

2025 Tribology and Surfaces Interactions Summer School 25 – 29 August, 2025 / Visp, Switzerland

- Part 1: Tribology - Friction and Wear
Real Surfaces - Chemical, Physical, and Mechanical Characteristics
- Part 2: Interaction between Surfaces: Stress and Strain Fields
Influence of Friction on the Stress Field
Influence of friction and mechanical properties of materials on failure modes
- Part 3: Abrasive wear - Micromechanisms and response of different materials



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- Tribology is the science and engineering of interacting surfaces in relative motion. It includes the study and application of the principles of friction, lubrication and wear.
- The word tribology derives from the Greek root τριβ- of the verb τρίβω, tribo, "I rub" in classic Greek, and the suffix -logy from -λογία, -logia "study of", "knowledge of". Peter Jost coined the word in 1966,[1] in the eponymous report which highlighted the cost of friction, wear and corrosion to the UK economy.

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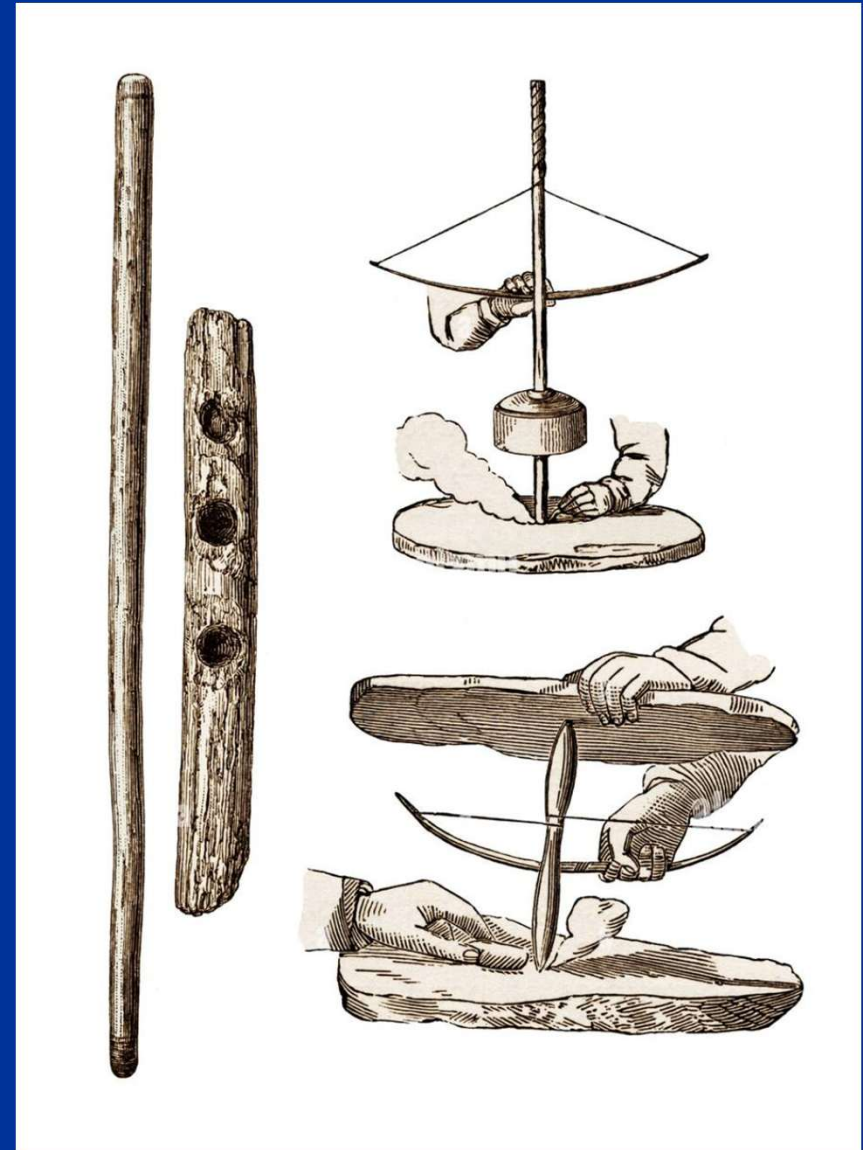
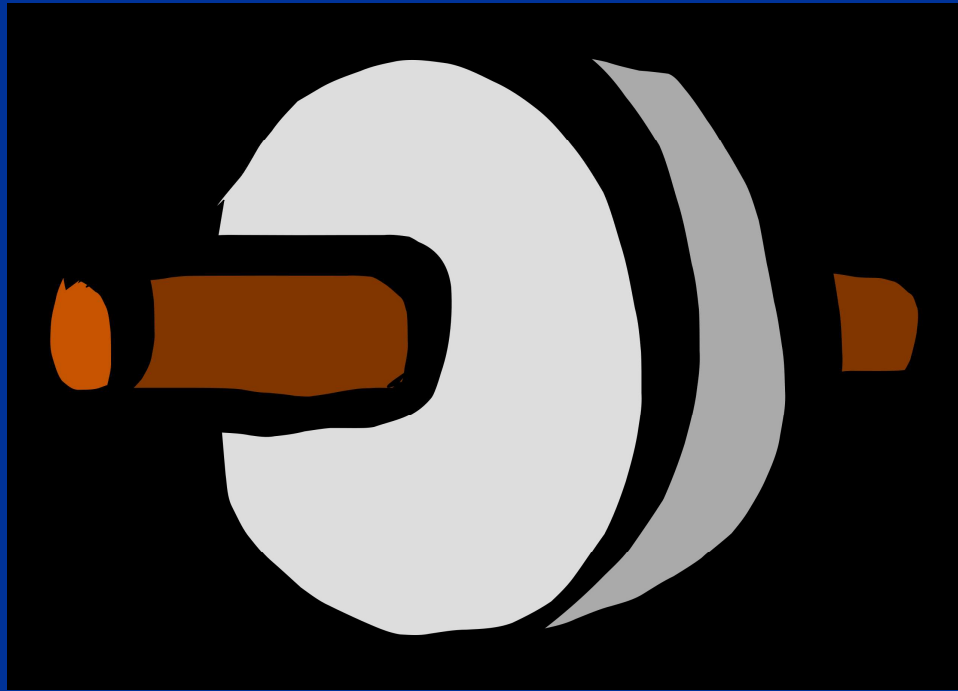
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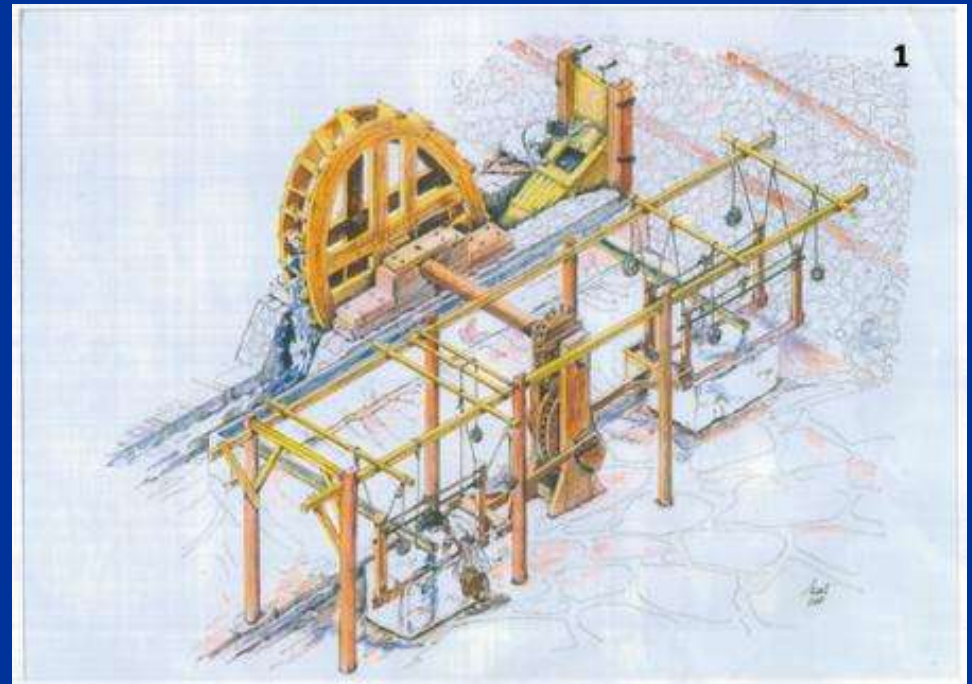
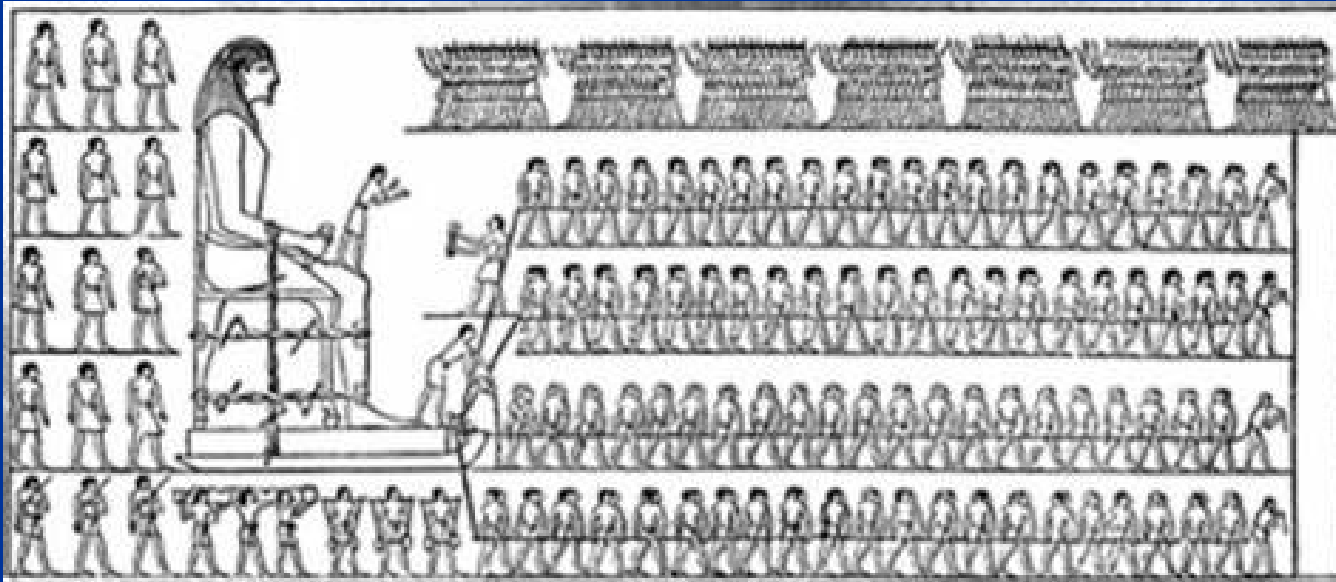
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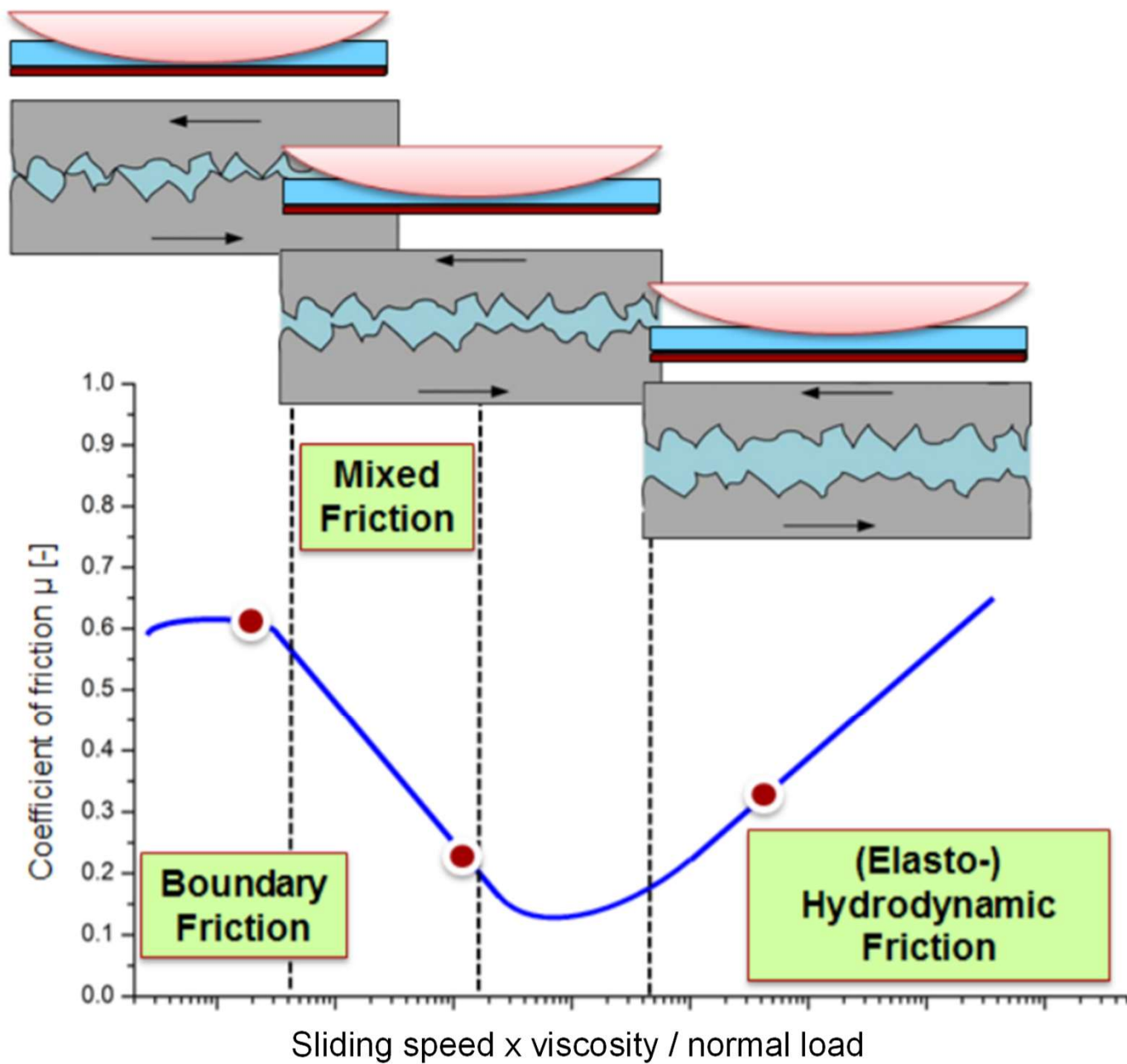
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Wear

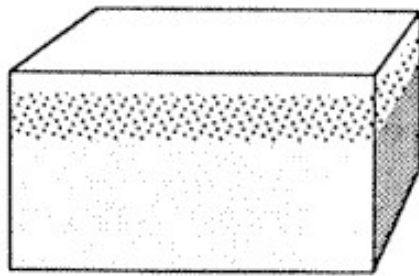
Desgaste - damage to the active surface of a body, usually with progressive loss of material, due to the action of relative movement between the surface and a material or materials with which it contacts.

Wear occurs progressively and can continue without widespread deformation of the components, however, is responsible for a significant number of in-service failures.

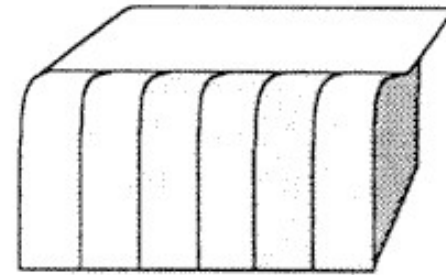
Wear

Contact between surfaces leads to different failure modes, depending on the micromechanisms involved

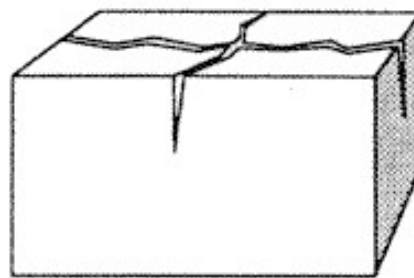
Surface failure modes without material loss



Microstructure evolution

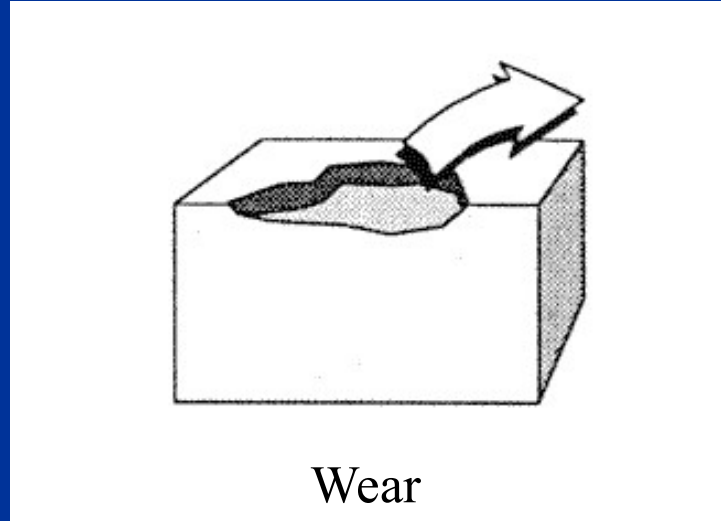


Plastic deformation

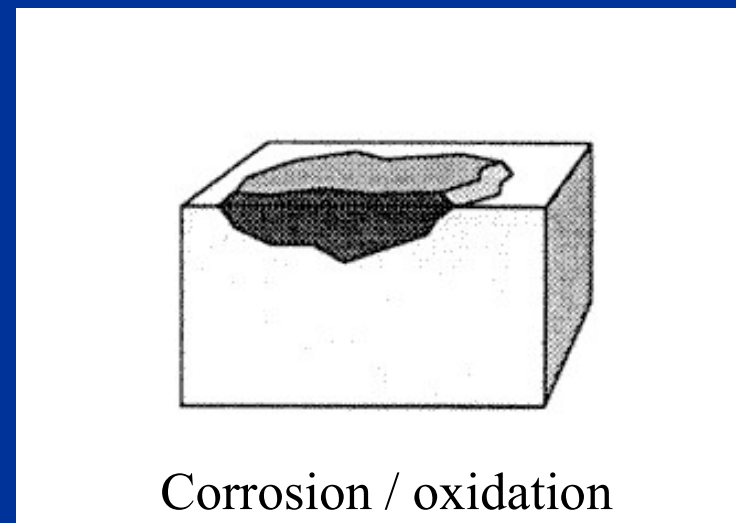
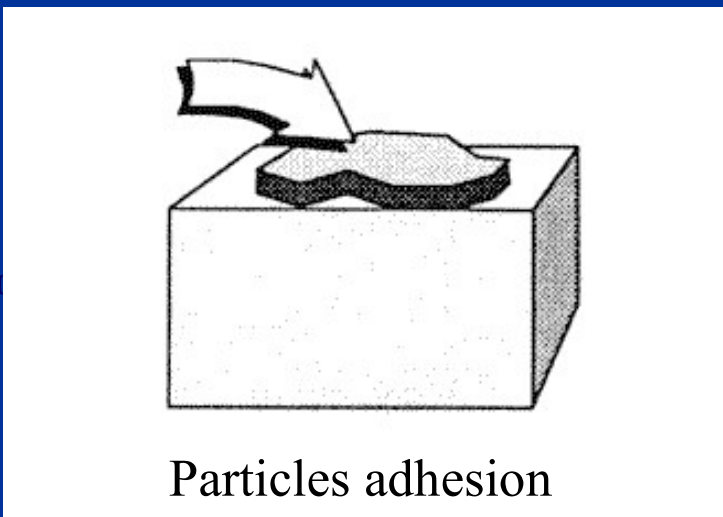


Surface cracking

Surface failure with material loss – wear



Surface failure with material gain



Desgaste - Classificação

Wear produced by particles or fluids

- Abrasion
- Erosion

Wear produced by sliding and rolling

- Adhesion
- Fretting wear
- Wear by fatigue

Wear influenced by chemical processes

- Wear by corrosion
- Oxidative wear

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The biggest challenge facing the designer in considering wear failures when designing is probably anticipating the type or types of wear mechanisms to which the component will be subjected under service conditions.

The fact that wear mechanisms are not conveniently defined for a wide range of applications has made it difficult to organize manuals containing an exact description of the stress states and service conditions specific to each application.

The lack of models, or rather the difficulty of using models that can be transferred to real-world situations, means that a very significant number of wear problems are solved by material selection based on a combination of failure analysis methods and laboratory testing.

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At the application level, in each component, the set of operating conditions will determine which wear mechanism(s) predominate.

Concerning the incidence of each mechanism, the following typical values are mentioned:

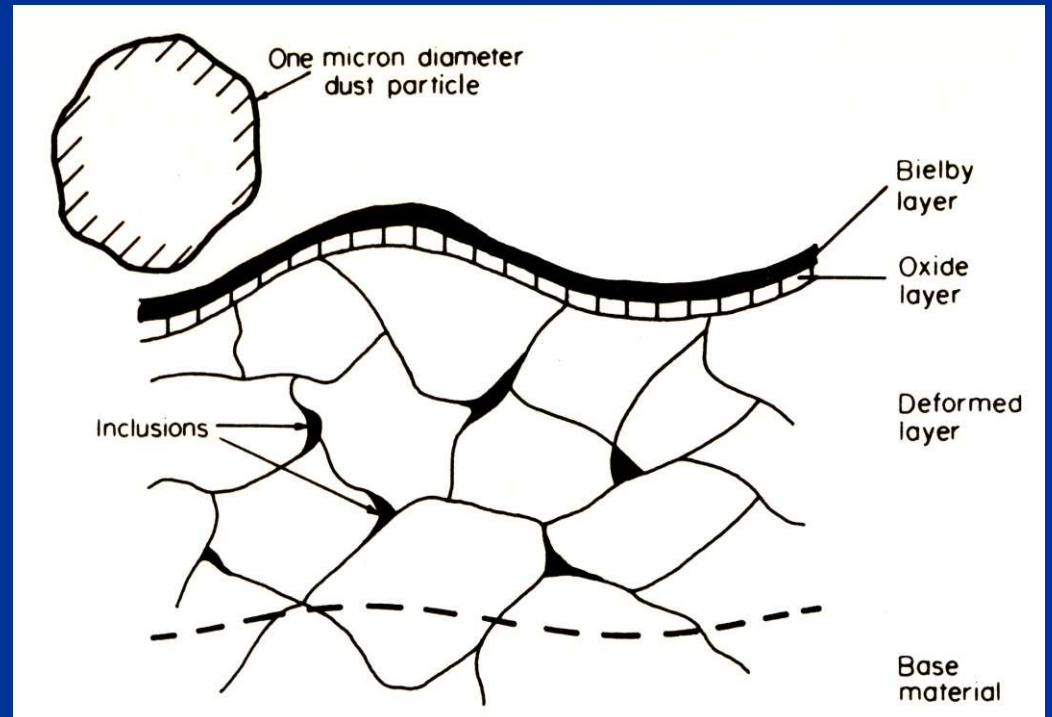
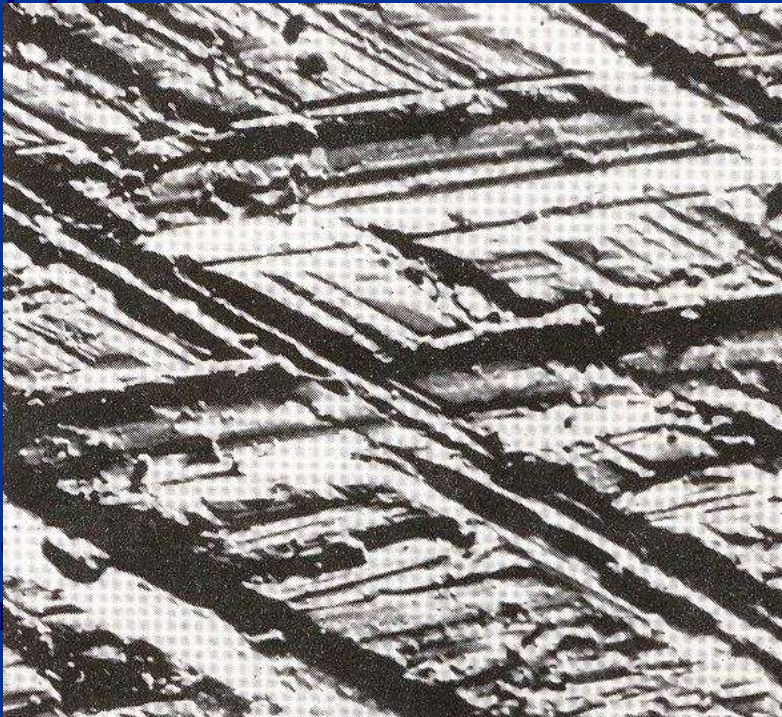
Abrasion	50%
Adhesion	15%
Erosion	8%
Fretting	8%

In numerous situations, classification is not easy, as not only can several mechanisms coexist, but there may also be evolution of the mechanisms involved.

