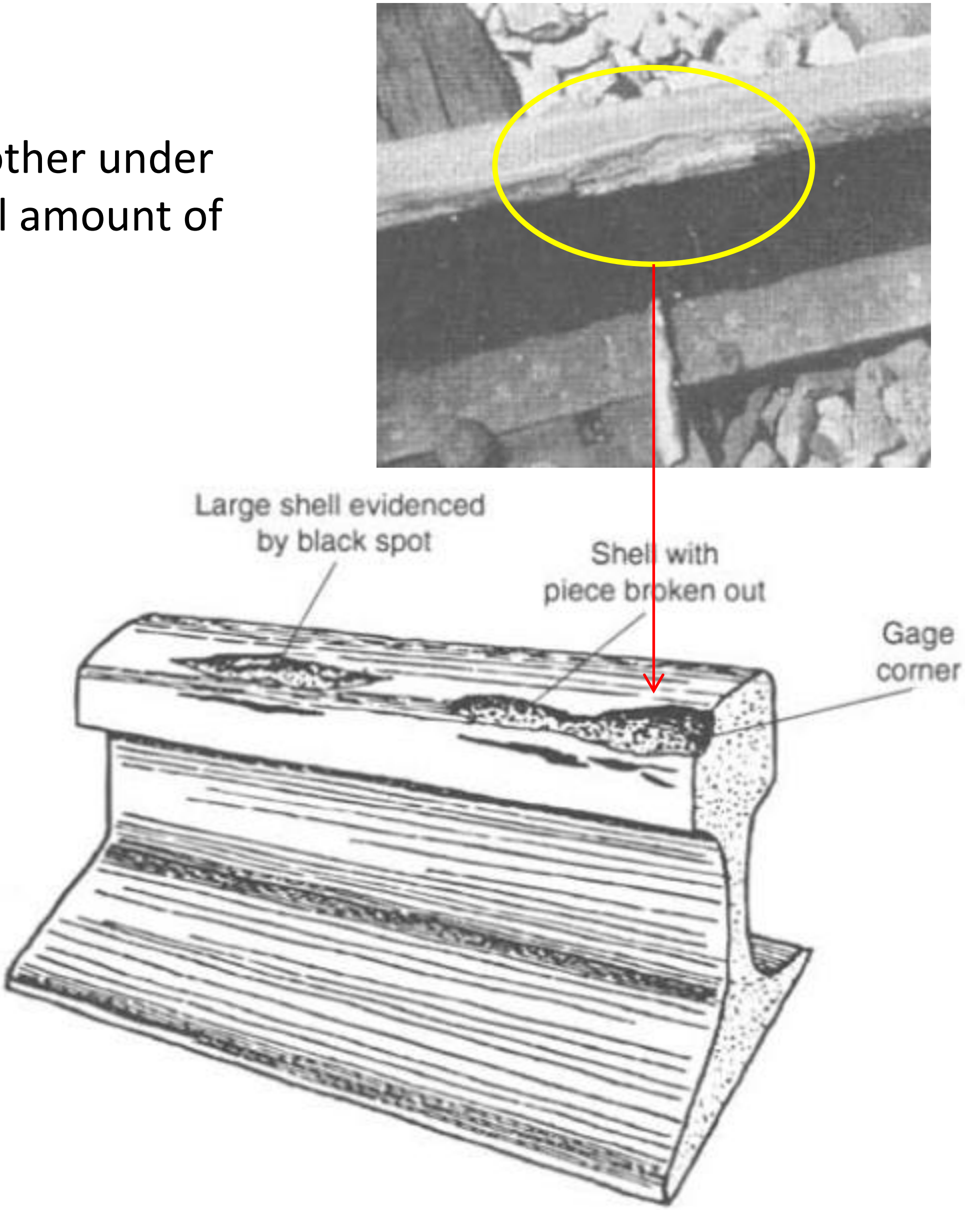
$V_e = K.A(\alpha).(\text{particle\_vel})^n.(\text{particle\_size})^3$.

