Introduction to Tribology

Tribology is defined as the science and technology of interacting surfaces in relative motion, having its origin in the Greek word *tribos* meaning rubbing. It is a study of the friction, lubrication, and wear of engineering surfaces with a view to understanding surface interactions in detail and then prescribing improvements in given applications.

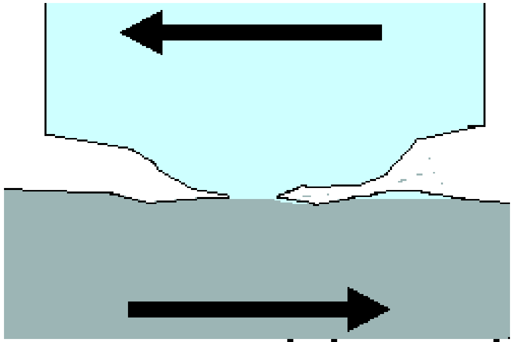
Wear

The process leading to loss of material is known as "wear“

Types of wear

- Adhesive wear
- Abrasive wear
- Surface fatigue
- Fretting wear

Adhesive wear

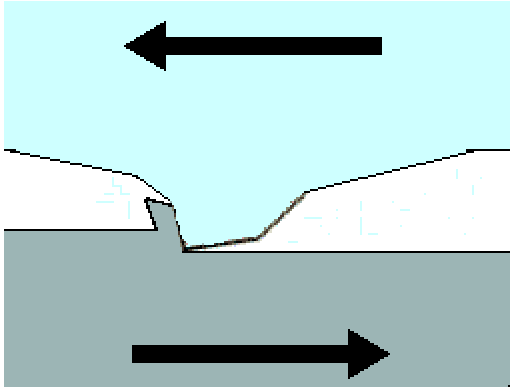


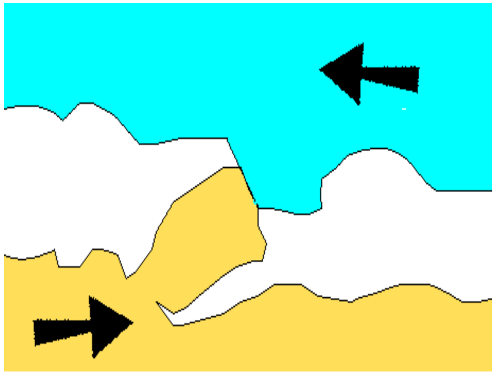
Adhesive wear are caused by relative motion, "direct contact" and plastic deformation which create wear debris and material transfer from one surface to another.

Example of Adhesive Wear:

- A Shaft rotating in a bushing
- Chalk on board-while writing

Abrasive Wear

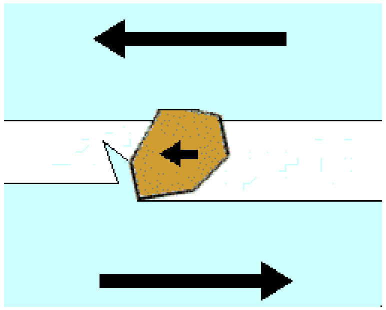




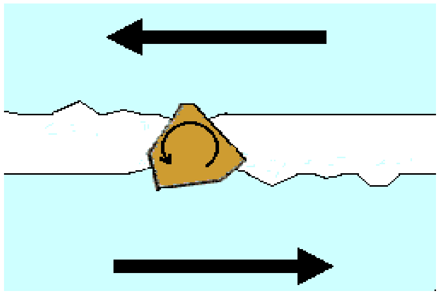
Abrasive wear occurs when a hard rough surface slides across a softer surface. ASTM International (formerly American Society for Testing and Materials) defines it as the loss of material due to hard particles or hard protuberances that are forced against and move along a solid surface.

Types of Abrasive wear

- Abrasive wear is commonly classified according to the type of contact and the contact environment
- The two modes of abrasive wear are known as two-body and three-body abrasive wear
- Two-body wear occurs when the grits or hard particles remove material from the opposite surface.
- Three-body wear occurs when the particles are not constrained, and are free to roll and slide down a surface.



Two-body wear

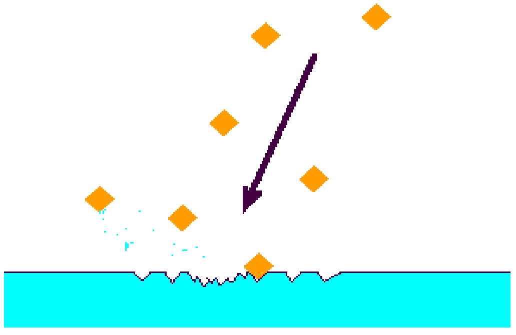


Three-body wear

Erosive Wear

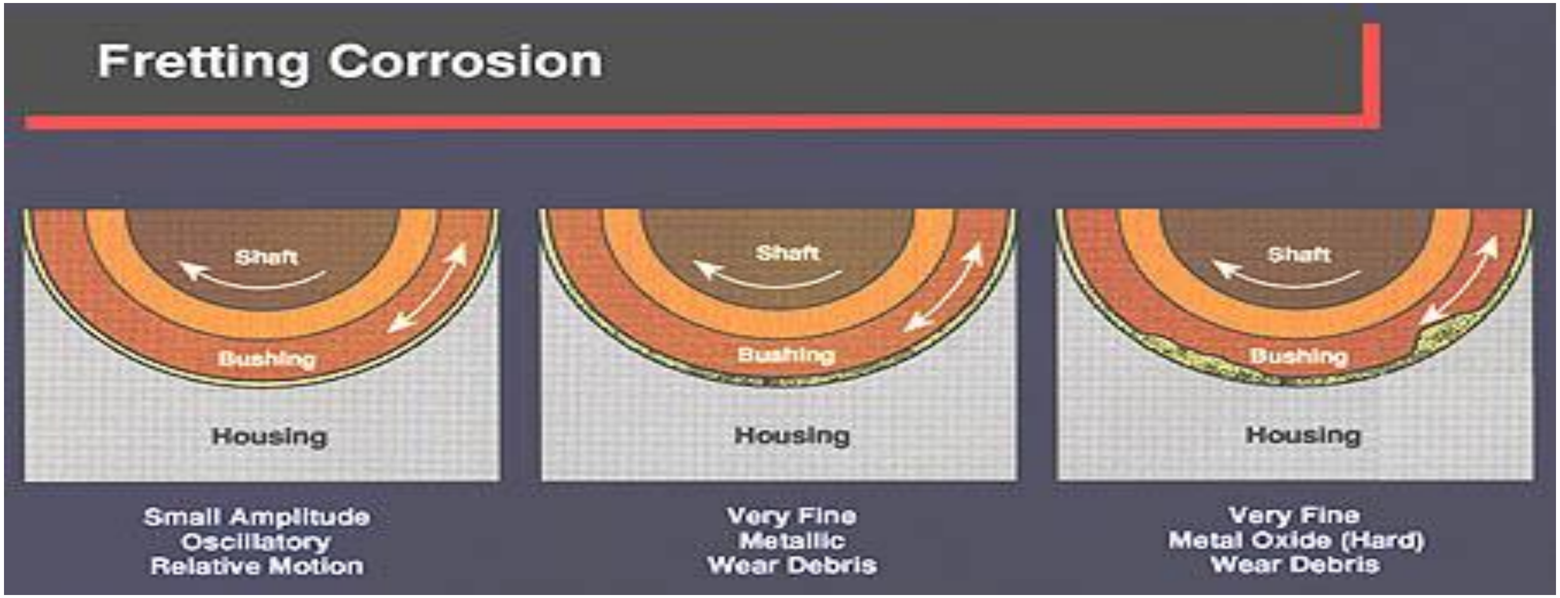
- **Erosive Wear**

  Erosive wear can be described as an extremely short sliding motion and is executed within a short time interval. Erosive wear is caused by the impact of particles of solid or liquid against the surface of an object.



Fretting wear

Fretting is the repeated cyclical rubbing between two surfaces, which is known as fretting, over a period of time which will remove material from one or both surfaces in contact



Friction

Friction is the force resisting the relative motion of solid surfaces, fluid layers, and material elements sliding against each other.

