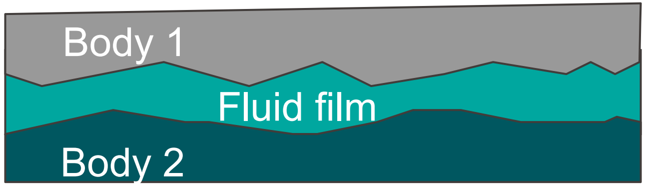
Chapter 4
Lubrication

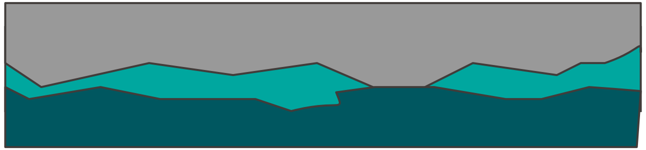
MSE 485
Tribology

1 Lubrication regimes
2 Fluid lubrication
3 Stribeck’s curve
4 Boundary lubrication
5 Lubricants

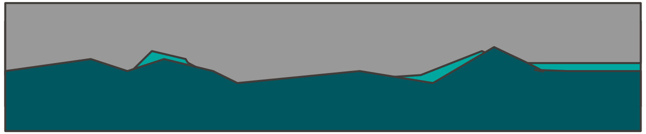
Regimes of fluid lubrication



Hydrodynamic regime
The film is thick enough to entirely separate the two surfaces.

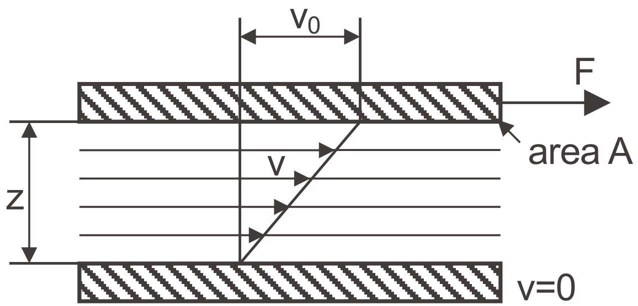


Mixed regime



Boundary regime
The film is not thick enough to separate the two surfaces. The friction is determined by the contacts between asperities.

Viscous flow



$$F/A = \eta \cdot v_0/z \quad \text{ou} \quad \tau = \eta \cdot dv/dz$$

η : dynamic viscosity [Pa s] f(fluid, temperature, pressure)

Reference values for viscosity [mPa s]				
Lubricant	30° C	60° C	100° C	***α*** at 130° C
Water	0.8	0.5	0.3	0
Light oil	40	12	4	28
Heavy oil	120	30	8	28
Castor oil	360	80	18	16

