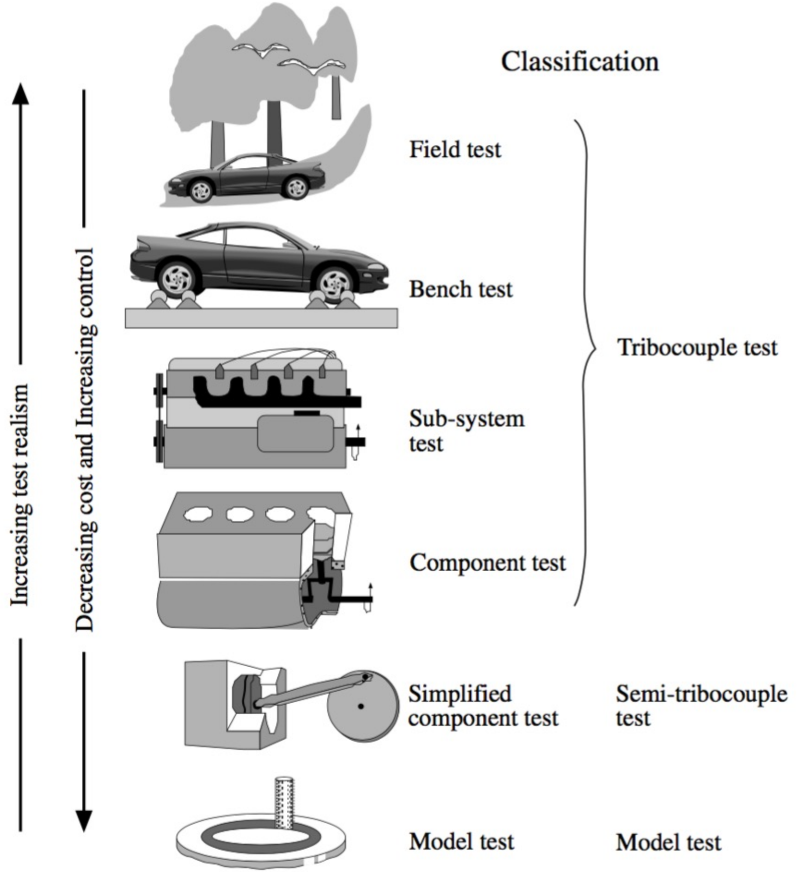
Chapter 5
Wear

MSE 485
Tribology

1 Experimental study
2 Wear transitions
3 Wear mechanisms
4 Prediction of wear rate
5 Results and perspectives

Classification of tribotest depending on the degree of realism

N. Axen et al. "Friction and wear measurement techniques" of Modern Tribology Handbook, CRC Press 2001



Experimental study

Main laboratory devices used to study wear (tribometers) :

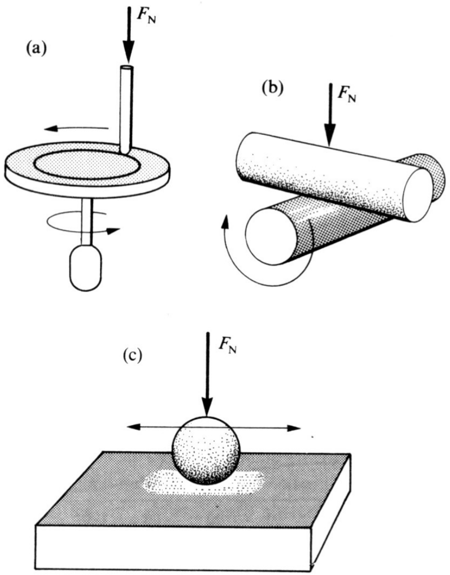


Fig. 10.11 -Devices used for the experimental study of wear : pin on disc test (a), Crossed-cylinder test (b), Alternating motion test (c)

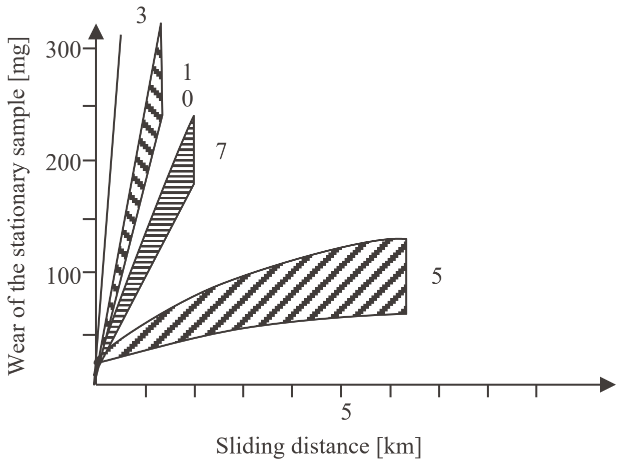
Wear is assessed by volumetric or gravimetric analysis of the material loss after experiment interruption.

Tribometers

Pin on disc tribometer at TIC

Wear tests

- **1964:** 1st inter-laboratory wear test



- 21 laboratories measured wear, as a function of sliding distance, of same materials couples using various tribometers under identical load and speed.