Types of friction:

- Dry friction
- Fluid friction
- Lubricated friction
- Skin friction (Fluid and solid) and
- Internal friction (Solids),

Lubrication

Lubrication is the process or technique employed to reduce wear of one or both surfaces in close proximity, and moving relative to each another, by interposing a substance called lubricant between the surfaces to carry or to help carry the load (pressure generated) between the opposing surfaces.

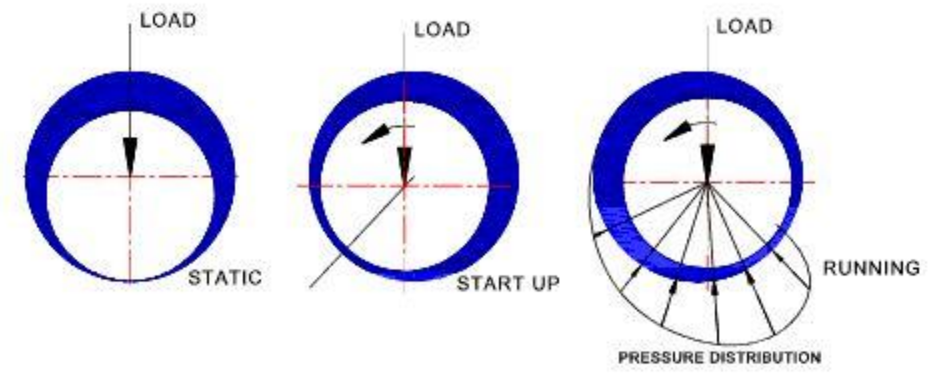
Regimes of Lubrication

As the load increases on the contacting surfaces three distinct situations can be observed with respect to the mode of lubrication, which are called regimes of lubrication:

- **Fluid film lubrication or boundary lubrication**
- **Hydrostatic lubrication**
- **Hydrodynamic lubrication (thick film)**
- **Extreme pressure lubrication**

Hydrodynamic Lubrication or Thick Film Lubrication

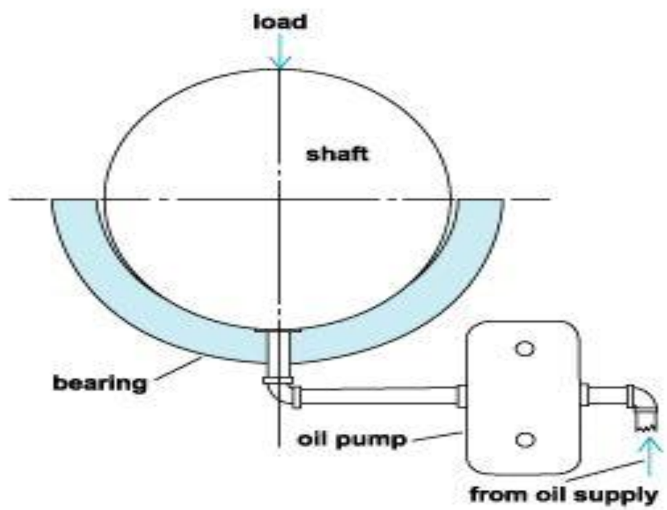
- Hydrodynamic lubrication is said to exist when the moving surfaces are separated by the pressure of a continuous unbroken film or layer of lubrication. In this type of lubrication, the load is taken completely by the oil film.
- The basis of hydrodynamic lubrication is the formation of an oil wedge. When the journal rotates, it creates an oil taper or wedge between the two surfaces, and the pressure build up with the oil film supports the load.
- Hydrodynamic lubrication depends on the relative speed between the surfaces, oil viscosity, load, and clearance between the moving or sliding surfaces.
- In hydrodynamic lubrication the lube oil film thickness is greater than outlet, pressure at the inlet increases quickly, remains fairly steady having a maximum value a little to the outside of the bearing center line, and then decreases quickly to zero at the outlet.



Hydrodynamic Lubrication

Hydrostatic Lubrication

- Hydrostatic lubrication is essentially a form of hydrodynamic 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 lube 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



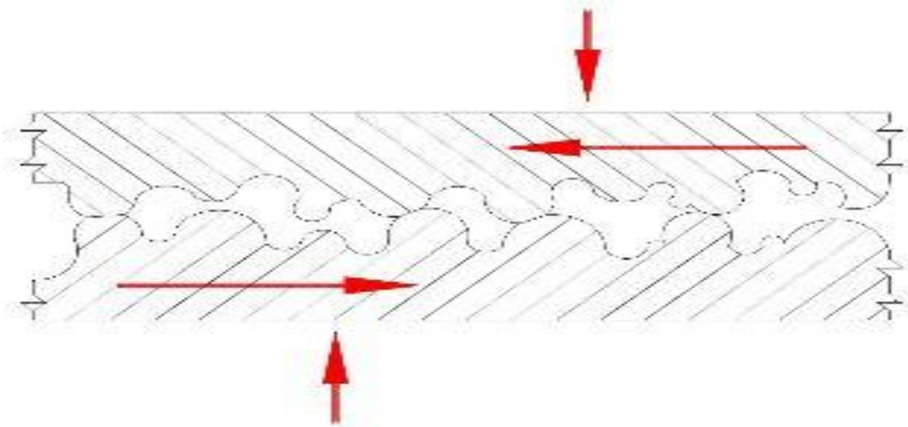
Hydrostatic Lubrication

Boundary Lubrication or Thin Film Lubrication

- Boundary lubrication exists when the operating condition are such that it is not possible to establish a full fluid condition, particularly at low relative speeds between the moving or sliding surfaces.
- The oil film thickness may be reduced to such a degree that metal to metal contact occurs between the moving surfaces. The oil film thickness is so small that oiliness becomes predominant for boundary lubrication.
- Boundary lubrication happens when

  A shaft starts moving from rest.

  The speed is very low.



Boundary Lubrication

Extreme pressure lubrication

- When the moving or sliding surfaces are under very high pressure and speed, a high local temperature is attained. Under such condition, liquid lubricant fails to stick to the moving parts and may decompose and even vaporize. To meet this extreme pressure condition, special additives are added to the minerals oils. These are called "extreme pressure lubrication." These additives form on the metal surfaces more durable films capable of withstanding high loads and high temperature. Additives are organic compounds like chlorine (as in chlorinated esters), sulphur (as in sulphurized oils), and phosphorus (as in tricresyl phosphate).

CLASSIFICATION OF WEAR

Definition : Wear is progressive damage, involving material loss , occurs on the surface as a result of relative motion between the surfaces.

Type	Typical characteristics and definitions	observed In
Sliding wear (delamintation wear)	**Wear due to localized bonding between contacting solid surfaces leading to material transfer between the two surfaces or the loss from either surface.** **Plastic deformation, crack nucleation and propagation in the surface**	**Sliders, bearing, gears and camshaft.**
Fretting wear	**Wear arising as a result of fretting (Small amplitude oscillatory motion, usually tangential, between two solid surfaces in contact).**	**Press fit parts with a small relative Sliding motion**
Abrasive wear	**Wear due to hard particles or hard protuberances forced against and moving along a solid surface.**	**Sliding surfaces ,earth-removing Equipment**
Erosive wear (solid particle impingement)	**Wear due to mechanical interaction between that surface and a fluid, a multi component fluid, or impinging liquid or solid particles**	**Turbine, pipes for coal slurries and helicopter blades**
Fatigue wear	**Wear of a solid surface caused by fracture arising from material fatigue.**	**Ball bearing, roller bearing glassy solid slider**
Cavitation wear	**A form of erosion causing material to wear by the action of vapour bubbles in a very turbulent liquid.**	**Soft Bearing Surfaces**

Wear Measurement

- Archard wear Equation :

$$W \alpha \frac{w}{H}$$

w = *wear*

w = *Normal Load on contact*

H= *surface hardness of the wearing material*

K= *wear coefficient (dimensionless)*

$$W = K \frac{w}{H}$$

$\frac{K}{H}$ = is called Dimensional wear constant

Unit =(volume)/(Load/meter)

Wear Dependence

For Dry/unlubricated surfaces sliding

- Normal Load
- Relative sliding speed
- The initial temperature
- Thermal, Mechanical , chemical properties of the material in contact
- No simpler Model to explain wear

