Fatigue Wear

Fatigue wear is a type of wear in which the surface damage of the material takes place due to strain induced on the surface for a particular number of cycles to a certain critical limit.

The wear occurring due to surface fatigue is termed fatigue wear. Surface fatigue is caused due to the repeated stressing—and unstressing of the contacts. Cracks develop due to the accumulation of irreversible changes.

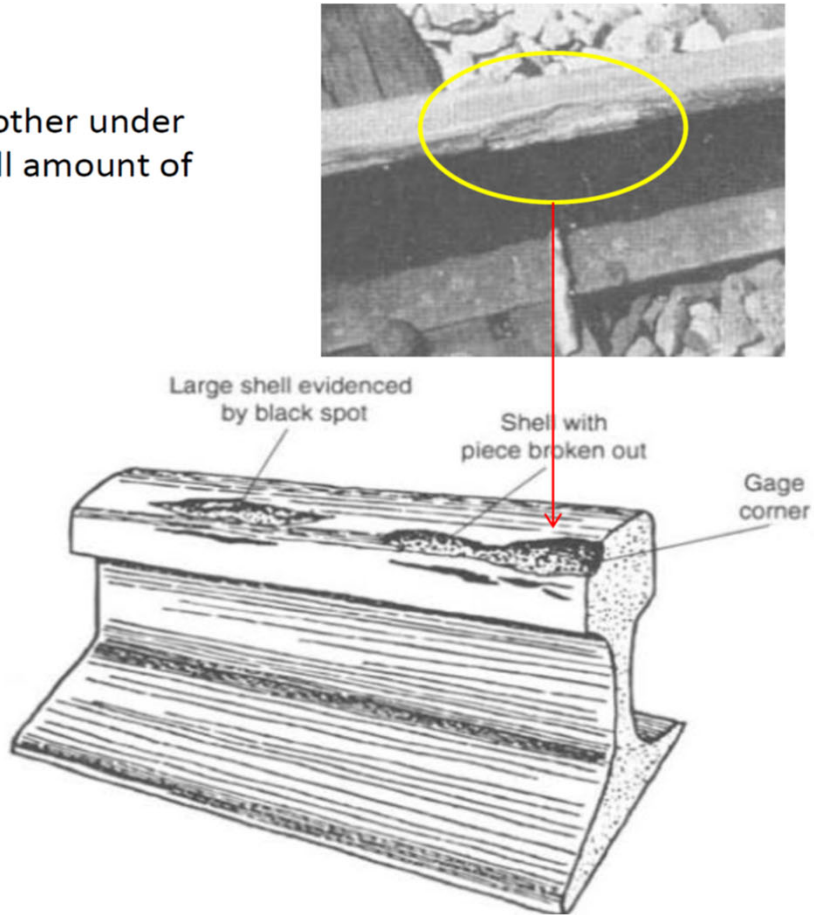
Fatigue Wear

Surface fatigue

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

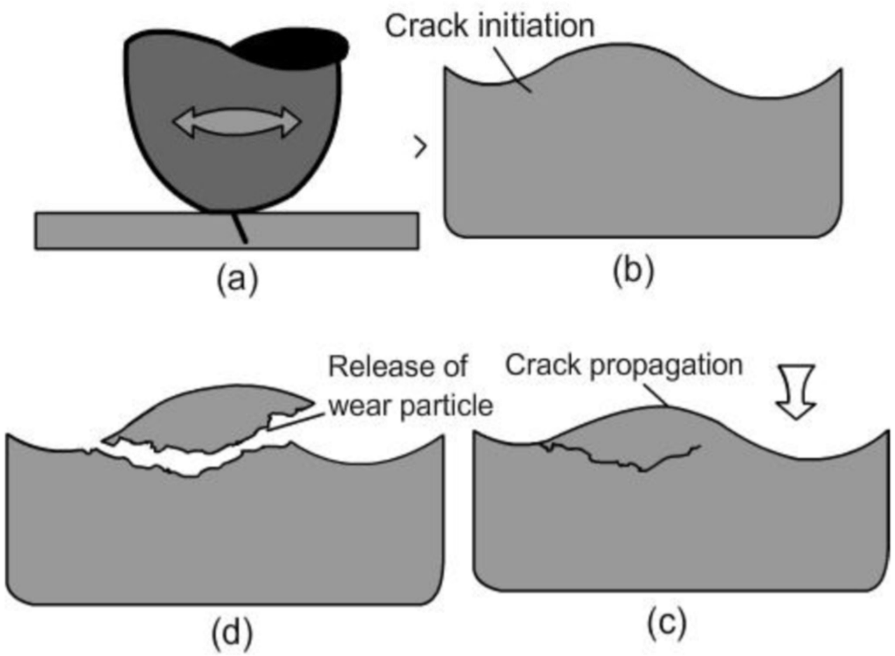
Contact fatigue

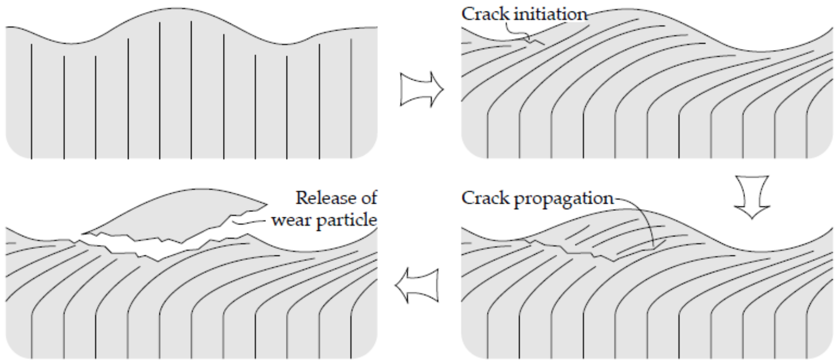
- As one element rolls many times over the other element
- Maximum shear stress is higher than fatigue limit



Fatigue wear steps

Mechanism of fatigue wear.