- **1986: 2nd** inter-laboratory wear test

- Thanks to a strict control of :
  - Surface roughness
  - Surface contamination (cleaning)
  - Geometry and size
  - Wear measurement procedures
  - Relative humidity (12-78%)
  - Type of motion
  - Load, speed, vibrations

- Replicability could be improved :
  - Steel on steel wear :

    70 ± 20 μm/km (steel)
  - Ceramic on steel wear :

    81 ± 29 μm/km (steel)

Quantification of wear

- Experience shows that the wear volume V_{wear} is often :

  V_{wear} α (sliding distance L)
  V_{wear} α (normal load F_n)
  V_{wear} α (1 /hardness H)

- Different ways to define the wear rate T_{wear} exist :

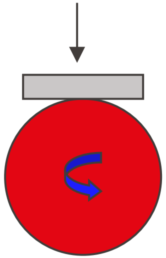
  $T_{wear} = V_{wear} / L$ (volume loss per unit of sliding distance [mm^3/m])
  $T_{wear} = V_{wear} / (L\ F_n)$ (wear coefficient [$mm^3/m\ N$])
  $T_{wear} = V_{wear}\ H / (L\ F_n)$ (dimensionless wear coefficient)

- NOTE : These expressions do not necessarily take into account chemical (oxidation, corrosion, …), metallurgical (hardening, …) or physical (T, particles, …) transformations that may occur during a tribological test.

Wear transitions

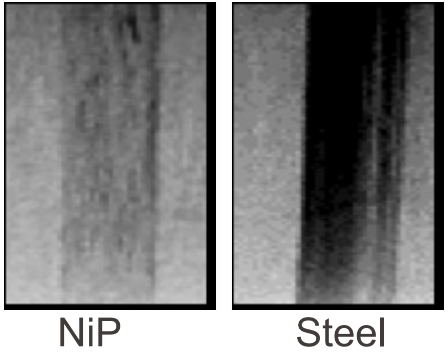
- Example 1 : wear of graphite reinforced PTFE sliding against a metal cylinder.