$$\eta_p = \eta \cdot e^{\alpha P}$$

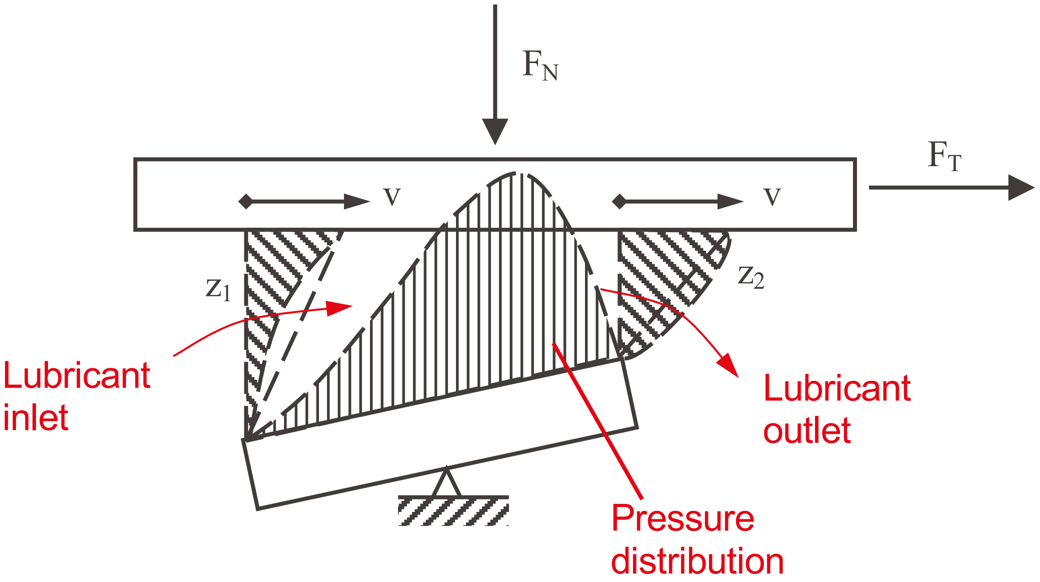
P: pressure [GPa] *(<0.5 GPa)*

α: visco-pressure coefficient

η_0: viscosity at atmospheric pressure

Effect of a convergence on the flow

- The velocity profile is distorted
- An hydrodynamic pressure appears



Tilting pad bearing

Source: Czichos, Tribology, Elsevier (1978)

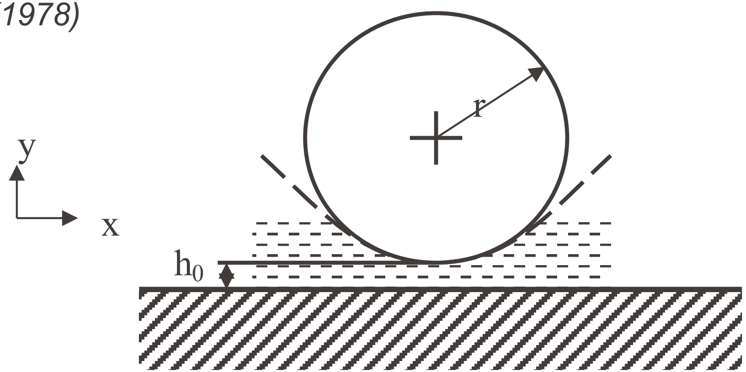
Formalism for hydrodynamic lubrication: Reynolds equation (1886)

- Based on Navier-Stokes equation for fluid mechanics, it allows to calculate the thickness of the lubricant film formed in the contact.

- Assumptions
  - The fluid is Newtonian
  - The flow is laminar
  - The fluid adheres to the walls
  - The fluid film is incompressible, and of negligible inertia and weight

Formalism for the cylinder/plate contact

Source: Czichos, Tribology, Elsevier (1978)



- Thickness of the film h_0 :

$$h_0 = 2.45 \cdot r \cdot L \cdot \eta \cdot v / F_N$$

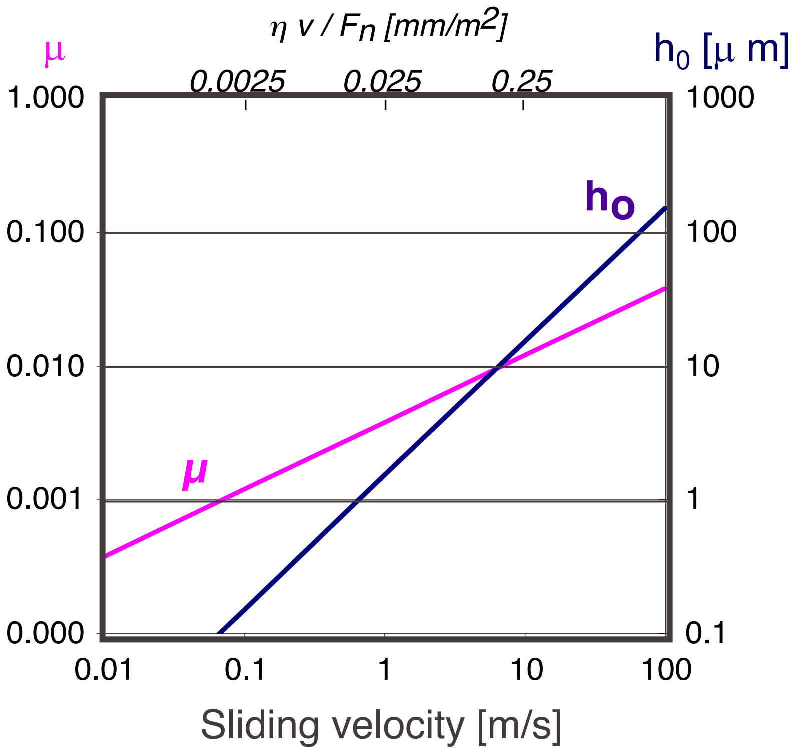
  L= length of the cylinder
  η = fluid viscosity
  v= linear speed of the cylinder relatively to the plate
  F_N= normal load