Chemical characterization: surface films

A solid surface, or more precisely, the solid-liquid or solid-air interface, has a complex structure and properties dependent on the nature of the solids, the surface preparation methods, and the interactions between the surfaces and the environment.

Due to their characteristics, surfaces are necessarily zones of discontinuity from both a physical and chemical perspective, and both aspects are crucial for performance in contact situations, especially with relative motion.



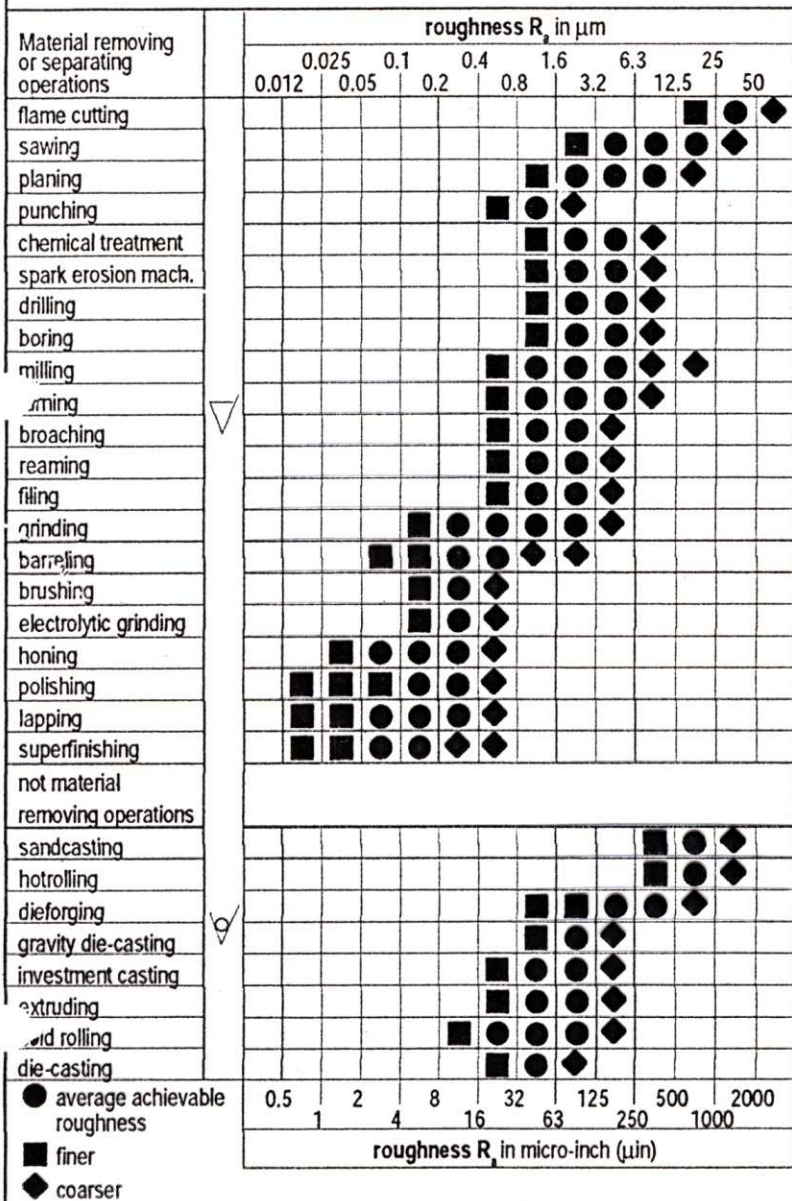
Physical characterization: surface topography

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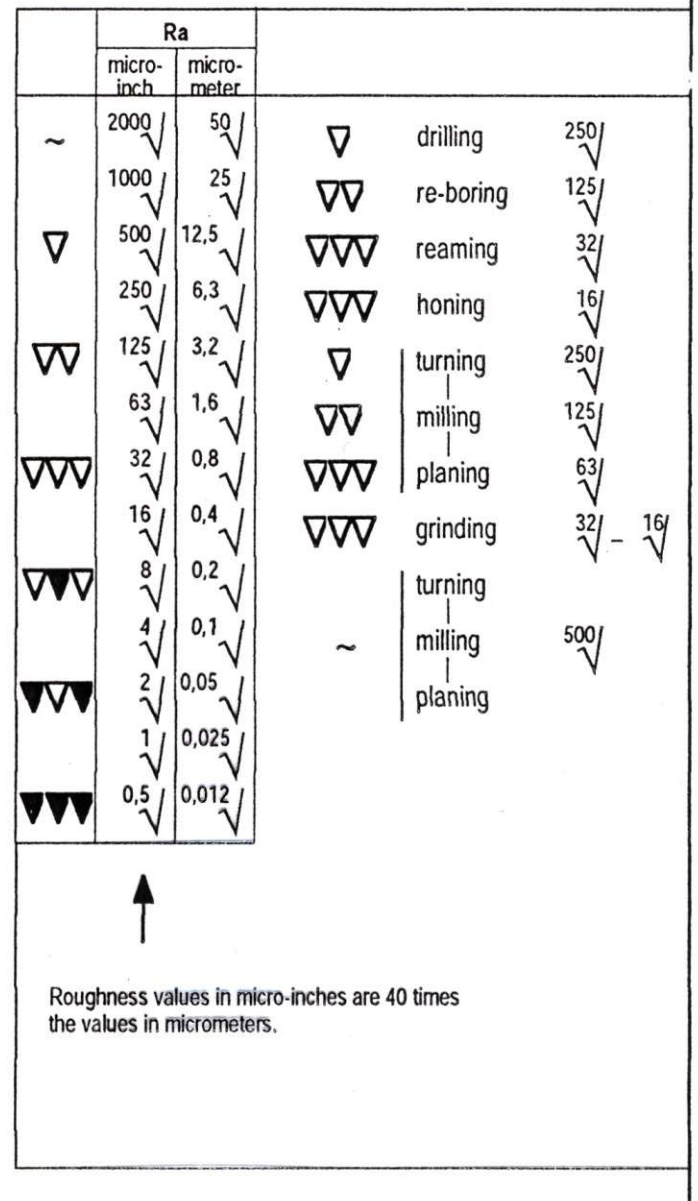
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STANDARD	TABLES	
ISO : - EN : - DIN : - NEN : 3638	Surface roughness	






Guidelines for feasible roughness R_a for different processing methods



Comparison of roughness symbols



Surface texture

<p>Class 1: Form error</p> 	<p>Straightness, flatness, roundness, cylindricity, profile of any line, profile of any surface</p>	
<p>Class 2: Waviness</p> 	<p>Waviness</p>	
<p>Class 3:</p> 	<p>Roughness</p>	
<p>Class 4:</p> 		<p>Roughness (score marks, flakes, protruberances)</p>
<p>Class 5:</p> <p>No longer capable of straightforward representation in pictorial form</p>		<p>Crystalline structure</p>
<p>Class 6:</p> <p>No longer capable of straightforward representation in pictorial form</p>	<p>Lattice structure of material</p>	
	<p>Superposition of class 1 to 5</p>	

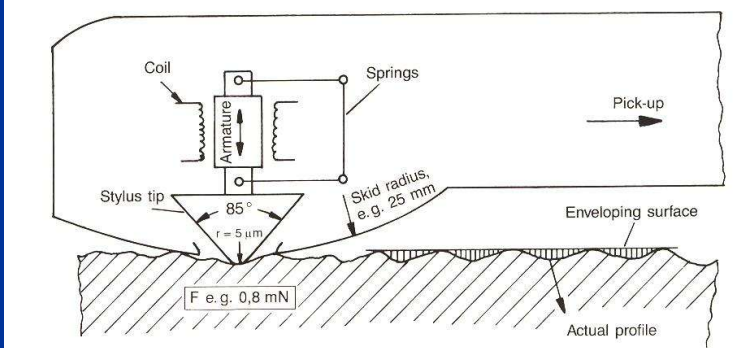
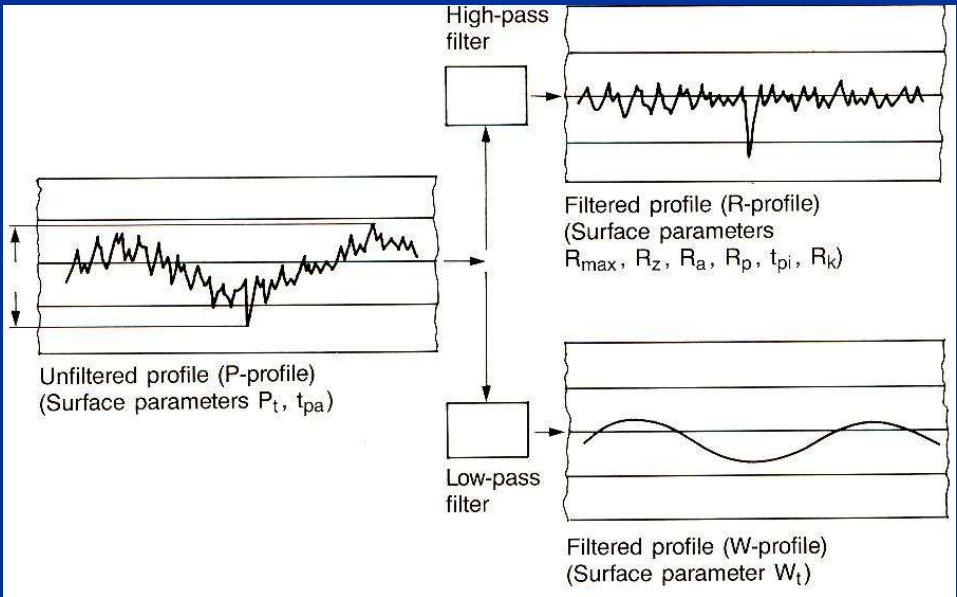
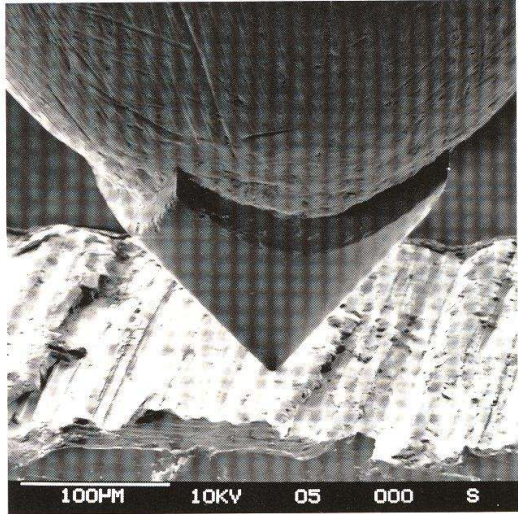


Fig. 42a: Stylus method – Principle of a pick-up

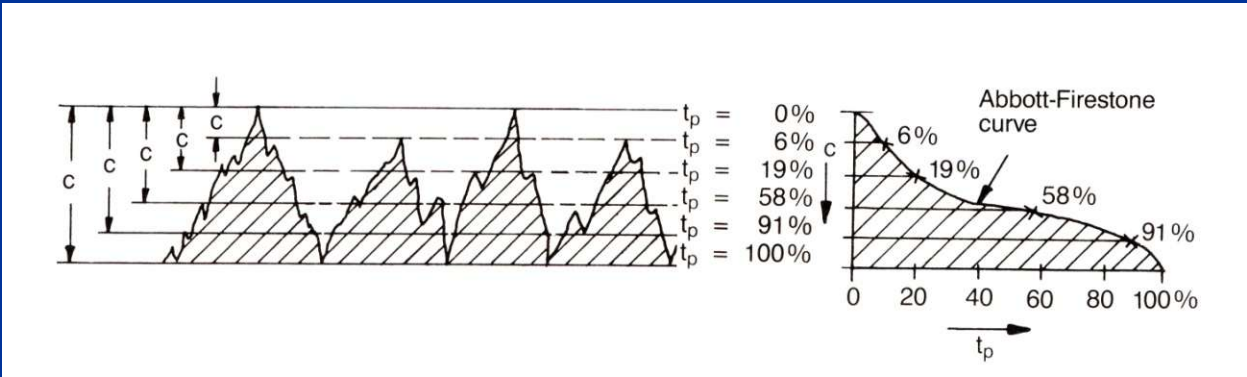


Surface texture

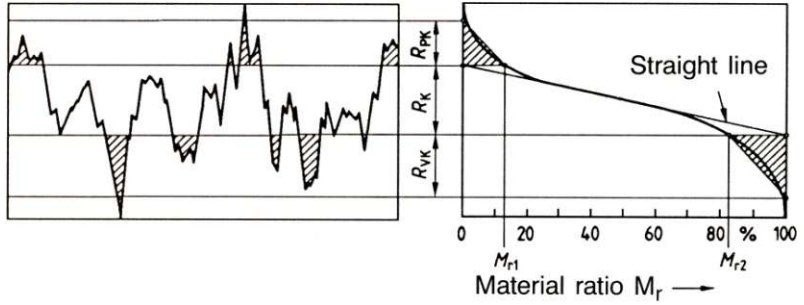
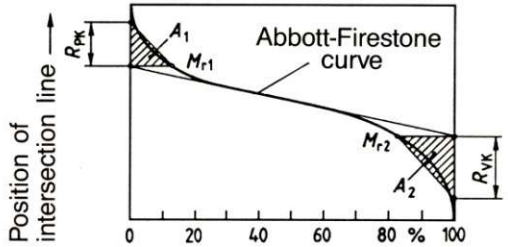
The most common quantitative parameters quantify vertical distribution: Ra, Rz, Rmax...

However, there are some parameters that quantify horizontal distribution: Sm, Pc...

There is currently a growing trend towards using parameters that allow for the simultaneous quantification and qualification of the roughness profile: Sk, Abbott-Firestone curve (Rk, Rpk, Rvk,...)...



- A₁ Material filled profile peak area
- A₂ Lubricant filled profile valley area
- R_k Core roughness depth
- R_{pk} Reduced peak height
- R_{vk} Reduced valley depth
- M_{r1} Material component relative to peaks
- M_{r2} Material component relative to valleys

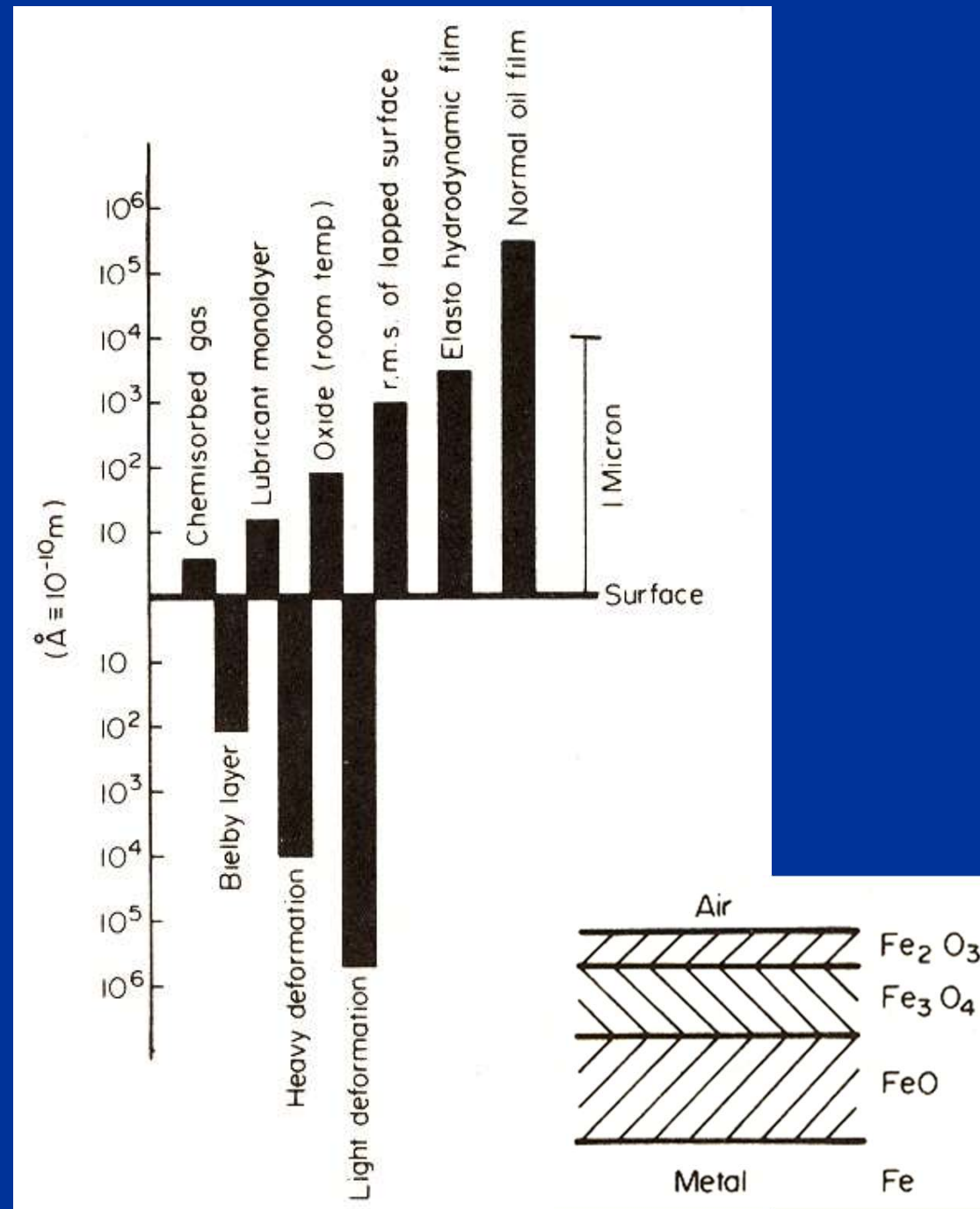


Surface layers

In addition to topographic texture, solid surfaces have unique physical and chemical properties relative to the substrate material itself.

As a result of metal and alloy forming processes, there is a layer of deformed material, usually strain-hardened, near the surface, on top of which there may be a thin film with an amorphous or microcrystalline structure called a Beilby film.

The interaction of surfaces depends on both the topography and the mechanical and physical properties of the outermost layers and, as such, is significantly influenced by the surface films.



Effect of surface strain field

The metallurgical properties of the surface layer of a metal, alloy, or ceramic can differ significantly from those of the bulk material due to the forming process used to produce the surface. For example, in grinding, lapping, chipping, and polishing, the most superficial layers are plastically deformed, with varying degrees of temperature gradient, resulting in high levels of deformation.

Deformation of the surface layers can also result from sliding processes due to the overlapping effects of friction and normal pressure.

Surface deformation usually results in work-hardening; however, on surfaces with high residual stresses, softening may occur due to a reduction in the stress level. A deformed surface layer is identified by grains significantly oriented parallel to the surface, or by very fine grains if conditions allow for recrystallization.

The thickness of the affected layer depends strongly on the material and the amount of energy supplied during the deformation process. The thickness of the highly deformed surface layer is in the order of 1 to 10 μm , however deformation of up to 100 μm can occur.

Beilby films

Beilby layers are the films that form on the surfaces of metals and alloys when subjected to significant deformation processes due to melting and surface flow. Melting and subsequent rapid cooling of the most superficial films due to contact with the cold underlying material give rise to films with an amorphous or microcrystalline structure.

The typical thickness of Beilby layers is on the order of 1 to 100 nm.

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Surface films formed by chemical reaction

When exposed to air, all metals, except for gold and platinum, react with oxygen to form oxide films. However, if the composition of the atmosphere varies, other compounds (sulfites, nitrites, chlorides, etc.) can form. Even in non-metals, oxides can form; see the formation of silica on silicon.

In some metals, such as aluminum, oxides form thin, coherent layers, protecting the original surfaces.

Processes that release energy by increasing the surface temperature, such as machining and sliding processes, increase the oxidation rate and lead to the formation of various types of oxides.

The presence of lubricants, especially their additives, can lead to the formation of reaction layers that play a very important role in sliding processes.

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Adsorption surface films

In the most common situations, adsorption layers are made up of water vapor, oxygen or hydrocarbon molecules from the environment that, when condensed on surfaces, can give rise to the formation of adsorbed layers.

In **physical adsorption**, there is no exchange of electrons between the surface and the molecules of the adsorbed species. The bond is established by weak van der Waals forces, so the binding energy is very low, on the order of 1 to 2 kcal/mole; for this reason, in high vacuum, surfaces are free of adsorbed species by physical adsorption.

In **chemical adsorption**, electrons are shared or exchanged between the surface and the molecules of the adsorbed species. The bonds established are covalent, with binding strengths of around 10-100 kcal/mole. The difference between chemical adsorption and layers formed by chemical reaction is that in chemical adsorption, the adsorbed species maintains its identity.

Surface tension, surface energy and wettability

The atoms and molecules on the surface have energy levels above, or possibly below, those on the interior; this energy difference is called surface tension in liquids and surface energy in solids.