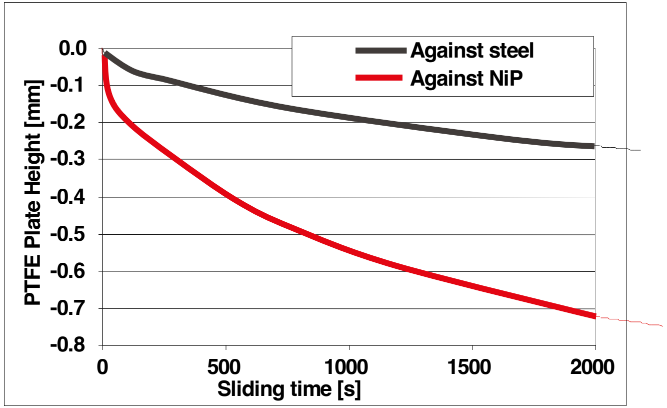
Speed 10 m/s, Fn= 5 N, air

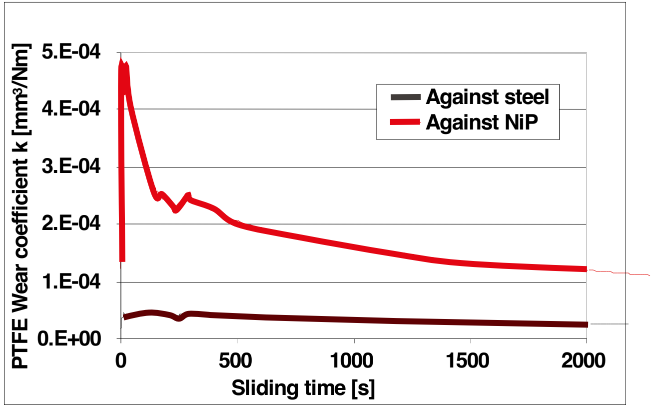


cylinder made of **steel** or steel with an **Ni-P** coating

PTFE transfer on metal

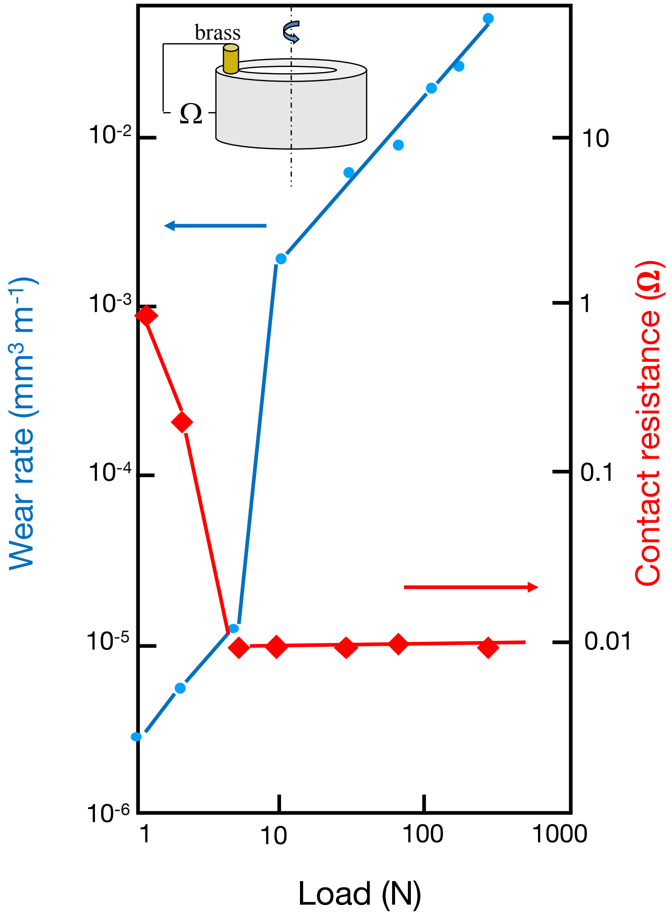






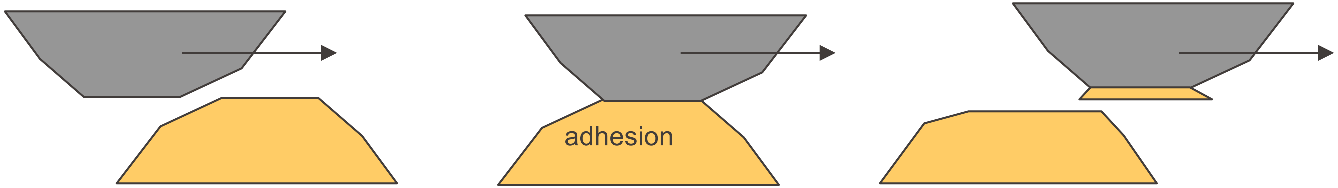
Wear transitions

- Wear transition of brass sliding against stellite with variable load, in air.
- Above 10N the load is sufficient to penetrate the thin oxide film at the surface of the brass

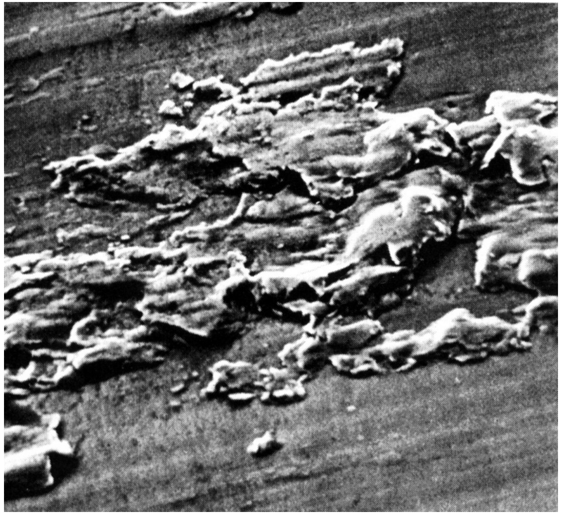


Hirst W and Lancaster JK J. Appl. Phys, 27, 1057-1065 (1956)

Wear mechanisms



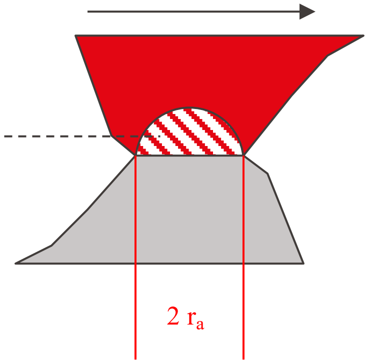
- Adhesive wear
- Critical factors :
  - size of the geometrical surface area
  - bonding (ionic, covalent, metallic, Van DerWaals)
  - surface contamination
  - surface oxidation



Steel on steel contact

H. Czichos, Tribology, Springer 1978

Adhesive wear model



- Plastic deformation at asperity junctions:
- Teared volume per unit junction:

  $Q_i = V_i / 2\ r_a = \pi\ r_a^2 / 3$

- Total teared volume:

  $Q = k \sum Q_i = k \sum \pi\ r_a^2 / 3$

  with k : probability that a junction breaks

  and : $\sum \pi\ r_a^2 = F_n / H$

$$V_{wear} = Q \cdot L = k_{adh} \cdot F_n \cdot L / H \qquad k_{adh} = k/3$$

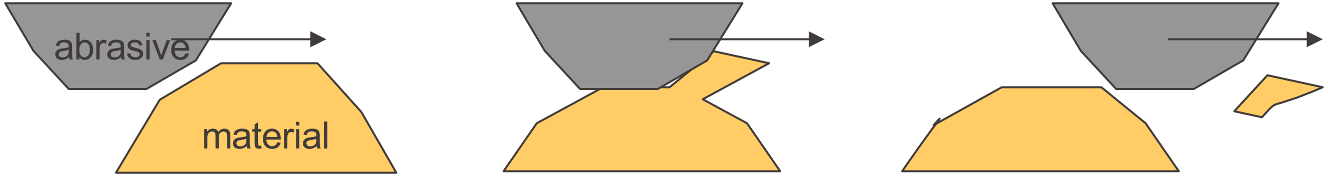
Adhesive wear model

- Mean diameter of particles created by two copper sliding against each other in various environment: (*réf :D. Landolt, Corrosion et … PPUR 1993*)

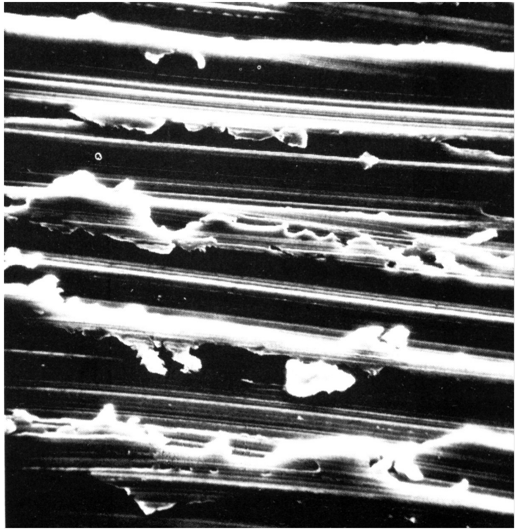
Environment	Mean diameter µm
Nitrogen	480
Helium	380
Carbonic acid	300
Dry air	224
Oxygen	201
Moist air	144
Liquid lubricant	8-12

- The adhesive wear model does not predict a change in particle size for identical mechanical conditions!

