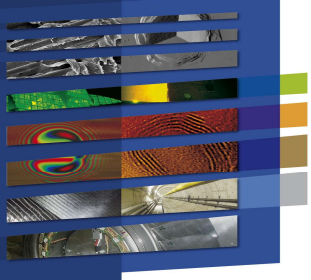
LTDS
Laboratoire de Tribologie et Dynamique des Systèmes

COnCOrD GdR 2081
COuplage méCanique Oxydation Diffusion

cnrs



Understanding and formalization of the fretting-wear behavior of a cobalt-based alloy at high temperature: a "glaze layer" dependent approach

Alixe Dreano, Siegfried Fouvry, Gaylord Guillonneau

Contact : siegfried.fouvry@ec-lyon.fr

Laboratoire de Tribologie et Dynamique des Systèmes,
Ecole Centrale de Lyon, France

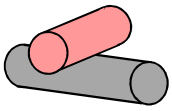
Laboratoire de Tribologie et Dynamique des Systèmes
LTDS UMR 5513
http://www.ltds.fr

LABEX MANUTECH-SISE · cnrs · ÉCOLE CENTRALE LYON · ENISE · ENTPE · Membres de UNIVERSITÉ DE LYON

LTDS
Laboratoire de Tribologie et Dynamique des Systèmes

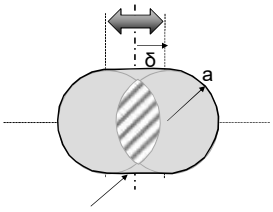
High-temperature fretting wear

➡ **Fretting :** small amplitude reciprocating displacements



Sliding criteria
$$e = \frac{\delta}{a}$$

Fretting : e < 1



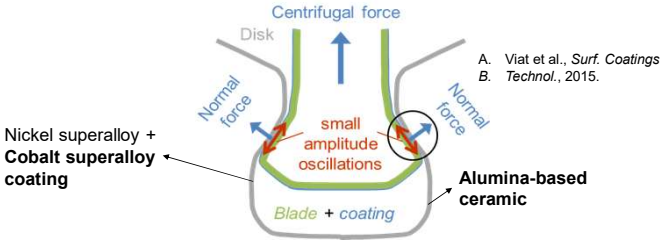
Wear track

- Retained debris particles
- Limited contact oxygenation
- Promoted the tribolayer formation

➡ **Example of industrial issue :** blade/disk contact



© Safran Transmission Systems



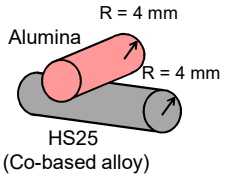
A. Viat et al., *Surf. Coatings B. Technol.*, 2015.

Objective : Investigation of the fretting wear rate evolution of a cobalt based alloy versus temperature

Experimental set-up

Friction coefficient
$\mu = \frac{Q^*}{P}$

Materials

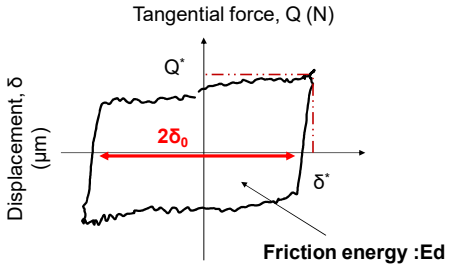


N : 10^3 – 10^5 cycles
f : 1- 80 Hz
P : 40 – 120 Newtons
δ_0 : 5- 140 ±µm
T : 25 – 600° C

Co	Cr	W	Ni	Fe	Mn	C
51	20	15	10	3	1.5	0.1

(Wt. %)