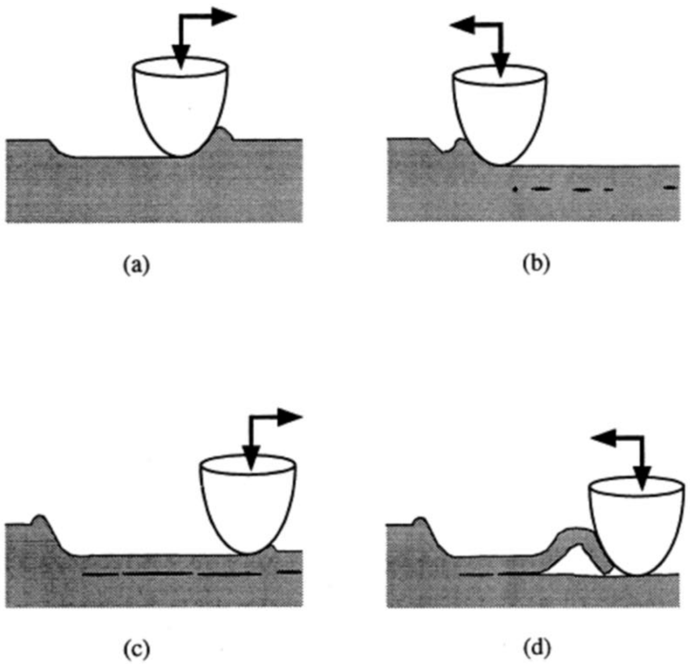


Delamination wear

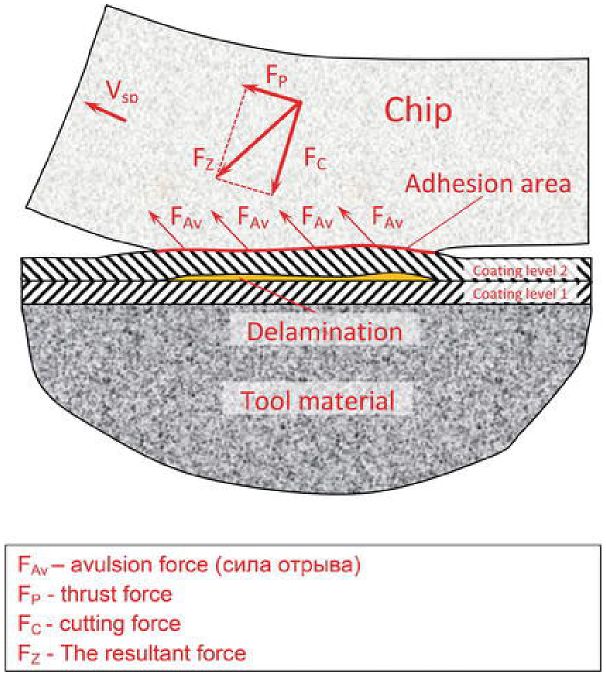
A wear process where a material loss from the surface by forces of another surface acting on it in a sliding motion in the form of thin sheets.

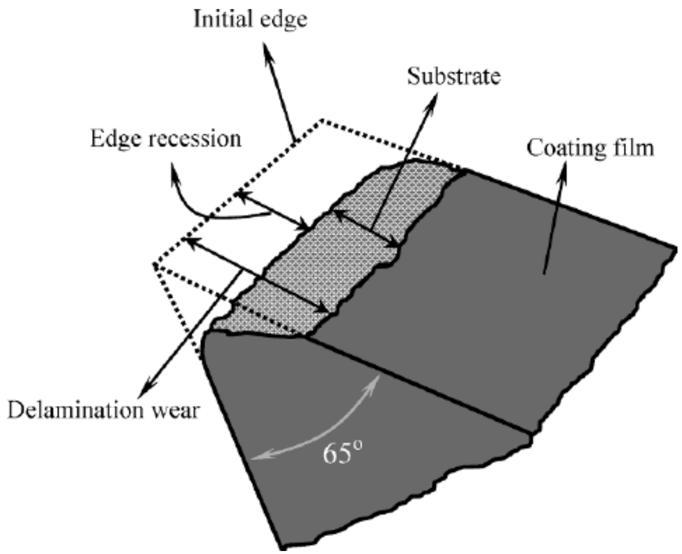
Mechanisms of delamination wear

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



Delamination Wear





Corrosive wear

Corrosive wear is defined as “a wear process in which chemical or electrochemical reaction with the environment predominates” (OECD, 1969).

In many cases, the mechanochemical mechanism combined of chemical reaction and mechanical action enhances the corrosive wear.

Corrosive Wear also known as oxidation or chemical wear, this type of wear is caused by chemical and electrochemical reactions between the surface and the environment. The fine corrosive products on the surface constitute the wear particles in corrosive wear.

Chemical wear

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

Stages of corrosive wear :

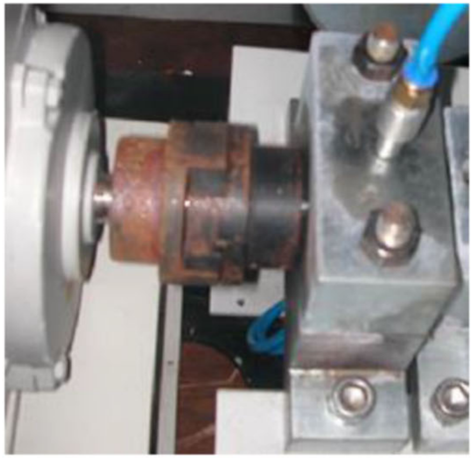
- Sliding surfaces chemically interact with environment (humid/industrial vapor/acid)

- A reaction product (like oxide, chlorides, copper sulphide)

- Wearing away of reaction product film.