- Coefficient of friction :

$$\mu = 0.76 \cdot L^{0.5} \cdot (\eta \cdot v / F_N)^{0.5}$$

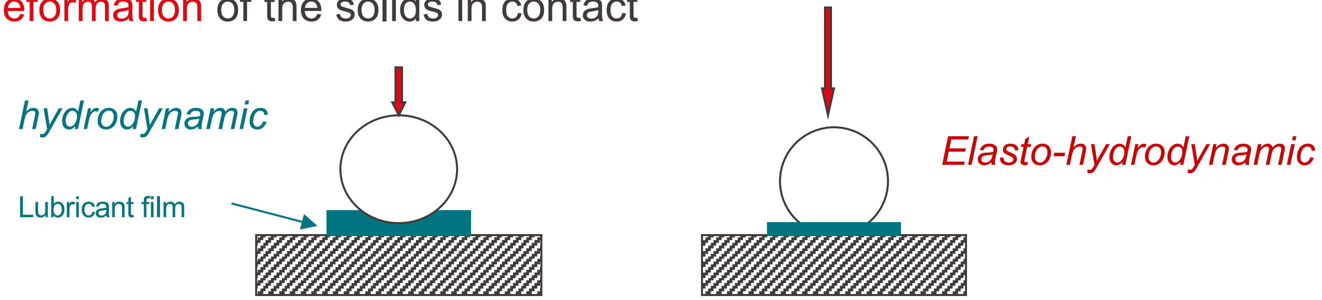
Application to a cylinder/plane contact

- Numerical calculation for F_n 400 N, η 0.1 Pa s, r 25 mm, L 100 mm



Elasto-hydrodynamic lubrication (EHL)

- For high pressures of contact – high loads, non conformal contacts – two phenomena become crucial:
  - Elastic deformation of the solids in contact



  - Increase in viscosity

$$\eta_p = \eta \cdot e^{\alpha P}$$

P: pressure
α: visco-pressure coefficient
η_0: viscosity at atmospheric pressure

- The combination of Reynolds' and Hertz's formalisms forms the basis of the theory of elasto-hydrodynamic lubrication.

Hamrock-Dowson equation for minimum film thickness h_{min} in EHL

$$h_{min} = 2.8 \left(\frac{v_s \eta}{E' R'}\right)^{0.65} \left(\frac{F_n}{E' R'^2}\right)^{-0.21} R'$$