Abrasive wear

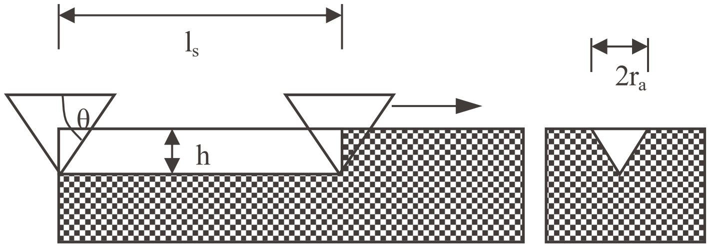


- Critical factors :
  - hardness ratio
    abrasive / material > 1
  - hardness of the material
  - roughness of the abrasive



Aluminium after abrasion against emery paper (SiC)
H. Czichos, Tribology, Springer 1978

Abrasive wear model



$$h = r_a \cdot \tan\theta$$

$$V_{wear} = r_a \cdot h \cdot l_s = r_a^2 \cdot \tan\theta \cdot l_s \qquad \pi \cdot r_a^2 = F_N / H$$

$$V_{wear} = \tan\theta \cdot F_N \cdot l_s / \pi \cdot H \qquad L = \sum l_s$$

$$V_{wear} = k_{abr} \cdot F_N \cdot L / H \qquad k_{abr} = \tan\theta / \pi$$

Abrasive wear model

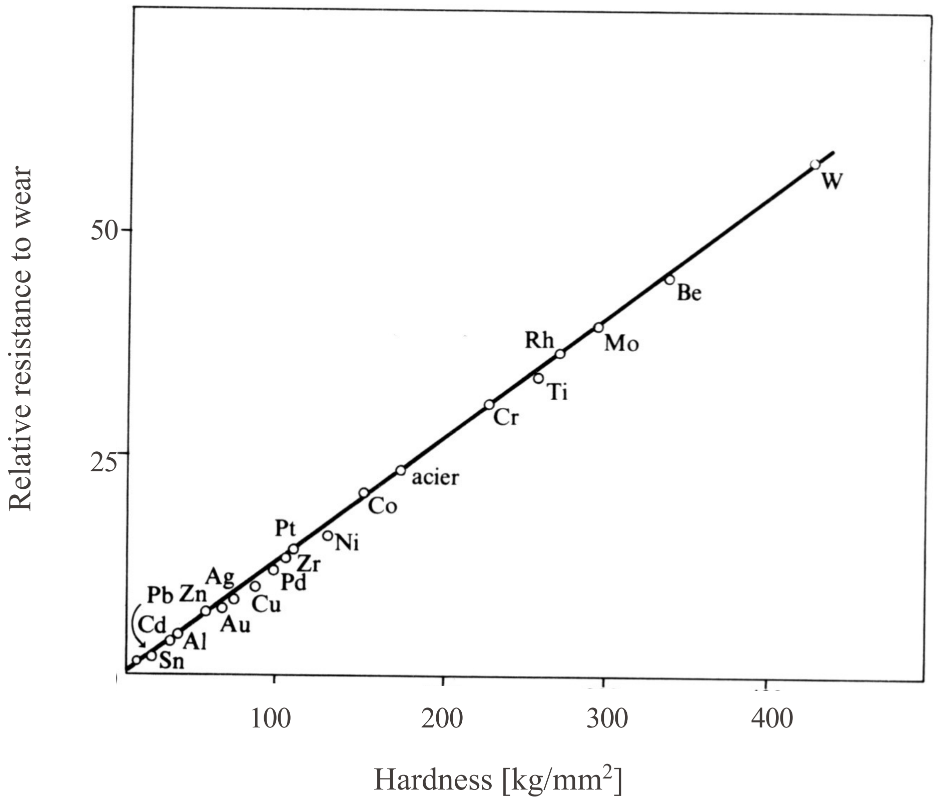
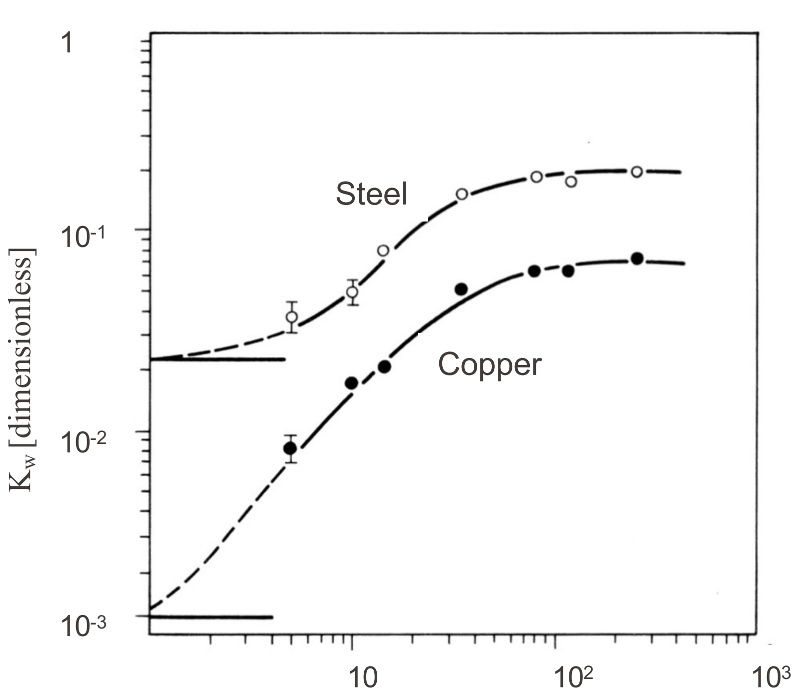


Fig. 10.15 Influence de la dureté sur la résistance relative à l'usure de différents métaux [8].

