13th TWC International Wear Seminar

Investigation of fretting wear of a flat-on-flat 34NiCrMo16 interface: Application and modelling of the contact oxygenation concept

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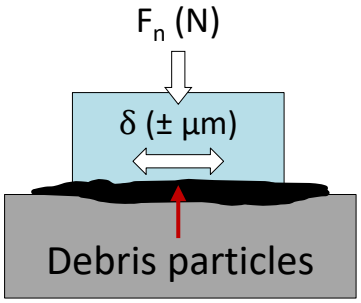
Tribological Challenges in Industrial Applications

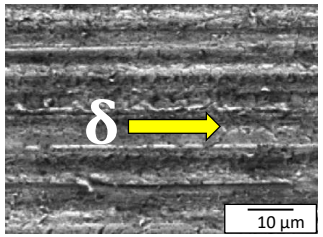
Fretting wear and damage mechanisms

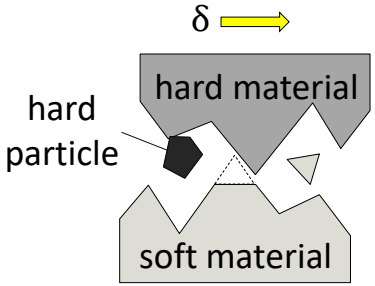
Collapse of Silver Bridge (1967)



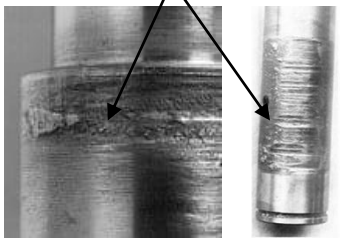
Amsterdam plane crash (1992)

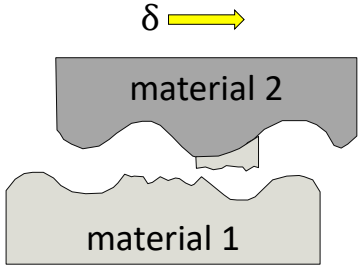
Abrasive wear



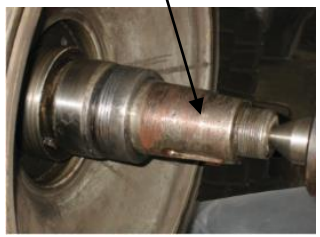


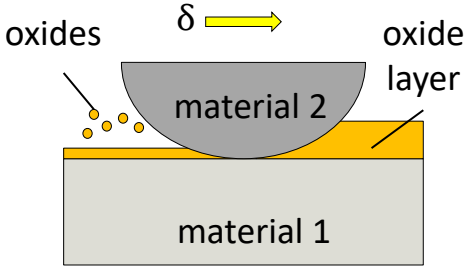
Adhesive wear



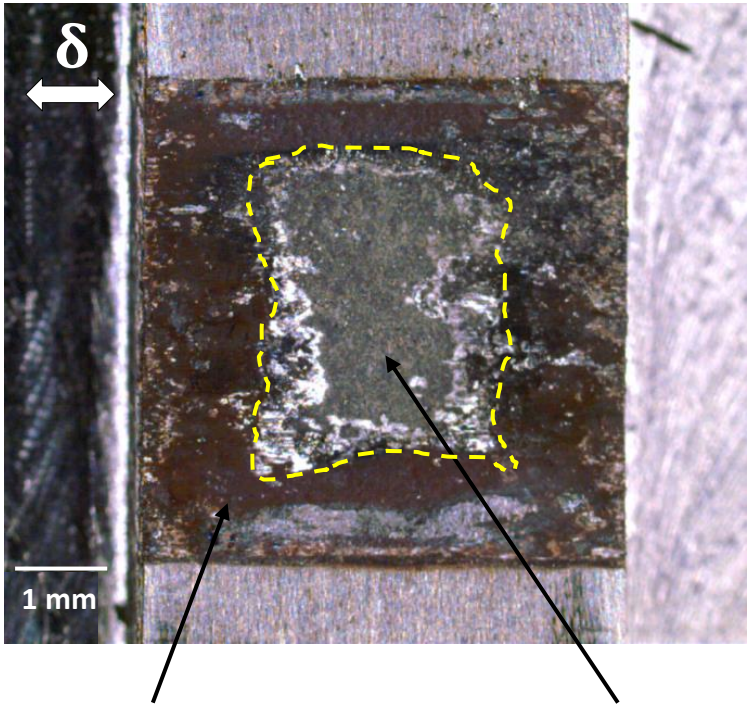


Corrosive wear



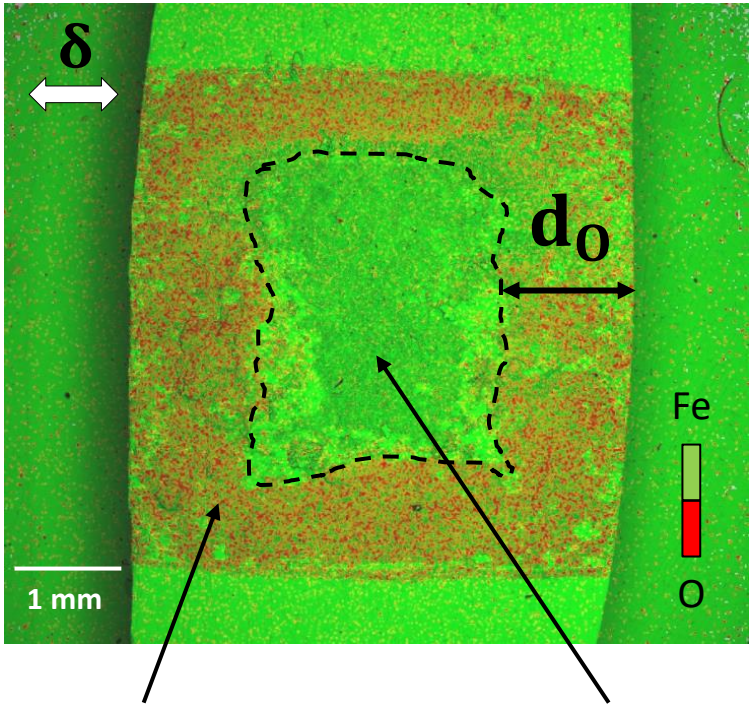


Fretting wear of flat-on-flat steel (34NiCrMo16) alloy



abrasion adhesion

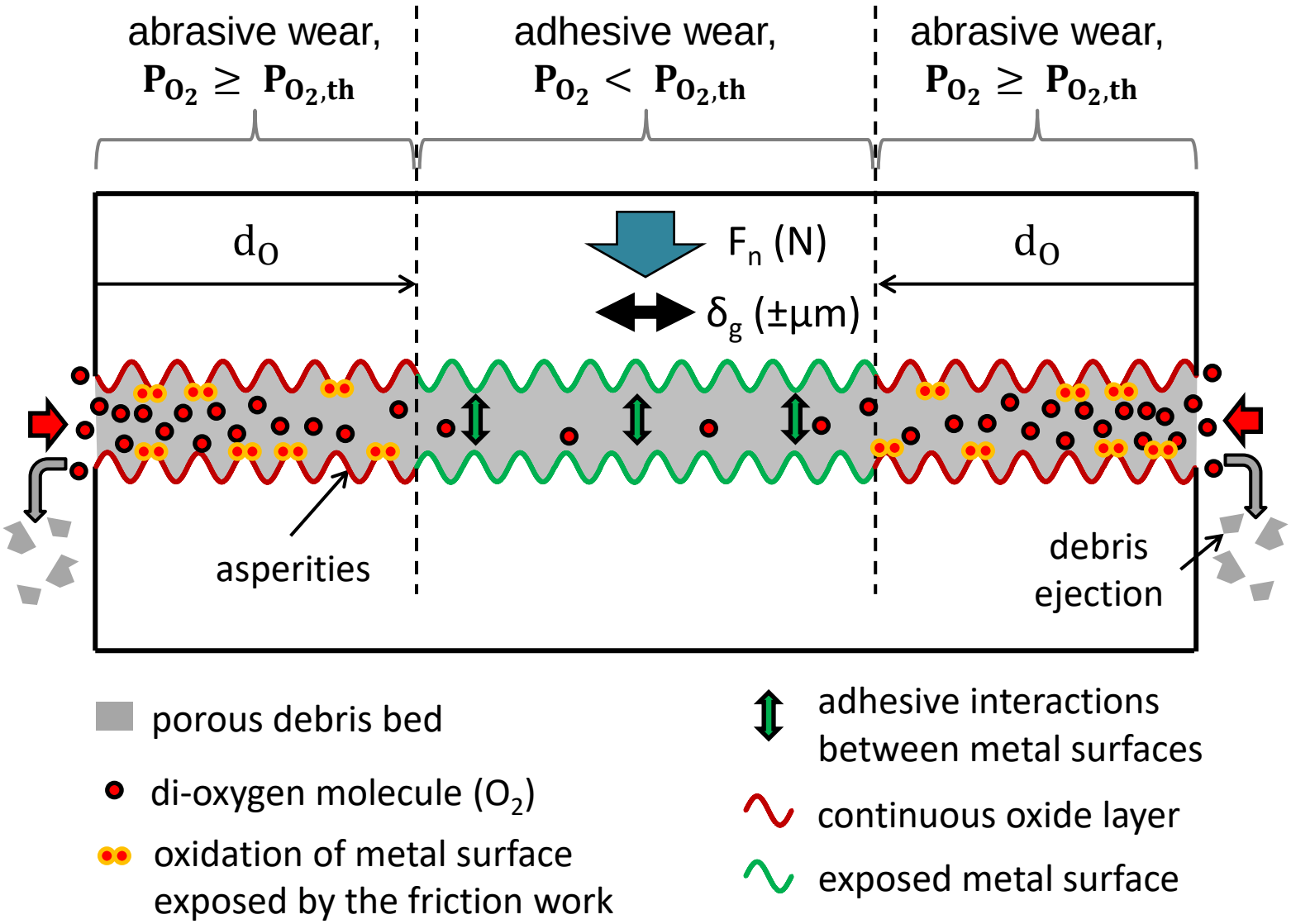
Optical observation



abrasion adhesion

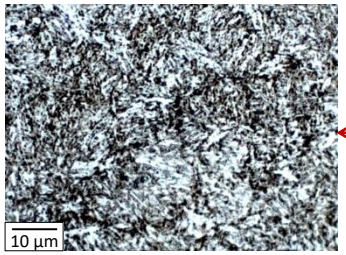
EDX map (Fe , O)