IDENTIFICATION OF WEAR MECHANISM

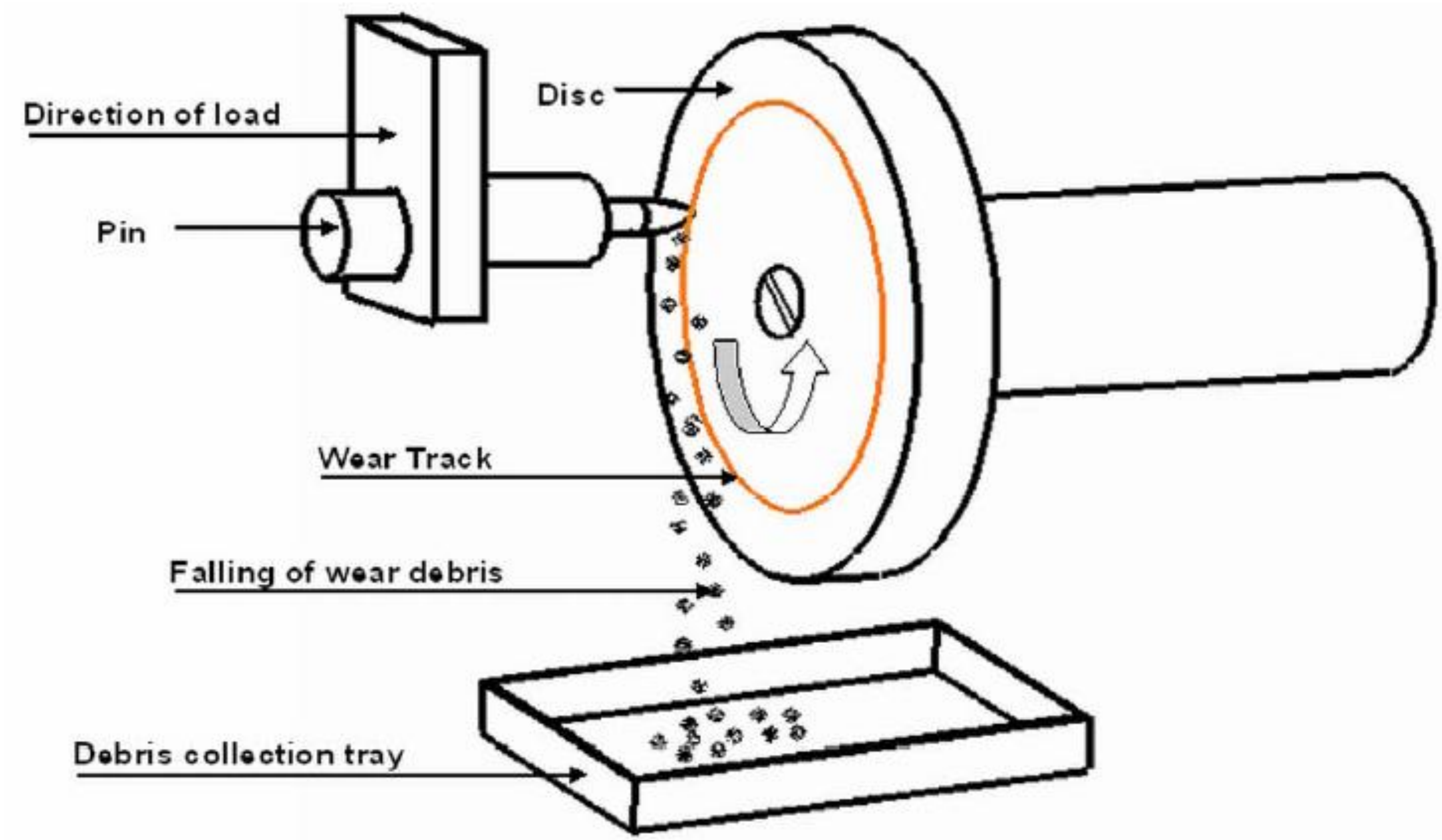
- **Examination of the wear debris (collected)**

  - large lumps imply- adhesive wear
  - fine particles- oxidative wear
  - chip like particles-abrasive wear
  - flake like particles- delamination wear

- **Examination of the worn surfaces:**

  - Heavy tearing implies - adhesive wear
  - Scratches imply -abrasive wear
  - burnishing indicates –non adhesive wear

EXPERIMENTAL SET-UP

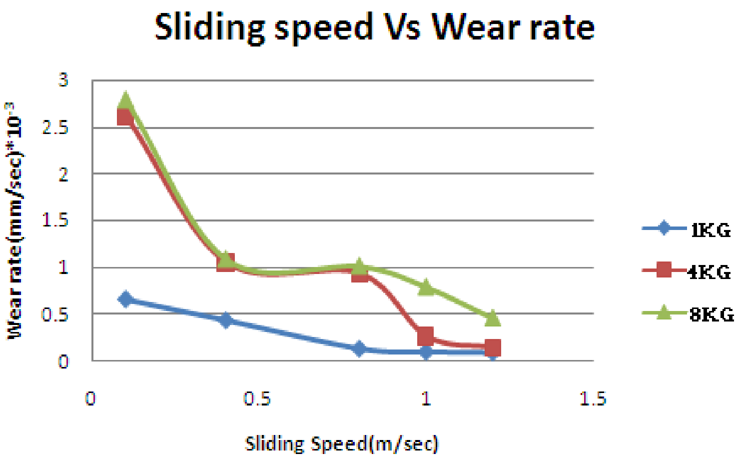


Schematic diagram of loading configuration of Pin-on-Disc.

METHODS

- pin and disc were fitted.
- wear track diameter was measured.
- Load applied in the dead cell.
- Values of displacement , Time, speed, load and diameter of disk were entered.
- Displacement value of every second and coefficient of friction were noted from LVDT.
- wear values were calculated from displacement value .

WEAR RATE

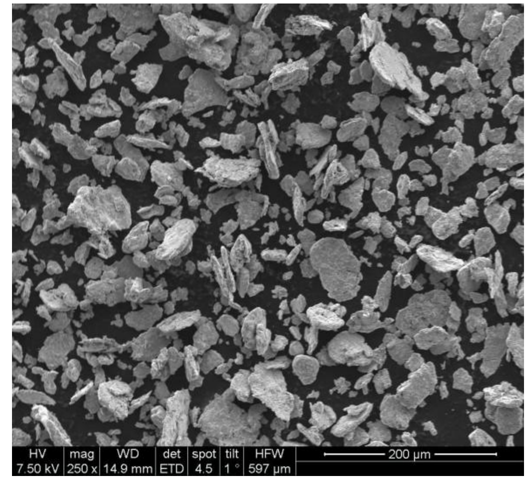


Wear rate of Ti-6Al-4V under ambient condition at 1kg,4kg and 8kg

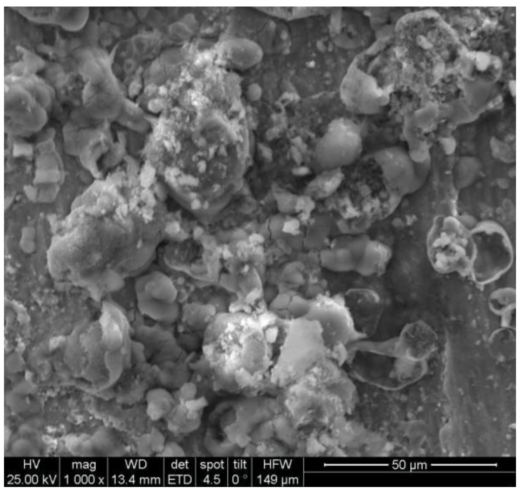
Wear rate of Ti-6Al-4V under vacuum condition at 1kg,4kg and 8kg