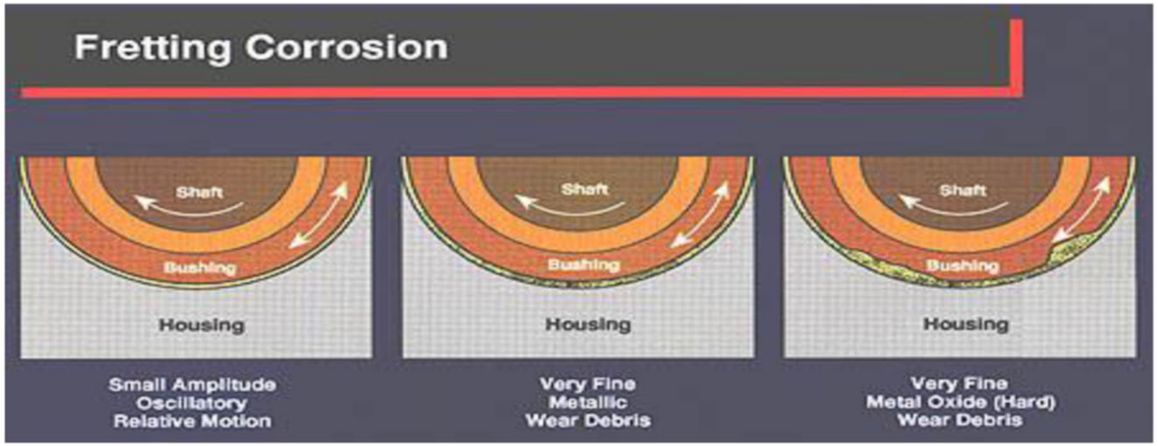
Corrosive wear

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



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



Fretting wear is a phenomenon that can occur between two surfaces which have a relative oscillatory motion of small amplitude, usually only a few tens of microns. The main characteristic of a fretting contact in ferrous material pairs is the appearance of reddish-brown debris made up of particles of the hard oxides of iron.   These can act as a grinding paste or lap producing highly polished patches on the fretted contact.

wear resistance measurement

Unlike many other engineering properties, wear resistance does not have well standardized tests for its measurement.

The main reason for this is the complexity of wear, which tends to make the tests highly specific and make translation of wear test data into valid predictions of service performance very uncertain

Abrasion Test according to

- ISO 9352
- ASTM G65 (Dry Sand) test
- ASTM D 968-93 (inorganic material)
- ASTM D1044, D3389, D4060 (Taber Abrasion: plastic's resistance to abrasion)

wear resistance measurement

Weight loss

Volume loss

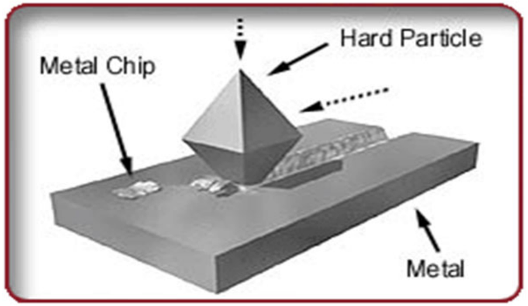
The volume loss gives a truer picture than weight loss, particularly when comparing the wear resistance properties of materials with large differences in density.

Particle Volume

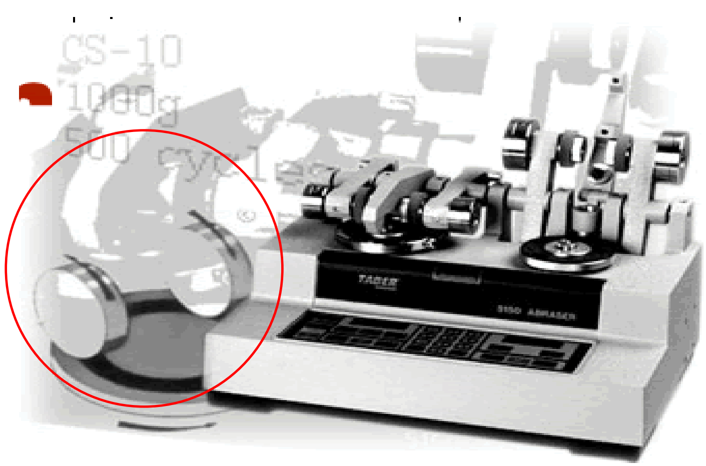
The abrasive wear theory expresses the total volume of wear particles generated V, per unit of sliding length L

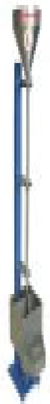
Abrasive Wear Test

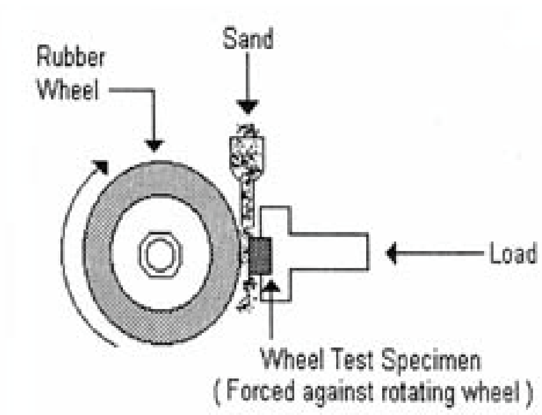
Depending on the material being examined, different wear test configurations can be used.



Taber Abrasion







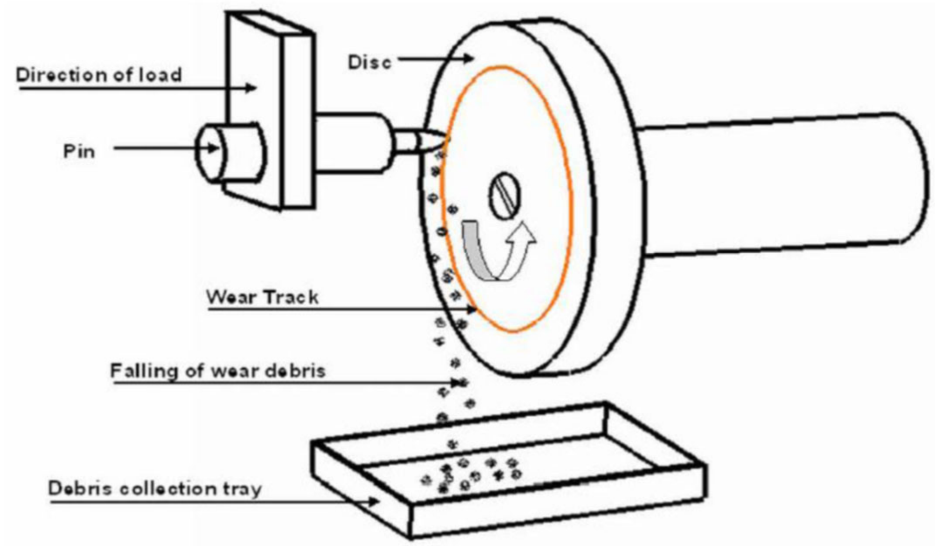
TRIBOLOGICAL INSTRUMENTS

TRIBOMETER

- Measures tribological quantities, such as coefficient of friction, friction force, and wear volume.
- Invented By- Dutch scientist Musschenbroek.