From a thermodynamic point of view, the surface free energy γ or surface tension is the reversible work W that is required to create a unit surface area.

$$\gamma = \frac{dW}{dA}$$

Surface energy is crucial for physical adsorption and is extremely important for adhesion. The interfacial energy W_{ab} quantifies the adhesive bond; the higher the W_{ab} , the stronger the bond.

$$W_{ab} = \gamma_a + \gamma_b - \gamma_{ab}$$

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γ_a – Surface free energy of body a
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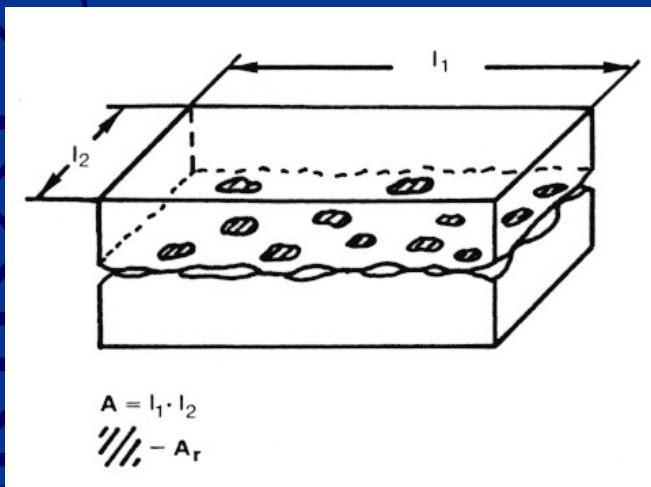
γ_b – Surface free energy of body b
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γ_{ab}^{ECT} – Surface free energy of the interface ab

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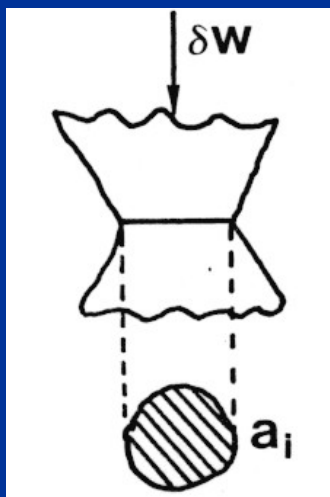
Contact mechanics: contacting surfaces with relative motion

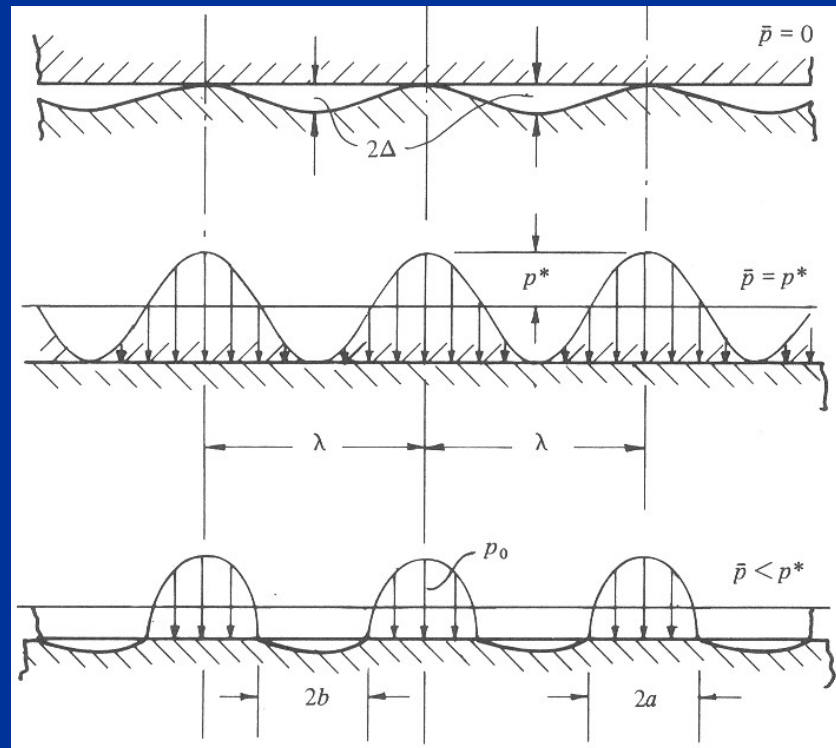
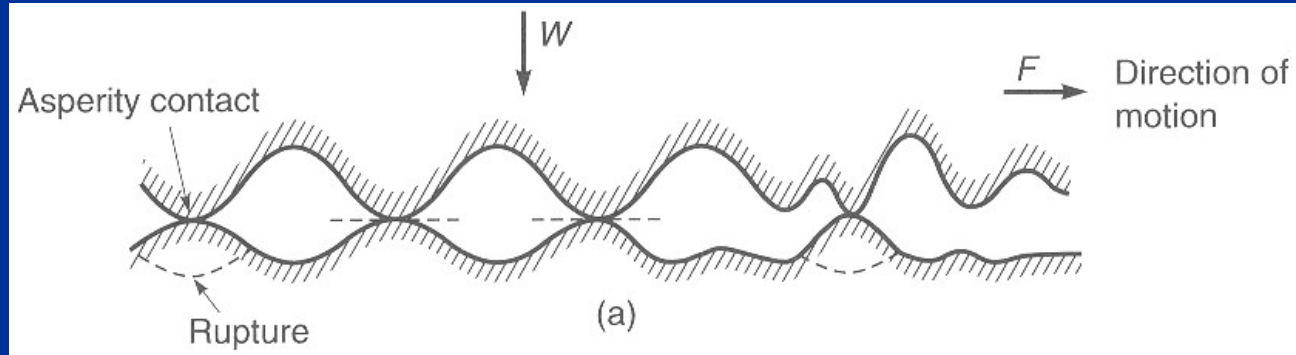
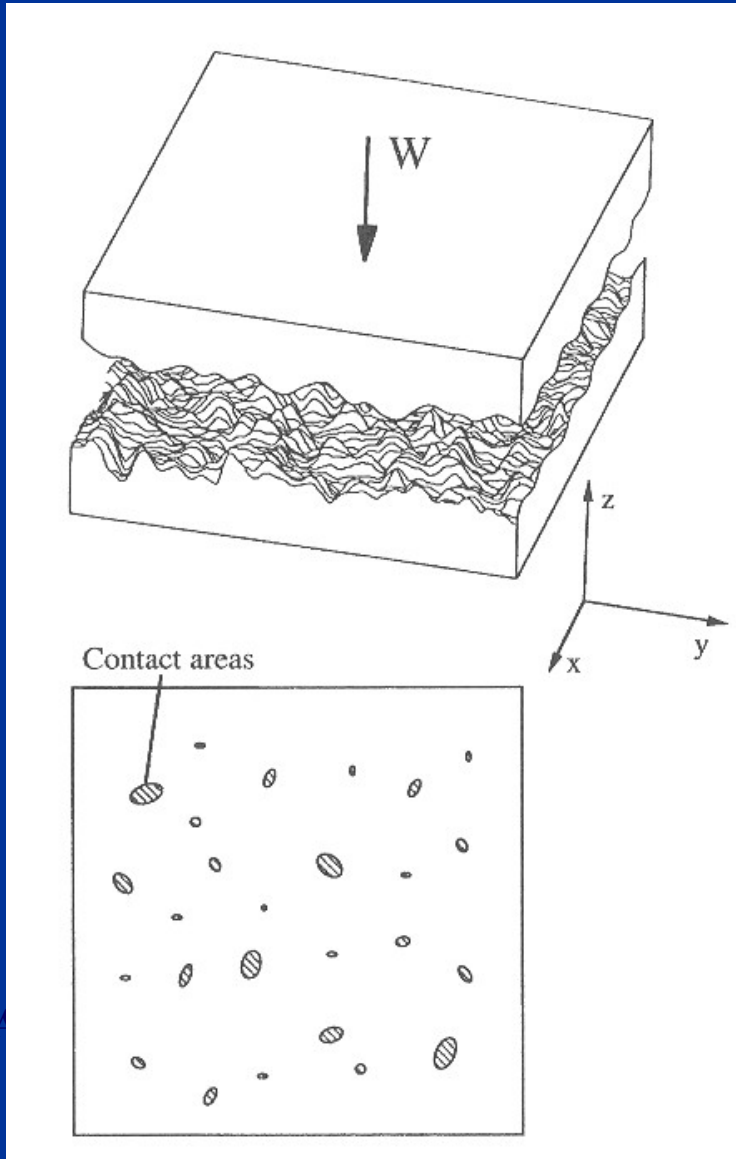
When two surfaces interact, they come into contact with each other at the peaks of the surface asperities, forming real contact areas that are usually very small, i.e. with very high contact pressures.



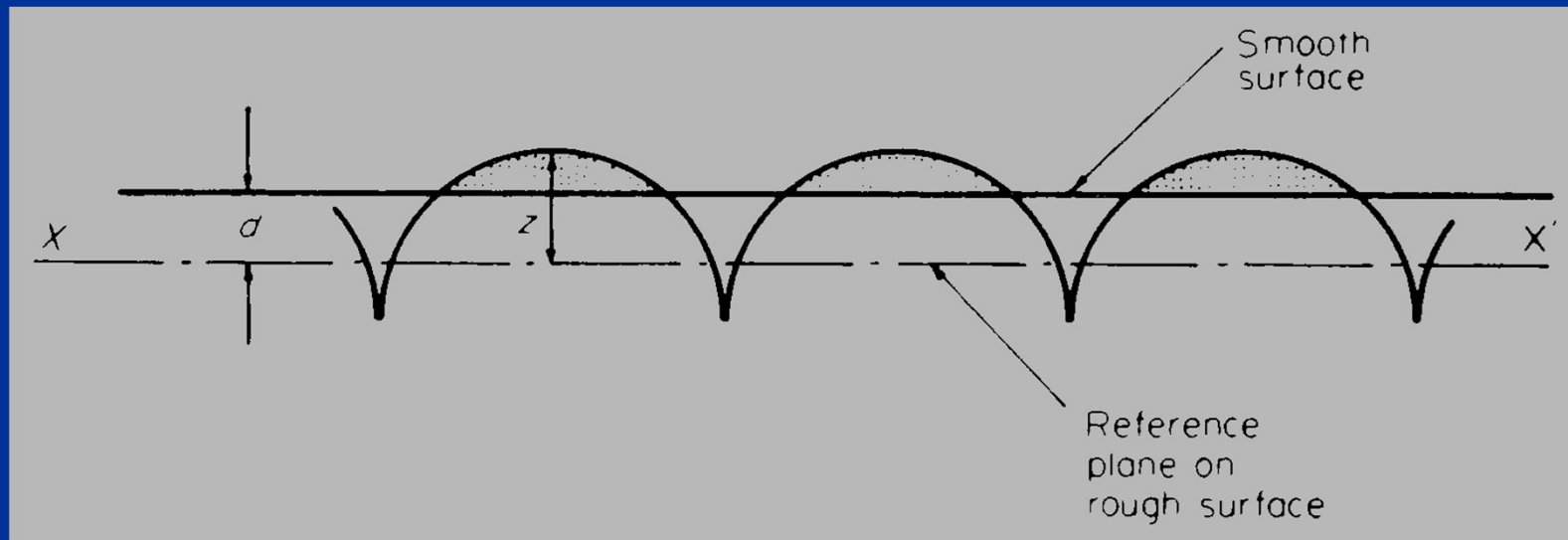
The behavior of a system that must move in a tangential direction is strongly dependent on the forces acting in contact and the nature of the contacting bodies.

In fact, these two aspects that govern tribological behavior are not independent. The mechanical behavior of surface films depends on contact forces, while contact stresses are strongly dependent on sliding friction.





Contact between rough bodies

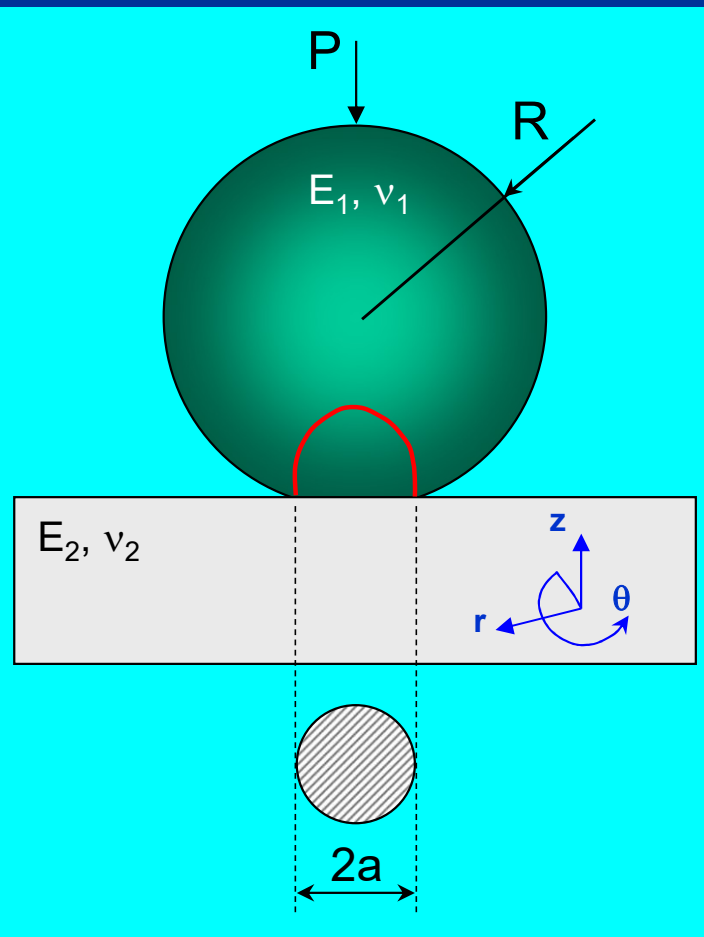


Although the surface of bodies has a very complex geometry and the interaction between surfaces is very difficult to model, each asperity has a tip that will be reasonably spherical, which is why it is very common to consider contact models with spherical asperity distribution.

Thus, the study of sphere-plane contact is of great importance for interpreting the contact between rough bodies as well as for studying the contact of polished bodies with spherical geometry (bearings, cams, gears, wheel/rail,...).

Contact sphere-plane under normal load

Hertz contact model

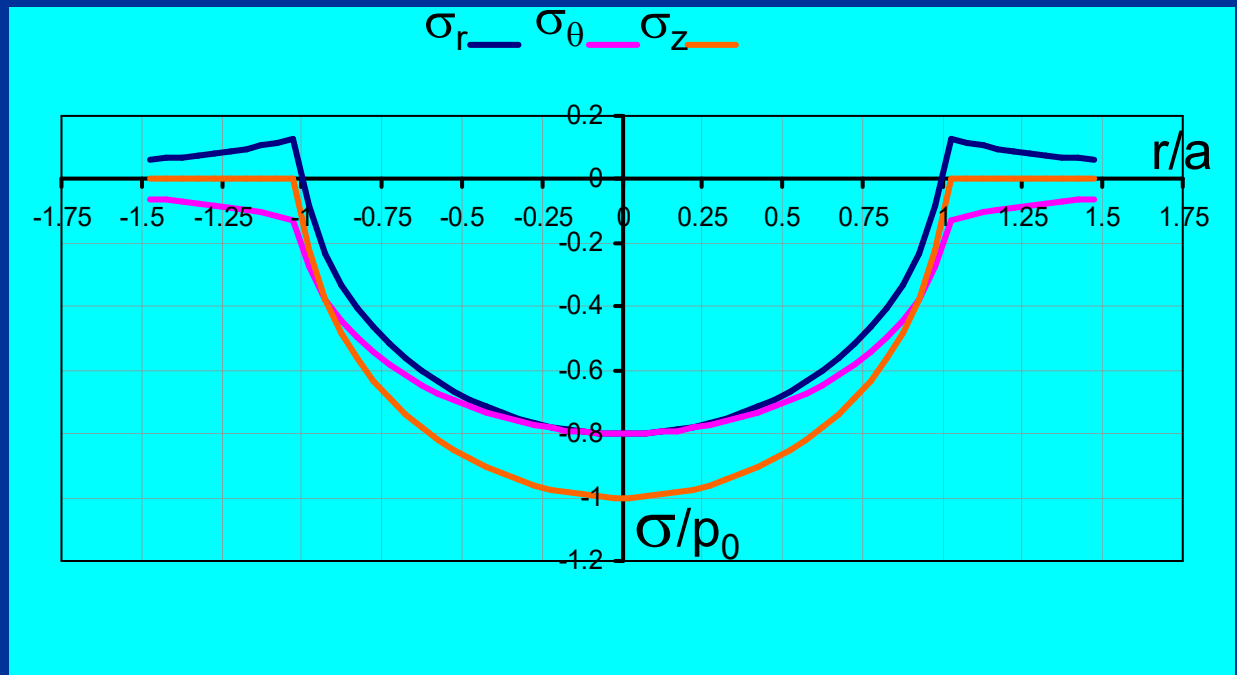
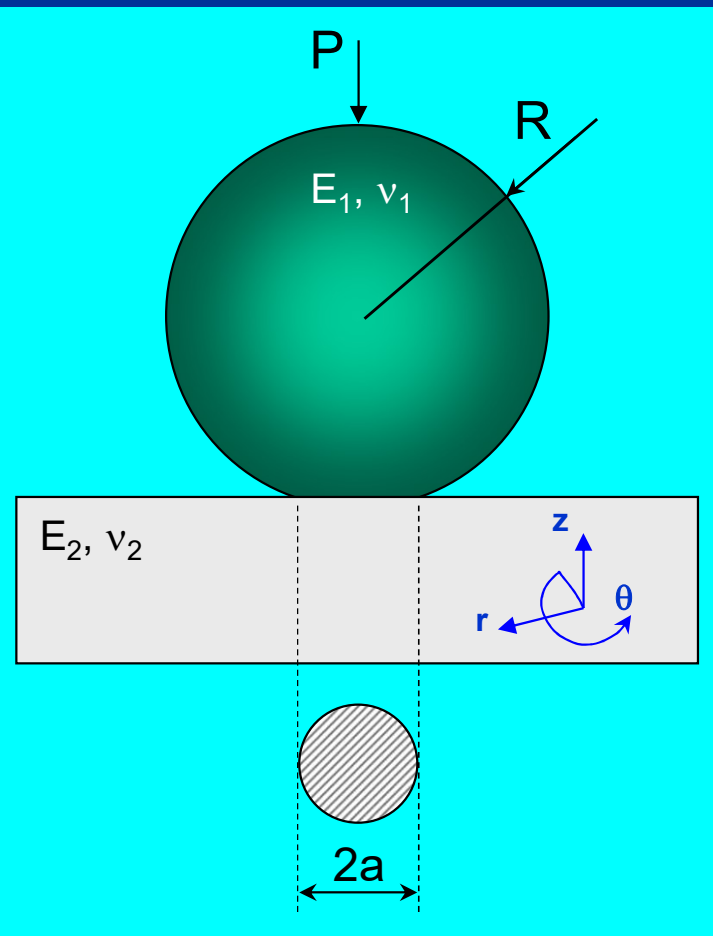


$$a = \sqrt[3]{\frac{3PR}{4E^*}} \quad p_0 = \frac{3P}{2\pi a^2} = \sqrt[3]{\frac{6PE^*}{\pi^2 R^2}}$$

$$\frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}$$

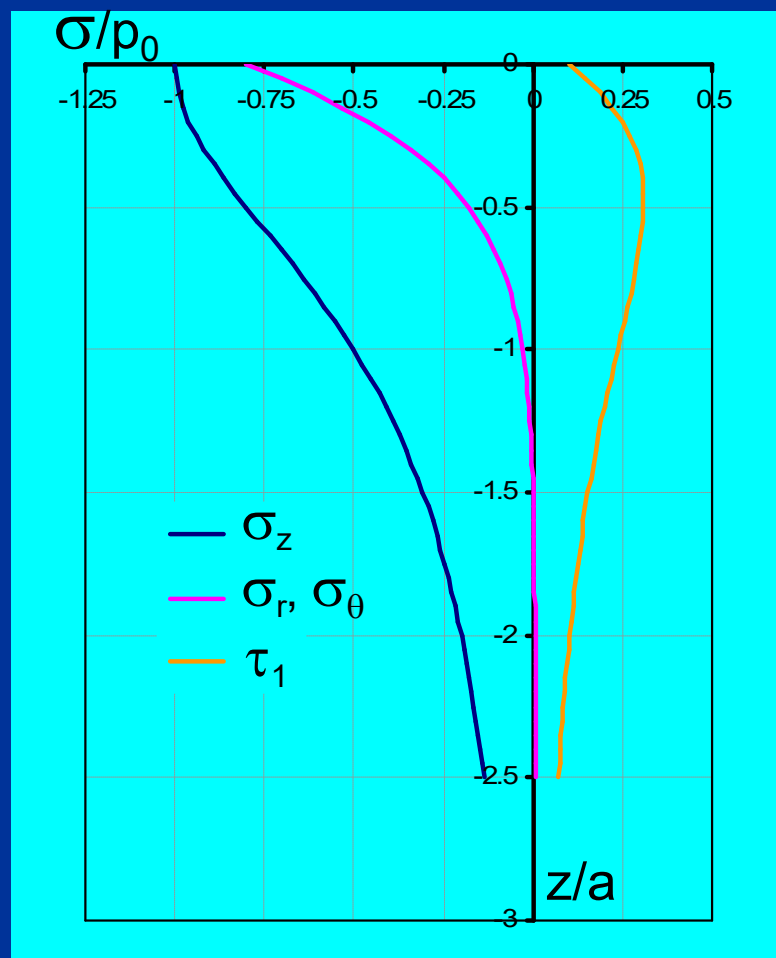
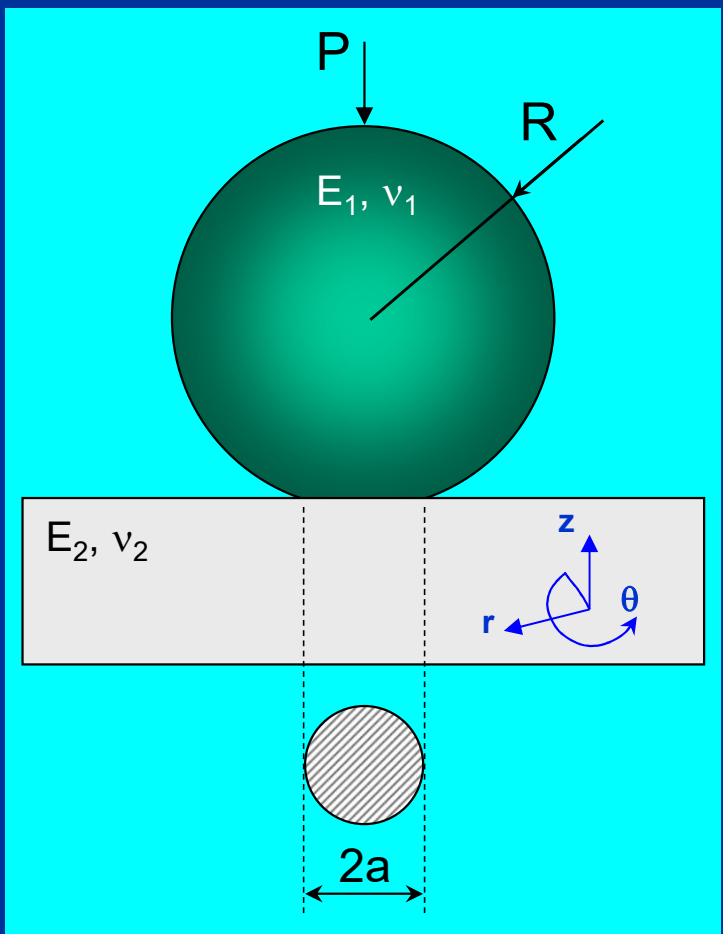
	$r \leq a$	$r > a$
σ_z / p_0	$-\left[1 - \left(\frac{r}{a}\right)^2\right]^{\frac{1}{2}}$	0
σ_r / p_0	$\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2 \left[1 - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{3}{2}}\right] - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{1}{2}}$	$\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2$
σ_θ / p_0	$-\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2 \left[1 - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{3}{2}}\right] - 2\nu \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{1}{2}}$	$-\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2$

TR



	$r \leq a$	$r > a$
σ_z/p_0	$-\left[1 - \left(\frac{r}{a}\right)^2\right]^{\frac{1}{2}}$	0
σ_r/p_0	$\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2 \left[1 - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{3}{2}}\right] - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{1}{2}}$	$\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2$
σ_θ/p_0	$-\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2 \left[1 - \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{3}{2}}\right] - 2\nu \left(1 - \left(\frac{r}{a}\right)^2\right)^{\frac{1}{2}}$	$-\frac{1-2\nu}{3} \left(\frac{r}{a}\right)^2$

III

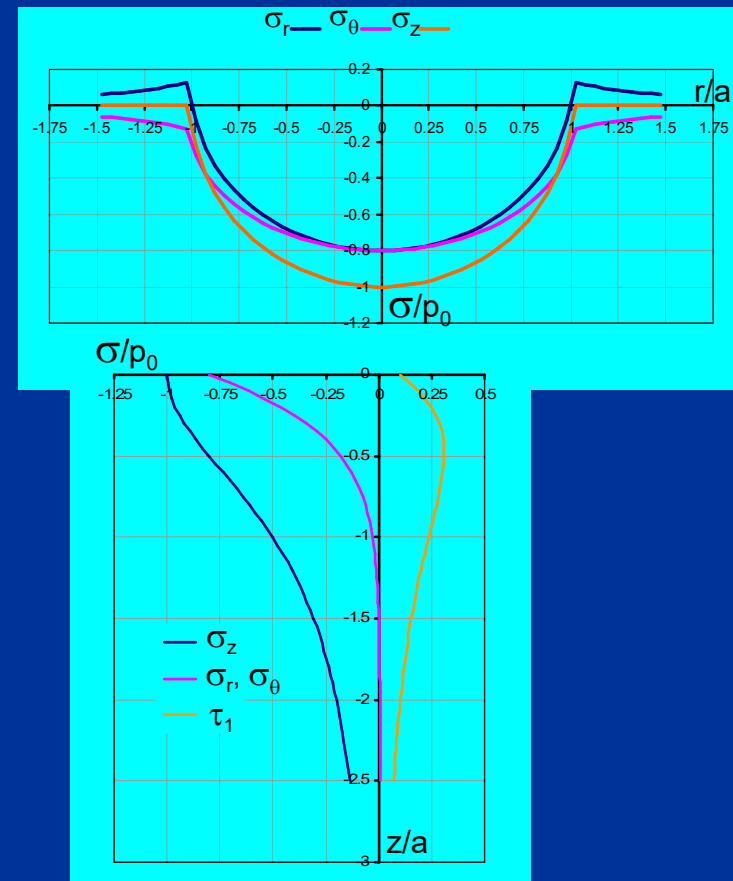


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Contact sphere-plane under normal load