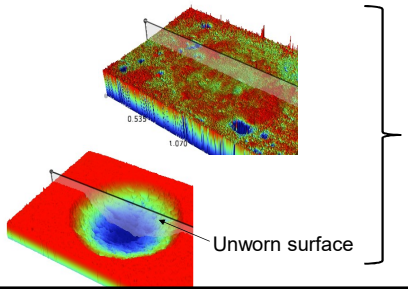
Fretting loop

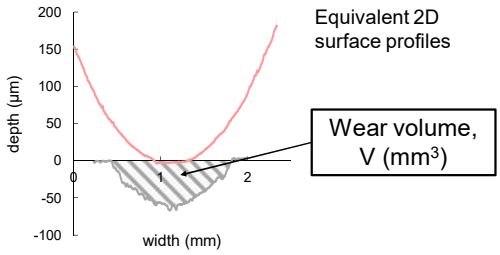


Wear volume measurements

Alumina

HS25



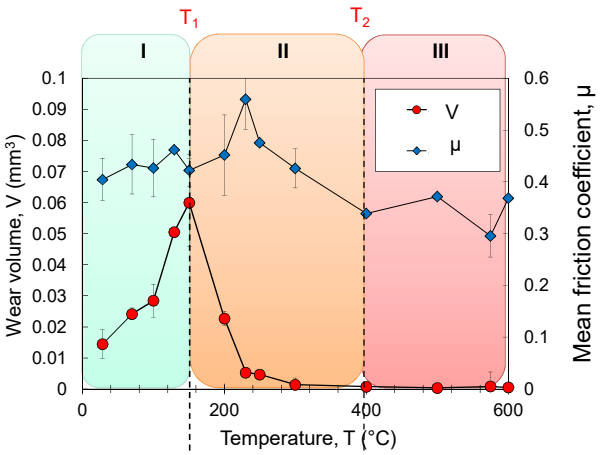


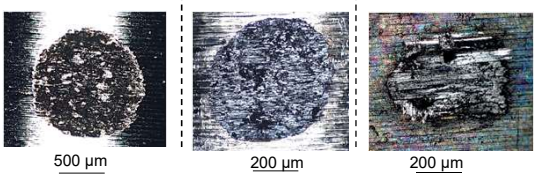
3

Tribological behaviour under temperature & structure of interface

4

Influence of temperature on friction and wear





Domain I
- Increase in wear
- Stable friction coefficient

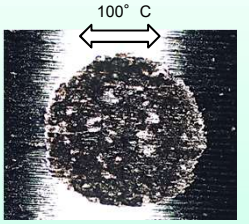
Domain II
- Decrease in wear
- Decrease in the friction coefficient
- Formation of a tribolayer

Domain III
- No more wear
- Low friction coefficient
- Formation of a tribolayer
- **Glaze layer** domain

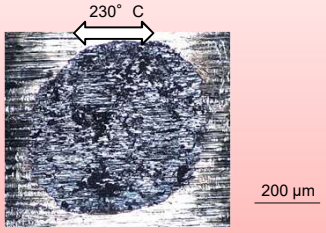
5

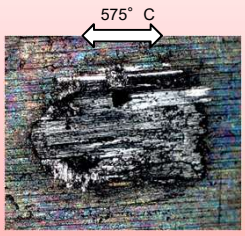
Fretted interface observations

Top view morphology



Domain I : severe wear
- Abrasive grooves
- Large scar



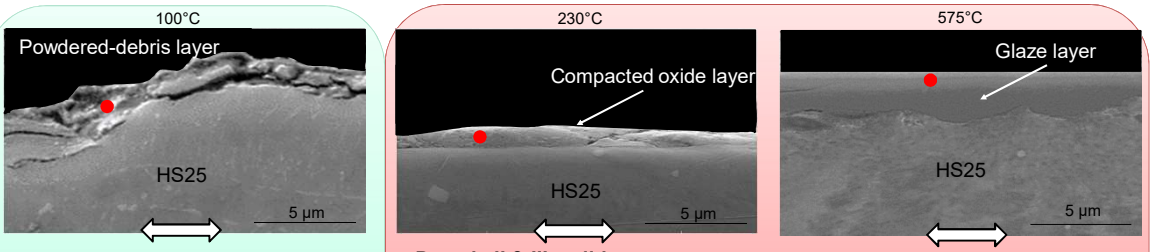


Domain II & III : mild wear
- Smaller scar
- Presence of bright and smooth tribolayer
- Oxidized tribolayer
- At high temperature : glaze layer

6

Fretted interface observations

Cross-sectional morphology



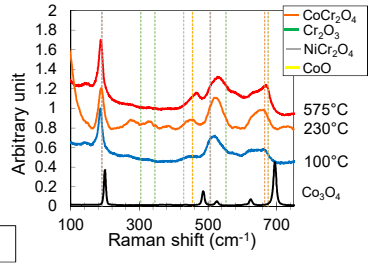
Domain I : severe wear
- Large and powdered debris
- Oxide debris
- Abrasive wear + oxidative wear

Domain II & III : mild wear
- Very small debris particles
- Agglomerated oxides

- Oxidized tribolayer
- Sintering process
- At high temperature : glaze layer

Chemistry (EDX, Raman analysis)

Spot	Co	O	Ni	Cr
A (I : 100°C)	36	**29**	10	7
B (II : 230°C)	31	**30**	6	13
C (III : 575°C)	38	**33**	5	7



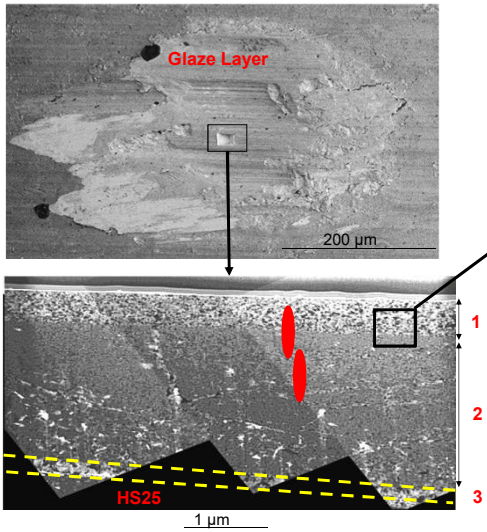
Co_3O_4 and others in lower quantities

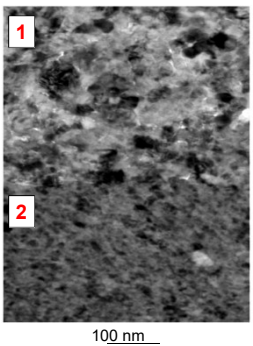
7

Characterisation of the glaze layer

T = 575° C ; f = 50 Hz ; P = 50 N ;
δ_0 = +/- 20 µm ; N = 200 000 cycles

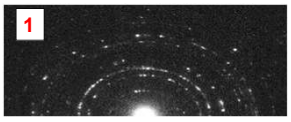
Microstructure observations



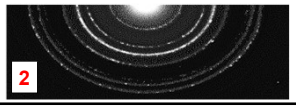


Sintered cobalt oxides

More Cr in the form of spinels or chromium oxides?



Co_3O_4



Co_3O_4, Cr_2O_3 or spinels?

