Surfaces and Films CHEM-E5150
Wear and Friction

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Relevance of wear and friction

- Wear is major cause of material wastage and mechanical performance - durability
- Friction is major cause of energy dissipation
- About 1/3 of global energy conssumptio is needed to work against friction
- Lubrication to control wear and friction
- Art of surfaces and films

Friction

Co-efficient of Friction

- $F_{tangental}/F_{normal} = \mu$

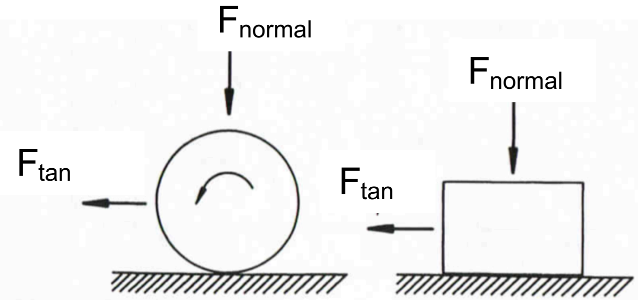

Fig. 3.1 A frictional force, *F*, is needed to cause motion by (a) rolling or (b) sliding

- μ_{static}
- $\mu_{kinetic} < \mu_{static}$

- $\mu = \mu_{adhesion} + \mu_{deformation}$

Traditional laws of friction

The elementary property of sliding (kinetic) friction were discovered by experiment in the 15th to 18th centuries and were expressed as three empirical laws:

- **Amontons' First Law**: The force of friction is directly proportional to the applied load.
- **Amontons' Second Law**: The force of friction is independent of the apparent area of contact.
- **Coulomb's Law of Friction**: Kinetic friction is independent of the sliding velocity.

Approximate coefficients of friction

Materials		Static Friction, μ_s		Kinetic/Sliding Friction, μ_k	
		Dry and clean	Lubricated	Dry and clean	Lubricated
Aluminium	Steel	0.61[26]		0.47[26]	
Aluminium	Aluminium	1.05-1.35[26]	0.3[26]	1.4[26]-1.5[27]	
Gold	Gold			2.5[27]	
Platinum	Platinum	1.2[26]	0.25[26]	3.0[27]	
Silver	Silver	1.4[26]	0.55[26]	1.5[27]	
Alumina ceramic	Silicon nitride ceramic				0.004 (wet)[28]
BAM (Ceramic alloy $AlMgB_{14}$)	Titanium boride (TiB_2)	0.04–0.05[29]	0.02[30][31]		
Brass	Steel	0.35-0.51[26]	0.19[26]	0.44[26]	
Cast iron	Copper	1.05[26]		0.29[26]	
Cast iron	Zinc	0.85[26]		0.21[26]	
Concrete	Rubber	1.0	0.30 (wet)	0.6-0.85[26]	0.45-0.75 (wet)[26]
Concrete	Wood	0.62[26][32]			
Copper	Glass	0.68[33]		0.53[33]	
Copper	Steel	0.53[33]		0.36[26][33]	0.18[33]
Glass	Glass	0.9-1.0[26][33]	0.005–0.01[33]	0.4[26][33]	0.09–0.116[33]
Human synovial fluid	Human cartilage		0.01[34]		0.003[34]
Ice	Ice	0.02-0.09[35]			
Polyethene	Steel	0.2[26][35]	0.2[26][35]		
PTFE (Teflon)	PTFE (Teflon)	0.04[26][35]	0.04[26][35]		0.04[26]
Steel	Ice	0.03[35]			
Steel	PTFE (Teflon)	0.04[26]-0.2[35]	0.04[26]		0.04[26]
Steel	Steel	0.74[26]-0.80[35]	0.005–0.23[33][35]	0.42-0.62[26][33]	0.029–0.19[33]
Wood	Metal	0.2–0.6[26][32]	0.2 (wet)[26][32]	0.49[33]	0.075[33]
Wood	Wood	0.25–0.62[26][32][33]	0.2 (wet)[26][32]	0.32–0.48[33]	0.067–0.167[33]

Wiki

Real surface topography

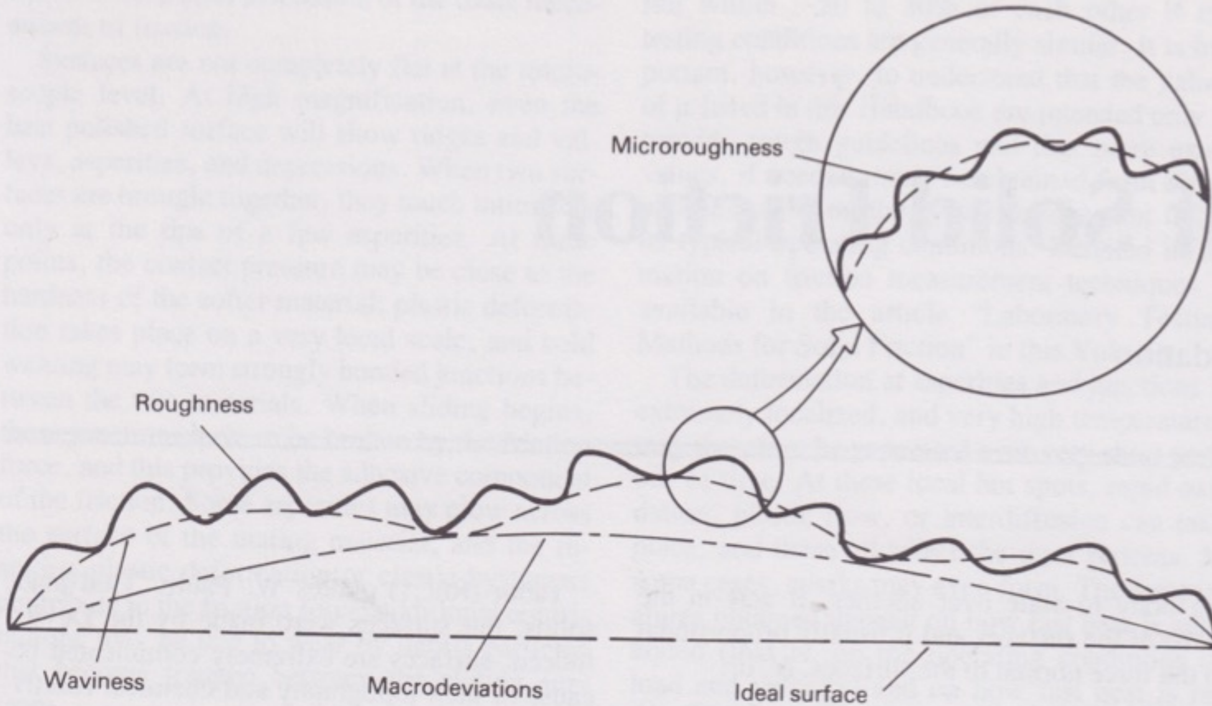

Fig 1 Schematic showing selected types of surface deviations relative to an ideal solid surface

Atomic surface "roughness"

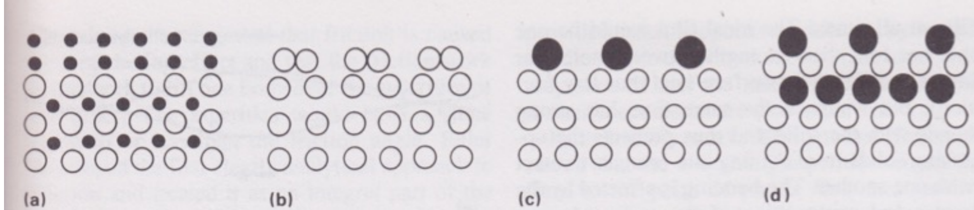

Fig 2 Effect of composition on surface roughness defects. (a) Segregation. (b) Reconstruction. (c) Chemisorption. (d) Compound formation. Source: Ref 8

Metal-Metal adhesion vs. solubility

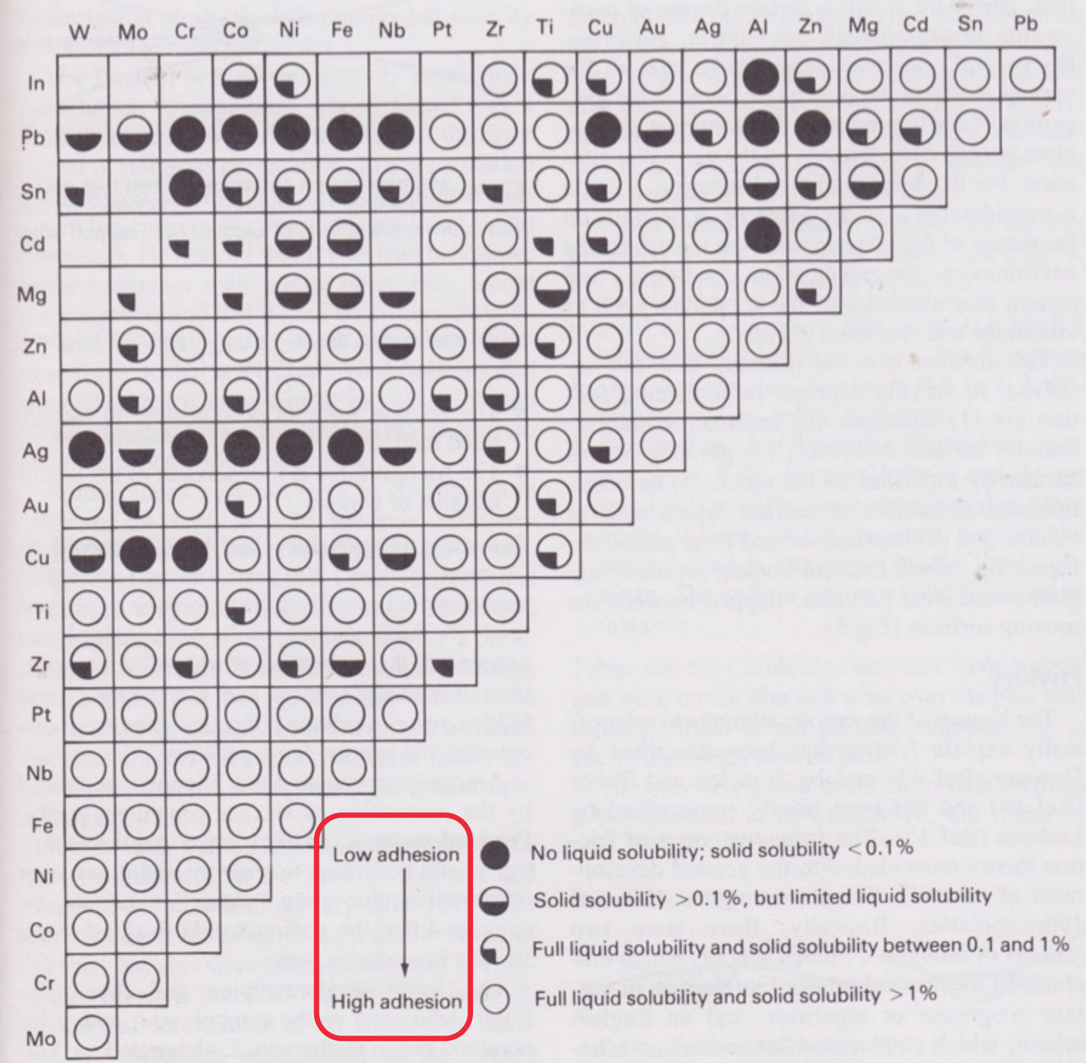

Fig 3 Compatibility chart developed by Rabinowicz for selected metal combinations derived from binary equilibrium diagrams. Chart indicates the degree of expected adhesion (and thus friction) between the various metal combinations. Source: Ref 10

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Surface and subsurface micro structurs in metals

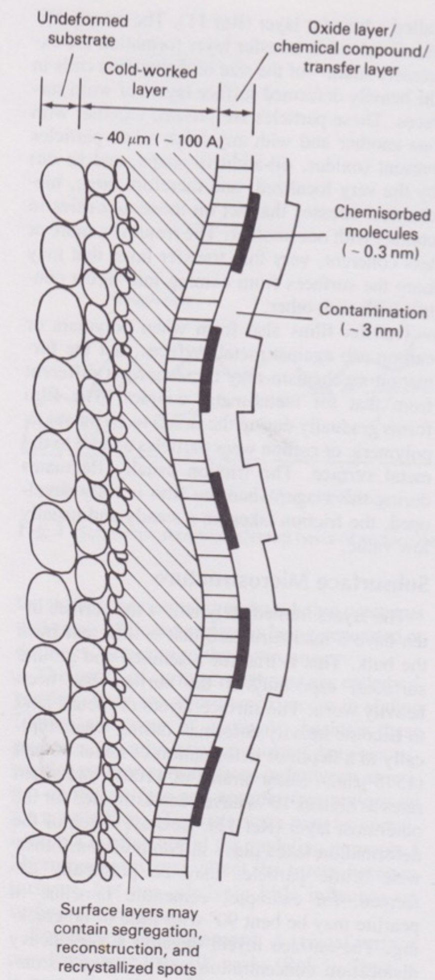

Fig 4 Schematic showing typical surface and subsurface microstructures present in metals subject to friction and wear. Microstructures are not drawn to scale.