EPFL

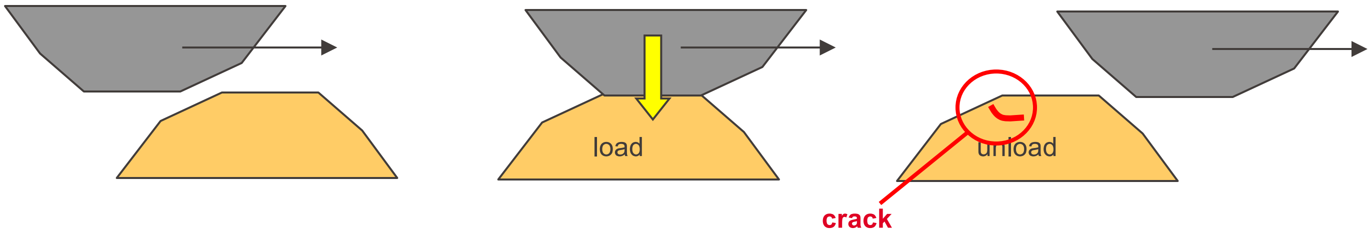
Abrasive wear model



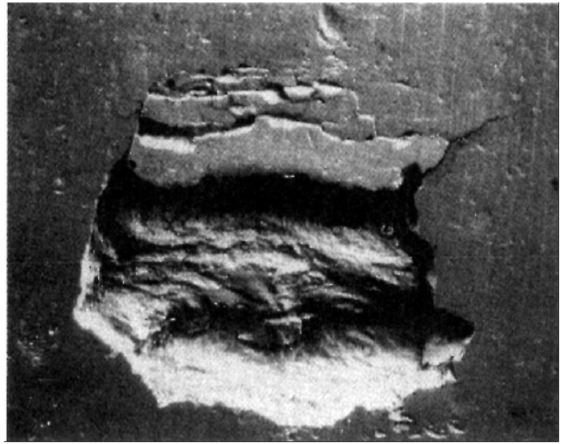
Abrasive wear : effect of the diameter of the abrasive on the wear coefficient

Fig. 10.16 Usure par abrasion: influence du diamètre de l'abrasif sur le coefficient d'usure [9].

Fatigue wear



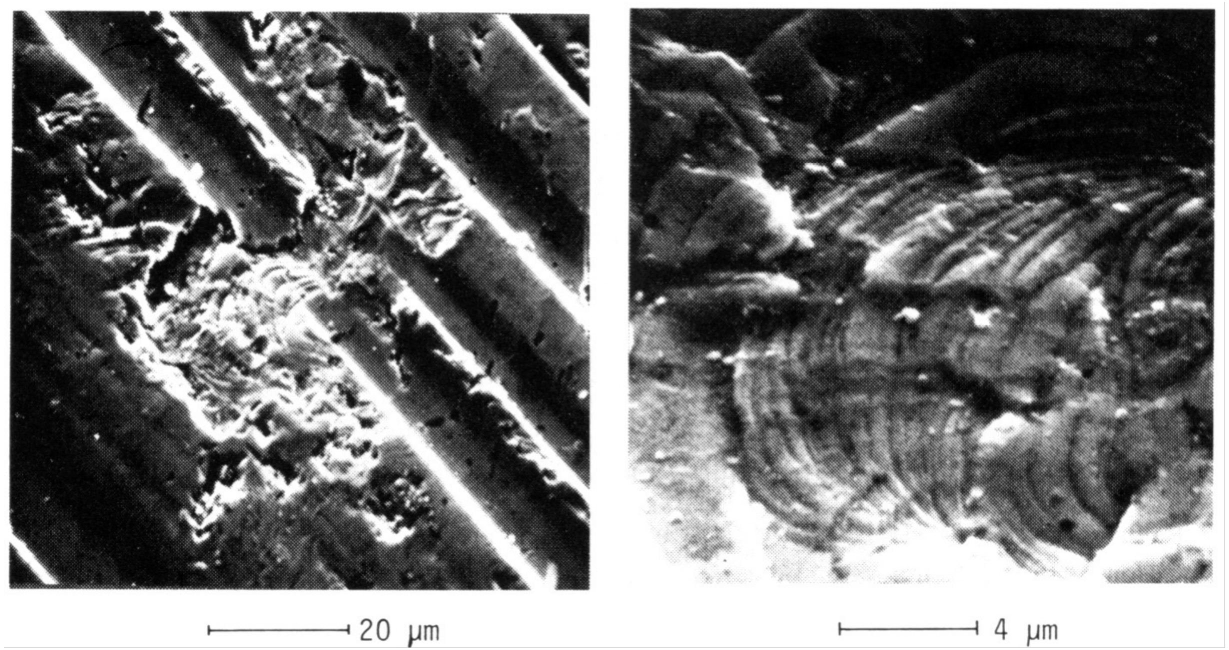
- Critical factors :
  - load and number of cycles
  - fatigue resistance of the material
  - residual stress
  - surface roughness



Fatigue failure of a bearing steel component.
H. Czichos, Tribology, Springer 1978

Typical morphologies

- Spalling, step-like cracks : *Czichos, Tribology (1978)*



Fatigue wear model

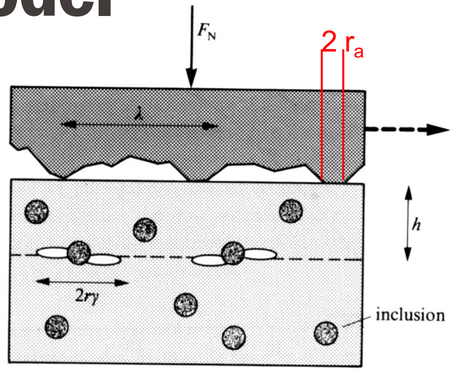


Fig. 10.18 Modèle de l'usure par délamination: les fissures se développent aux inclusions situées à une profondeur *h* de la surface [10].