EDX measurements (at. %)

Layer	O	Co	Cr	Ni
1	68	24	2.7	2.0
2	67	15	8.9	2.7

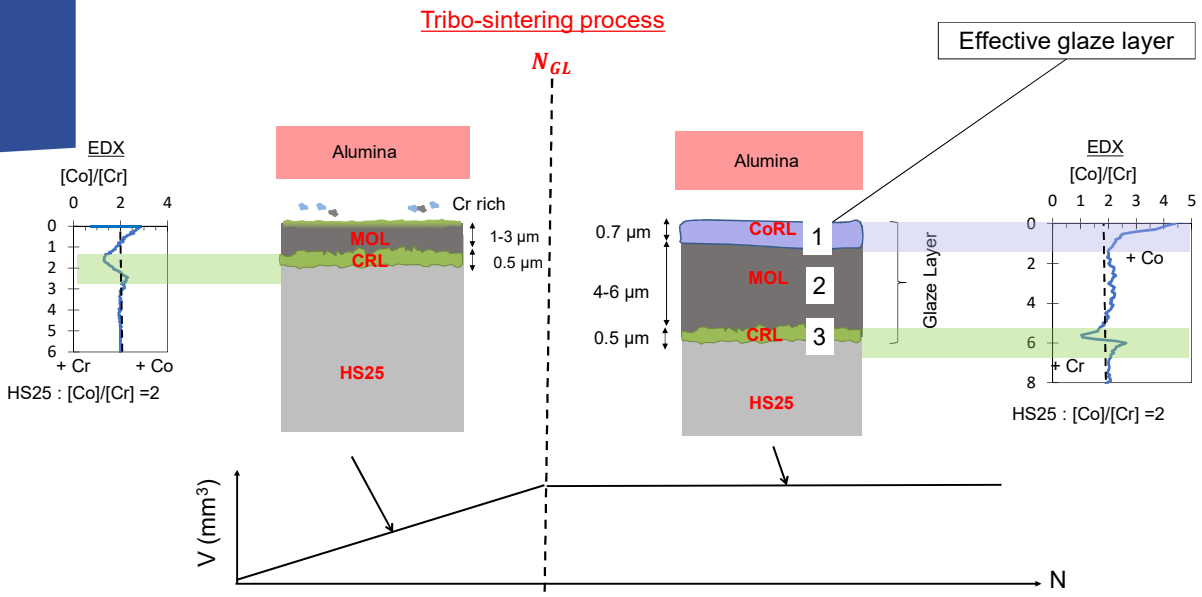
8

Characterisation of the glaze layer

MOL : Mixed Oxide Layer
CRL : Chromium-Rich Layer
CoRL : Cobalt-Rich Layer

Formation of the layered structure

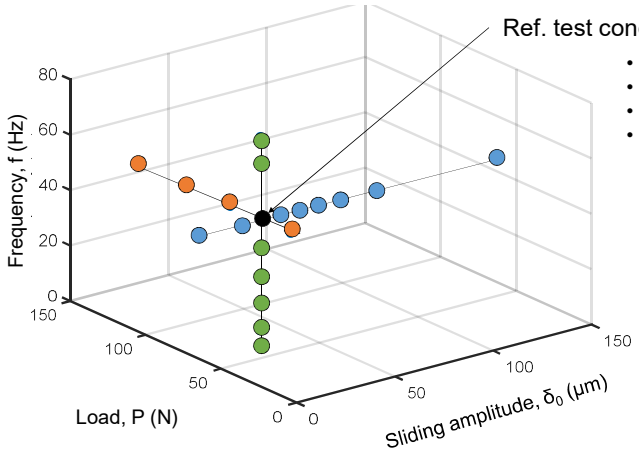
Dreano et al., *Wear*, 2019 (2)



9

Wear volume extension as function of the fretting loading conditions

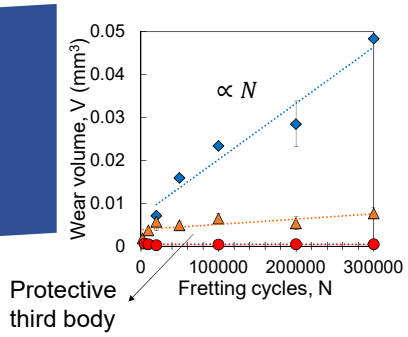
$T_{ref,I}$= 100° C; $T_{ref,II}$ = 230 ° C, $T_{ref,III}$=575° C

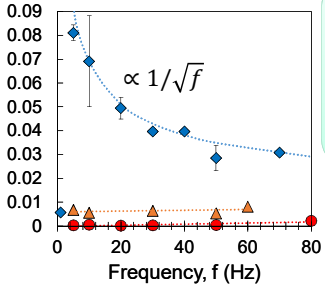


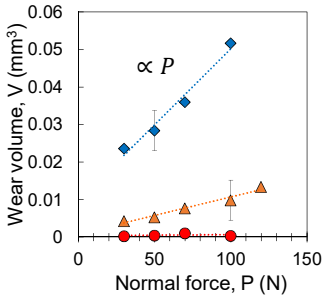
- Normal load P_{ref} : 50 N
- Fretting cycles N_{ref} : 200 000
- Frequency f_{ref} : 50 Hz
- Sliding amplitude $\delta_{0,ref}$: +/- 20 µm