Mechanisms which generate friction

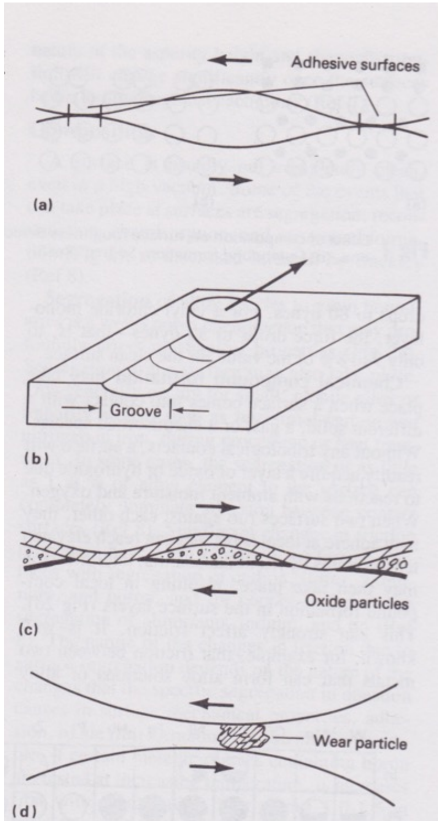

Fig 5 Mechanisms on microscopic level that generate friction. (a) Adhesion. (b) Plowing. (c) Deformation and fracture of oxides. (d) Trapped wear particle

Adhesion

Plowing

Defomation fracture of oxides

Trapped wear particles

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Co-efficient of friction of metals
vs.
d-bond character

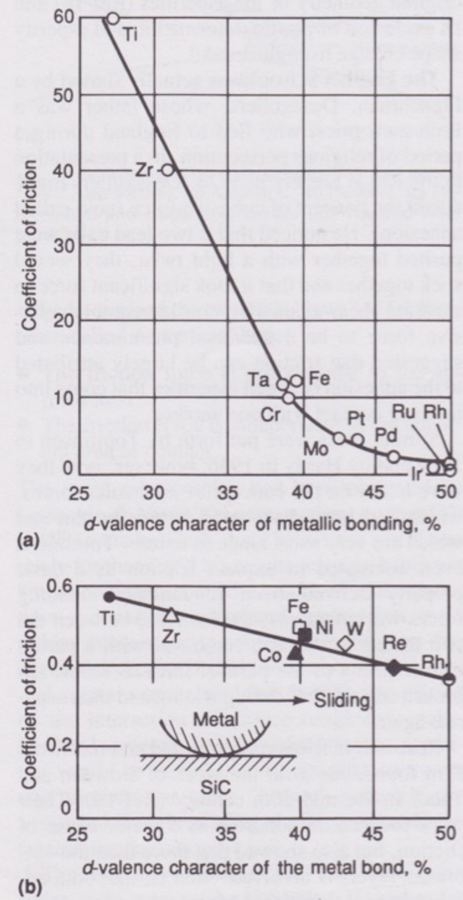

Fig 9 Plot of coefficient of friction in a vacuum versus *d*-bond character of selected metals. (a) Metals in contact with themselves at very low load and sliding velocity. (b) Metals sliding in contact with single-crystal SiC. Source: Ref 19

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Wear

Surface damage:

Changes to microstructure

Plastic deformation

Cracks

Loss of material

Gain of material

Corrosion

Surface damage without exchange of material

Structural changes: Damage by structural changes, such as aging, tempering, phase transformations, recrystallization, and so on.

Plastic deformation: Damage characterized by residual deformation of the surface layer, either locally or extensively. The latter is often revealed as a change in shape.

Surface cracking: Damage caused by excessive local contact strains or cyclic variations of thermally or mechanically induced strains. The latter case can cause dense patterns of parallel cracks whereas thermal cycling lattice generates a network of cracks.

Surface damage involving loss of material: wear

Material loss from the surface leaves behind wear scars of various shapes and sizes. Fundamental elements in the process of material removal can be shear fracture, extrusion, chip formation, tearing, brittle fracture, fatigue fracture, chemical dissolution, and diffusion.

Surface damage involving gain of material

Pickup of loose particles, transfer of material from the countersurface, and so on.

Corrosion: Material degradation by chemical reactions with ambient elements or elements from the countersurface

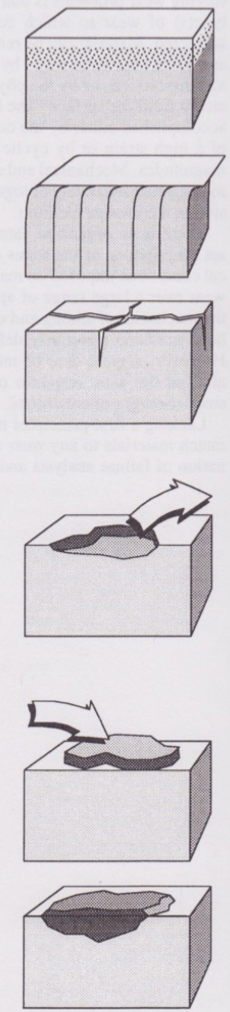

Fig 1 Classification of surface damage

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Tribo events in sliding contact

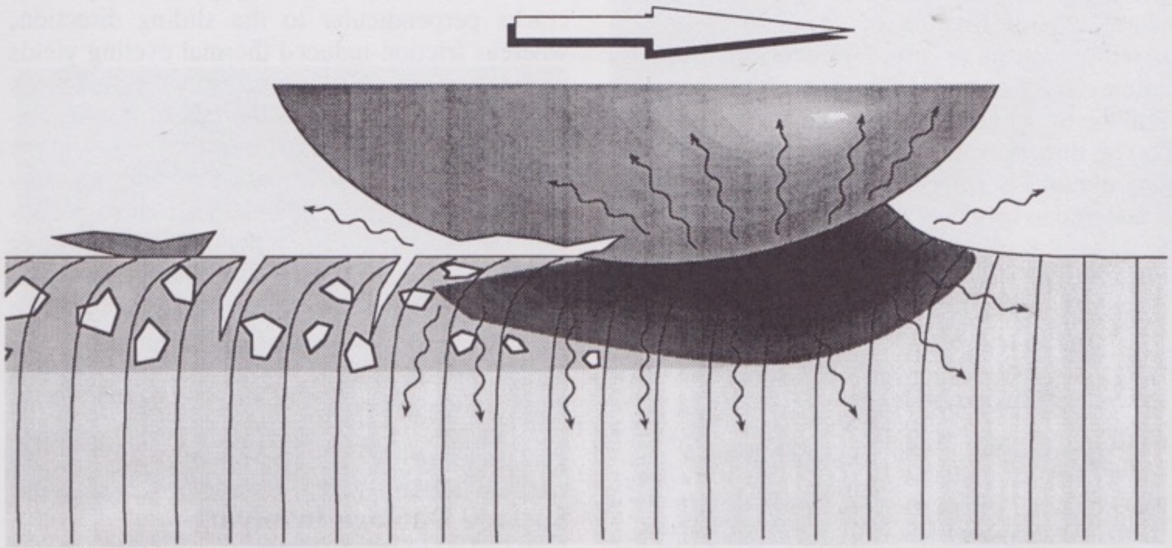

Fig 2 Schematic of a single triboevent generating an active layer by transforming the original surface material under the influence of high normal and shear forces and frictional heat. Relaxation of this layer, involving additional phase transformations, will occur some time after the contacting asperity has passed.

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Wear hard against soft

- chip formation
- plastic deformation
- pickup of ceramic particles

180/ Wear

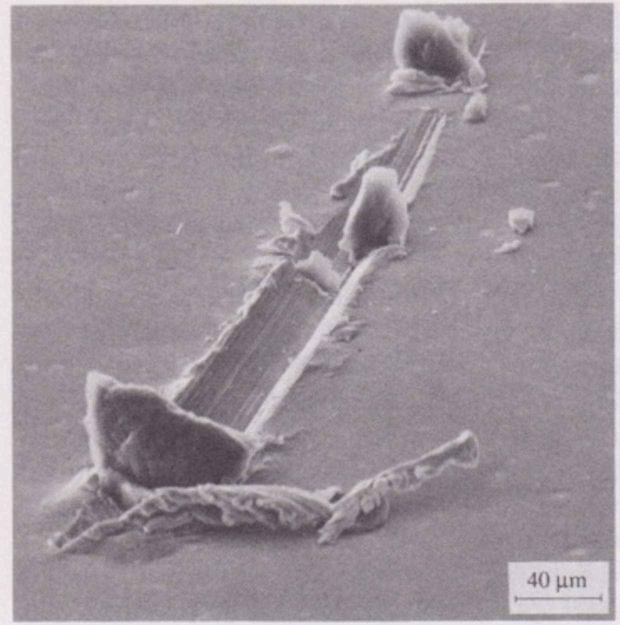

Fig 11 Scanning electron micrograph showing surface damage by chip formation, plastic deformation, and pickup of fragments of a ceramic parti-

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Wear metal against gravel

- chip formation
- plastic deformation
- pickup of silica

Fig 12 Scanning electron micrograph of the surface and cross section of a road grader blade worn against gravel. The surface has been damaged by chip formation, plastic deformation, and pickup of silica, revealed as dark, rough patches at A.