TRIBOMETER

EXPERIMENTAL SET-UP



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

Testing Methods for Abrasive Wear

Group 1: The specimen pin slides over the fixed abrasive particles. This causes two body abrasive wear.

1. Pin on abrasive disc
2. Pin on abrasive plate
3. Pin on abrasive drum

Group 2: Loose abrasive particles are supplied as dry powder or mixed with liquid to form a slurry.

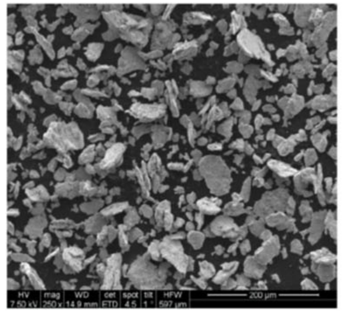
1. Rubber wheel abrasion test
2. Micro scale abrasion test

WEAR RATE

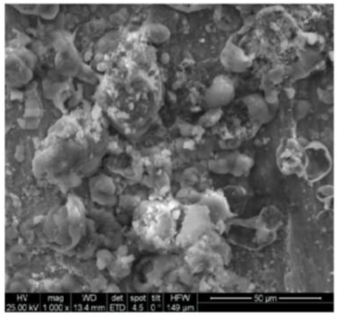
Wear rate of Ti-6Al-4V under ambient condition at 1kg,4kg and 8kg

SEM ANALYSIS

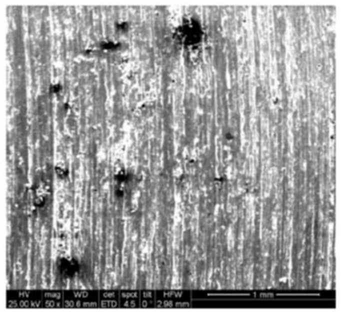
Abrasive wear



AT AMBIENT CONDITION



Speed 0.1m/sec at 1kg



Speed 0.8m/sec at 1kg

Source :Materials engg,IISc,Bangalore

Wear Prevention

• Common approaches to minimizing wear are:
-Lubricants (Use oil free of abrasive particles, Use more viscous oil, frequent oil changes)
-Recognizing the type of wear
-Making changes in the operation
-Making changes in the design (Wear resistance materials, Surface-hardening treatments).

• Surface-hardening treatments for reducing wear include:
- case carburizing commonly used in engine crankshafts,
- ion implantation used in surgical instruments
- hard-faced ceramic coatings used in turbine blades and fiber guides in the textile industry .

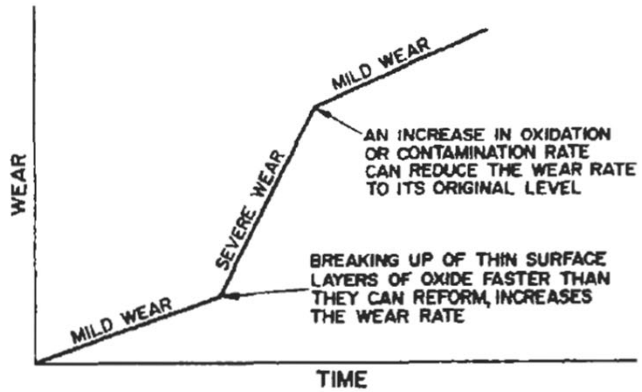
IDENTIFICATION OF WEAR MECHANISM

❑ 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



Wear resistance materials

1- Austenite manganese steel
2- Hardened and tempered alloy steel
3- Abrasion resistant cast-iron
4- High chromium steel
5- Based (nickel ,iron or cobalt alloyed) matrix containing tungsten or titanium carbides particles.

Using such a combination, both high degrees of hardness and toughness can be obtained

Wear resistance of ferrous alloys

Requirement: combination of hardness and toughness
Usually, austenite and bainite phase are better than martensite, by fatigue mechanism
Low alloy steels:
Hypo-eutectoid: Bainite > Tempered martensite > ferrite/pearlite
Hyper-eutectoid: Annealed with presence of carbides is best

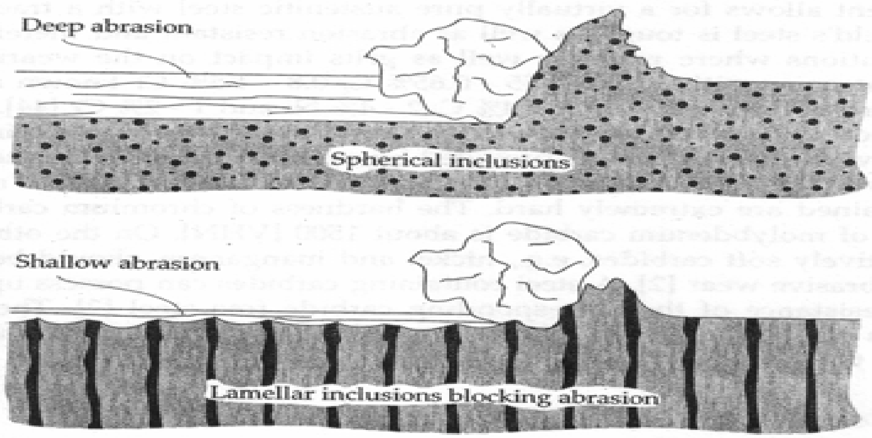


FIGURE 11.19 Influence of carbide inclusion morphology on the abrasion process.