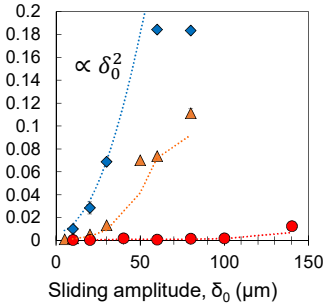
10

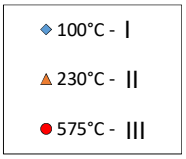
Influence of other parameters on wear : parametric study











Domain I
- Wear kinetics : abrasive process
- Frequency : oxidative process
- Normal load : abrasive process
- Sliding amplitude : abrasive and oxidative processes

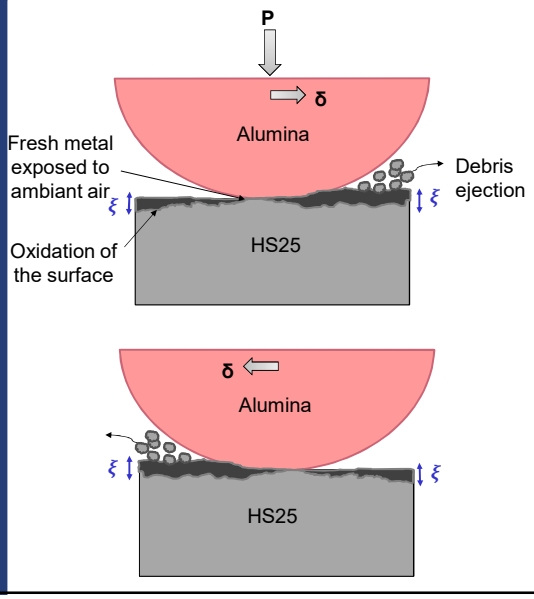
Domain II & III
- Wear kinetics : formation of a protective layer
- Frequency : protective layer
- Normal load : abrasive process
- Sliding amplitude : abrasive process? Destruction of the tribolayer?

11

Wear law (domain I, T < 150°C)

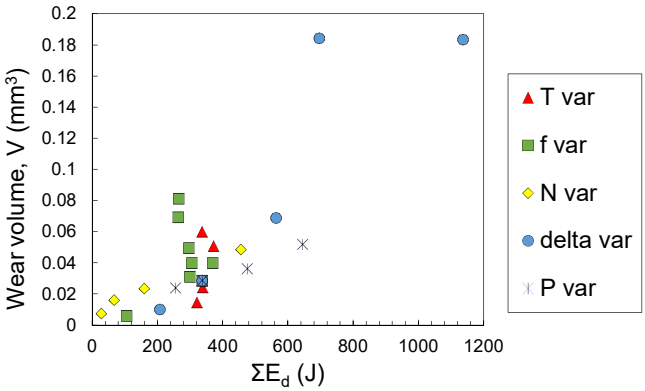
Wear mechanism

Oxidation + abrasion



Classical energetic wear law

$$V = \alpha \sum Ed$$



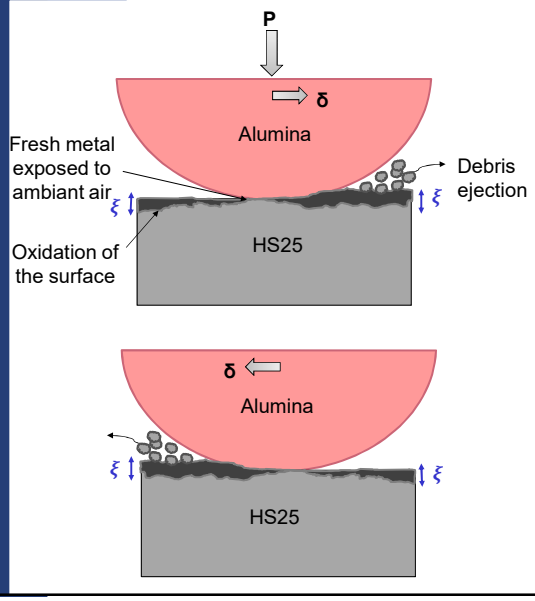
12

Wear law (domain I, T < 150°C)

E_a : activation energy for the oxidation process (kJ/mol)

Wear mechanism

Oxidation + abrasion



Oxidative-abrasive wear law

$$V = V_\Phi + \alpha_{ox} \times \boldsymbol{\psi} \times \sum Ed$$

$$\psi = \underbrace{\frac{1}{\sqrt{f}} exp\left(-\frac{E_a}{RT}\right)}_{\xi} \times \delta_0$$

ξ : *thickness oxide layer after each sliding*

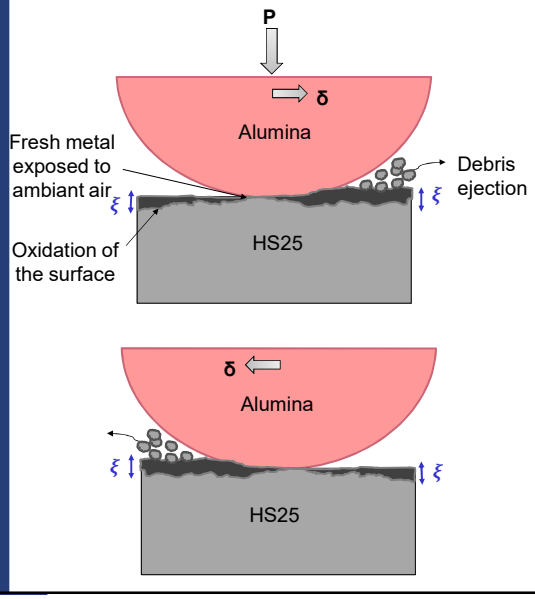
- α wear rate weigthed by a term related to the oxidation process Ψ
- Ψ is directly related to the growth of the oxide layer of thickness ξ
- ξ depends on temperature (T), the allowed time for the oxidation process to happen ($f^{-0.5}$) and quantity of oxygen available at the interface (δ_0)

