TRIBOLOGY
Module 1:

Introduction to tribology: Historical background, practical importance, and subsequent use in the field.

Lubricants: Types and specific field of applications. Properties of lubricants, viscosity, its measurement, effect of temperature and pressure on viscosity, lubrication types, standard grades of lubricants, and selection of lubricants. **8 hours**

Examination theory and numerical questions:

1. What is tribology? Explain in detail historical background of tribology. **(Dec.19/Jan.20)**
2. Explain the industrial importance of tribology. **(Dec.19/Jan.20)**
3. What are the functions of lubrications? Explain. **(Dec.19/Jan.20)**
4. Define the following:

Viscosity Fluidity Newtonian fluid Viscosity index.

5. **Distinguish between:**

Dynamic and kinematic viscosity Fluidity and viscosity

Newtonian and non-Newtonian fluid Mineral oil and vegetable oil (for lubrication)

Full and partial journal bearing.

6. State and explain the Newton's law of viscous flow and deduct the relation for fluidity of a Newtonian fluid. **(Dec.2015/Jan.2016) (May/June 2010)(June/July 2013) (06 M)**
7. Discuss various factors which affect the viscosity of fluids. **(June/July 2018) (June 2012) (Dec.2013 / Jan. 2014) (06 Marks)**
8. Sketch and explain working of any two viscosity measuring apparatus types. Add a note on the effect of temperature and pressure on viscosity of a fluid. **(Dec.2013 / Jan. 2014) (10 Marks)**
9. Explain with a neat sketch the principle of working of:

MAC-MICHEL viscometer Flower's viscometer.

Torsion wire viscometer. Saybolt viscometer

Ostwald viscometer Falling sphere viscometer **(Dec.19/Jan.20)** **(June/July 2018) (June/July 2017) (June/July 2016) (June/July 2015) (Dec.2014/Jan.2015) (Dec.2013 / Jan. 2014) (June 2012) (10 Marks)**

10. State and prove Hagen-Poiseullie law. Also state the assumptions made in the derivation. **(June/July 2016) (Dec.2014/Jan.2015) (Dec.2013 / Jan. 2014) (June/July 2011)(May/June 2010) (10 Marks)**
11. State Hagen-Poiseuille law and derive an expression for velocity distribution across the capillary tube. **(Dec.2015/Jan.2016) (June/July 2015) (June/July 2013) (10 M)**
12. Derive an expression for the flow of oil between two parallel stationary planes. **(June/July 2018) (December 2012) (12 Marks)**
13. An oil supply line 1.2 m long having an internal diameter 6.25 mm and delivery $6 \times 10^{-5}\ m^3/s$ of oil having a viscosity of 0.0555 Pa - S. Calculate the pressure drop in the supply line and energy required in forcing the oil through the supply line against viscous fiction. **(June/July 2013) (04 Marks)**

14. A slot 100mm wide, 0.125 mm thick and 300 mm long is used to connect two tanks filled with an oil of viscosity $0.01\ pa-s$ at the operating temperature, if the rate of flow is $8 \times 10^3\ mm^3/s$ and if the lower pressure is $0.20\ N/mm^2$, determine the higher pressure. **(December 2012) (08 Marks)**

15. An oil supply line of 3 m long with internal diameter of 0.8 mm delivers 2 liters of oil per minute, The oil has viscosity of 0.065 pas-sec. Determine the pressure drop in the supply line and the maximum fluid flow velocity. **(Dec.2015/Jan.2016) (08 Marks)**

16. Tanks A and B are connected by a capillary tube and the system filled with a liquid of viscosity 2 cP. The pressures in tanks A and B are 0.01 and 0.04 MPa respectively. The outer diameter of the tube is 0.000835 mm with a wall thickness of 0.0001 mm. The length of the capillary is 2 m. assuming laminar flow, determine the rate of flow through We capillary tube. **(Dec.2015/Jan.2016) (08 Marks)**

17. The diameter of capillary tube connecting two reservoirs is 0.025 cm and its length is 160 cm. the viscosity of oil filling the system is 24.1 cP. Determine the difference between pressure in reservoirs A and B if maximum velocity of flow at the center line of capillary is equal to 8 m/min. **(June/July 2011)**

Introduction:

What is tribology **(Dec.19/Jan.20)**

Tribology is derived from the greek word “tribos”, meaning of tribos is rubbing.

Tribology is a science that deals with friction, lubrication and wear in all contacting pairs.

Tribological knowledge helps to improve service life, safety and reliability of interacting machine components and yields substantial economical bebefits.

Tribology Historical Background:

Explain in detail historical background of tribology. **(Dec.19/Jan.20)**

In 3500 BC our ancestors use wheels in order to reduce friction in translatory motion.

Drifts were made during palcolithic period for drilling holes or producing fire and they were fitted with bearings made from bones or antlers.

Potters wheels or stones for grinding cereals indicates the use and knowledge of some form of bearings.

The celebrating engineer – artist Leonardo da Vince (1452-15719) was the first to develop the basic concept of friction. Amontons conducted experiments and formulated his laws of friction in 1699. Later in 1985 coulomb conducted some careful experiments and suggested that friction was independent of velocity.

Petroff’s(1883) was the first to consider the viscous friction in the fluid film bearing. The important contributions in the science of lubrication are the experiments of Beauchamp Tower (1884) and the work of Osborne Reynold’s(1886). The solution of Reynold’s equation was then given by Sommerfeld for a infinitely long journal bearing.

Lord Rayleigh investigated the effect of lubricant film shape on the operating characteristics of a bearing using the calculus of variations. The investigation of cavitations in the lubricating film was initiated by Coles and Hughes. Their experiments showed that the end of pressure curve was coinciding with the position of zero pressure derivatives.

Taylor studied theoretical flow between two concentric rotating cylinders and found the conditions under which the laminar flow broke down to turbulent. An exhibit in Paris in an industrial exposition in 1886 where in a heavy mass was supported on frictionless pressurized oil film probably marked the beginning of the concept of supporting load on fluid film.

Over the 20th century, knowledge in all areas of tribology has expanded tremendously due to enormous industrial growth leading to demand for tribology.

Need of tribology as a subject:

Friction, wear and lubrication have been taught in many science and engineering classes at a rudimentary level. It means empirically derived trends (friction forces 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 a the only predictive tools available. These approaches have drawbacks of being predictive are not well understood, often one does not even know which are the important parameters or over what range the observed trends are valid. This poor predictive power has led the field of tribology being perceived in many scientific quarters.

Most tribological phenomenon are inherently complicated and interconnected, making it necessary to understand the concepts of tribology in details.

Integration of knowledge from multifaceted disciplines (solid mechanics, fluid mechanics, material science, chemistry etc.) is essential and therefore a separated subject is required.

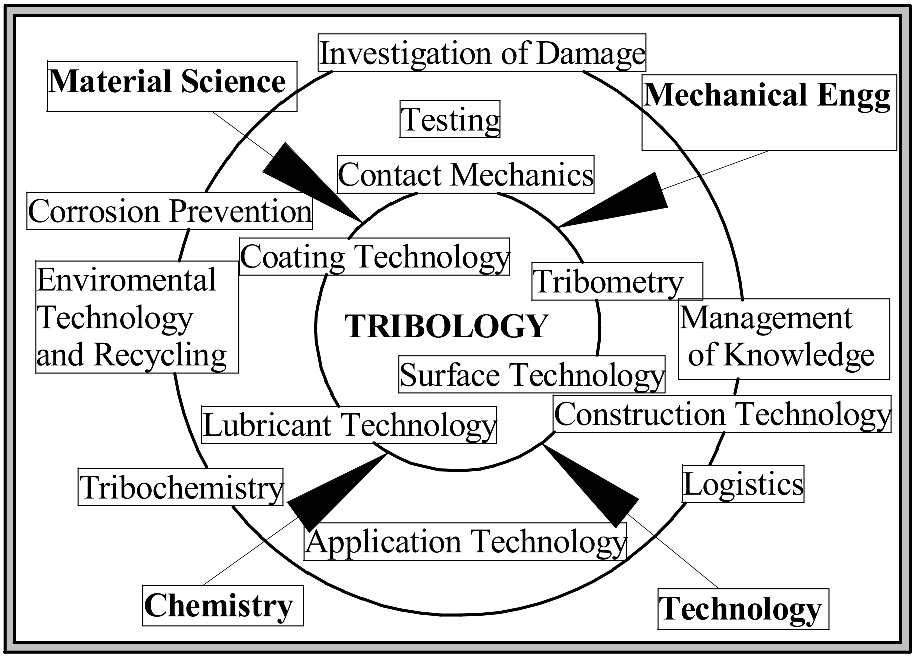
Solid mechanics: focus is on expressions of contact stresses / deformations and surface temperatures due to rolling/sliding.

Fluid mechanics: study on lubricant film formed between various geometric shapes of rolling / sliding surfaces.

Material science: focus is on atomic and micro scales mechanisms whereby solid surface degradation or alteration occurs during relative motion.

Chemistry: deals with reactivity between lubricants and solid surfaces.

Thermodynamics: heat and mass transfer in fluids and bounding solids.



Components of Tribology

Explain the industrial importance of tribology. **(Dec.19/Jan.20)**

Practical / Industrial applications:

Tribology plays vital role while designing of modern machineries involving sliding & rolling surfaces. Brakes, clutches, bolts nuts, driving wheels on automobiles etc. wear is also used in productive manner in many cases, such as writing with pencil, polishing, machining & shaving. Unproductive friction & wear takes place in engines gears, cams, bearings and scale. It has been estimated that approximately one third of the worlds energy resources, in present use, appear as friction in one form or the other. Wear can also cause accidents. Thus, the knowledge of tribology can lead to various substantial and significant savings without deployment of large capital investment. Resources in tribology lead to increased plant efficiency, fewer breakdowns, better performance and above all significant savings.

Seal: Carbon graphite seal is employed to avoid leakage of steam from rotary joints of paper industry. Failure of this component occurs due to adhesive wear. Adhesive wear occurs uneven surface that leads to reduction in mechanical contact area. For some imposed load, reduction in mechanical contacts, increases the level of stress and hence chances of failure.

Cam: Cams are used to transmit rotary motion in reciprocating motion. These components are subjected to jerks in sliding distance, which leads to form some pits on the cam surface. Creation of pits on the cam surfaces increases noise pollution and reduces mechanical performance.

Journal bearings: Tribology plays an important role in journal bearings, since wear increases the clearance between shaft and bearing and leads to reduction in load carrying capacity of the bearing. Often such failures occur in absence of sufficient lubricant hydrodynamic film thickness due to relative low speed.

Gear: The pt generally occurs due to excessive contact stress in gears. Understanding the effect og contact stress helps in developing an equation for estimation of perspective gear life.

Studies of fluid film bearing, rolling element bearing, seals, cams, gears and brakes are some of the applications in which tribology is required. Basic knowledge gained by tribology course is very useful for industries related to power, steel, cement, oil etc. practicing such knowledge in problems ranging from house hold appliances to large size ships earns great economic benefits. Therefore tribology course is often named as “Industrial tribology”, “Applied tribology”.

Lubrication:

It is an art of reducing friction resistance by means of some kind of substance introduced between the two surfaces having relative motion known as lubrication.

Type of lubrication:

Friction between two surfaces moving relatively to each other depends upon a number of factors such as applied load, relative velocity of surfaces, geometry of the surfaces, physical properties of metals in contact. Depending upon these conditions, the following principal types of sliding friction exists.

- Sliding with fluid film lubrication
- Sliding with extreme boundary lubrication
- Sliding with boundary lubrication
- Sliding of clean surfaces.

Fluid film lubrication:

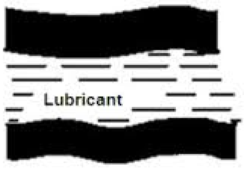


Fig: Fluid film lubrication

In this type of lubrication film of liquid lubricants is so thick and metal to metal contact between the moving parts is prevented and only friction is that occurs within fluid film is called an fluid film lbrication or perfect film lubrication. The friction is considerably less than metal to metal friction. under these conditions, the viscosity of lubricant is the important factor, since it determine bearing friction, temperature rise, rate of flow of lubricant and load carrying capacity.

Boundary lubrication:

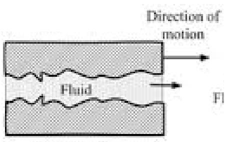


Fig : Boundary lubrication

During starting and stopping of bearing where the velocity is too low, the oil film is not capable of supporting the entire load, the thin film or boundary lubrication is preferable. Boundary lubrication exists also in a journal bearing if the bearing load becomes too high or if the viscosity of the lubricant is too low.

If the surfaces approaches each other close enough, boundary lubrication exists, hydrodynamic theory can no longer be used.

Extreme Boundary lubrication:

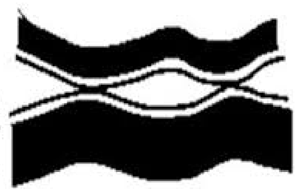


Fig : Extreme Boundary lubrication

Under certain load and temperature condition. The boundary film will fail, so direct contact will taken palce. This condition is called extreme boundary lubrication. Under these conditions seizure of metallic surfaces and the destruction of one or both surfaces begins. Due to this effect breakdown of the surfaces of the bearings unit. Ussualy starts at tiny points, called hot spots, where the localized temperature rises to such a degee that the welding of metal occurs.

Standard grades of lubricants:

There are two systems for lubricant oil grade classification. The **SAE** (Society of Automotive Engineers) viscosity grade and the **API** (American Petroleum Institute) classification that designates the type of engines for which the oil was designed.

Lubricants are classified into following three categories

- Lubricating oils
- Greases
- Solid lubricants

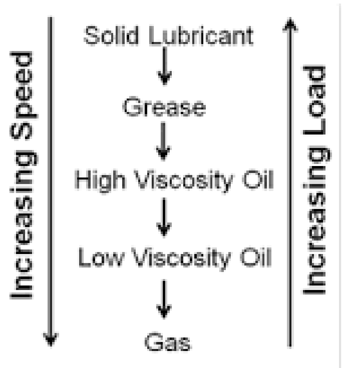
Lubricating oils are classified into following categories

- Automotive oils
- Industrial lubricating oils
- Metal working oils
- Industrial specialty oils
- Marine and aviation lubricating oils, etc.

Lubricant:

Lubricant is substance that reduces friction and wear at the interface of two materials. The lubricant at interface reduces the adhesive friction by lower the shear strength of interface. Based on the shear strength of lubricant or molecular state, lubricants are classified in four categories.

Classification of Lubricants:



- Solid lubricants
- Semi-solid lubricants
- Liquid lubricants
- Gaseous lubricants

Solid Lubricants :

A solid lubricant is basically any solid material which can be placed between two bearing surfaces and which will shear more easily under a given load than the bearing materials themselves. solid lubricant include graphite, molybdenum disulphide (MoS_2) and different dichalcogenides. Some self lubricating solids are also available, such as polymers and polymer composites. The coefficient of friction in dry lubrication is related to the shearing force and the bearing load.

Two primary property requirements are:

1. Material must be able to support applied load without significant distortion, deformation or loss in strength.

2. Coefficient of friction and the rate of wear must be acceptably low.

Solid lubricants in use are self-lubricating composites. These composites are classified as polymer, metal-solid, carbon and graphite, and ceramic and cermet.

E.g.., Molybdenum disulfide and Graphite.

Advantages

More effective than fluid lubricants.

High resistance to deterioration in storage,

Highly stable in extreme conditions.

Permits Equipment to be lighter and simpler.

Superior cleanliness.

Disadvantages

Poor Self healing Properties.

Poor Heat dissipation.

Higher Coefficient of Friction and Wear.

Semi-Solid Lubricant:

Grease: Greases are oils that are thickened with solids (thickener) to form semi fluid products. Greases are preferred to liquid lubricants in cases where the application of continuous supply of lubricant is not needed or there is no sufficiently tight enclosure to retain a liquid lubricant. The grease will act as lubricant as well as seal dirt.

They are variety of grease such as soap thickeners, clay thickeners, lithium thickeners, sodium thickeners, **Base Oil, Additives,** MOLY Grease. Teflon grease and Graphite grease.

Advantages of Greases:

- Remains at application point & adhere to surface.
- Less-frequent application needed.
- Good for inclined/vertical shafts.
- Seal out contaminants & less expensive seals needed.
- Water resistant & reduce oil vapor problems.
- Prolong the life of worn parts by filing irregularities.
- Provide better mechanical lubrication cushion for extreme conditions such as shock loading, reversing operations, low speeds & high loads.
- Reduce noise and vibration.

Disadvantages of Greases:

- Because of semi-solid nature of greases, it does not perform the cooling, so poor dissipation of heat.
- Once dust or dirt enters the grease, it cannot be easily removed and would act as deterrent in performance.
- No filtration, so contaminants/wear-debris cannot be separated.

Liquid Lubricants

These are specific class of lubricants which remain in liquid phase at all temperature and pressure conditions.

Classification of Liquid Lubricants :

Vegetable (Castor, Rapeseed) oils :
- Less stable (rapid oxidation) than mineral oils at high temp
- Contain more natural boundary lubricants than mineral oils.

Animal fats: These are fatty substances extracted from animals, and fish. They are composed of fatty acids and alcohols. They are called fixed oils because they do not volatilize unless they decompose. This process is known as drying. The fixed oils which are slow to dry(slow in oxidation) are used for lubrication. Fixed oils are usually added to mineral oils to improve film formation as these lubricants have extreme pressure properties. Common examples of these lubricants are tallow, castor oil and fish oil. One of major problem of this class of lubricants in the availability.

Mineral oils: Extracted from crude oil. Mineral oil consists of hydrocarbons.

Mineral oils are classified as paraffins, naphthene and aromatic. Paraffins are preferrable choice compared to napthenes or aromatics.

Gas Lubrication: Gas (i.e, Air, Nitrogen, and Helium) lubrication is used for ultra thin film thickness (separation) between tribo-pairs.

Advantages:

- Temperature range– (-200^{0}C) to (2000^{0}C). No vaporization, cavitations, solidification, decomposition.
- Very low viscosity (1000 times less viscous than even the thinnest mineral oil), therefore ultra low friction.
- Possible high speed.
- Cleanliness.
- No seal requirement for lubrication.

Disadvantages:

- Very low load capacity.
- Low damping.
- Ultra low film thickness.
  Smooth surfaces & very low clearance (to maximize load capacity & minimize flow rate) needs a specialist designers & manufacturer (close tolerance).
- Less forgiving of errors in estimating loads or of deviations from specifications during manufacture and installation.

Advantages of lubrications:

- Reducing instant failures
- Reducing fatigue failure
- Reduce surface failure
- Reduce stress concentration

Applications of lubricant:

- Transmission parts
- Bearings
- Cam and followers
- Journals
- Seal faces
- Brakes
- Any situation involving metal to metal contact

What are the functions of lubrications? Explain. **(Dec.19/Jan.20)**

Functions of lubricants

- Reduce the frictional resistance
- Reduce wear and tear, surface deformation
- Acts as coolant
- Provides protection against corrosion
- Acts as a seal in some cases
- Improves the efficiency of the machine.

*** **Properties of lubricants:**

Viscosity	Fire point	Extreme pressure
Viscosity index	Oiliness	Corrosion resistance
Cloud point	Total acid number (TAN)	Oxidation stability
Pour point	Volatility	
Flash point	Emulsification	

Viscosity: The property of the fluid, which opposes the relative motion between its layers (resistance to shear), is called viscosity.

Viscosity refers to the resistance of a fluid to a change in shape, or movement of neighboring portions relative to one another. Viscosity denotes opposition to flow. The reciprocal of the viscosity is called the fluidity, a measure of the ease of flow. Grease, for example, has a greater viscosity than Vegetable oil.

Viscosity is a major factor in determining the forces that must be overcome when fluids are used in lubrication. For many fluids the tangential, or shearing, stress that causes flow is directly proportional to the rate of shear strain, or rate of deformation, that result. In other words, the shear stress divided by the rate of shear strain is constant for a given fluid at a fixed temperature. This constant is called the dynamic, or absolute, viscosity and often simply the viscosity.

For some applications the kinematic viscosity is more useful than the absolute, or dynamic, viscosity. Kinematic viscosity is the absolute viscosity of a fluid divided by its mass density. (Mass density is the mass of a substance divided by its volume.) The dimensions of kinematic viscosity are area divided by time; the appropriate units are meter squared per second. The unit of kinematic viscosity in the centimeter-gram-second (CGS) system, called the stokes in Britain and the stoke in the U.S., is named for the British physicist Sir George Gabriel Stokes. The stoke is defined as one centimeter squared per second.

Viscosity index: The rate of change of viscosity with temperature is known as viscosity index. This change can be evaluated numerically and the result is expressed as Automobile **(SAE)** & industrial **(V.I)**

Cloud point: The lubricating oil cool slowly the temperature at which it becomes cloudy is called cloud point.

Pour point : The lubricating oil cool slowly the temperature at which it ceases to flow or pour is called pour point. It reflects on the capacity of the oil to work at low temperature.

Flash point: The lowest temperature at which the oil gives off enough vapors that ignite for a moment when brought near it is called flash point. It reflects on the capacity of the oil to work at high temperature without any fire hazard.

Fire point: The lowest temperature at which the oil gives off enough vapors which burns continuously for 5 seconds when a small flame is brought near it is called fire point.

Total acid number (TAN): The number of milligram of potassium to neutralize the free acid present in 1 Gm of oil is called TAN.

Oiliness: The capacity of oil to stick to the surface of machine under condition of heavy pressure or load is called oiliness.

Oxidation stability: Ability of resist oxidation. Determine life of the oil.

Corrosion resistance: Ability to protect metal against corrosion and rust.

Extreme pressure: Ability to withstand shock and impact loading.

Emulsification: The property of oil to get intimate mixed with water forming a colloidal solution or emulsion is called emulsification.

Volatility: The tendency of oil vaporized with increase of temperature is called volatility.

Newtonian and Non-Newtonian fluids

Lubricants are often classified as "Newtonian” and "Non-Newtonian" fluids. This classification is on basis of relation between shear stress and shear strain rate. In this relation, η is known as dynamic viscosity, which is one of the important lubrication parameters.

$$\tau = \eta\phi = \eta\frac{dx}{dy} = \eta\frac{du}{dy}$$

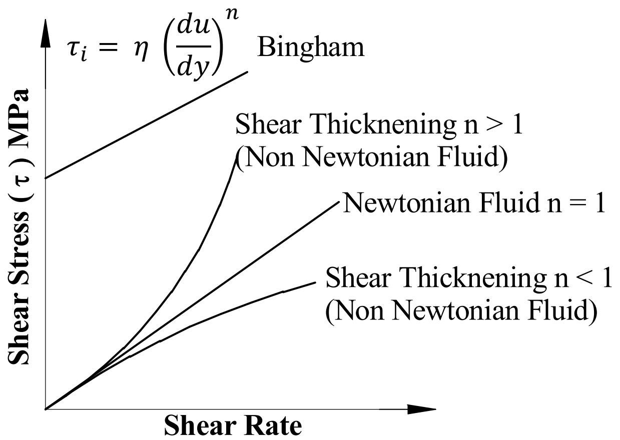


Fig : Shear Stress Vs Shear Rate for various lubricants

From the above Fig, it is evident that the shear stress and shear rate are the major aspects to analyze the behavior of any fluid , its characteristics and in particular, the value of the viscosity index (n) that will eventually help analyze whether the lubricant is Newtonian, or non Newtonian. Thus for any lubricant, if $n = 1$, then the fluid is Newtonian; if $n < l$, then it is a shear thinning lubricant; if $n > l$, then it is a shear thickening lubricant.

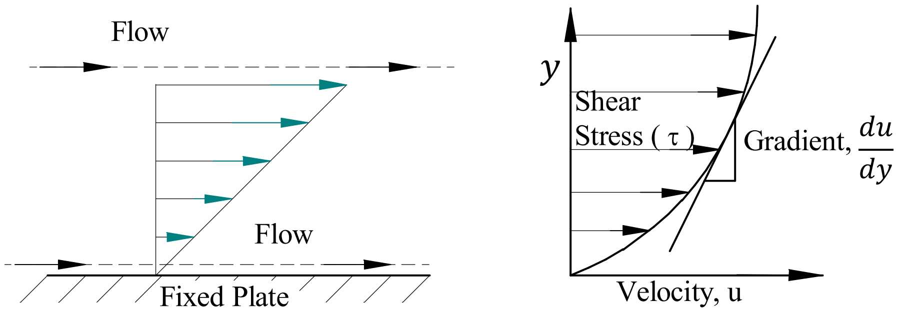


Fig : Viscosity of Fluids (Newton's Law of Viscosity)

$\tau = \eta \frac{du}{dy}$ (As per Newton's law of viscosity, shear stress is proportional to rate of shear strain)

$F = -\eta A \frac{du}{dy} \quad (\because \tau = F/A)$

The negative sign implies that the direction of forces is opposite to velocity.

Where, the proportional constant (η) is called coefficient of viscosity.

The cgs unit of q is called 'poise' in honor of the French scientist Poiseulli.

Characteristics of good lubricant:

- Low vapor pressure
- High boiling point
- Non corrosion nature
- Good thermal conductivity
- Adequate viscosity
- High flash and fire point
- High oiliness
- Low volatility
- Low freezing point
- Does not form emulsion

*** **Apparatus for measuring viscosity**

1. Couette – Hatschck (Torsion Wire) viscometer
2. Flowers viscometer
3. Falling sphere viscometer
4. Mac-Michell viscometer
5. Ostwald viscometer
6. Saybolt universal viscometer

1. Couetta – Hatschek Viscometer (primary viscometer)

This apparatus consists of two cylinders (l) and (2). The Inlet cylinder (1) is fixed to z table which can be rotated about its vertical axis at a constant speed. The inner cylinder (2) is suspended, by the torsion wire (4). The tested fluid fills the space between the two cylinders. When the liquid cylinder rotates the motion in the liquid between the two cylinders is similar to the condition of flow of a liquid between two parallel planes as shown in fig (1.1). When the torque T is applied on the outer cylinder it rotates and tends to rotate the inner cylinder. Due to this. Wire (4) is twisted.