Surface fatigue

- Two surfaces contacting to each other under pure rolling, or rolling with a small amount of sliding in contact

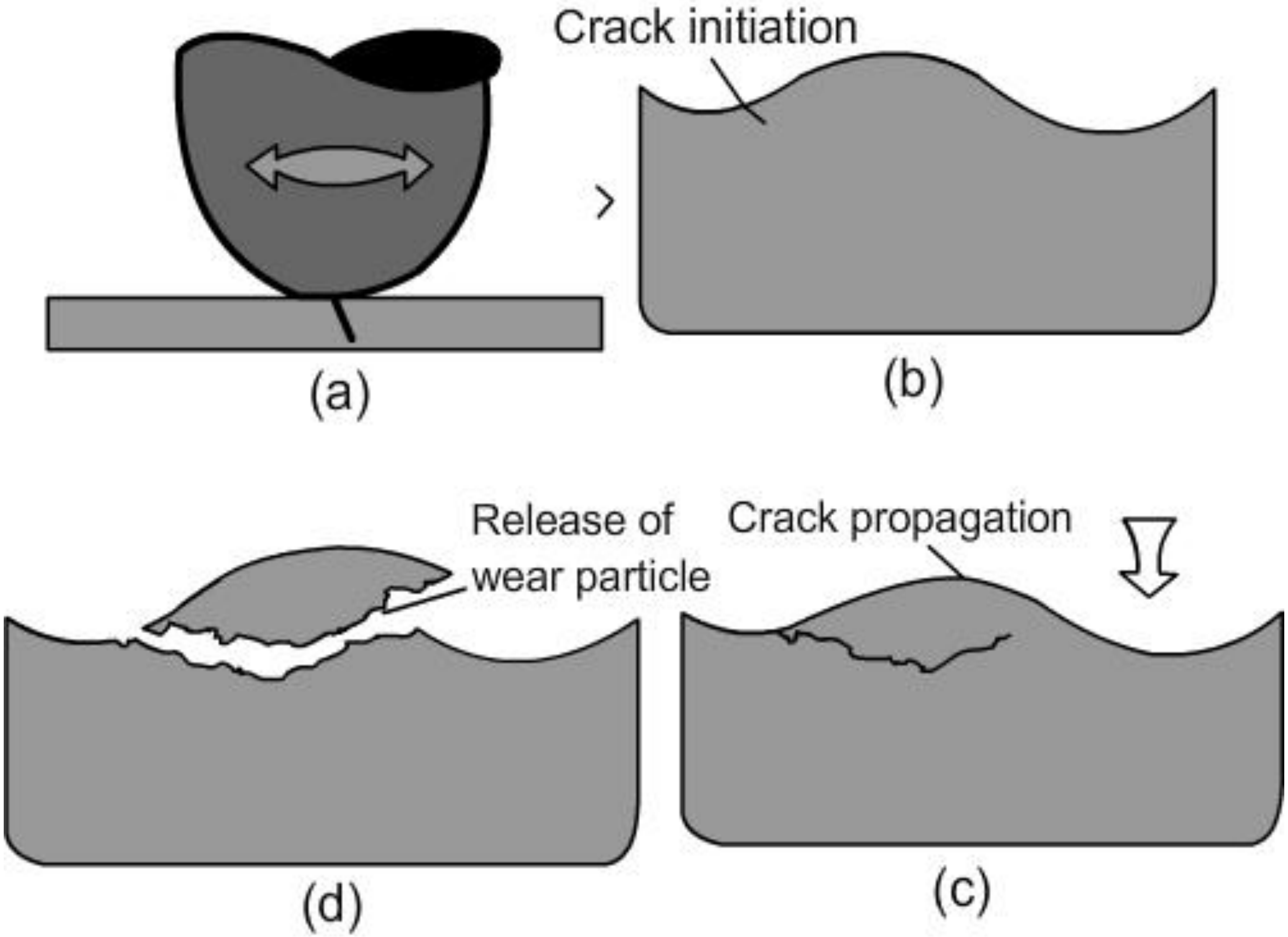
Contact fatigue

- As one element rolls many times over the other element
- Maximum shear stress is higher than fatigue limit



Ref.:W.A. Glaeser and S.J. Shaffer, Battelle Laboratories

Mechanism of fatigue wear.