Hertz contact model

- At the contact surface, the stresses are strongly compressive, except for σ_θ which at the limit of the contact circle reaches the value of 13% p_0 ($\nu = 0.3$);
- The central part of the contact surface is highly compressed, in an almost hydrostatic state (for $\nu = 0.5$ the compression is actually hydrostatic).
- On the contact surface, the shear stresses have very low values, only on the periphery are values of 13% p_0 ($\nu = 0.3$) reached;
- Stresses are distributed in depth and still have significant values at depths of the order of $3a$;



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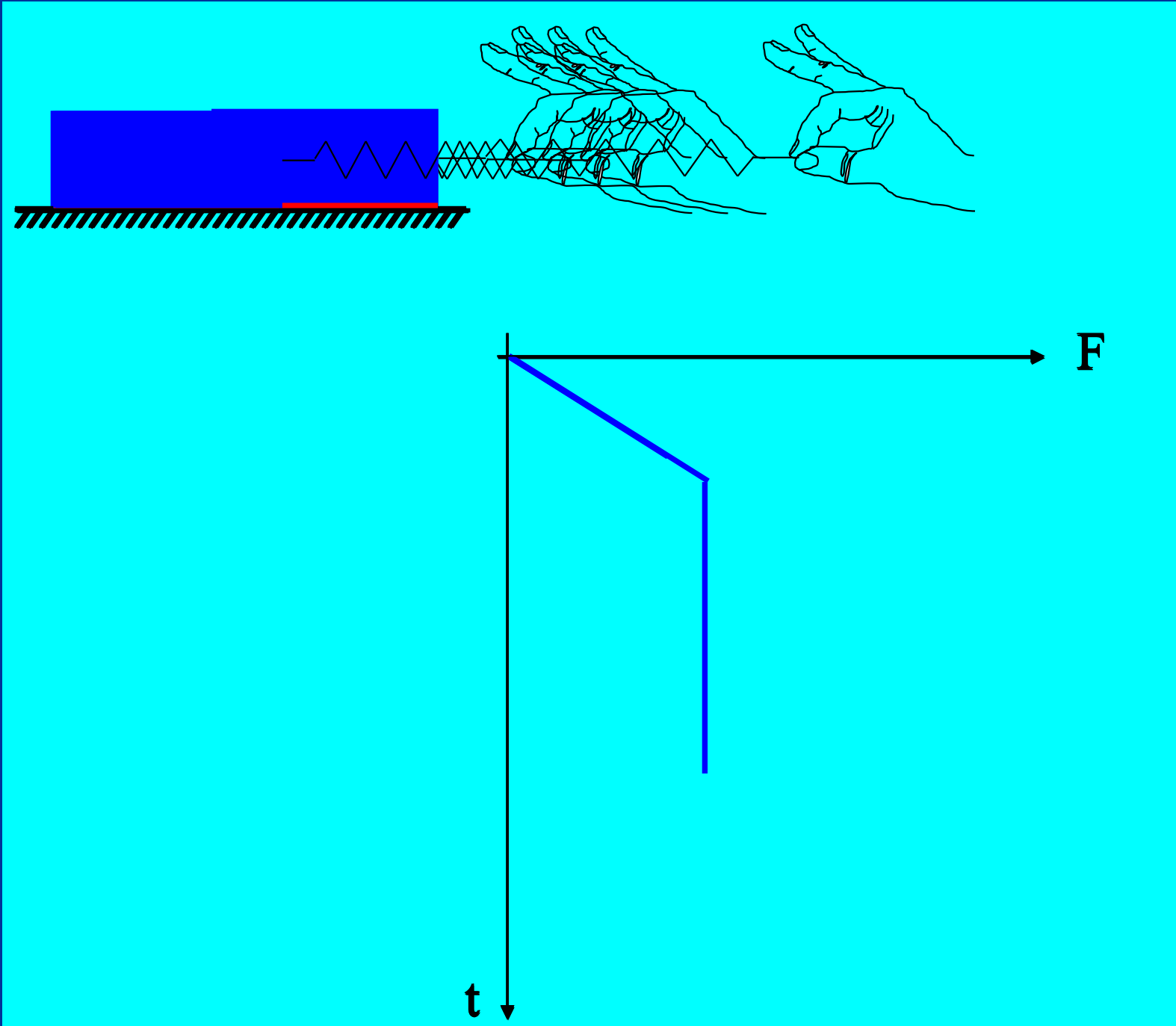
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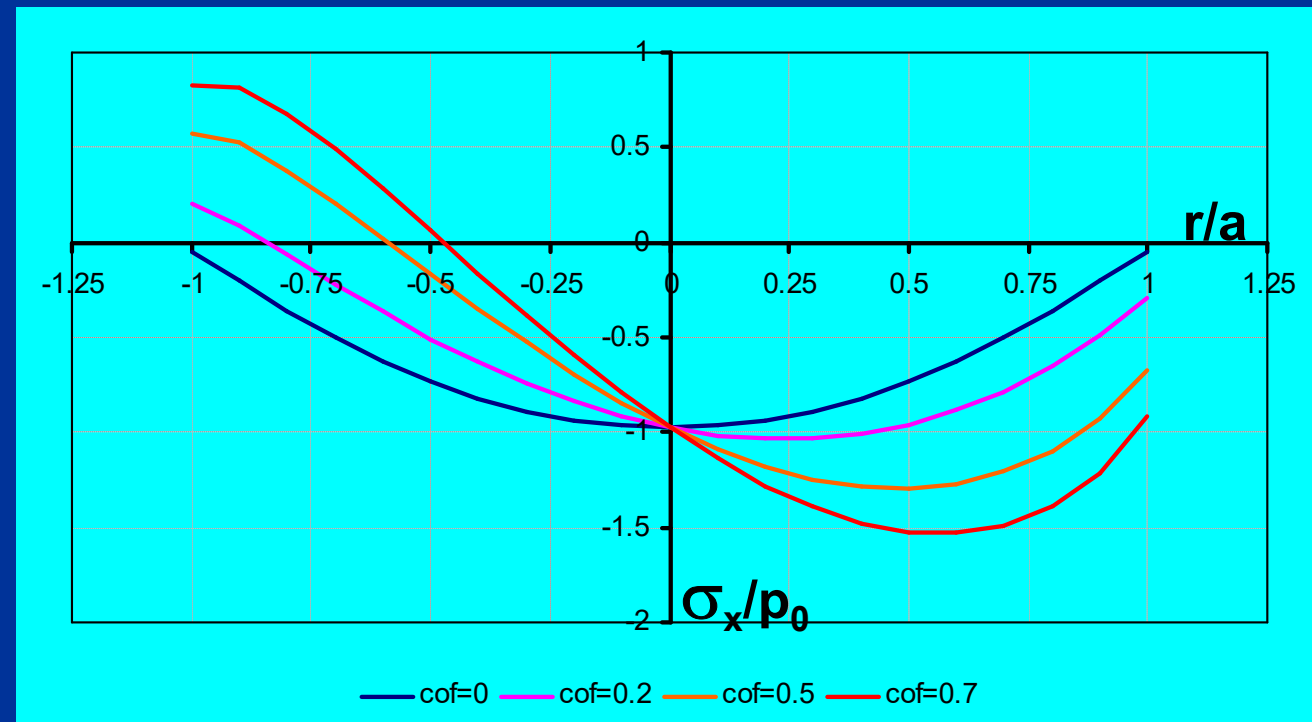
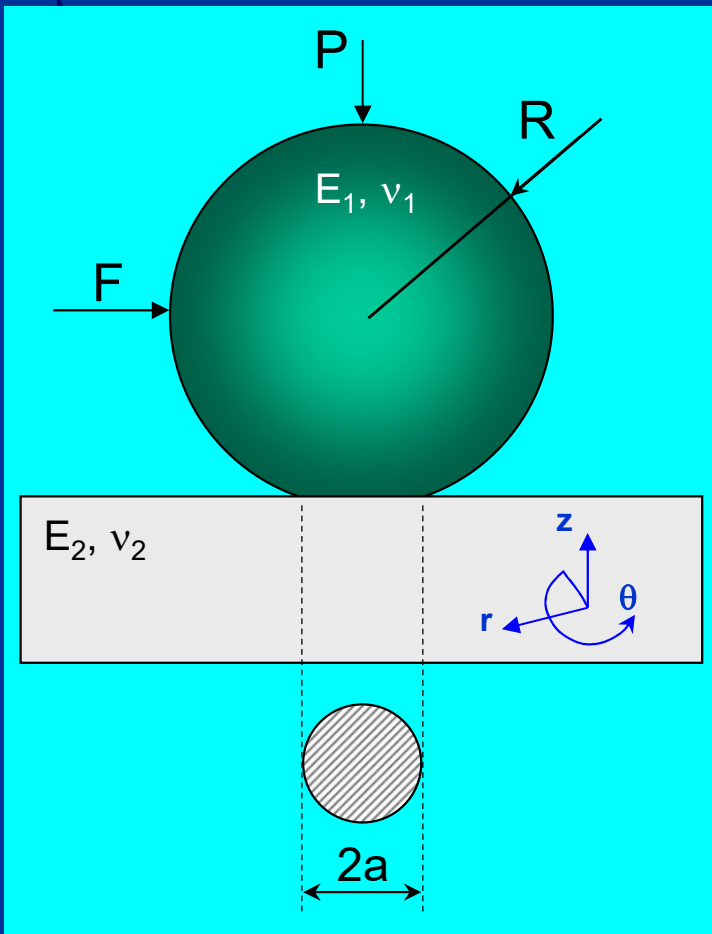
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- The maximum value of the shear stress is reached in the subsurface. For $\nu = 0.3$ the maximum value is 0.31 p_0 and is reached at a depth of $0.48a$.

Sliding friction



Contact sphere-plane under normal load with friction



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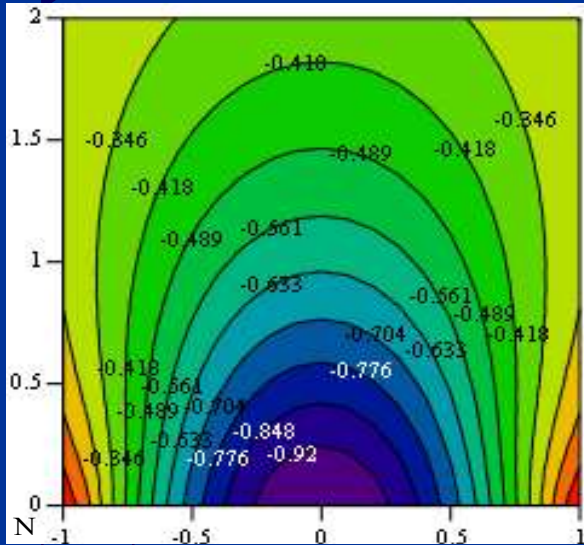
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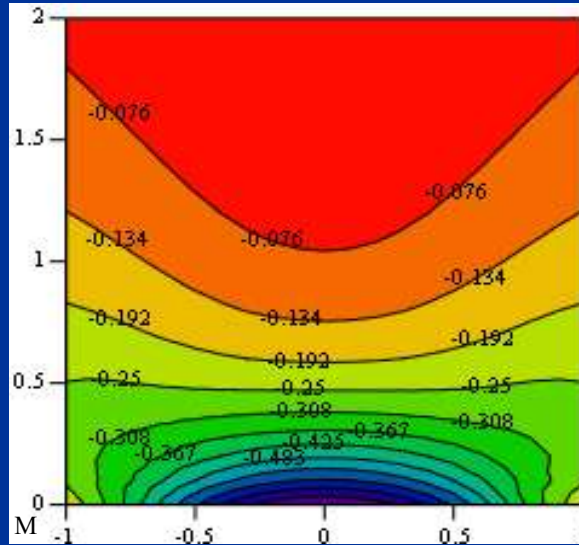
COF = 0

Y

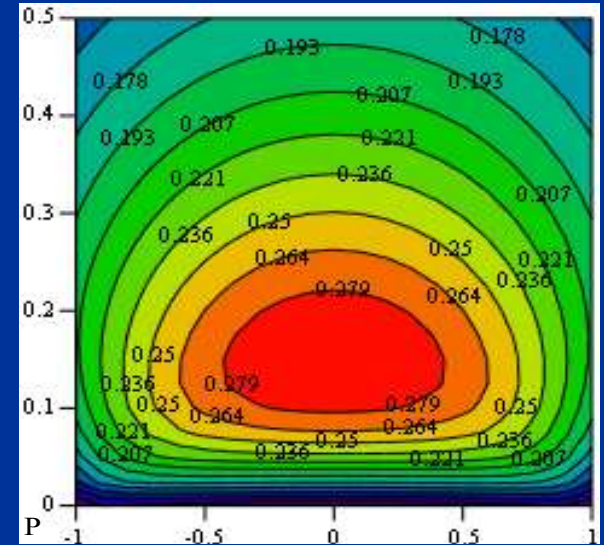
σ_z



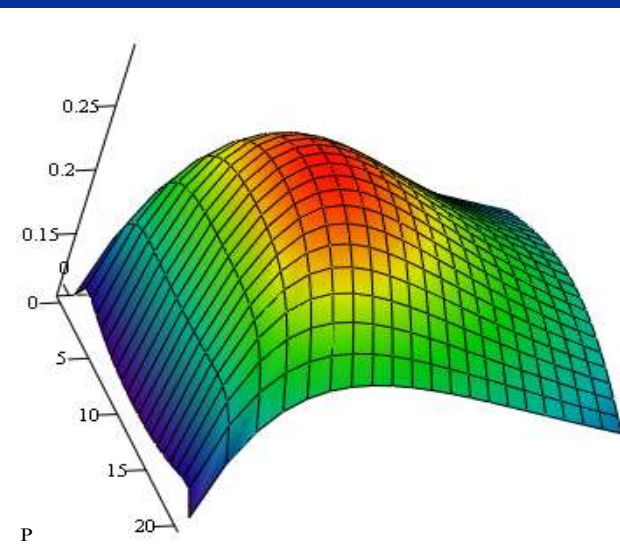
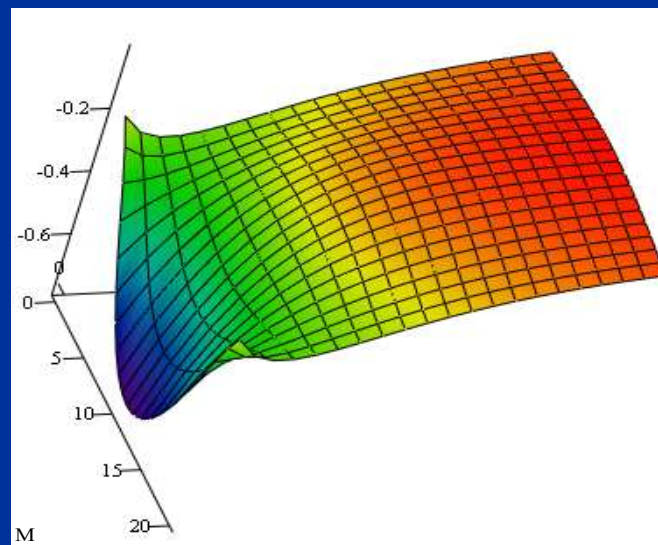
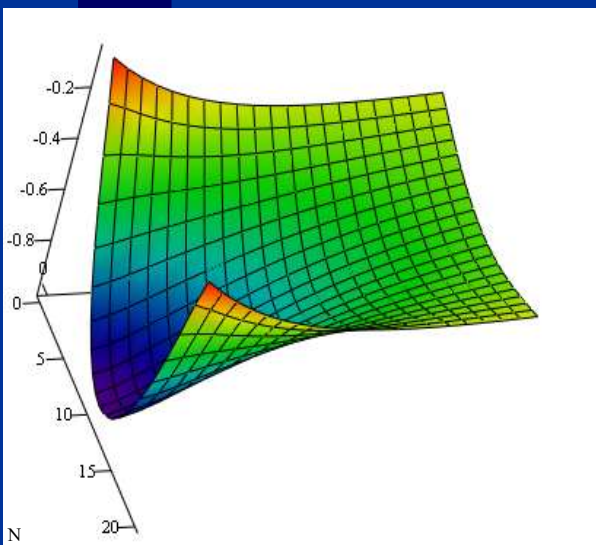
σ_r



σ_v Mises



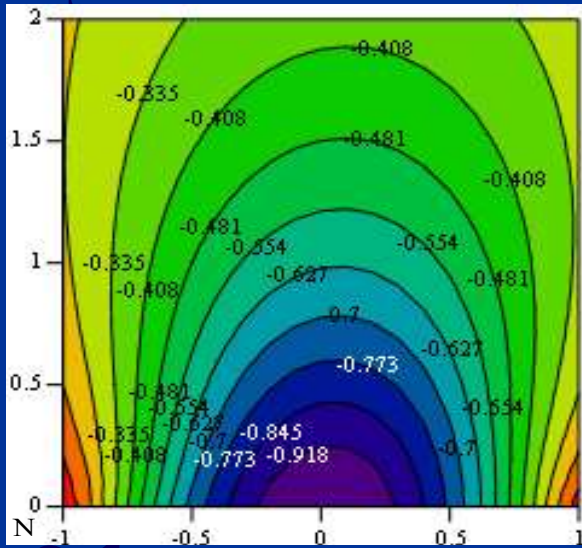
R



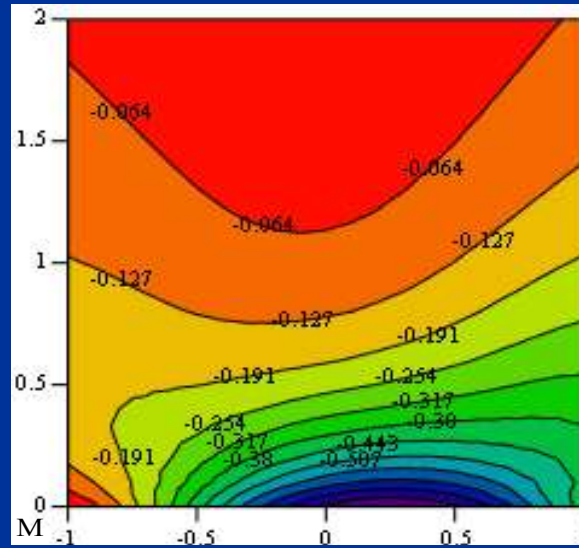
COF = 0.2

Y

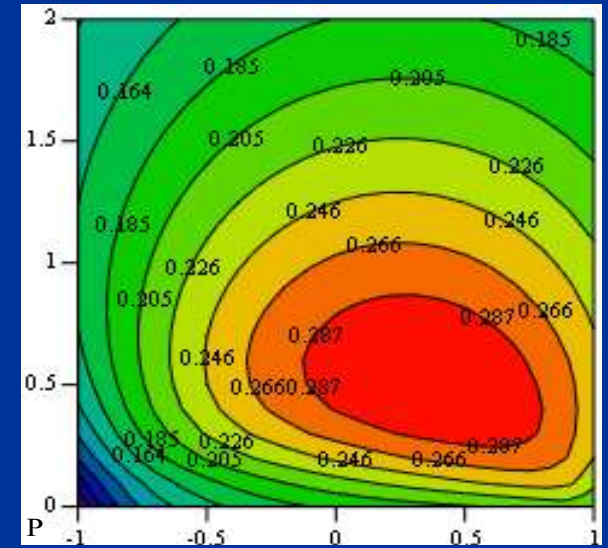
σ_z



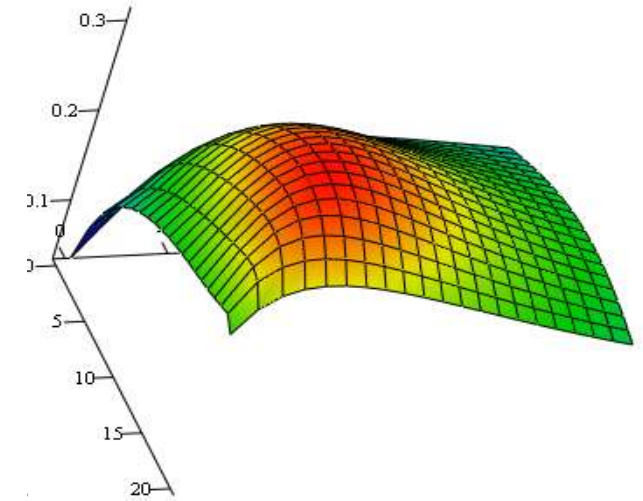
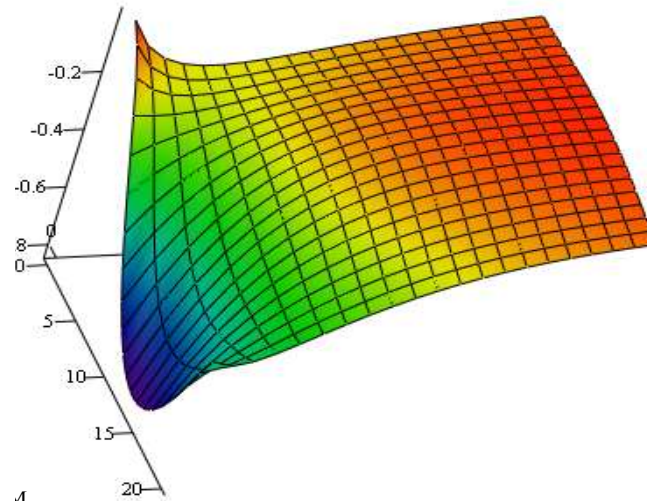
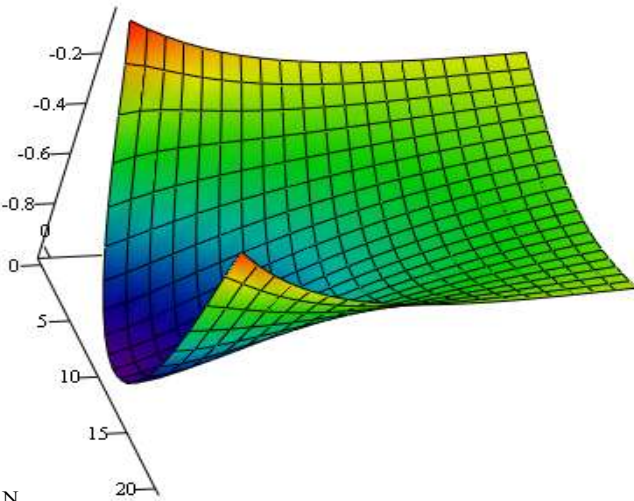
σ_r



σ_V Mises



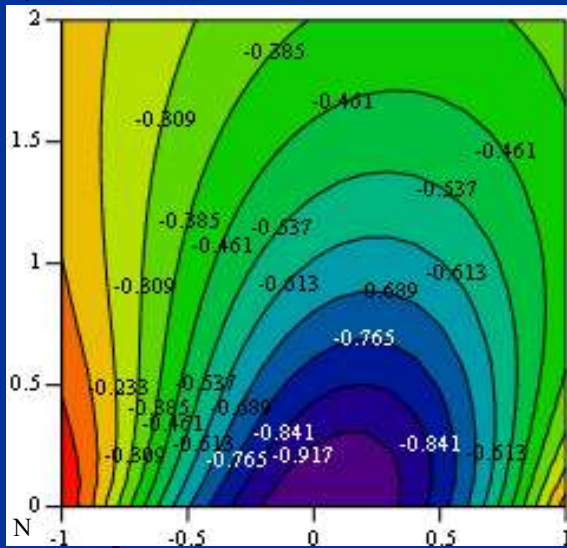
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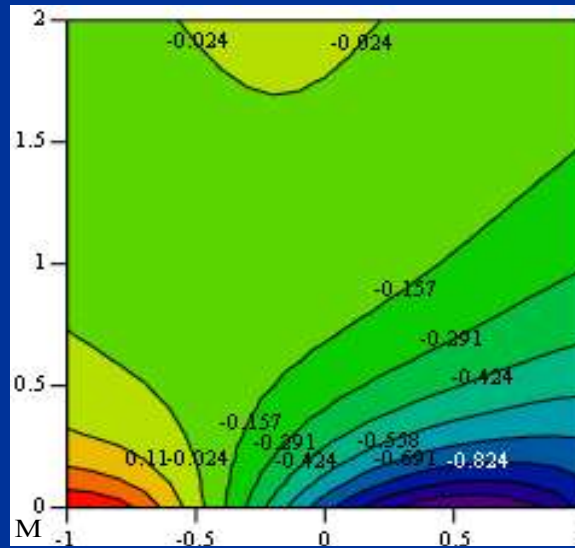
COF = 0.7