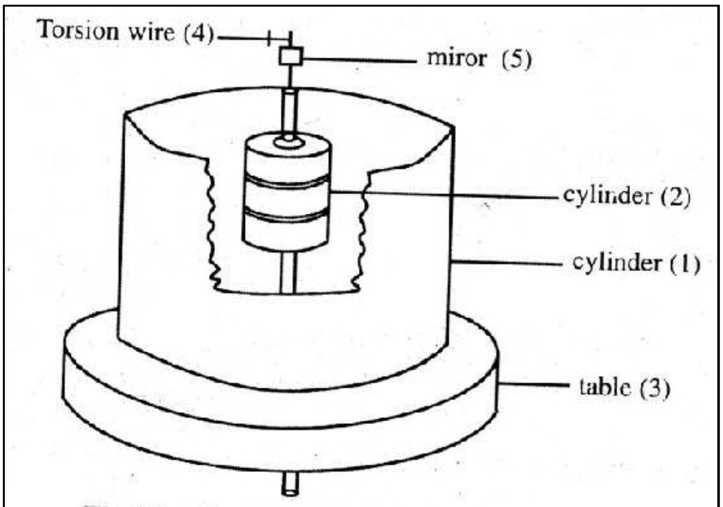


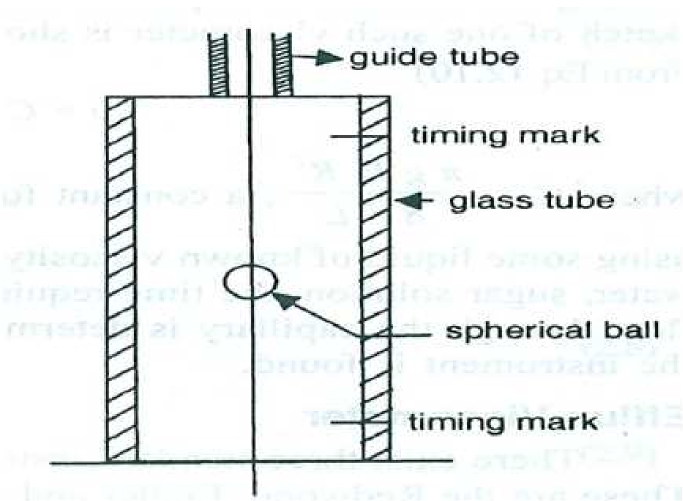
Fig 1.7 : Couette Hatschek Viscometer

A mirror (5) is connected to this wire. The angular displacement of the inner cylinder is measured by the deflection of a beam of right reflected from the mirror. The wire is calibrated such that the deflection of wire gives a measure of viscosity, This instrument is usually used for determining viscosity of liquid having higher viscosity.

$$\tau = \frac{F}{A} = \eta \frac{U}{h}$$

$$T = F \times R$$

2. **Falling sphere viscometer:**



<u>Fig: Falling sphere viscometer</u>

If a sphere is filling through a viscous liquid under a constant force, it will assume a constant velocity. Stokes formula can be applied for a sphere moving through an infinite fluid. A sphere falling freely under gravity in liquid will be attending a velocity (v) given by

$$v = \frac{2\, R^2\, (\rho - \rho^{'})g}{9\, \eta} \qquad \boldsymbol{(E-1)}$$

Where R is the radius of the sphere and ρ & $\rho^{'}$ are the densities of sphere material and liquid, respectively. In above Fig a sphere from the top of a vertical tube containing oil is released. The time (t) taken for the falling body to cover a measured distance (H) is recorded by an electronic clock. Knowing the velocity $v = \frac{H}{t}$ and using equation (E-1), the viscosity can be computed.

3. Flowers viscometer (Secondary Viscometer)

This instrument belongs to the category of second viscometer. Absolute viscosity of liquid cannot be obtained directly by using a secondary viscometer. To use this instrument for measuring viscosity, it must be calibrated first by using liquids of known viscosity.

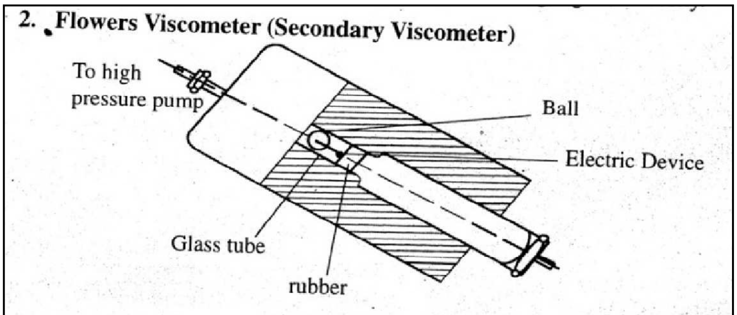


Fig 1.8 : Flowers Viscometer

It consists of a glass tube with a small ball whose diameter is smaller than the inner diameter of the tube. The tube is filled with the liquid whose viscosity is to be measured. After placing the tube in an inclined position to the horizontal, the ball at the left end of the tube is released. The ball starts to roll down the tube and electric device is used to indicate the instant when the ball reaches the lower end of the tube. The time taken by the ball to travel from left end to right end of the tube is a measure of viscosity of the liquid.

4. Michell viscometer

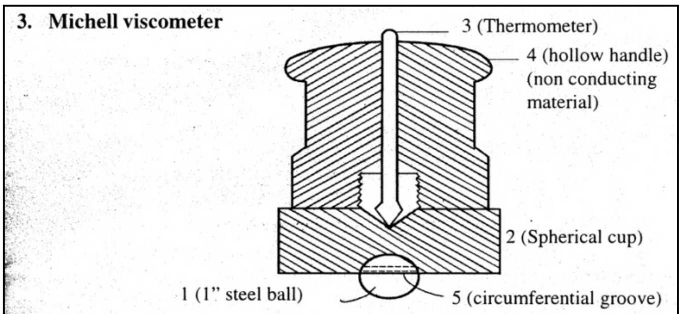


Fig 1.9 : Michell viscometers.

It consists of a stainless steel ball (1) of 1 inch diameter and a spherical cup (2) with hollow groove, Three small projections are provided on the cup 120^0 apart. These projection maintain a minimum clearance of about 0.01 mm between ball and cup surface. The hollow handle (4) of non conducting material is connected to the cup. Thermometer (3) is inserted into the handle for measuring the temperature of the cup.

To determine the viscosity of an oil, a small sample of the oil is placed in the cup while the instrument is held with the cup upwards. Then the ball is placed in the cup and pressed so that excess oil enters the circumferential groove (5). In the cup only a layer of oil of aborts 0.01 mm thick fills the space between ball and the cup. Then the whole instrument is inverted and held vertically with the ball at the lower end as shown in fig 1.9. In this position the ball is suspended for some period of time by the negative pressure in the film between the ball and the cup. Due to the negative pressure in the oil film, oil is sucked from the groove gradually into the space between ball and the cup. When the thickness of the oil becomes so high that it can no longer maintain negative pressure, the ball falls down. The time required for this process is proportional to absolute viscosity of the oil.

5. Ostwald Viscometer:

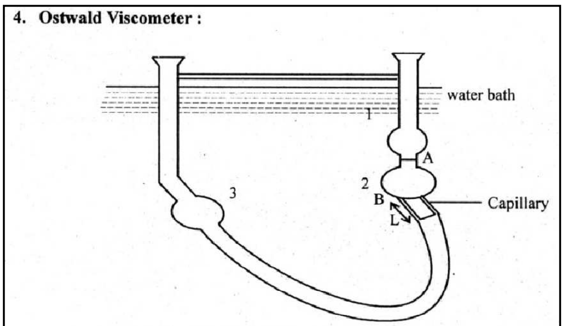


Fig 1.10 : Ostwald viscometer

The arrangement for Ostwald Viscometer is as shown in fig.1.10. Kinematic viscosity is determined by measuring the time required for the liquid level to drop from mark (A) to (B). This instrument is usually made of glass and during the test it is immersed in a temperature controlled water bath. The instrument is calibrated as discussed below.

$$Q = \frac{\pi\, d^4}{128\,\eta}\,\frac{dp}{dx} = \frac{V}{t}$$

$$\frac{dp}{dx} = \frac{\rho\, g\, h}{L}$$

$$Q = \frac{\pi\, d^4}{128\,\eta}\,\frac{\rho\, g\, h}{L} = \frac{V}{t}$$

$$\frac{\eta}{\rho} = \left(\frac{\pi\, d^4}{128\,\eta}\,\frac{g\,h}{V\,L}\right)t \qquad Where, K = \frac{\pi\, d^4}{128\,\eta}\,\frac{g\,h}{V\,L}$$

$$\nu = K\,.\,t$$

Here K is a constant value for the given instrument. By using some liquid of known viscosity and density such as distilled water the time required for a known volume (V) to flow through the capillary is determined. This constant is established for the particular instrument. After calibration, the kinematic viscosity and dynamic viscosity of any fluid can be measured.

6. Saybolt Viscometer:

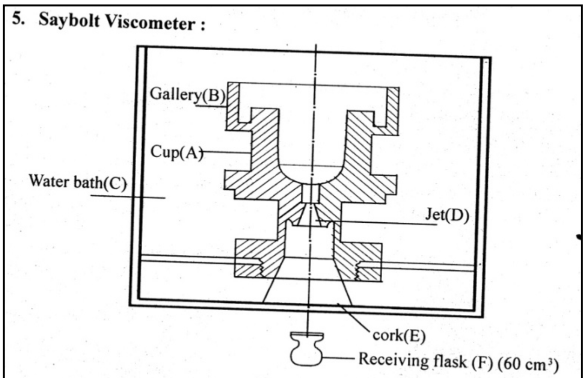


Fig. 1.11 : Saybolt universal viscometer

The standard method of measuring the viscosity of lubricating oil is by using Saybolt universal viscometer shown in fig.1.11.

To measure the viscosity of oil, the oil to be tested is heated approximately to the required temperature in a separate vessel and poured into cup (A) until it reaches the rim of the cup and just begins to overflow into the gallery (B). now the water bath (C) is heated to the oil temperature by means of by an electric heater. The flow of oil through the jet starts when cork (E) is removed. The time required in seconds t_0 fill the receiving flask upto $60\,cm^3$ graduation mark is a measure of viscosity of the oil and is designated as Saybolt universal viscosity (SUV). To convert SUV to absolute viscosity following formula may be used.

$$\eta = \nu_t \left(0.22\,t - \frac{180}{t}\right) \qquad (\boldsymbol{E-23.7})(\boldsymbol{P-23.8})$$

$$\nu_t = \nu_{15.5} - 0.000637(t - 15.5) \qquad (\boldsymbol{E-23.10})(\boldsymbol{P-23.10})$$

Effect of Temperature and Pressure on Viscosity:

1.8 : Effect of Temperature and Pressure on Viscosity :

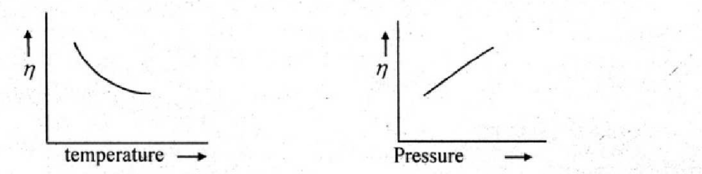


Fig 1.12 : Chart showing variation of viscosity with temperature. **Fig. 1.13 : Chart showing variation of viscosity with pressure.**

Effect of Pressure: Viscosity of liquid lubricant is a function of temperature. When temperature increases molecular move away from each other reducing inter molecular force. Hence viscosity of lubricating oil decreases with increase in temperature. This change is different for different oils. Two oils of some viscosity at a particular temperature may have different viscosities at another temperature. A term is called viscosity index $(V.I)$ is need to indicate the effect of temperature on change in viscosity. A low viscosity index indicates that the change in viscosity is lager for a given change of temperature. A high viscosity index indicates small change in viscosity for a specified change in temperature. Fig 1.12 shows the variation of absolute viscosity with temperature:

$$V.I = \frac{L - U}{L - H} \times 100$$

Effect of Pressure: As pressure of the fluid is increased the molecules are forced to come together. Hence viscosity of fluid increases with increase in pressure. At los pressure this increase relatively slows but at higher pressure this increase is greater. Fig 1. 13 show variation of viscosity with pressure. it is quite difficult to have a single equation to express the variation of viscosity with pressure. For most mineral oils the following equations give reasonable accuracy

$$\eta = \eta_0 \exp(\alpha\, p) \qquad and$$

$$\ln(\eta) + 1.2 = [\ln(\eta_0) + 1.2]\left[1 + \frac{p}{2000}\right]^{z_1}$$

$\alpha =$ Pressure coefficient of viscosity

z_1 =Viscosity pressure index, a dimensionless constant.

Classification of Lubricant Grades

There are two systems for oil classification. The SAE (Society of Automotive Engineers) viscosity grade and the API (American Petroleum Institute) classification that designates the type of engines for which the oil was designed.

SAE Classification

The SAE viscosity grade is known as the "W" number when classifying winter oils. In general, the lower the first number, the better the oil performance in extremely cold conditions. Conversely, the higher the second number the better the oil protection at higher temperatures. Kinematic viscosity measured at 100°C defines SAE degrees from 20 to 60 for rising levels of viscosity. Dynamic viscosity at low temperatures defines the SAE "W" degrees, from the initial "winter", from 0W to 25W on the basis of viscosity levels measured at temperatures from -35° to -5°C. The temperature represents the lowest possible temperature at which the engine can be started when lubricated with an oil of the corresponding SAE degree (e.g. a 15W oil makes it possible to start the engine at up to -20°C). The minimum pumping temperature is the minimum temperature at which oil, in addition to allowing start up, can flow freely and lubricate the critical parts of the engine.

API Classification

The API designation is typically "S" designation for gasoline engines and a "C" designation for diesel engines. Most of today's oils carry an SH,CF or SJ,CF designation signifying that they are suitable for use in all gasoline or diesel automotive applications.

API stands for American Petroleum Institute. In 1970 along with the SAE and ASTM (American Society for Testing and Materials), they established the API Service Classification System to define the performance level of a given oil, unrelated in the main, t© oil viscosity. The API requirements "S" for Spark Ignition (petrol) and "C" for Compression Ignition (diesel) can be briefly described as follows. For automotive gasoline engines, the latest engine oil service category includes the performance properties of each earlier category. If an automotive owner's manual calls for API SJ or SL oil, API SM oil will provide full protection. For diesel engines, the latest category usually - but not always – includes the performance properties of an earlier category.

Based on-Applications

Lubricants are largely used for automobiles, heavy industries, industries, and vessels, Based on that the lubricant grades are classified as

For Transportation Facilities

Diesel Engine Oil	Gasoline Engine Oil	LPG Engine Oil
Diesel-electric locomotive Engine Oil	Aero motor Engine Oil	CNG Engine Oil
Motorcycle Engine Oil	2-cycle Motor Engine Oil	
Automatic Transmission Oil	Automotive Gear Oil	

For Industrial Machine

Hydraulic Oil Machine Oil Industrial Gear Oil

Turbine Oil Circulating Oil Compressor Oil Refrigerant Oil

For Vessel

Cylinder Oil Trunk Piston Oil System Oil

Metal Working Oil

Cutting Oil Rolling Oil Heat Treating Oil Inhibited Oil

Process Oil ***Electrical Insulating Oil*** ***Grease***

Based on Constituents (raw material)

A lubricant refers to a substance; that makes parts of something move smoothly and liquid lubricants account for about 80% of it. Lubricants are developed using base oils produced from crude oil refining by adding additives according to mixing ratio for each use or developed by compounding chemicals such as PAO.

	< Lubricants >	
Liquefied: Lubricating oils	**Petroleum oils:** Mineral oils	**Pure mineral oils +Additives**
Semisolid lubricants: Grease	**Vegetable and animal oils:** Fatty oils	
Solid lubricants: MoS2. PbO, Graphite, etc	**Synthetic oils:** Polyalphaolefins (PAO). Alkytoenzene. Phosphoric acid ester. Polyglycole. etc	

Lubricant Selection Criteria

- Tribological System
- Analysis of the tribological system for a given application is essential to the selection of the appropriate lubricant.
- Service temperature range
- Speed factor
- Hydrodynamic lubrication
- Elasto-hydrodynamic lubrication *(BHD)*
- Extreme pressure
- Emergency lubrication Fretting

Other Requirements

- Lubricant selection can also be affected by a variety of other specialized requirements:
- Design life
- Lubrication equipment
- Acceptable re-lubrication intervals
- Cost
- Special certifications such as NSF registration
- Biodegradability

Lubrication Regimes

In engineering, lubrication is usually divided into three regimes, fluid film, boundary and mixed lubrication. The tribological characteristics associated with each lubrication regime are listed below:

Fluid-film lubrication: a complete separation is achieved between the two bearing surfaces. The most important lubricant parameter is viscosity. Under the fluid film lubrication regime, both friction and wear are minimized. However, a complete elimination of friction and wear is impossible in artificial joints due to the viscous shearing of the lubricant and the breakdown of fluid film lubrication associated with start-up and stop motions.

Boundary lubrication: extensive asperity contacts occur and both wear and friction are significantly increased. Boundary lubricating films play an important role in this lubrication regime, which depend on both the physical and chemical properties of the lubricant.

Mixed lubrication: this lubrication regime consists of a mixture of both fluid film and boundary lubrication regions. The tribological characteristics in this lubrication regime depend on the relative contribution of the fluid film and boundary lubrication.

Module 2

Friction: Origin, friction theories, measurement methods, friction of metals and non-metals.

Wear: Classification and mechanisms of wear, delamination theory, debris analysis, testing methods and standards. Related case studies. **8 hours**

Examination theory and numerical questions:

1. Define wear and explain the types of wear with sketches.
   (Dec.19/Jan.20) (June/July 2018) (June / July 2017) (May /June 2017) (Dec.2013 / Jan. 2014(June / July 2013)) (December 2012) (June 2012) (10Marks)

2. Explain:
   i. State friction
   ii. Laws of friction
   iii. Coefficient of friction
   iv. Friction measuring devices

3. List out various wear testing methods clearly, mentioning their standards.
   (Dec.19/Jan.20)

4. Explain briefly about corrosive wear and fretting.

5. Explain erosive wear with examples.

6. Write short note on wear of polymers.

7. Define friction and friction forces. Briefly explain about static and rolling friction.

8. What are different types of friction? Explain. **(Dec.19/Jan.20)**

9. What are the different methods of measuring frictional forces? Explain any one.
   (Dec.19/Jan.20)

10. Write short note on
    i. Friction of metals
    ii. Friction of polymers.

11. Explain the concept of abrasive and adhesive wear.

12. Explain cavitations erosion and liquid impingement erosion.

Friction:

Friction is the tangential 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. 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 forces can be either good or bad, without friction it would be impossible to walk, use automobile tires on a roadway or pick up objects, even in some machine application such as vehicle brakes and clutches and fictional transmission of power (such as belt drives) friction is maximized.

However, in most other sliding and rotating components such as bearings and seals friction is undesirable. Friction causes energy loss and wear of moving surface in contact, in these cases, friction is minimized.

Coefficient of friction(μ):

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 below Table, has been observed. Generally coefficients of friction depend on parameters such as temperature, surface roughness and hardness.

Table: Co- Efficient of friction for different materials

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

Static and kinetic friction:

The resistive tangential force, which acts in a direction directly opposite to the direction of motion, is called friction force.

If the solid bodies are loaded together and tangential force (F) is applied, and then the value of the tangential force that is required to initiate motion is the static friction force, F_{static} or F_s.

It may take a few milliseconds before relative motion is initiated at the interface. The tangential force required to maintain relative motion is known as the kinematic (or Dynamic) friction force, $F_{kinetic}$ or F_k. The static friction force is either higher than or equal to the kinetic friction force. 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.

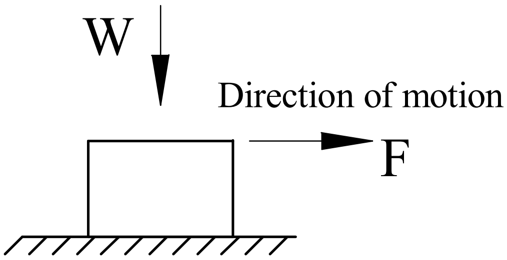


Fig: A body sliding on a surface with a free body diagram

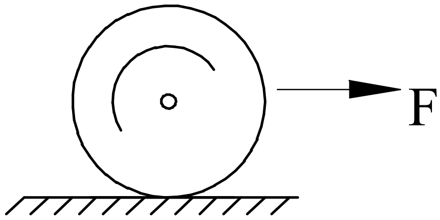


Fig: A body rolling on a horizantal surface

W is the normal load (force) and F is the friction force.

Friction is not a material property, it is a system response.

If two solid surfaces are clean without chemical films and absorbents, high friction occurs. Surface contaminants or thin films affects friction with well lubricated surfaces, weak adhesion and friction is generally observed. However, a small quantity of liquid present at the interface result in liquid mediated adhesion. Which may result in high friction, especially between two smooth surfaces.

The Laws of Friction:

First law states that the friction is independent of the apparent area of contact between the contacting bodies.

Second law states that the friction force is proportional to the normal load between the contacting bodies.

Third law states that the kinetic friction is nearly independent of the speed of sliding.

First two laws are often referred to as Amontons laws and Coulomb introduced third law.

Theories of 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 give an overview of the concept of friction.

Theory of Leonardo da Vinci:

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, $F \propto W$.

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.

Theory of G.Amontons:

The friction force is independent of the nominal area ($F \# A$) of contact between two solid surfaces. The friction force is directly proportional $F \propto N$ to the normal component of the load. He considered three cases refer below Fig and showed that friction force will vary as per the angle of application of load. As per Amontons $\mu = 0.3$ for most of materials.

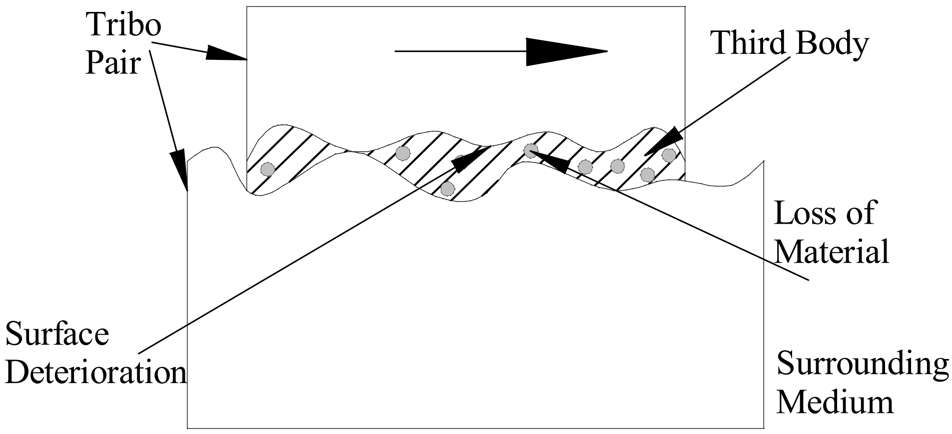


Fig: Amonton's Work

Theory of C. A. Coulomb

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

Contact at discrete points $\mu_{\text{Static}} \geq \mu_{\text{Kinetic}}$

$$F \neq Func(A)$$

$$F \neq Func(v)$$

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.

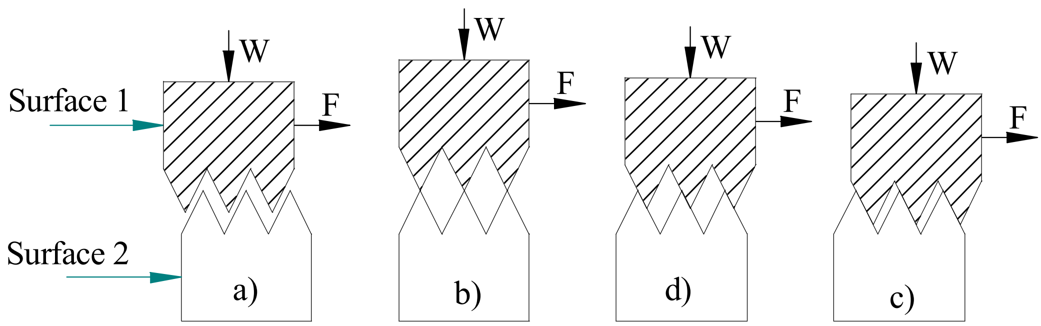


Fig: Coulomb Friction Model

TOMLISON's Theory of Molecular attraction:

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.

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

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

Where, E is young modulus, GPa and G is shear modulus , GPa

Clean Steel E = 206 GPa G = 83 GPa

Aluminum E = 69 GPa G = 25 GPa

Titanium E = 106 GPa G = 45 GPa

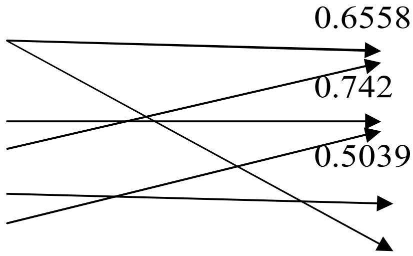


Fig. Examples on Tomlinson formula

Above Fig. 2.6 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.

Bowden and Tabor's simple adhesion theory:

It has already been discussed the when two surfaces are loaded, the intimate contacts occur at the peaks of the asperities and the real area of contact is very less compared to the nominal area.

The pressure at the points of real contact is so high that the asperity tips of the softer material deform plastically and the plastic flow causes the total contact area to grow.

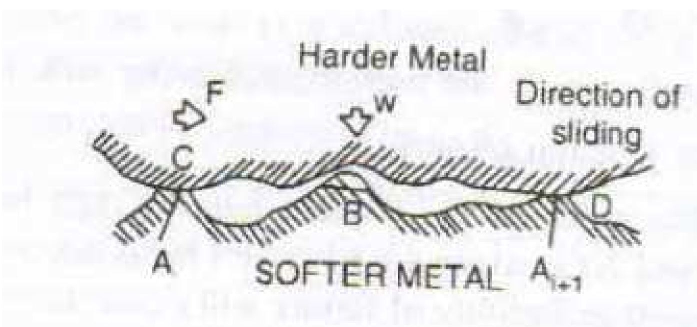


Fig: Mechanism of welding, shearing and ploughing

This growth of contact area takes place by two means

One by growth of individual contact spot By initiation of new contacts.