Coatings methods

These coatings are traditionally applied using a variety of methods such as:

- weld overlays (MIG, plasma transfer arc, laser-cladding)
- thermal spray processes (high velocity oxygen fuel, plasma spray)
- Brazing

Typical Low Stress Abrasive Wear Rankings

Low Wear Rate (best)	Thermally Sprayed WC/Co
	Plasma Sprayed Chromium Oxide
	Plasma Electrolytic Oxidation
	Plasma Sprayed Alumina
	CVD CrN
	CVD CrC
	Nitrided 316 Stainless Steel
	Thin PVD Ceramic
	Thermochemically Formed Ceramic
	Hard Chrome Plate
	Carburised Steel
	Electroless Nickel/SiC
	Anodised Aluminium Alloy
	Hardened Electroless Nickel
	As-Plated Electroless Nickel
	Austenitic Stainless Steel
High Wear Rate (worst)	Aluminum Alloy

Typical high Stress Abrasive Wear Rankings

Low Wear Rate (best)	Thermally Sprayed WC/Co
	CVD CrC
	CVD CrN
	Salt Bath Carbide Diffusion Coating
	Thick PVD Ceramic Coating
	Hard Chrome Plate
	Sprayed and HIPPED CrC/Ni/Cr
	Plasma Sprayed Alumina
	Electroless Nickel/SiC
	Boronised Stainless Steel
	Plasma Sprayed Chromium Oxide
	Spray Fused Ni/Cr/CrC
	Carburised Steel
	Induction Hardened Steel
	Thermo chemically Formed Ceramic
	Nitride 316 Stainless Steel
	Hardened Electroless Nickel
	As-Plated Electroless Nickel
	Thin PVD Ceramic
High Wear Rate (worst)	Anodized Aluminum Alloy

Lubricant

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.

Role of lubricants

1. Change surface energy (monolayer)
2. Reduce metal to metal contact through wetting
3. Prevent particle agglomeration through wetting

LUBRICATION

- Thin layers of gas, liquid and solid interposed between two surface.
- Layers of material separate contacting solid bodies.
- The thicknesses of these films range from 1 - 100 [pal].
- Main aim of lubrication is to reduce the wear and friction.

TYPES OF LUBRICATIONS

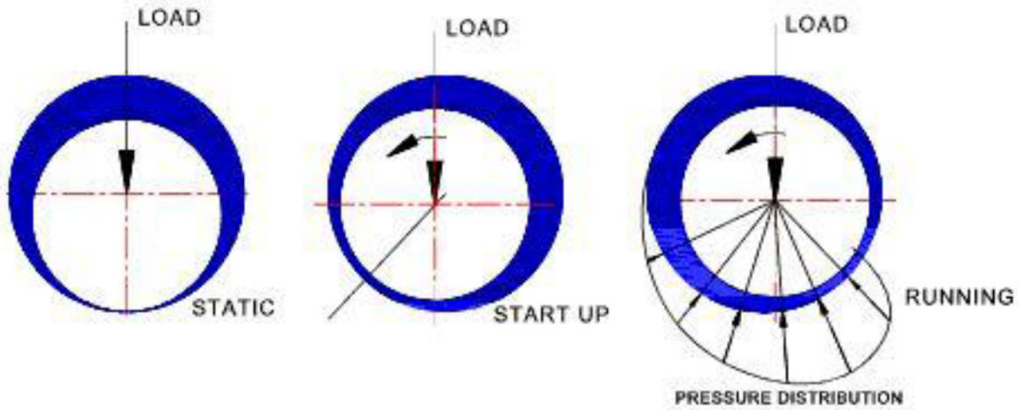
- **Hydrodynamic lubrication-** Analysis of Gaseous or liquid films is usually termed
- **Solid lubrication-** Lubrication by solids is termed, Ex. Graphite
- **Elastohydrodynamic lubrication-** Physical interaction between the contacting Bodies and the liquid lubricant.
- **Hydrostatic lubrication**- Complete separation of sliding surfaces with negligible wear and very low friction. Applied to aerostatic and hybrid bearings.

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**

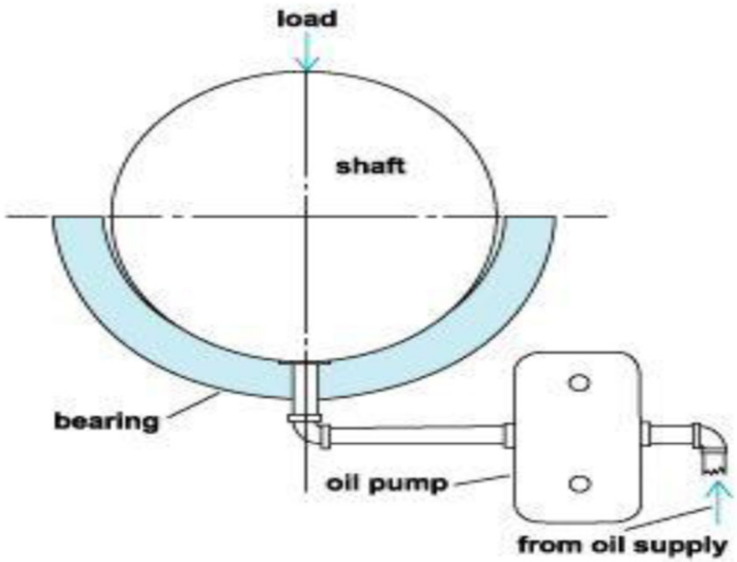
- Hydrodynamic lubrication depends on the relative speed between the surfaces, oil viscosity, load, and clearance between the moving or sliding surfaces.
- In hydrodynamic lubrication the lube oil film thickness is greater than outlet, pressure at the inlet increases quickly, remains fairly steady having a maximum value a little to the outside of the bearing center line, and then decreases quickly to zero at the outlet.



LOAD
STATIC
LOAD
START UP
LOAD
RUNNING
PRESSURE DISTRIBUTION

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



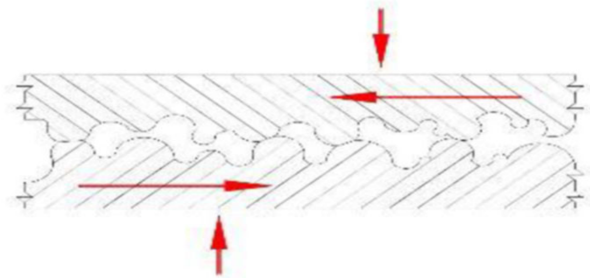
Hydrostatic Lubrication

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.