Y

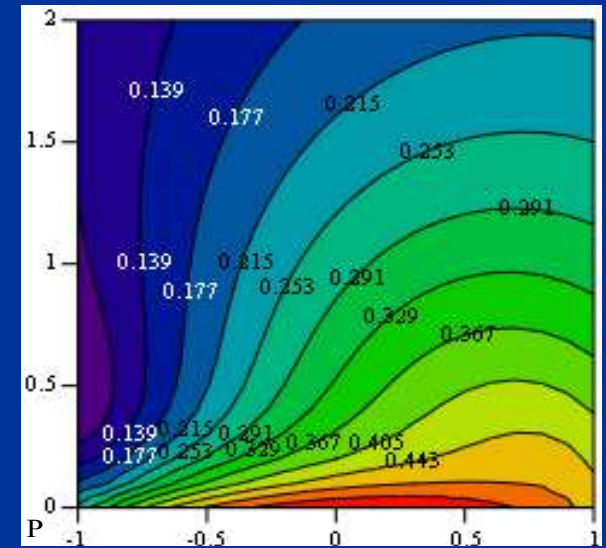
σ_z



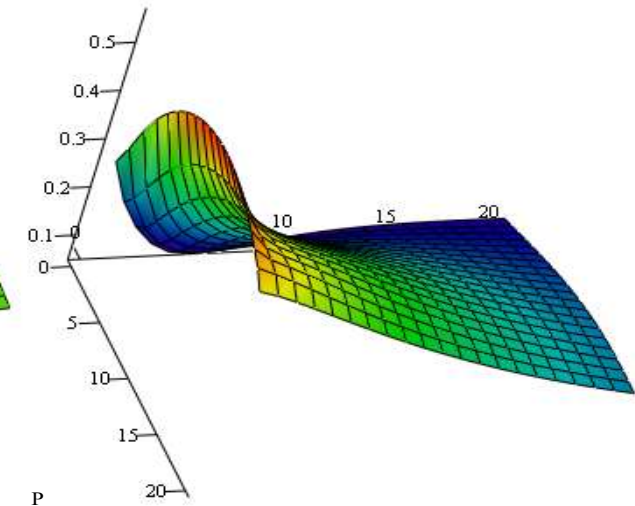
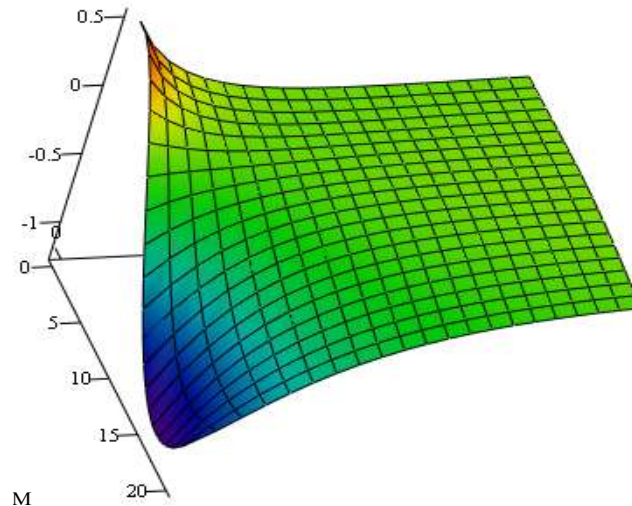
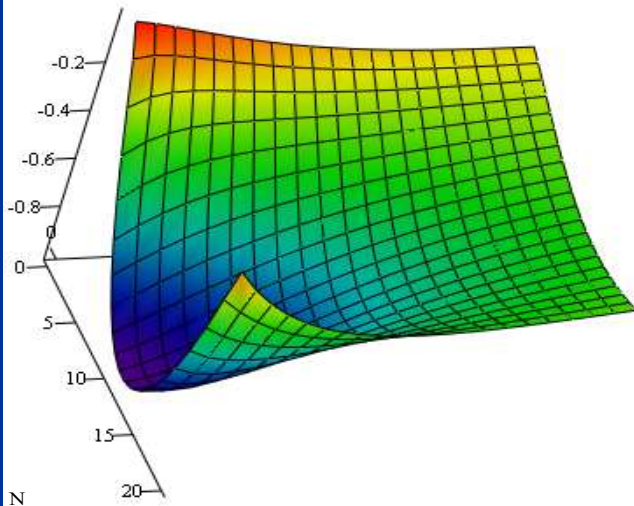
σ_r



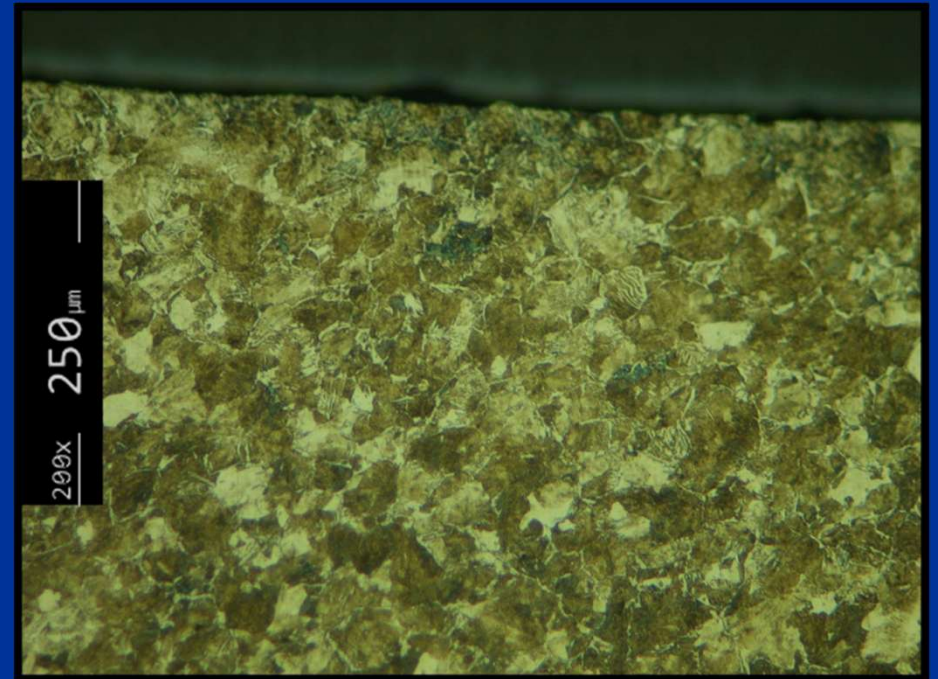
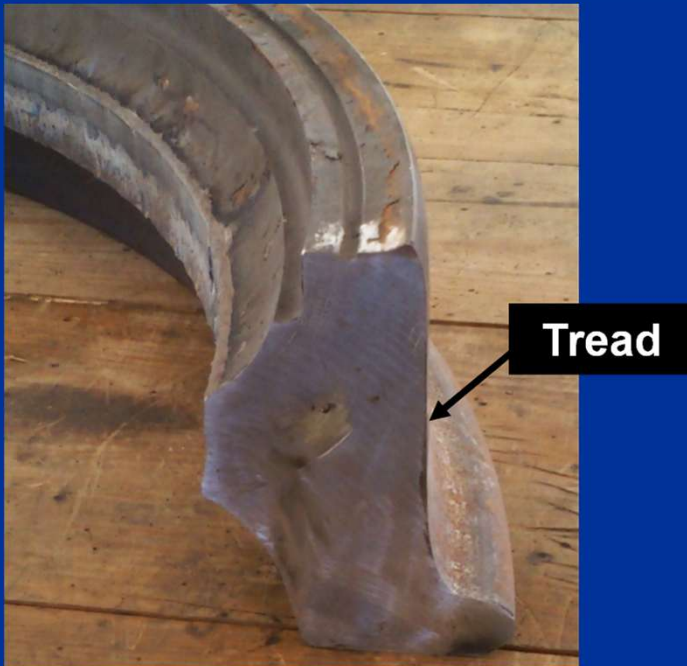
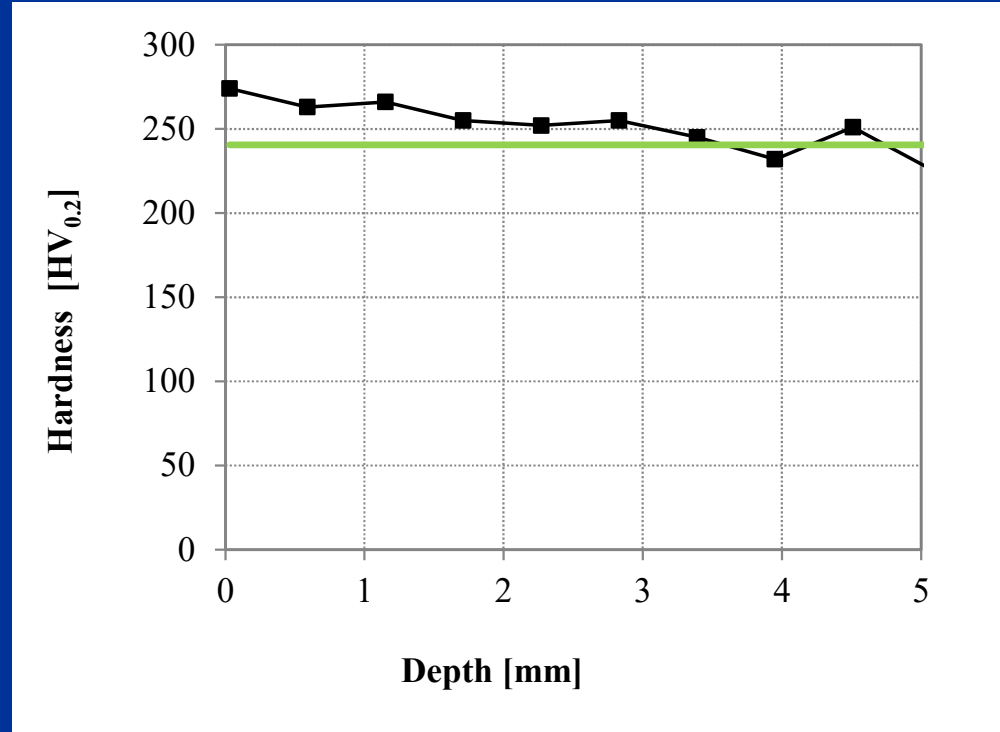
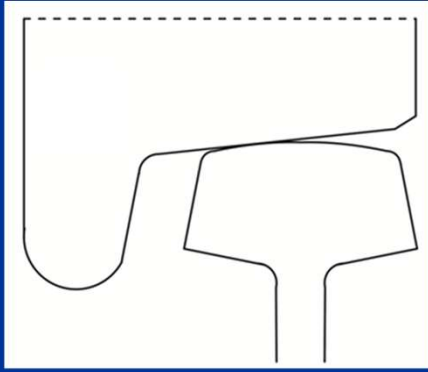
σ_v Mises

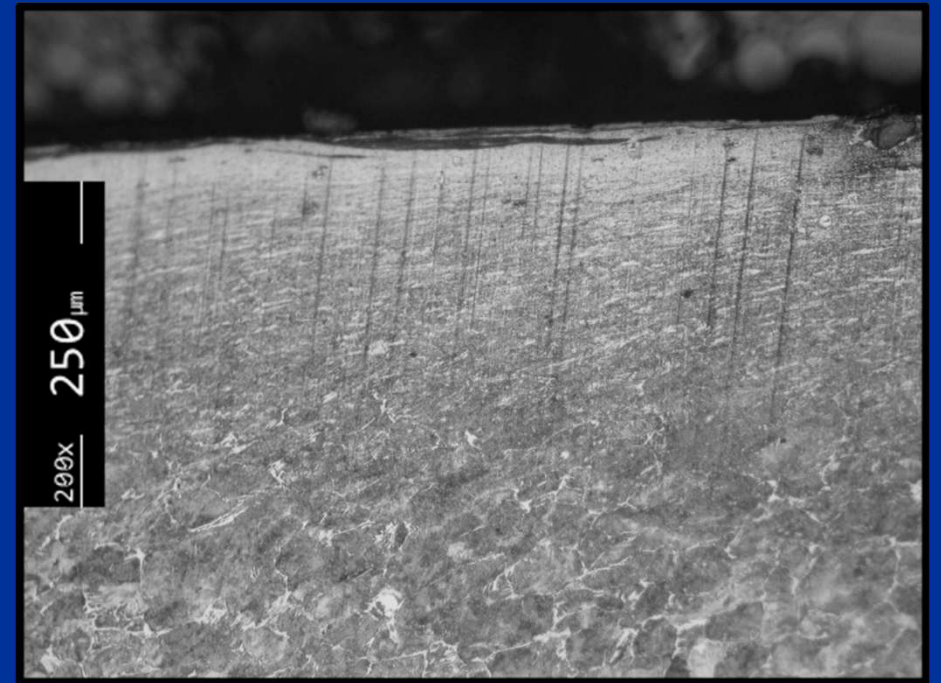
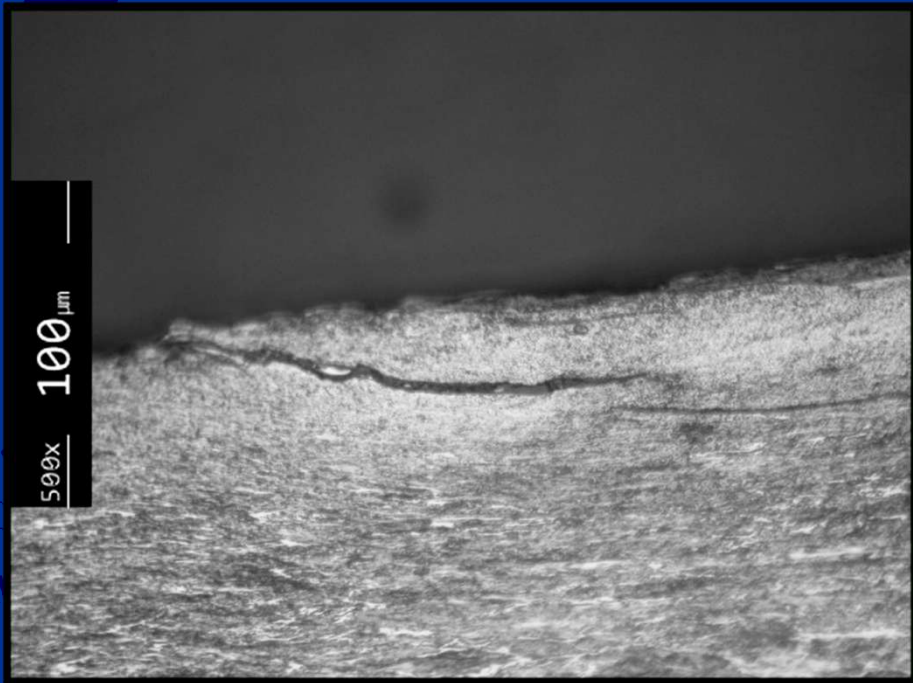
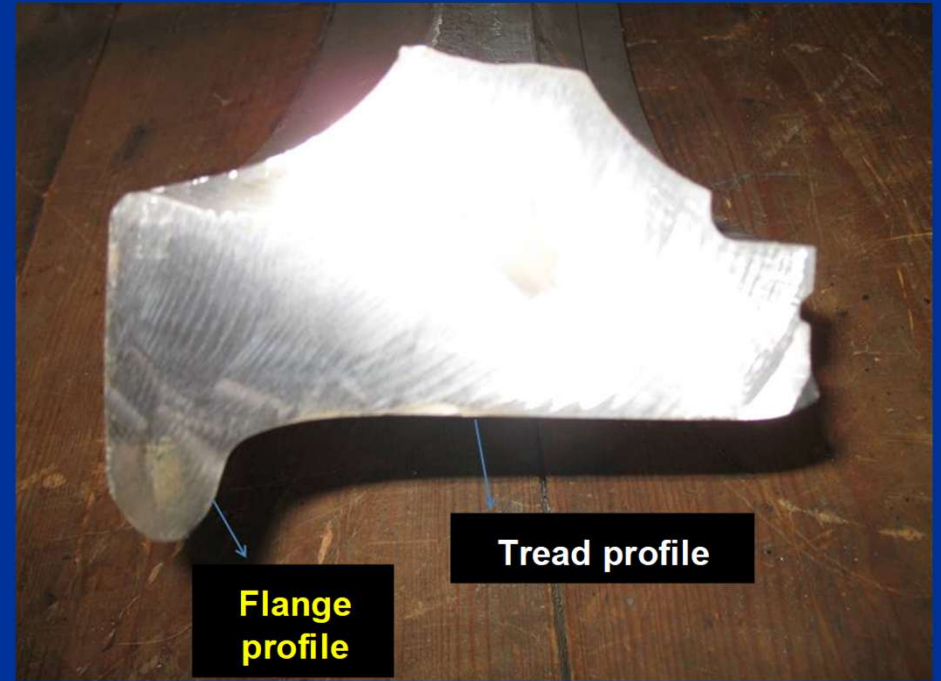


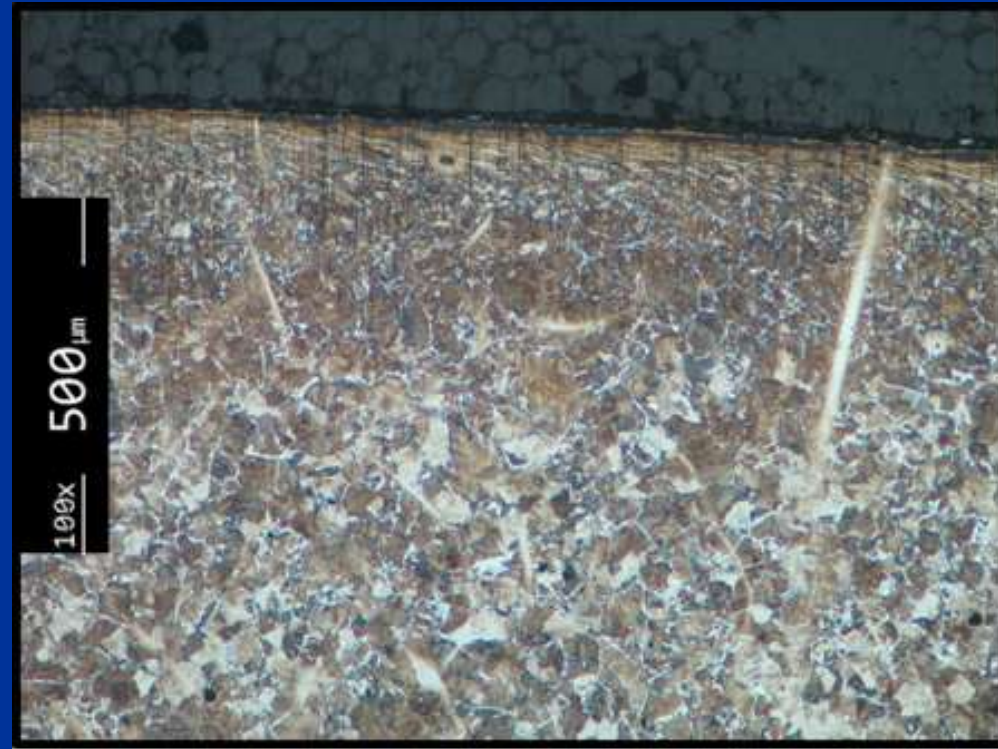
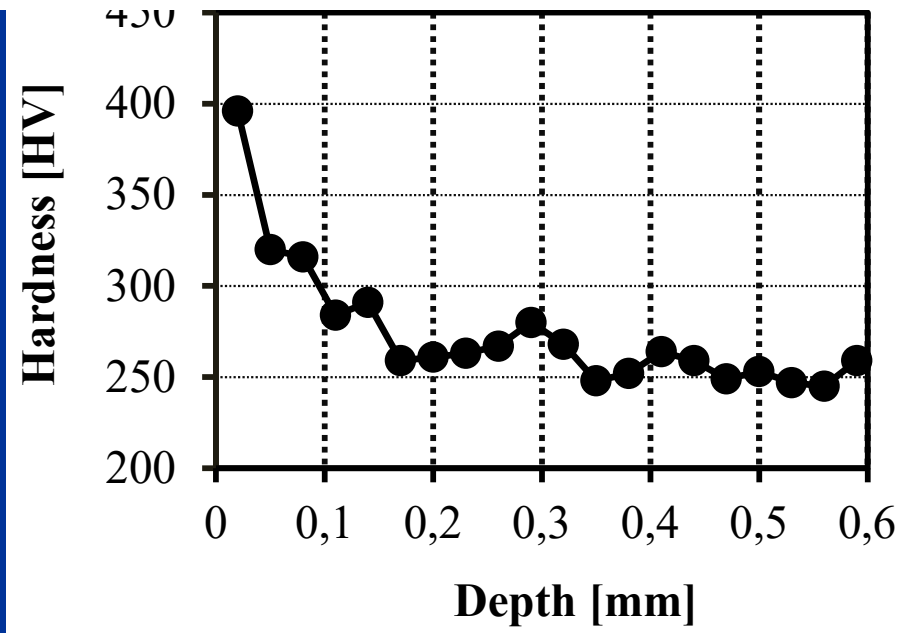
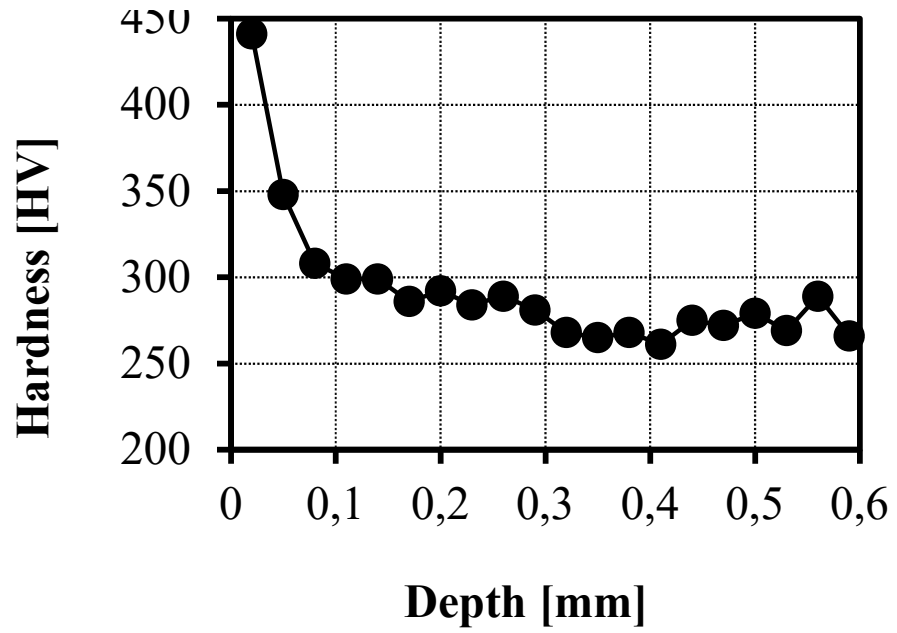
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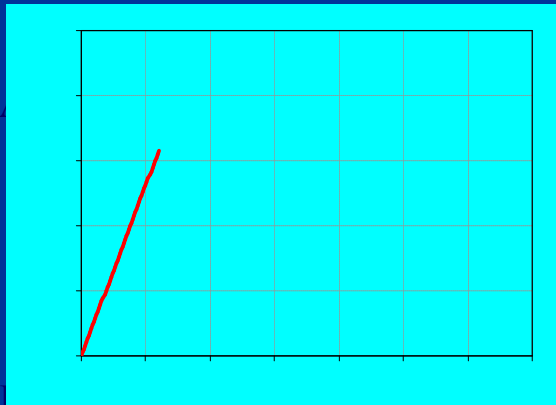
U. Coimbra

Influence of friction in the contact stress field

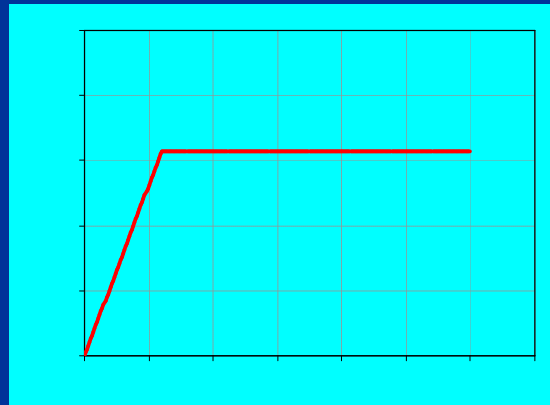
- At the contact surface, the stresses are no longer symmetrical. The normal stresses in the direction of the friction force undergo a substantial variation, becoming strongly compressive downstream of the contact and tensile upstream.
- Under the contact point, the stress distribution also changes significantly. The stresses are no longer symmetrical about the load axis. The maximum shear stress value approaches the surface, and for typical unlubricated sliding friction coefficients, the maximum value is reached at the surface.