The process continues until the total real area of contact is sufficient to support the load elastically. Then, for an elastic plastic material. The normal load W may be expressed as

$$W = A\,.\,P_0 \qquad \ldots\ldots(i)$$

Where A is the real area of contact and P_0 is the yield pressure of softer material and it is very close to the hardness, H hence

$$W = A \, . H \qquad \ldots \ldots (ii)$$

As the plastic deformation becomes severe, the asperity junctions get ; cold welded' and strong ' adhesive bonds' are formed.

The force required to causes shear failure of the asperity junction i.e, the friction force due to adhesion, F_{adh} is then

$$F_{adh} = A \, . S \qquad \ldots \ldots (iii)$$

Where S is the shear strength of the softer material. Thus the coefficient of friction due to adhesion may be written as

$$\mu_{adh} = \frac{F_{adh}}{W} = \frac{S}{H}$$

For most materials, this ratio of $\frac{S}{H}$ is almost constant. Typical value for most metals is 0.2. Hence this theory predicts a value of friction coefficient as 0.2.

Theory of Rolling Friction

According to theory of rolling friction, "Rolling resistance, sometimes called rolling friction or rolling drag, is the force resisting the motion when a body (such as a ball, tire, or wheel) rolls on a surface. It is mainly caused by non-elastic effects; that is, not all the energy needed for deformation (or movement) of the wheel, roadbed, etc. is recovered when the pressure is removed. Two forms of this are hysteresis losses (see below), and permanent (plastic) deformation of the object or the surface (e.g. soil). Another cause of rolling resistance lies in the slippage between the wheel and the surface, which dissipates energy".

Coefficient of friction due to rolling (μ_r) is generally smaller than that caused by sliding action. Therefore wherever possible rolling friction compared to sliding friction is desired, μ_r is defined as the force required to maintain steady rolling, divided by the load carried by the roller. Rolling friction coefficients often depend on hardness of contacting solids. On increasing hardness, elastic deformation under load decreases. Therefore, hysteresis loss and so the value of μ_r decreases. For hard smooth steel rollers, the coefficient of rolling friction ranges between 0.01 and 0.001. A roller or sphere made of soft material (as shown in Fig. 2.8) when rolled over other soft surface, generates a higher level of rolling friction.

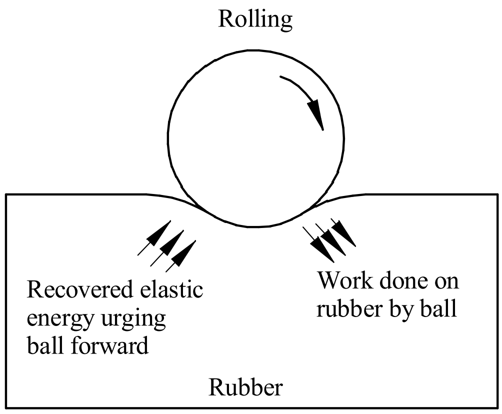


Fig : Rolling Friction in Rubber

What are different types of friction? Explain. **(Dec.19/Jan.20)**

Types of friction:

The types of friction that needs to be considered for understanding the principle of tribology can be classified into the following types.

Dry friction

Static friction

Kinetic friction

Fluid friction

Lubricated friction

Skin friction

Internal friction

Radiation friction

Rolling friction

Braking friction

Belt friction

Tribo-electric friction

****** Explain in brief friction measuring methods**

What are the different methods of measuring frictional forces? Explain any one.

Friction Measurement Techniques **(Dec.19/Jan.20)**

The measurement of the force or coefficient of friction, the limiting friction, and the extent of wear of rubbing surfaces. Friction measurements are divided into the following two types: laboratory measurements, in which the fictional forces and wear resistance of materials under various conditions are evaluated, and field measurements, in which a given friction unit is evaluated as a whole.

In laboratory tests, one uses specimens that are in point or line contact, such as a sphere on a plane or two crossed cylinders rubbing along a generatrix, and specimens that have small areas of contact, such as a ball in a spherical hollow, a pin with its end touching a disk, or two neighboring cylinders. With these specimens it is possible to obtain the frictional force and the wear per unit of actual contact. These quantities can be used to calculate the frictional force and wear for any area of the surface. Gauges containing elastic elements are ordinarily used to measure frictional force.

Some of the methods of friction measurement are listed below:

Method 1: Weight ratio

The sketch shown originates from Leonardo da Vinci (ca 1500). He studied friction by measuring the load hanging on a cord, at which the block begins to slide. The co- efficient of friction is found by the quotient of the dead weight of the mass hanging on the cord and the mass of the block, i.e.

$$\mu = \frac{F\,f}{N} = \frac{Dead\,Weight}{Block}$$

Static coefficient of friction - dynamic coefficient of friction

The moment at which the block begins to slide (break away force) is the so called static friction, the force at which the block continues to slide is the dynamic or kinetic coefficient of friction. For most material combinations the value of the static friction exceeds that of the dynamic friction. Be aware that the dynamic friction can still be dependent on velocity, contact pressure, temperature and surface roughness. The static friction can be dependent on the time that the block is in rest, which is typically the case when lubricated.

Method 2: Spring balance

Pull a spring balance connected to the block and slowly increase the force until the block begins to slide. Make sure the spring balance is parallel to the surface. The reading on the spring balance scale when the load begins to slide is a measure for the static friction, while the reading when the block continues to slide is a measure of dynamic friction. The coefficient of friction is simply.

$\mu = \frac{F_{Spring}}{F_{Normal}} = \frac{F_{Spring}}{(M_{Block}\,g)}$, $\quad (g = 9.81\ \frac{m}{s^2})$

Method 3: Tilted plane

Place a block on a tilted plane and increase the angle of tilt until the block begins to slide. The tangent of the tilting angle just found is the so called "friction angle". This angle is related to the coefficient of friction μ), i.e.

$$\mu = \tan \emptyset = \frac{F_f}{F}$$

Method 4: Clamping

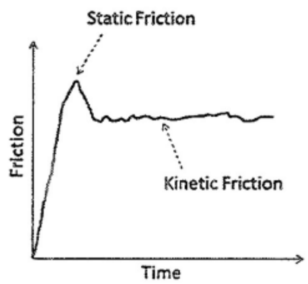
To measure the static coefficient of fiction under conditions of high contact pressure the object may be clamped between two surfaces. The force necessary to put the object in motion must be shared to obtain the friction force because of the two contacting surfaces.

Method 5: Pendulum

The pendulum is suitable to analyze the static and dynamic friction under reciprocal motion by monitoring the bearing torque. This however requires a torque sensor. The energy loss of combined static and dynamic friction can be analyzed by considering the reduction of the amplitude of motion in time. This only requires a simple rotary potentiometer or pulse rotation sensors to visualize the amplitude reduction in time.

Method 6: Motorized Tribometers

In the measuring methods discussed above the friction coefficient is measured in fresh contacts, not after running in. The coefficient of friction may change significantly during first half hour of sliding. The time necessary to obtain a stable value of the coefficient of friction can be observed in a motorized tribometer by monitoring the friction over time. This method is common for measuring the specific wear rate and the contact temperature during operation. You may visit the useful links on the right of this window to find more information about motorized tribometers.



Principle of Friction measurement

Friction of metals and Non metals:

The coefficient of friction of a particular material depends on 3 factors

Mating material

Surface roughness

Operating conditions.

Friction of metals:

When the metal surfaces are cleaned in high vacuum and placed in contact, strong adhesion is observed and consequently high friction is observed.

In vacuum typically 2 to 10 or even more.

With no interfacial contamination, the extent of junction growth is limited by ductility of material.

Gold is ductile but it does not forms oxide layers in the air, thus considerable amount of junction growth in gold contact leads to high friction.

Most metals forms oxide layer in air and the layer will be in the range of 1 to l0 nm. These films play important role in frictional characteristics.

Variation of coefficient of friction with normal load for copper sliding on copper in air.

At low normal loads, the oxide films separate the two metals.

Coefficient of friction is low because the oxide has low shear strength.

At higher loads the surface films deforms and metallic contact occurs leading to high frictions.

Friction of metals is affected by number of parameters like,

Sliding velocity Contact Pressure Temperature

Relative Humidity Environmental conditions

Friction of Non-Metallic Materials

Ceramics combine low density with excellent mechanical properties (Example: high strength, stiffness, hardness, etc) up to high temperatures.

The Engineering ceramics include silicon nitride (Si_3N_4), silicon carbide (SiC), alumina (Al_2O_3) and zirconia $(Zr\,O_2)$. Ceramic pairs are commonly used in extreme environment applications. Such as high load, speed, temperature, corrosive environment application.

Because of different nature of bonds in ceramics compared with metals they show limited plastic flow at room temperatures.

Correspondingly much less ductility than metals.

Although adhesive forces are present the very low real area of contact makes them to have relatively low coefficient of friction.

In clean environment friction coefficient does not reach high values as in the case of metals show high friction in vacuum.

The reason for this less friction is the coefficient of friction decreases with an increase in fracture toughness.

Polymers:

Polymers include plastic and elastomers. The coefficient of the friction of polymers ranges between 0.15 to 0.6 in general, with the only exception of poly tetra fluoro ethylene (PTFE) which has typically a very low coefficient of friction 0.05.

Thus polymers exhibits in general, low friction in comparison to metals and ceramics, but very low elastic modulus, typically one – tenth of metals or even less.

Since polymers lack in rigidity and strength, polymer composites are used to provide a combination of mechanical strength with low friction and wear. Carbon, graphite and glass are commonly used as fillers in polymer composites.

When plastic slide against hard metal surface transfer film of plastic in formed on the mating surface and their governs the friction and wear behavior.

Sliding tends to occur at the interface between the bulk polymer and the transfer film, leading to low wear rates. As sliding continues, the coefficient of friction drops to a much lower value. The transfer film becomes much thinner and contains molecular chains strongly oriented parallel to the sliding direction. Such behaviour for high density polyethylene (HDPE) sliding on glass is shown in fig. PTFE also shows similar behaviour. Because of lower friction behaviour HDPE and PTFE have important applications as solid lubricants and bearing materials.

The friction of polymers is also governed by the strong time dependent mechanical properties of polymers (visco elasticity). The main sources of friction are adhesion, deformation and elastic hysteresis. According to the analysis of adhesion, the coefficient of friction is affected by surface roughness and normal load.

For smooth poly methyl metha crylate (PMMA), the coefficient of friction decreases with an increase in a normal load while for rough PMMA, friction coefficient remain constant at low loads and decreases with a load at high loads.

Wear:

****** Define wear and explain the types of wear with sketches.**
(June/July 2018) (June / July 2017) (May /June 2017) (Dec.2013 / Jan. 2014(June / July 2013)) (December 2012) (June 2012) (10 Marks)

Wear may be defined as "progressive loss of substance from surface of a body due to relative motion with respect to another body".

Wear may also be defined as "removal of material or loss of material from the surface of a body which is in relative motion due to mechanical or chemical action".

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.

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.

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:

Types of wear mechanisms:

Adhesive wear: (Polishing, Scouring, Scratching, Grinding, Gouging)

Abrasive wear: (Galling, Scuffing, Scoring)

Cavitation wear: (interaction with fluid)

Erosive wear:

Fretting wear

Corrosive wear: (Chemical nature)

Fatigue wear: (Delamination)

1. Adhesive Wear

Adhesive wear is defined as sliding wear. It occurs when one solid surface slides along another surface.

During sliding, a small patch of one of the surface comes into intimate contact with a small patch of the other surface. If this bond is strong, this contact is broken from one of the material and not from the interface of the two patches.

As the formation of adhesive junctions depends more on cleanliness of the surfaces, adhesive wear can occur on both rough and smooth surfaces.
It has been observed that wear rate decreases with the increase of the ratio of hardness of the two materials.

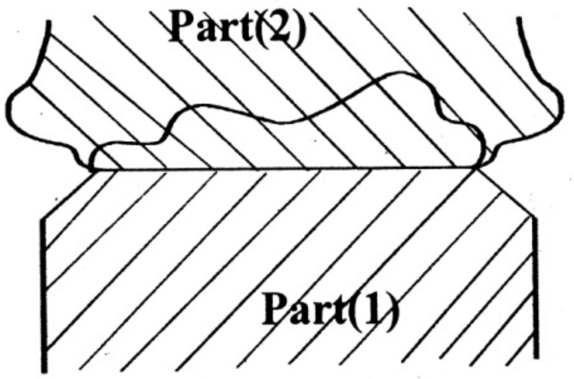


Fig 9.1 : Adhesive wear

The volume wear depends on the following relations Volume of wear directly proportional to sliding distance (d)Volume of wear directly proportional to the Load (L)

Volume of wear inversely proportional to the hardness (p) of the surface being worn out.

It is dependent on the area of contact.

$$\text{Volume of wear;} \qquad V = k\,\frac{L \times d}{P}$$

When a hard rough surface slides against a soft surface, digs into it and forms a series of grooves, abrasive wear occurs. This is known as two body wear.

2. Abrasive wear: Abrasive wear also occurs when hard abrasive particles are introduced between two sliding surfaces and these particles abrade either or both materials.

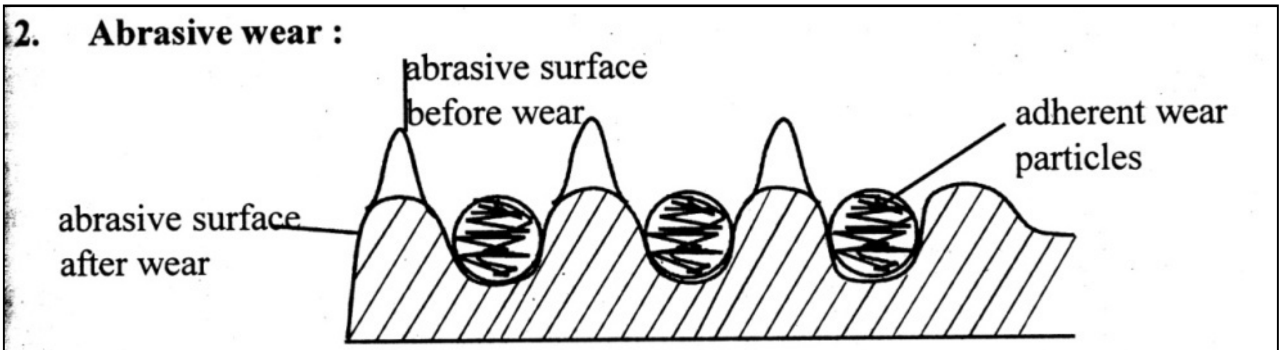


Fig : 9.2 : Abrasive wear

The mechanism is that an abrasive particle adheres temporarily to one of the sliding surfaces or else get embedded in it and plows out grooves in the other surface This form is known as three body wear.

When the sliding system contains a limited amount of abrasive particles, which are used over and over again as the sliding continues, the wear rate tends to decrease as the abrasive particles get smoother and smaller.

3. Corrosive wear:

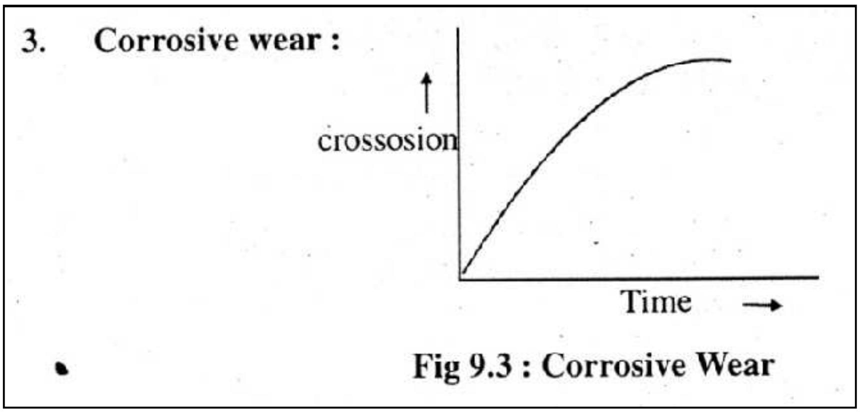


Fig 9.3 : Corrosive Wear

Chemical reaction + Mechanical action = Corrosive wear.

Corrosive wear is defined as the degradation of material in which both corrosion and wear mechanism are involved. Corrosive wear occurs when the environment surrounding a sliding surface is corrosive and interacts chemically with the sliding surfaces. Therefore this wear is al so known as chemical wear

Corrosive wear differs from corrosion since no sliding of surface takes place in corrosion and formation of reaction films on the surface tends to slow down with the increase of thickness of the layer and may arrest further corrosion after some critical thickness. But it becomes corrosive wear when sliding of surface occurs and the sliding action continuously wears off the products of reaction from the surface. Figure 9.3 shows the variation of corrosion with time.

4. Erosive wear:

The damage produced by sharp particles impinging on an object is called erosive wear. Particles in water eroding the rocks over which a river flows or the erosion of both rope and stone pulley. when the rope continuously slides over the pulley are some of the common examples of erosive wear.

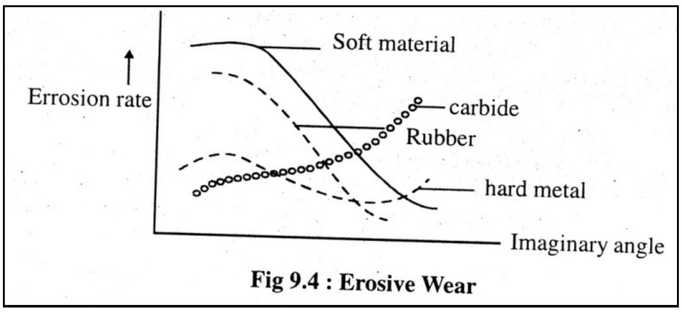


Fig 9.4 : Erosive Wear

The mechanism is somewhat similar to abrasive wear. The main difference is that in erosive wear the surface roughness produced may become relatively greater because an impinging particle may readily remove materials from a low strength point on the surface.

The erosive wears are two types

Solid particle erosion : Solid particle erosion takes place whenever hard particles are entrained in a gas of liquid medium impinging on a solid at a velocity greater than 1 m/s. Solid particle erosion can occur in a gaseous or liquid medium containing solid particles. In both cases, particles can he accelerated or decelerated, and their directions of motion can be changed by fluid.

Materials are broadly classified as ductile or brittle, based on the dependence of their erosion rate. Ductile materials, such as pure metals, have a maximum erosion rate at low angles of incidence (typically 15^0 to 30^0), while for brittle materials, such as ceramics, the maximum is or near 90^0,

Liquid impingement erosion: Liquid impingement erosion has been defined as "progressive loss of original material from a solid surface due to continued exposure to impacts by liquid drops or jets". Liquid impingement erosion consists of repeated impacts or collisions between the surface being eroded and small discrete liquid bodies.

Examples : (i) Steam turbine blade erosion : In the last stages of the low pressure turbine, the steam expands to well below saturation conditions, and a portion of the vapour condense into liquid.

(ii) Aircraft Rain Erosion: The impact of rain drops. 2 mm (0.08 in.) or more in size on unprotected aluminum alloy surfaces, optical and infrared windows, and radar domes caused severe erosion which seriously limited operational time in rain storms.

(iii) Cavitations Erosion: Whereas liquid impingement connotes a continuous vaporous or gaseous phase containing discrete liquid droplets. Cavitations connote a continuous liquid phase containing discrete vaporous or gaseous bubbles or cavities.

Cavitations :

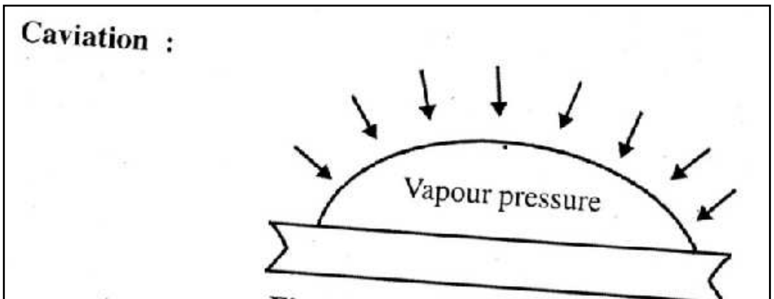


Fig 9.5 : Vapour bubble in cavitation

When liquid flows parallel to a flat plate or in a pipe or cylinder, the momentum of a liquid produces a lower pressure at the solid liquid interface than in the centre of the system.

When the inside radius of the pipe or cylinder is small or the velocity of liquid is high the pressure at the solid liquid interface may be less than the vapour pressure of the liquid. This results in the formation of bubbles or cavities of vapour which collapses quickly and reforms.

Fretting : Fretting is the small-amplitude oscillatory movement that may occur between contacting surfaces, which are usually nominally at rest. One of the immediate consequences of the process in normal atmospheric conditions is the production of oxide debris, hence the term "Fretting wear" or "Fretting corrosion- is applied to the phenomenon. The movement is usually the result of external vibration. but in many cases it is the consequence of one of the members of the contact being subjected to a cyclic stress, which gives rise to another and usually more damaging aspect of fretting, namely the early initiation of fatigue cracks. This is termed "Fretting fatigue" or "contact fatigue'.

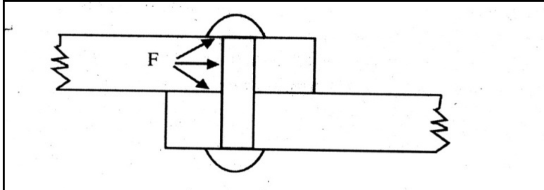


Fig : 9.6 : Location (indicated by F) prone to fretting in an aluminum-steel riveted joint.

Mechanism of Fretting Wear:

When fretting wear is taking place between two flat surfaces or two conforming cylindrical surfaces the progress with time (or number of cycles) can be recognized as occurring in three stages.

(i) Initial stage of a few thousand cycles when metal-to-metal contact is common, resulting in local welding, roughening of the surface, high friction and low contact resistance. Fatigue cracks are initiated in this stage if the movement is a result of cyclic stressing.

(ii) Formation of beds of compacted oxide with a fall in coefficient of friction and erratic behaviour of contact resistance as it oscillates between high and low values.

(iii) Onset of a steady state in which the friction is more or less constant and the contact resistance is generally high with occasional momentary falls to a low value.

Prevention of Fretting Damage:

(i) Improved Design: Because fretting arises where there is relative movement between two surfaces, the elimination of this movement is a prime objective. Fretting often arises as a result of a stress concentration. Reducing the stress by improved design (for example, raised wheel seats or stress-relieving groves in hub/ axle assemblies) is demanded by fatigue considerations. Increasing the normal pressure by reducing the area of contact or increasing the normal load will reduce the area of slip, but such action may introduce fatigue problems. The ultimate goal is to make the component in one piece and to get rid of the junction, but this is not always possible.

(ii) Surface finish: Rough surfaces are less prone to fretting damage than highly polished surfaces. Rough surfaces can be obtained by shot penning with glass beads or steel shot. Shot penning has the advantage of work hardening the surface, although the residual compressive stress appears to have little effect on the wear process; however, it has a considerable effect if fatigue crack initiation and propagation is involved. Shot penning is often applied as a surface preparation for the application of coatings.

(iii) Coatings : Surface treatments that radically change the chemical composition of the surface.

Carburizing and nitriding of steels is a well established treatment for reducing v,/ear in gears and is also effective against fretting. Electrodeposited coatings are extensively used in electrical contacts; gold alloys are the preferred coating because they are not subject to oxide formation.

Anodizing is applied to aluminum alloys and the hard coating provides protection against fretting, but is may cause wear of the opposite surface.

(iv) Inserts : Separation of the two surfaces by an insert, either a shim of a soft metal or a shim of a polymer with a low elastic modulus, will sometimes be effective. The intention is to take up the movement by either plastic deformation or elastic deformation of the material. A combination of metal and polymer can be more effective because it combines the advantages of both materials-the low elasticity of the polymer and the good conductivity of the metal.

(v) Lubricants : Lubricants are usually difficult to apply in fretting contacts because of the difficulty of maintaining the lubricant In the contact, but lubricants are included in the construction of steel ropes.

Wear Analysis

Generally, wear does not involve a single mechanism, are therefore 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.

Delamination theory

Delamination wear is sometimes referred to as surface fatigue wear. It is a relatively recently discovered form of wear being first theorized about by Nam P. Sub. at M.I.T. in 1973. It takes place in three stages: (i) Voids form near the surface; (ii) Voids grow as cracks parallel to the surface (iii) Detachment of long thin wear particles when the crack reaches a critical length and breaks through to the surface.

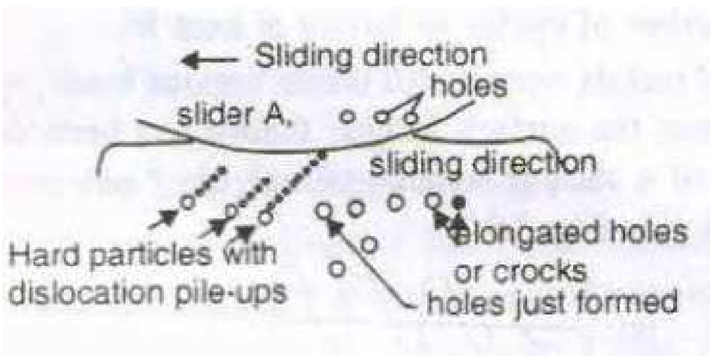


Fig: Wear model developed by Sub

Voids usually form at the location of inclusions or other imperfections in the material. Dislocations in the metal pile up at these impurities causing the voids to grow. Because metal impurities are key in the nucleation of these voids, materials with few inclusions will suffer less wear from Delamination wear.

A crack growing from a void will not initially go to the surface because it is under a trilateral compressive state of stress and there is plastic strain at the surface. Crack growth requires stress reversals; in this case the stress reversals are supplied by asperities on the surface. As an asperity slides over a surface the material facing the asperity sees alternating shear stresses. Because the crack grows parallel to the surface at a shallow depth, wear particles formed by this mode of wear will be long and thin.