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Soft against hard - tearing

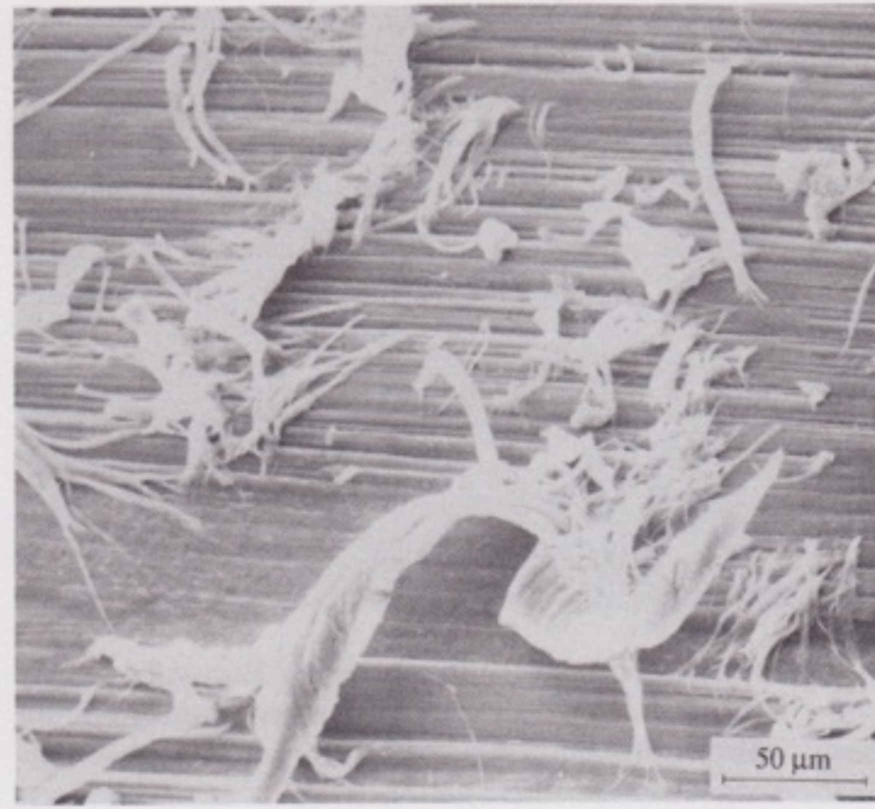

Fig 13 Scanning electron micrograph showing damage caused by tearing in the cylinder surface of a small polytetrafluoroethylene (PTFE) piston pump used to portion human body liquids into an analytical instrument

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Soft against hard
- rolling

Fig 14 Scanning electron micrograph showing roll formation associated with tearing of material from the surface of polyurethane during sliding against a flat metal surface. Sliding direction of counterface was from left to right.

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Brittle fracture

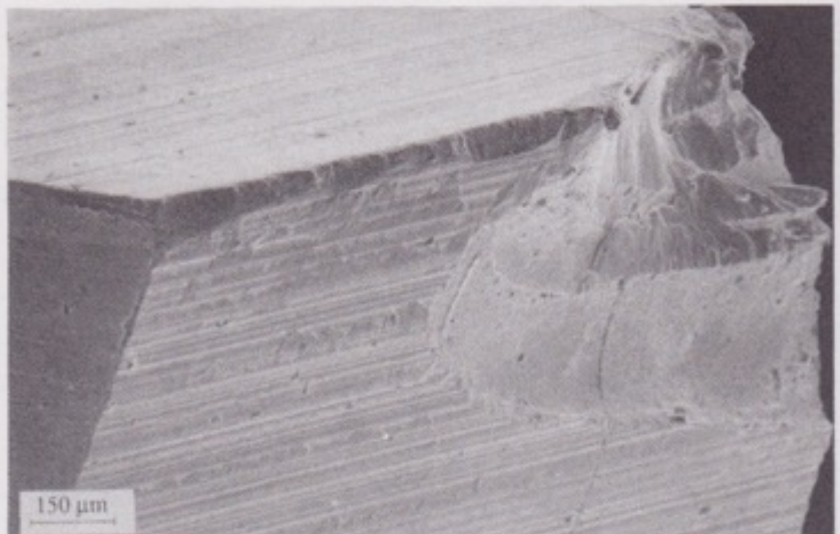

Fig 15 Scanning electron micrograph showing brittle fracture of a cemented carbide tool tip used to cut aluminum

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Brittle fracture of Al_2O_3

due to SiC particle erosion

Fig 16 Scanning electron micrograph showing brittle fracture by particle erosion of an Al_2O_3 surface (250 µm SiC particles, 70 m/s velocity, 90° angle of impingement). Courtesy of Mikael Olsson

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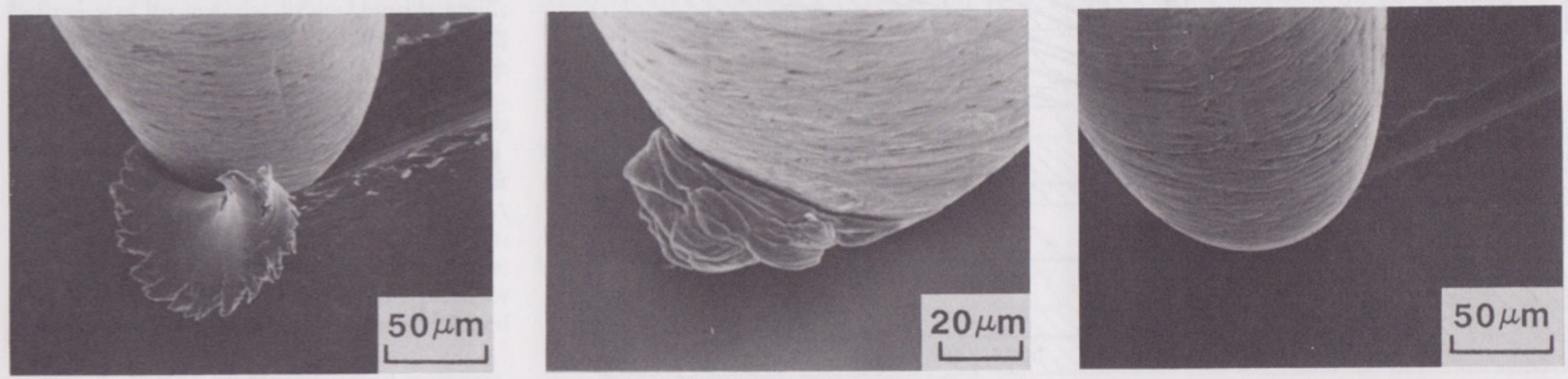
Types of abrasive wear



(a) Cutting (b) Wedge formation (c) Plowing

Fig 3 Examples of three processes of abrasive wear, observed using a scanning electron microscope. (a) Cutting. (b) Wedge formation. (c) Plowing. Source: Ref 5

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Abrasive wear vs. hardness

Hardnesses

$H_{surface}/H_{abrasive}$

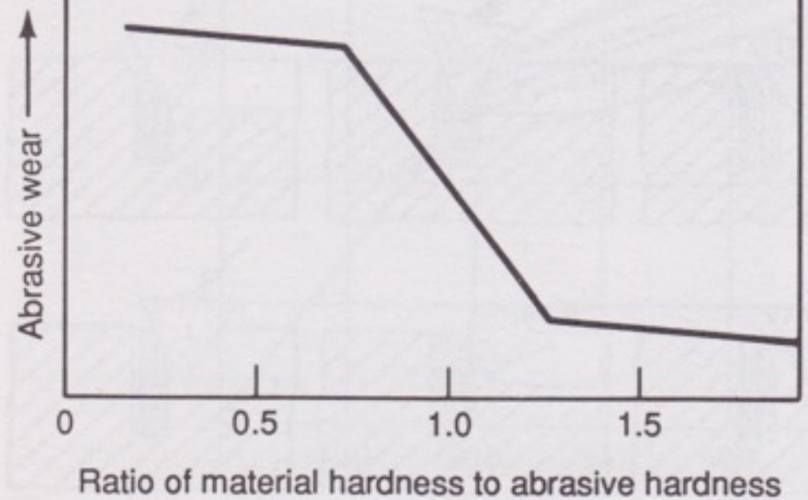

Fig 8 Effect of abrasive hardness, relative to material hardness, on abrasive wear

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Hardness of materials

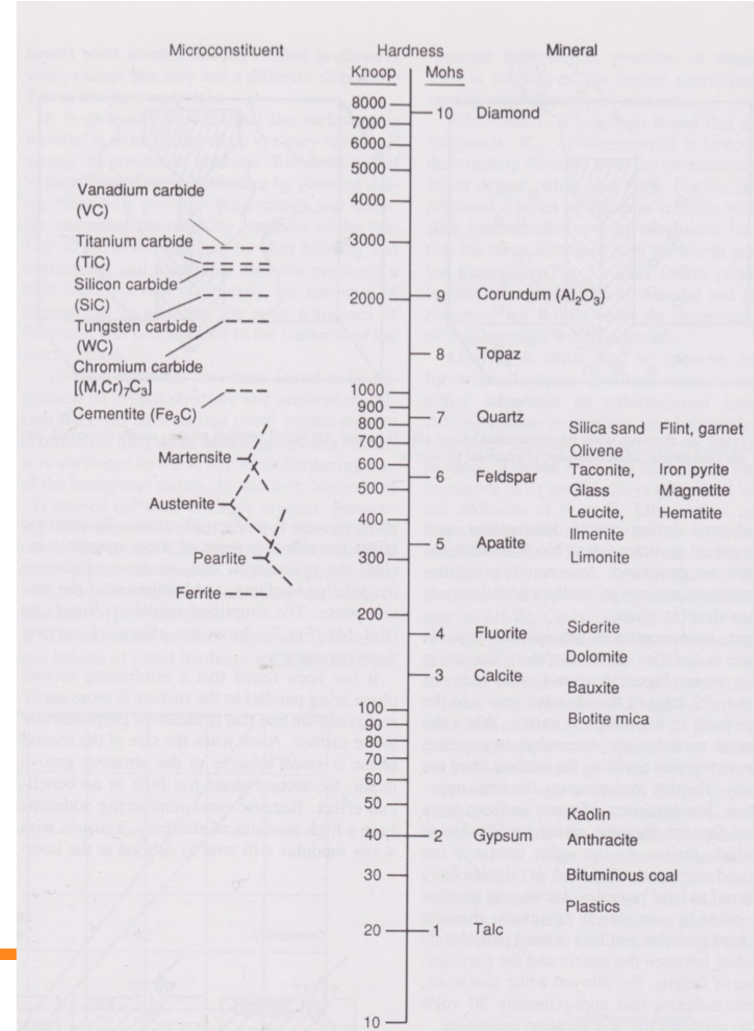

Fig 9 Hardness of some minerals and alloy microconstituents

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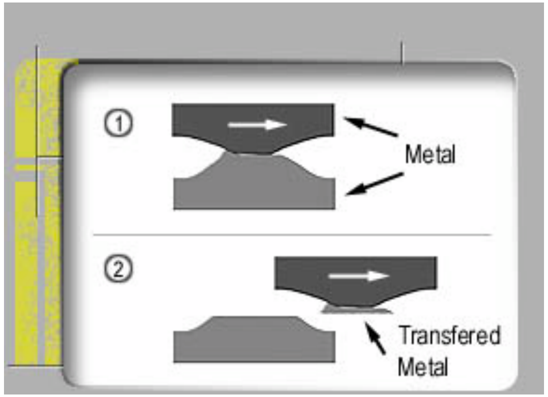
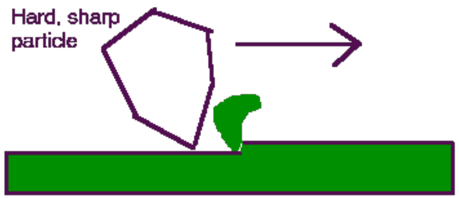
Basic types of Wear