SEM ANALYSIS

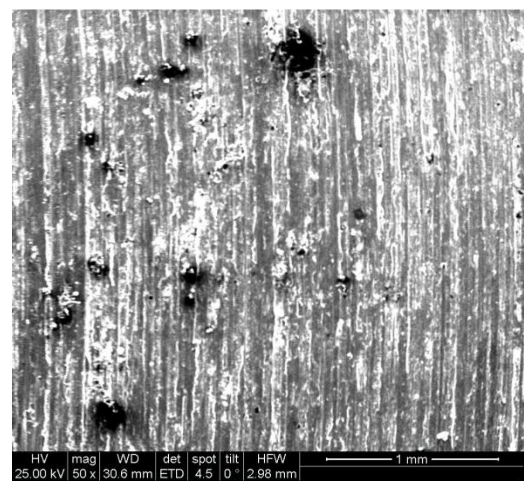
Abrasive wear



AT AMBIENT CONDITION



Speed 0.1m/sec at 1kg

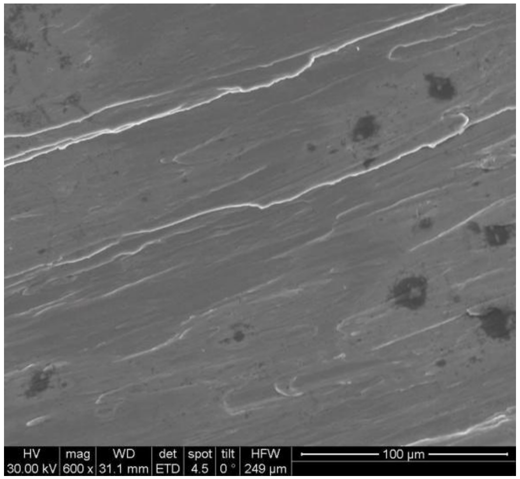


Speed 0.8m/sec at 1kg

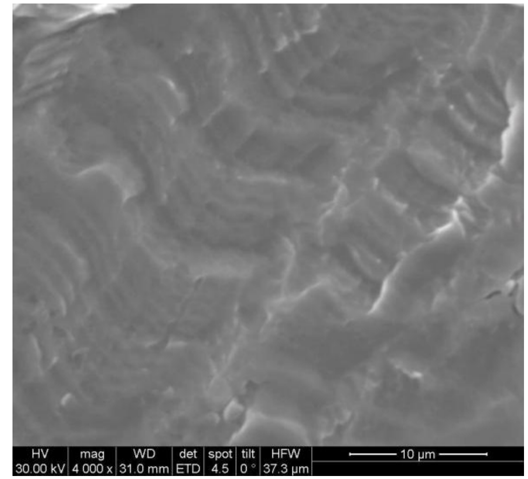
Source :Materials engg,IISc,Bangalore

SEM ANALYSIS

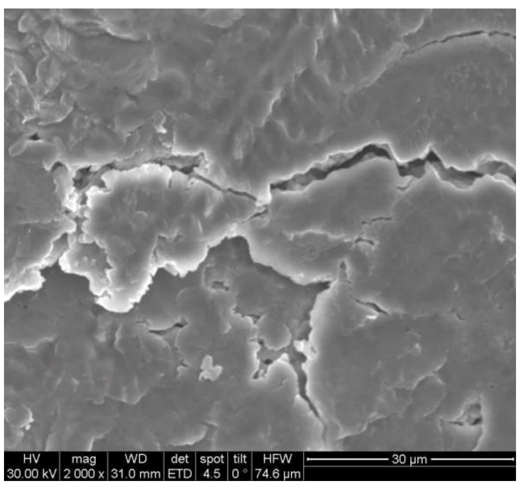
AT VACUUM CONDITION



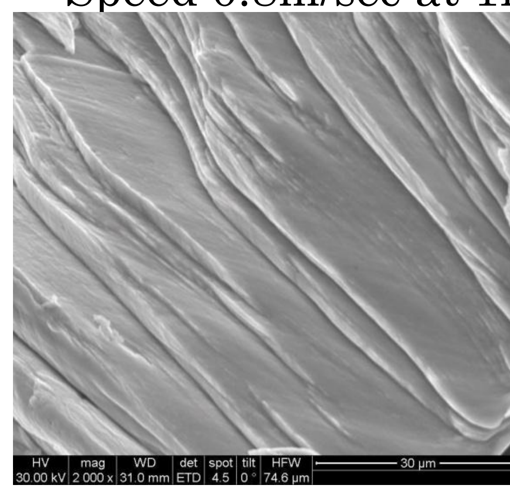
Speed 0.1m/sec at 1kg



Speed 0.8m/sec at 1kg



Speed 0.4m/sec at 1kg

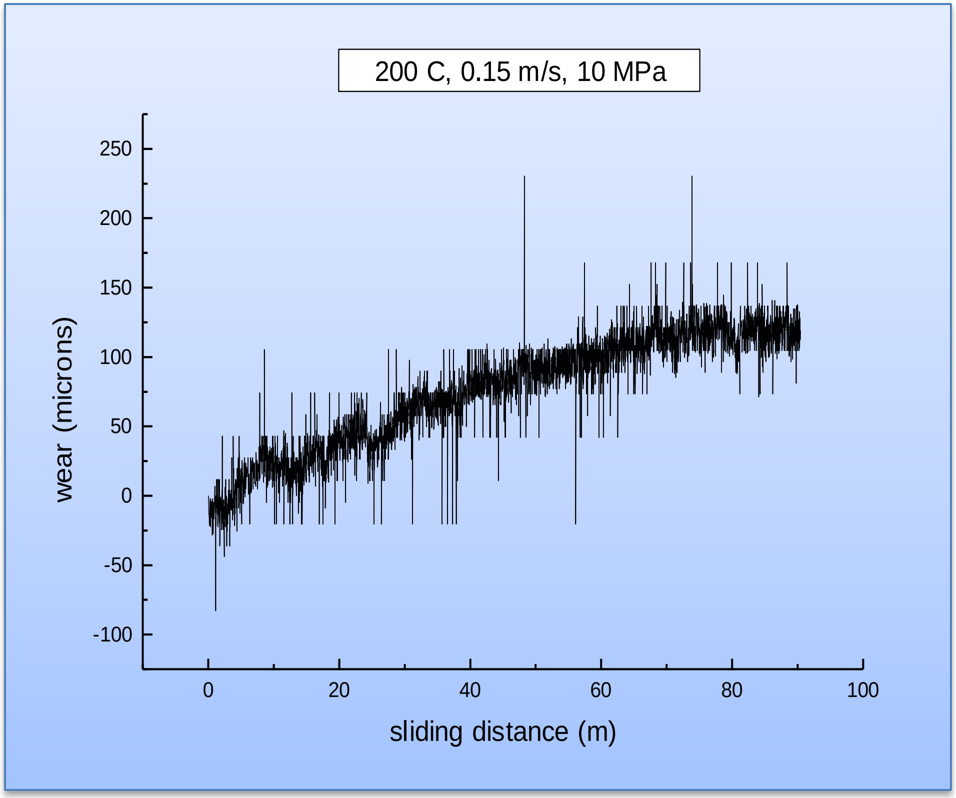


Speed 0.2m/sec at 1kg

Source :Materials engg,IISc,Bangalore

SAMPLE CALCULATIONS

Wear Rate Calculations

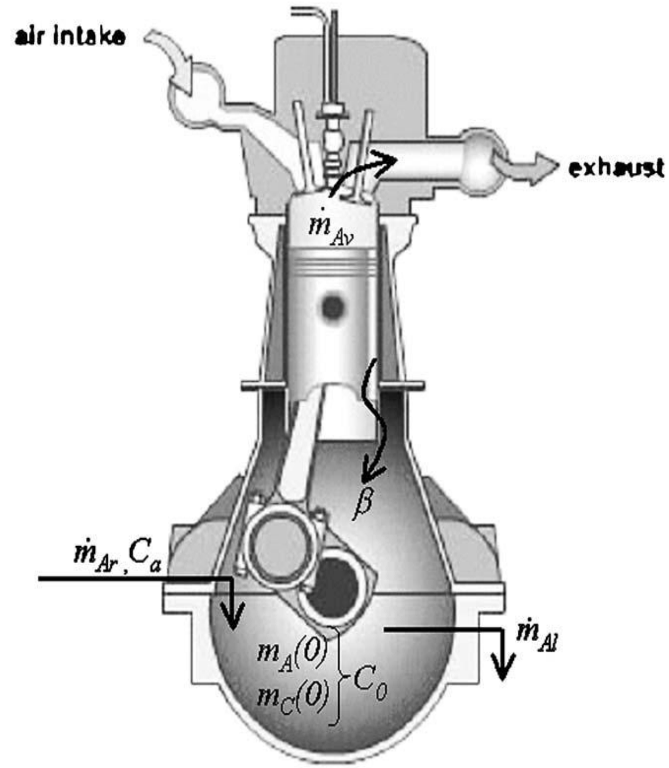


Wear Rate = Slope of the steady state region in the graph

= (Y2 – y1)/(x2 – x1)