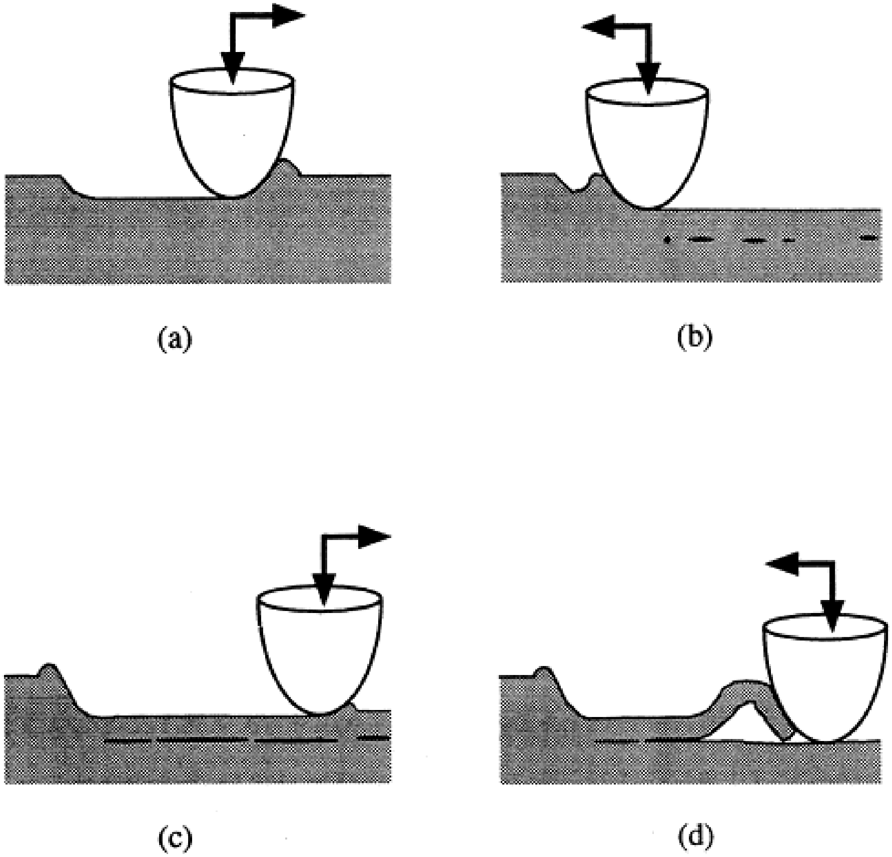


Delamination wear

A wear process where a material loss from the surface by forces of another surface acting on it in a sliding motion in the form of thin sheets.

Mechanisms of delamination wear

- Plastic deformation of the surface
- Cracks are nucleated below the surface
- Crack propagation from these nucleated cracks and joining with neighbouring one
- After separation from the surface, laminates form wear debris



Ref.: K Kato, M Bai, N Umehara, Y Miyake

Chemical wear

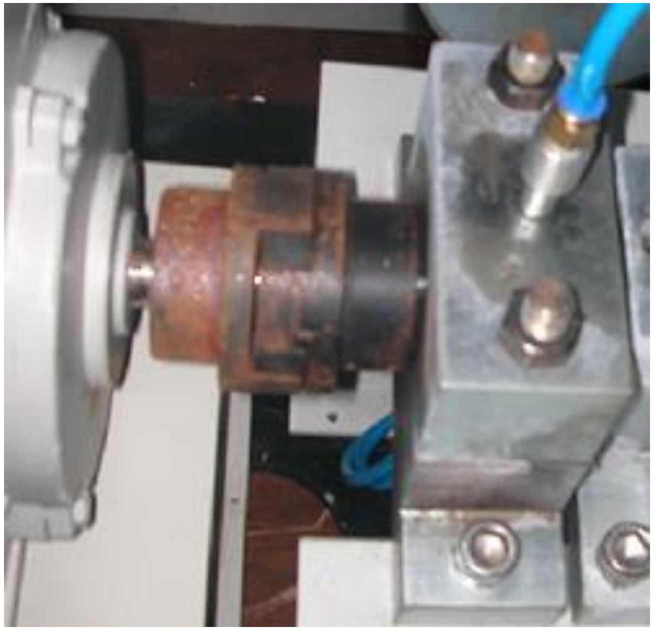
Environmental conditions produce a reaction product on one or both of rubbing surface and this chemical product is subsequently removed by the rubbing action.