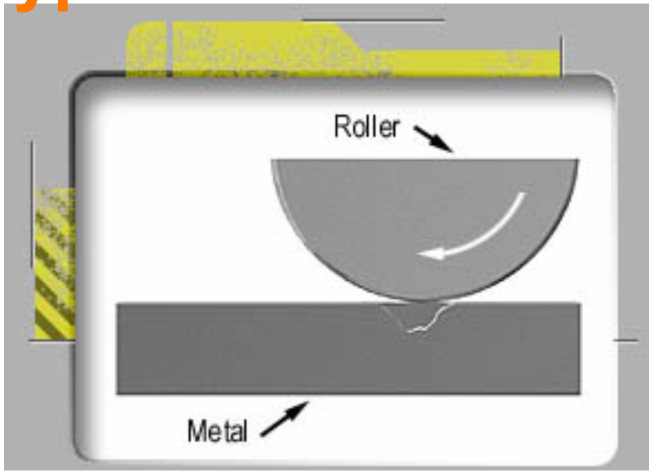


Adhesive

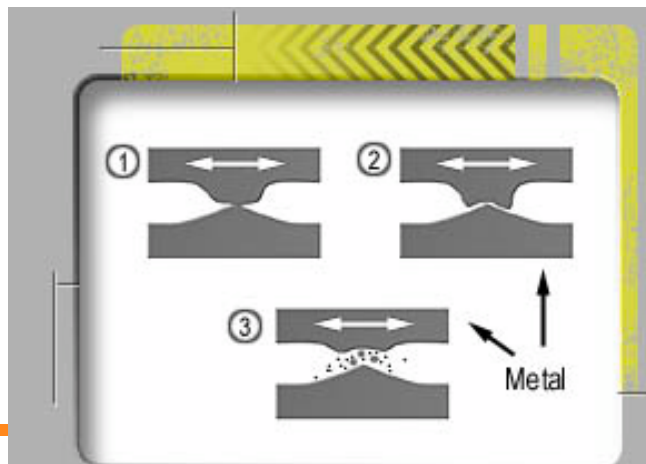


Abrasive

Basic types of Wear

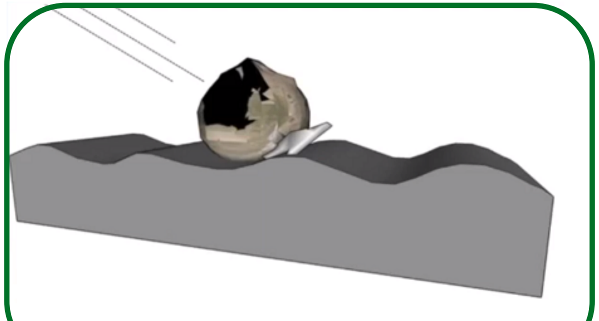


Fatique
cyclic loading



Fretting
cyclic loading
minute relative movement

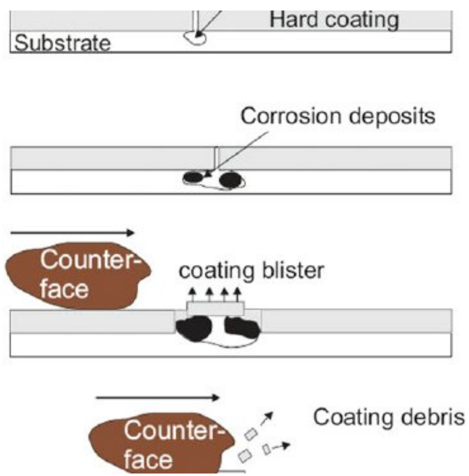
Basic types of Wear



Erosion

particle impact, cyclic loading

deformation, cracking



Chemical wear

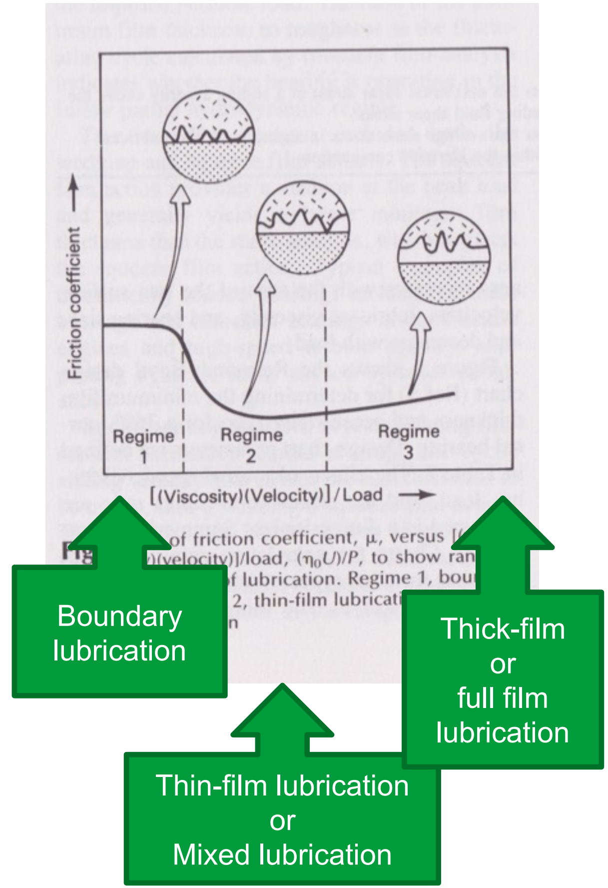
corrosion + wear

Robert Wood, researchgate.net

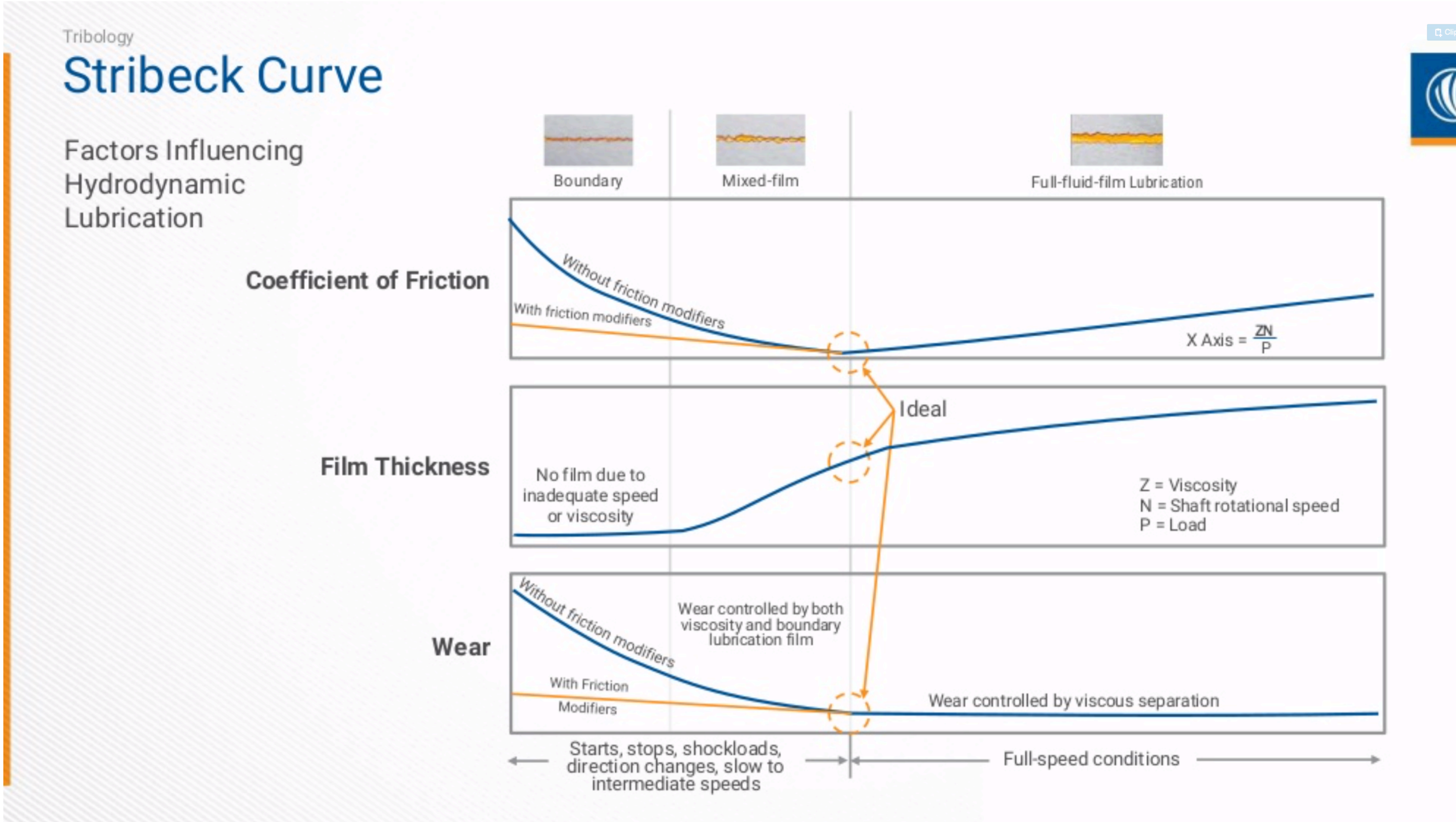
Lubricated contact

Lubricated contact

modes of lubrication



Modes of lubrication: boundary- mixed- full film



Mike Ramsey Noria Corporation 2019

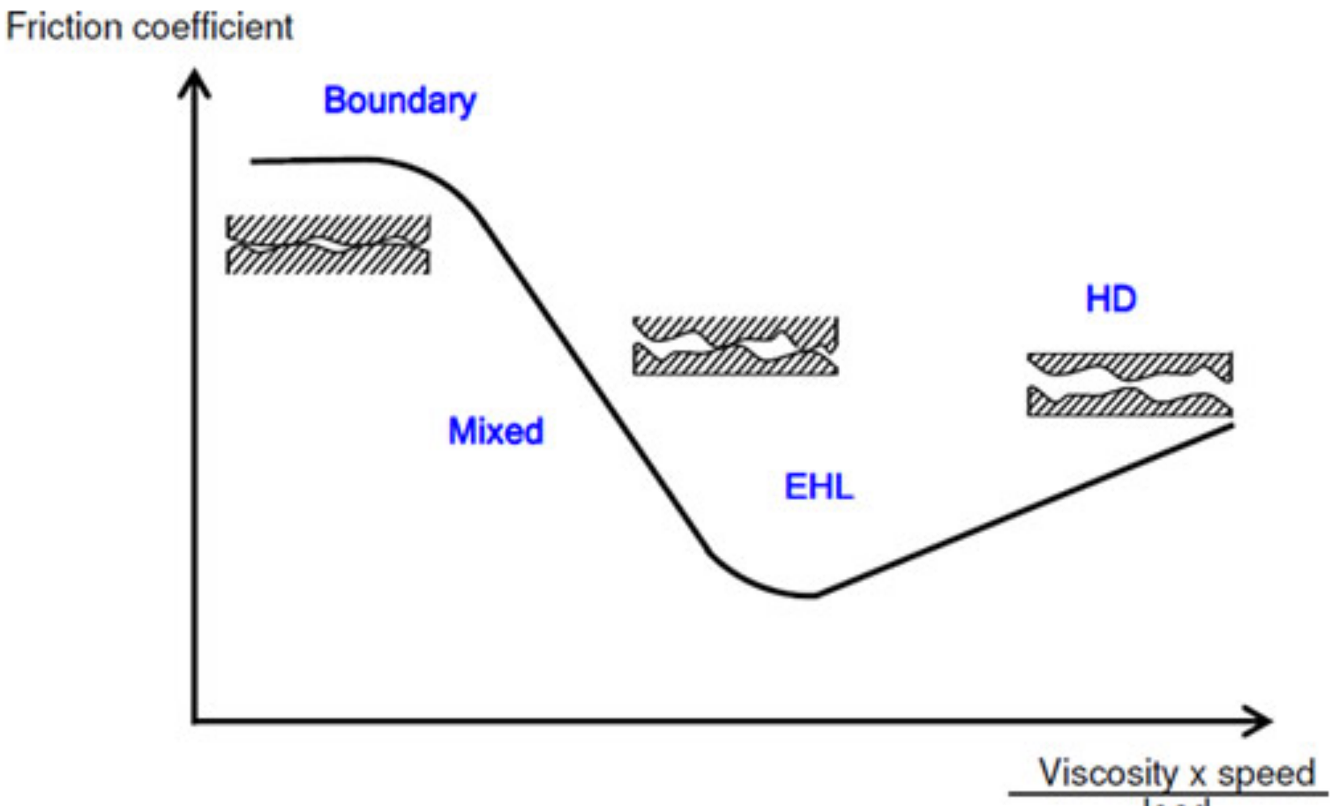
Boundary lubrication

Decrease of viscosity

- Problems begin when fluid lubrication breaks down
  - May be caused by:
    - Breakage of the molecules
    - Heat produced by dissipation decrease viscosity