Contact oxygenation concept



Contact configuration

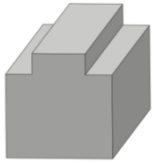
- Material: 34NiCrMo16 (Low-alloyed steel)
- Contact geometry: crossed flat-on-flat
- Contact area: $A = L_C \times L_T$



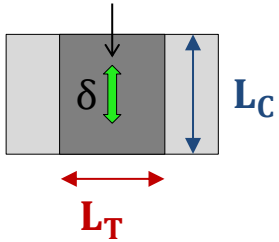
Martensite structure

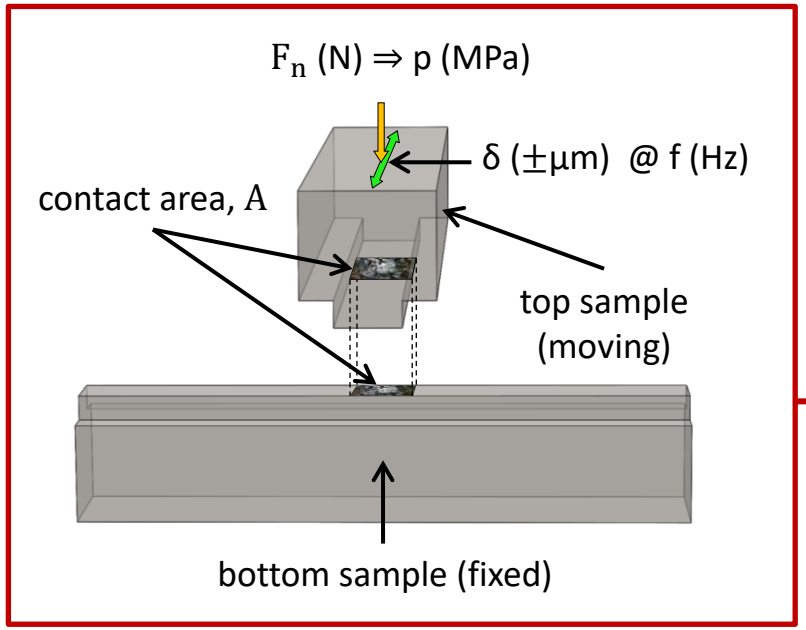
H (HV)	E (GPa)	ν	$\sigma_{y\,0.2\%}$ (MPa)	σ_u (MPa)
400	205	0.3	950	1130

flat contact

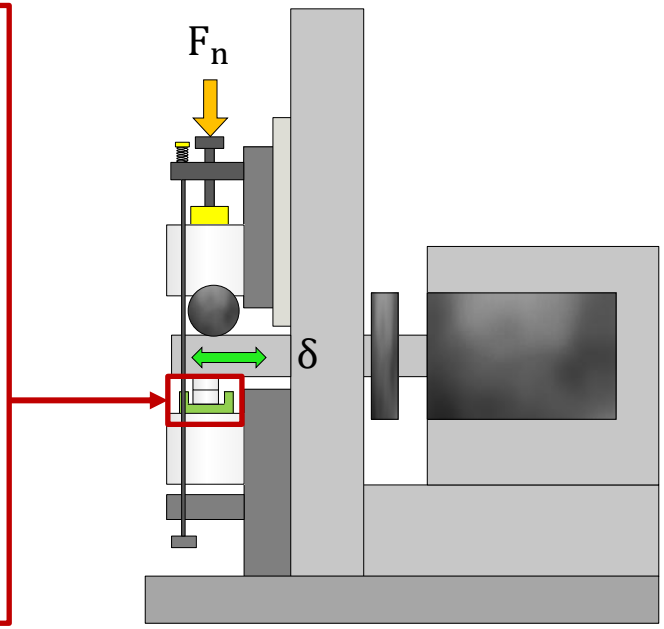


$A = L_C \times L_T$





Tribometer



Crossed-experimental strategy

Multi-scale experimental strategy is used starting from a reference condition having:

N=20 000 cycles

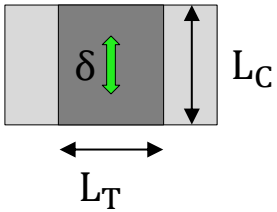
f=1 Hz

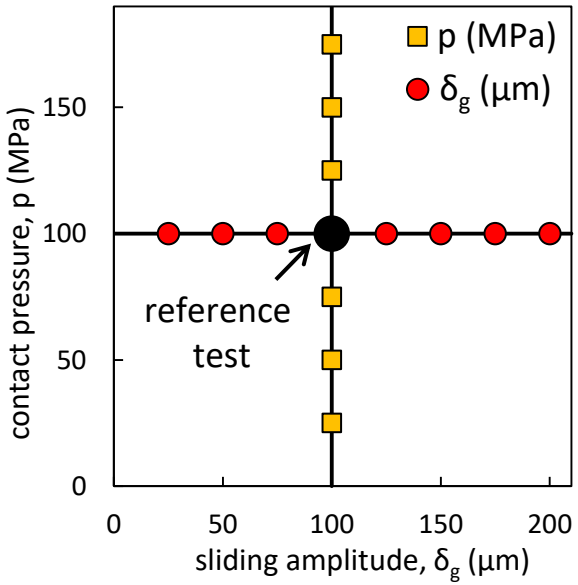
A=5x5=25 mm²

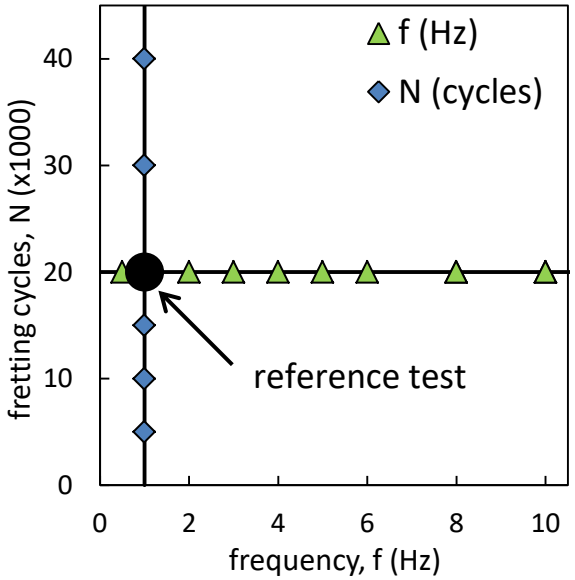
δ_g=100 µm

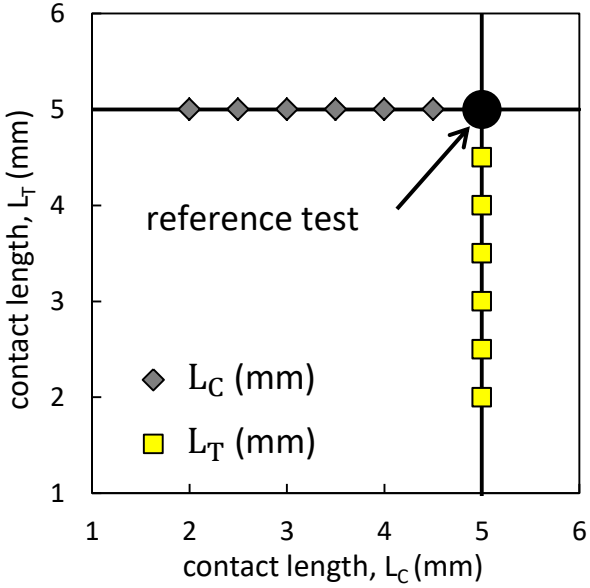
p=100 MPa

F_n=2500 N









Method

Crossed oxygen EDX line scans

Calculation of oxygen distance

$$d_{O,X} = \frac{1}{2} \cdot \left(d_{O,X_1} + d_{O,X_2}\right)$$

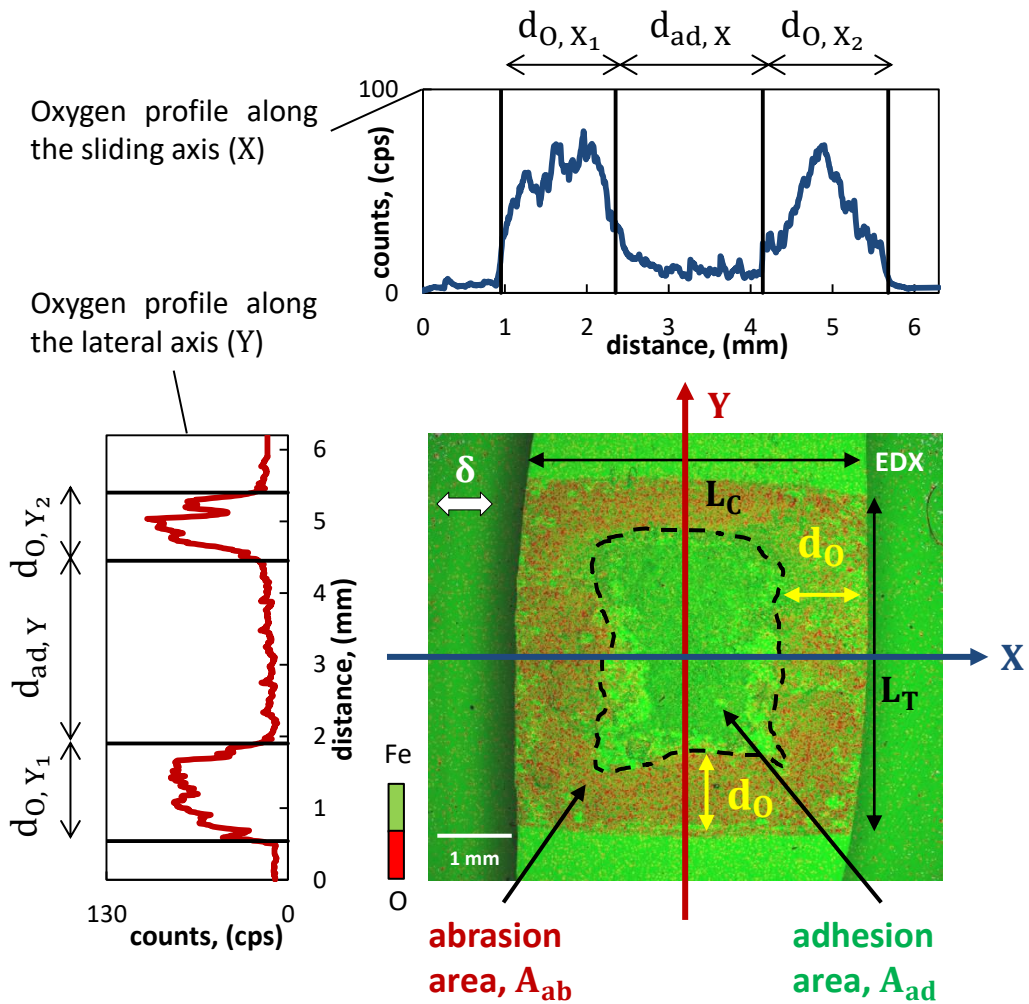
$$d_{O,Y} = \frac{1}{2} \cdot \left(d_{O,Y_1} + d_{O,Y_2}\right)$$