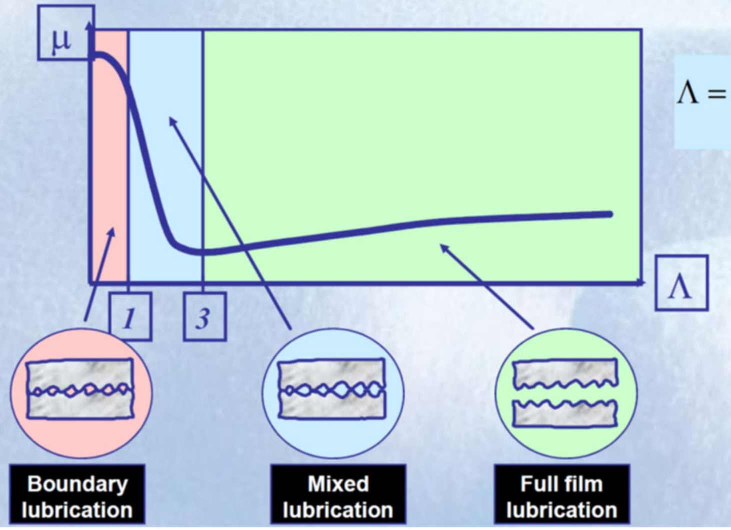


Boundary Lubrication

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).

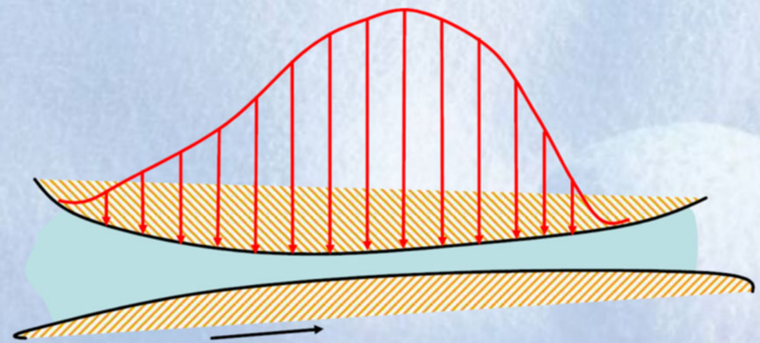
Lubricated Friction Classification



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

Full film lubrication: The lubricant film separates the surfaces

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



EHL - What is that?

Elastohydrodynamic lubrication (EHL)

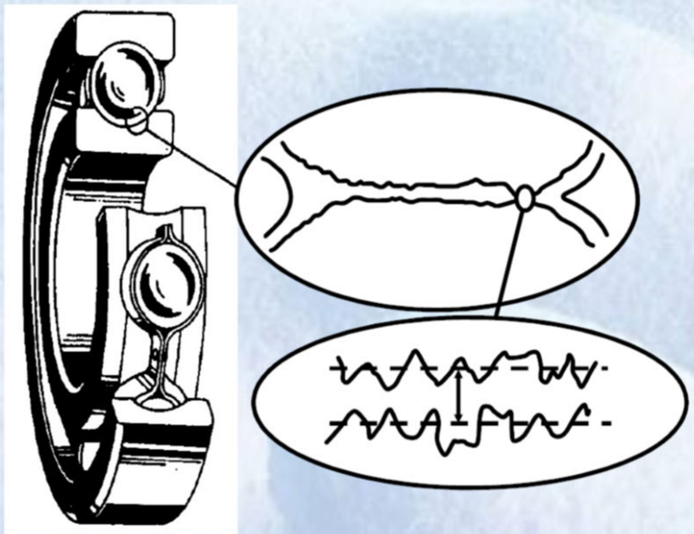
Non-conformal surfaces → small contact region