- Partially problem with the viscosity change can be solved by viscosity modifiers
  - Decrease the reduction of viscosity due to temperature rise

Lubrication regimes
Stribeck's curve



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Boundary lubrication

- Low speeds, low viscosity or high contact pressure/load situations

- Increase in surface rougness increase asperity contacts

- Lubrication mechanisms depend on
  - Molecule
  - Temperature
  - Load
  - Surface material

Adsorption lubrication

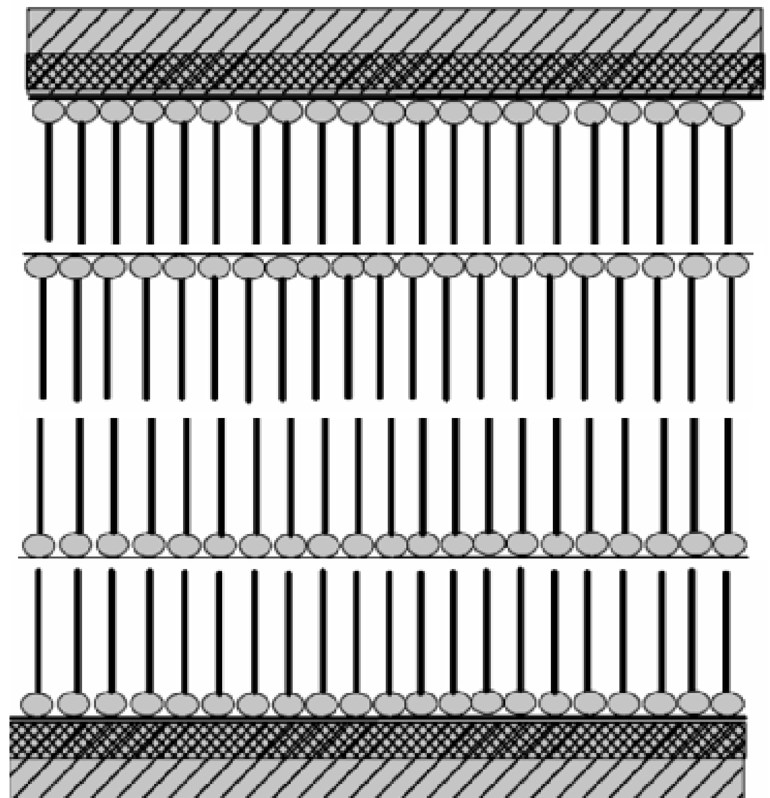
Adsorption lubrication

- Lubricity by surface adhered polar molecules (Friction modifiers)
  - Alcohols
  - Amines
  - Fatty acids
  - Paraffins
  - Esters
- Lubricating molecules adsorbed onto the surface and prevent contact between surfaces
  - Physisorption
  - Chemisorption

Adsorption lubrication

- Lubrication mechanisms can be divided into two categories
  - **Multilayer lubrication**
    - Low load (contact pressure few MPa’s)
    - Low temperature
  - **Monolayer lubrication**
    - High load (contact pressure up to few GPa’s)
    - Low temperature

Multilayered films



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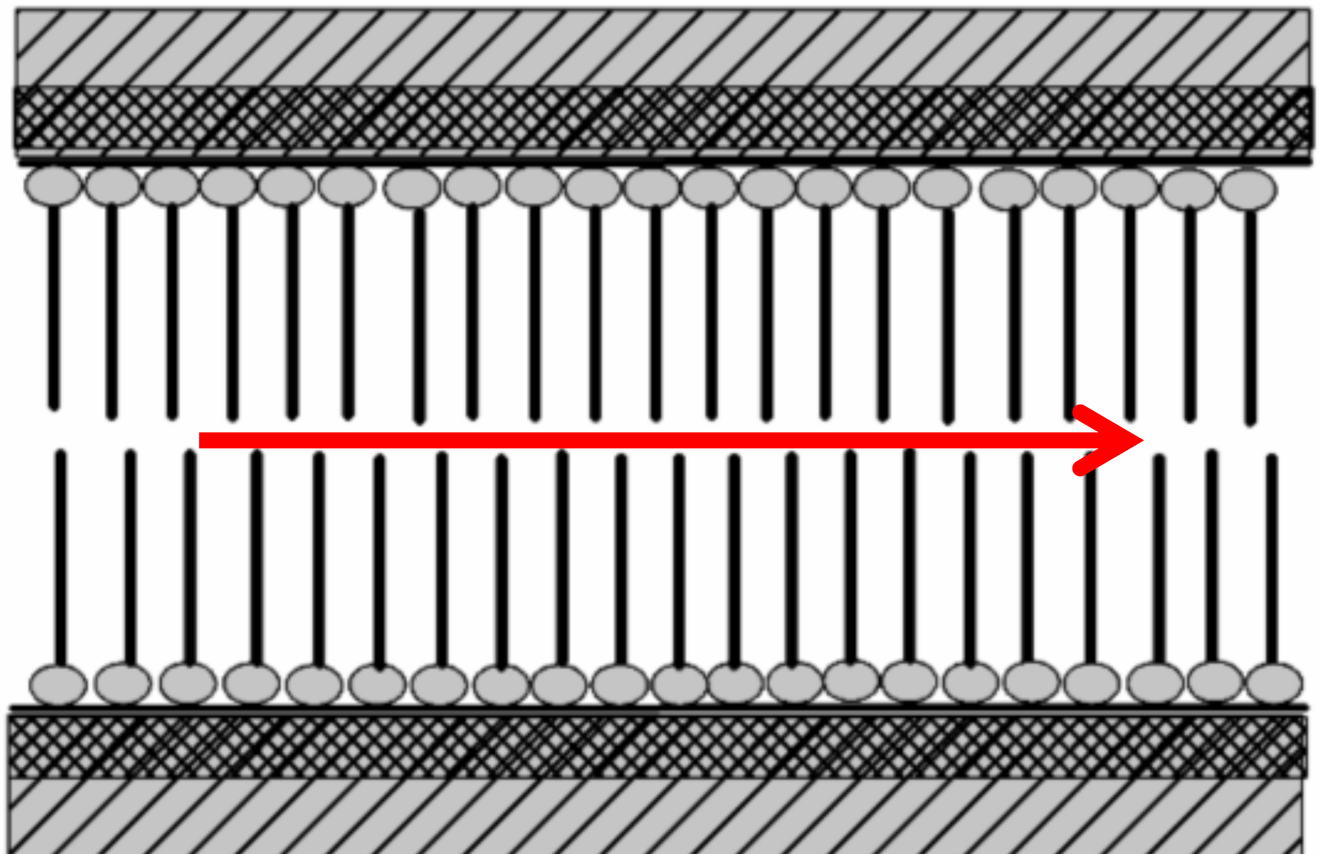
Monolayer film



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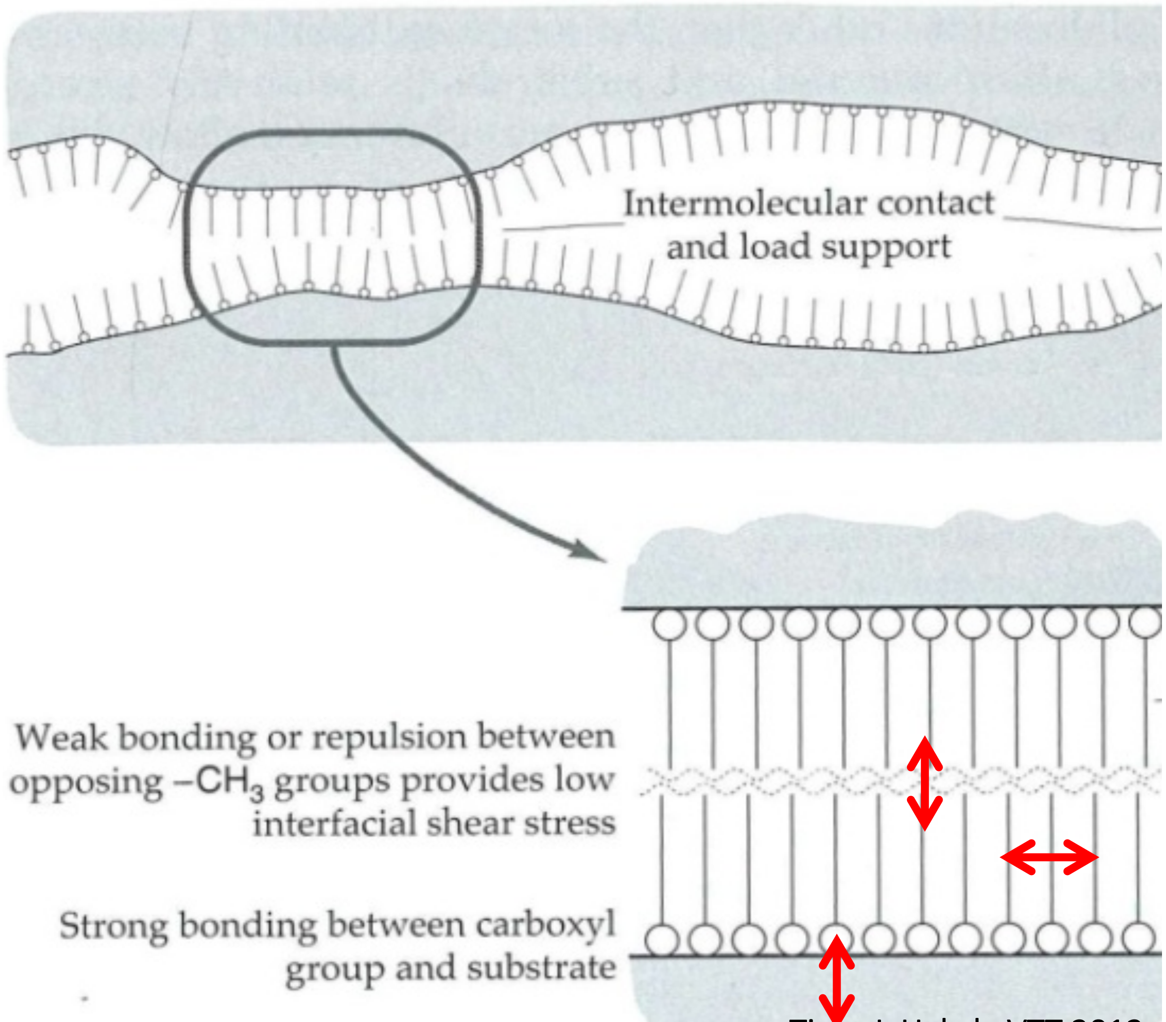
Important film properties