Based on this, wear equation has been obtained by Sub and it is given as

$$w = \frac{B_1 \ h_1}{d_{c1} \ H}.W.s + \frac{B_2 \ h_2}{d_{c\,2} \ H}.W.s = k.W.s$$

Where B_1& $B_2$are constants, H is the hardness of softer material and k is the wear factor, d_c is the critical plastic displacement to form loose particle.

Wear debris Analysis

Wear debris analysis is an important aspect to analyze the wear mechanism and evaluate the process of wear and the effect of lubrication if used on the mechanism of wear process. The basic principle of operation is simple. A representative sample of wear and lubricant oil debris is tested through the following cycle.

Obtain wear debris and oil sample from the tribometer machine.

In the laboratory take a measured amount of the fluid and deposit into a clean beaker. The sample is then diluted with a solvent

Draw the sample through a membrane filter or use a magnetic separation technique such as the rotary particle depositor to separate the solids from the fluid. The amount of ferrous wear is quantified by means of a debris analyses.

Visually analyses the debris at 100x magnification under a reflected light microscope quantifying the following parameters:

Type of particle (relating to the mechanism of removal)

Average particles size

Maximum particle size

Contamination index

These parameters are then trended in a custom designed software package and the diagnostician awards the unit a Health Status. The health status is a single parameter which gives the unit a level of threat. (Health status is a parameter between 1 -5 with 1 being a healthy machine and 5 being a machine which is imminently threatened with failure.)

Repeat the procedure at a decided time interval.

Wear debris analysis is a relatively simple procedure not requiring a high skills level to perform. Even so the results give a direct indication as to the level of threat and damage within industrial drives absent from some of the more sophisticated techniques.

Visual and microscopic examination of the sample is as important a source of information as the regular testing of the debris samples.

Prior to filtering the sample, examination of the sample visually within the sample bottle gives useful information. Water present within the oil sample can clearly be seen either in the form of emulsification or as a distinct water layer. The general cleanliness level of the oil may also be determined.

Once filtered the debris should be visually examined prior to microscopic examination. The presence of water within the lubricant can be detected from the filter paper. This is seen in the form of light circular areas on the filter paper. Water also sometimes oxidizes the ferrous material, and the presence of rust indicates the ingress of water. Water affects the viscosity of the lubricant, considerably reducing the effect of the lubricant, thus the wear debris analysis helps in avoiding the deposition of debris that affects the performance of the machine.

List out various wear testing methods clearly, mentioning their standards.
(Dec.19/Jan.20)

Wear Test

Wear test is carried out to predict the wear performance and to investigate the wear mechanism.

Two specific reasons are as follows:

From a material point of view, the test is performed to evaluate the wear property of a material so as to determine whether the material is adequate for a specific wear application.

From a surface engineering point of view, wear test is carried out to evaluate the potential of using a certain surface engineering technology to reduce wear for a specific application, and to investigate the effect of treatment conditions (processing parameters) on the wear performance, so that optimized surface treatment conditions can be realized.

Three levels of wear testing

Wear test is performed in three levels, namely,

- Laboratory test,
- Component simulation test,
- In-service test.

We may use an example to describe the difference among each type of test. A new surface engineering (SE) technology has been developed, which could be potentially used to improve the wear resistance of parts for a metal-on-metal hip joint (for human body). Perhaps the ideal and logical sequence of wear testing in this example will be as follows:

Stage 1 Laboratory test with small samples are initially carried out under testing conditions simulated insofar as conveniently possible to determine whether the surface engineering technology warrants further consideration, and if so, to find out under what treatment conditions, the highest wear resistance improvement can be achieved.

Stage 2 In the next stage, the optimized surface treatment condition will be used to treat some real joint parts, e.g. femoral head or cup, which will then be tested in a hip-joint simulator, with the testing conditions being controlled as close as possible to those for a real human joint, for example, lubricated with body liquid, temperature around 37°C, and moving like a human walking or running.

Stage 3 Only when the surface treated parts have survived the simulation tests, and indeed show considerably improved wear resistance yet without losing other properties (e.g. corrosion and bio-compatibility), can the in-service tests be carried out. The surface treated joint parts will be implanted in a human body and tested (monitored) for a prolonged period of time if there is no immediate side effect after implantation. As we can see, simulation test and in-service test produce more reliable results, however, laboratory test is cheap, safe and quick and thus serve a most useful function. In the following sections, we will introduce the methods for laboratory wear test. The working principles of three widely used laboratory wear testers will be given, followed by an introduction of wear measurement. An example of laboratory wear testing and measurement can be found in a short case study.

**** **Explain with neat sketch abrasive wear tester.**

Laboratory wear testing method

An apparatus for wear testing is termed as wear tester, tribotester or tribometer. The prefix of "tribo" refers to wear, friction and lubrication. Many, probably more than several hundreds, different wear testing arrangements and procedures are used in laboratories around the world and described in technical literature. However big difference of one arrangement as compared with another, a wear tester will always involve two components loaded against and relatively moving each other. The movement can be driven by a motor or by an electro-magnetic device. For convenient purpose, the material or component being investigated is normally referred to as specimen, the other material is termed as counter face.

Example 1: An abrasive wear tester

Fig. 1 is a schematic of an abrasive wear tester, in which a wheel or a ball is driven by a motor, rotating and sliding against a fixed sample in the presence of abrasive particles. The specimen is in the form of a plate or a block. Contact pressure is controlled by dead weight through a loading lever. The abrasive particles, such as silica, are added through a nozzle connecting to a hopper above, giving a three-body wear situation. After a set time of running, the sample is removed, and wear loss is measured. The parameters to be controlled include contact load, sliding speed, type of abrasive particles and its flow rate.

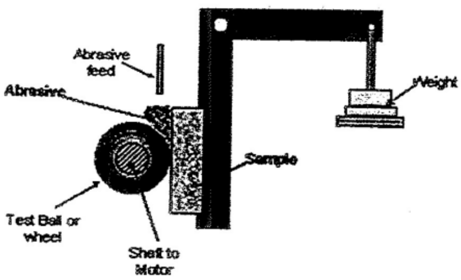


Fig. 2.16 An abrasive wear tester

Example 2: A rolling sliding wear tester

Rolling-sliding wear tester is the most popular tribometer for investigating wear as well as frictional behavior of a materials under conditions of rolling, sliding, or a combination of both. Two discs (wheels), as show in Fig. 2.17 a), are fixed to two parallel shafts and pressed against each other under a constant contact load. Driven by a motor through a train of gear, the specimens are rotated along with the shafts and the wear of the specimens in microns is noted, further the wear rate is calculated. Abrasive particles may be added to the contact area, achieving a three body abrasive wear testing.

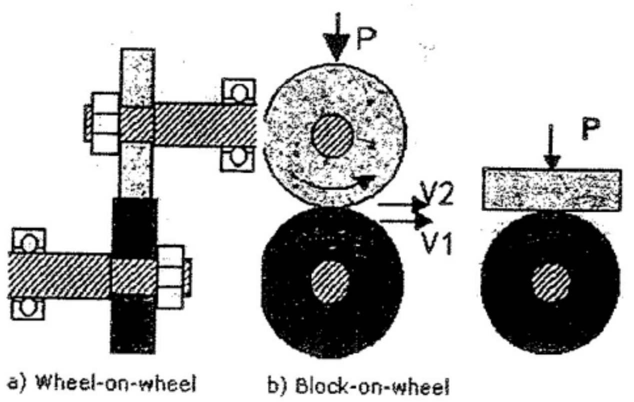
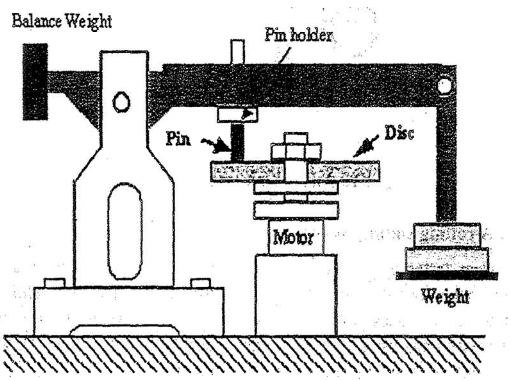


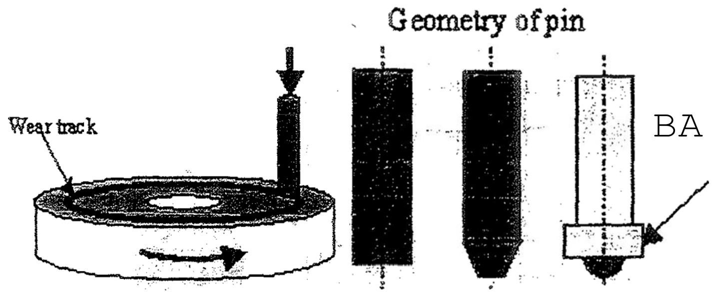
Fig. 2.17 Sample arrangement in a rolling sliding wear test

Sample 3: A pin on-disc wear tester

In a pin-on-disc wear tester, a pin is loaded against a flat rotating disc specimen such that a circular wear path is described by the machine. The machine can be used to evaluate wear and friction properties of materials under pure sliding conditions. Either disc or pin can serve as specimen, while the other as counter-face. Pin with various geometry can be used. A convenient way is to use ball of commercially available materials such as bearing steel, tungsten carbide or alumina (Al2O3) as counter-face, so that even materials of other geometries like cylinders, rectangles, circular discs can be evaluated for wear characteristics.



pin-on-disc-machine



arrangement on samples c) geometry of pin

Fig. 2.18 Schematic of a pin-on-disc wear test and the arrangement of sample

Wear Measurement/Quantification:

Wear measurement is carried out to determine the amount of materials removed (or worn away) after a wear test, (and in reality after a part in service for a period of time) The material worn away can be expressed either as weight (mass) loss, volume loss, or linear dimension change depending on the purpose of the test, the type of wear, the geometry and size of the test specimens, and sometimes on the availability of a measurement facility.

Common techniques of wear measurement include using a precision balance to measure the weight (mass) loss, profiling surfaces, or using a microscope to measure the wear depth or cross-sectional area of a wear track so as to determine the wear volume loss or linear dimensional change.

Mass loss

Mass loss measurement by a precision balance is a convenient method for wear measurement, especially when the worn surface is irregular and unsymmetrical in shape. Sample to be measured is carefully cleaned, and the weight is measured before and after a wear test. The difference in weight before and after test represents the weight loss caused by wear. The unit can be gram (g) or milligram (µg).

Volume Loss

Wear volume is normally calculated from the wear track (scar) depth, length, width and/ or scar profile according to the geometry of the wear track/scar. A surface profilometer, e.g. a stylus type, or sometimes a microscope with scale is used for the measurement. The reporting unit of wear volume loss is mm3 or um3. Wear volume loss enables a better comparison of wear among materials having different densities. However, it is not easy to measure volume loss when a wear track is irregular. In this case, mass loss may be measured first, and the volume loss is calculated if the material is uniform and its density is known.

Linear dimension loss

Measuring wear by linear dimension change is very useful in many engineering situations, where certain dimension such as length, thickness or diameter is more critical to the normal function of the system. A surface profilometer, e.g. a stylus type, a micrometer or a microscope can be used. The unit for linear dimension loss can be pm or mm.

Wear rate

Wear rates are calculated results reflecting wear mass loss, volume loss or linear dimension change under unit applied normal force and/or unit sliding distance. Wear rate can be expressed in many different ways.

Wear resistance

Wear resistance is a term frequently used to describe the anti-wear properties of a material. However, the scientific meaning of wear resistance is vague, and there is no specific unit to describe wear resistance. Nevertheless, the inverse of mass loss or volume loss is sometimes used as the (relative) wear resistance. The ratio of wear loss for a reference material over that of the investigated material under same testing conditions can also be used as relative wear resistance. In any case, if a numeric value of wear resistance is given, its meaning should be clearly indicated.

Table: Measurement Methods for Wear

	Measurement Methods	Units of Wear	Units of wear rate
Mass loss	Direct measurement by a precision balance. Calculated from volume loss for known density material.	μg g	$\frac{\mu g}{m}, g/m$ $\frac{\mu g}{N}, g/N$ $\frac{\mu g}{(N\,m)}, g/(N\,m)$
Volume loss	Calculated from depth, width, wear profile and/or other dimensions data of a wear track. Surface profilometer. or microscopy techniques can be used for the measurement. Calculated from mass loss for known density material.	mm^3	$\frac{mm^3}{m}$ $\frac{mm^3}{N}$ $\frac{mm^3}{(N\,m)}$
Linear dimension	Direct measurement by surface profilometer, microscopy and other dimension measurement techniques.	μm mm	$\frac{\mu m}{year}$ $\frac{mm}{year}$

Wear of Polymers: Polymers can be classified as "Plastics" and "rubbers"

(a) Plastics: Wear of plastics takes place in following three stages -

- Break-in period.
- Steady-wear period
- Severe wear period

Break-in period is the initial time when a film of polymer is transferred to the mating material. In this period, the rate of build-up of transfer film depends on the orientation of the surface finish relative to the sliding direction. The loss rate from the polymer is high in this period.

During steady-wear period, the surface finish appears to have no effect on wear rate. Wear, in this period is very small and the loss rate of the polymer reduces to less than 1% of the initial rate.

Severe wear period starts when the transfer film formed during the initial period, is removed or damaged by thermal degradation.

Rubber: Rubber is a polymer but differs from the plastic as rubber molecules are cross linked and often known as elastomer. Rubber wears generally by two mechanisms; tearing and fatigue.

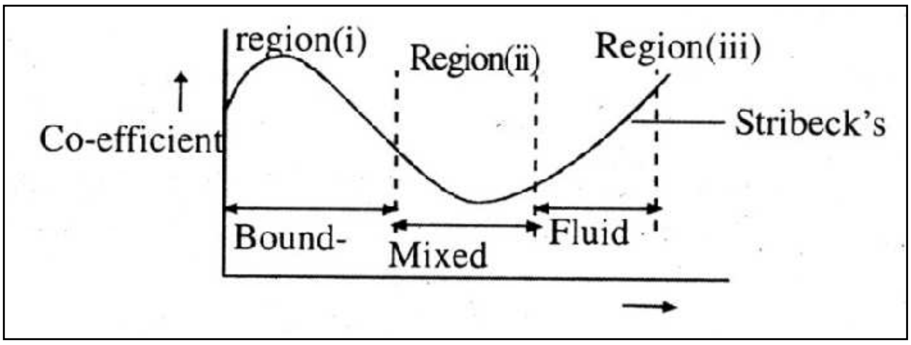
The tearing mechanism occurs when sliding on rough surfaces. The fatigue wear occurs when slides on undulating surfaces without sharp protrusions.

Wear of Ceramic Materials:

Ceramics, which are inert non-metallic solids, and a variation of ceramics called cermets. Which are metallic bonded ceramics have been used for tribological purposes for decades. Although high manufacturing costs have limited their applicability. They have been used in special applications, such as high-temperature or highly corrosive environments and in situations that require high resistance to wear.

Ceramics are used for bearing s operating at high-temperature and in very aggressive environments. They are also used as substitute for conventional metal alloys in some applications. Examples: Bearings, Mechanical seals, High-speed machine tools, Guides and Rollers, Wear plates, Advanced Heat Engines, Medical prostheses, Ceramic dies.

Ceramics can wear by chipping because of their brittleness. Surface and subsurface cracks form, join and release small chips of material. A fine powder is produced as this wear debris is ground up in the wear process. Therefore, ceramics are sensitive to high contact stresses or to any contact condition leading to a state of stress that contains tensile components. Metals and plastics can deform plastically to relieve high contact stresses before fracture occurs. Ceramics can deform plastically under the hydrostatic stress associated with concentrated contact, but the plastic deformation involved is very small. When compared with metals and polymers.



Because of repeated stress application, involving repeated pass sliding and repeated impacts etc., the fatigue mode of wear is predominant. In ceramic materials, with ductile grain boundaries, the fatigue mechanisms are similar to the low cycle fatigue mechanisms of metals. Because of brittle behaviour, wear of ceramics occur by the damage mechanism formed by sharp static indenter. For materials with brittle grain boundaries, fracture occurs in fewer cycles and cracks propagate quickly because of high residual and induced stress.

Module 3:

What is lightly loaded bearing? Derive petroff's equation for frictional force and co-efficient of friction in lightly loaded bearing stating the assumption. **(June/July 2018) (June/July 2017) (June/July 2016) (June/July 2015) (Dec.2014/Jan.2015) (June/July 2014) (June/July 2013) (December 2012) (June/July 2011) (May/June 2010) (10 Marks)**

Explain the formation of a continuous oil film in a Journal bearing, with sketches.
(June/July 2018) (Dec.2013 / Jan. 2014) (05 Marks)

Explain with a neat sketch mechanism of pressure development in an oil film and explain its significance. **(June/July 2015) (10 Marks)**

Explain with a neat sketch Tower's experiment and conclusions drawn. **(June/July 2015) (Dec.2014/Jan.2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June/July 2011) (10 Marks)**

Explain the significance of Sommer field number in distinguishing bearings.
(July 2014) (05 Marks)

Bearing and explain the significance of zones. **(July 2014) (05 Marks)**

A full journal bearing has the following specification: Journal diameter = 75mm; Bearing length 75mm, Journal speed = 900 rev/min, Radial clearance = 0.045 mm, Mean viscosity of the lubricant = 12×10^{-3} pa − s; Attitude = 0.75. Neglecting the effects of end leakage, determine i) Minimum film thickness under the given conditions ii) Load the bearing could support iii) Frictional force on the Journal surface iv) Coefficient of friction under the given conditions v) Power loss in the bearing.
(Dec.2013 / Jan. 2014) (15 Marks)

A lightly loaded bearing has the following data:

Diameter of journal	= 60 mm	Bearing length	= 75mm
Diameter clearance ratio	= 0.001	Speed	= 1800 rpm
Radial load	= 2 kN	Viscosity of oil used	= 27 cp

Calculate the power loss in the bearing. **(December 2012) (08 Marks)**

A full journal bearing has following specification : i) Shaft diameter = 46mm ii) Bearing length = 66mm iii) Radial load = 820N iv) Radial clearance to radius ratio 0.0015 v) Journal speed = 2800 rpm vi) Viscosity of oil at operating temperature 8.4×10^{-3} pa − s Considering the bearing as lightly loaded bearing determine , 1) Frictional force , Frictional torque on Journal 2) Coefficient of friction 3) Power loss from bearing.
(Dec.2013 / Jan. 2014) (14 Marks)

A lightly loaded journal bearing has the following specifications: Journal diameter = 100 mm; Bearing length = 80 mm; radial clearance = 0.05 mm; radial load = 1000 N; absolute viscosity of oil = 0.015 pas -sec. Using Petroff's equation, determine:

Speed of journal which corresponds to a co-efficient of friction of 0.4.

Power loss at this speed. **(June 2012)(10 Marks)**

An idealized full journal bearing has the following data: Diameter of journal = 50 mm; bearing length = 65 mm; speed = 1200 rpm; radial clearance = 0.025 mm; average viscosity = 0.001125 pas-sec; attitude = 0.8. Calculate:

Load carrying capacity

Co-efficient of friction

Power loss in bearing. **(June 2016) (June 2012) (10 Marks)**

A lightly loaded journal bearing has the following specification : Diameter of Journal = 50 mm ; Bearing length = 80 mm ; Diametral clearance ratio = 0.002, Radial load = 750 N , Viscosity of lubricant = 10 cP ; Speed = 4000 rpm. Determine

Frictional torque on journal

Co - efficient of friction

Power loss. **(June/July 2015) (12 Marks)**

A lightly loaded journal bearing has the following specifications:

Diameter of journal = 50 mm Bearing length = 80 mm

Diametral clearance ratio= 0.002 Speed = 4000 rpm

Radial load = 750 N Viscosity = 10 cP Determine:

i) Frictional torque, ii) Coefficient of friction, iii) Power loss.
(June/July 2014) (10 Marks)

A lightly loaded bearing has the following specifications: Journal diameter = 25mm, bearing length = 57mm, Radial clearance = 5×10^{-2} mm, Journal speed = 25,000 rpm, Radial Load= 910 N, Viscosity of the lubricant = 24cP.Calculate:

i)Coefficient of friction. ii) Frictional Torque iii) Power loss due viscous friction.
(June/July 2016) (10 Marks)

Compute the frictional torque and power loss in lightly loaded bearing with following specifications: Journal radius $= 10 \times 10^{-3}$ m, Bearing length $= 24 \times 10^{-3}$ m, Journal speed = 3000 rpm, Nominal clearance $= 24 \times 10^{-6}$ m, Oil viscosity 28×10^{-3} $\mathrm{N - S/m^2}$. **(10 Marks)**

A lightly loaded journal bearing is to support a radial load of 1 kN. The diameter of the shaft is 50 mm and length of the bearing is 60 mm. the oil used as the lubricant is SE 30 at 70^0 C. Determine the coefficient of friction and power loss in the bearing if the speed is 750 rpm and the diametral clearance ratio is 0.001. **(May/June 2010)(10 Marks)**

Determine load carrying capacity, frictional force and power loss due to friction for an ideal full journal bearing having following specifications.

Diameter of journal = 5 cm length of bearing = 6.5 cm

Speed of journal = 1200 rpm radial clearance = 0.0025 cm

Average viscosity = 1.6×10^{-6} Reynolds attitude = 0.8
(June/July 2011)(06 Marks)

A full journal bearing has the following specifications: Diameter = 70 mm; Length = 80 mm; speed = 1800 rpm; radial clearance = 0.05 mm; Mean viscosity = 0.013 pa-sec; Minimum oil film thickness under operating condition = 0.01 mm. Neglecting end flow from the bearing. Find:

Frictional resistance on the journal.

Power loss in the bearing due to viscous friction.

Load carrying capacity.

A partial 120^0 centrally loaded bearing has the following specifications: Diameter of journal = 90 mm: Radius of bearing = 45.5 mm Length of bearing = 125 mm

Speed of journal = 850 rpm Viscosity of lubricant = 0.017 Pa.s

Minimum film thickness = 0.0625 mm Sommerfield number = 0.025

Determine: i) Load carrying capacity, ii) Power loss.

(Dec.2014/Jan.2015) (10 Marks)

A partial self contained 120^0, centrally loaded bearing has the following specifications : Journal diameter = l00 mm, Bearing length = 125 mm, Journal speed = 400 rpm, Radial clearance=0.0625 mm, Minimum film thickness = 6.25×10^{-3} mm, Viscosity of lubricating oil =0.018 Pa.S. Determine : Load carrying capacity of the bearing ii) Power loss in the bearing iii) Maximum pressure in oil film.**(June / July 2016) (10 Marks)**

A machine tool bearing has a length of 50 mm and its journal diameter is also 50 mm. the diametral clearance ratio is 0.001 and the operating viscosity of the lubricant is 0.05 pa-sec. If the journal speed is 950 rpm and the bearing sustains a load of 100 kN, calculate: i) Eccentricity ratio ii) Thickness of oil film. **(Dec.2015/Jan.2016) (10 Marks)**

A Journal bearing operating under steady load condition has the following specifications:

Diameter of journal = 62.5 mm Length of bearing = 50 mm

Radial clearance = 0.03125 mm Speed of journal = 2000 rpm

Load on bearing = 9090 N Lubricating oil used = SAE 20

Expected oil temperature = 82^0 C. Consider the influence of end flow in the performance of bearing. Determine:

Minimum oil film thickness

Coefficient of friction

Power loss. Assume $\beta = 180^0$.**(Dec.2015/Jan.2016)(10 Marks)**

A 120^0 centrally loaded bearing has the following specifications :

Diameter of journal = 100 mm; length of bearing = 130 mm; diameter clearance = 0.15 mm; oil used SAE 60; minimum film thickness = 0.0045 mm; speed of journal = 600 rpm; bearing operating temperature = 95^0 C; considering end leakage determine : i) Load carrying capacity ii) Power loss in the bearing iii) Expected maximum pressure in the bearing.

(June 2012) (14 Marks)

The following specification refer to a full journal bearing, Journal diameter = 60 mm, Bearing length = 75 mm, Journal speed = 2000 rpm, Radial clearance = 0.04 mm,. Viscosity of lubricant = 0.01 PaSec, Eccentricity ratio = 0.8, Inlet pressure = 0.3 MPa, Location of inlet hole = 300^0. Determine maximum and minimum pressure and their location.**(June / July 2015)(10 M)**

A full journal bearing has the following specifications: Diameter of journal = 75 mm Length of bearing = 60 mm Oil film temperature = 96^0 C Radial clearance 0.05 mm oil film thickness = 7.9×10^{-3} mm Lubrication oil is SAE 20. Lubricant is delivered to the bearing under a pressure through a single inlet pressure hole in an unloaded bearing region. Determine inlet pressure required if the rate of oil flow through the bearing material $4925\ mm^3/s$ in order to control bearing temperature.

(June/July 2014) (10 Marks)

A lightly loaded full journal bearing has the following specifications. Bearing diameter = 80 mm, Bearing Length = 60 mm, Diametral clearance = 0.12 mm, Journal speed = 24000 rpm, Viscosity of the Lubricating oil = 4cP, Radial load = 900N. Determine : i) Frictional Force ii)Torque iii)Power loss iv) Coefficient of friction. **(June/July 2018) (06 Marks)**

1. Derive Reynolds equation in two dimensions. State the assumptions made. List out various wear testing methods clearly, mentioning their standards.
   (Dec.19/Jan.20)(June/July 2018) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (June / July 2011) (May/June 2010) (20 Marks)

Petroff's equation

Consider a vertical shaft rotating in a guide bearing. It is assumed that the bearing

Carries a very small load

The clearance ' c' is completely filled with oil

The end leakage is completely negligible

The oil used is of high viscosity

The journal revolves at very high speed

The bearing run concentrically

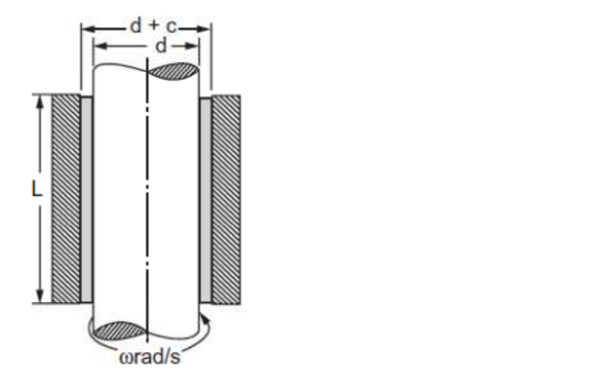


FIGURE 23-5 Vertical shaft rotating in a cylindrical bearing.