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

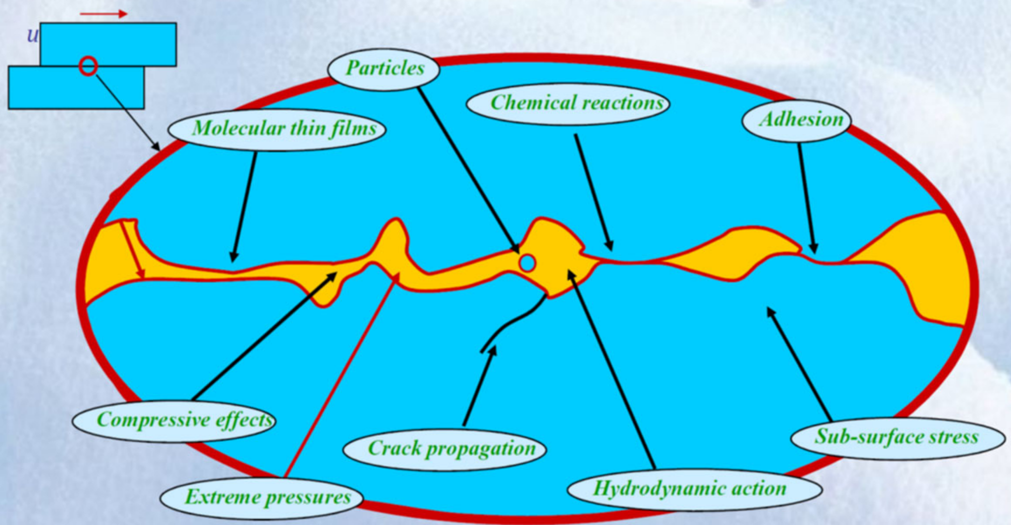
The surfaces are deformed

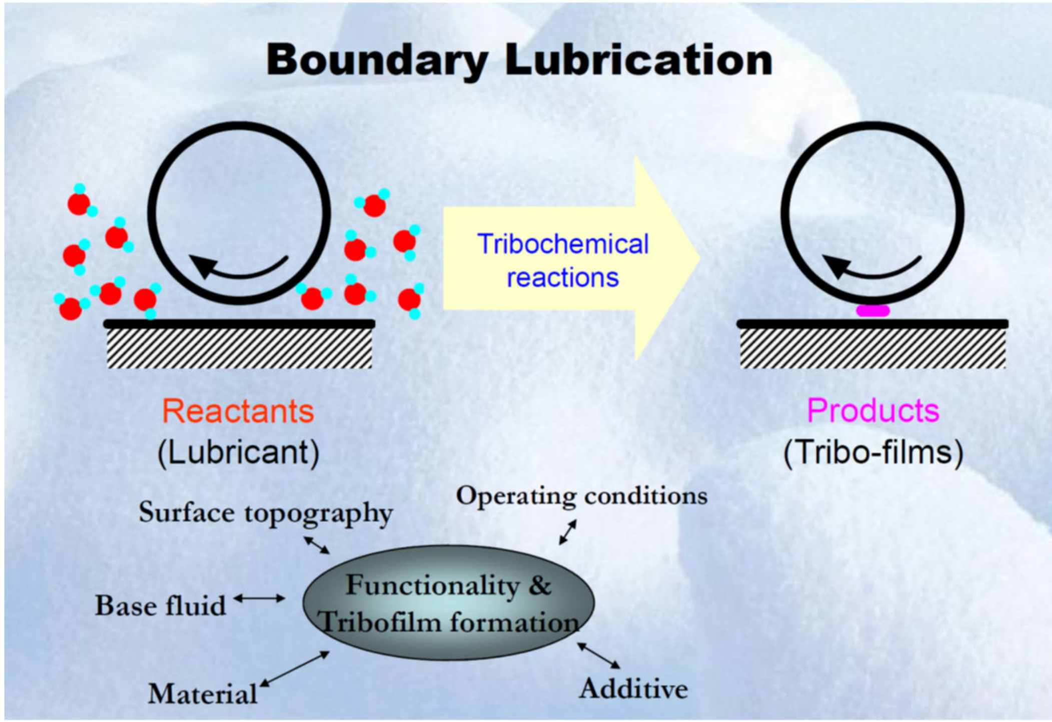
Thin lubricant films <1µm

Example: the ball bearing



Lubricated Contacting Surfaces




Boundary Lubrication
Tribochemical reactions
Reactants
(Lubricant)
Products
(Tribo-films)
Surface topography
Operating conditions
Base fluid
Functionality &
Tribofilm formation
Material
Additive

Viscosity

Introduction

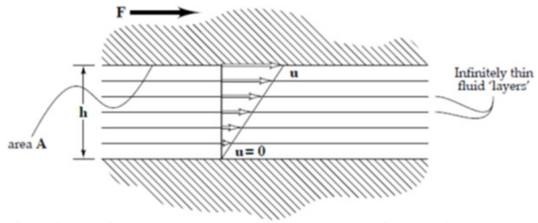
- Viscosity is a quantitative measure of a fluid's resistance to flow.

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.

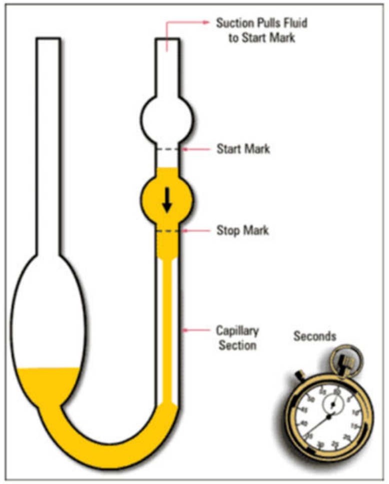
$$\nu = \eta/\rho \quad m^2/s \quad ; \quad \rho = \text{density of fluid}$$

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.

$$\upsilon = \pi r^4 glt \ / \ 8LV = k(t_2 - t_1)$$



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.

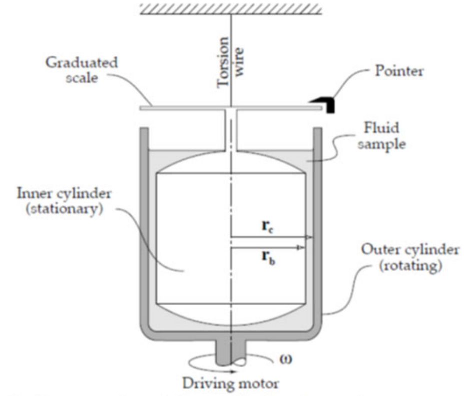
Viscosity Measurements

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.

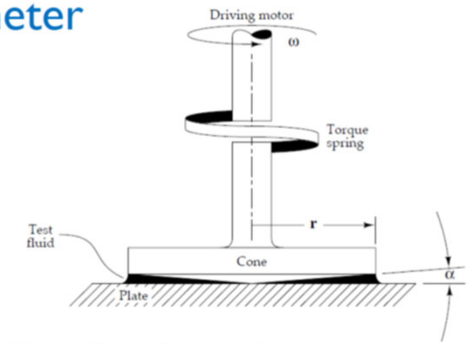
$$\eta = M(1/r_b^2 - 1/r_c^2) / 4\pi d\omega = kM / \omega$$

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.

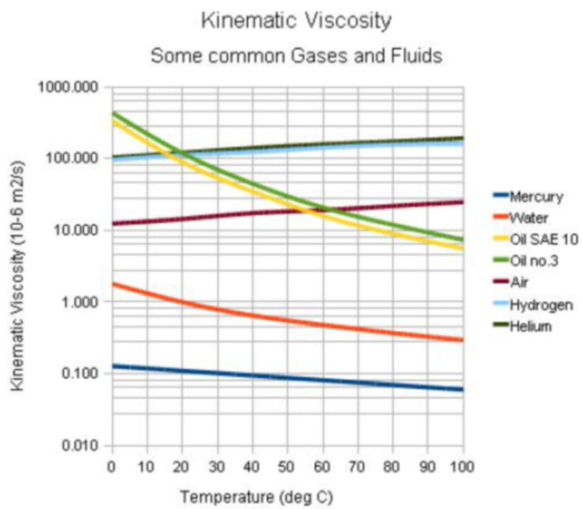
$$\eta = 3M\alpha\cos^2\alpha(1 - \alpha^2/2) \; / \; 2\pi\omega r^3 = kM \; / \; \omega$$

where:

η	is the dynamic viscosity [Pas];
r	is the radius of the cone [m];
M	is the shear torque on the cone [Nm];
ω	is the angular velocity [rad/s];
α	is the cone angle [rad];
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	$\eta = \mathbf{b}e^{-\mathbf{a}\mathbf{T}}$	Early equation; accurate only for a very limited temperature range
Slotte	$\eta = \mathbf{a}/(\mathbf{b}+\mathbf{T})^{\mathbf{c}}$	Reasonable; useful in numerical analysis
Walther	$(\upsilon + \mathbf{a}) = \mathbf{b}\mathbf{d}^{1/\mathbf{T}^{\mathbf{c}}}$	Forms the basis of the ASTM viscosity-temperature chart
Vogel	$\eta = \mathbf{a}e^{\mathbf{b}/(\mathbf{T}-\mathbf{c})}$	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