- A crack develops at depth h after n_{crit} asperities have passed, i.e. at the sliding distance l n_{crit}.

- Teared volume per distance travelled at a junction : $Q = A \cdot h / (n_{crit} l)$

$$Q = A \cdot r_a / (n_{crit} \lambda) = A_r / n_{crit} = F_N / (n_{crit} H)$$

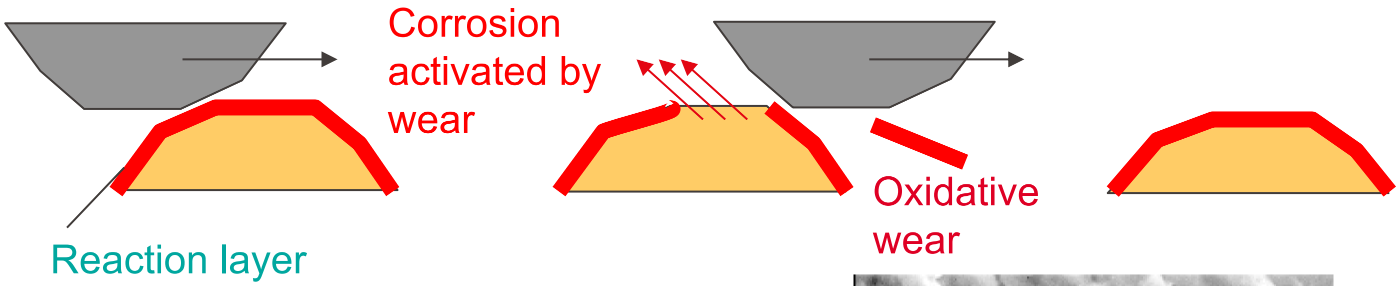
approximations $A/A_r \approx \lambda / r_a$ $\quad h \approx r_a$

- n_{crit} is related to fatigue phenomena : initiation and propagation of cracks.

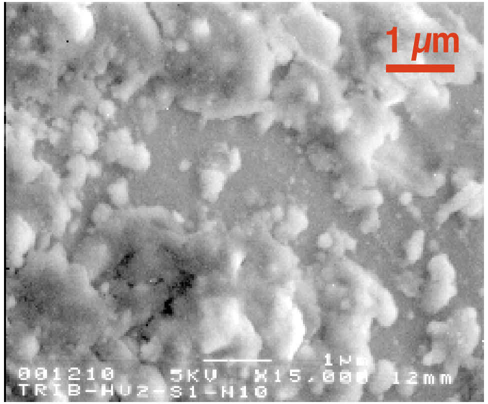
$$V_{wear} = F_N \cdot L / H \cdot n_{crit}$$

- It depends on mechanical stress, structure, and state of deformation of the material.

Oxidative or tribochemical wear

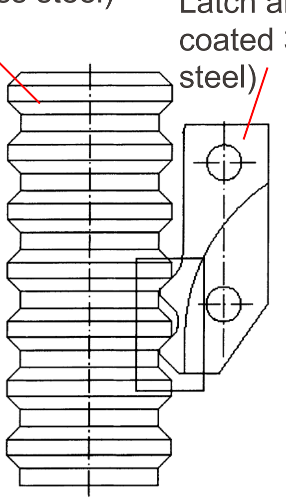


- Critical factors :
  - mechanical properties of the surface
  - kinetics of the reactions
  - kinematics and loads

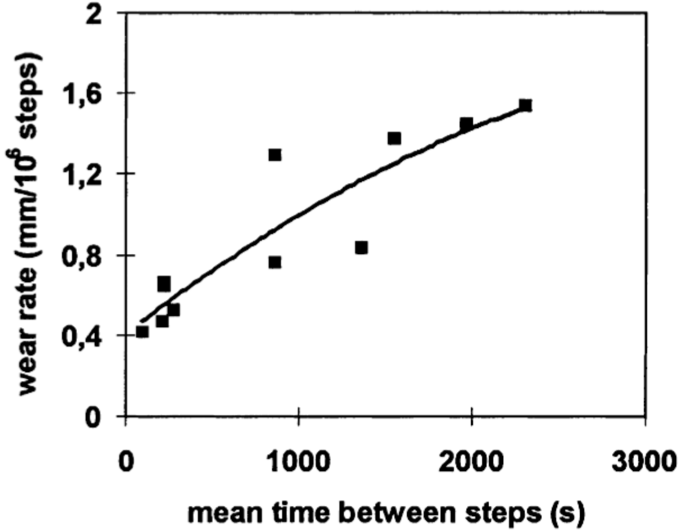


Agglomerated oxide particles after wear of a passive steel sample (2nm-thick oxide layer on surface)

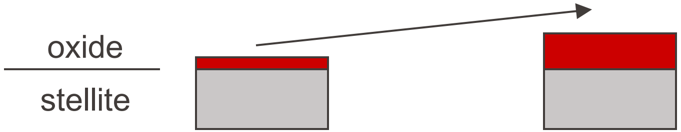
Tribochemical wear in nuclear power generators: wear of the latch arm in contact with the driver rod