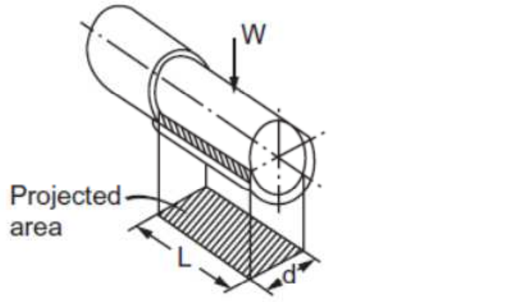


FIGURE 23-6 Projected area of a bearing.

Shear stress, $\tau = \frac{F_\mu}{A} = \eta \frac{U}{h}$ $\quad (\boldsymbol{E-23.1})(\boldsymbol{P-23.5})$

$$U = \pi d \frac{n}{60} = \pi d n' \qquad (\boldsymbol{E-23.18})(\boldsymbol{P-23.18})$$

$$h = c_r = \frac{c}{2}$$

Surface area, $A = \pi d L$

Force, $F_\mu = \tau A = \eta \frac{U}{h} A = \frac{\eta \times \pi d n' \times \pi d L}{\left(\frac{c}{2}\right)}$

$$F_\mu = \frac{2 \pi^2 \eta n' L d^2}{c} \qquad \left(\psi = \frac{c}{2} \; Diametral\ Clearance\ Ratio\right)$$

$$F_\mu = \frac{2 \pi^2 \eta n' L d}{\psi}$$

Torque, $M_t = Force \times Radius = F_\mu \times r = F \times \frac{d}{2}$

$$M_t = \frac{2 \pi^2 \eta n' L d}{\psi} \times \frac{d}{2}$$

$$M_t = \frac{\pi^2 \eta n' L d^2}{\psi} \qquad (\boldsymbol{E-23.20})(\boldsymbol{P-23.13})$$

Coefficient of friction

$$\mu = \frac{F_\mu}{W}$$

$$Load, \; W = p A = p L d$$

Where, p = bearing pressure in MPa

Bearing projected area $A = L d$

$$\mu = 2 \pi^2 \eta n' L d \frac{1}{p L d}$$

$$\mu = 2 \pi^2 \left(\frac{\eta n'}{p}\right)\left(\frac{1}{\psi}\right) \qquad (\boldsymbol{E-23.21})(\boldsymbol{P-23.13})$$

Coefficient of friction

$$\mu = 2 \pi^2 \left(\frac{\eta n'}{p}\right)\left(\frac{1}{\psi}\right) \qquad (\boldsymbol{E-23.21})(\boldsymbol{P-23.13})$$

This equation is called Petroff's equation.

Power loss due to friction

$$P = \frac{F_\mu U}{1000} \qquad (\boldsymbol{E-23.49c})(\boldsymbol{P-23.34})$$

$$F_\mu \; in\ N, \; U \; in \frac{m}{s}, \; P \; in\ kW$$

Explain the mechanism of hydrodynamic lubrication in journal bearing

Hydrodynamic theory of lubrication

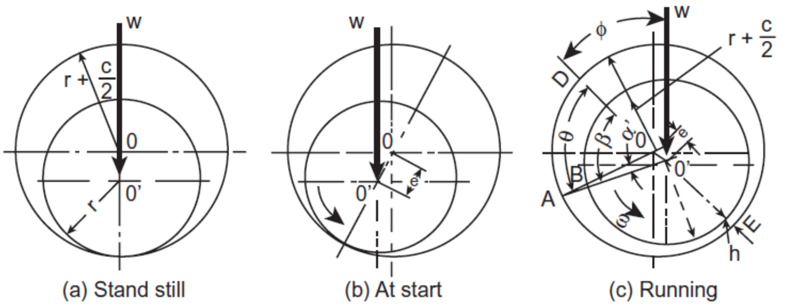
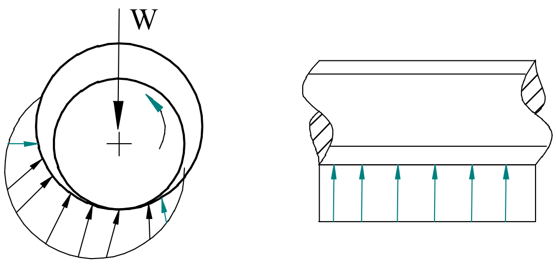


FIGURE 23-8 Behaviour of a journal in its bearing.

When the journal is at rest, it comes in metal to metal contact with the bearing at its lowest point as shown in Fig (a)

When the shaft rotates in counter clockwise direction as shown in Fig (b), it tends to move above slightly and the point of contact will move as the speed of the shaft increase it carries the oil with it and the fluid pressure in the oil rises then a thin fluid pressure in the oil rises the a thin absorbed film of the lubricant. May partially separate the bearing and journal.

When the speed is increases, the pressure is sufficient to carry the weight of the journal. Then there is no metal to metal contact, but the shaft is supported by the oil. The point of maximum fluid pressure and position of the shaft will be shown in Fig (c)



Tower's experiments

Write a short note on Tower's experiments

Explain with a neat sketch Tower's experiment and conclusions drawn.

(June/July 2015) (Dec.2014/Jan.2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June/July 2011) (10 Marks)

Tower conducted experimental investigation on friction of bearings. These bearings were partial bearings, 4 inch in diameter, 6 inches long with arc of contact 157^0. Friction forces on the journal surface and co efficient of friction were determined by using different systems for supplying the lubricant and by using different kind of liquid lubricant. The influences of speed, load and temperature on friction were investigated using a special testing machine used to conduct these experiments.

TOWER'S EXPERIMENT

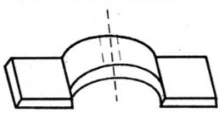


Fig 2.3 (a) : Bearing with a central groove parallel to axis

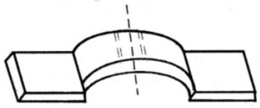


Fig 2.3 (b) : Bearing with two grooves parallel to axis

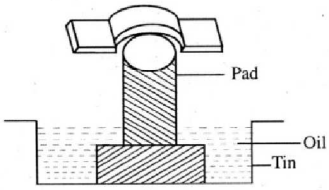


Fig 2.3 (c) : Bearing with pad

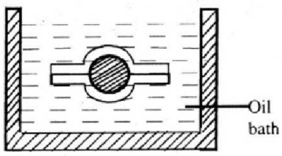


Fig 2.3 (d) : Bearing immersed in oil bath

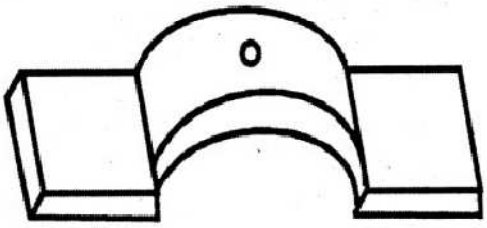


Fig 2.3 (e) : Bearing with hole in the cap.

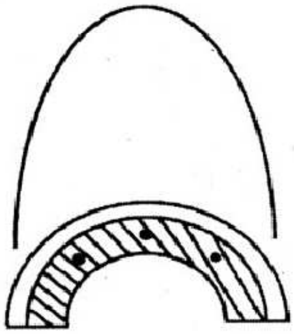


Fig 2.3 (f) : Pressur distribution curves

In the first of the series of tests, Tower tried to feed the lubricating oil to the bearing through a oil hole which led the oil to a groove in the middle of the bearing parallel to the axis of the journal [Fig 2.3(a)]. With this experiment it was found that the bearing would not run cool even at low loads. Two grooves parallel to the axis on either side of the center [Fig 2.3(b)] somewhat improves the performance of the bearing but seized at loads which were little higher than in previous case.

In the next series of test, grooves and holes were sealed and a pad was placed under the journal so that the journal dropped against the pad while rotating. The pad was supplied with oil by capillary action from the oil in the tin in which the pad was placed. This arrangement also did not give satisfactory bearing performance since the oil supplied to the journal was little. The load which the bearing could withstand was low and co efficient of friction was high.

After this Tower made the bearing to run immersed in a bath of oil [Fig 2.3(d)]. This method of bearing gave satisfactory results. The friction was steady during the experiment and the coefficient of friction was surprisingly low. From the result of this investigation, Tower made the following conclusions. When an oil bath is used to provide sufficient lubrication.

Friction force is nearly constant under different load with some limits.

Friction followed the laws of liquid friction.

Friction is almost independent of pressure and increases with velocity of the journal.

Frictional resistance in the bearing decreases as the temperature increases.

In the next step, a hole was drilled through the cap in the center of the bearing in order to install an ordinary lubricator. When the shaft rotated the oil began to flow out through this hole[Fig 2.3(e)]. The journal appeared to act as a pump, pumping the oil from the reservoir out of the bearing. This experiment showed that the bearing was actually floating on an oil film.

In the next step Tower drilled '9' holes of ¼ inch in the bearing and connected them to pressure gauges. This arrangement helped to measure pressure distribution. This experiment established the important fact that the journal bearing should be properly designed and lubricated by a liquid lubricant. The journal is supported by pressure developed in the oil film so that no direct contact takes place between journal and bearing.

MECHANISM OF PRESSURE DEVELOPMENT IN OIL FILM.

Case 1:

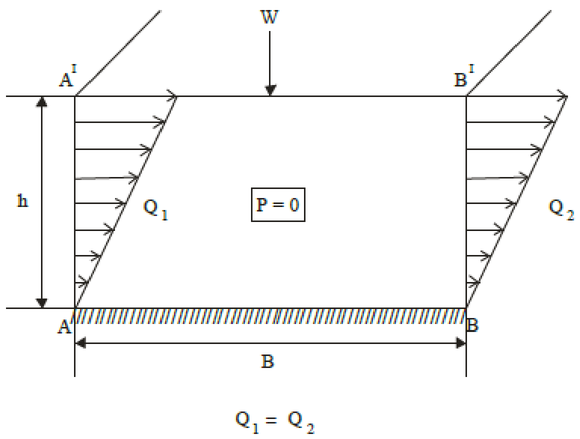


Fig : Viscous Drag

Let upper plate A'B' is moving with constant velocity 'u' while AB is stationary the velocity varies uniformly from 0 at surface A&B and U at the surface A'B' & rate of shear is constant throughout the oil film. Assuming that this surfaces are wide in the direction perpendicular to the motion so that the flow of the lubricant in this direction is negligibly small under these conditions. Volume of the fluid flowing across AA' is equal to that of flow across the BB'.

Therefore there is no pressure built up in the oil film and pressure at all the points in the oil film is zero.

The ability of the film to support the load depends upon the pressure build up in the film.

A bearing with parallel surfaces are not able to support the load by fluid film and if load is applied to the surface A'B' the lubricant will be squeezed out and bearing will operate under extreme boundary condition.

Case 2:

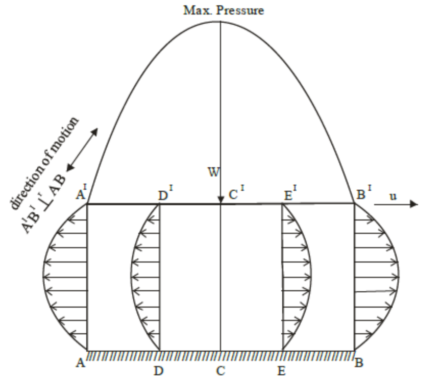


Fig : Pressure Induced Flow

Consider 2 parallel surfaces AB & A'B' in which AB is stationary and A'B' is in motion in the direction perpendicular to A&B. There is no relative motion of the surface in the horizontal direction. The oil is squeezed so that it is going both to the right and left of the section CC', the rate of flow increases gradually as the distance from the centre of cross section increases so that maximum rate of flow across at the section AA' & BB' in each section the velocity of the oil film will be maximum in middle layer and zero at the surfaces this type of flow is possible if there is a pressure gradient along the surface with the maximum pressure at the middle section and falling gradually to zero at the end section. The pressure developed at the different section of film depends on viscosity, rate of flow, velocity and instantaneous clearance.

Case 3:

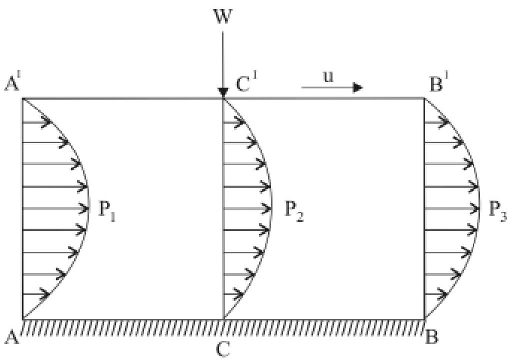


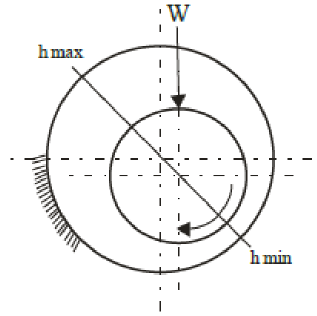
Fig : Flow Through Parallel Stationary Planes

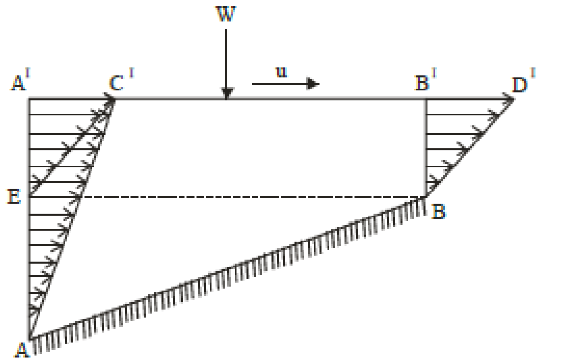
The flow of the lubricant caused by difference is pressure in different cross section is called pressure induced flow when the lubricant flows between 2 parallel stationary plates with a pressure at AA' is P1 which is greater than pressure P2 & P3 at sections CC' and BB'. The important factor is that pressure in the oil film is always present supports the applied load.

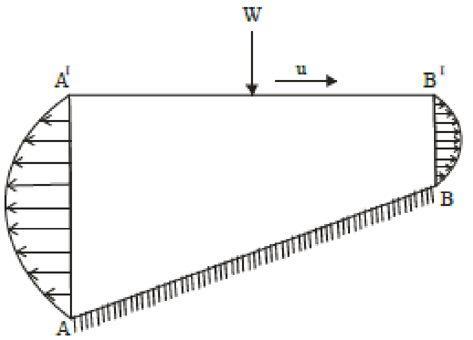
Case 4:

Converging Film Area AHC'A' is equal to area BID'B'.

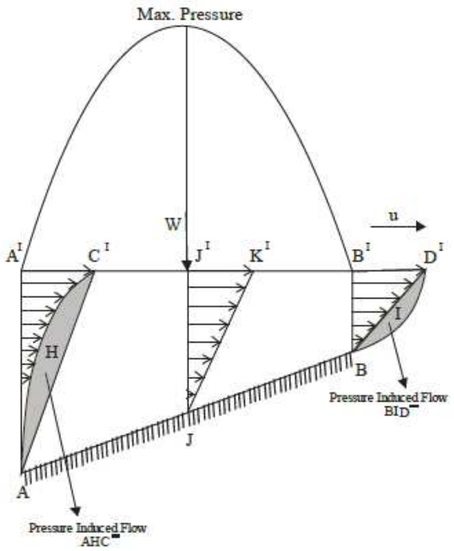
Area of JK'J' is equal to area of AHC'A + area of BID'B.







Viscous Drag Pressure Induced Flow



Flow Through Inclined Surfaces or Non Parallel Surfaces

The form of the velocity distribution curve obtained in this way must satisfy the condition that the rate of flow through AA' is equal to rate of flow at BB'. Because of the pressure developed in the oil film the plane A'&D' is able to support the vertical load.

Therefore the positive pressure in the oil film is developed in the direction of the motion of the surface A'B' is such that the volume of the lubricant which surface tends to drag in to the space between the surface is greater than the volume it tends to discharge from the space, such film is known as converging film.

If the motion of the upper surface is reversed with the inclination of lower surface unchanged the volume of the lubricant that the moving surface tends to drag in to the space becomes less than the volume it tends to discharge. Therefore pressure developed will be negative bearing is not to with stand the load such a film is known as diverging film.

Converging and diverging fluid film:

A positive pressure is developed in the oil film if the direction of motion of the surface A'B' is such that a converging fluid film is produced. The volume of lubricant dragged into the space between the surfaces is greater than the volume that is discharged from this space. Under these conditions the fluid film is capable of supporting a load. Such a film is known as converging film.

If the motion of the upper surface is reversed with the inclination of the lower surface unchanged, the volume of lubricant entering into the space is less than volume discharged from this space. Pressure developed in the film will be negative and bearing will not be able to support any load. Such a film is known as diverging film.

Reynolds investigation:

Some of the significant contributions of Reynolds are

The importance of bearing clearance was shown

The importance of viscosity of a lubricant on friction characteristics, load capacity and other characteristics of bearing performance was shown.

A general pitcher of physics of fluid film lubrication was given.

It was shown that a lubricant which adheres to both moving and stationary surfaces of bearing develops positive pressure in converging film preventing metal to metal contact and his pressure cannot be developed between parallel surfaces.

Differential equation for pressure distribution in oil film was derived by him.

Derive Reynolds equation in two dimensions. State the assumptions made.
(Dec.19/Jan.20) (June/July 2018) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (June / July 2011) (May/June 2010) (20 Marks)

Reynolds equation in 2-D:

Assumptions:

Flow of fluid is laminar

Fluid is incompressible

The viscosity of lubrication is constant throughout the oil film

No slip occurs between lubricant and bearing surface.

The clearance between bearing and journal surface is so small that change in pressure across the clearance can be neglected.

The inertia force developed is so small that it may be neglected.

Shear stress is directly proportional to rate of shear strain i.e lubricant is Newtonian fluid.

There is no flow in the direction perpendicular to motion i.e there is no leakage.

Consider the converging oil film as shown in fig3.6. The surface (B) is fixed while surface A is in motion with constant velocity (U) in x- direction. This surface is loaded with a vertical force (W). Since there is no flow in z-direction. Pressure along the –direction is constant. Consider a infinitesimal element of lubricant between surfaces. The positive directions of velocity components u, v & w are shown in figure.

Fig 3.6: Converging oil film with forces acting on an element

The forces acting on the elemental fluid are

Pressure force on the left end of the elemental fluid $= p\ dy\ dz$

Pressure force on the right end of the elemental fluid

$$= \left[p + \frac{dp}{dx}\ dx\right] dy\ dz$$

Shear force on the top $= \tau_x\ dx\ dz$

Shear force on the bottom of the elemental fluid $= \left[\tau_x + \frac{d\tau_x}{dy}\ dy\right] dx\ dz$

Step (i): Considering the equilibrium of forces:

$$\sum F_x = 0$$

$$p\ dy\ dz - \left[p + \frac{dp}{dx}\ dx\right] dy\ dz + \tau_x\ dx\ dz - \left[\tau_x + \frac{d\tau_x}{dy}\ dy\right] dx\ dz = 0$$

$$\text{p dy dz} - \text{pdy dz} - \frac{dp}{dx}\ dxdy\ dz + \tau_x \text{ dx dz} - \tau_x \text{dy dz} - \frac{d\tau_x}{dy} dxdy\ dz = 0$$

$$\left[\frac{dp}{dx} + \frac{d\tau_x}{dy}\right] dxdy\ dz = 0$$

$$\frac{dp}{dx} = -\frac{d\tau_x}{dy} \qquad \mathbf{(1)}$$

According to Newton's law of viscosity

From the equation $\tau = \eta \frac{du}{dy}$ $\qquad \mathbf{(E-23.1)(P-23.5)}$

In this case as 'y' increases the velocity 'u' decreases. (- ve Velocity gradient)

$$\tau = -\eta \frac{du}{dy} \qquad \mathbf{(2)}$$

Substituting equation (2) in (1), we get $\quad \frac{dp}{dx} = -\frac{\partial}{\partial y}\left[-\eta \frac{du}{dy}\right]$

$$\frac{dp}{dx} = \eta \frac{d^2u}{dy^2}$$

$$\frac{d^2u}{dy^2} = \frac{1}{\eta}\frac{dp}{dx} \qquad \mathbf{(3)}$$

Integrating above equation twice w.r.t 'y' $\quad \frac{du}{dy} = \int \frac{1}{\eta}\frac{dp}{dx} dy$

$$\frac{du}{dy} = \frac{1}{\eta}\frac{dp}{dx}\int dy$$

$$\frac{du}{dy} = \frac{1}{\eta}\frac{dp}{dx}y + C_1$$

Again integrating w.r.t to 'y'

$$u = \int\left[\frac{1}{\eta}\frac{\partial p}{\partial x}y + C_1\right]dy$$

$$u = \int\left[\frac{1}{\eta}\frac{dp}{dx}y\,dy + C_1 dy\right]$$

$$u = \frac{1}{\eta}\frac{dp}{dx}\frac{y^2}{2} + C_1 y + C_1$$

$$\frac{1}{2\eta}\frac{dp}{dx}y^2 + C_1 y + C_2 \qquad \mathbf{(4)}$$

Where C_1 & C_2 are constants of integration.

Applying the boundary condition

i.e., $(i)\ at\ y = 0, u = U$

$(ii)\ at\ y = h, u = 0$

From boundary condition (i) $U = 0 + 0 + C_2$

$$C_2 = U \qquad (2)$$

From boundary condition (ii) $u = \frac{1}{2\eta}\frac{dp}{dx}y^2 + C_1 y + \square_2$

$$0 = \frac{1}{2\eta}\frac{dp}{dx}y^2 + C_1 y + U$$

$$C_1 = \frac{1}{h}\left[-\frac{h^2}{2\eta}\frac{dp}{dx} - U\right]$$

$$C_1 = -\frac{1}{2\eta}\frac{dp}{dx}h - \frac{U}{h}$$

Substituting the value of C_1 & C_2 in equation (4), we get

$$u = \frac{1}{2\eta}\frac{dp}{dx}y^2 + \left[-\frac{U}{h} - \frac{1}{2\eta}\frac{dp}{dx}h\right]y + U$$

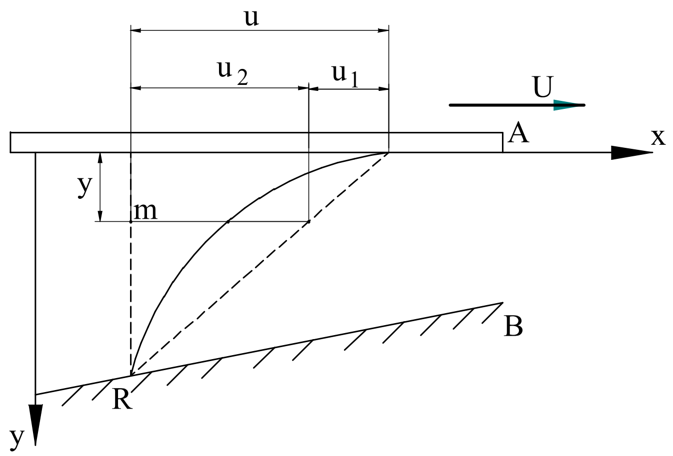
$$u = \frac{1}{2\eta}\frac{dp}{dx}y^2 - \frac{U}{h}y - \frac{1}{2\eta}\frac{dp}{dx}hy + U$$

$$u = \frac{1}{2\eta}\frac{dp}{dx}(y^2 - h\,y) + U\left[1 - \frac{y}{h}\right] \qquad \mathbf{(5)}$$

or $u = u_1 + u_2$

Where $u_1 = \frac{1}{2\eta}\frac{dp}{dx}(y^2 - h\,y)$ & $u_2 = U\left[1 - \frac{y}{h}\right]$

Equation (5) gives the velocity distribution across any section of the oil film as shown in the Figure below



The term $u_1 = \frac{1}{2\eta}\frac{dp}{dx}(y^2 - h\,y)$ given parabolic velocity distribution due to pressure induced flow in the film. u_1 depends on viscosity of the lubricant η & the pressure gradient $\frac{dp}{dx}$

$$at \quad y = 0, u_1 = 0$$

$$at \quad y = h, u_1 = 0$$

$$at \quad y = \frac{h}{2}$$

$$u_1 = \frac{1}{2\eta}\frac{dp}{dx}\left(\frac{h^2}{4} - \frac{h^2}{2}\right)$$

$$u_1 = \frac{1}{2\eta}\frac{dp}{dx}\left(\frac{-h^2}{4}\right)$$

$$u_1 = \frac{-h^2}{8\,\eta}\frac{dp}{dx}$$

The term $u_2 = U\left[1 - \frac{y}{h}\right]$gives a linear velocity distribution, which is caused by the velocity of the moving surface relative to the stationary one.