Methods for control of the wear

- Lubrication technology
- Materials substitution
- Load reduction
- Removal of impact conditions

Corrosive Wea:

- Chemical reaction + Mechanical action = Corrosive wear
- The fundamental cause of Corrosive wear is a chemical reaction between the material and a corroding medium which can be either a chemical reagent, reactive lubricant or even air. Understanding the mechanisms of corrosive is important to reduce this kind of wear.
- Let us consider a jaw coupling used for connecting shaft and motor, as shown in Fig. This coupling is corroded, due to moist environment and its outer dimensions have increased. If we rub this coupling with fingers, brown colour debris will get detached from the coupling surface. In other words, after chemical reactions, mechanical action is essential to initiate corrosive wear.



Stages of corrosive wear :

- Sliding surfaces chemically interact with environment (humid/industrial vapor/acid)
- A reaction product (like oxide, chlorides, copper sulphide)
- Wearing away of reaction product film.

Case Study - Wear

- Generally, wear does not involve a single mechanism, so, it is advisable to take an integrated wear analysis approach assuming the wear behavior as a system property.
- In other words wear analysis is not limited to the evaluation of the effects of materials on *wear behavior*, but recommends *changes in contact geometry, roughness, tolerance*, and so on so that overall favorable results can be achieved.

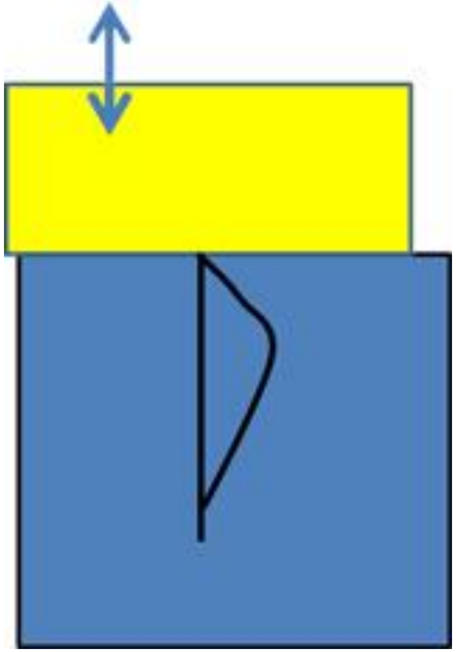
Example : Cam Wear Analysis

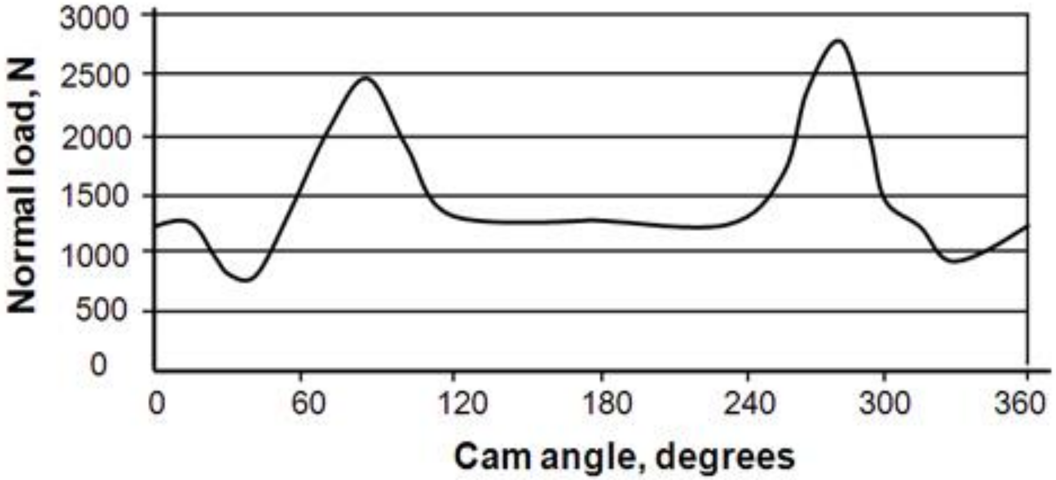
- Cam having pits on surface as shown in the Fig. was rejected because it was making noise and it was not performing intended function.
- It is necessary to dig-out the cause of failure of such pitting so that in future service life is improved.