Case study from Tribology international journal

- Wear rate determination by oil examination
- Helps to avoid secondary damage by identification of wear debris .
- Wear debris quantification does not always correlate with the real wear .
- Methodology used : spectrometric wear debris measurement data to obtain parameter of wear condition

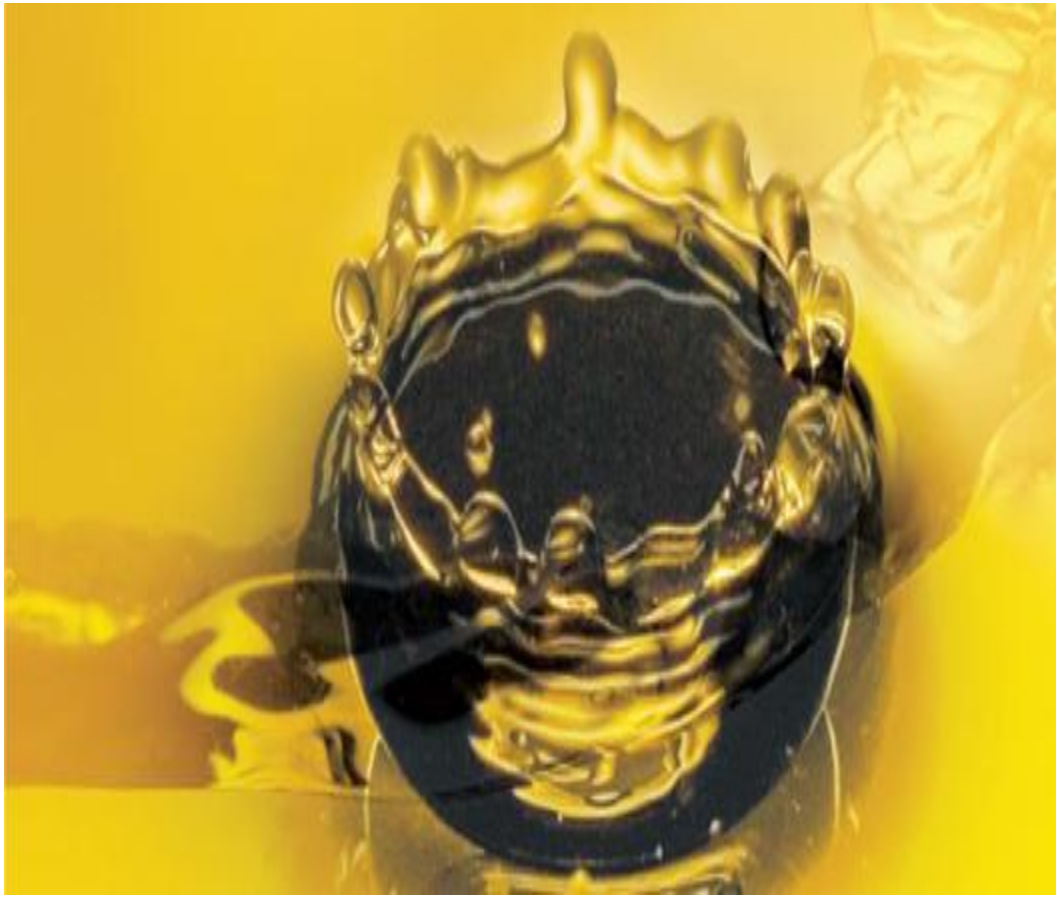


Reference : *Analytic approch to wear tare determinationFor internal combustio engine condition monitering based on oil analysis (Author:V Macian, B Tormos,P.Olmeda, L.Montoro)*

Case study from Tribology international journal

- The spectrometer purpose is to determine the elemental content of each debris particle .
- Inductively Coupled Plasma (ICP) spectrometer is used , typically maximum size of 5 micron can be measured .
- Quantative information (concentration) is related to the amount of electromagnetic radiation that is emitted while qualitative information (which element is present is related to the wavelength at which radiation is emitted .

Viscosity



Introduction

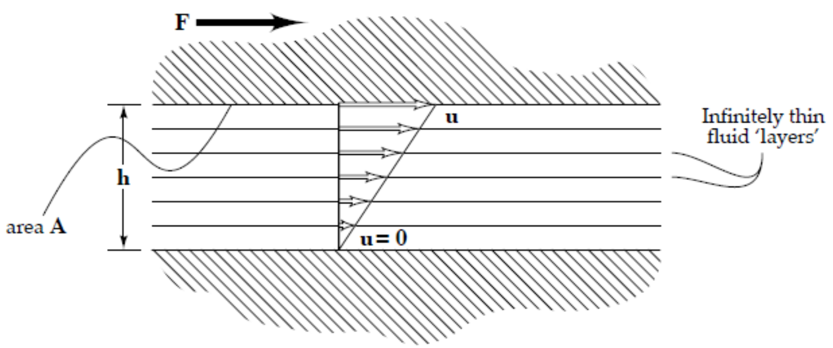
- Viscosity is a quantitative measure of a fluid's resistance to flow.

Dynamic (or Absolute) Viscosity:

- The dynamic viscosity(η) of a fluid is a measure of the resistance it offers to relative shearing motion.

$$\eta = F / [A \times (u/h)]$$

$$\eta = \tau / (u/h) \quad N\text{-}s/m^2$$



Kinematic Viscosity :

- It is defined as the ratio of absolute viscosity to the density of fluid.

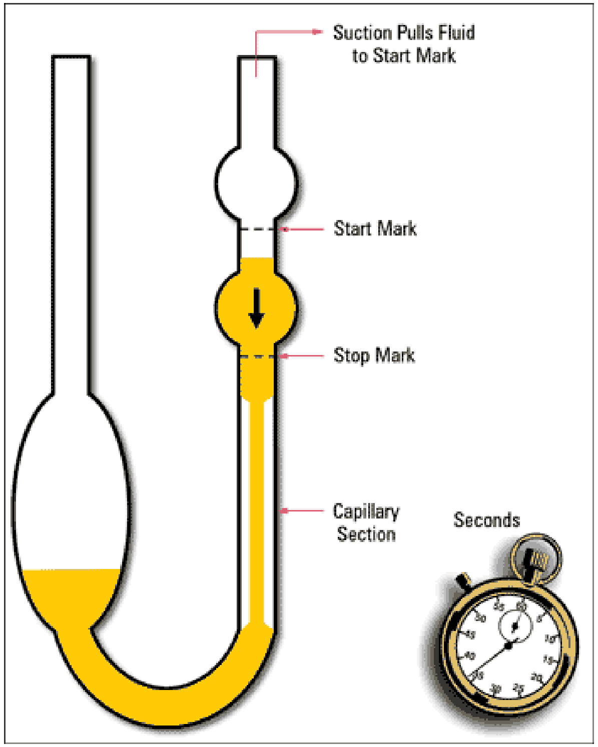
$$\nu = \eta/\rho \qquad m^2/s \qquad ; \quad \rho = \text{density of fluid}$$

Viscosity Measurements

Capillary Viscometers

- It gives the ‘**kinematic viscosity’** of the fluid. It is based on Poiseuille’s law for steady viscous flow in a pipe.

$$\upsilon = \pi r^4 g l t \,/\, 8LV = k(t_2 - t_1)$$



where:

υ	is the kinematic viscosity [m^2/s];
r	is the capillary radius [m];
l	is the mean hydrostatic head [m];
g	is the earth acceleration [m/s^2];
L	is the capillary length [m];
V	is the flow volume of the fluid [m^3];
t	is the flow time through the capillary, **t** = (**t**$_2$ – **t**$_1$), [s];
k	is the capillary constant which has to be determined experimentally by applying a reference fluid with known viscosity, e.g. by applying freshly distilled water. The capillary constant is usually given by the manufacturer of the viscometer.