$$\Rightarrow d_O = \frac{1}{2} \cdot \left(d_{O,X} + d_{O,Y}\right)$$

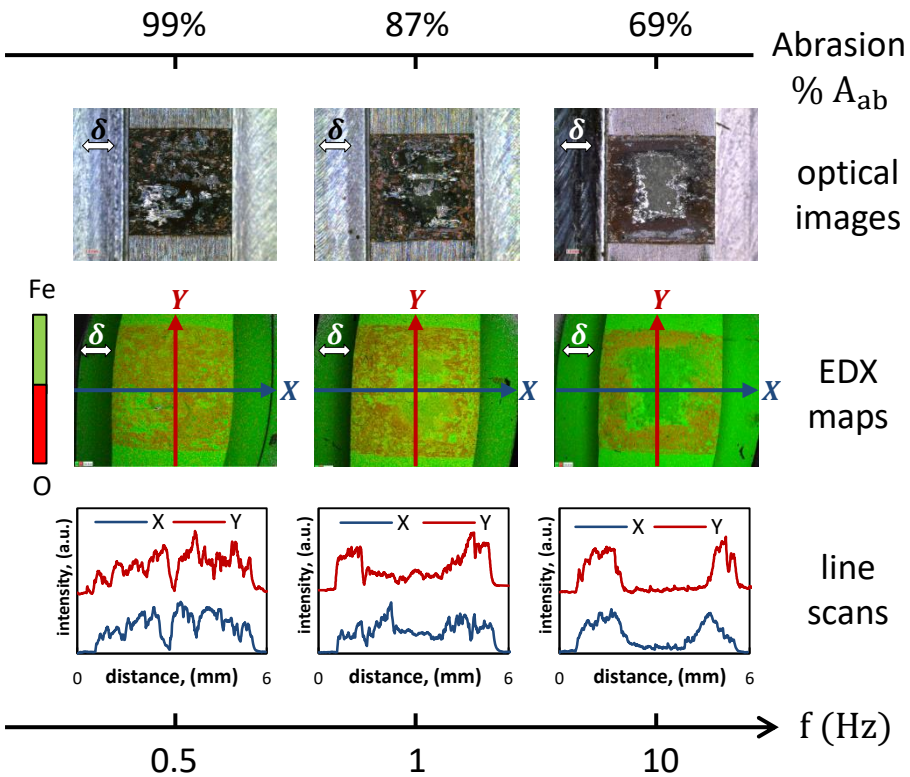
Adhesion and abrasion areas

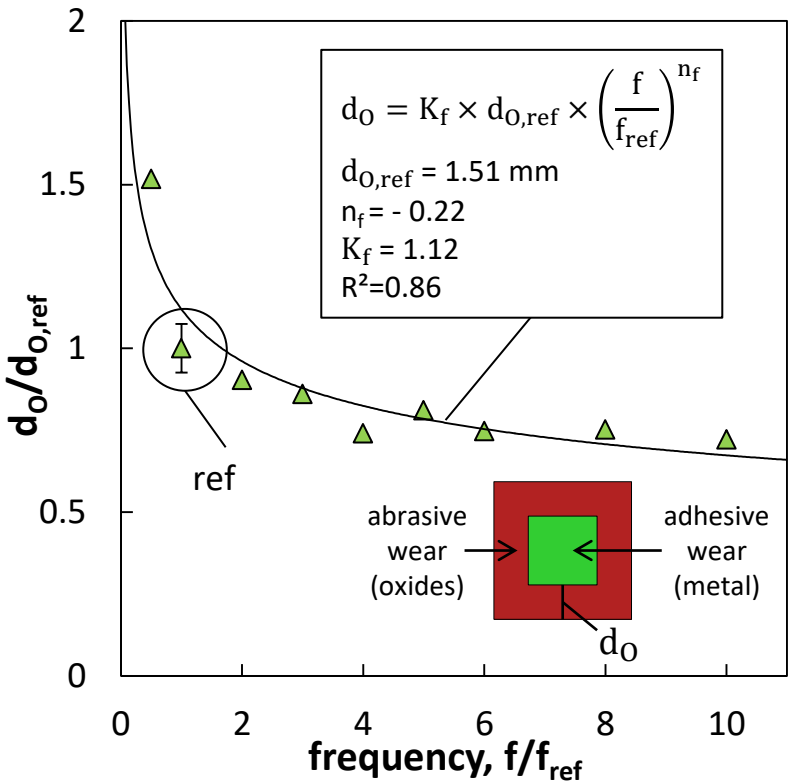
$$A_{ad} = d_{ad,X} \cdot d_{ad,Y}$$

$$A_{ab} = A - A_{ad}$$



Effect of sliding frequency

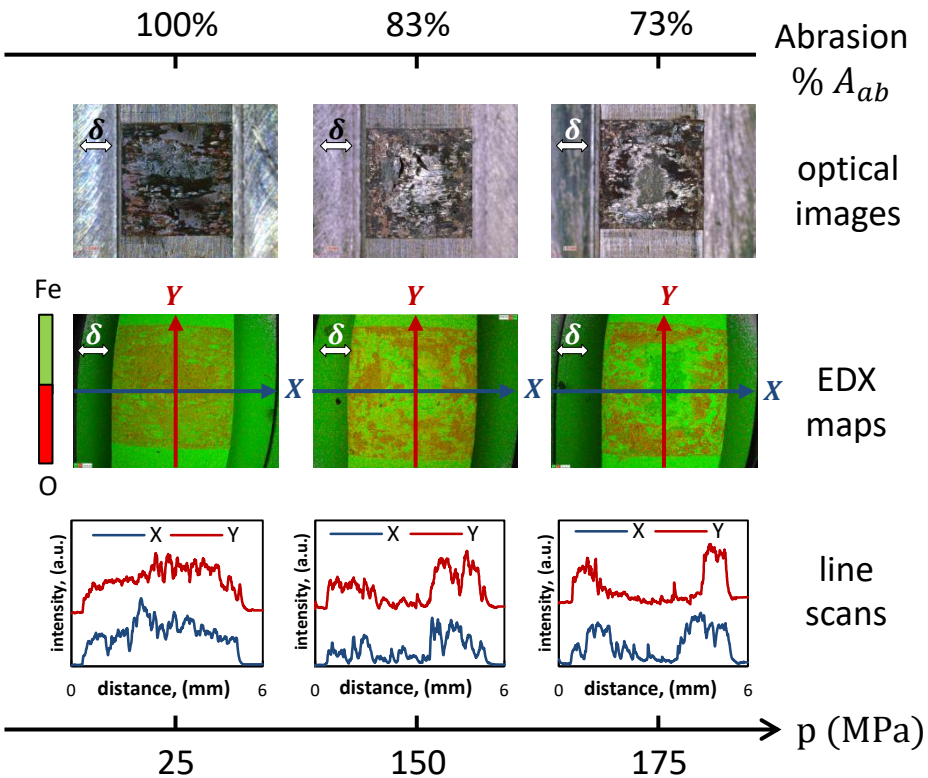


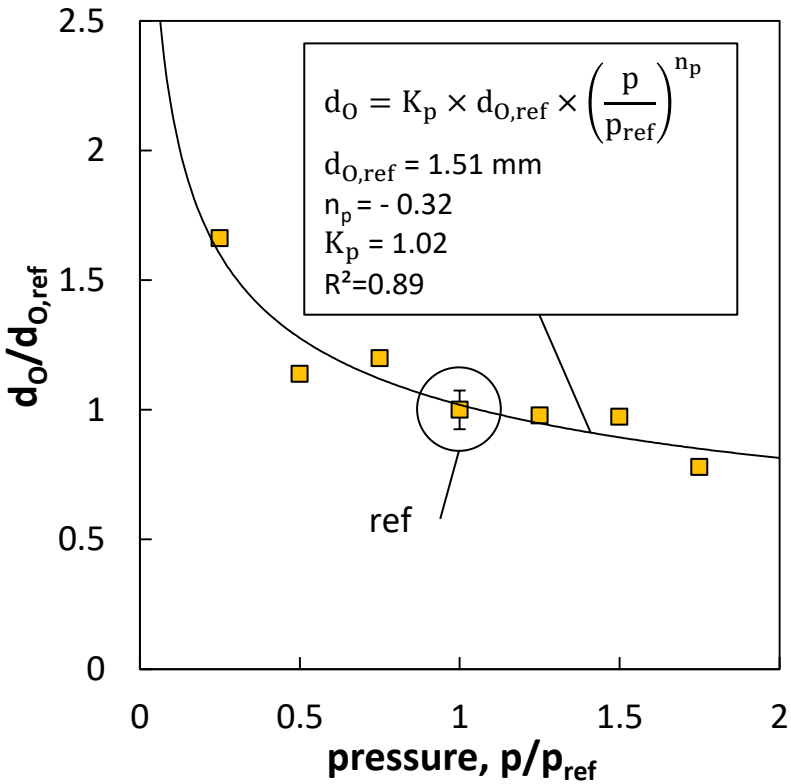


↗ frequency ⇒ ↗ reaction of fresh Fe with O_2 ⇒ O_2 depletion towards the contact center