v_s: sliding speed

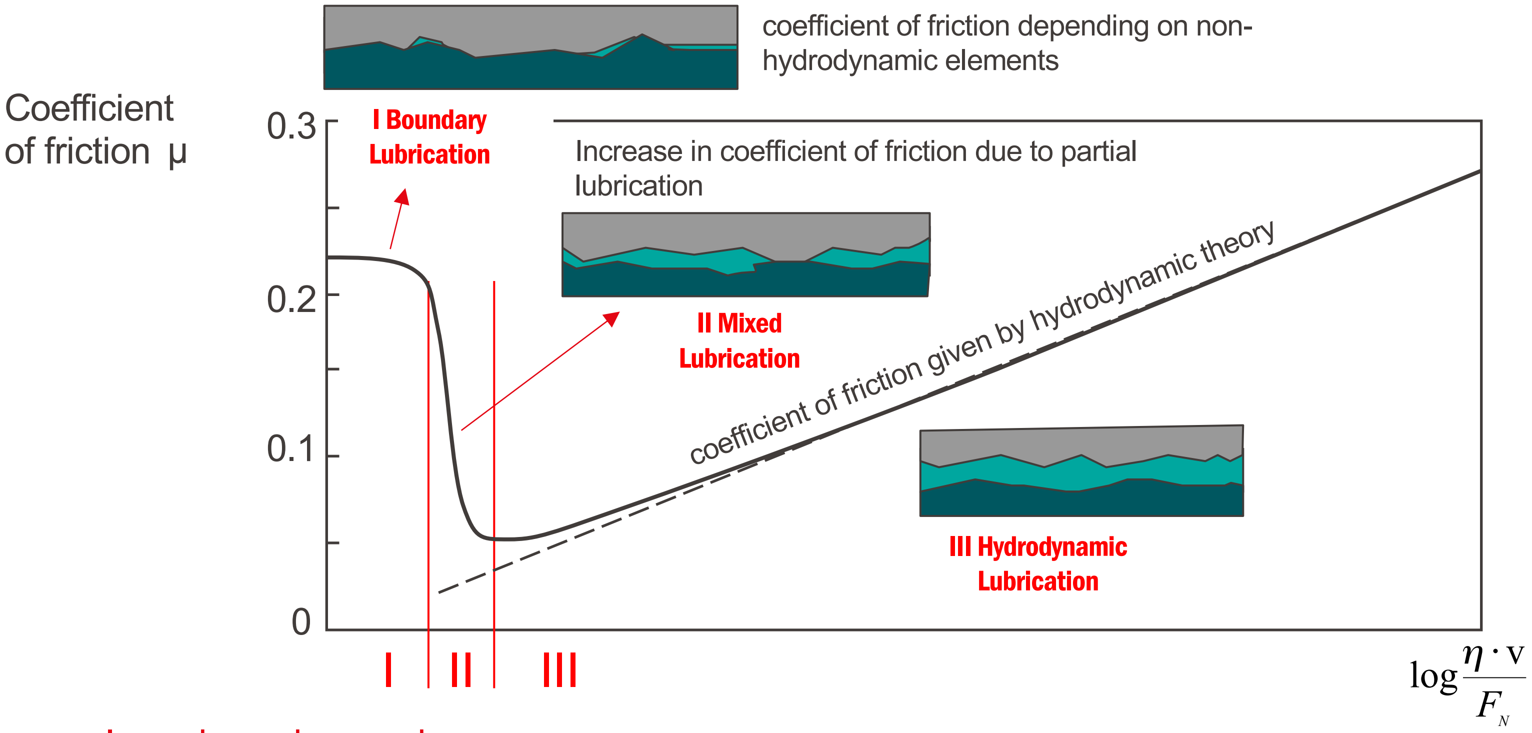
η: fluid viscosity

E’: reduced Young’s modulus

R’: composite radius of curvature (for ball on ball: $1/R' = 1/R_1 + 1/R_2$ where R1 and R2 are the ball radiuses)

F_n: normal force

Stribeck's curve: transitions in lubrication regime



I: boundary regime
II: mixed regime
III: elastohydrodynamic and hydrodynamic regimes

v sliding velocity
η viscosity of the lubricant
F_N normal load

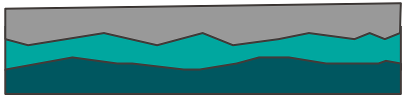
The λ factor: criterion for regime transition

$$\lambda = h_0 / R_q$$

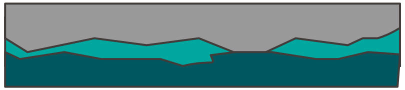
h_0 = *thickness of the hydrodynamic film* $h_0 \propto (\eta \cdot v / F_N)$