Wear out of cam after one year HSL 6 photo on 3rd age 07machine overhauled N age 06 year out is at the angle 91 degree on the touch screen.

Continue…

- Pitting is a fatigue wear and reversible stresses are main cause of such failure.
- To illustrate it, a sketch is shown. In which yellow block, which is supported on blue block, is subjected to reversible stresses. Due to this arrangement, blue block will experience compressive and shear stresses. The variation in magnitude of shear stress is shown by a free curve, which shows that maximum force occurs at 90 and 270 degrees, remains constant in magnitude between 120 to 240 degrees.
- This means applied load on cam surface is dynamic and shall induced dynamic stresses.





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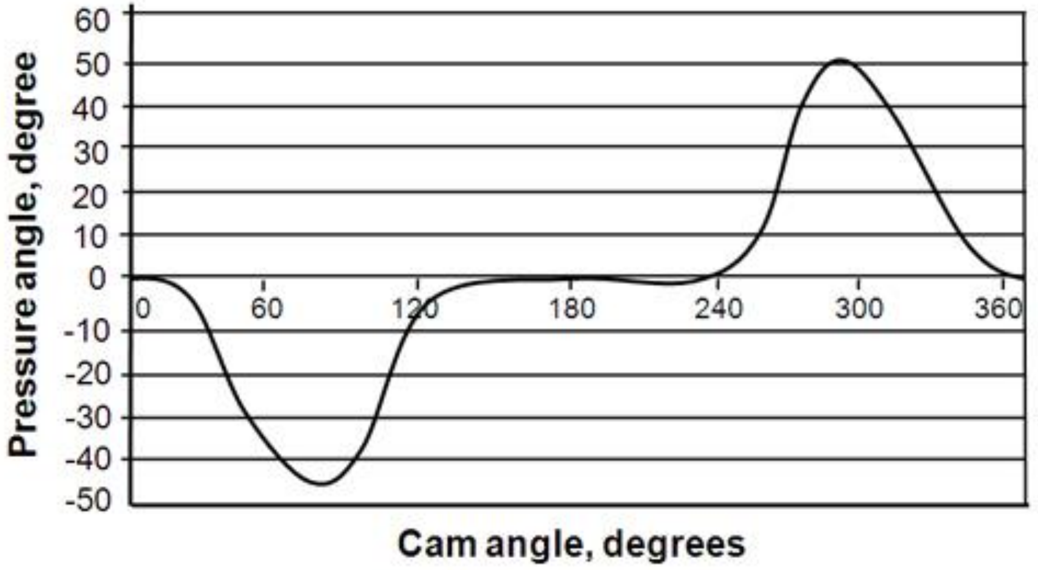
- **Can dynamic load be reduced ?** It is very obvious to explore whether this dynamic load can be reduced or not. Variation in pressure angle with cam rotation is given in Fig.
- It is possible by redesigning cam so that pressure angle remain lesser than 10 degrees. Pressure angle Φ is angle between direction of motion (velocity of follower) and axis of force transmission.

  - ø = 0 --> Transmitted force is completely utilize to move the follower
  - ø = 90^0 --> No motion of the follower. Gross sliding.