⇒ adhesion ↗ ⇒ d_O ↘

Effect of contact pressure

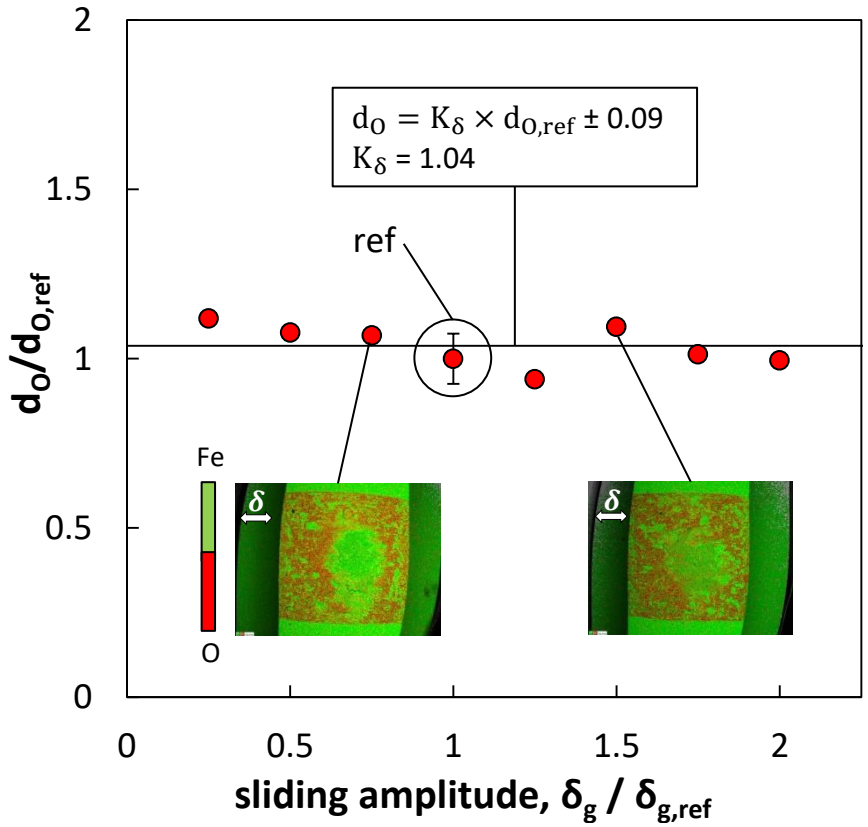


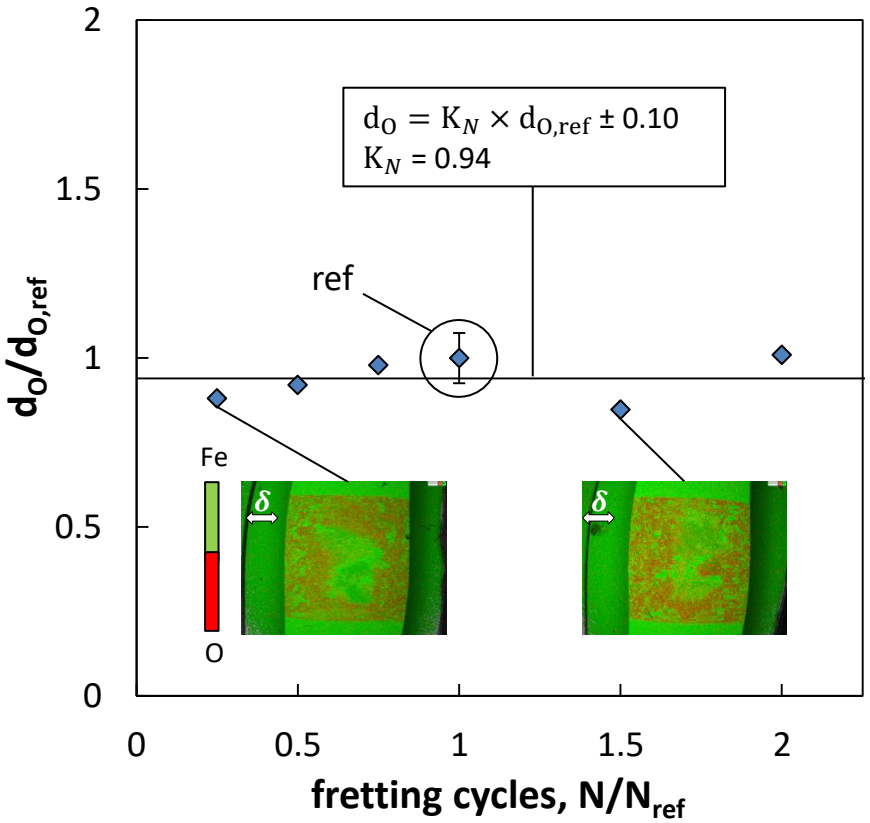


↗ pressure ⇒ ↗ reaction of fresh Fe with O_2 ⇒ O_2 depletion towards the contact center

⇒ adhesion ↗ ⇒ d_O ↘

Effect of sliding amplitude and fretting cycles

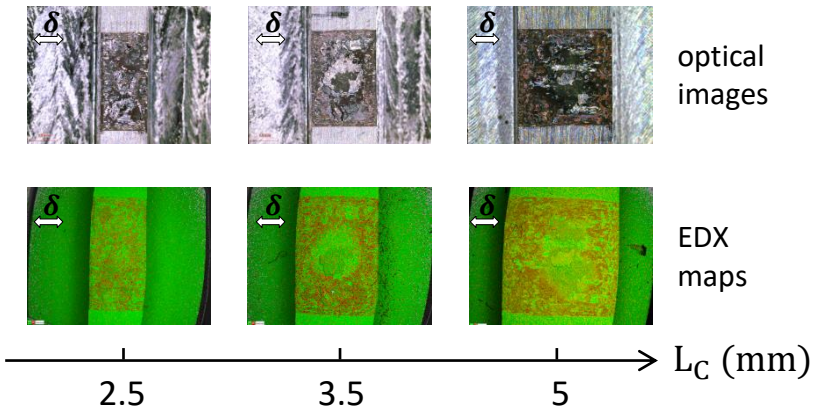




- Stable evolution of oxygen distance with sliding amplitude and fretting cycles
- Fretting cycles ⇒ Constant friction power ⇒ Constant reaction rate O_2 ⇒ d_O= constant
- Sliding amplitude ⇒ Counterbalancing effect of third body ejection process

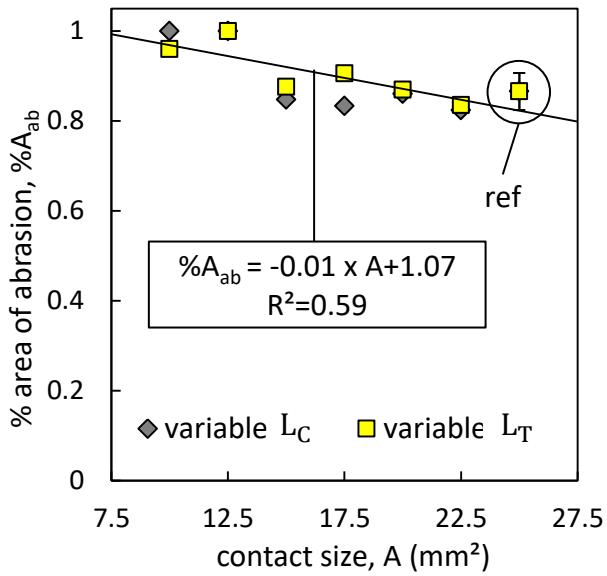
Effect of contact size

Effect of contact length L_C

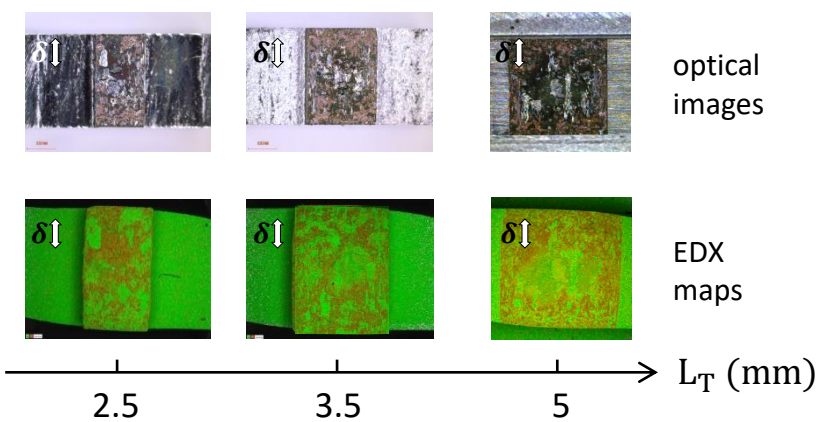


A ↗

% Abrasion ↘

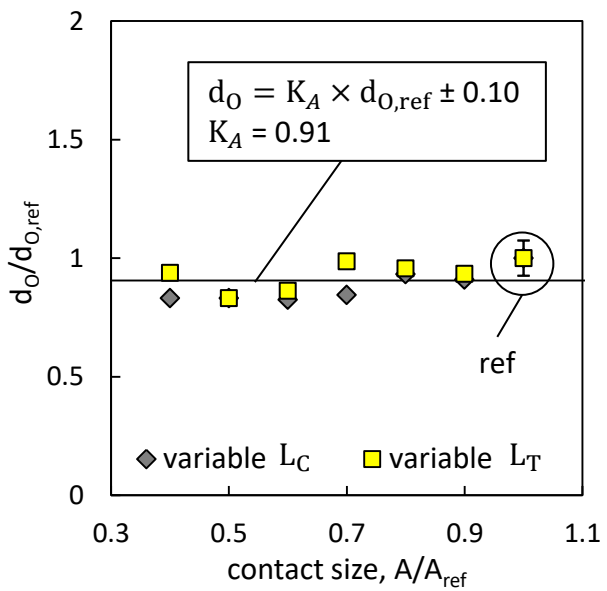


Effect of contact length L_T



A ↗

$d_O \approx$ cte



Parametric "oxygen distance" modeling

$$d_{O,\,pred} = d_{O,\,ref} \times \left(\frac{f}{f_{ref}}\right)^{n_f} \times \left(\frac{p}{p_{ref}}\right)^{n_p}$$