Changing the stress field means that the damage modes also vary and depend on the friction and elasto-plastic behavior of the materials.

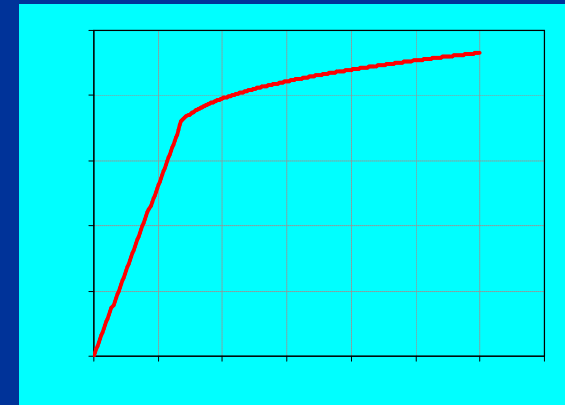
Linear elastic



Elastic perfectly plastic



Elasto-plastic with strain hardening



Influence of contact stresses on failure mode

- In elastoplastic materials, with or without strain hardening, such as most metal alloys and pure metals, plastic shear deformation precedes failure.
- In rigid-brittle elastic materials, such as cermets and ceramics, failure generally occurs through tensile fracture.

Contacts with low friction

- In this case, the stresses due to friction are very low and a Hertzian type of contact predominates.
- Considering elastoplastic materials, failure occurs by shearing in the sublayer. Considering $\nu = 0.3$, the damage is located at a depth of $0.48 a$, where the maximum shear stress reaches $0.31 p_0$. Assuming the Tresca criterion, deformation occurs when $p_0 = 1.6 \sigma_c$. Consequently, failure occurs when the applied load reaches the value

$$P = 21.17 R^2 \sigma_c \left(\frac{\sigma_c}{E^*} \right)^2$$

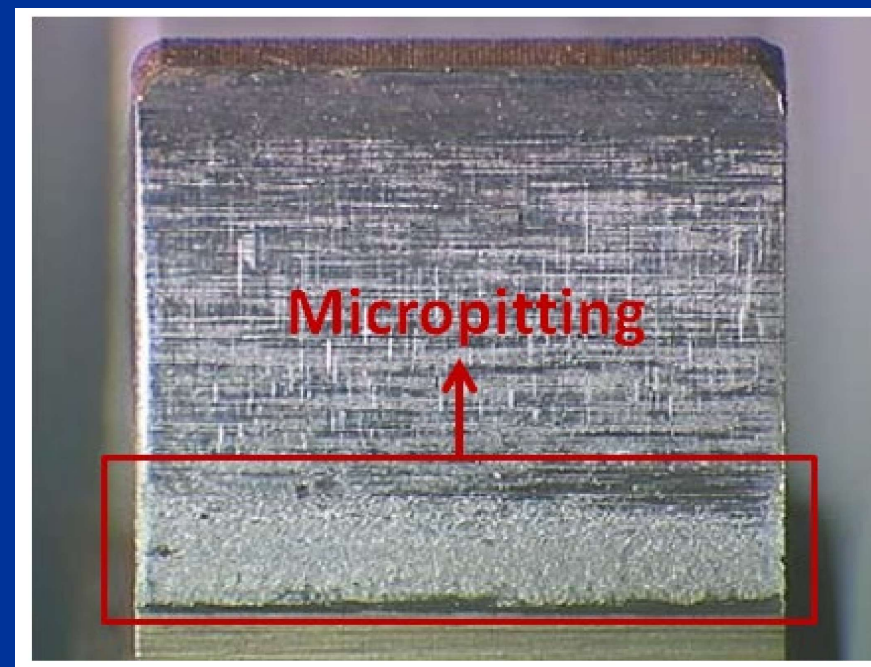
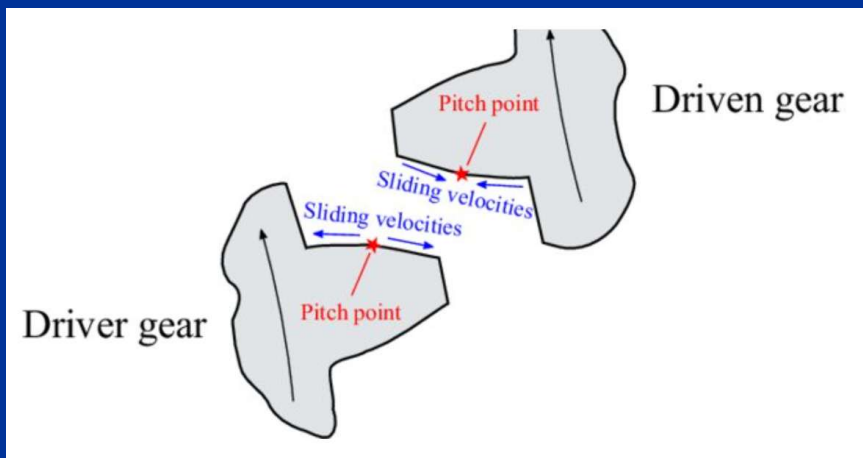
- Considering rigid-brittle elastic materials, failure occurs by traction at the limit upstream of the contact circle. Fracture occurs when the stress applied at that location equals the fracture limit stress. The maximum normal load that can be applied will therefore be given by

$$P = \left(\frac{3\sigma^*}{1-2\nu} \right)^3 \frac{\pi^2 R^2}{6E^*}$$

Contacts with high friction

- In this case, the stresses due to friction are not negligible and change the stress field.
- Considering elastoplastic materials, failure occurs due to plastic flow at the contact surface.

- Considering rigid-brittle materials, failure occurs by tensile fracture downstream of the contact.



A.
D.

Mecânica

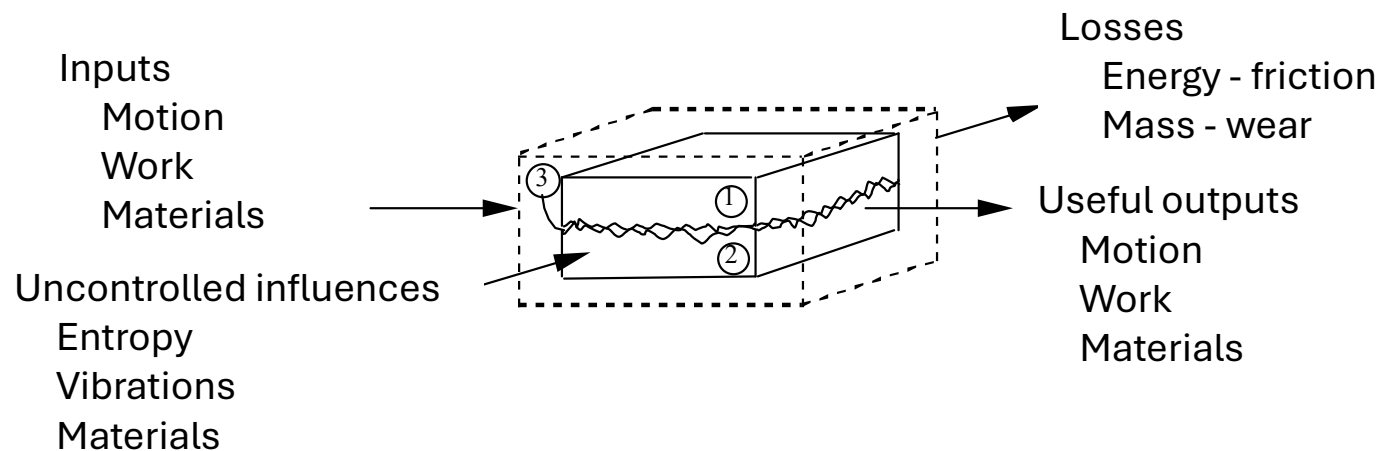
FCT

U. Coimbra

Snidle, R.W.; Evans, H.P.; Alanou, M.; Holmes, M. Understanding Scuffing and Micropitting of Gears. In The Control and Reduction of Wear in Military Platforms, Proceedings of the RTO AVT Specialists' Meeting on "The Control and Reduction of Wear in Military Platforms"; RTO-MP-AVT-109, Williamsburg, VA, USA, 7–9 June 2003; NATO STO: Williamsburg, VA, USA 2004.

Tribological system

The parameters used to quantify tribological performance (coef. of friction, wear resistance, etc.) depend not only on the material in question but also on the antagonist and a wide range of interaction conditions. This multiple dependence led H. Czichos (Tribology, Tribology Series 1 (1978) Elsevier) to apply the principles of thermodynamic systems to the study of tribological systems by considering an open control volume surrounding the contact region.



Tribological System

1 e 2 – contacting materials; 3 – interfacial medium

A tribological system, S , is therefore a set of elements interconnected by their structure and function.

The structure of a tribological system can be defined by:

- the set of its elements, A ;
- the relevant properties of the elements, P ;
- the connections, or couplings, between its elements, R .

Thus, the system can be defined by the set:

$$S = \{A, P, R\}$$

Each system can be considered separated from the environment by an envelope or control surface. The control surface severs the connections between the system and the environment. These connections, depending on whether they correspond to inputs or outputs, are defined as:

- Inputs, X ;
- Outputs, Y .

The function of a tribological system is to fulfill a specific technical purpose, that is, to match a set Y of output variables to a set X of input variables. In other words, a system S can be considered as an operator T :



The function of a system can be analyzed from both an energy and a mass analysis perspective.

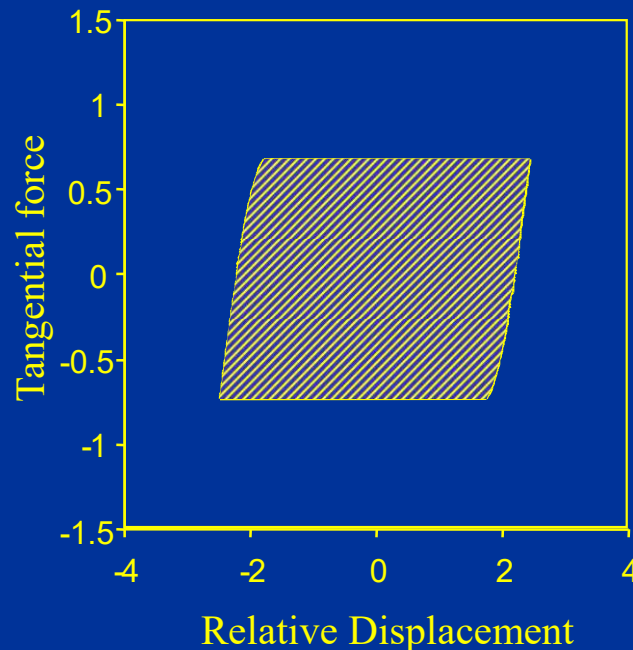
At least theoretically, it's plausible that for a given set of materials, there's a relationship between the energy balance and the mass balance. That is, given that in a sliding situation, the main energy input to the system is the work performed by the frictional force, it's expected that there's some dependence between friction and the wear produced.

The work W done by the friction force, F , can be calculated by the integral of the friction force along the displacement, x , that is:

$$W = \oint_x F dx$$

Thanks to the work of J.-P. Celis and collaborators (P.Q. Campbell et.al., *Wear*, 174(1994)47; H. Mohrbacher et.al., *Wear*, 180(1995)43), the energy approach to fretting wear is currently widely used.

The application to fretting is based on the fact that the energy dissipated by friction in each cycle, corresponds to the area inscribed by the evolution of the tangential force along the relative displacement.



Wear – quantitative models

$$V = kNx$$

Archard model: This model establishes that the wear volume (V) varies linearly with the normal load applied to the contact (N) and the sliding distance (x).

The proportionality constant k is usually referred to as the specific wear rate.

Typical units:

$$V - \text{mm}^3$$

$$N - N$$

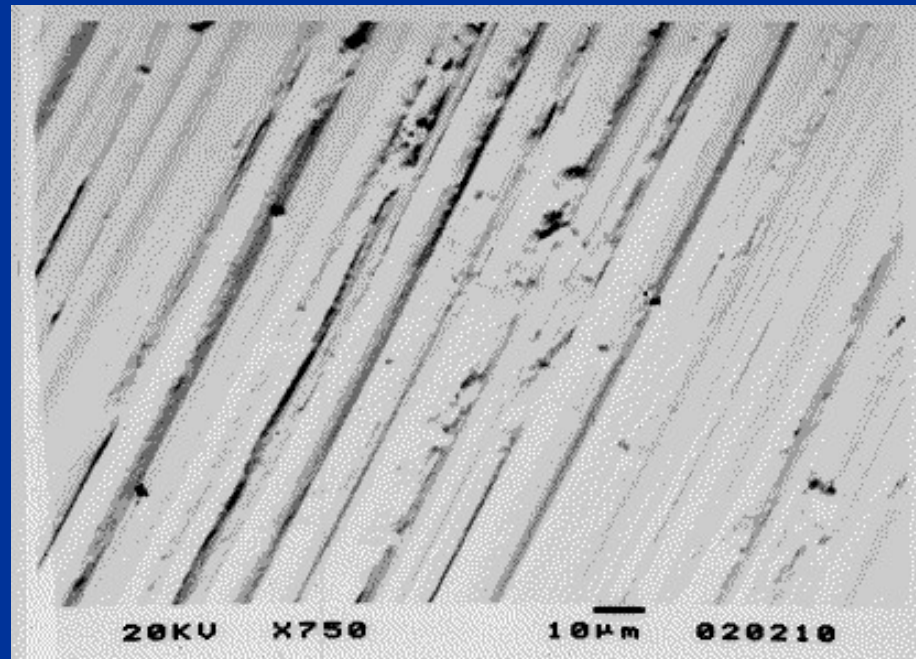
$$x - m$$

$$k - \text{mm}^3\text{N}^{-1}\text{m}^{-1}$$

Abrasion wear

Abrasion - A type of wear where material from a surface is removed or displaced by the action of hard particles, or irregularities on an opposing surface with high hardness, when performing a relative sliding movement under pressure.

In ductile materials, abrasion is easily identified by a surface morphology characterized by parallel grooves oriented according to the direction of movement.



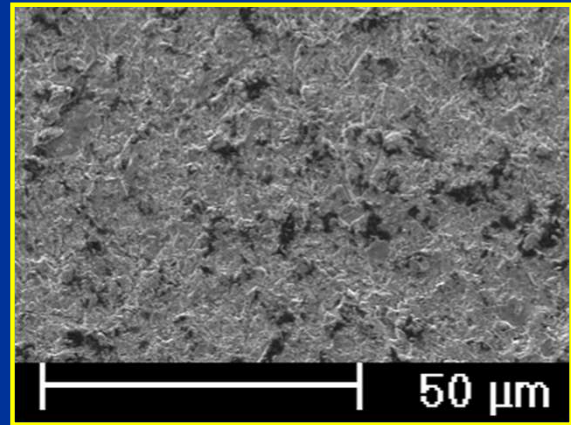
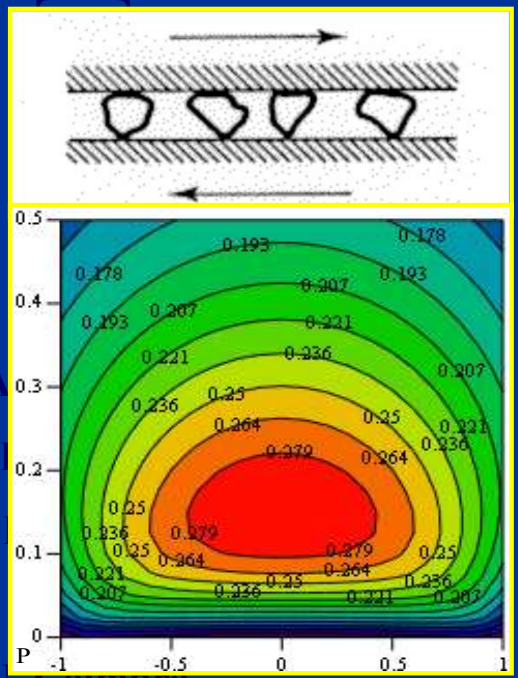
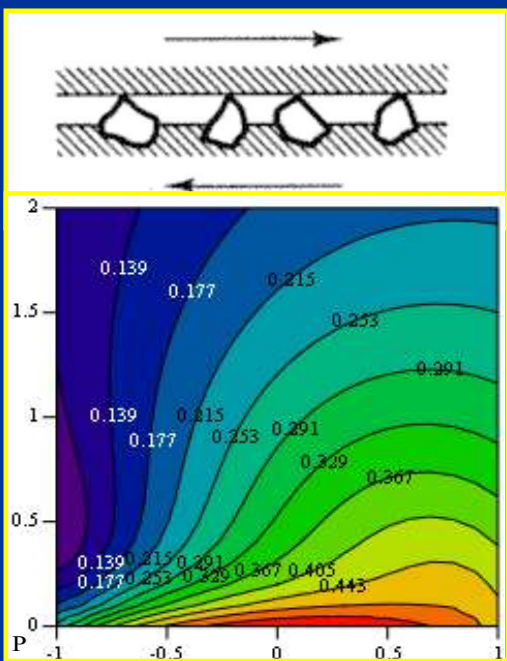
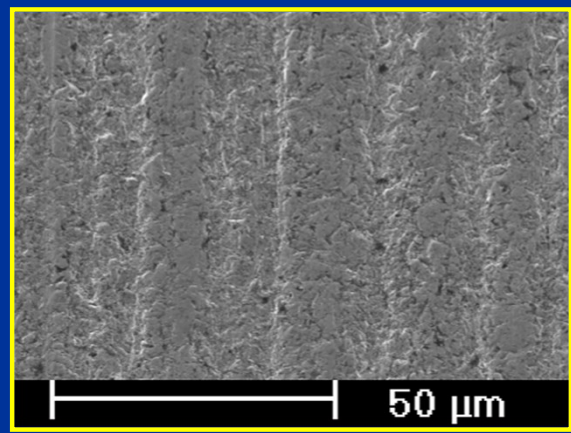
Abrasion wear

Abrasive wear is characterized by very significant material removal rates, which, combined with the fact that abrasion is very frequent, leads to very high costs, which in an industrialized country are in the order of **1 to 4% of GDP**.

The incidence of abrasion is most evident in agriculture and mining, but it also has great significance in all industries and services where minerals or rocks are handled.

Abrasion wear– interaction between the abrasive particle and the surface

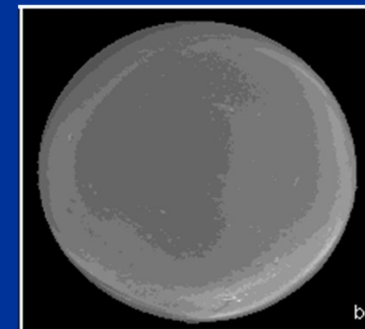
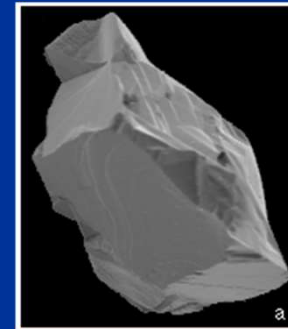
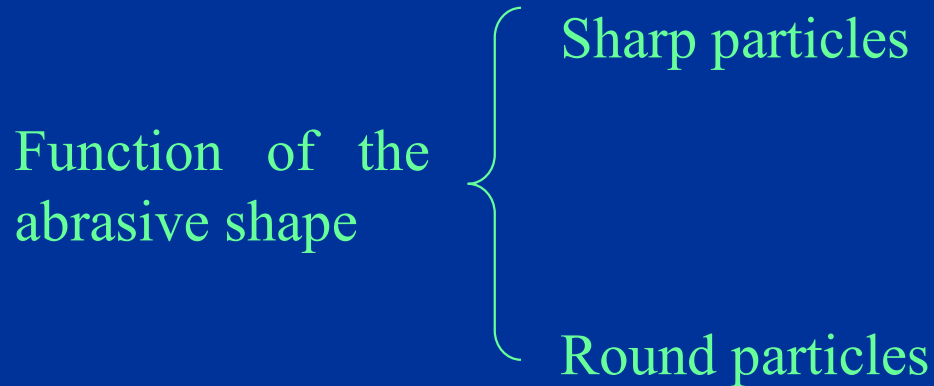
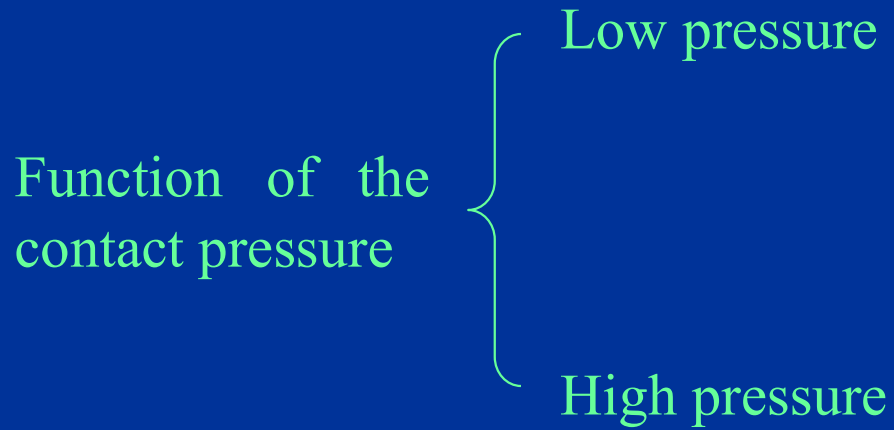
Two-body or grooving abrasion - Abrasive fixed to one of the surfaces or resulting from the high roughness of the harder surface. As this type of wear is produced by plastic deformation, the increase in hardness in relation to the abrasive or in relation to the countersurface produces an increase in abrasion resistance.



Three-body or rolling abrasion - Abrasive material located between moving surfaces, freely rotating between them. Because this type of wear results from pitting, increasing surface hardness may not result in increased abrasion resistance, especially when it causes a significant reduction in toughness.