Step (ii) : Considering discharge through the element:

Since the fluid is assumed as incompressible, the volume quantity of the fluid flowing into the stationary cube is equal to the quantity of the fluid flowing out of this cube.

$$\therefore \quad Q_{in} = Q_{out}$$

$$u\,dy\,dz + v\,dx\,dz + w\,dx\,dy$$
$$= \left[u + \frac{du}{dx}dx\right]dy\,dz + \left[v + \frac{dv}{dy}dy\right]dx\,dz + \left[w + \frac{dw}{dz}dz\right]dx\,dz$$

$$\frac{du}{dx}dx\,dy\,dz + \frac{dv}{dy}dx\,dy\,dz + \frac{dw}{dz}dx\,dy\,dz = 0$$

$$\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0$$

$$\therefore \frac{du}{dx} + \frac{dv}{dy} = 0 \qquad \left(\because no\ flow\ in\ Z - direction\ \frac{dw}{dz} = 0\right)$$

$$\frac{dv}{dy} = -\frac{du}{dx}$$

Substituting the value 'u' from equation (5)

$$\frac{dv}{dy} = -\frac{d}{dx}\left(\frac{1}{2\eta}\frac{dp}{dx}(y^2 - h\,y) + U\left[1 - \frac{y}{h}\right]\right) \qquad \mathbf{(6)}$$

Since velocity 'v' is equal to zero when,

$$y = 0\ or\ y = h$$

$$\int_{y=0}^{y=h} \partial v = 0$$

Integrating equation (6) w.r.t 'y' $\quad -\int_0^h \frac{d}{dx}\left(\frac{1}{2\eta}\frac{dp}{dx}(y^2 - h\,y) + U\left[1 - \frac{y}{h}\right]\right) dy = 0$

$$or \qquad -\frac{d}{dx}\int_0^h \left(\frac{dp}{dx}\frac{1}{2\eta}(y^2 - h\,y) + U\left[1 - \frac{y}{h}\right]\right) dy = 0$$

$$-\frac{d}{dx}\int_0^h \frac{dp}{dx}\frac{1}{2\eta}y^2 dy + \frac{d}{dx}\int_0^h \frac{dp}{dx}\frac{1}{2\eta}h\,y dy - \frac{d}{dx}\int_0^h U dy + \frac{d}{dx}\int_0^h \frac{U}{h}y\,dy = 0$$

$$-\frac{d}{dx}\left[\frac{dp}{dx}\frac{1}{2\eta}\frac{y^3}{3}\right]_0^h + \frac{d}{dx}\left[\frac{dp}{dx}\frac{1}{2\eta}\frac{h\,y^2}{2}\right]_0^h - \frac{d}{dx}[U\,y]_0^h + \frac{d}{dx}\left[\frac{U}{h}\frac{y^2}{2}\right]_0^h = 0$$

$$-\frac{d}{dx}\left[\frac{dp}{dx}\frac{1}{2\eta}\frac{h^3}{3}\right] + \frac{d}{dx}\left[\frac{dp}{dx}\frac{1}{2\eta}\frac{h^3}{2}\right] - \frac{d}{dx}[U\,h] + \frac{d}{dx}\left[\frac{U}{h}\frac{h^2}{2}\right] = 0$$

$$-\frac{d}{dx}\left[\frac{dp}{dx}\frac{h^3}{6\eta}\right] + \frac{d}{dx}\left[\frac{dp}{dx}\frac{h^3}{4\eta}\right] - \frac{d}{dx}[U\,h] + \frac{d}{dx}\left[\frac{U\,h}{2}\right] = 0$$

$$\frac{d}{dx}\left[\frac{dp}{dx}\frac{h^3}{12\,\eta}\right] = \frac{U}{2}\frac{dh}{dx}$$

$$\frac{d}{dx}\left[\frac{dp}{dx}\frac{h^3}{6\,\eta}\right] = U\frac{dh}{dx}$$

$$\boldsymbol{\frac{d}{dx}\left[h^3\frac{dp}{dx}\right] = 6\,\eta\,U\frac{dh}{dx}}$$

This equation is the **Reynold's equation** in 2 dimensions.

Module 4:

Distinguish a pivoted shoe slider bearing from a fixed shoe slider bearing.
(June/July 2014) (05 Marks)

Derive an expression for load carrying capacity of an idealized plane slider bearing.
(Dec.19/Jan.20) (June/July 2015) (10 Marks)

Discuss locating centre of pressure in fixed shoe slider bearing.
(June/July 2014) (05 Marks)

Derive an analytical expression for pressure distribution along an idealized plane slider bearing with a fixed shoe. **(Dec.19/Jan.20) (June / July 2017)(June/July 2013) (June / July 2011) (May/June 2010) (20 Marks)**

Derive an expression for the load carrying capacity of a plane slider bearing with a fixed shoe.
(Dec.2013 / Jan. 2014) (June 2012) (10 Marks)

Derive an expression for load carrying capacity of a plane slider bearing with pivoted shoe.
(Dec.2015/Jan.2016) (10 Marks)

The shoe of a slider bearing has square shape. The load acting on the bearing is 15 kN. The velocity of moving member is 7.5 m/s. the lubricating oil has a viscosity of 0.03 $Pa - s$. The permissible minimum film thickness is 0.125 mm. Determine the required dimensions, resistance force and coefficient of friction under given operating conditions.
(Dec.2014/Jan.2015) (10 Marks)

A rectangular plain slider bearing with fixed shoe with no end leakage has the following specifications bearing length = 90 mm, width of shoe = 90 mm, Load on the bearing = 7800 N, Slider velocity= $250\ cm/sec$, indication $\propto = -0.00035$ radians, viscosity of oil at operating temperature = 40 cP, Determine: i)Minimum Film thickness ii)Power loss iii) Co - efficient of friction.**(June/July 2018) (June/July 2016) (10 M)**

A rectangular plane slider bearing with fixed shoe is operating under the following conditions : Width of the shoe = 80mm, Length of the shoe in the direction of motion = 150mm, Velocity of the moving member = 2 m/s , Absolute viscosity of the oil = 0.02 Pas ;Minimum oil film thickness = 0.02mm ; Maximum oil film thickness = 0.05mm. Find i) The load carrying capacity ii) Coefficient of friction iii) Pressure at a distance of 50 mm measured from the maximum film thickness point. Neglect end leakage.
(Dec.2013 / Jan. 2014) (10 Marks)

A rectangular plane slider bearing with fixed shoe has the following details:

Length of bearing in the direction of motion = 80 mm

Width of bearing = 60 mm Velocity of slider = 2 m/s

Viscosity of oil = 0.1 $pa - s$ Minimum fluid film thickness = 0.02 mm

Maximum fluid film thickness = 0.06 mm

Draw the pressure distribution curve for the slider bearing.
(Dec.2014/Jan.2015) (December 2012) (10 Marks)

A slider bearing with a rectangular pivoted shoe has the following specifications:

Length of shoe in direction of motion= 75 mm   Width of shoe = 115 mm

Velocity of moving member= 2 m/s Expected mean temperature of oil= 80^0C

Permissible film thickness = 0.023 mm, Viscosity of oil=34.5×10^{-3} pa − s

Determine: i) load carrying capacity   ii) power loss in the bearing.

Assume that the inclination of the bearing surface corresponds to the maximum load carrying capacity. Neglect the effects of end flow.

(December 2012) (10 Marks)

A pivoted shoe slider bearing has the following data:

Length of shoe = 100 mm   Width of shoe = 120 mm

Velocity of moving member = 5 m/s   Viscosity= 25 cp

Minimum oil film thickness = 0.002 mm , Determine:

Maximum load carried

Coefficient of friction.   **(Dec.2015/Jan.2016) (10 Marks)**

A pivoted shoe of the slider bearing has square shape. The load acting on the bearing is 13.34 kN velocity of the moving member is 5.08 m/sec. Lubricating oil is SAE 40. The expected mean temperature of oil film is 90^0 C. Permissible minimum oil film thickness is 1.905×10^{-5} m, Find: Required dimensions of the shoe.   Power loss.

Coefficient of friction in the bearing under given operating condition.

Assume that inclination of surface corresponds to maximum load carrying capacity. Neglect effect of end flow of oil.   **(June/July 2018) (June/July 2016) (June/July 2014) (10 Marks)**

The following data refers to a slider bearing with pivoted shoe:

Length of the bearing = 500 mm, Width of the bearing = 500 mm, Velocity of runner = 8 m/sec, Oil viscosity = 0.054 PaSec. Maximum and minimum film thickness = 0.15 mm and 0.075 mm. Determine (i) Load that may be carried by the bearing. (ii) Coefficient of friction (iii) Power loss.   **(June/July 2015) (10 Marks)**

A pivoted shoe of a slider bearing has a square shape. The load acting on the bearing is 15 kN. Velocity of the moving member is 5 m/sec. Lubricating oil is SAE 30 and mean tempœature of the oil is 70^0 C. The minimum oil film thickness as 0.02 mm. Take q = 1.4. Determine:

The dimensions of the shoe   Coefficient of friction   Power loss due to friction.

Assume that the inclination of bearing surface corresponds to the maximum load carrying capacity of the bearing.   **(May/June 2010) (10 Marks)**

A slider bearing with a rectangular pivoted shoe has the following specifications:

Length of shoe in the direction of motion = 75 mm

Width of shoe = 112 mm

Velocity of moving member = 200 mm/s

Viscosity of fluid = 32 cP

Permissible minimum oil film thickness = 0.255 mm

Assume inclination of bearing corresponding to q = 1.2.

Determine:

Load carrying capacity   Power loss in bearing   Coefficient of friction

Take into consideration the influence of end leakage on the performance of the bearing

(June / July 2011) (08 Marks)

Plane slider bearings with fixed/pivoted shoe:

Slider Bearings:

Sliding bearings are bearings where only sliding friction is generated. The shaft is generally supported by the sliding surface, with oil and air in between to facilitate sliding movement. Sliding bearings are lightweight and have a long operating life while introducing minimal vibrations or noise.

The vast number of industrial slider bearing designs initially evolved from a desire to create a bearing having better load-carrying capacity and/or reduced friction and wear. Thus, a great deal of emphasis was placed on the effectiveness of the bearing geometry to generate pressure (self-acting bearings) and thus increase load capacity.

Idealized Plane Slider Bearing

The principal characteristics of a plane slider bearing depend on the geometry of the bearing, lubricant viscosity and the speed of the moving member. In case of a plane slider bearing with fixed shoe, if the load increases beyond the capacity, the bearing may cease to operate under hydrodynamic conditions. To improve the performance of the bearing under such conditions i.e. to improve the stability of the bearing, the normal practice is to pivot the shoe so that the inclination of the fixed member is changed automatically to suit the load conditions. Moreover, the difficulty in manufacturing a very thin fluid film in the plane slider bearing is also overcome.

An idealized plane slider bearing consists of two non parallel plane surfaces separated by an oil film. One surface is stationary while the other one is moving with a uniform velocity (U) and inclinations are such that a converging oil film is formed between the surfaces. The positive pressure built up in the oil film supports a load. Further the letter (L) represents the length of the bearing and (B) is the width of the bearing.

HYDROSTATIC LUBRICATION:

State the principles, advantages, disadvantages and applications of hydrostatic lubrication.
(June/July 2014) (05 Marks)

Explain the two main systems of hydrostatic lubrication.
(June/July 2014) (05 Marks)

Derive the expressions for rate of flow of oil, load carrying capacity and pressure distribution for on hydrostatic step bearing. State the assumptions.
(Dec.19/Jan.20)(June/July 2018) (June July 2017) (June July 2016) (Dec.2015/Jan.2016) (June/July 2015) (Dec.2014/Jan.2015) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June July 2011) (May/June 2010) (12 Marks)

The following are the particulars of hydrostatic step bearing:

Diameter of shaft = 147 mm

Diameter of pocket = 106 mm

Vertical thrust on bearing = 25 kN

External pressure =0

Viscosity of lubricant = $20 \times 10^{-3}\ pa - s$

Oil film thickness = 0.12 mm

Shaft speed = 2400 rpm

Determine: i) Rate of flow through bearing; ii) Power loss due to viscous friction.
(December 2012) (08 Marks)

Hydrostatic step bearing has the following specifications:

i) Diameter of shaft = 150mm ii) Diameter of pocket = 100mm iii) Vertical thrust on bearing = 60000N iv) Shaft speed=1500 rev/min v) Viscosity of oil = $30 \times 10^{-3}\ pa - s$ vi) Oil film thickness = 0.125mm. Determine i) Discharge ii) Power loss due to friction iii) Co-efficient of friction. **(Dec.2013 / Jan. 2014) (12 Marks)**

A hydrostatic step bearing has the following particular:

Inlet pressure = 4.5 MPa

Viscosity of lubricant = 0.03 pas.sec

Oil film thickness = 0.005 mm

Vertical load on bearing = 18750 N

Shaft speed = 900 rpm

Ratio of $r_2/r_1 = 2$.

Determine: i) The diameter of shaft

ii) The rate of oil flow through the bearing iii) Power loss due to viscous friction.
(Dec.2015/Jan.2016) (Dec.2014/Jan.2015) (10 Marks)

A hydrostatic step bearing for a turbine rotor has the following specification:

Diameter of shaft = 150 mm; diameter of pocket = 100 mm; vertical thrust = 70 kN; shaft speed = 1000 rpm; viscosity = 0.025 pa.sec; oil film thickness = 0.125 mm. Determine:

Rate of oil flow through the bearing.

Power loss due to viscous friction.

Co-efficient of friction. **(June / July 2013) (10 Marks)**

A hydrostatic step bearing has the following specifications. Diameter of shaft = 150 mm, Pocket diameter = 102 mm, Vertical thrust of bearing = 40 kN, shaft speed 900 rpm, Viscosity of lubricant 25 $\times 10^{-3}$ $Pa.s$, Oil film thickness = 0.15 mm, External pressure = Zero. Find :

Required inlet pressure   Rate of flow through the bearing

Power loss due to viscous friction   **(June/July 2018) (08 Starks)**

A hydrostatic circular thrust bearing has the following data:

Shaft dia = 300 mm   Dia of pocket = 200 mm

Shaft speed = 100 rpm   Pressure at the pocket = $500\ kN/m^2$

Film thickness = 0.07 mm   Viscosity of lubricant = 0.05 PaS.

Determine: Load carrying capacity,

Oil flow rate   Power loss due to friction.   **(June/July 2014) (10 Marks)**

A hydro static step bearing has following specification: Shaft diameter = 130 mm, Pocket diameter = 55 mm, Shaft speed = 1800 rpm, Inlet pressure = 3.75 MPa, External pressure = 0 MPa, Expected oil temperature $= 50^0\ C$ Desirable oil film thickness = 0.00875 mm, Lubricating oil used = SAE60. Determine

Load the bearing can support

The rate of flow through bearing

Power loss due to viscous friction.

(June/July 2015) (May/June 2010) (10 Marks)

A hydrostatic step bearing for a turbine rotor has the following specifications:

Diameter of shaft = 150 mm, Diameter of pocket = 100 mm, Vertical thrust of bearing =70 KN, Shaft speed = 1000 rpm, Viscosity = 0.025 pa.sec, film thickness = 0.125 mm. Determine

Rate of oil flow

Power loss

Coefficient of friction.   **(June July 2017) (10 Marks)**

A hydrostatic thrust bearing has the following specifications:

Vertical thrust = 60 kN   Shaft diameter = 500 mm

Pocket diameter = 300 mm   Viscosity = 35 cP

Film thickness = 0.01 mm. determine:

Rate of oil flow through the bearing

Power loss due to viscous friction.   **(June July 2017) (08 Marks)**

A hydrostatic step bearing has following specifications shaft diameter = 0.150 m, recess diameter = 0.100 m, vertical thrust load = 60 kN, speed of the shaft = $1500\, rev/min$, viscosity of the lubricant is 30 cP, minimum oil film thickness = $1.25 \times 10^{-4}\, m$. Determine:

Discharge

Power loss due to viscous friction

Coefficient of friction. **(June July 2016) (08 Marks)**

Plane slider bearings with fixed/pivoted shoe:

Slider Bearings:

Sliding bearings are bearings where only sliding friction is generated. The shaft is generally supported by the sliding surface, with oil and air in between to facilitate sliding movement. Sliding bearings are lightweight and have a long operating life while introducing minimal vibrations or noise.

The vast number of industrial slider bearing designs initially evolved from a desire to create a bearing having better load-carrying capacity and/or reduced friction and wear. Thus, a great deal of emphasis was placed on the effectiveness of the bearing geometry to generate pressure (self-acting bearings) and thus increase load capacity.

Idealized Plane Slider Bearing

The principal characteristics of a plane slider bearing depend on the geometry of the bearing, lubricant viscosity and the speed of the moving member. In case of a plane slider bearing with fixed shoe, if the load increases beyond the capacity, the bearing may cease to operate under hydrodynamic conditions. To improve the performance of the bearing under such conditions i.e. to improve the stability of the bearing, the normal practice is to pivot the shoe so that the inclination of the fixed member is changed automatically to suit the load conditions. Moreover, the difficulty in manufacturing a very thin fluid film in the plane slider bearing is also overcome.

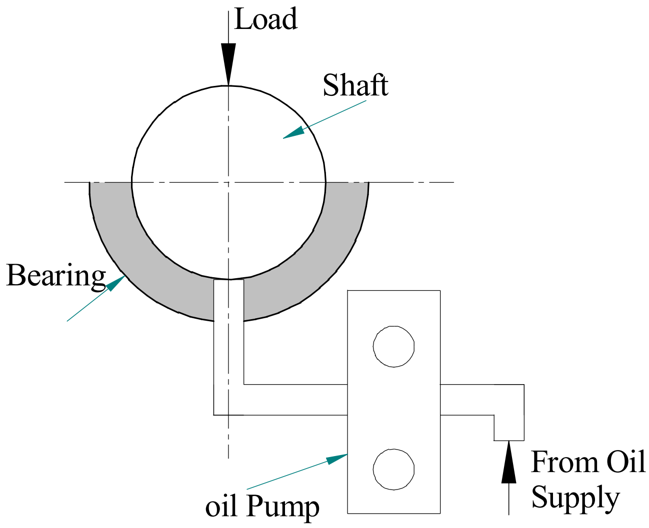
An idealized plane slider bearing consists of two non parallel plane surfaces separated by an oil film. One surface is stationary while the other one is moving with a uniform velocity (U) and inclinations are such that a converging oil film is formed between the surfaces. The positive pressure built up in the oil film supports a load. Further the letter (L) represents the length of the bearing and (B) is the width of the bearing.

Hydrostatic Lubrication

Hydrostatic lubrication is defined as a system of lubrication in which the load supporting fluid film, separating the two surfaces, is created by an external source, like a pump, supplying sufficient fluid under pressure. Since the lubricant is supplied under pressure, this type of bearing is called *externally pressurized bearing*. Hydrostatic bearings are used on vertical turbo-generators, centrifuges and ball mills.

Hydrostatic lubrication is essentially a form of lubrication in which the metal surfaces are separated by a complete film of oil, but instead of being self-generated, the separating pressure is supplied by an external oil pump. Hydrostatic lubrication depends on the inlet pressure of lubrication oil and clearance between the metal surfaces, whereas in hydrodynamic lubrication it depends on the relative speed between the surfaces, oil viscosity, load on the surfaces, and clearance between the moving surfaces.

Example: the cross head pin bearing or gudgeon pin bearing in two stroke engines employs this hydrostatic lubrication mechanism. In the cross head bearing, the load is very high and the motion is not continuous as the bearing oscillation is fairly short. Thus hydrodynamic lubrication cannot be achieved. Under such conditions, hydrostatic lubrication offers the advantage. The oil is supplied under pressure at the bottom of bearing. The lube oil pump pressure is related to the load, bearing clearance, and thickness of the oil film required, but is usually in the order of $35 - 140\ kg/cm^2$.



Principle

When sufficient pressure is not created in the oil film hydro-dynamically to support a load, oil under pressure is supplied from an external source. Bearing operating under this principle are called *externally pressurized or hydrostatic bearings*.

In hydrostatic lubrication the bearing surfaces are separated by a lubricating film of liquid or gas forced between the surfaces by an external pressure. The pressure is generated by an external pump instead of by viscous drag as is the case with hydrodynamic lubrication. As long as a continuous supply of pressurized lubricant is maintained, a complete film is present even at zero sliding speed. Hydrostatic films usually have a considerable thickness reaching $100\ \mu m$ and therefore, prevent contact between the asperities of even the roughest surfaces. This ensures a complete absence of sticking friction. The friction generated by viscous shear of the lubricant decreases to zero at zero sliding speed. Hydrostatic bearings can support very large masses and allow them to be moved from their stationary positions with the use of minimal force. In hydrostatic bearing analysis, load and flow are frequently expressed for simplicity in terms of non-dimensional parameters. Examples of this treatment are presented for flat circular pads and flat square pads.

Difference between Hydrodynamic and Hydrostatic Journal.

Sl No	*Hydrodynamic Journal*	*Hydrostatic Journal*
1	Fluid pressure is created by the relative motion between the moving parts.	Pressurized supply of fluid is provided to maintain the fluid lubricant film between the journal and the bearing, where it would otherwise be squeezed out.
2	Cost is less.	Cost is high
3	The speed is high.	Speed is low
4	Load carrying capacity is less.	Load carrying capacity is High.
5	Design of bearing house is less complicated.	Design of bearing house is more complicated.
6	It cannot be used as air bearings.	It can be used as air bearing.

Principle:

When sufficient pressure is not created in the oil film hydrodynamically to support a load, oil under pressure is supplied from an external source. Bearing operating under this principle are called Externally pressurized or Hydrostatic Bearings.

Advantages and Disadvantages:

Advantages:

Very low frictional characteristics

Supports heavy loads at low speeds

High positional accuracy

Disadvantages:

Auxiliary equipments such as pump, flow meters, etc are required.

Overall power requirement is high.

Applications:

Due to low friction characteristics, they are used in gyroscopes and other precision instruments.

Since they can take high loads at low speed they are used in telescopes.

Due to high positional accuracy, they are used in machine took

Systems of Hydrostatic Lubrication:

There are two-main systems of hydrostatic lubrication,

Lubrication at constant supply pressure

Lubrication at constant flow rates.

Constant supply pressure

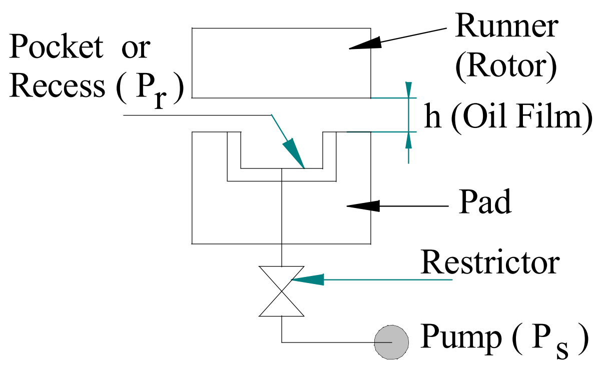


Fig: Constant supply pressure hydrostatic Bearing

Above fig shows a simple hydrostatic thrust bearing. The bearing consists of a pad & a runner. Pad is stationary & runner is rotating. The pad has a central recess or pocket surrounded by land or sill.

The lubricant is supplied at constant pressure through a restrictor when the machine is to be operated. The pump which supplies the lubricant under pressure is started. The flow of lubricant takes place through the restrictor & hence supply pressure drops to pocket pressure and equilibrium position is attained. When the flow builds up the necessary pressure to balance the load.

In this case if there is an increase in the load, flow reduces due to decrease in bearing clearance (h). Pocket pressure increases to restore equilibrium. If load decreases, pocket pressure decreases & clearance increases.

Constant Flow system:

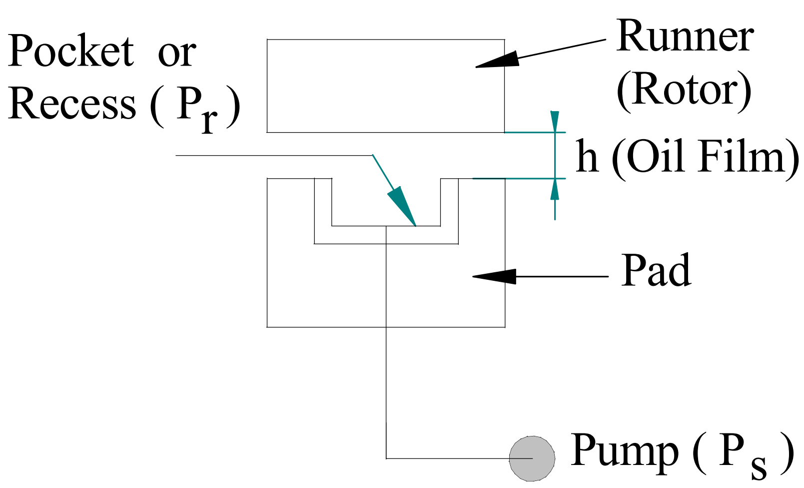


Fig: Constant Flow System

In this system there is no restrictor & hence supply pressure & pocket pressure are same. If load increases, clearance decreases & hence flow decreases. To maintain a constant (h) for balancing the load, supply pressure is increased to keep flow constant. Flow is held constant by using pressure compensated valve.

Load Carrying capacity for Hydrostatic bearing:

Assumptions:

1. Flow is considered to be laminar

Pocket is deep enough for the pressure in it to be uniform.

Bearing has low frictional characteristics and hence viscous drag can be neglected.

Step 1: Discharge:

$$Q = \int_0^h dQ = \int_0^h u\, da$$

Discharge, $Q = \int_0^h u\, da$

$$\underset{Pressure\ induced\ flow}{\overset{u=\frac{1}{2\eta}\frac{dp}{dx}(y^2-hy)}{\Longleftrightarrow}} \quad + \quad \underset{Viscous\ drag}{\overset{U\left(\frac{h-y}{h}\right)}{\Longleftrightarrow}}$$

$$u = \frac{1}{2\eta}\frac{dp}{dx}(y^2 - hy)$$

$$da = 2\pi r\, dy$$

$$Q = \int_0^h \frac{1}{2\eta}\frac{dp}{dx}(y^2 - hy) \times 2\pi r\, dy$$

$$Q = \frac{2\pi r}{2\eta}\frac{dp}{dx}\left[\int_0^h y^2\, dy - \int_0^h y\, dy\right]$$

$$Q = \frac{\pi r}{\eta}\frac{dp}{dx}\left[\frac{h^3}{3} - \frac{h^3}{2}\right]$$

$$Q = -\frac{\pi r}{\eta}\frac{dp}{dx}\frac{h^3}{6}$$

$$Q = -\frac{\pi r h^3}{6\eta}\frac{dp}{dx}$$

Step 2: Pressure Distribution:

$$dp = -\frac{Q\, 6\eta}{\pi r h^3}dx$$

Since co – ordinate system is cylindrical

$$dp = -\frac{6\,Q\,\eta}{\pi\, r h^3}\,dr$$

$$p = -\frac{6\,Q\,\eta}{\pi\, h^3}\int \frac{dr}{r}$$

$$p = -\frac{6\,Q\,\eta}{\pi\, h^3}\ln r + C \qquad \ldots\ldots \boldsymbol{Equ\ (i)}$$

This equation for general pressure distribution. For finding value of 'C' apply the boundary conditions.