$$d = \min\left(\frac{L_C}{2}, \frac{L_T}{2}\right) > d_O$$

$$A_{ad} = L_T . L_C - 2 . d_O (L_T + L_C) + 4 . {d_O}^2$$

$$A_{ab} = A - A_{ad}$$

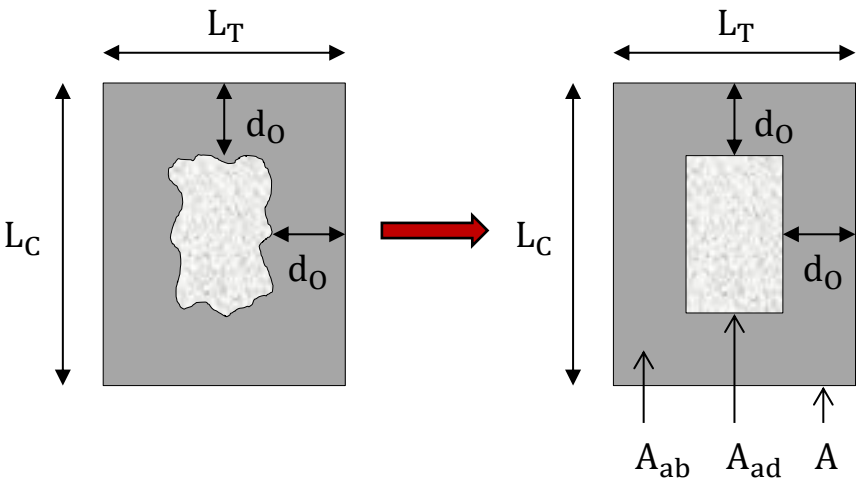
$d_{O,ref} = 1.51$ mm

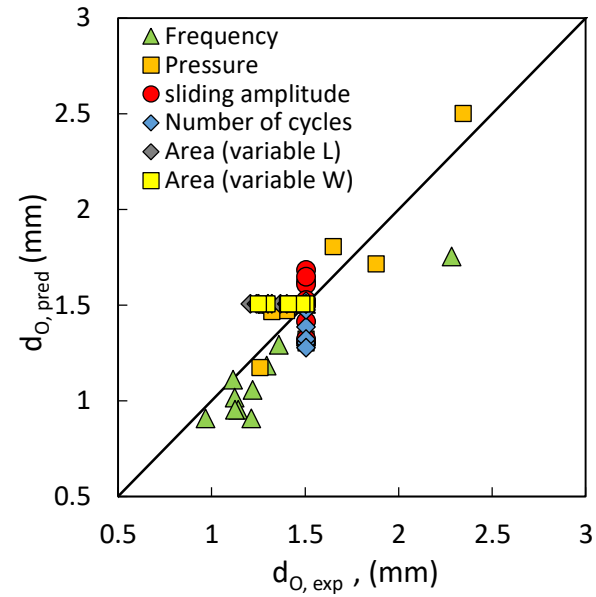
$f_{ref} = 1$ Hz

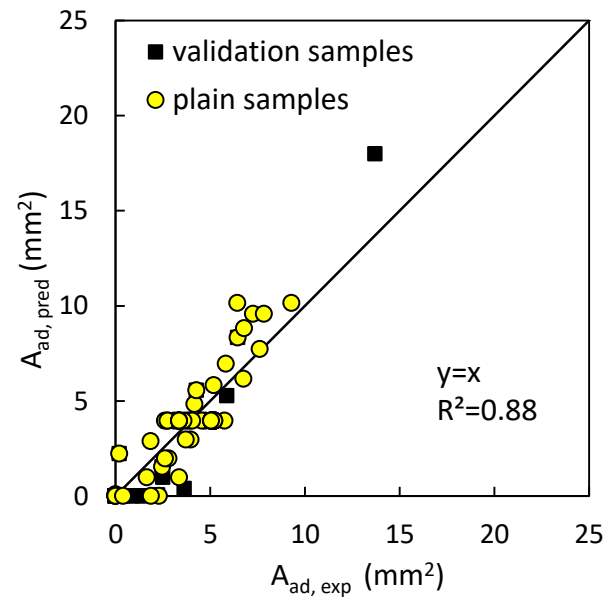
$p_{ref} = 100$ MPa

$n_f = -0.22$

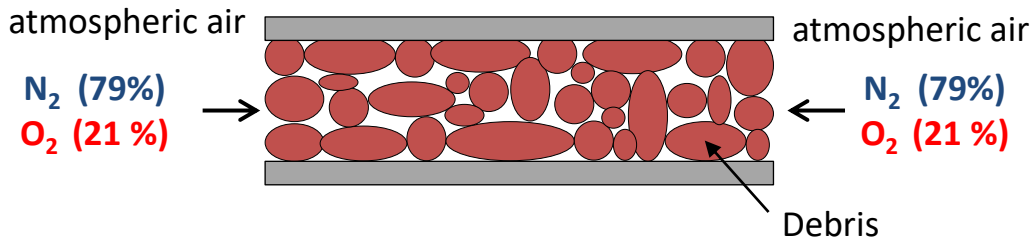
$n_p = -0.32$







Advection-Dispersion-Reaction ADR approach



ADR Model

Advection

$J_{a,i} = vP_i$

$(i = O_2, N_2 \text{ gases})$

Darcy's law:

$v = -\frac{k}{\mu}\nabla P \quad (P = \sum P_i)$

Carman–Kozeny model:

$k = \frac{{d_p}^2 . a^3}{180.(1-a)^2}$

Dispersion

Fick's law:

$J_{d,i} = -D_i \nabla C_i$

$D_i = D_{mech.\,mixing} + D_{dif,\,i}$

$D_{dif,\,i} = \tau . D_{im}$

$D_{mech.\,mixing} = \alpha_L |v|$

Reaction

No nitriding reaction:

$R_{N_2} = 0$

Oxidation reaction:

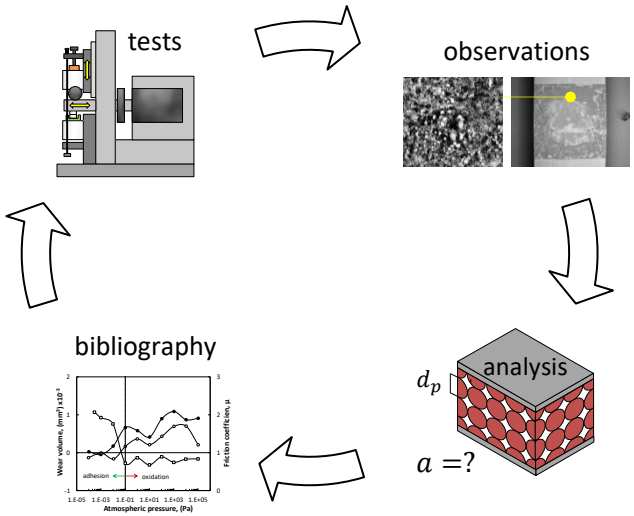
$R_{O_2} = -r_{O_2} . P_{O_2}$

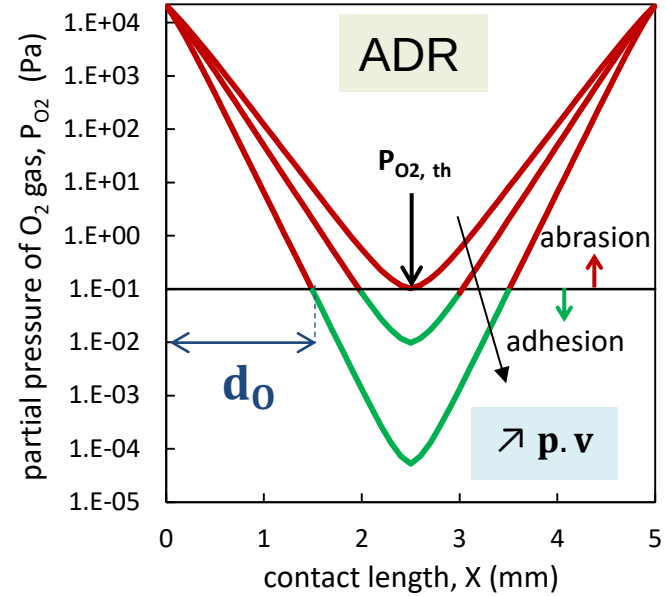
$r_{O_2} = \beta \left(\frac{\omega}{\omega_{ref}}\right)^{\gamma}$

$\omega = \text{p.v} = 4.p.\delta_g.f$

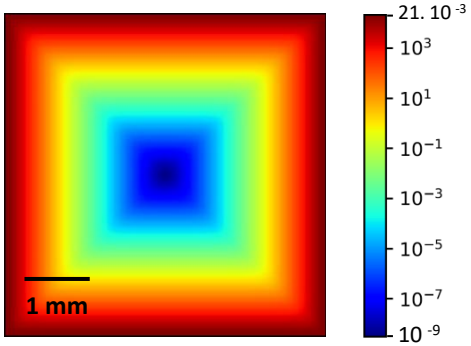
ADR continuity equation: $\boldsymbol{a\frac{dP_i}{dt} = -\nabla.(J_{a,i} + J_{d,i}) + R_i = -\nabla.(-D_i \nabla P_i + vP_i) + R_i}$