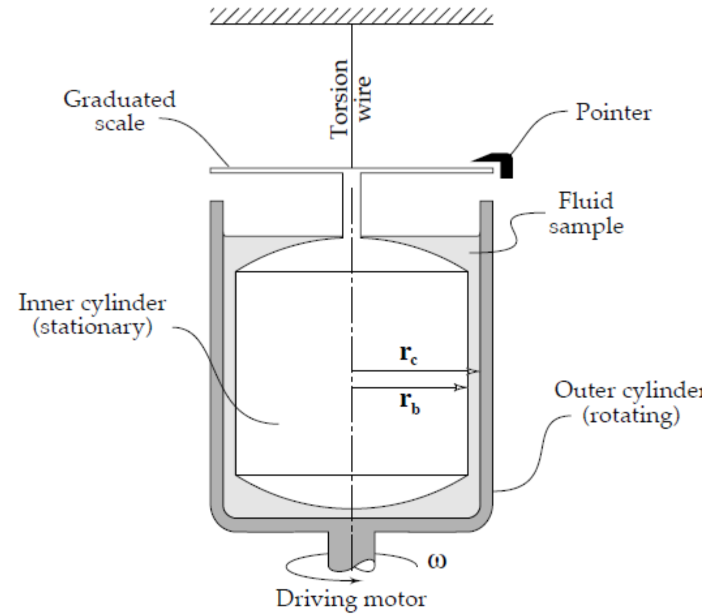
Viscosity Measurements

Rotational Viscometers

- These viscometer give the value of the '**dynamic viscosity'.**
- It is based on the principle that the fluid whose viscosity is being measured is sheared between two surfaces.
- In these viscometers one of the surfaces is stationary and the other is rotated by an external drive and the fluid fills the space in between.
- The measurements are conducted by applying either a constant torque and measuring the changes in the speed of rotation or applying a constant speed and measuring the changes in the torque.
- There are two main types of these viscometers: rotating cylinder and cone-on-plate viscometers

Viscosity Measurements

Rotating cylinder viscometer



Schematic diagram of a rotating cylinder viscometer.

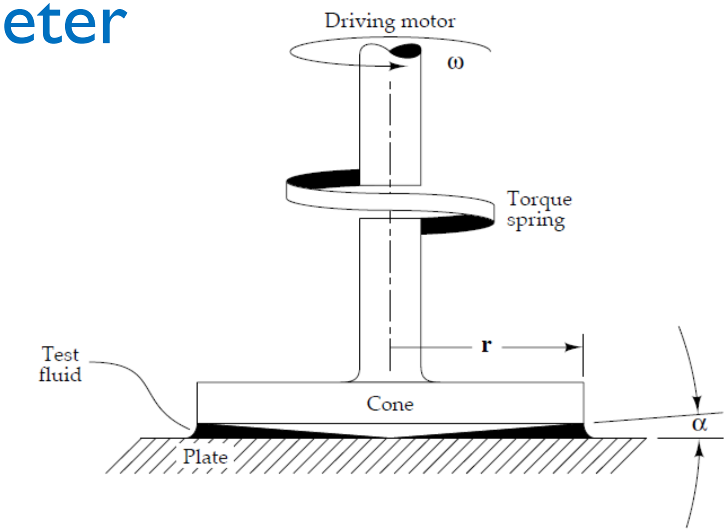
$$\eta = M(1/r_b^2 - 1/r_c^2) / 4\pi d\omega = kM / \omega$$

where:

η	is the dynamic viscosity [Pas];
r_b, r_c	are the radii of the inner and outer cylinders respectively [m];
M	is the shear torque on the inner cylinder [Nm];
ω	is the angular velocity [rad/s];
d	is the immersion depth of the inner cylinder [m];
k	is the viscometer constant, supplied usually by the manufacturer for each pair of cylinders [m^{-3}].

Viscosity Measurements

Cone-on-plate viscometer



Schematic diagram of a cone on plate viscometer.

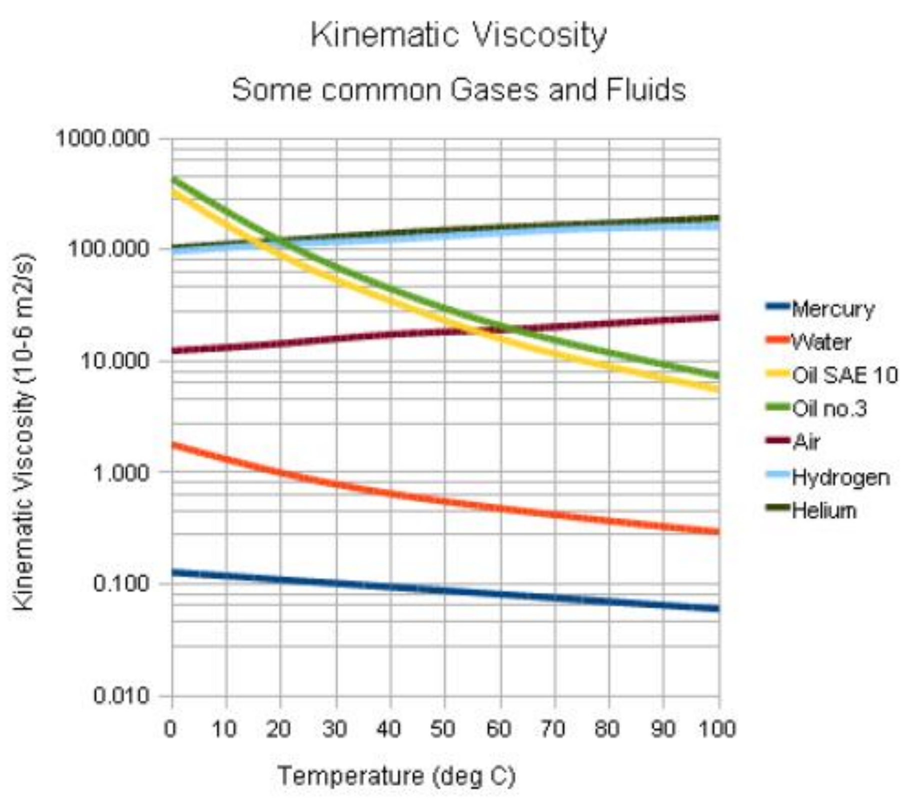
$$\eta = 3M\alpha\cos^2\alpha(1 - \alpha^2/2) \;/\; 2\pi\omega r^3 = kM \;/\; \omega$$

where:

η	is the dynamic viscosity [Pas];
$\mathbf{r}$	is the radius of the cone [m];
$\mathbf{M}$	is the shear torque on the cone [Nm];
ω	is the angular velocity [rad/s];
α	is the cone angle [rad];
$\mathbf{k}$	is the viscometer constant, usually supplied by the manufacturer [m^{-3}].

Effects of temperature

- The viscosity of liquids decreases with increase the temperature.
- The viscosity of gases increases with the increase the temperature.



Effects of temperature

- The lubricant oil viscosity at a specific temperature can be either calculated from the viscosity - temperature equation or obtained from the viscosity-temperature ASTM chart.

Viscosity-Temperature Equations

Name	Equation	Comments
Reynolds	$\eta = \mathbf{b}e^{-\mathbf{a}T}$	Early equation; accurate only for a very limited temperature range
Slotte	$\eta = \mathbf{a}/(\mathbf{b} + T)^{\mathbf{c}}$	Reasonable; useful in numerical analysis
Walther	$(\upsilon + \mathbf{a}) = \mathbf{b}\mathbf{d}^{1/T^{\mathbf{c}}}$	Forms the basis of the ASTM viscosity-temperature chart
Vogel	$\eta = \mathbf{a}e^{\mathbf{b}/(T - \mathbf{c})}$	Most accurate; very useful in engineering calculations

where:

$\mathbf{a}, \mathbf{b}, \mathbf{c}, \mathbf{d}$ are constants;

υ is the kinematic viscosity $[m^2/s]$;

$\mathbf{T}$ is the absolute temperature [K].