13

Wear law (domain I, T < 150°C)

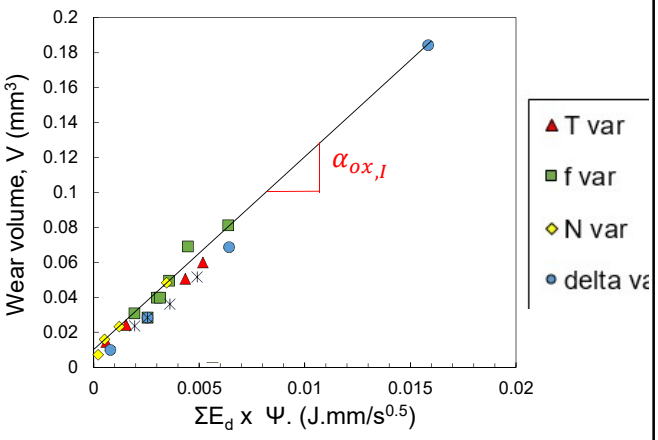
Wear mechanism

Oxidation + abrasion



Oxidative-abrasive wear law

$$V = V_\Phi + \alpha_{ox} \times \boldsymbol{\psi} \times \sum Ed$$



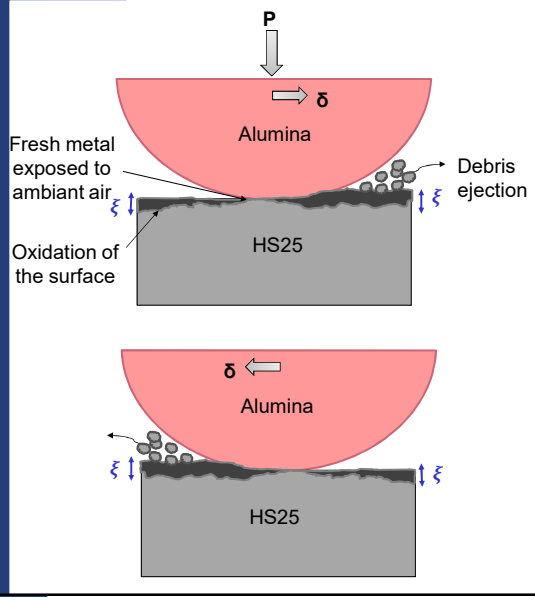
E_a : activation energy for the oxidation process (kJ/mol)

14

Wear law (domain II & III, T > 150°C)

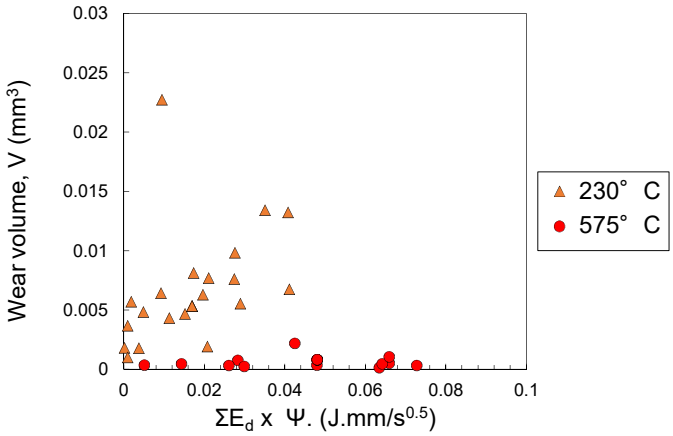
Wear mechanism

Oxidation + abrasion



Oxidative-abrasive wear law

$$V = V_\Phi + \alpha_{ox}\Psi \sum Ed$$

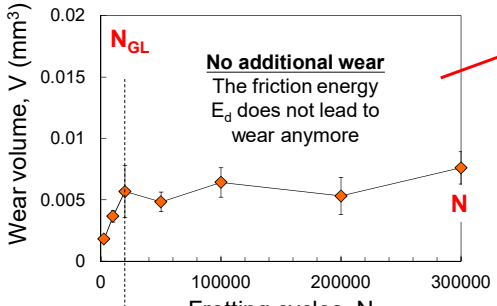


15

Wear law (domain II & III, T > 150°C)

Wear kinetics at high temperature

$P = 50N\,;f = 50Hz\,;\delta_0 = \pm 20\mu m\,;T = 230°C$

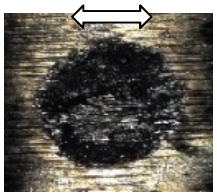


N replaced by N_{GL} !

$$V = \alpha_{ox}\Psi \sum_{i=0}^{N_{GL}} E_d + V_\phi$$

Formulation of N_{GL}?