Model calibration



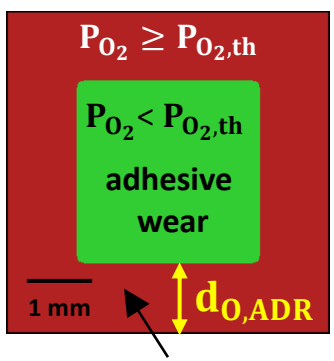


ADR modelling



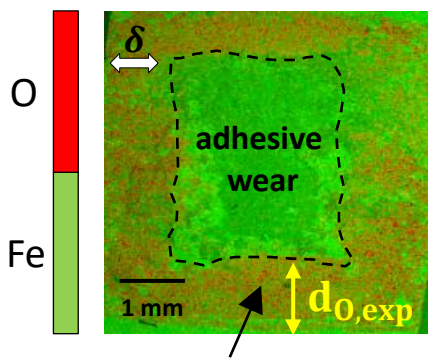
O_2 contact partial pressure

Wear modelling



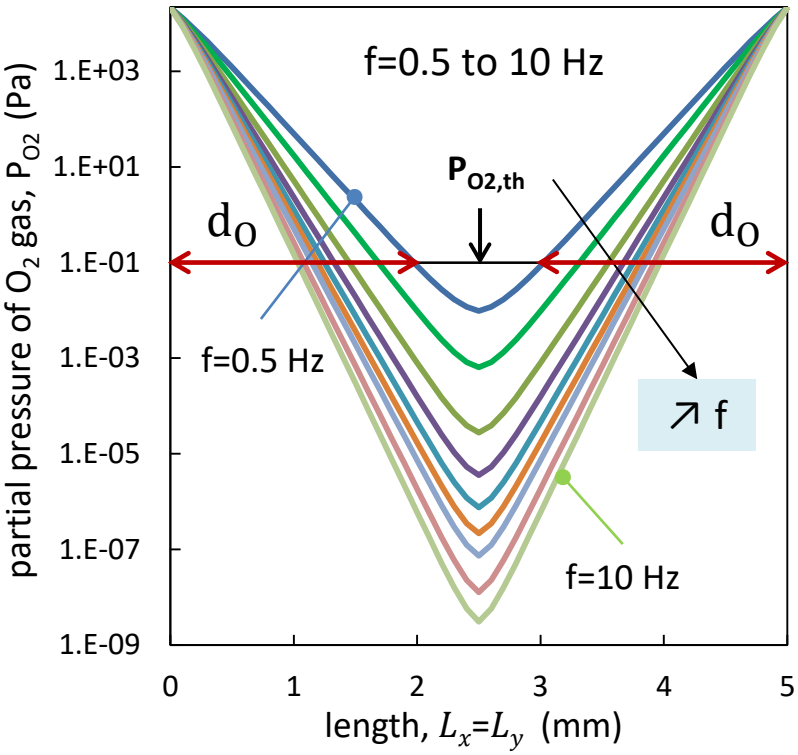
abrasive wear

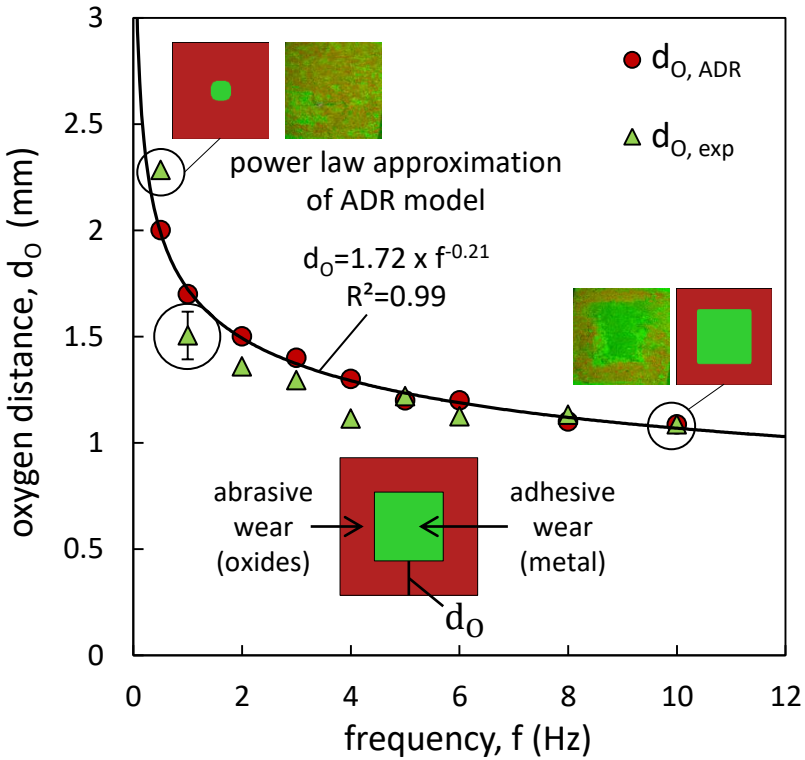
EDX of a steel fretting scar



abrasive wear

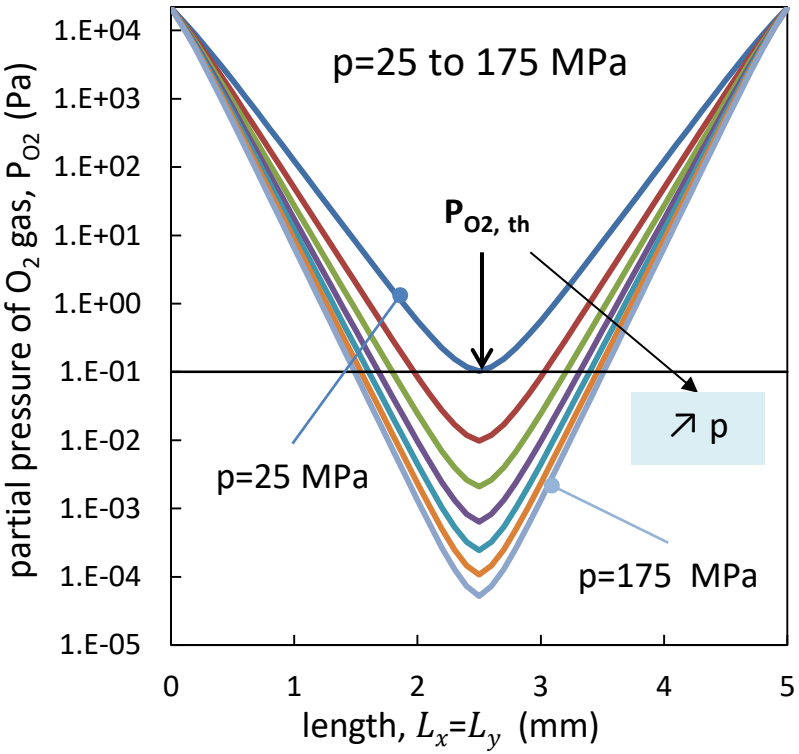
Effect of sliding frequency

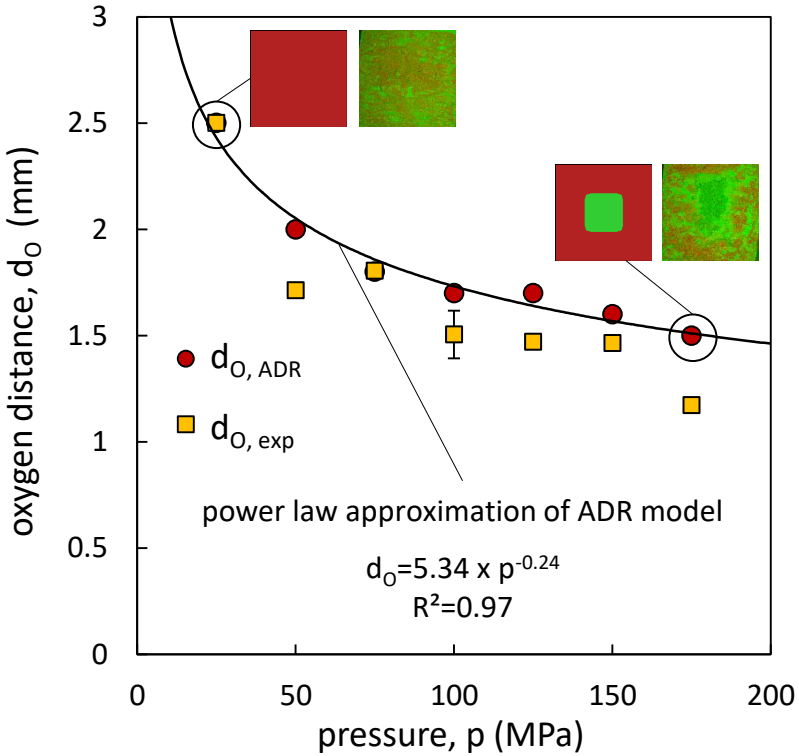




- Decrease in P_{O_2} below $P_{O_2,th}$ with the increase in frequency from 0.5 to 10 Hz
- Very good prediction of d_O with ADR model