Step 3: Boundary condition

$(i)\ At\ \ r = r_2, \qquad p = 0$

$(ii)\ At\ \ r = r_1, \qquad p = p_0$

$(i)\ At\ \ r = r_2, \qquad p = 0$

$$0 = -\frac{6\,Q\,\eta}{\pi\, h^3}\ln r_2 + C$$

$$C = \frac{6\,Q\,\eta}{\pi\, h^3}\ln r_2$$

$$p = -\frac{6\,Q\,\eta}{\pi\, h^3}\ln r + \frac{6\,Q\,\eta}{\pi\, h^3}\ln r_2$$

$$p = \frac{6\,Q\,\eta}{\pi\, h^3}(\ln r_2 - \ln r)$$

$$p = \frac{6\,Q\,\eta}{\pi\, h^3}\, ln\left(\frac{r_2}{r}\right) \qquad \ldots\ldots \boldsymbol{Equ\ (ii)}$$

$(ii)\ At\ \ r = r_1, \qquad p = p_0$

$$p = \frac{6\,Q\,\eta}{\pi\, h^3}\ ln\left(\frac{r_2}{r_1}\right)$$

$$Q = \frac{\pi\, p_0\ h^3}{6\,\eta\ ln\left(\frac{r_2}{r_1}\right)}$$

$$Q = \frac{p_0\,\pi\, h^3}{6\,\eta\ ln\left(\frac{d_2}{d_1}\right)} \qquad \boldsymbol{(E-24.144)(P-23.67)}$$

Substituting for Q in equation (ii)

$$p = \frac{6\ \eta}{\pi\, h^3}\, ln\left(\frac{r_2}{r}\right) \times \frac{p_0\,\pi\, h^3}{6\,\eta\ ln\left(\frac{r_2}{r_1}\right)}$$

$$p = p_0 \frac{ln\left(\frac{r_2}{r}\right)}{ln\left(\frac{r_2}{r_1}\right)} \qquad \ldots\ldots \boldsymbol{Equ\ (iii)}$$

Step 4: Load carrying capacity:

$$W = p_0 \pi r_1^2 + \int p\, dA$$

$$W = p_0 \pi r_1^2 + \int_{r_1}^{r_2} p \times 2\pi r\, dr$$

$$W = p_0 \pi r_1^2 + 2\pi \int_{r_1}^{r_2} p_0 \frac{ln\left(\frac{r_2}{r}\right)}{ln\left(\frac{r_2}{r_1}\right)}\ r\, dr$$

$$W = p_0 \pi r_1^2 + \frac{2\pi p_0}{ln\left(\frac{r_2}{r_1}\right)} \int_{r_1}^{r_2} ln\left(\frac{r_2}{r}\right)\ r\, dr$$

$$W = p_0 \pi r_1^2 + \frac{2\pi p_0}{ln\left(\frac{r_2}{r_1}\right)} \int_{r_1}^{r_2} [ln\, r_2 - ln\ r]\ r\, dr$$

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$$W = p_0 \pi r_1^2 - p_0 \pi r_1^2 + \frac{\pi\, p_0 (r_2^2 - r_1^2)}{2\, ln\left(\frac{r_2}{r_1}\right)}$$

$$W = \frac{\pi\, p_0 (r_2^2 - r_1^2)}{2\, ln\left(\frac{r_2}{r_1}\right)}$$

$$p_0 = \frac{2\, W\, ln\left(\frac{r_2}{r_1}\right)}{\pi\, (r_2^2 - r_1^2)}$$

$$p_0 = \frac{2\, W\, ln\left(\frac{d_2/2}{d_1/2}\right)}{\pi\left(d_2^2/4 - d_1^2/4\right)}$$

$$p_0 = \frac{8\, W\, ln\left(\frac{d_2}{d_1}\right)}{\pi\left(d_2^2 - d_1^2\right)} \qquad \boldsymbol{(E - 24.142\ a)(P - 24.67)}$$

$$W = \frac{\pi\, p_0 \left({d_2}^2/_4 - {d_1}^2/_4 \right)}{2\, ln \left(\dfrac{d_2/_2}{d_1/_2} \right)}$$

$$W = \frac{\pi\, p_0 \left({d_2}^2 - {d_1}^2 \right)}{8\, ln \left(\frac{d_2}{d_1} \right)} \qquad (\boldsymbol{E-24.143})(\boldsymbol{P-24.67})$$

Step 5: Power loss due to friction:

Power, $P_\mu = \frac{2\,\pi\, n\, T}{60000} \quad kW$

Torque, $T = \int_{r_1}^{r_2} \delta\, T$

$$\delta\, T = \delta\, F\ \times r$$

Shear force, $\delta\, F = \tau\ \times dA$

Shear stress, $\tau = \eta\, \frac{U}{h}$

$$U = r\, \omega$$

$$\omega = \frac{2\,\pi\, n}{60}$$

Area, $dA = 2\,\pi\, r\, dr$

$$\delta\, F = \tau\ \times dA = \eta\, \frac{U}{h} \times\ 2\,\pi\, r\, dr$$

$$\delta\, F = \eta\, \frac{r\, \omega}{h} \times\ 2\,\pi\, r\, dr = \eta\, \frac{\omega}{h} \times\ 2\,\pi\, r^2\, dr$$

$$\delta\, T = \delta\, F\ \times r = \eta\, \frac{\omega}{h} \times\ 2\,\pi\, r^2\, dr\ \times r$$

$$\delta\, T = \eta\, \frac{\omega}{h} \times\ 2\,\pi\, r^3\, dr$$

$$T = \int_{r_1}^{r_2} \delta\, T = \int_{r_1}^{r_2} \eta\, \frac{\omega}{h}\, 2\,\pi\, r^3\, dr$$

$$T = \eta\, \frac{\omega}{h}\, 2\,\pi \int_{r_1}^{r_2} r^3\, dr$$

$$T = \eta\, \frac{\omega}{h}\, \frac{2\,\pi}{4} \left[r^4 \right]_{r_1}^{r_2}$$

$$T = \eta\, \frac{\pi\, \omega}{2h} \left[{r_2}^4 - {r_1}^4 \right]$$

$$P_\mu = \left[\frac{2\,\pi\,n}{60000}\right] \times \left[\eta\ \frac{\pi}{2h} \times \left[2\,\pi\left(\frac{n}{60}\right)\right][r_2{}^4 - r_1{}^4]\right]$$

$$P_\mu = \frac{2\,\pi^3}{1000}(n') \times (n') \times \frac{\eta}{h}[r_2{}^4 - r_1{}^4]$$

$$P_\mu = 0.062\ \frac{\eta(n')^2}{h}\left[\left(\frac{d_2}{4}\right)^4 - \left(\frac{d_1}{4}\right)^4\right]$$

$$P_\mu = 0.062\ \frac{\eta(n')^2}{16\,h}\left[d_2{}^4 - d_1{}^4\right] \quad (\boldsymbol{E - 23.145\,a})(\boldsymbol{P - 23.67})$$

Module 5: Bearing Materials: Commonly used bearings materials, and properties of typical bearing materials. Advantages and disadvantages of bearing materials.

Introduction to Surface engineering: Concept and scope of surface engineering. Surface modification – transformation hardening, surface melting, thermo chemical processes. Surface Coating – plating, fusion processes, vapour phase processes. Selection of coating for wear and corrosion resistance. **8 hours**

1. Explain important desirable properties (characteristics) ofbearing material. **(Dec.19/Jan.20) (June/July 2018) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2014/Jan.2015) (June/July 2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (10Marks)**
2. List the commonly used bearing materials and give the advantages and disadvantages of bearing materials. **(May /June 2017) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2014/Jan.2015) (June / July 2013) (10 Marks)**
3. List the commonly used bearing materials. Explain any five of them with respect to their typical properties and advantages. **(Dec.19/Jan.20)(June/July 2015) (June/July 2014) (10 Marks)**
4. Briefly discus behaviour of tribological components. **(June 2012) (10 Marks)**
5. Explain with graphs the influence of speed, temperature and pressure on wear. **(June/July 2015)(10 Marks)**
6. List out traditional coating techniques? Explain any two. **(Dec.19/Jan.20)**
7. What is surface engineering? Write a brief history of surface engineering? **(Dec.19/Jan.20)**
8. **Write short notes on the following:**
   i. Wear ofceramic materials
   ii. wear of Polymers
   iii. Surface engineering.
   iv. Improved design of a tribological component..
   v. Advanced material's use in tribology application.
   vi. Tribological measures
   vii. Wear measurements
   viii. Effect of speed, temperature and pressure on wear
   ix. Material selection.
   x. Seals and packing. **(June/July 2018) (June/July 2017) (June/July 2016) (Dec.2015/Jan.2016) (June/July 2015) (Dec.2014/Jan.2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (June/July 2011) (May/ June 2010)**

Bearing materials and Surface engineering:

Bearing materials:

*** **Explain important desirable properties of bearing material.** (June/July 2018) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2014/Jan.2015) (June/July 2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (10 Marks)

Properties of Bearing Materials.

The most important characteristic of bearing materials are as follows.

Compatibility

Conformability & Embedability

Compressive strength

Fatigue strength

Corrosion Resistance

Availability

Cost

Machinability

Thermal conductivity

Co-efficient of expansion

Modulus of Elasticity

Compatibility: Some bearing materials have a tendency to weld to the shaft when there is direct contact between the journal and bearing surfaces. In some materials this tendency is more in some materials it is less. The measure of anti-welding (anti-scoring) property of a bearing material, when operating with a given journal material is called compatibility.

Conformability: The ability of a bearing material to yield to deformation under operation is referred to as conformability. This characteristic is very important if deflection of the bearing or shaft takes place.

Embedability is the ability of a bearing material to absorb foreign particles to avoid scoring and wear. This property is important when there is possibility of dirt or any foreign particles getting into the lubricant. Alloys having a good conformability and Embedability have relatively low hardness, low fatigue strength, and low modulus of elasticity.

Compressive Strength: The ability of bearing material to resist pressure without plastic deformation or disintegration is called compressive strength. The compressive strength of the bearing material should increase proportionately with load per unit area of the bearing.

Fatigue Strength: The fatigue strength of a bearing alloy is a function of the range and number of stress cycles to which it is subjected. This characteristic is important when the load applied on the bearing fluctuates or sometimes changes direction.

Corrosion Resistance: Under the influence of time and temperature. Lubricating oil tends to form organic acids and peroxide. This tendency is strong especially on the piston and cylinder walls of an internal combustion engine. The oxidation of mineral oil accelerates with increase of temperature. These acids and peroxides cause corrosion of some metals. Due to this insoluble organic soaps are deposited in the system.

Bearings are subjected to greater corrosion when the volume of the oil circulating through the bearing is small compared to its surface area. Materials containing lead, cadmium, zinc, copper and silver are the ones mostly subjected to corrosion.

Relative Hardness of Bearing Material:

The bearing material should usually be softer than that of the journal to prevent shaft wear but hard enough to resist adhesive and abrasive wear of its own surface.

Bearings are more easy to replace than shafts (that require dismantling of the whole engine). If one bearing is worn out only that bearing needs replacement instead of the whole shaft.

Availability of Material:

The material should be readily and sufficiently available, not only for initial installation but also to facilitate replacement in the event of bearing failure.

Cost of Material:

The economic consideration is the ultimate deciding factor in for selecting a bearing material

****** List the commonly used bearing materials and give the advantages and disadvantages of bearing materials.**

(May /June 2017) (June / July 2017) (Dec.2015/Jan.2016) (Dec.2014/Jan.2015) (June / July 2013) (10 Marks)

****** List the commonly used bearing materials. Explain any five of them with respect to their typical properties and advantages.**

(June/July 2015) (June/July 2014) (10 Marks)

Common Bearing Alloys:

White Metals: Generally bearing alloys of tin, lead, antimony and copper are referred to as Babbitt or white metals.

There are two general classes of Babbitt's tin-base and lead-base alloy. The tin-base alloys have more or less the same structure as the original Babbitt. The lead-base Babbitt consists of a matrix of pure lead containing compounds of tin and antimony.

These alloys are considered to be among the best bearing materials due to their low hardness; Tin & lead based Babbitt's also have excel no scoring characteristics and are outstanding in their conformability and ability to embed dirt. These characteristics make Babbitt's the most popular alloys as bearing material. The main disadvantage of Babbitt's is their relatively low load-carrying capacity due to their relatively low compressive and fatigue strength. Also, their strength and fatigue resistance decrease rapidly with an increase of temperature.

Alkali-hardened Lead: When small amounts of calcium, tin, and mercury are added to lead, the hardness of lead increases considerably making it as hard as or even harder than Babbitt. Such an alloy is called alkali-hardened lead. It has a melting point somewhat higher than Babbitt and can be used for bearings operating at much higher temperature than Babbitt bearings. The mechanical characteristics of this alloy are similar to that of Babbitt.

Cadmium -Base Alloys: The alloys of cadmium are called Cadmium-base alloys. They have good conformability and Embedability.

The relatively low corrosion resistance and high cost of these alloys are their main disadvantages. By plating a thin layer of indium on the bearing surface and diffusing it into the alloy, the corrosion resistance of these alloys can he increased.

Copper - Lead Alloys: These are made of a mixture of copper and lead. The hardness of these alloys is considerably higher than that of Babbitt's. The fatigue strength of this alloy is also considerably higher than that of Babbitt's. Due to this, the copper-lead alloy is suitable for heavy-duty applications where the operating temperature and load carrying capacity are higher than for Babbitt's.

Bronzes: Bronzes are widely used as bearing material for certain aircraft bearings, railway bearing's and in other machinery, and for cast bushings.

This type of bearing alloy is limited to applications where alignment is good and both the shaft and the frame supporting the bearing are rigid due to their relatively poor conformability.

Aluminum Alloys: Their high load-carrying capacity is one of the most important characteristics of these alloys. Because of this characteristic they have found application in rolling mills machinery, heavy diesel engines, and other machines where high load-carrying capacity is a primary requirement.

The disadvantages of these alloys are their relatively low compatibility and high coefficient of expansion. The maximum temperature at which the aluminum alloy bearing can be used should not exceed 150^0C.

Silver: Silver bearings with lead-indium overlay have found extensive use in highly loaded aircraft-engine bearings and in various other heavy-duty applications. Their resistance to fatigue under is the highest among. Other common bearing materials and the compressive strength is also very high. Therefore, the load-carrying capacity of these bearings is high.

Sintered Metals: Sintered bearings are used mostly as bushings. The method of producing these metals is as follows: two fine metal powders are mixed together and pressed in dies: after compression. They are sintered by heating at a high temperature. The temperature used for this process is between the melting points of the two metals. Sintered bearings can be mass-produced. Which makes their cost relatively low.

Bearings are submerged in oil for impregnation before use. A bearing of this kind is self-lubricating, supplying oil through the interconnected pores and providing an oil film on the bearing surface. When the shaft stops rotating, the bearing cools off and the oil is reabsorbed into the bearing metal by capillary action.

Cast Iron: Cast iron is still in use due to its low cost. Cast iron is used as a material for self-aligning. Low-loaded transmission bearings. Because of the poor conformability of cast iron. The application of this material is restricted to installations in which shaft deflections are minimum.

Plastics:

Celoron, Formica and Micarta bearings are made from a special woven duck impregnated with phenolic resin. The materials are fused together under a very high pressure and at a high temperature. These materials have good mechanical properties and great resilience. Such bearings can be lubricated with oil, grease or water, they are used on heavy rolling mills as a replacement for bearings of bronze or lignum vitae without any changes in the roll stand itself. With water lubrication they can stand pressures up to 5,000 psi and peripheral velocities of 2,000 feet per minute (fpm), with a friction coefficient (u) less than 0.007.

Rubber:

In hydraulics turbines, in stem bearings of ships and in other machines where water is available, rubber bearings lubricated with water are commonly used. Rubber bearings are particularly suitable for use on shafts running at high speeds.

Oil-Less Bearings:

Oil-less bearing depends on a lubricant incorporated in the bearing during its manufacture. This is done in several ways:

In some types, flaked graphite is inserted into the metallic (usually bronze) surface in the shape of spirals or studs.

Another development consists in suspending graphite in a Babbitt alloy under high pressure at the fusing temperature of Babbitt.

In other types, oil is impregnated into wood or some other porus or fibrous carrier.

Self Lubricating Bearings

In powder-metal bearings, pulverized graphite and bearing bronze or iron are mixed with a binder and are pressed into molds with the application of heat. This process is called sintering. A sintered bearing is porus. It can absorb an amount of lubricating oil up to 30 percent of its own weight and can give the soil up very slowly in operation. Sintered bearings maintain a thin oil film for a long time and are correctly called self-lubricating bearings.

Advantages of Self-Lubricating Bearing

No need of additional oil feeding device;

Reduce operating cost of bearing;

Reduce equipment halt maintenance;

Simplify design and physical structure;

No need of waste oil treatment, in favor of environmental protection.

Introduction to Surface Engineering

Surface engineering is the sub-discipline of materials science which deals with the surface of solid matter. It has applications to chemistry, mechanical engineering, and electrical engineering (particularly in relation to semiconductor manufacturing).

The surface phase of a solid interacts with the surrounding environment. This interaction can degrade the surface phase over time. Environmental degradation of the surface phase over time can be caused by wear, corrosion, fatigue and creep.

Surface engineering involves altering the properties of the Surface Phase in order to reduce the degradation over time. This is accomplished by making the surface robust to the environment in which it will be used. It provides a cost effective material for robust design. A spectrum of topics that represent the diverse nature of the field of surface engineering includes Plating technologies, Nano and emerging technologies and Surface engineering, characterization and testing.

Concept and Scope of Surface Engineering

Surface engineering techniques are being used in the automotive, aerospace, missile, power, electronic, biomedical, textile, petroleum, petrochemical, chemical, steel, cement, machine tools and construction industries including road surfacing. Surface engineering techniques can be used to develop a wide range of functional properties, including physical, chemical, electrical, electronic, magnetic, mechanical, wear-resistant and corrosion-resistant properties at the required substrate surfaces. Almost all types of materials, including metals, ceramics, polymers, and composites can be coated on similar or dissimilar materials. It is also possible to form coatings of newer materials (e.g., met glass. beta-C3N4), graded deposits, multi-component deposits etc.

In recent years, there has been a paradigm shift in surface engineering from age-old electroplating to processes such as vapor phase deposition, diffusion, thermal spray & welding using advanced heat sources like plasma, laser, ion, electron, microwave, solar beams, pulsed arc, pulsed combustion, spark, friction and induction.

Surface Engineering helps in systematic and comprehensive understanding of various aspects related with surface engineering of metallic components for enhanced tribological life. It is proposed to include fundamental mechanisms of wear such as adhesive, abrasive, erosive, cavitations, corrosion etc., governing laws, materials properties importance for improved wear resistance under different wear conditions, materials increased tribological life, processes for engineering surfaces of three board categories

Regulating the micros-structure without changing chemical composition

Modification of chemical composition of near surface layers and

Developing of films, coating, and cladding on the.

Methods of characterization needed for evaluating the metallurgical and mechanical and tribological properties and performance of engineered surfaces shall also be presented. Presentations will be supported with case studies for effective communication of concepts and procedures. Case studies will be taken up regarding surface engineering of various metal systems like ferrous and non-ferrous metals using different approaches discussed.

Surface modification

Surface modification is the act of modifying the surface of a material by bringing physical, chemical or biological characteristics different from the ones originally found on the surface of a material. This modification is usually made to solid materials, but it is possible to find examples of the modification to the surface of specific liquids. The modification can be done by different methods with a view to altering a wide range of characteristics of the surface, such as: roughness.

Surface Hardening

Case-hardening or surface hardening is the process of hardening the surface of a metal object while allowing the metal deeper underneath to remain soft, thus forming a thin layer of harder metal (called the "case") at the surface. For iron or steel with low carbon content, which has poor to no hardenability of its own, the case-hardening process involves infusing additional carbon or nitrogen into the surface layer. Case-hardening is usually done after the part has been formed into its final shape, but can also be done to increase the hardening element content of bars to be used in a pattern welding or similar process. The term face hardening is also used to describe this technique, when discussing modern armour.

Because hardened metal is usually more brittle than softer metal, through-hardening (that is, hardening the metal uniformly throughout the piece) is not always a suitable choice for uses where the metal part is subject to sliding contact with hard or abrasive materials. In such circumstances, case-hardening can provide a part that will not fracture (because of the soft core that can absorb stresses without cracking) but also provides adequate wear resistance on the surface.

Flame or induction hardening

Flame or induction hardening are processes in which the surface of the steel is heated very rapidly to high temperatures (by direct application of an oxy-gas flame, or by induction heating) then cooled rapidly, generally using water; this creates a "case" of martensite on the surface. A carbon content of 0.3-0.6 wt. % C is needed for this type of hardening. The outcome of flame or induction hardening depends on duration of heating, Target temperature to be reached, Composition of the metal being treated.

Typical uses of Flame hardening are for the shackle of a lock, where the outer layer is hardened to be file resistant, and mechanical gears, where hard gear mesh surfaces are needed to maintain a long service life while toughness is required to maintain durability and resistance to catastrophic failure. Flame hardening uses direct impingement of an oxy-gas flame onto a defined surface area.

CARBURIZING

Carburizing is a process used to case-harden steel with a carbon content between 0.1 and 0.3 wt.% C. In this process steel is introduced to a carbon rich environment and elevated temperatures for a certain amount of time, and then quenched so that the carbon is locked in the structure; one of the simpler procedures is repeatedly to heat a part with an acetylene torch set with a fuel-rich flame and quench it in a carbon-rich fluid such as oil. Carburization is a diffusion-controlled process, so the longer the steel is held in the carbon-rich environment the greater the carbon penetration will be and the higher the carbon content. The carburized section will have a carbon content high enough that it can be hardened again through flame or induction hardening. It is possible to carburize only a portion of a part, either by protecting the rest by a process such as copper plating, or by applying a carburizing medium to only a section of the part. The carbon can come from a solid, liquid or gaseous source; if it comes from a solid source the process is called pack carburizing. Packing low carbon steel parts with a carbonaceous material and heating for some time diffuses carbon into the outer layers. A heating period of a few hours might form a high-carbon layer about one millimeter thick. Liquid carburizing involves placing parts in a bath of a molten carbon-containing material, often a metal cyanide; gas carburizing involves placing the parts in a furnace maintained with a methane-rich interior.

Nitriding

Nitriding heats the steel part to 482-621 °C (900-1,150 °F) in an atmosphere of ammonia gas and dissociated ammonia. The time the part spends in this environment dictates the depth of the case. The hardness is achieved by the formation of nitrides. Nitride forming elements must be present for this method to work; these elements include chromium, molybdenum, and aluminum. The advantage of this process is that it causes little distortion, so the part can be case-hardened after being quenched, tempered and machined. No quenching is done after nitriding.

Cyaniding

Cyaniding is a case-hardening process that is fast and efficient; it is mainly used on low-carbon steels. The part is heated to 871-954 °C (1600-1750 °F) in a bath of sodium cyanide and then is quenched and rinsed, in water or oil, to remove any residual cyanide.

$$2NaCN + O_2 \Rightarrow 2NaCNO$$

$$2NaCNO + o_2 \Rightarrow Na_2CO_3 + CO + N_2$$

$$2CO \Rightarrow CO_2 + C$$

This process produces a thin, hard shell (between 0.25 - 0.75 mm, 0.01 and 0.03 inches) that is harder than the one produced by carburizing, and can be completed in 20 to 30 minutes compared to several hours so the parts have less opportunity to become distorted. It is typically used on small parts such as bolts, nuts, screws and small gears. The major drawback of cyaniding is that cyanide salts are poisonous.

Carbonitriding

Carbonitriding is similar to cyaniding except a gaseous atmosphere of ammonia and hydrocarbons is used instead of sodium cyanide. If the part is to be quenched, it is heated to 775-885 °C (1,427-1,625 °F); if not, then the part is heated to 649-788 °C (1,200-1,450 °F).

Ferritic nitrocarburizing

Ferritic nitro-carburizing diffuses mostly nitrogen and some carbon into the case of a workpiece below the critical temperature, approximately 650 °C (1,202 °F). Under the critical temperature the workpiece's microstructure does not convert to an austenitic phase, but stays in the ferritic phase, which is why it is called ferritic nitro-carburization.

Applications

Parts that are subject to high pressures and sharp impacts are still commonly case-hardened. Examples include firing pins and rifle bolt faces, or engine camshafts. In these cases, the surfaces requiring the hardness may be hardened selectively, leaving the bulk of the part in its original tough state. Firearms were a common item case-hardened in the past, as they required precision machining best done on low carbon alloys, yet needed the hardness and wear resistance of a higher carbon alloy. Many modern replicas of older firearms, particularly single action revolvers, are still made with case-hardened frames, or with *case coloring,* which simulates the mottled pattern left by traditional charcoal and bone case-hardening. Another common application of case-hardening is on screws, particularly self-drilling screws. In order for the screws to be able to drill, cut and tap into other materials like steel, the drill point and the forming threads must be harder than the material (s) that it is drilling into. However, if the whole screw is uniformly hard, it will become very brittle and it will break easily. This is overcome by ensuring that only the case is hardened and the core remains relatively soft. For screws and fasteners, case-hardening is achieved by a simple heat treatment consisting of heating and then quenching.

For theft prevention, lock shackles and chains are often case-hardened to resist cutting, whilst remaining less brittle inside to resist impact. As case-hardened components are difficult to machine, they are generally shaped before hardening.