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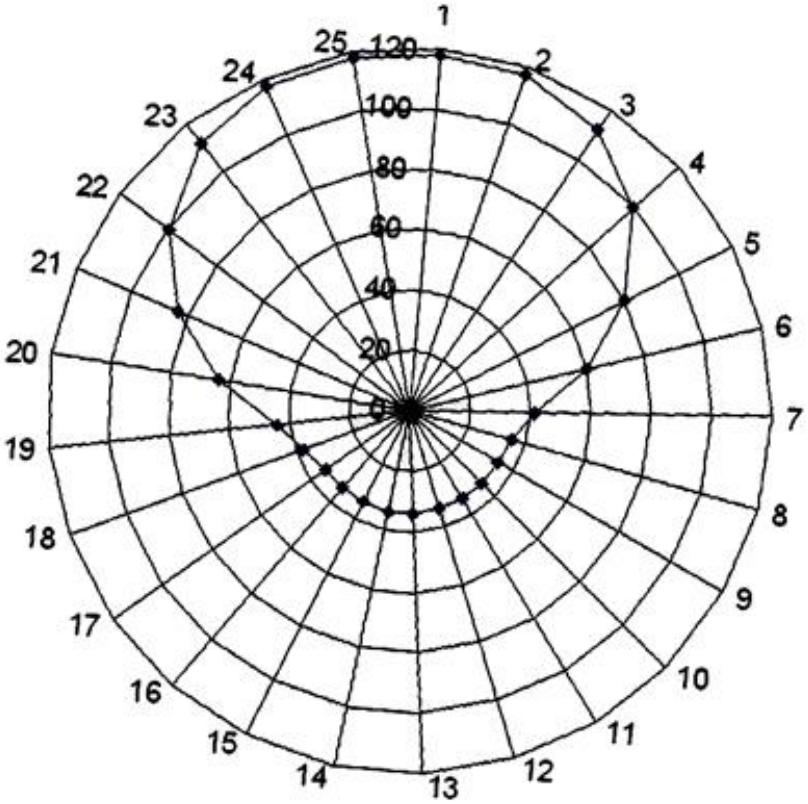
Contact Stresses Calculation:

- Cam and follower remain in convex contact from point 8 to 18. Contact between points 1 to 7, and 19 to 25 can be modeled as “concave contact" using Eq.
- Values of contact stresses are given in table.

$$\sigma_c \propto \sqrt{\frac{1}{R_{\text{follower}}} \pm \frac{1}{R_{\text{cam}}}}$$