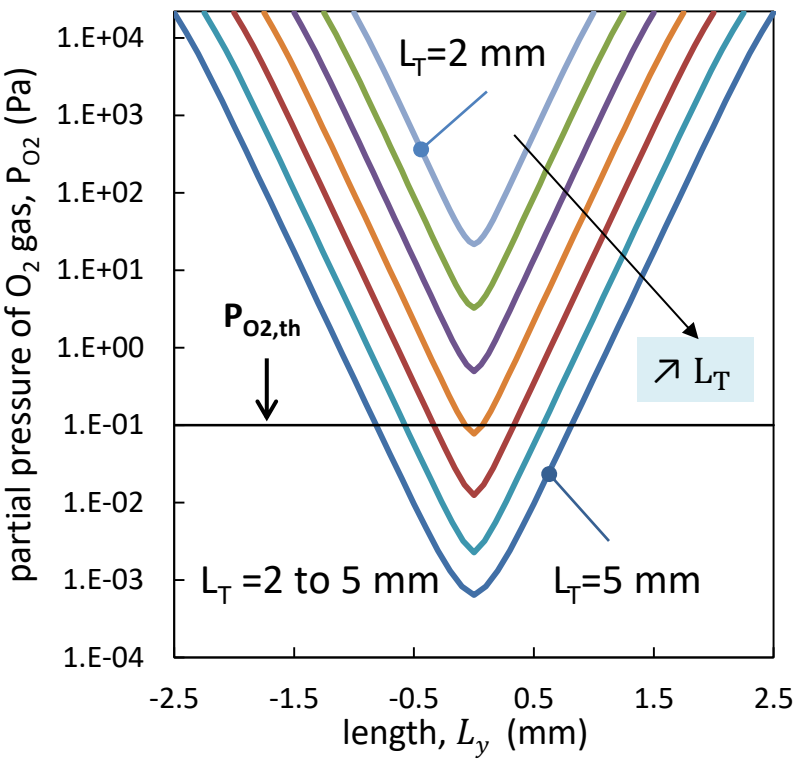
Effect of contact pressure

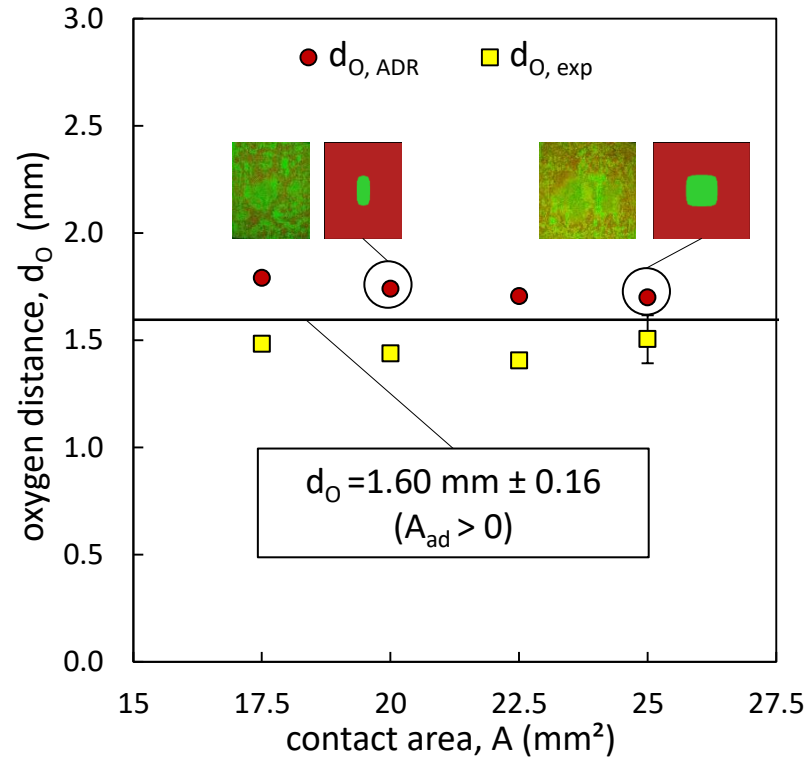




- Decrease in P_{O_2} below $P_{O_2,th}$ with the increase in pressure from 25 to 175 MPa
- Very good prediction of d_O with ADR model

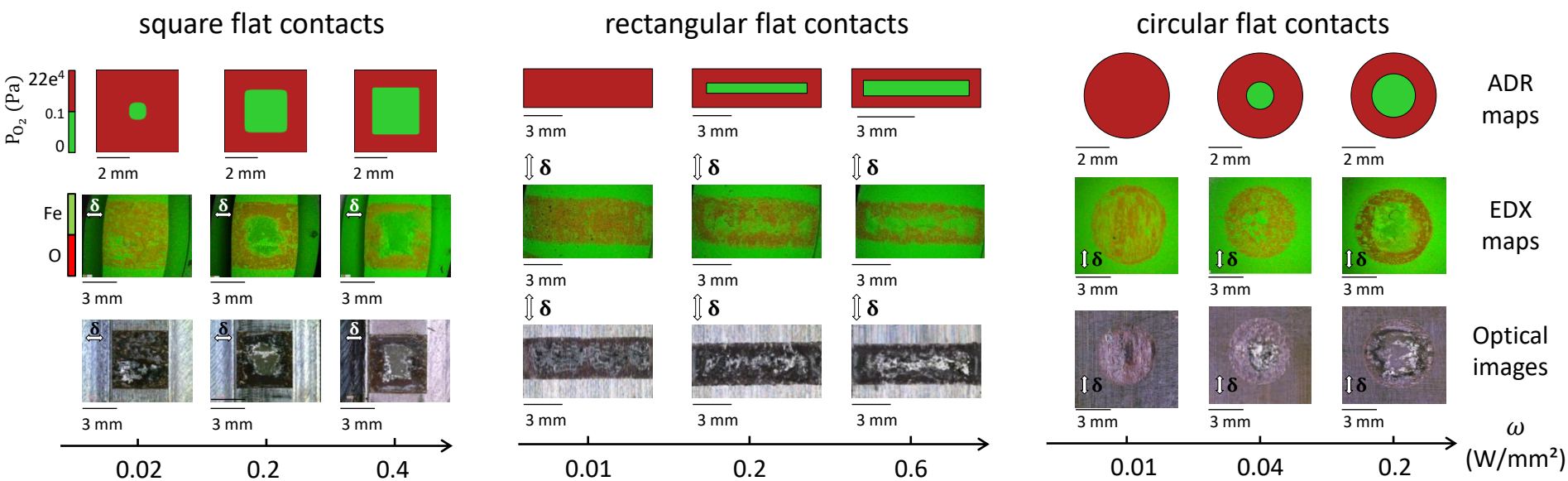
Effect of contact size





- Decrease in P_{O_2} below $P_{O_2,th}$ with the increase in area from 10 to 25 mm²
- Very good prediction of d_O with ADR model

Application of ADR on other contact configurations



ADR analytical solutions

$$P_{O_2}(x) = A \times \exp(-\eta x) + B \times \exp(\eta x)$$

"A" and "B" are constants

$$\eta = \sqrt{\frac{r_{O_2}}{D_{diffusion,O_2}}}$$

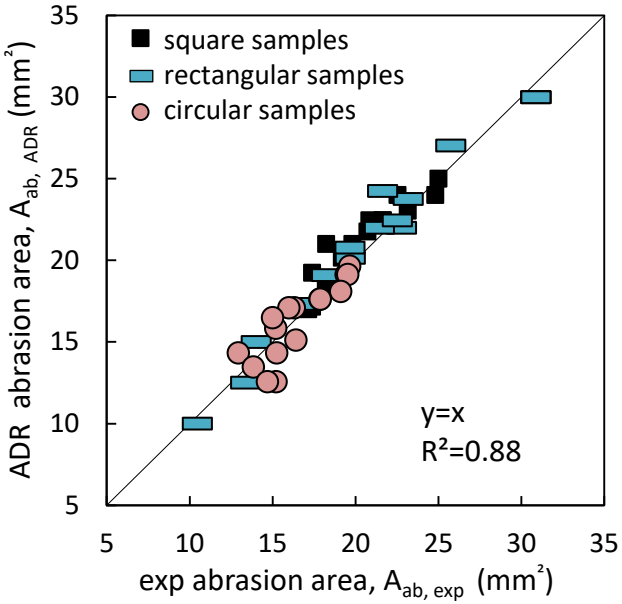
square and rectangular contacts

$$P_{O_2}(r) = \frac{I_0(\eta r)}{I_0(\eta R)} \times P_{O_2}(R)$$

$$I_0(\eta r) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left(\frac{1}{2}\eta r\right)^{2n} \qquad \eta = \sqrt{\frac{r_{O_2}}{D_{diffusion,O_2}}}$$

circular flat contacts

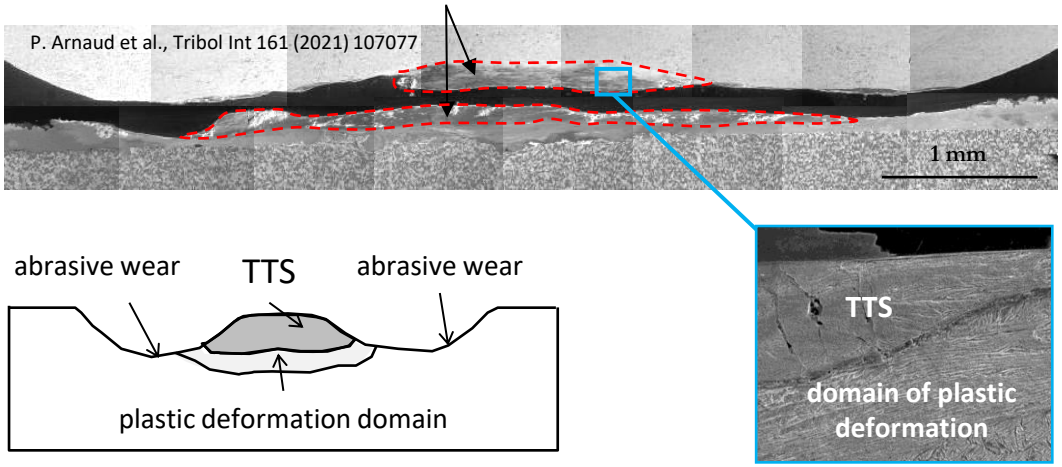
Application of ADR on other contact configurations



Good prediction of abrasion and adhesion zones

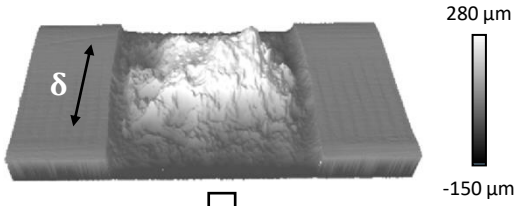
Tribologically transformed structure (TTS)

SEM Observations



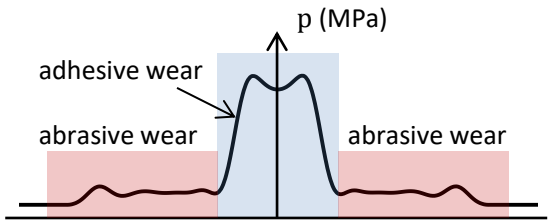
Wear modelling?