Surface Melting

Pre-melting (also surface melting) refers to a quasi-liquid film than can occur on the surface of a solid even below melting point. The thickness of the film is temperature dependent. This effect is common for all crystalline materials. Pre-melting shows its effects in frost heave, the growth of snowflakes and, taking grain boundary interfaces into account, maybe even in the movement of glaciers.

Considering a solid-vapour interface, complete and incomplete pre-melting can be distinguished. During a temperature rise from below to above, in the case of complete pre - melting, the solid melts homogeneously from the outside to the inside; in the case of incomplete pre-melting, the liquid film stays very thin during the beginning of the melting process, but droplets start to form on the interface. In either case, the solid always melts from the outside inwards, never from the inside.

Techniques of Surface Treatments

Surface treatment Methods

A simplified classification of various groupings of non-mechanical surface treatments could be reduced as 1. Thermal treatments 2.Thermo-chemical treatment 3.Plating and coating 4. Implantation

The effectiveness depends on particular surface and modification technique.

PVD process

CVD process

Electoless Nickel

Composite

Thermal spraying

Surface welding

Ion Implantation

Anodising

Boronizing

Nitriding

Car-bonitriding

Carburizing

Nitrocarburising

Surface alloying

Thermal hardening.

Numerous processes are used for surface treatments, based on mechanical, chemical, thermal and physical. Their principles and characteristics are obtained as follows: There are two categories of vapor deposition processes: physical vapor deposition (PVD) and chemical vapor deposition (CVD). In PVD processes, the work piece is subjected to plasma bombardment. In CVD processes, thermal energy heats the gases in the coating chamber and drives the deposition reaction.

Surface treatment (hardening)

Surface hardening: These are thermal and thermo chemical treatment and deposition done on the surfaces, by which surface properties are changed from those of the substrate. Such processes can be classified into following three basic categories.

Heat treatment process: in which no change 1s done in surface chemistry and difference in hardness is achieved only by heat treatment.

Mechanical working process: involving minor plastic flow .There is no change in surface chemistry but surface hardness is achieved by mechanical working.

Heat treatment with minor surface improvement in this process, there is minor change in surface chemistry to some shallow depth.

Briefly discus behaviour of tribological components.

(June 2012) (10 Marks)

*** **Write short notes on the following:**

Wear of ceramic materials

wear of Polymers

Surface engineering.

Improved design of a tribological component..

Advanced material's use in tribology application.

Tribological measures

Wear measurements

Effect of speed, temperature and pressure on wear

Material selection.

Seals and packing.

(June/July 2018) (June/July 2017) (June/July 2016) (Dec.2015/Jan.2016) (June/July 2015) (Dec.2014/Jan.2015) (June/July 2014) (Dec.2013 / Jan. 2014) (June / July 2013) (December 2012) (June 2012) (June/July 2011) (May/ June 2010)

Other Tribological Measures

To improve the tribological behavior of components, some of the ways to reduce friction in addition to improvements in lubricants, lubrication systems and principles are.

Improved design.

Improved material selection.

Surface engineering (treatment and modification).

Improved design:

Design includes material selection and surface treatment and improvement in design to reduce stress and strains and to improve tribological behaviours.

Sharp edges should be avoided as far as-possible at design stage itself as these are potential stress raisers. In order to have a reduced friction and fretting failure problems, the area of contact should be minimum. Generally, fretting scars appear at asperities at mating surfaces where intimate metal to metal contact is there. This is due to lack of flatness,-distortions due to cutting or forming, asperities in the form of burrs around the holes, dusts, broken paint barriers in painted components etc. and these may lead to fretting scars. These can be avoided by taking proper care at manufacture and assembly stage.

Following are few measures for protection against wear etc.

Using non-contact labyrinths and other seals.

Introducing friction between two components which are not supposed to slide against each other.

Improving fits and eliminating loose fitting by adopting suitable-tight-fit measures.

Preventing slip by eliminating vibration

Using spherical locating seats/surfaces rather than cylindrical.

Use of expansion joints/bellows to take up shock load and vibrations, etc,.

Reduce reversing or repetitive loads, as far as possible.

Permitting rolling friction in place of sliding.

Material selection: As a perfect material should have all the properties such as high strength, high toughness, good ductility, good fabricability, good wear and corrosion resistance and good resistance against high and low temperature and other environmental factors, material selection is a complex problem.

Generally following factors are considered for selection of material for engineering components.

Type of loading

Friction and wear resistance

Strength

Cost considerations

Size, shape and weight considerations.

Fabric-ability and formability

Life requirement.

Existing specifications. codes and standardization.

Feasibility of recycling or resale value

Selection is done in following two steps

Selection of basic material.

Selection of manufactured condition.

Selection of basic material: Large varieties of ferrous and non-ferrous materials are available for selection. Ferrous materials are used abundantly for their easy availability, easy formability, easy weld-ability and repair-ability, and overall low cost. However, due to its higher weight and lower resistance to corrosion, wear and fatigue etc,. Steel is now being gradually replaced by other metals such as aluminum and some low weight high strength bronzes etc. And non-metallic items.

Though aluminum is quite costly, as compared to price of steel for equivalent strength, considering its qualities, aluminum is becoming quite cost effective. It has growing uses in aeronautics, automobiles, packaging and canning industries and building industries.

Some materials gaining importance for use in tribological and other components are.

Fibre reinforced plastics (FRP)

Low weight, high strength anti-friction bronze

Sintered self lubricating materials

Cast nylon

Ultra high molecular weight polyethylene

Impregnated wood.

Selection of manufactured condition: Various products can be manufactured in a number of ways such as fabrication, casting and machining etc,. Each process has its own merits and demerits. Therefore selection is made depending on tribological and other needs.

Some of the points to be considered with respect to friction and wear are

Cast structures (cast iron or cast steel etc) are less susceptible to fretting and other wears than forged or fabricated structures. Cast structures are more wear resistant.

Cast structures are less prone to buckling and distortion in heat and are more corrosion resistant.

Annealed materials are less susceptible to fatigue; fretting wear and cracking etc, then work hardened material.

Materials with lower fatigue strength are less influenced by fretting. Low impact strength will have low fracture toughness which is susceptible to fretting failures.

***** **Surface engineering:** All the techniques, technologies and processes which are used to treat. Induce, modify and enhance the performance of surface of component in order to improve the tribological behavior of the component together form surface engineering.

Surface engineering consists of

Improving the performance of existing products

Creating new products by advanced coating and treatment process.

The techniques can be divided into two groups.

Surface treatment (hardening)

Surface modification (coating etc).

Surface modification (coating): This category includes techniques and processes for modifying the surface of the components by deposition, coating and other physical or chemical means to get a surface of improved tribological behavior.

**** **Few common techniques are**

Metal spraying

Electroplating

Conventional welding process

Friction surfacing

Laser assisted coating.

Ion implantation process

Electro less and electro pulse plating

Techniques of Surface Treatments

Surface treatment Methods

A simplified classification of various groupings of non-mechanical surface treatments could be reduced as

Thermal treatments

Thermo-chemical treatment

Plating and coating

Implantation

The effectiveness depends on particular surface and modification technique.

PVB process CVD process E1ectoless Nickel Composite

Thermal spraying Surface welding Ion Implantation Anodising

Boronizing Nitriding Carbonitriding Carburizing Nitrocarburising

Surface alloying Thermal hardening.

Numerous processes are used for surface treatments, based on mechanical, chemical, thermal and physical. Their principles and characteristics are obtained as follows: There are two categories of vapor deposition processes. Physical vapor deposition (PVD) and chemical vapor deposition (CVD). In PVD processes, the

Work piece is subjected to plasma bombardment. In CVD processes, thermal energy heats the gases in the coating chamber and drives the deposition reaction.

Physical Vapor Deposition (PVD)

In this process, the work piece or substrate is subjected to high temperature vacuum evaporation or plasma sputter bombardment to deposit thin films by the condensation of a vaporized form of the material onto substrate surfaces.

This process contains the three major techniques; evaporation, sputtering and ion plating. It produces a dense, hard coating. The primary PVD methods are Ion plating, Ion implantation, Sputtering and Laser surface alloying.

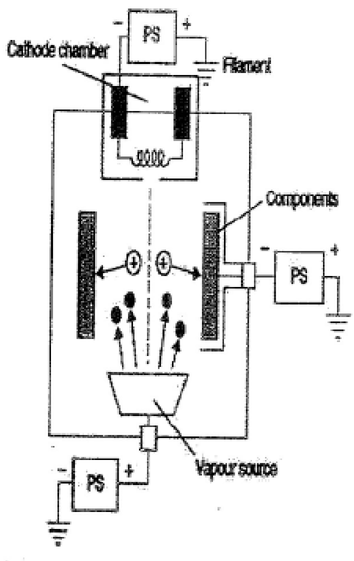


Fig.2.2. PVD process using Plasma evaporation

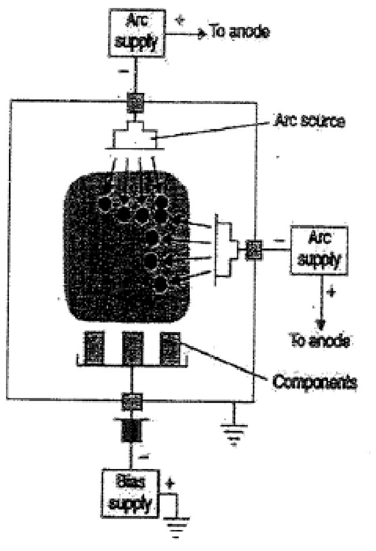
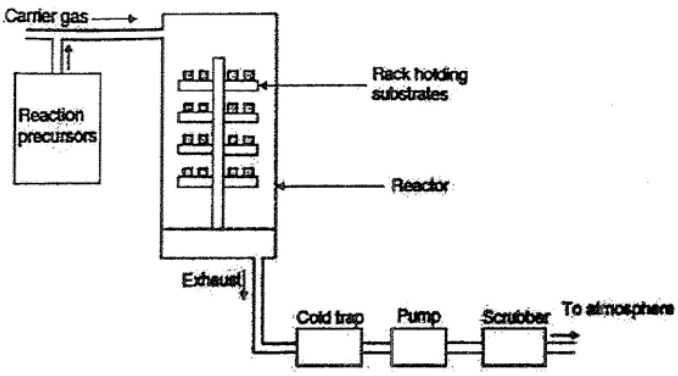


Fig.2.3. PVD process using arc sputtering

PVD is used in the manufacture of semiconductor wafers, aluminized PET film for snack bags and balloons, cutting tools for metalworking and generally used for extreme thin films like atomic layers and mostly for small substrates.

Chemical Vapor deposition (CVD)

In these processes, thermal energy heats the gases in the coating chamber and drives the deposition reaction and then this reactant gas mixture (mixture of gas precursors and coating material also known as a reactive vapour) impinges on the substrate. CVB processes can be used to deposit coating materials, form foils, powders, composite materials in the shape of spherical particles, filaments, and whiskers and also in structural applications, optical, chemical, photovoltaic and electronics. Start-up costs are typically very expensive. CVD includes sputtering, ion plating, plasma-enhanced CVB, low pressure CVD, laser-enhanced CVD, active-reactive evaporation, ion beam, laser beam evaporation, and many other variations. These variants are distinguished by the manner in which precursor gases are converted into the reactive gas mixtures.



Electroless nickel plating:

Electroless nickel (EN) plating is a chemical reduction process that depends upon the catalytic reduction process of nickel ions in solution containing a chemical reducing agent and water and the subsequent deposition of nickel metal without the use of electrical energy. Thus in the EN plating process, the driving force for the reduction of nickel metal ions and their deposition is supplied by a chemical reducing agent in solution. This driving potential is essentially constant at all points of the surface of the component, provided the agitation is sufficient to ensure a uniform concentration of metal ions and reducing agents. The electro less deposits are therefore very uniform in thickness all over the part's shape and size. The process is advantageous when plating complex shape devices, holes, recesses, internal surfaces, valves, threaded parts etc. Electroless (autocatalytic) nickel coating provides a hard, uniform, corrosion, abrasion, and wear-resistant surface to protect machine components in many industrial environments. EN is chemically deposited, making the coating exceptionally uniform in thickness. If carefully process is controlled good surface finish can be produced which eliminates costly machining after plating. In a hue electroless plating process, reduction of metal ions occurs only on the surface of a catalytic substrate in contact with the plating solution. Once the catalytic substrate is covered by the deposited metal, the plating continues because the deposited metal is also catalytic.

Ion Plating Process

In the Ion plating (IP) process, the target material is initially melted while the substrate is bombarded with ions before deposition to raise it to the required temperature. The coating flux ion is attracted to the substrate by biasing the substrate with a negative voltage. Thus sufficient ion energy is available for good inter mixing of coating and substrate at the interface Ion implantation is the introduction of ionized dopant atoms into a substrate with enough energy to penetrate beyond the surface. The most common application is substrate doping. The use of 3 to 500 keV energy for boron, phosphorus or arsenic dopant ions is sufficient to implant the ions from 100 to 10,000A below the silicon surface. The depth of implantation, which is proportional to the ion energy, can be selected to meet a particular application.

Implantation offers a clear advantage over chemical deposition techniques. The major advantage of ion implantation technology is the capability of precisely controlling the number of implanted dopant atoms. Furthermore, the dopants depth distribution profile can be well-controlled. Disadvantages of Ion Implantation are very deep and very shallow profiles are difficult, not all the damage can be corrected by annealing, typically has higher impurity content than does diffusion. Often uses extremely toxic gas sources such as arsine (AsH_3), and phosphine (PH_3) and expensive.

Anodizing

Anodizing involves the electrolytic oxidation of a surface to produce a tightly adherent oxide scale that is thicker than the naturally occurring film. Anodizing is an electro- chemical process during which aluminium is the anode.

The electric current passing through an electrolyte converts the metal surface to a durable aluminium oxide. The difference between plating and anodizing is that the oxide coating is integral with the metal substrate as opposed to being a metallic coating deposition. The oxidized surface is hard and abrasion resistant, and it provides some degree of corrosion resistance. Anodic coatings can be formed in chromic, sulphuric, phosphoric, or oxalic acid solutions. Chromic acid anodizing is widely used with 7000 series alloys to improve corrosion resistance and paint adhesion, and unseated coatings provide a good base for structural adhesives. However these coatings are often discolored and where cosmetic appearance is important, sulphuric acid anodizing may be preferred.

Boronising

Boronising is also called as boarding. It is a thermo-chemical treatment involving diffusion of boron into the surface of a component from the surrounding environment which results in the formation of a distinct compound layer of a metal boride.

The reaction takes place between boron and component, therefore it can be generally limited to steels, titanium-based alloys and cobalt based hard metals. In steels, boronising is carried out in the austenite regime (between 810-1020 °C) for several hours, resulting in the formation of layers commonly between 60 and 165 microns thick. The surface reaction layer thus formed consists of two separate phases, namely a layer of Fe2B adjacent to the substrate and an outer layer of FeB.

Cladding

It is the bonding together of dissimilar metals. It is distinct from welding or gluing as a method to fasten the metals together. Cladding is often achieved by extruding two metals through a die as well as pressing or rolling sheets together under high pressure.

It can be controlled to achieve alloying, cladding, grain refining or transformation hardening a metal surface without actually affecting the bulk of the metal itself. A laser beam can enhance surface properties to a controlled, confined extent depending on the power, dwell rime of the beam and the thermal characteristics, i.e., heating and cooling of the surface treated. Surface treatment prospects by lasers were observed with pulsed lasers at first. Being inertia less, it has high processing speeds with very rapid stop and start facility. A material of poor oxidation or corrosion or wear resistance but low cost can be modified with a surface alloy which can show improved resistance.

Other Surface Treatment Processes

Numerous processes are used for surface treatments, based on mechanical, chemical, thermal and physical. Their principles and characteristics are obtained as follows. Short Peening, Water-Jet Peening and Laser Peening.

In short peening the surface of the work piece is hit repeatedly with large number of cast-steel, glass or ceramic shot (size of 0.125 mm to 5 mm diameter), making overlap- ping indentation on the surface; this action causes plastic deformation of the surfaces. Thus improving the fatigue life of the component. Extensively used on shafts, gears, springs, oil-well drilling equipment, and jet engine parts. In water-jet peening, a water jet at pressure as high as 400 MPa impinges on the surface of the work piece, inducing compressive residual stresses. This have been successfully used on steels and aluminum alloys. In laser peening, the surface is subjected to laser shocks from high powered laser up to 1 KW and at energy levels of 100 J/pulse. This method has been used on jet engine fan blades with compressive residual stresses deeper than 1 mm.

Electroplating

The work-piece (cathode) is plated with a different metal (anode) while both are suspended in a bath containing a water-base electrolyte solution. The metal ions from the anode are discharged under the potential from the external source of electricity, combine with the ions in the solution, and are deposited on the cathode. All metals can be electroplated, with thickness ranging from a few atomic layers to a maximum of about 0.05 mm. Typical application include copper plating aluminum wire and phenolic boards for printed circuits, chrome plating hardware, tin plating copper electrical terminals for ease of soldering and plating various components for good appearance and resistance to wear and corrosion.

Electro forming

A variation of electroplating, electroforming is actually a metal fabrication process. Metal is electro deposited on a mandrel, which is then removed; thus, the coating itself becomes the product. Simple and complex shapes can be produced by electroforming, with wall thickness as small as 0.025 mm.

Conversion Coating

In this process, also called chemical-reaction priming, a coating forms on metal surfaces as a result of chemical or electro chemical reactions. Various metals, particularly steel, aluminum, and zinc, can be conversion coated. Oxides that naturally form on their surfaces are a form of conversion coating; phosphates, chromates, and oxalates are used to produce conversion coatings. These coatings are used for purposes such as pre-painting, decorative finishes, and protection against corrosion.

Organic coatings

Metal surfaces maybe coated or pre-coated with a variety organic coatings, films and laminates to improve appearance and corrosion resistance. Coatings are applies to the coil stock on continuous lines, with thickness generally of 0.0025 mm to 0.2 mm. Such coatings have a wide range of properties: flexibility, durability, hardness, resistance to abrasion and chemicals, color, texture and gloss. Application of organic coatings are coatings for naval aircraft that subjected to high humidity, rain, sea water, pollutants, aviation fluids, Deicing fluids and battery acids that are also impacted by particles such as dust, gravel, stones and deicing salts.

Diamond Coating

Important advances have been made in diamond coating of metals, glass, ceramics and plastics, using various chemical and plasma assisted vapor deposition process and ion beam enhanced deposition techniques. Development of these techniques, combined with important properties of diamonds, such as hardness, wear resistance, high thermal conductivity and transparency to ultra violet light and microwave frequencies has enabled the production of various aerospace and electronic parts and components.

Diamond Like Carbon (DLC)

By using a low temperature, ion beam assisted deposition process, this relatively recently developed materials is applied as a coating of a few nanometers in thickness. Less expensive than diamond films, but with cylinder properties as diamond, DLC has applications in such areas as tools and dies, gears, bearing, micro electro-mechanical systems, and micro scale probes.

Surface Coatings

A coating is a covering that is applied to the surface of an object, usually referred to as the substrate. The purpose of applying the coating may be decorative, functional, or both. The coating itself may be an all-over coating, completely covering the substrate, or it may only cover parts of the substrate. An example of all of these types of coating is a product label on many drinks bottles- one side has an all-over functional coating (the adhesive) and the other side has one or more decorative coatings in an appropriate pattern (the printing) to form the words and images. Paints and lacquers are coatings that mostly have dual uses of protecting the substrate and being decorative, although some artists paints are only for decoration, and the paint on large industrial pipes is presumably only for the function of preventing corrosion. Functional coatings may be applied to change the surface properties of the substrate, such as adhesion, wettability, corrosion resistance, or wear resistance. In other cases, e.g. semiconductor device fabrication (where the substrate is a wafer), the coating adds a completely new property, such as a magnetic response or electrical conductivity, and forms an essential part of the finished product.

A major consideration for most coating processes is that the coating is to be applied at a controlled thickness, and a number of different processes are in use to achieve this control, ranging from a simple brush for painting a wall, to some very expensive machinery applying coatings in the electronics industry. A further consideration for 'non-all-over' coatings is that control is needed as to where the coating is to be applied. A number of these non-all-over coating processes are printing processes.

Functions of coatings

Adhesive - adhesive tape, pressure-sensitive labels, iron-on fabric

Changing adhesion properties

Non-stick PTFE coated- cooking pans

Release coatings e.g. silicone-coated release liners for many self-adhesive products

primers encourage subsequent coatings to adhere well (also sometimes have anti-corrosive properties)

Optical coatings

Reflective coatings for mirrors

Anti-reflective coatings e.g. on spectacles

UV- absorbent coatings for protection of eyes or increasing the life of the substrate

Tinted as used in some coloured lighting, tinted glazing, or sunglasses

Catalytic e.g. some self-cleaning glass

Light-sensitive as previously used to make photographic film

Protective coatings

Most surface coatings or paints are to some extent protecting the substrate e.g.

Sealing and waterproofing wood

Sealing the surface of concrete

Film-forming sealers and floor paint

Seamless polymer/resin flooring

Bund wall/containment lining

Waterproofing and damp proofing of concrete walls

Roof coating

Concrete bridge deck membranes

Sealing and waterproofing of masonry

Preserving machinery, equipment and structures

Maintenance coatings/paints for metals, alloys and concrete

Chemical resistant coatings

Wear resistance

Anti-Friction, Wear and Scuffing Resistance Coatings for Rolling-element bearings

Hard anti-scratch coating on plastics and other materials e.g. of titanium nitride to reduce scratching and abrasion loss

Barrier coatings on concrete, metals and alloys subject to erosion/abrasive attack Anti-corrosion - ensure metal components have the longest possible lifespan. Underbody sealant for cars Many plating products

Preserving equipment and structural steel from degradation

Under thermal insulation and under protective fireproofing for structural steel

Passive fire protection

Insulation

Waterproof fabric and waterproof paper Anti-graffiti Antimicrobial surface Foul release and anti-fouling

Magnetic properties such as for magnetic media like cassette tapes, floppy disks, and some mass transit tickets

Electrical or electronic properties

Conformal Antenna, e.g., metal coatings on plastic airframes

Conductive coatings e.g. to manufacture some types of resistors

Insulating coatings e.g. on magnet wires used in transformers

Scent properties such as scratch and sniff stickers and labels

Decorative- often to impart a specific colour, but also to create a particular reflective property such as gloss or mat finish.

Coating processes

Coating processes may be classified as follows:

Vapor deposition Techniques

Chemical vapor deposition

Metalorganic vapour phase epitaxy

Electrostatic spray assisted vapour deposition (ESAVD)

Sherardizing

Some forms of Epitaxy

Molecular beam epitaxy

Physical vapor deposition

Cathodic arc deposition

Electron beam physical vapor deposition (EBPVD)

Ion plating

Ion beam assisted deposition (IBAD)

Magnetron sputtering

Pulsed laser deposition

Sputter deposition

Vacuum deposition

Vacuum evaporation, evaporation (deposition)

Pulsed electron deposition (FED)

Chemical and electrochemical techniques

Conversion coating

Autophoretic, the registered trade name of a proprietary series of autodepositing coatings specifically for ferrous metal substrates.

Anodizing

Chromate conversion coating Plasma electrolytic oxidation Phosphate (coating) Ion beam mixing

Pickled and oiled, a type of plate steel coating

Plating

Electro-less plating Electroplating

Spray Coating

Spray painting

High velocity oxygen fiiel (HVOF)

Plasma spraying

Thermal spraying

Kinetic metallization (KM)

Plasma transferred wire arc thermal spraying

The common forms of Powder coating

Roll to Roll coating Processes

Common roll-to-roll coating processes include:

Air knife coating

Ani-lox coater

Flexo coater

Gap Coating

Knife-over-roll coating

Gravure coating

Hot melt coating- when the necessary coating viscosity is achieved by temperature rather than solution of the polymers etc. This method commonly implies slot-die coating above room temperature, but it also is possible to have hot-melt roller coating; hot-melt metering-rod coating, etc. Immersion dip coating Kiss coating

Metering rod (Meyer bar) coating

Roller coating

Forward roller coating

Reverse roll coating

Silk Screen coater

Rotary screen

Slot Die coating

Extrusion coating - generally high pressure, often high temperature, and with the web travelling much faster than the speed of the extruded polymer.

Curtain coating- low viscosity, with the slot vertically above the web and a gap between slot die and web.

Slide coating- bead coating with an angled slide between the slot die and the bead. Commonly used for multilayer coating in the photographic industry. Slot die bead coating- typically with the web backed by a roller and a very small gap between slot die and web.

Tensioned-web slot die coating- with no backing for the web.

Inkjet printing

Lithography

Flexography

Selection of coating for wear and corrosion resistance:

The selection of coating for wear and corrosion resistance is a major aspect for prevention of wear and corrosion in the material. The figures and charts given below clearly describes the different coatings, their thickness, specifications for corrosion resistance.

Application of corrosion-resistant coatings is one of the most widely used means of protecting steel. There are a wide variety of coatings to choose from, and proper selection is based on the component size and accessibility, the corrosive environment, the anticipated temperatures, component distortion, the coating thickness attainable and costs. Painting is probably the most widely used engineering coating used to protect steel from corrosion. There are a wide variety of coating formulations that have been developed for outdoor exposure, marine atmospheres, water immersion, chemical fumes, extreme sunlight, high humidity, and moderately high temperatures (less than about 200 °C, or 400 °F). The most widely used corrosion-resistant metallic coatings are hot dipped zinc, zinc-aluminum, and aluminum coatings. These coatings exhibit excellent resistance to atmospheric corrosion and are widely used in the construction, automobile, utility, and appliance industries. Other important coating processes for steels include electroplating, electro less plating, thermal spraying, pack cementation aluminizing (for high-temperature oxidation resistance), and cladding (including weld cladding and roll-bonded claddings).

The material selected for wear resistance should make the wearing surface hard through the use of hard facing, diffusion heat treatments, hard chromium plating, or more recently developed vapor deposition techniques or high-energy processes (e.g., ion implantation).; make the wearing surface resistant to fracture. Many wear processes involve fracture of material from a surface; thus toughness and fracture resistance play a significant role in wear-resistant surfaces.