R_q = *parameter characterizing the height of asperity*

$\lambda > 3$ Hydrodynamic regime



$1 < \lambda < 3$ Mixed regime



$\lambda < 1$ Boundary regime

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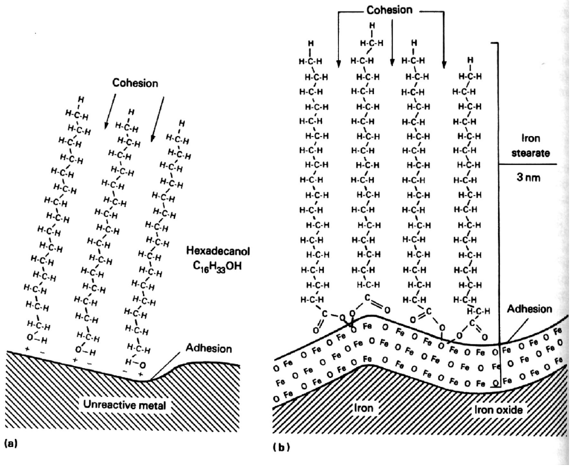
Boundary lubrication

- Intimate contact between bodies
- Controlled by the formation of nanometer-thick films either through adsorption or through chemical reaction on the contacting materials.
- Physico-chemical properties of the oil, of its additives, and of the materials are crucial.



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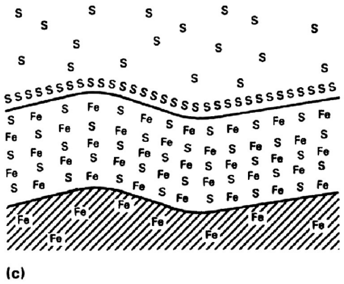

Surface orientation

- Effect of surface orientation and of the size of lubricant molecules on the coefficient of friction. *Hutchings (1992)*

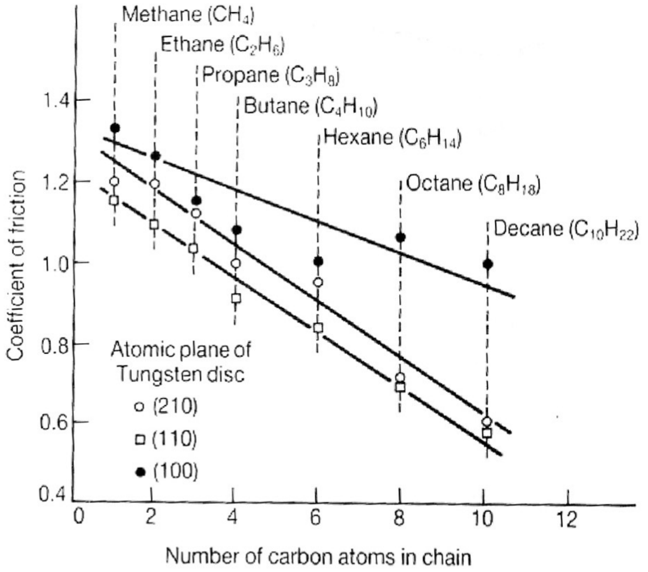

Fig. 4.12 The variation in coefficient of friction with molecular chain length for tungsten surfaces exposed to hydrocarbon vapours in vacuum (from Buckley D H, *Surface Effects in Adhesion, Friction, Wear and Lubrication*, Tribology Series no. 5, Elsevier, 1981)

Lubricants

- **Mineral oils**

  Blend of : 90-95% base oil (mineral or synthetic oil)

  5-10% additives (organic and organometallic compounds)

- The formulation of an oil must take into account application, operating conditions, desired lubrication regime, recycling and … cost.

- The physical properties (viscosity, visco-pressure coefficient, …) of the base oil are determining for hydrodynamic regimes.

- Additives form surface films in boundary lubrication and are determining for the lifetime of the oil and of its physico-chemical reactivity.