- Adhesion and surface coverage
  - Prevents direct asperity contacts and heat formation
- Repulsion
  - Between molecule layers
  - Reduce friction between sliding surfaces
- Cohesion
  - Within the molecule layer
  - Prevents film breakage



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Stachowiak, G. W. and Batchelor, A. W. Engineering tribology, 3rd edition, 2005, p. 801 (Elsevier, Amsterdam, The Netherlands)

Adsorped film in contact

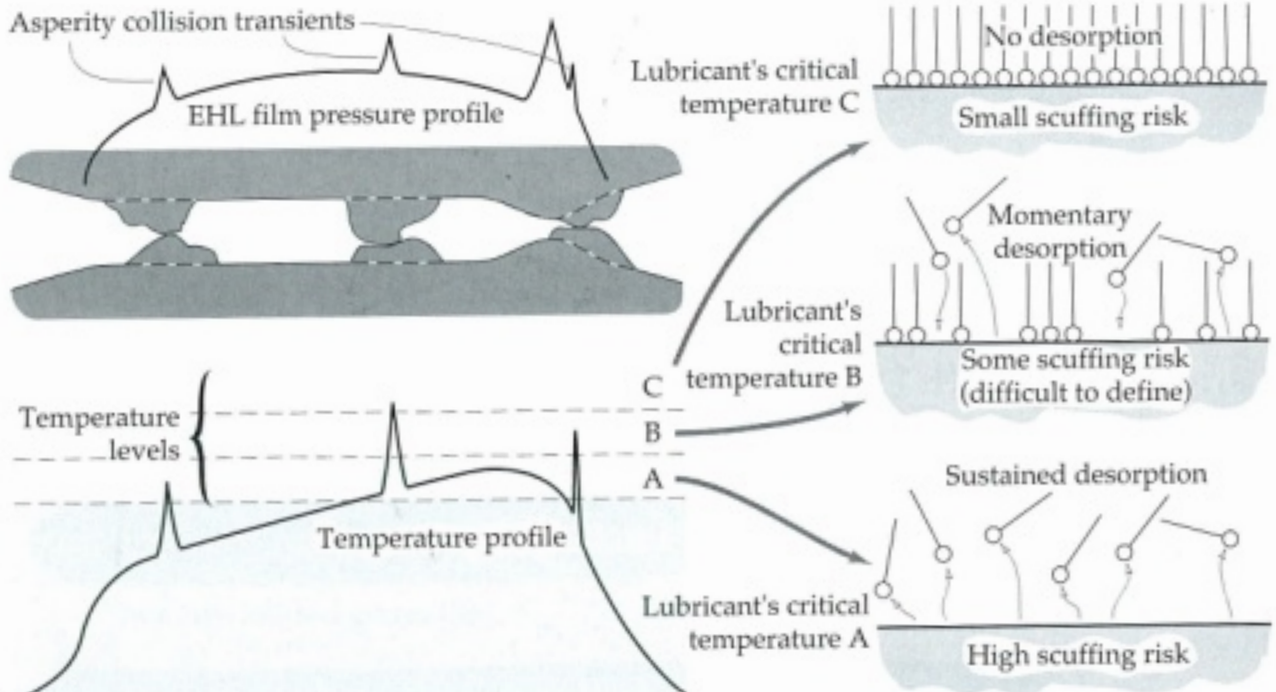

FIGURE 8.24 Model of transient and steady state temperatures in a mixed lubrication sliding contact.

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Effect of amount of molecular films

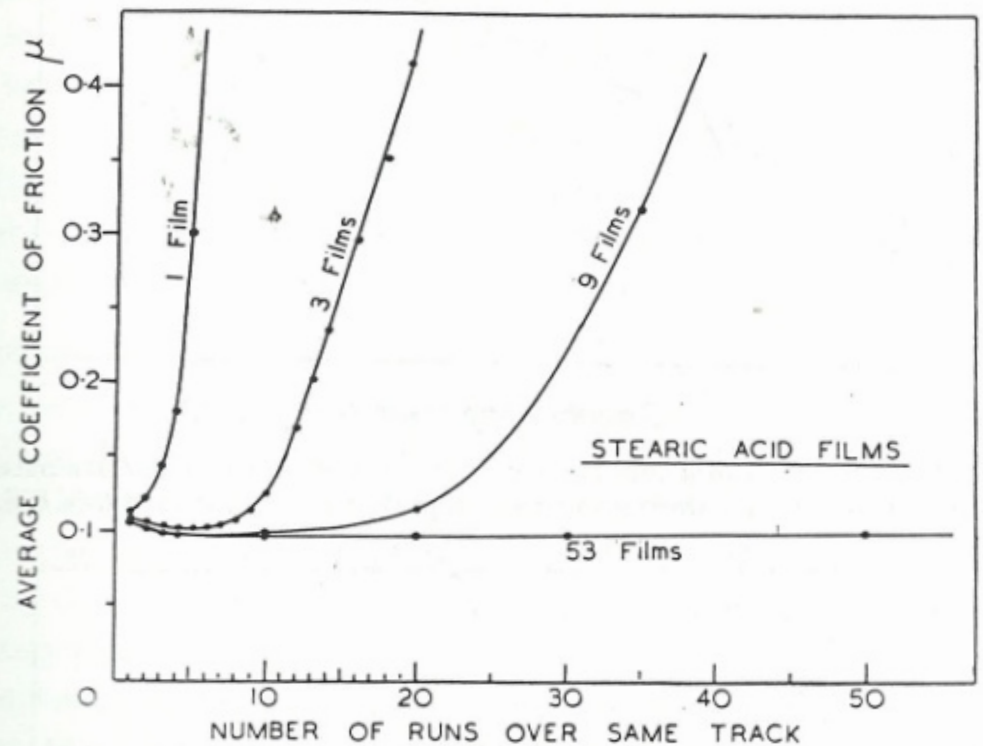


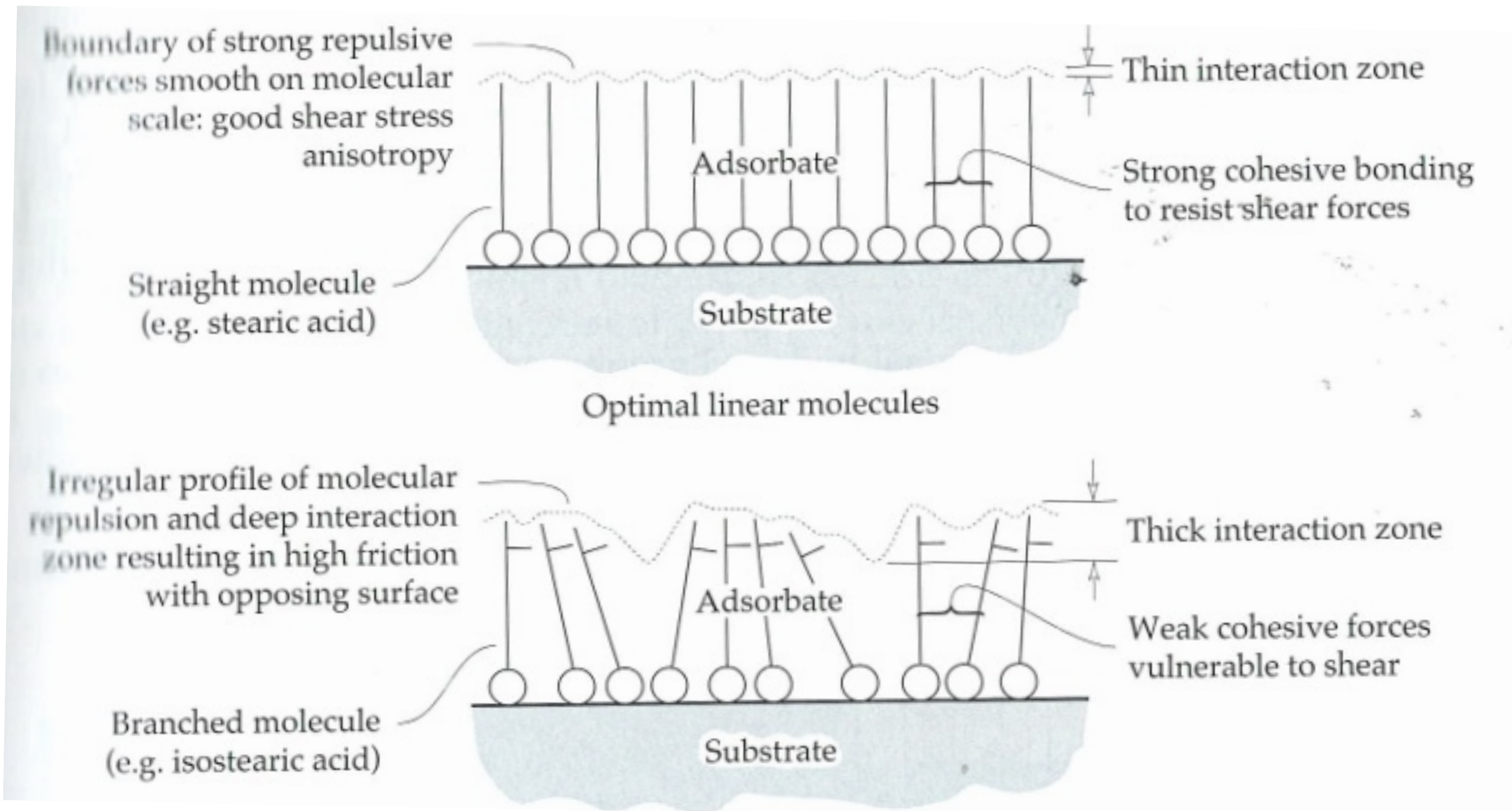
FIG. 70. Wear of stearic acid films deposited on the lower surface (stainless steel surfaces). A single molecular layer produces the same reduction in friction as a thick film but it is worn away far more rapidly.

F.P. Bowden, D. Tabor. The Friction and Lubrication of Solids. Great Britain: Clarendon Press, Oxford; 1986

Effect of molecule structure

- Chain length
  - Polarity
  - Cohesion forces
- Linear structured molecules lubricates better than brached molecules
  - Branching reduces cohesive forces
  - Area / molecule higher, less surface coverage
- Silanes can form polymerized structures
  - Covalent bonds between molecules
  - Increased cohesion

Effect of branched molecules



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Examples of molecules

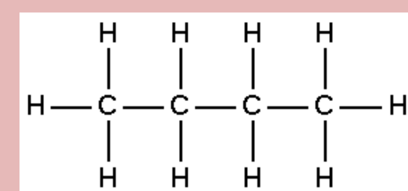
Linear acid molecules

Stearic acid

Alcohol molecules

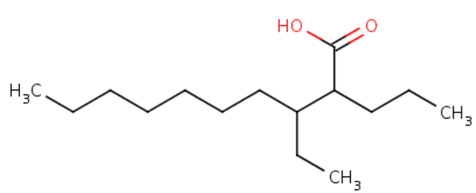
Octanol

Hydrocarbon molecules



Butane

Branched acid molecules



3-ehtyl-2-propyl-decanoic acid

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Limitations for adsorption lubrication

- High temperature
  - Adsorption isoterm, molecules deadsorbed (usually 80 to 150 °C)
  - Molecules break down
  - Lubricant film melts