Effects of temperature

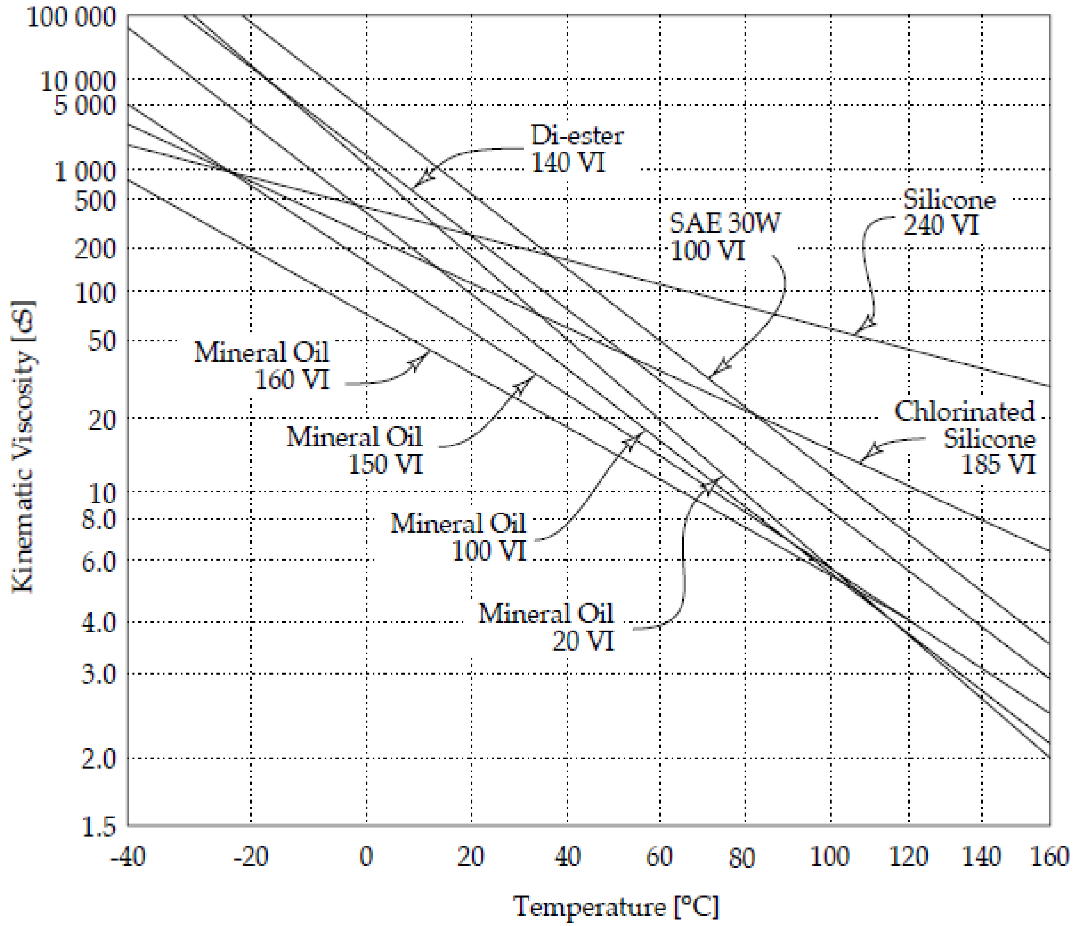


fig: Viscosity-temperature characteristics of selected oils

Viscosity index

- An entirely empirical parameter which would accurately describe the viscosity- temperature characteristics of the oils.
- The viscosity index is calculated by the following formula:

$$VI = (L - U)/ (L - H) * 10$$

where ,

VI is viscosity index

U is the kinematic viscosity of oil of interest

L and H are the kinematic viscosity of the reference oils

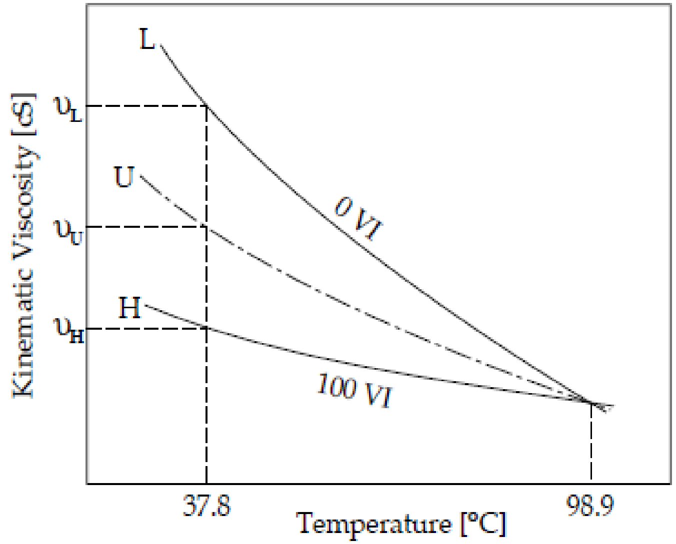


Fig . Sh

Effects of pressure

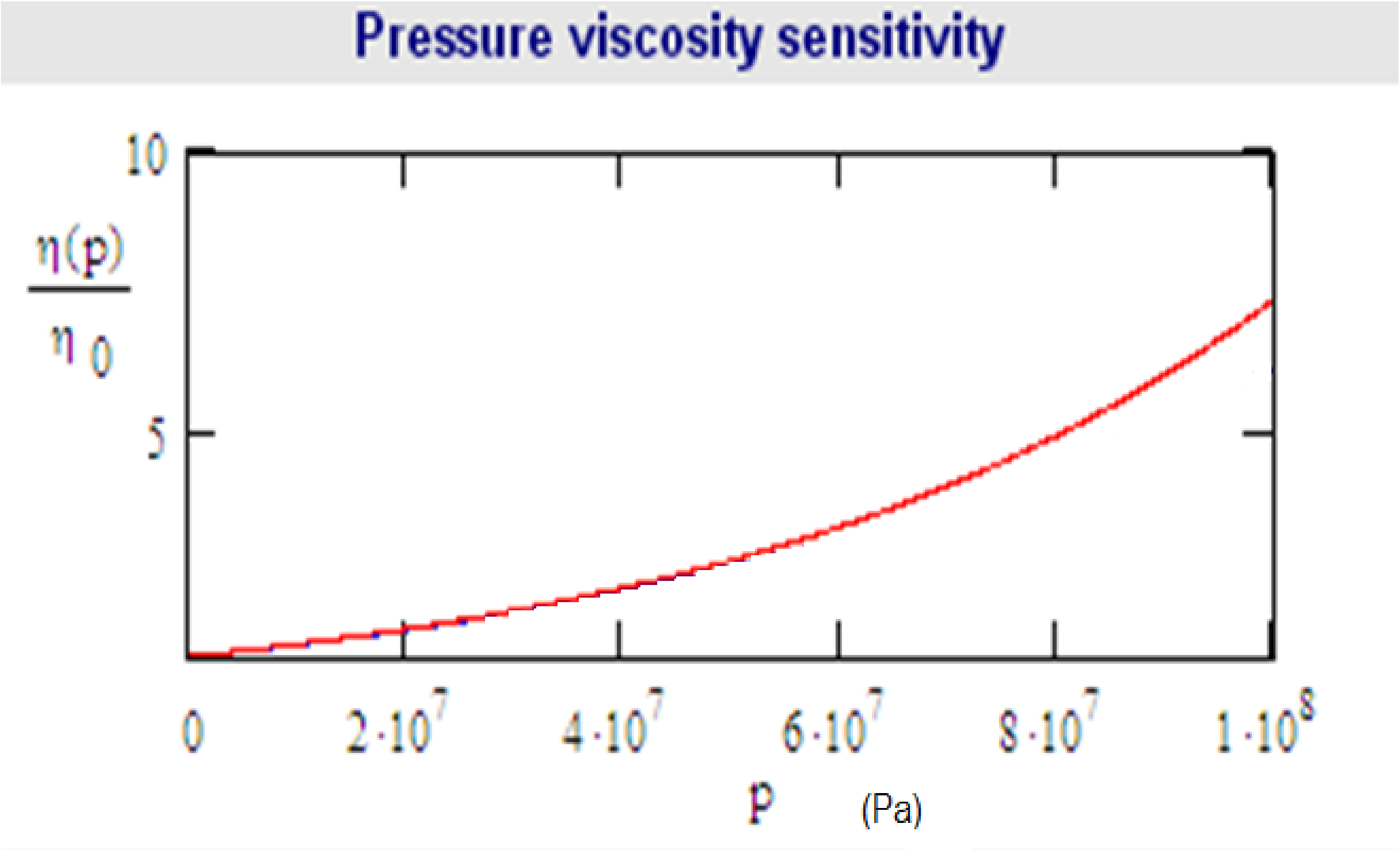
- Lubricants viscosity increases with pressure.
- For most lubricants this effect is considerably largest than the other effects when the pressure is significantly above atmospheric.
- The Barus equation :

$$\eta_p = \eta_0 e^{\alpha p}$$

where:

η_p	is the viscosity at pressure '**p**' [Pas];
η_0	is the atmospheric viscosity [Pas];
α	is the pressure-viscosity coefficient [m^2/N], which can be obtained by plotting the natural logarithm of dynamic viscosity 'η' versus pressure '**p**'. The slope of the graph is 'α';
p	is the pressure of concern [Pa].