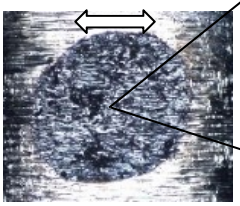
Oxidative-abrasive wear



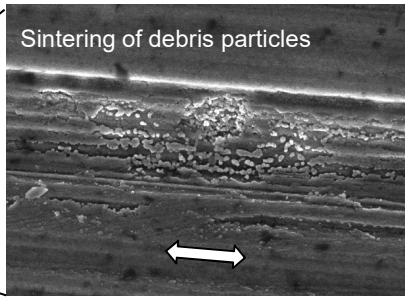
500 µm

Sintering process

Compacted debris layer



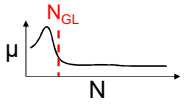
500 µm



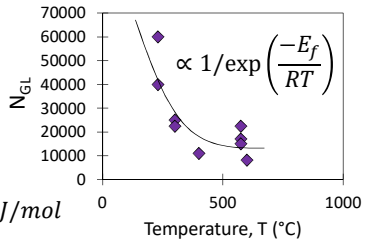
2 µm

16

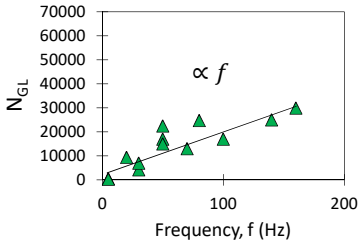
Wear law (domain II & III, T > 150°C)



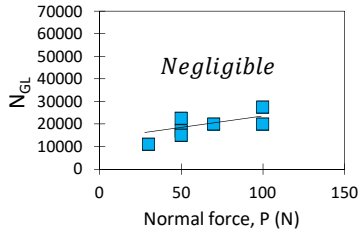
Evolution of N_{GL} with various tribological parameters

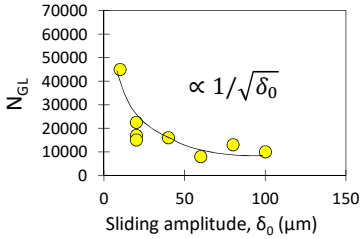


$E_f = 37\ kJ/mol$



T_{ref} = 575° C ;
f_{ref} = 50 Hz ;
P_{ref} = 50 N ;
$\delta_{0,ref}$ = +/- 20 µm ;
N_{ref} = 200 000 cycles



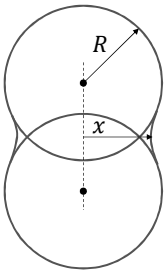


Formulation semi-empirique $\quad N_{GL} \propto \dfrac{f}{\sqrt{\delta_0} \times \exp\left(\frac{-E_f}{RT}\right)}$

Introduction of a « fretting » sintering parameter

Sintering rate for particles

Sintering rate: $\lambda = \frac{x}{R}$



$$\lambda^n = \frac{k_i}{R^m} \times t \times D_{0,i} \exp\left(\frac{-E_{f,i}}{RT}\right)$$

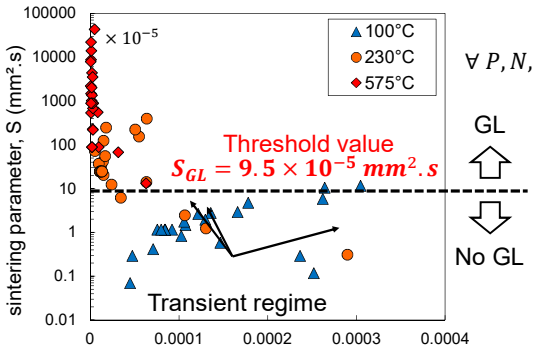
n, *m* and k_i are constants ; $E_{f,i}$ is the activation energy ; *t* is the time ; D_i is the diffusion coefficient

D. Bernache et al, Tech. Ing., 2005

$E_f = 37\ kJ/mol$

$$S = t \times \left(exp\left(-\frac{E_f}{RT}\right)\right) \times \sqrt{\delta_0}$$

Mixing process ?



$\forall\ P, N, f, \delta_0$

GL

No GL

$$t = \frac{N}{f} \Rightarrow N_{GL} = \frac{S_{GL} \times f}{\sqrt{\delta_0} \times \exp\left(\frac{-E_f}{RT}\right)}$$

Wear law (domain II & III, T > 150°C)

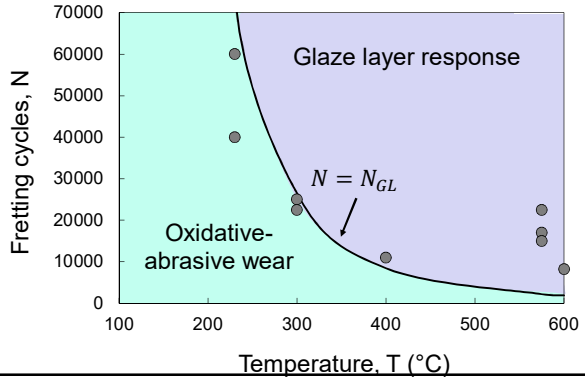
Prediction of N_{GL}

$$N_{GL} = \frac{S_{GL} \times f}{\sqrt{\delta_0} \times \exp\left(\frac{-E_f}{RT}\right)}$$

- The formula is able to predict the glaze layer formation which depends on many parameters : sliding amplitude, frequency, temperature

$$S_{GL} = 9.5 \times 10^{-5}\ mm^2.s$$
$$E_f = 37\ kJ/mol$$

Wear map



Example

- Prediction of the glaze layer formation as a function of the operating temperature
- Good prediction compared to experiments