Usual types of additives

Type of additive (weight %)	*Properties*	*Microstructure example*
Antioxidant (0.5-3%)	Prevents oxidation, which increases viscosity and creates corrosive compounds	Phenyl naphtylamine, phenols, zinc dialkyldithiophosphate
Corrosion inhibitor (0.05%)	Opposes to the chemical attack of sulphides on non-ferrous metals	Benzotriazole, substitute azoles
Rust inhibitor (0.05-2%)	Opposes to the attack of water/oxygen by absorption on the metallic surface	Long phosphate chain, metallic sulphide
Friction modifier (1-3%)	Antiwear (AW) Extreme pressure (EP)	Zinc dithiosulphide, organosulphide
Pour point depressant	Prevents the formation of wax at low temperatures	Methylmetacrylate polymer
Viscosity modifier	Increases the viscosity of the base oil at high temperature	Long polymeric chain, PMMA, olefin copolymer
Detergent (4%)	Prevents the formation of deposits on the engine, and neutralizes the acids formed during combustion	Metallic sulphide, phenate
Dispersant	Prevents the carbon deposits from coagulating in fuels	Succinimide
Anti-foam agent (0.001%)	Makes foams unstable	Silicone polymers

Lubricants

- **Greases**

Greases consist of a thickener or a gelling agent dispersed in an oil to produce a stable gel maintaining the oil in a matrix structure.

They have applications in mechanisms which are difficult to continuously lubricate with oil. They do not dissipate heat well but are good lubricants.

- **Water-based emulsions**

Emulsion of small oil droplets (1-5 µm) in water. Volume fraction of oil particules 3-10%.

The liquid has a low lubricating power but dissipates heat well.

Major application : cutting fluids.

Lubricants

- **Solid lubricants**

Soft metals : Pb, Sn, Au, Ag, Cu, In, are often used as thin films or as second phase (brass or lead bronze)

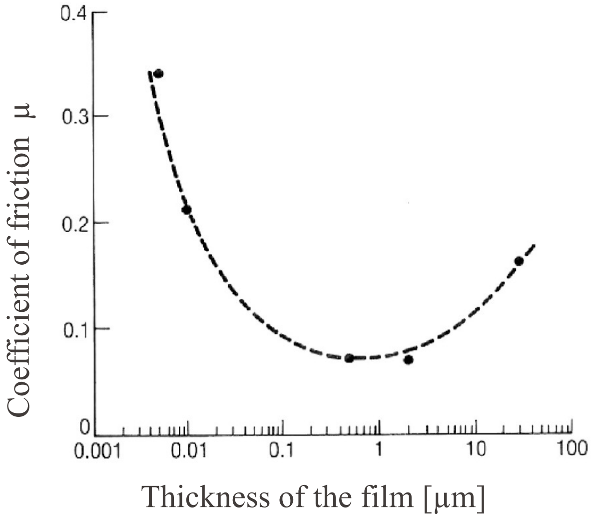

Fig. 4.14 The coefficient of friction for steel sliding against tool steel carrying a thin film of indium metal, plotted against the thickness of the indium film (from Bowden F P and Tabor D, *The Friction and Lubrication of Solids*, Clarendon Press, Oxford, 1950)

Solid lubricants

- *Polymers* : PE, PTFE, PA, PET
- *Non lamellar mineral solids* : a non exhaustive list and with some doubts!

Oxides	B_2O_3, PbO, ZnO, Cu_2O, MoO_3,WO_3, TiO_2
Amorphous	DLC
Chalcogenides	PbS, CdS,Ag_2S, Cu_2S
Halides	BaF_2, LiF, NaF, CaF_2, $CdCl_2$, CdI_2, $CoCl_2$
Phosphates	$Zn_3(PO_4)_2$ hydrates
Molybdates	$PbMoO_4$, $NiMoO_4$
Tungstates	$PbWO_4$, $NiWO_4$

- *Lamellar mineral solids* : MoS_2, graphite, WS_2
- *Blend* : e.g PTFE charged with graphite