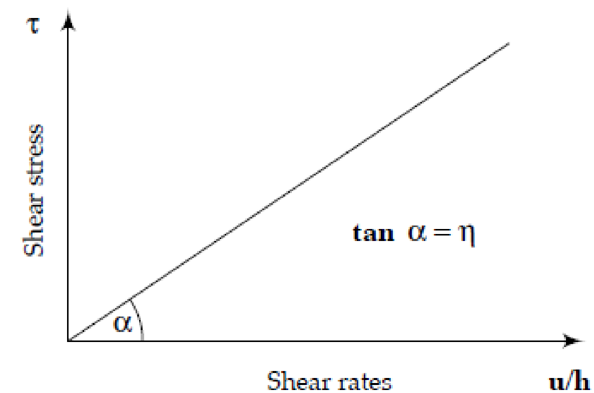
Effects of pressure



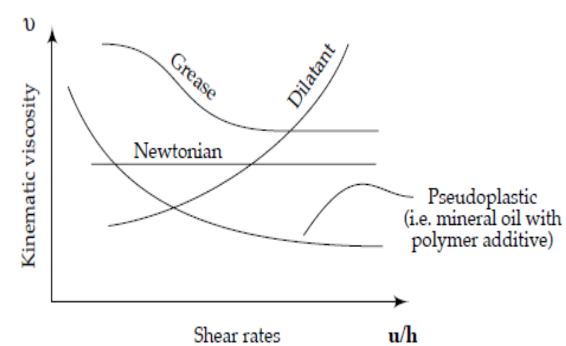
Viscosity - shear relationship

- For Newtonian fluids, shear stress linearly vary with the shear rate as shown in Figure. Viscosity is constant for this kind of fluid.

$$\tau = \eta\ (u/h)$$



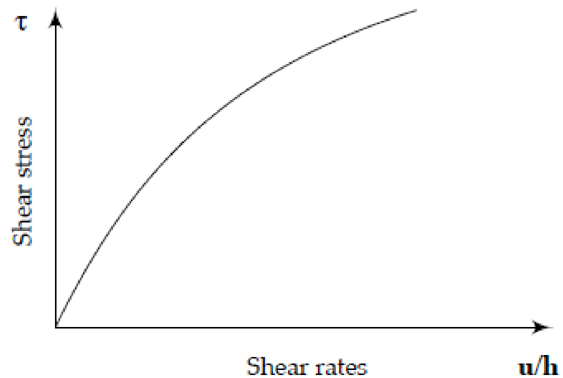
- Non Newtonian fluid doesn't follow the linear relation between viscosity and shear rate.

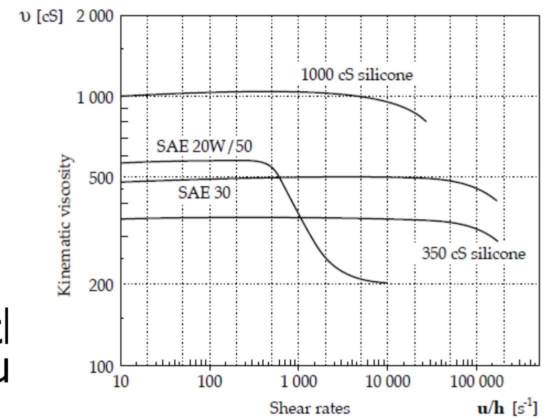


Viscosity – shear relationship

Pseudoplastic Behaviour

- Pseudoplastic or shear thinning and is associated with the thinning of the fluid as the shear rate increases.





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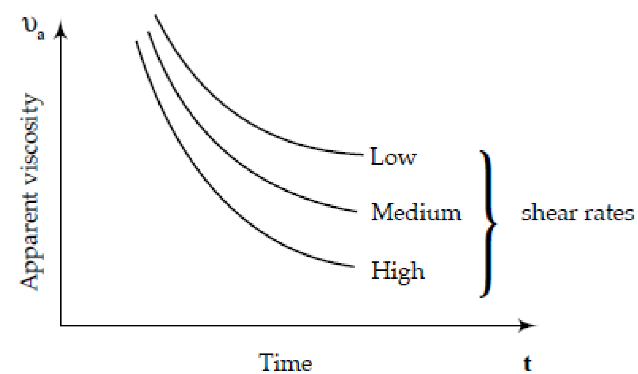
- The opposite of this behavior is known as inverse thixotropic.



Applications

- Selection of lubricants for various purpose.

  - we can choose an optimum range of viscosity for engine oil.

  - for high load and also for speed operation high viscous lubricants is required.

- In pumping operation

  - for high viscous fluid high power will require.

  - for low viscous fluid low power will require.

- In making of blend fuel

  - less viscous fuels easy to mix.

- In the operation of coating and printing.

How to measure friction?

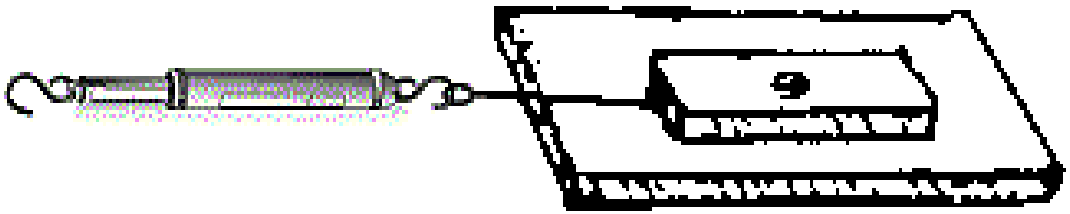
Method 1 Weight ratio

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 coefficient 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.

$\mu = F_f / N = m_{dead\ weight} / m_{block}$

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.

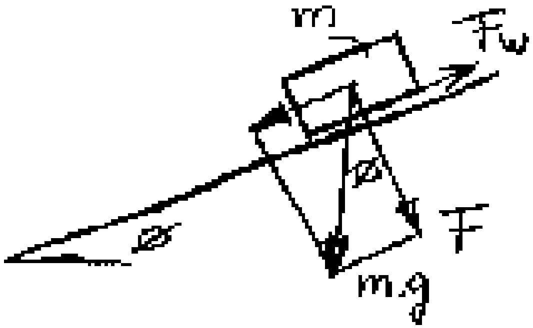
Method 2:
Spring balance



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 $\mu = F_{spring} / F_{normal} = F_{spring} / (m_{block} \cdot g)$, $g = 9.81\ m/s^2$

Hint: Pulse rotation sensors (multi-turn potentiometers, pulse encoders) often prove to be very useful to create low cost sensors for measuring displacement by combining the sensor with a cable and a pulley, for measuring torque with a torsional spring, for measuring force with a wire, a pulley and a spring etc.

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. $\mu = \tan\varnothing = F_f / F$

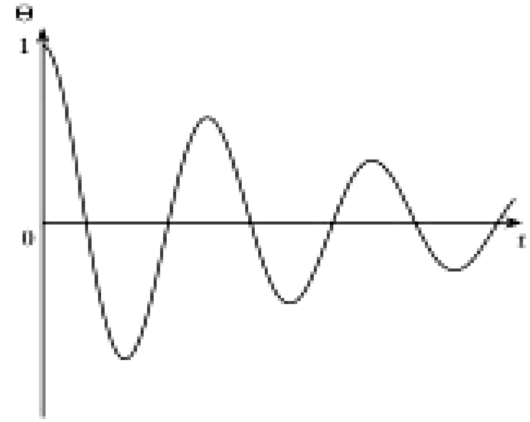
from	Angle of tilt in degrees ▼	45
to	Angle of tilt in degrees ▼	
		Solve

Method 4: Clamping

To measure the static coefficient of friction 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 halved 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.