19

A global wear law

Formulas

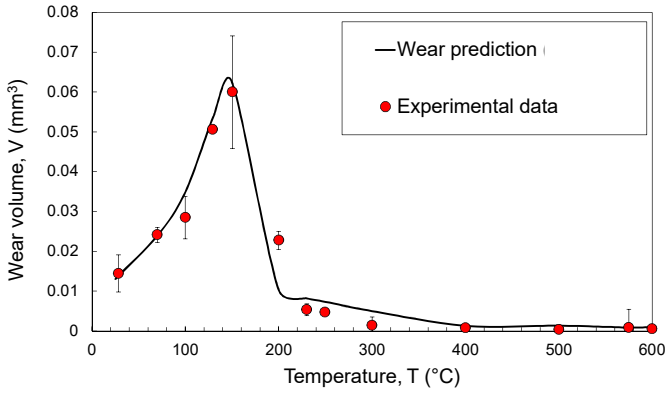
$$V = \alpha_{ox}\Psi \sum_{i=1}^{N_{eff}} E_d + V_\phi \qquad N_{eff} = \begin{cases} N \text{ if } N < N_{GL} \\ N_{GL} \text{ if } N > N_{GL} \end{cases}$$

N : applied fretting cycles
N_{GL} : fretting to form a protective glaze layer

$$N_{GL} = \frac{S_{GL} \times f}{\sqrt{\delta_0} \times \exp\left(\frac{-E_f}{RT}\right)}$$

$$S_{GL} = 9.5 \times 10^{-5}\ mm^2.s$$
$$E_f = 37\ kJ/mol$$

Results

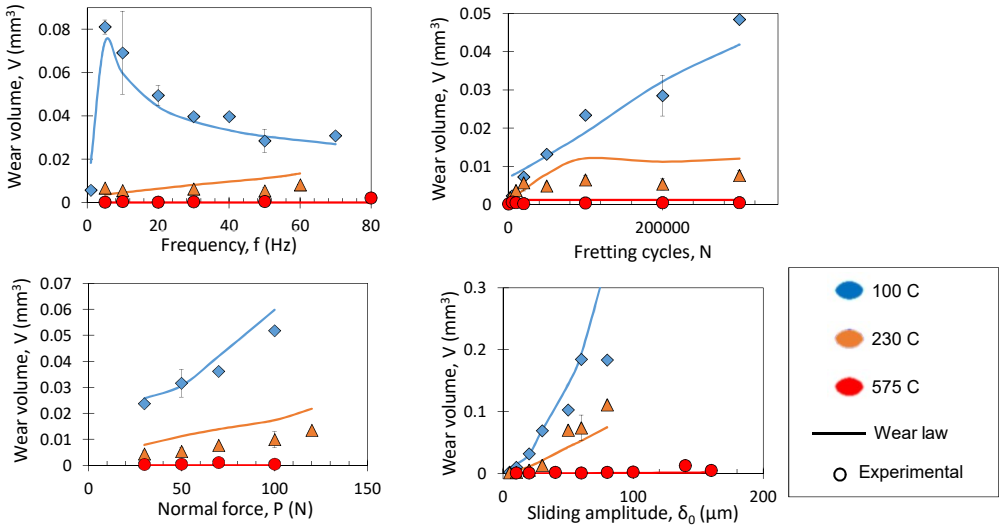


20

A global wear law

$$V = \alpha_{ox}\Psi \sum_{i=1}^{N_{eff}} E_d + V_\phi \qquad N_{eff} = \begin{vmatrix} N \; if \; N < N_{GL} \\ N_{GL} \; if \; N > N_{GL} \end{vmatrix} \qquad N_{GL} = \frac{S_{GL} \times f}{\sqrt{\delta_0} \times \exp\left(\frac{-E_f}{RT}\right)}$$

Results



Why cobalt is favoring the Glaze layer formation ?

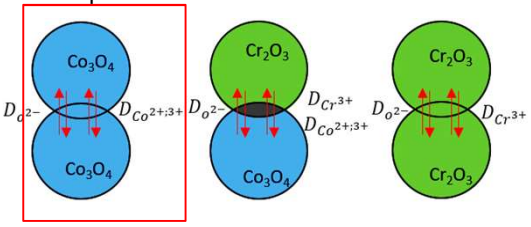
sintering rate

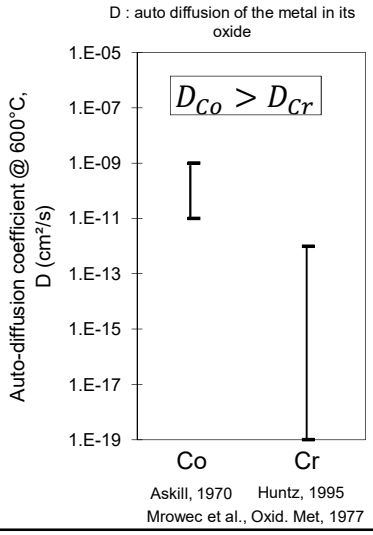
$$\lambda^n = \frac{k_i}{R^m} \times t \times D_{0,i} \exp\left(\frac{-E_{f,i}}{RT}\right) \Rightarrow N_{GL} \propto \frac{1}{\lambda^n} \Rightarrow N_{GL} \propto \frac{1}{D_{0,i}}$$

- The effective glaze layer is mainly made of cobalt oxides

- **Among all the oxides particles, the cobalt oxides are more likely to sinter**