Abrasion wear- Classification

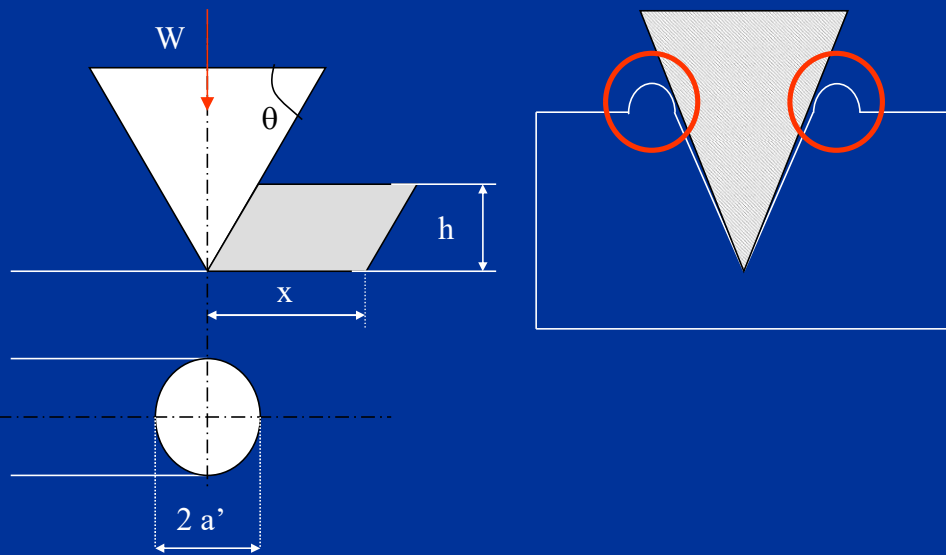
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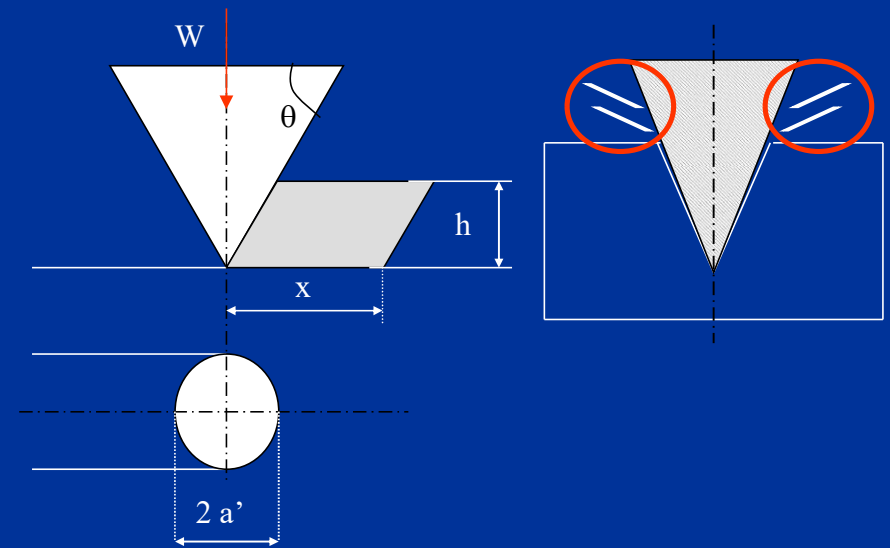
Abrasion wear- Micromechanisms

GY

Microdeformation or ploughing



Microcutting or microchipping



A. Ramalho

Dep. Eng^a

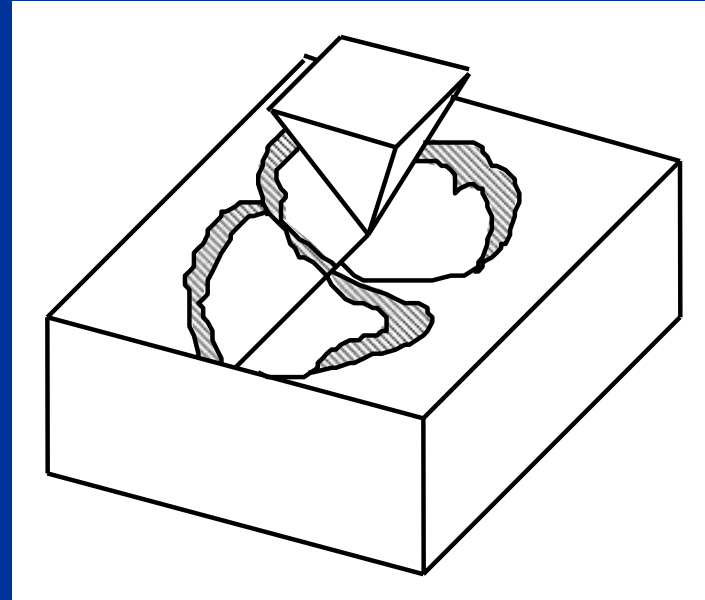
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Microfracture



A. Ramalho

Dep. Eng^a

Mecânica

FCT

U. Coimbra

Abrasion wear- Micromechanisms

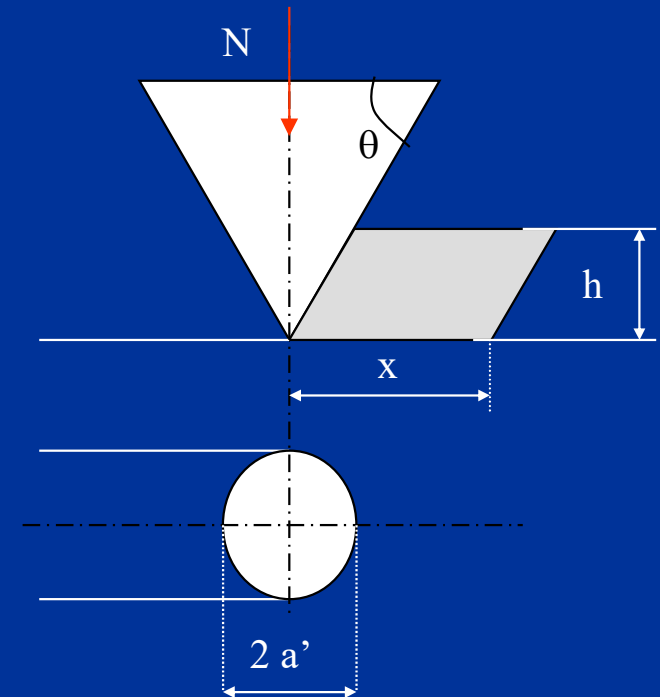
In a more systematic way, those mechanisms can be grouped into:

- Material removal processes controlled by plastic deformation
- Fracture-controlled material removal processes

Abrasion processes controlled by plastic deformation

Considering a single asperity model, with a conical shape, a simple law is obtained for wear:

$$\frac{V}{x} = \frac{N \operatorname{tg} \theta}{\pi H}$$



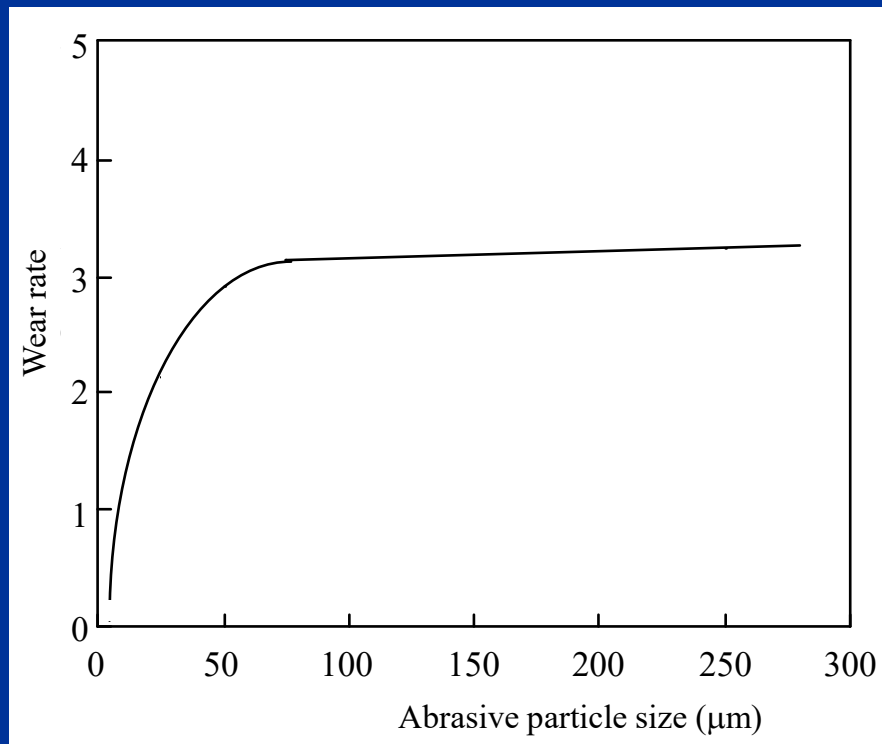
Wear \propto Roughness, abrasive particle size [θ]

Wear \propto Normal Load [N]

Wear \propto Inverse value of the hardness [1/H]

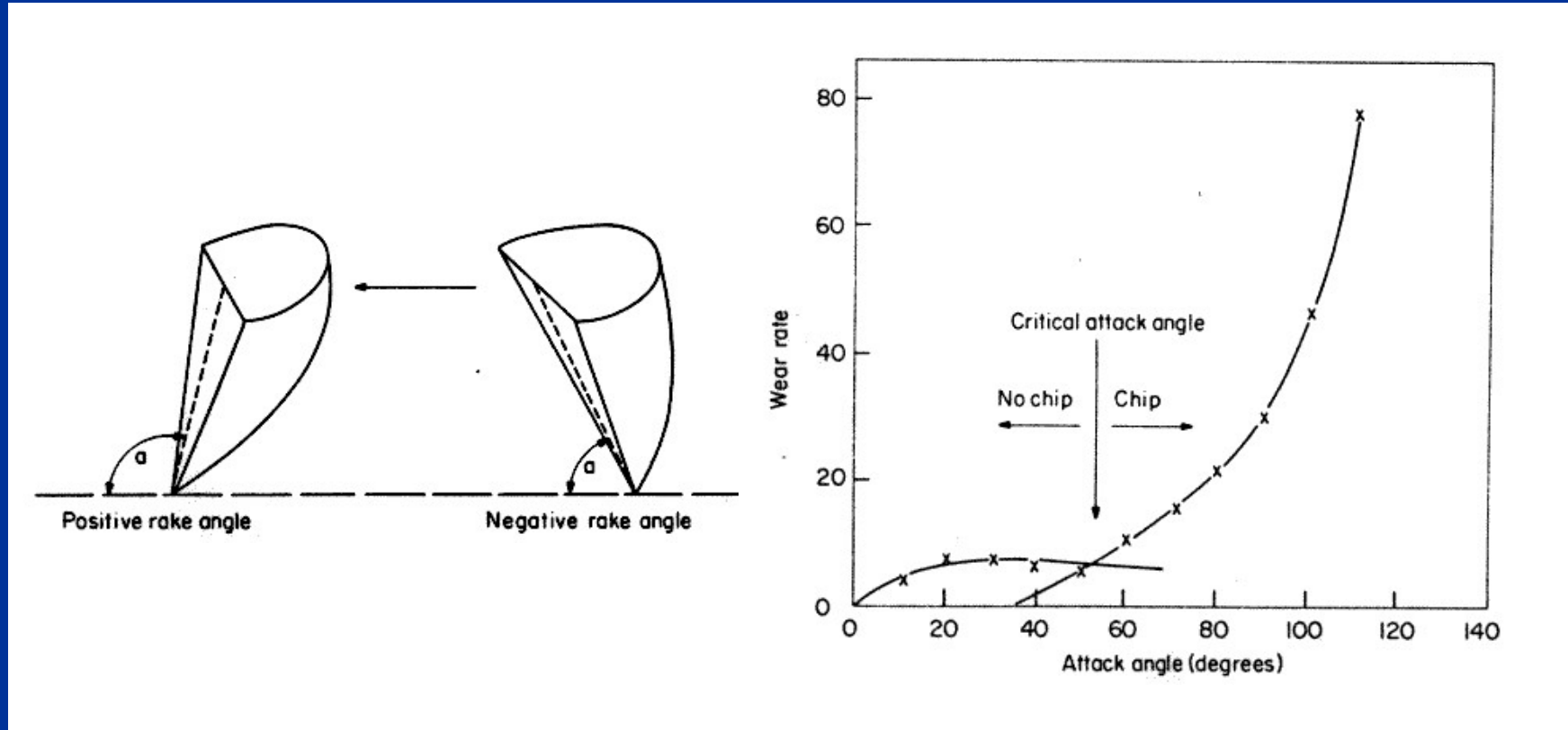
Analysis of the model

- Effect of abrasive particle size (roughness)



- Effect of the particle shape (orientation particle/surface)

In the model presented previously, 100% microcutting was assumed (wear volume = groove volume), this only occurs if the particle/surface attack angle is adequate.



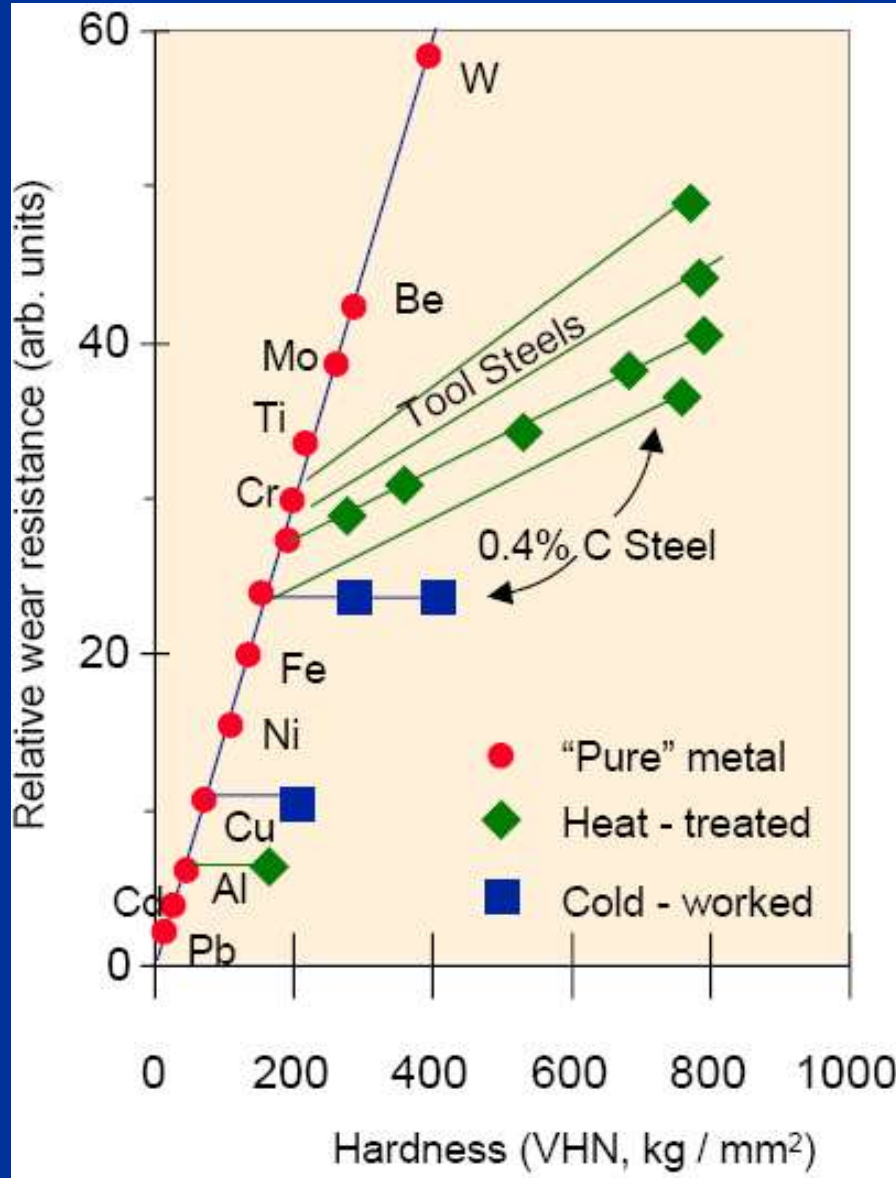
Therefore, a more appropriate equation for the wear volume would be:

$$\frac{V}{x} = \varphi \frac{N}{H}$$

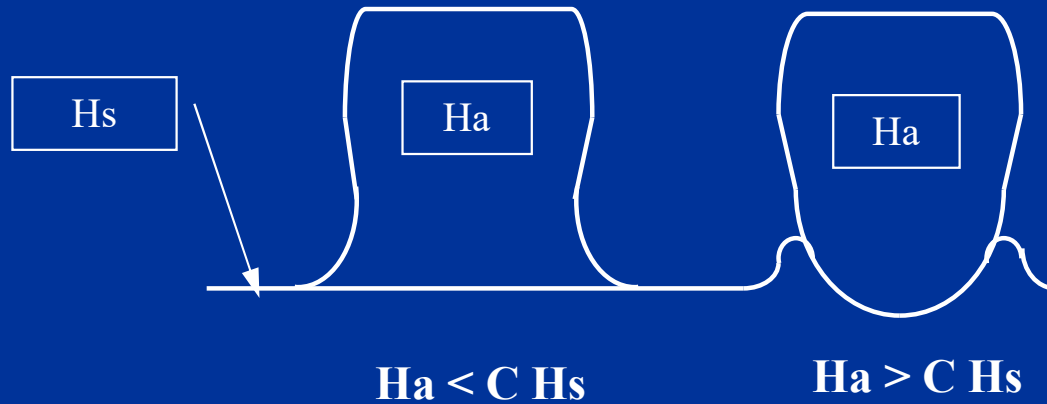
φ – fraction of the particles with $\alpha > \alpha_{\text{critical}}$

- Effect of the hardness

In deformation-controlled abrasion processes, penetration of the surface by the abrasive is implicit. Therefore, hardness should be the primary property related to abrasion resistance. However, hardness cannot be dissociated from microstructure.

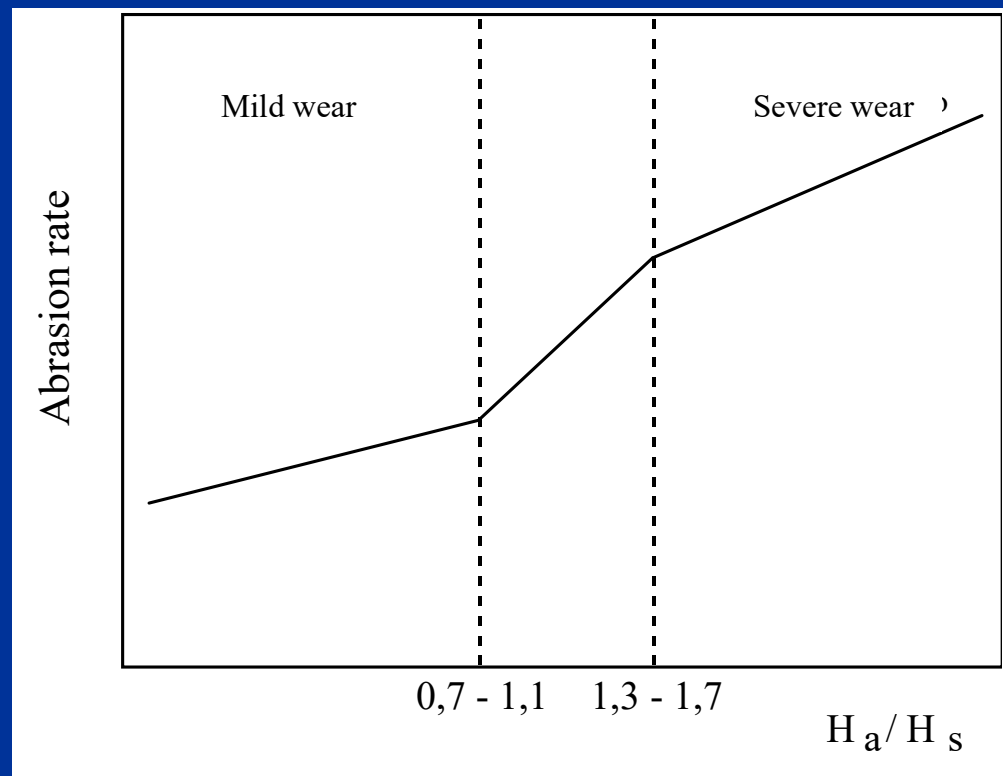


Most materials show a transition from mild to severe abrasive wear with increasing abrasive/surface hardness ratio.



$C = 1.2$ Sharp particles

$C = 1.25$ Spherical particles



Therefore, depending on the predominant abrasive, an appropriate selection of material must be made considering its hardness.

Abrasive	Hardness HV
Diamond	6000 - 10000
Boron carbide	2700 - 3700
Silicon carbide	2100 - 2600
Alumina	1800 - 2000
Quartz	750 - 1200
Silica	600 - 1000
Magnetite	370 - 600
Glass	~500
Calcium fluoride	180 - 190

Steel - phase	Hardness HV
Ferrite	70 - 200
Pearlite (carbon steel)	250 - 320
Pearlite (alloy steel)	300 - 460
Austenite (high Mn)	170 - 230
Austenite (low alloy)	250 - 350
Austenite (high alloy)	300 - 600
Martensite	500 - 1000
Cementite	840 - 1100
M ₇ C ₃ type Carbide	1200 - 1600

Non-ferrous metals	Hardness HV
Aluminum	25 - 45
Aluminum alloys	100 - 170
Brass	80 - 140
Chromium (electroplat)	500 - 1250
Copper	40 - 130
Copper - Beryllium	300 - 600
Lead	4
Molybdenum	160 - 180
Nickel (electroplat)	200 - 400
Silver	25 - 80
Tin	5 - 6
Tungsten	260 - 1000
Zinc	30 - 35

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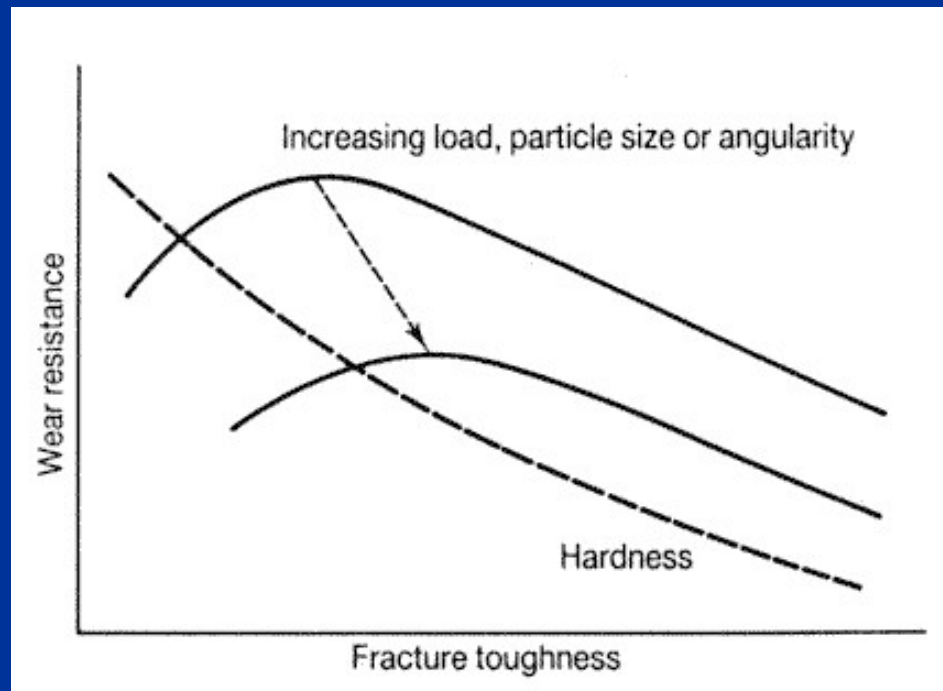
Ceramics Carbides	Hardness HV
Chromium	1300 – 1600
Hafnium	2270 – 2650
Molybdenum	1500
Niobium	2400 – 2850
Tantalum	1800 – 2450
Titanium	2000 – 3200
Tungsten	2000 – 2400
Vanadium	2460 – 3150
Zirconium	2360 – 2600

Ceramics Nitrides	Hardness HV
Chromium	2200
Hafnium	1640
Niobium	1400 – 1720
Tantalum	1220
Titanium	1200 – 2000
Vanadium	1520 – 1900
Zirconium	1150

Ceramics Borides	Hardness HV
Chromium	1800
Hafnium	2250 – 2900
Molybdenum	2350
Tantalum	2450 – 2910
Titanium	2200 – 3500
Tungsten	2400 – 2660
Vanadium	2070 – 2800
Zirconium	2250 – 2600

Given the high availability of materials it could be concluded that the elimination of abrasion problems would always be resolved by increasing the hardness of the material.

However, if the contact pressures are high, this solution is only satisfactory as long as the increase in hardness does not compromise the toughness value.



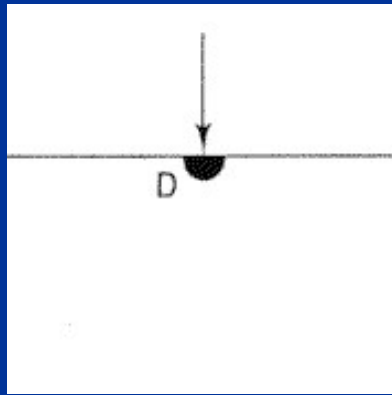
Abrasion processes controlled by fracture

When materials are very hard and contact very hard abrasives plastic deformation in contact is very limited, giving rise to stress levels that may lead to fracture processes.