- Nascent surfaces
  - Catalyses and gasification of the adsorbed molecules

High temperature – medium load lubrication mechanisms

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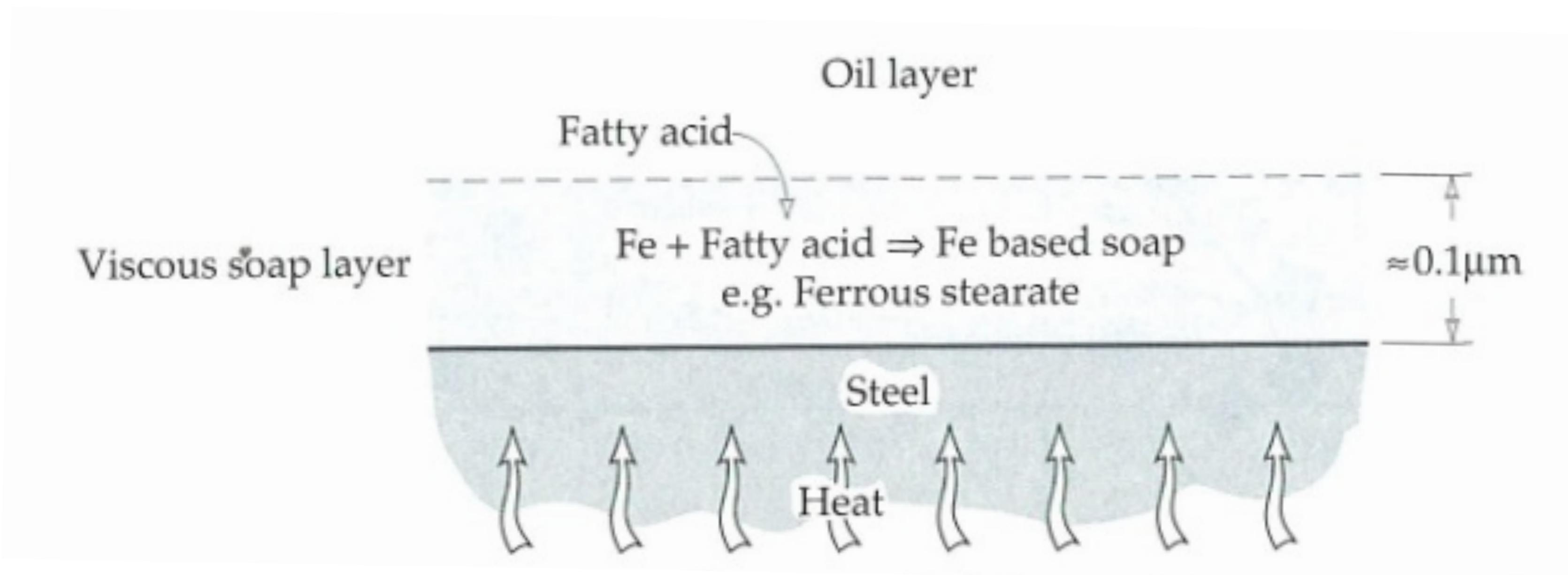
Thick film of soapy or amorphous material

- Chemical reaction between additive molecule and metallic surface
  - Layer thickness normally 100 – 1000 nm
- Soap layers
  - Reaction between metal hydroxide and fatty acid
  - Do not form on the surface of noble metals because required chemical reaction
- Amorphous layers
  - Very fine particles or molecule structures
  - E.g. phosphate together with iron and zinc can form amorphous solid layer on the surface

Soap layer formation



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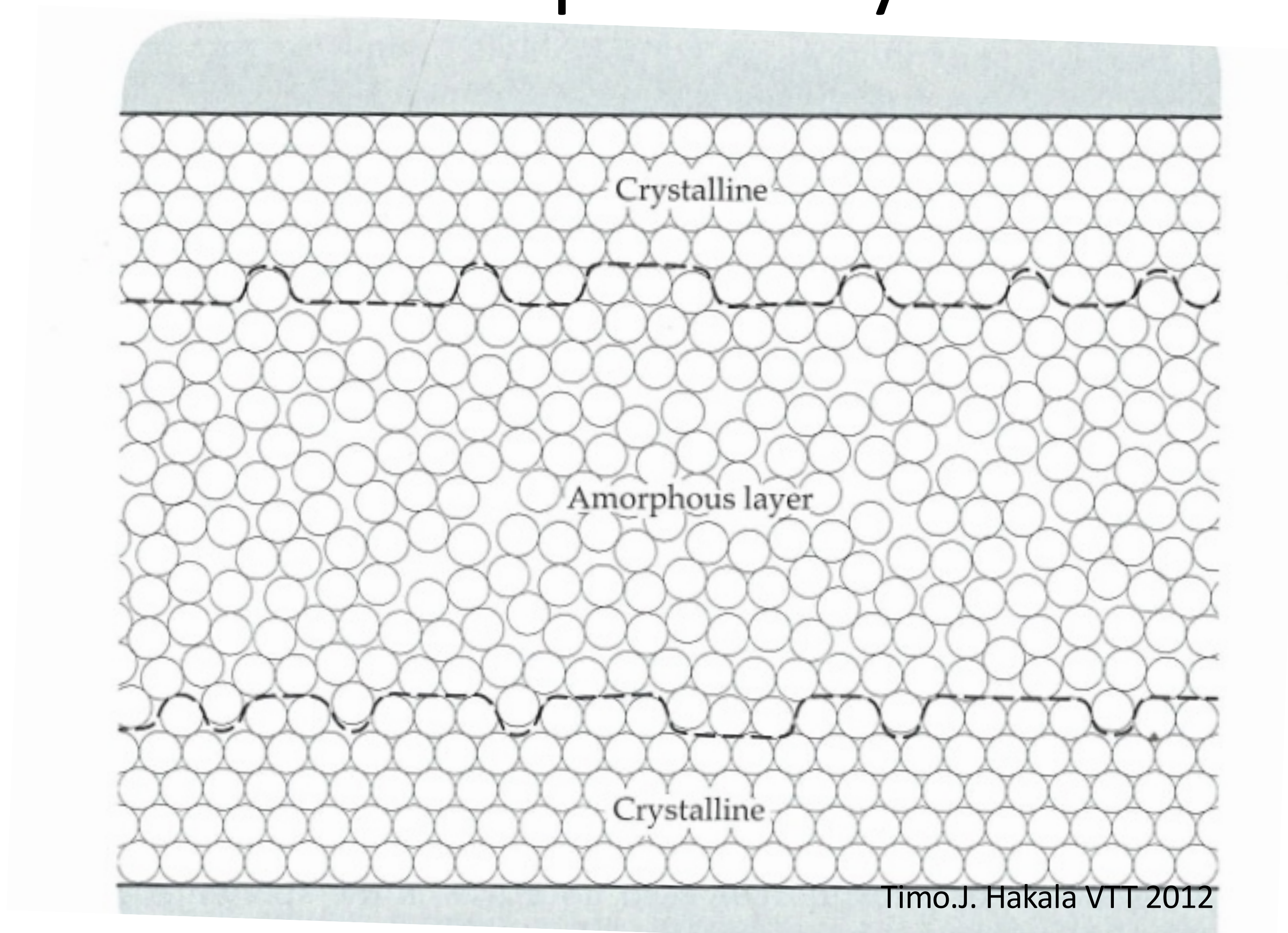
Amorphous layers



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High temperature – high load lubrication mechanisms

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Extreme pressure lubrication

- High temperature lubrication
  - Adsorbed molecules desorbed
  - Lubrication by sacrificial films e.g. FeS

- Sacrificial film formed by reaction between nascent surface and sulphur, phosphorus and chlorine containing additives
  - Reduction of adhesion between contacting surfaces
  - Easily shearing layer
  - No scuffing
  - Growth dependent on oxygen, time...

- Controlled corrosion process

EP film formation mechanism by EP-additives

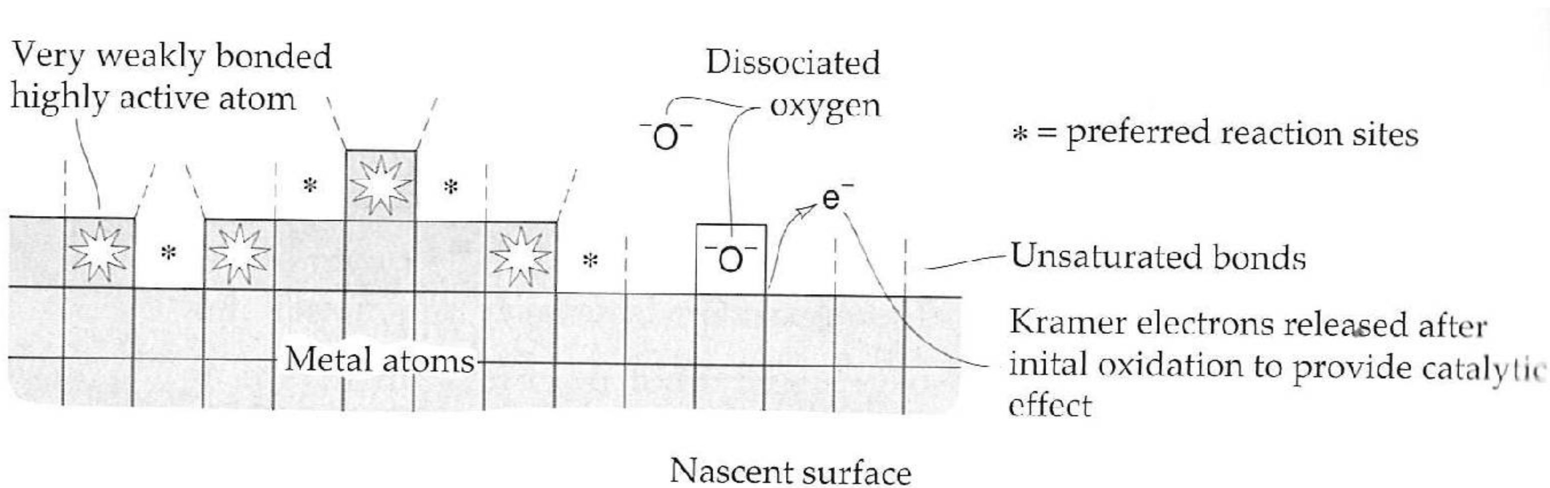
1. Release of electron from nascent surface (Kramer electron)

2. Electron ionize additive molecules

3. Ionic radicals (ionized molecules) adsorb onto positive points on the surface

EP film formation mechanism by EP-additives

Lubricant



Substrate

Stachowiak, G. W. and Batchelor, A. W. Engineering tribology, 3rd edition, 2005, p. 801 (Elsevier, Amsterdam, The Netherlands)

Mechanism of film formation by milder EP additives

1. Additive chemisorption onto the surface
   – Similar to adsorption lubrication

2. Decomposition of the additive molecule by temperature, sliding speed or load

3. Reaction between active element and surface

Mechanism of film formation by milder EP additives

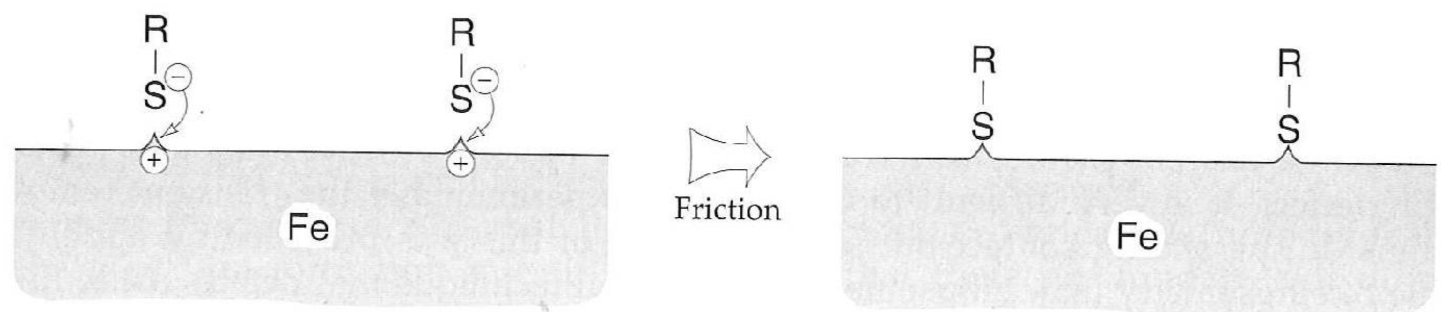


FIGURE 8.45 Ionic model of reaction between an additive and a worn surface [87].