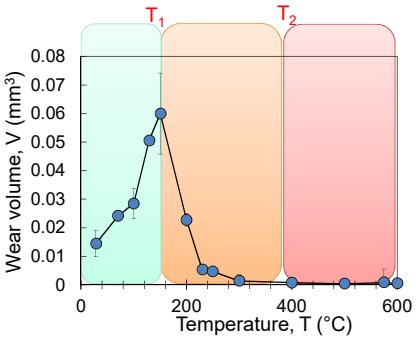
Main process





Conclusions





$T_1 < T < T_2$

- Oxide debris starts to agglomerate due to the elevation of temperature
- Formation of a compacted layer leading to a diminution of wear

➢ **Wear rate is controlled by the tribolayer formation**

$T < T_1$

Oxide debris is powdered and brittle : easily ejected from the interface

➢ **Wear rate is controlled by the debris formation rate (oxidative-abrasive wear law)**

$T > T_2$

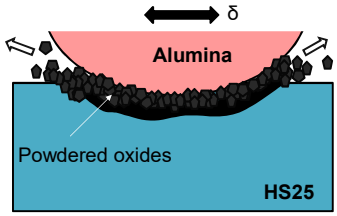
- The sintering of the compact layer forms the so-called « glaze layer »
- Debris flow ejection tends to zero

➢ **Wear rate is controlled by the tribolayer formation**

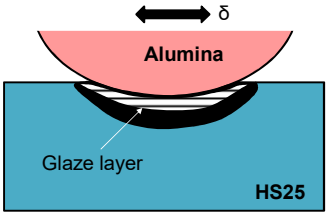
23

Conclusions

Oxidative-abrasive wear



Protective glaze layer

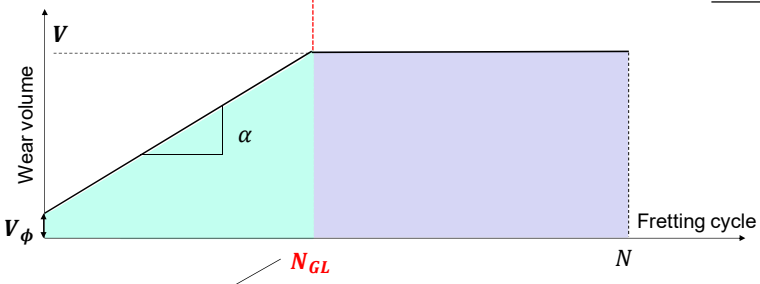


No sintering process

$S < S_{GL}$

Sintering process

$S > S_{GL}$



$$N_{GL} = \frac{S_{GL} f}{\sqrt{\delta_0} exp\left(-\frac{E_a}{RT}\right)}$$

$$V = \alpha_{ox} \Psi \sum_{i=0}^{N_{GL}} E_d + V_\phi$$

24

Perspectives

- Fretting wear response versus variable temperature sequences : Dynamics of GL formation / GL destruction
- Influence on contact size and debris trapping process regarding the GL formation
- Influence of counterface materials (roughness and chemical composition) on the activation of GL
- …

25

Thank you for your attention

Publications related to this research work :

R. Rybiak, S. Fouvry, B. Bonnet, Fretting wear of stainless steels under variable temperature conditions: Introduction of a 'composite' wear law, Wear 268 (2010) 413–423

A. Viat, S. Fouvry, M.-I. De Barros Bouchet, L. Pin, Influence of carbon-based solid lubricant on fretting wear response for alumina-based ceramics versus cobalt superalloy contact, Surface & Coatings Technology 284 (2015) 327–333.

A.Viat, M.I. De Barros Bouchet, B. Vacher, T. Le Mogne, S.Fouvry, J.F. Henne, Nanocrystalline glaze layer in ceramic-metallic interface under fretting wear, Surface and Coatings Technology 308 (2016) 307–315.

A. Viat , A. Dreano , S. Fouvry , M. I. De Barros Bouchet , J. F. Henne, Fretting wear of pure cobalt chromium and nickel to identify the distinct roles of HS25 alloying elements in high temperature glaze layer formation, Wear 376-377 (2017) 1043–1054.

A. Viat, G. Guillonneau, S. Fouvry, G. Kermouche, S. Sao Joao, J. Wehrs , J. Michler , J. F. Henne, Brittle to ductile transition of tribomaterial in relation to wear response at high temperatures, Wear 392–393 (2017) 60–68

A. Dreano, S. Fouvry, G. Guillonneau, A tribo-oxidation abrasive wear model to quantify the wear rate of a cobalt based alloy subjected to fretting in low-to-medium temperature conditions, Tribology International 125 (2018) 128–140 (https://doi.org/10.1016/j.triboint.2018.04.032).

A. Dreano, S. Fouvry, G. Guillonneau, A combined friction energy and tribo-oxidation formulation to describe the high temperature fretting wear response of a cobalt-based alloy, Wear 426–427 (2019) 712–724 (https://doi.org/10.1016/j.wear.2019.01.023).

A. Dreano, S. Fouvry, S. Sao-Joao, J. Galipaud, G. Guillonneau, The formation of a cobalt-based glaze layer at high temperature: A layered structure, Wear 440-441 (2019) 2031015 (https://doi.org/10.1016/j.wear.2019.203101)

A. Dreano , S. Fouvry, G. Guillonneau, Understanding and formalization of the fretting-wear behavior of a cobalt-based alloy at high temperature, Wear 452–453 (2020) 203297 (https://doi.org/10.1016/j.wear.2020.203297)