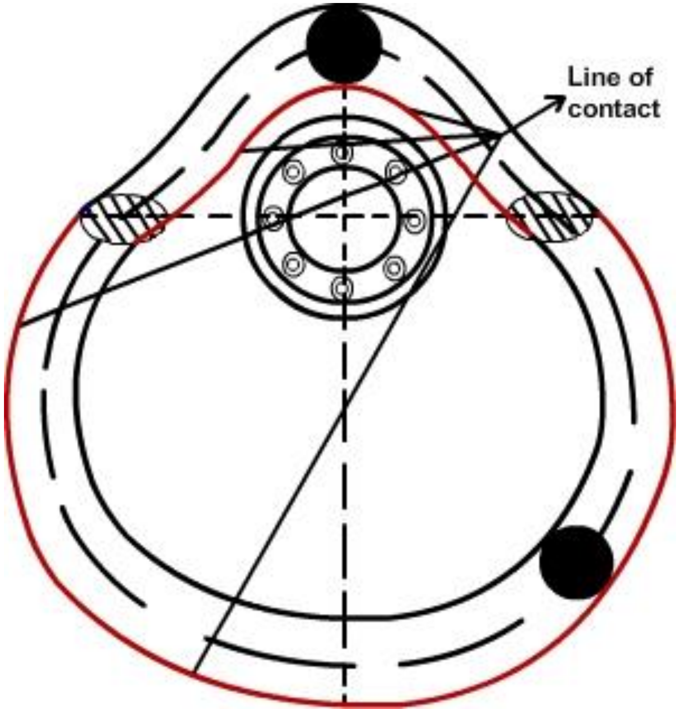
Convex – Convex
Convex – Concave



Cam angle	Cam contact radius, mm	Normal load on cam surface, N		Maximum normal stress, MPa
0	118.6	1195		-283
45	106.7	862	Compressive stress does not initiates fatigue failure.	-242
60	86.2	1653		-342
75	64.4	2174		-404
90	45.7	2489		-453
105	36.5	1794		-399
120	74.4	1344	Shear stress associated with compressive stresses causes crack formation.	-237
240	74	1258		-229
255	74.5	1428		-244
270	38.1	2553		-473
285	55.2	2716		-461
300	79.4	1510		-329
315	99.1	1166		-283
330	113	866		-241
345	118.2	1008		-260
360	118.6	1196		-283

Continue…

- **Cam-Follower Interaction:** Transition from convex to concave contact introduces sliding. Present cam - follower mechanism is subjected to variable stresses and sliding conditions, which repeat at frequency of cam rotation.
- Increasing rotational speed will reduce operating life of cam-surface.
- Further clearance between groove & follower(required to avoid jamming) reduces support area.
- Follower contacts only one side of groove. Red color thick curve indicates contact curve between follower and cam. Sudden change in velocity of roller follower particularly at areas shown by green colored hatched ellipse in Fig. occurs. Sudden change in the velocity causes gross sliding at interface. Therefore, cam-follower interface needs proper lubrication.



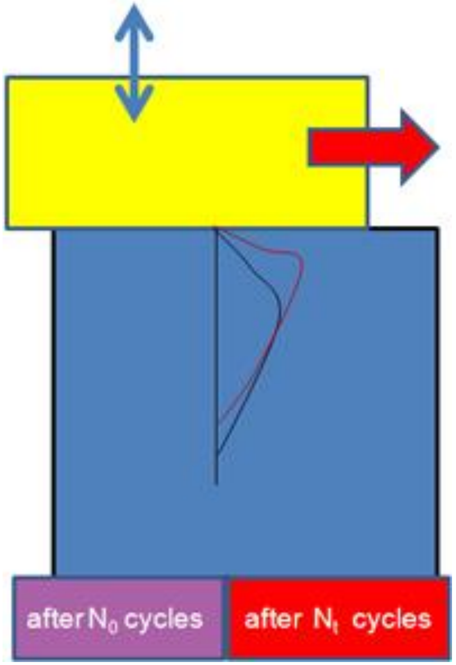
Continue…

How sliding reduces life ?