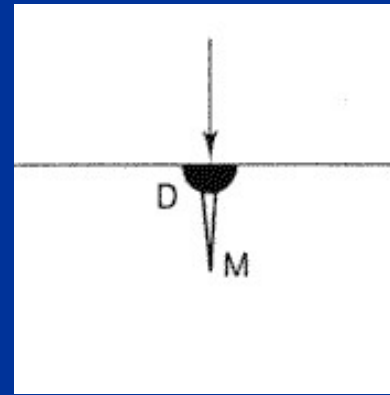


$\left(\frac{H}{K_{IC}} \right)$ is an adequate measure of the material's brittleness.
A low value means difficult fracture.

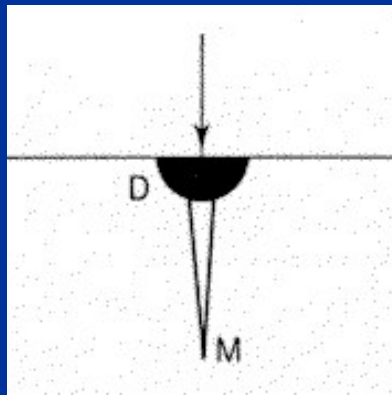
The occurrence of fracture in contact with abrasive wear of brittle materials is due to a sequential phenomenon that involves the following phases:



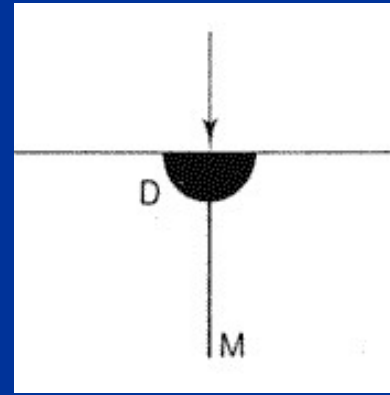
Very punctual load application



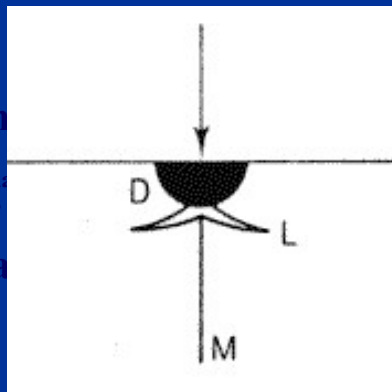
Plastic deformation due to quasi-hydrostatic compression and shear stresses. Initiation of median crack.



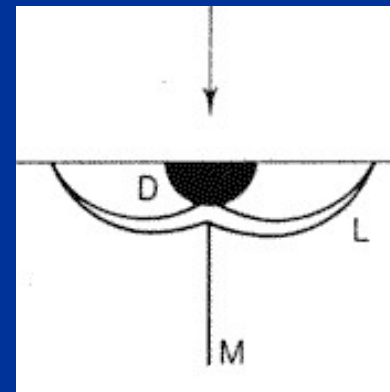
Initiation and propagation of median crack, if load $>$ critical load.



Unloading - Closure of the median fissure.



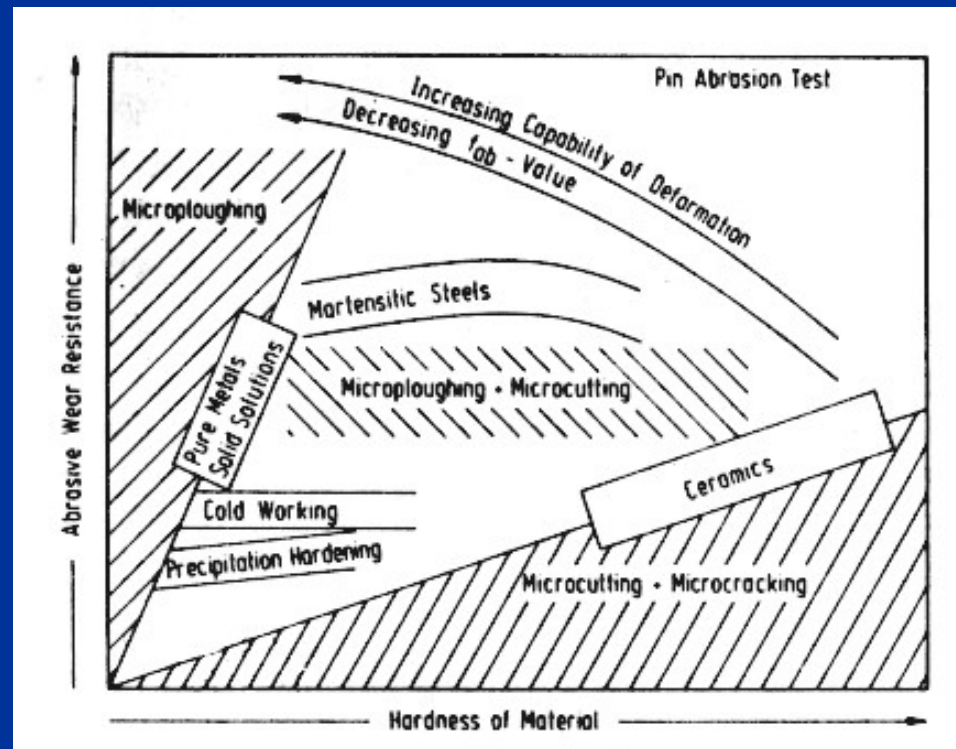
Formation of lateral cracks due to relaxation of the elastic deformation of the surrounding material.



Propagation of lateral cracks.

Effect of the material in abrasion resistance

If the hardness of the abrasive is always greater than the hardness of the material considered, then the abrasion resistance of metals is greater than that of ceramics and polymers.



$\left(\frac{E}{H}\right)$ is a suitable parameter for comparing abrasion resistance, the higher its value, the greater the abrasion resistance. (It is a measure of the inverse of the deformation relative to yielding)

- Strain hardening

A material's ability to strain harden produces some increase in its abrasion resistance.

However, prior strain hardening does not add any abrasion resistance.

$\left(\frac{\sigma_R}{\sigma_C} \right)$ Is a suitable parameter for comparing the increase in abrasion resistance resulting from the material's ability to harden through deformation; the higher this parameter, the greater the increase resulting from deformation hardening.

- microstructure

The influence of crystal structure occurs primarily through the changes produced during strain hardening. Therefore, cubic-structured metals are typically more resistant to abrasion than hexagonal-structured metals.

- Hardening by precipitation

The precipitation of coherent fine particles is a widely used method for hardening some alloys. This hardening method does not significantly affect abrasion resistance.

However, the precipitation of non-coherent or semi-coherent fine particles can, in some cases, lead to increases in abrasion resistance.

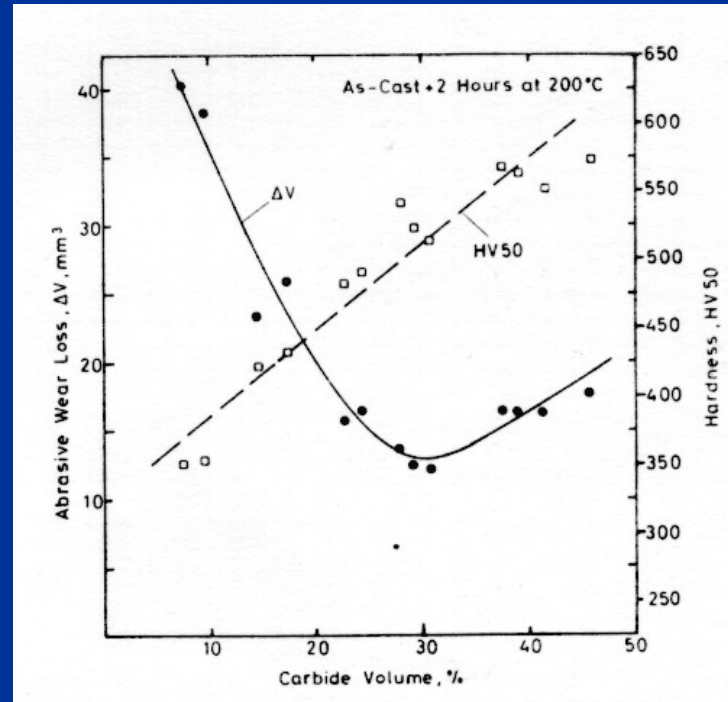
- Carbides

The presence of carbides is especially important for abrasion resistance, as it significantly affects the behavior of steels and cast irons.

The influence of carbides on abrasion resistance varies depending on the hardness of the matrix.

- Soft matrix

An increase in the volume fraction of carbides results in a reduction in the material removed by abrasion. However, above an optimum value, this trend reverses.



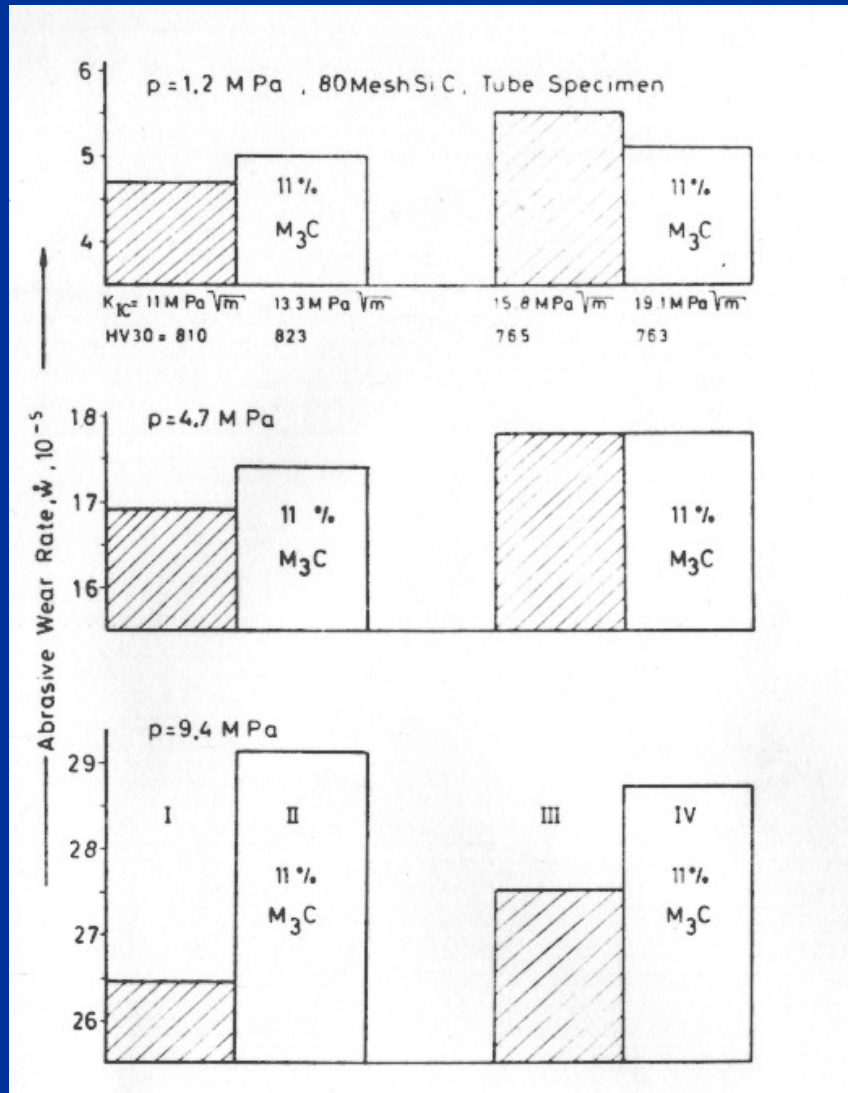
Very fine, dispersed carbides are typically used to resist large, heavily loaded abrasives.

Larger carbides are used to resist finer abrasives, but the loss of carbide support due to preferential abrasion of the matrix can compromise this solution. When the abrasive is harder than the carbides and the pressures are high, large carbides are removed by fracture.

- Hard matrix

As matrix hardness increases, the carbides present in the matrix can act as stress concentrators and significantly reduce toughness.

Therefore, if contact pressures are high and the matrix hardness is high, it is preferable to dissolve the carbides into the matrix.



Tool steel with
martensitic microstructure

- Solid solutions

The use of alloying elements to form both substitutional and interstitial solid solutions is commonly used to improve abrasion resistance.

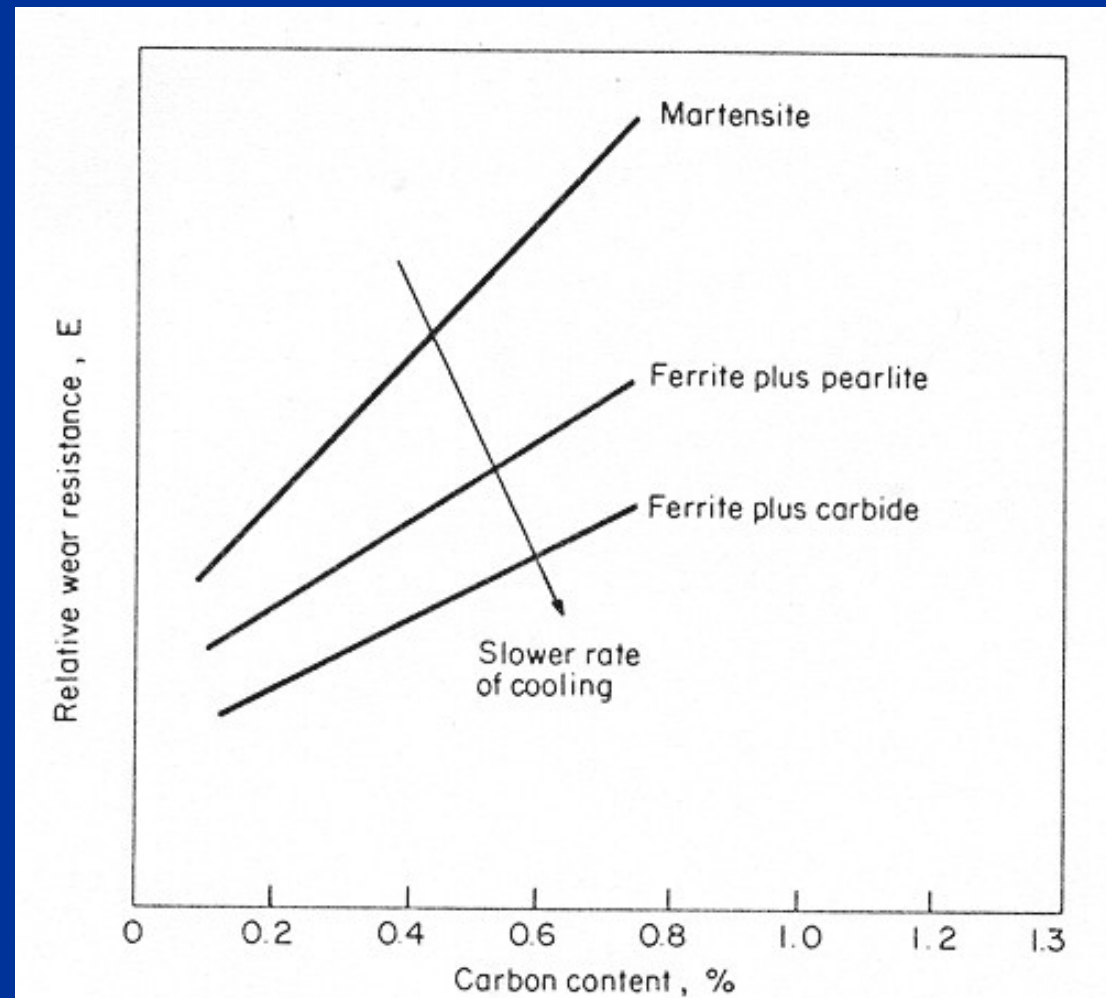
Many substitutional alloy systems show that abrasion resistance is proportional to the content of the reinforcing element (Hf-Zr; Cu-Ni; Cr-V), so elements with greater abrasion resistance than the metal in question must be added.

In interstitial solid solutions, the addition of the alloying element generally leads to an increase in abrasion resistance.

Abrasive Wear in Steels and Cast Irons

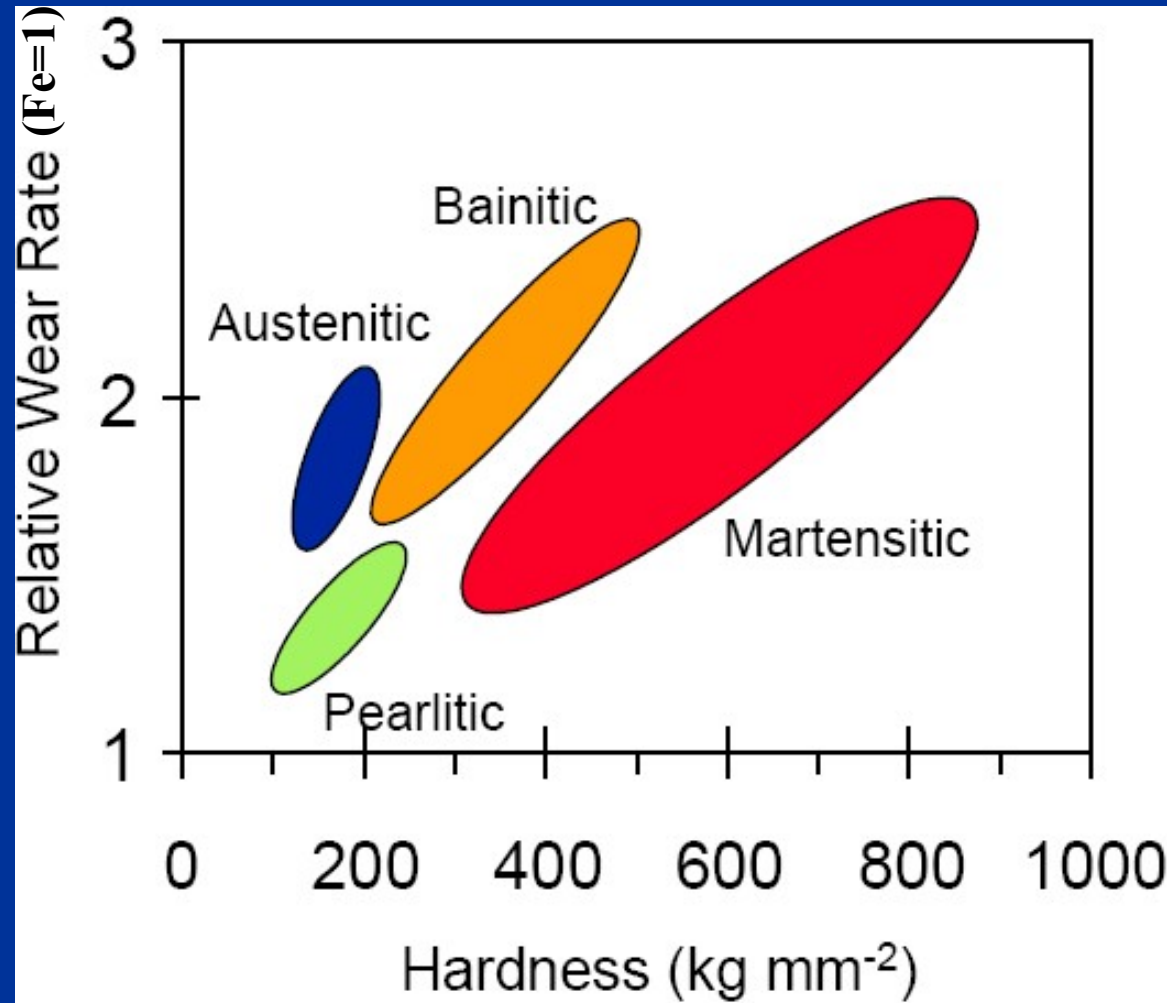
Effect of Microstructure

Increasing the carbon content always leads to an increase in abrasion resistance, whatever the microstructure.



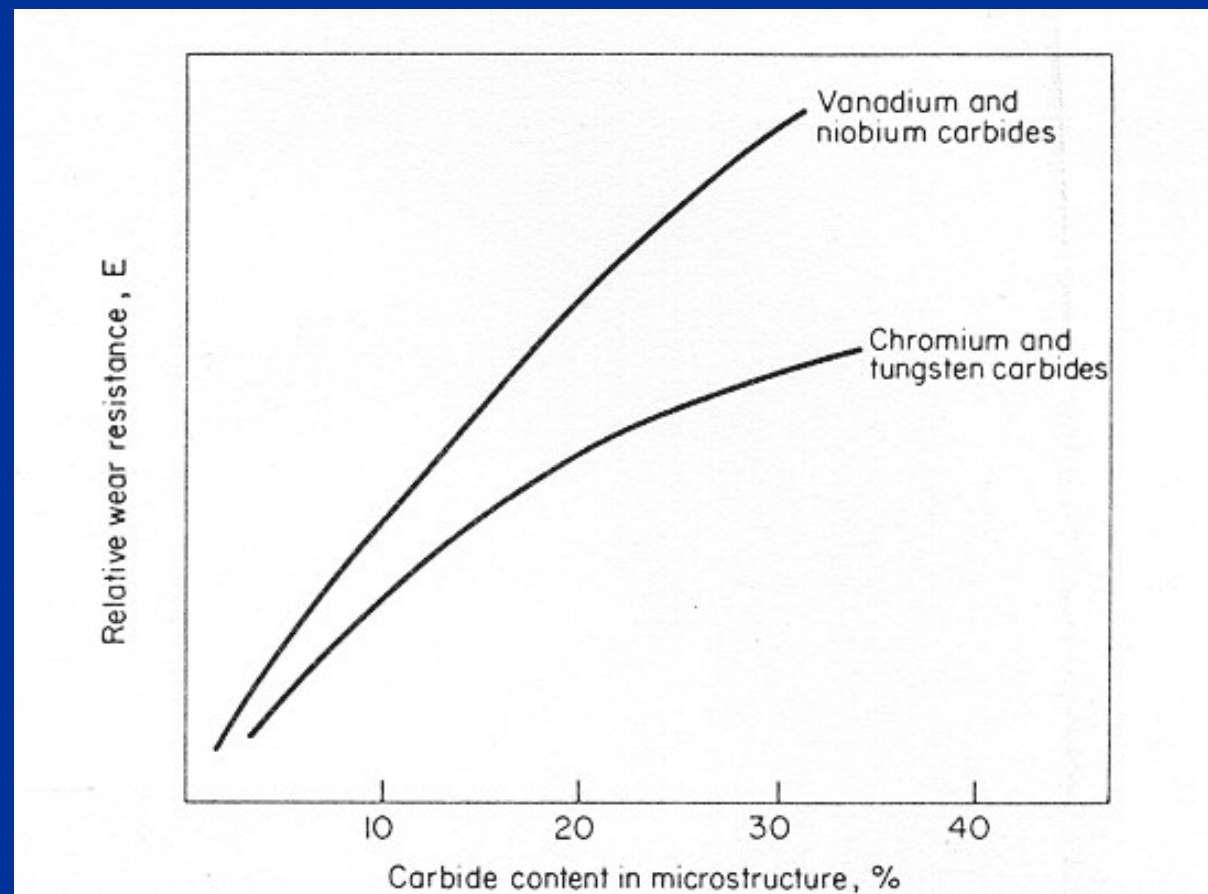
Comparing steels with different microstructures and similar hardnesses, an increasing evolution in abrasion resistance is observed when the microstructure varies as follows:

Martensite < Pearlite < Bainite < Austenite



To increase abrasion resistance, the presence of chromium and tungsten, carbides is common.

However, vanadium and niobium carbides provide greater abrasion resistance.



Abrasive Wear in Steels and Cast Irons

Effect of Retained Austenite

A particularly important aspect in the abrasion resistance of steels is the role of retained austenite.

Fine abrasives and low contact pressures: Pre-transformation of retained austenite

Very hard abrasives with high contact pressures: High percentages of retained austenite are favourable in both bainitic and martensitic microstructures.

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