Stachowiak, G. W. and Batchelor, A. W. Engineering tribology, 3rd edition, 2005, p. 801 (Elsevier, Amsterdam, The Netherlands)

EP – film structure

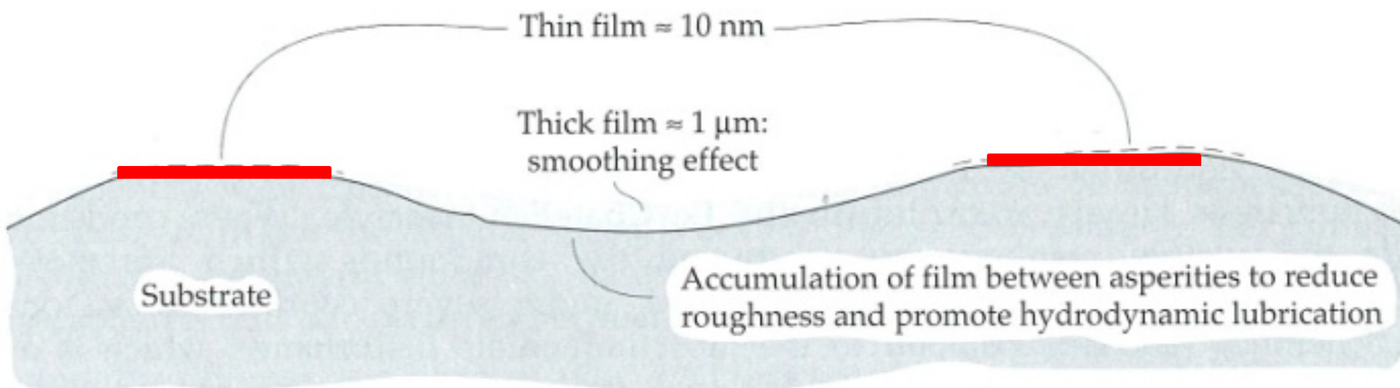


FIGURE 8.48 Probable structure of the EP film.

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Stachowiak, G. W. and Batchelor, A. W. Engineering tribology, 3rd edition, 2005, p. 801 (Elsevier, Amsterdam, The Netherlands)

Anti-wear and EP - additives

- Anti-wear additives used in mild conditions and high temperatures

- Adhered to surface by chemisorption
  - Additives such as ZnDDP

- Reactivity of the EP - additives depend on molecule structure as well
  - For example all sulphur containing molecules do not react with iron surface to form FeS

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Nanoparticle additives

- Nanoparticles (~1 – 100 nm) can be added into oil, water or emulsions to improve lubrication properties

- Usually reduced friction and wear is related to mechanically/chemically formed thin film layer onto the surface

- For example Nickel oxythiomolyblate ($NiMoO_2S_2$) improved lubrication properties of synthetic oil when temperature was abowe 300 ̊C

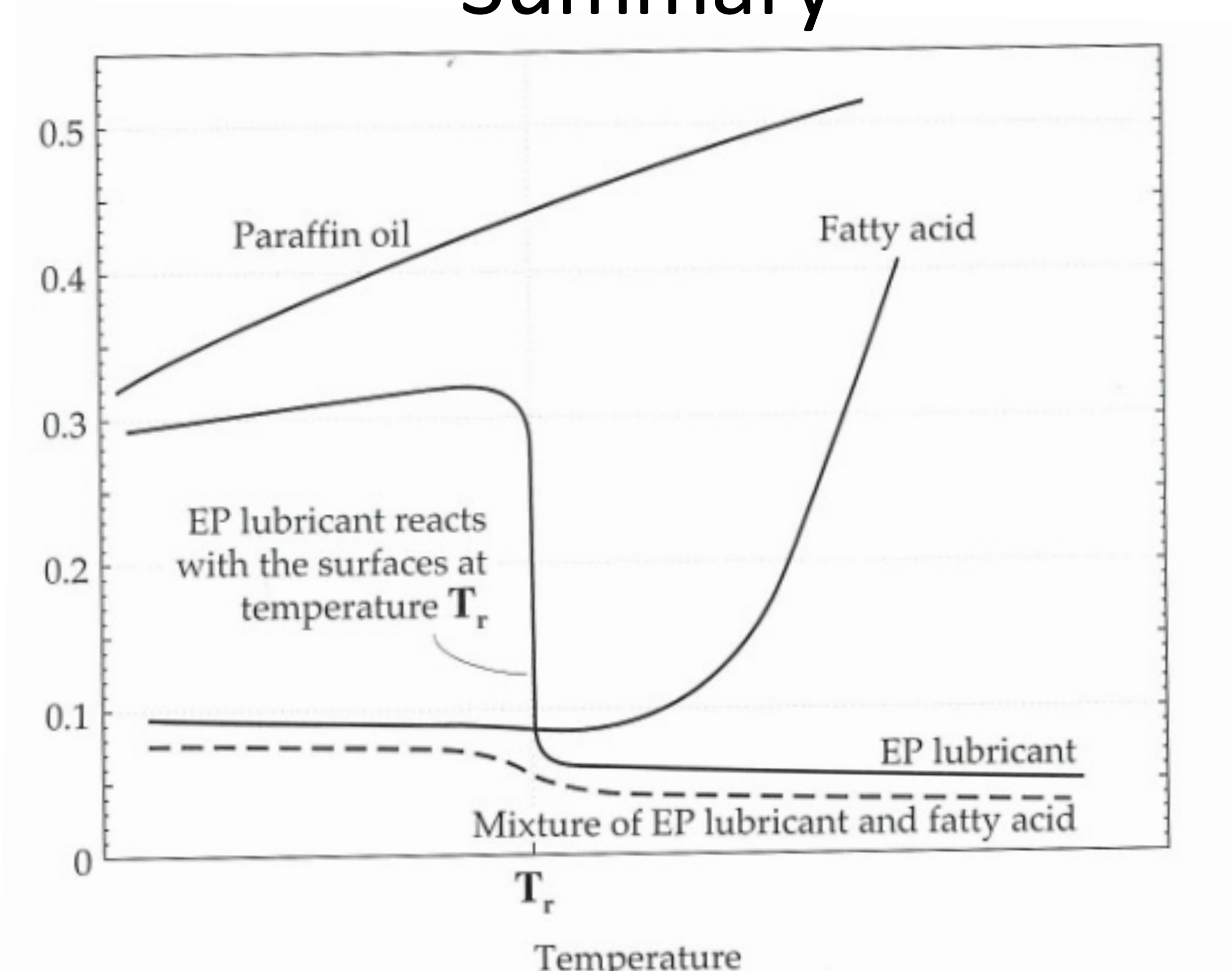
- Novel solutions for extreme lubrication without corrosiveness

Summary

- Lubrication mechanisms are different in different load and temperature regimes
- Different types of additives used in different lubrication regimes
  - Adsorption additives
  - Anti-wear additives
  - Extreme pressure (EP) additives

Summary

μ



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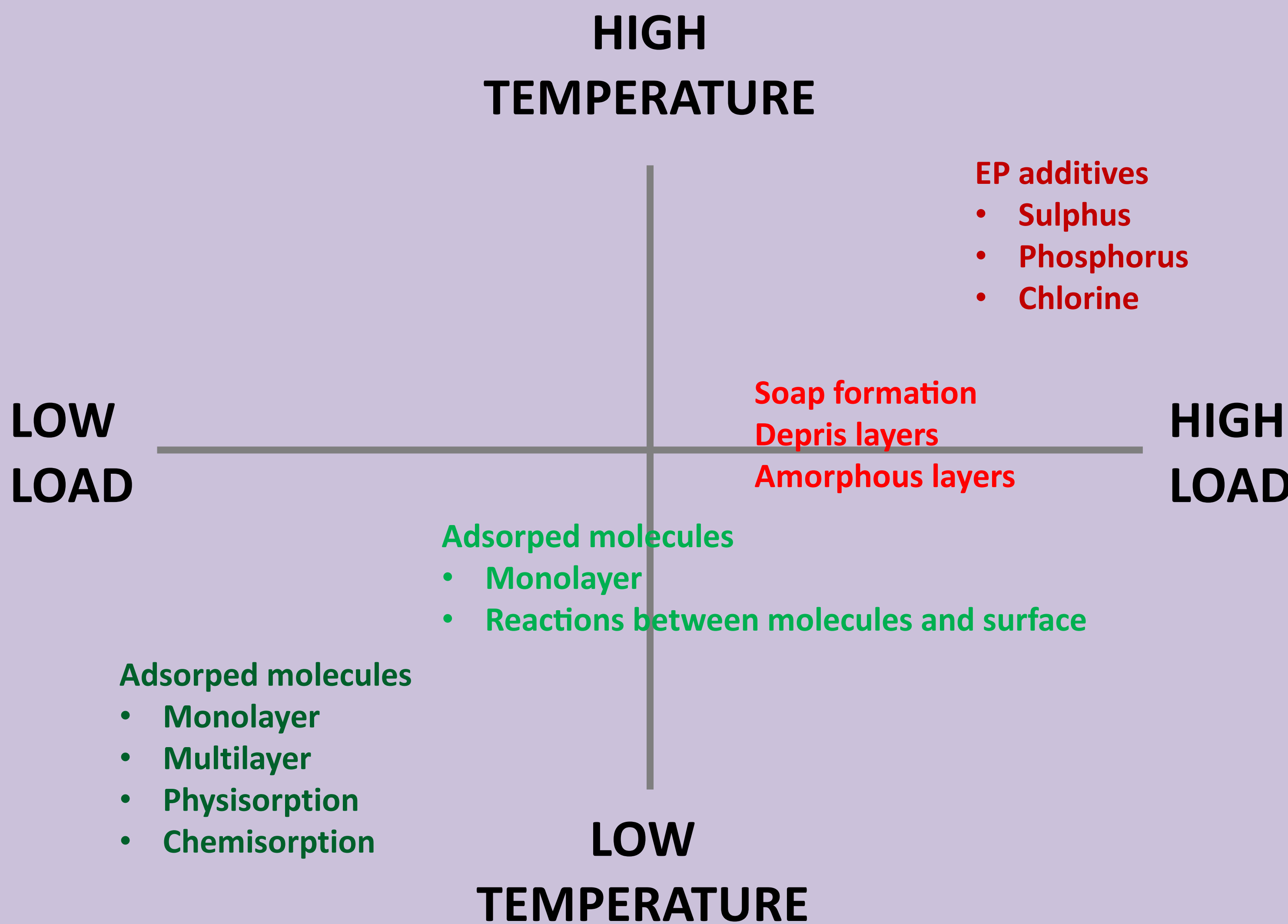
Stachowiak, G. W. and Batchelor, A. W. Engineering tribology, 3rd edition, 2005, p. 801 (Elsevier, Amsterdam, The Netherlands)



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Conclusions

- Boundary lubrication has different regimes
- Different types of additives function in different conditions
- In real applications several boundary lubrication regimes can be obtained
- In oil lubrication more than one type of boundary additives are needed

Title

Title