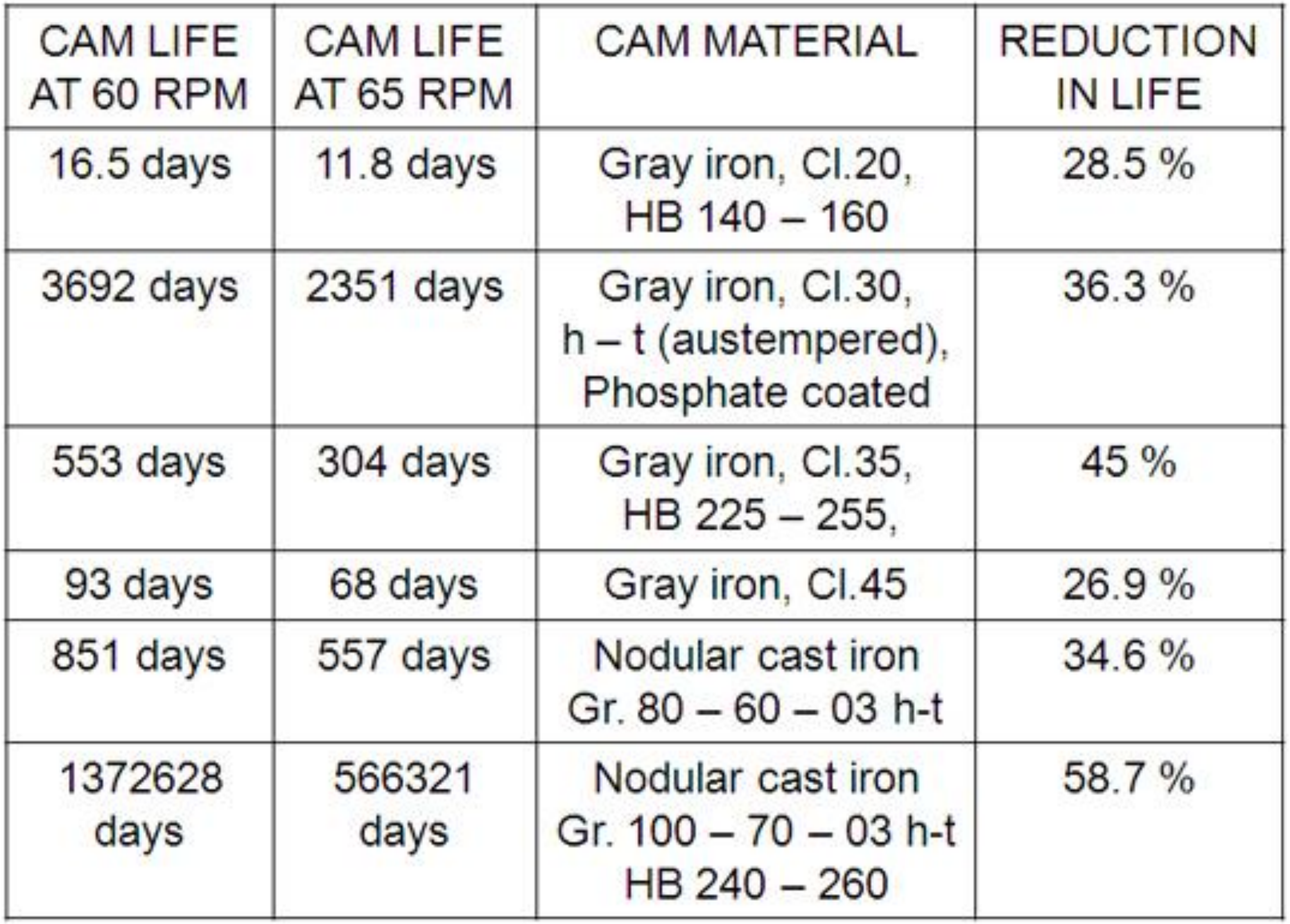
- Pitting, a fatigue wear, initiates on or near the surface of component.
- Tangential force not only increases (Fig.) τ_{max} but also shifts position of τ_{max} to the surface. The pitting occurs if $\tau_{max} > S_{ys}$.

  where S_{ys} is yield shear strength of the material.

- Total pitting life(N_f) = non-cracking life (N_O) + crack propagation life(N_p)
- In lubrication, τ_{max} is reduced in magnitude and occurs below surface. This means lubrication delays the crack to reach at the surface.



Cam life for various materials



CAM LIFE AT 60 RPM	CAM LIFE AT 65 RPM	CAM MATERIAL	REDUCTION IN LIFE
16.5 days	11.8 days	Gray iron, Cl.20, HB 140 – 160	28.5 %
3692 days	2351 days	Gray iron, Cl.30, h – t (austempered), Phosphate coated	36.3 %
553 days	304 days	Gray iron, Cl.35, HB 225 – 255,	45 %
93 days	68 days	Gray iron, Cl.45	26.9 %
851 days	557 days	Nodular cast iron Gr. 80 – 60 – 03 h-t	34.6 %
1372628 days	566321 days	Nodular cast iron Gr. 100 – 70 – 03 h-t HB 240 – 260	58.7 %

- *Theoretical study shows 25-30% reduction in cam life on increasing speed from 60 rpm to 65 rpm.*
- *Nodular cast iron provide much higher life compared to CI 45 material. Therefore, nodular cast iron will be a better choice if cam is operated at higher rpm.*