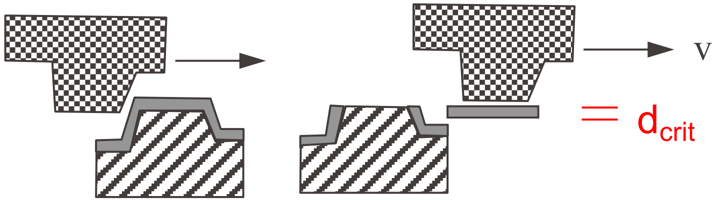
Wear of stellite (worn depth per 10^6 step) depends on time between two steps



Environment: water, 200-250° C, 155 bar



Oxidative wear model



- Oxide growth (diffusion mechanism) :

$$d^2 = k_p \cdot t$$

d : oxide thickness   λ: distance between 2 asperities

k_p: parabolic oxidation rate

- Time between two interactions : $t_{crit} = \lambda / v$
- Thickness d_{crit} of the oxide formed during t_{crit} : $t_{crit} = d_{crit}^2 / k_p \rightarrow \lambda = v\, d_{crit}^2 / k_p$
- Volume lost during the interaction : $V_i = A_i \cdot d_{crit}$
- Lost volume per distance travelled : $Q_i = V_i / \lambda = A_i \cdot k_p / d_{crit} \cdot v$

$$Q = \sum Q_i = \left(k_p / d_{crit} \cdot v\right) \sum A_i = k_p \cdot F_N / d_{crit} \cdot v \cdot H$$

- Sum over all the interactions :

$$V = k_{ox} \cdot F_N \cdot L / H \quad \text{with} \quad k_{ox} = k_p / d_{crit} \cdot v$$

Oxidative wear model

$$k_p = A \exp\left(\frac{-Q}{RT}\right)$$

A : Arrhenius constant   Q: activation energy

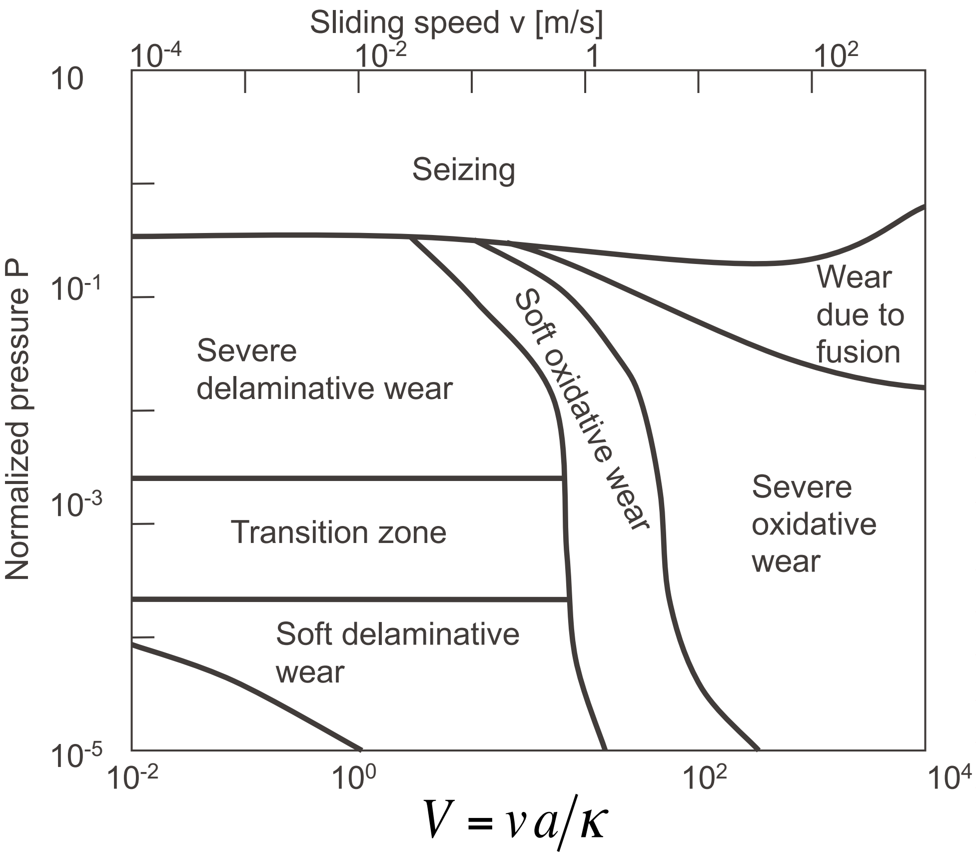
Steel	T<450°C	T>600°C
A Static [kg²/m⁴s]	1.5 *10^6	1.1 *10^6
A during sliding [kg²/m⁴s]	10^{16}	10^8
Q [kJ/mol]	208	210

- The k_p rate hence depends on A and thus on diffusion. Defects of the cristalline structure introduced by loading during sliding increase diffusion and thus oxidation rate. *Source: Hutchings, p 104*

Predicting wear rate

- The models that have been introduced up to now enable us to identify critical parameters, but cannot be used to quantitatively predict wear because :
  - Some factors are ill-defined (for example k_{adh} as a probability factor)
  - The prevailing mechanism is a priori not known.
  - Materials properties may change during wear
  - The wear phenomena are often more complex than the simplified situations considered in the models.