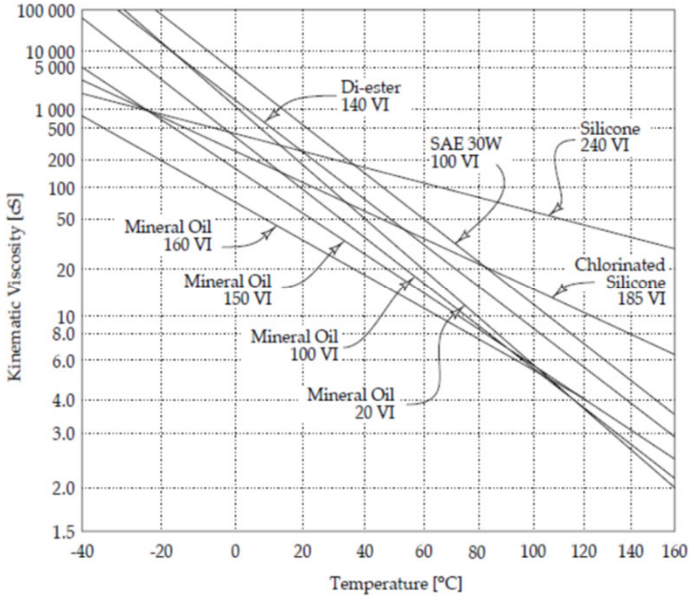


fig: Viscosity-temperature characteristics of selected oils

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

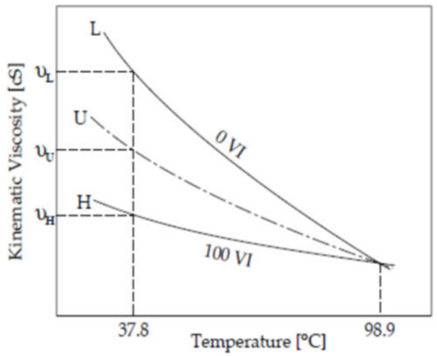


Fig . Sh

Effects of pressure

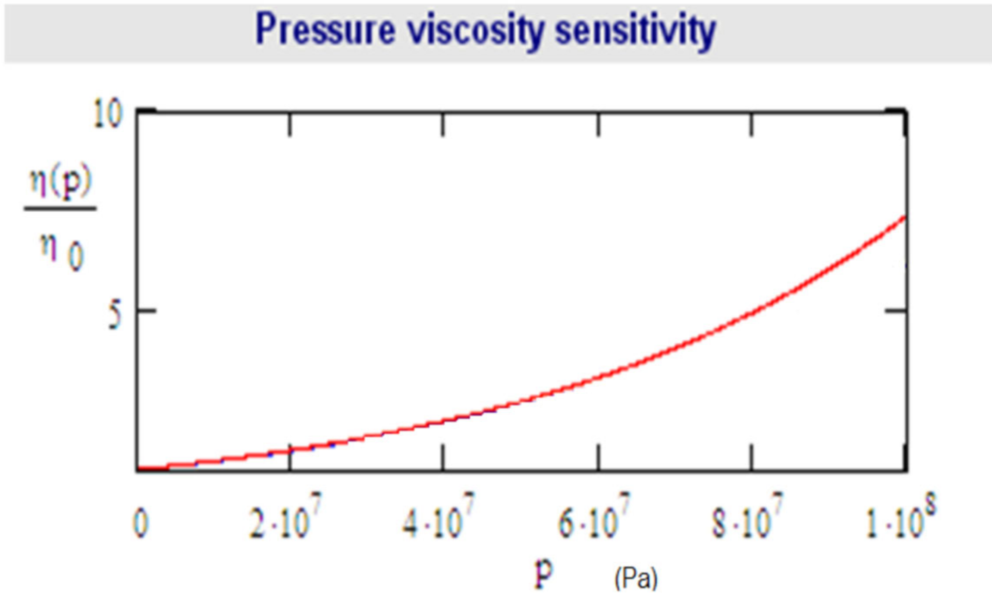
- Lubricants viscosity increases with pressure.
- For most lubricants this effect is considerably largest than the other effects when the pressure is significantly above atmospheric.
- The Barus equation :

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

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].

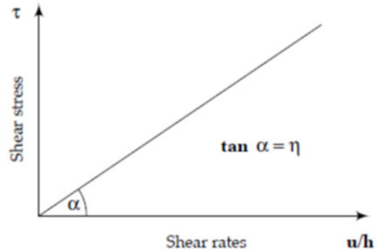
Effects of pressure



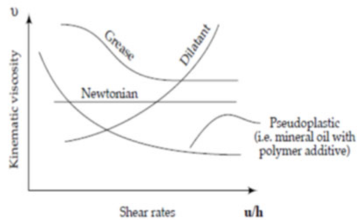
Viscosity - shear relationship

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

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



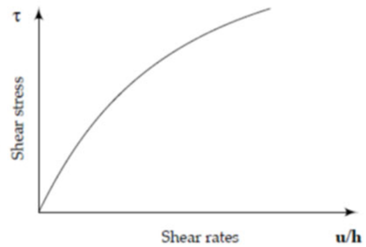
- Non Newtonian fluid doesn't follow the linear relation between viscosity and shear rate.

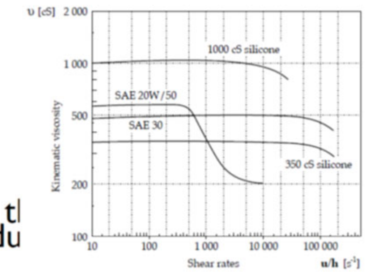


Viscosity – shear relationship

Pseudoplastic Behaviour

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

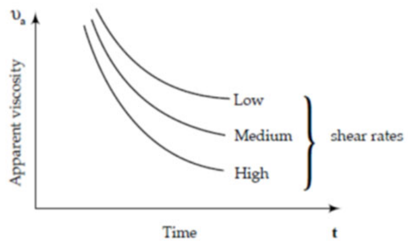




T

- ation tl the du a loss of

- 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.

Future challenges in tribology

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