Wear-transition maps of steel against steel by Lim & Ashby



- Normalized pressure :

$$P = F_N / HA_N$$

- Normalized speed :

$$V = v\,a/\kappa$$

- Normalized wear :

$$W = w/A_N$$

- ✓ *A_n: nominal contact area*
- ✓ *w : dimensionless wear coefficient*
- ✓ *$V_{wear}\,H / (L\,F_n)$*
- ✓ *a : radius of the nominal contact zone*
- ✓ *κ: f(conductivity, specific heat)*
- ✓ *v: sliding velocity,*
- ✓ *F_n: normal force*
- ✓ *H: steel hardness*
- ✓ *L: sliding distance*
- ✓ *V_{wear}: wear volume*

Changes in materials during friction

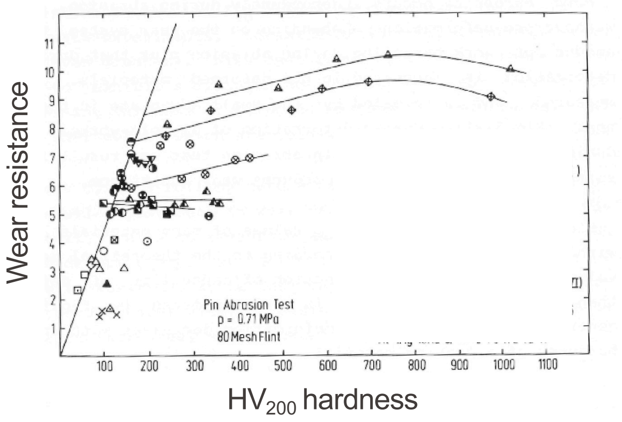
- Example of hardening :

- **Diagrams :** wear resistance versus hardness

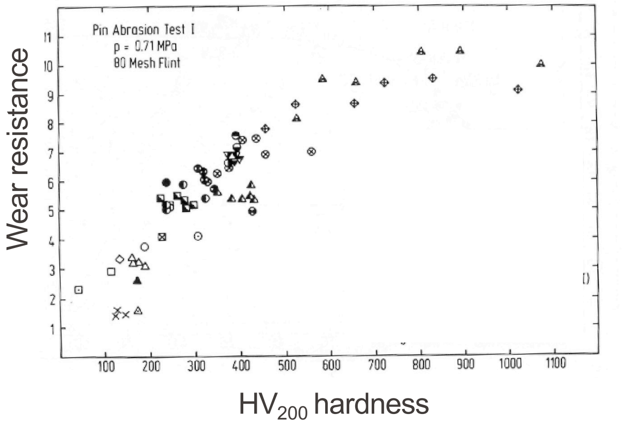
  a) of the metal before friction

  b) of wear debris

ZumGahr, Microstructure and Wear of Materials, Elsevier (1987)



a)

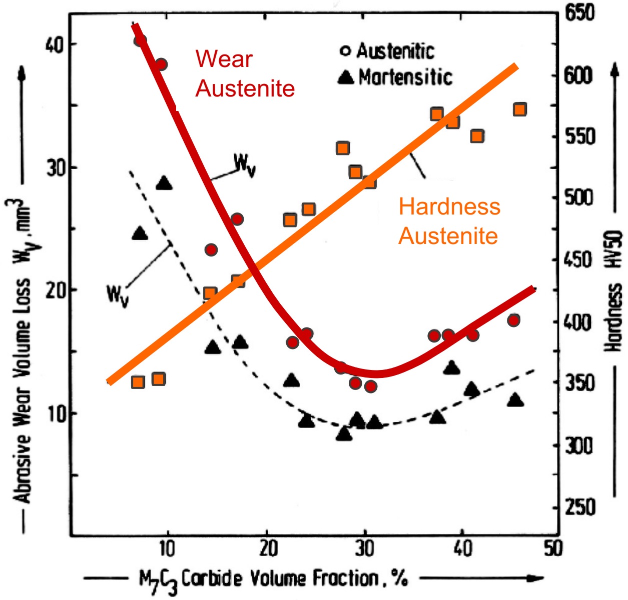


b)

The complexity of wear

- Abrasion does not solely depend on hardness

ZumGahr, Microstructure and Wear of Materials, Elsevier (1987)



ɟure 5-78. - Abrasive wear volume loss in the wet rubber wheel abrasion test and hardness of white cast irons as a function of the volume of massive carbides.

Summary from wear studies

- Almost two centuries of scientific effort to describe wear through either empirical or mechanistic laws (V_{wear} f (P1, P2, P3 …) have resulted in :

  182 wear laws

  involving 625 variables

  used either as a numerator or a denominator

- laboratory results can seldom be directly applied in practice.
- tests conducted under « the same conditions» and with the same materials on different tribometers do not always lead to the same results.

14 W.H. Jennings, W.J. Head and C.R. Manning Jr., A mechanistic model for the prediction of ductile erosion, *Wear, 40* (1976) 93

$$\epsilon = \frac{K_T^{5/2}}{R} \frac{G^{1/3}}{\rho_t^{1/3} k T_m \Delta H_m}$$

K_T	kinetic energy transferred from impacting particle to target per unit mass of particles
G	gram molecular weight of target
R	roundness of particle
ρ_t	density of target
k	thermal conductivity of target
T_m	melting temperature
ΔH_m	enthalpy of melting of target

1 Experimental study

2 Wear transitions

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5 Results and perspectives

Conclusions and perspectives on wear

- Some determining parameters and mechanisms have yet to be identified.
- Results from a given tribological system generally cannot be extrapolated to other systems.
- Hence, wear tests are not really representative since they highly depend on the tribometer used.
- A more holistic approach is necessary to deal with wear and wear predictions.