abrasive-adhesive wear profile



Wear modelling

Multiphysics wear modelling including third body and contact oxygenation concepts



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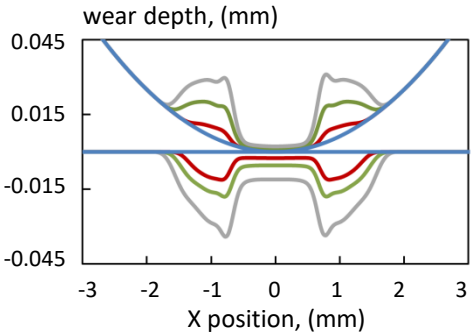
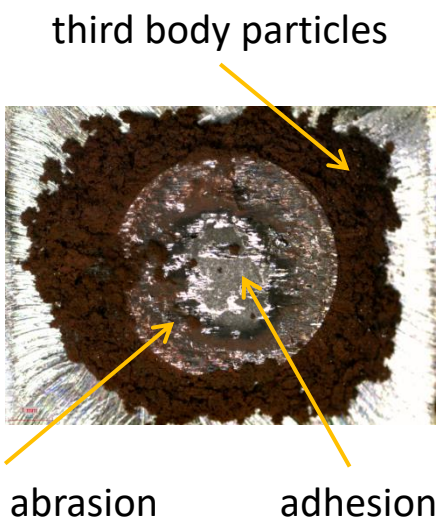


WTO modelling

- Modelling **W**ear evolution (friction energy approach)
- Modelling **T**hird body evolution (Third body approach - TBA)
- Model contact **O**xygenation (COC ADR)



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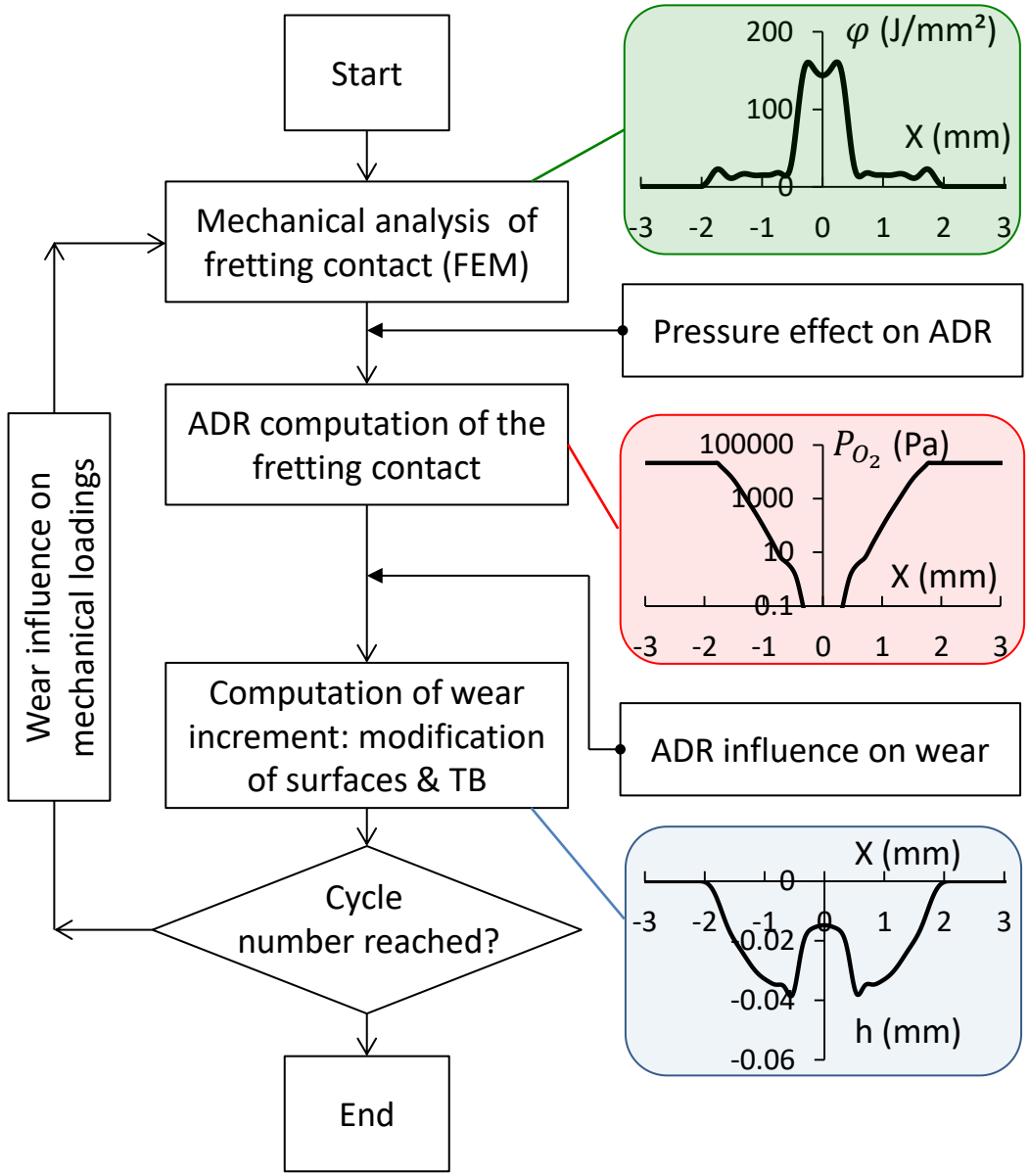
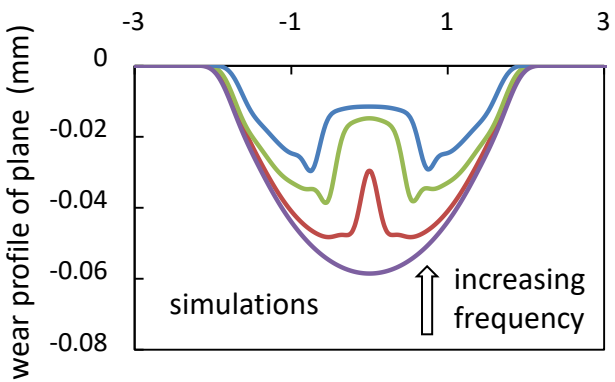


Comparison with experiments

- Detection of pure abrasive wear at low sliding frequency
- Detection of mixed abrasive-adhesive wear at high frequency



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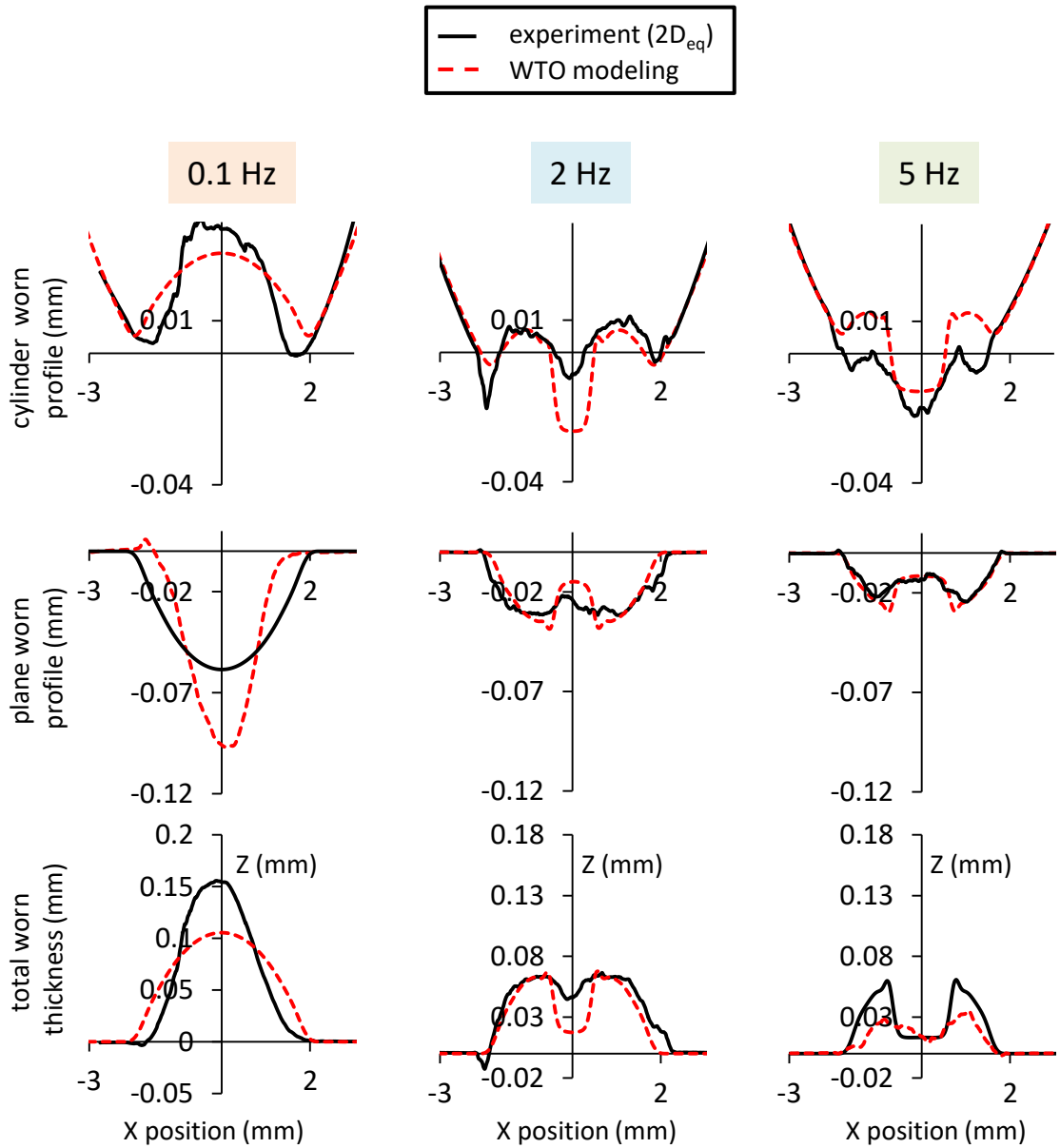


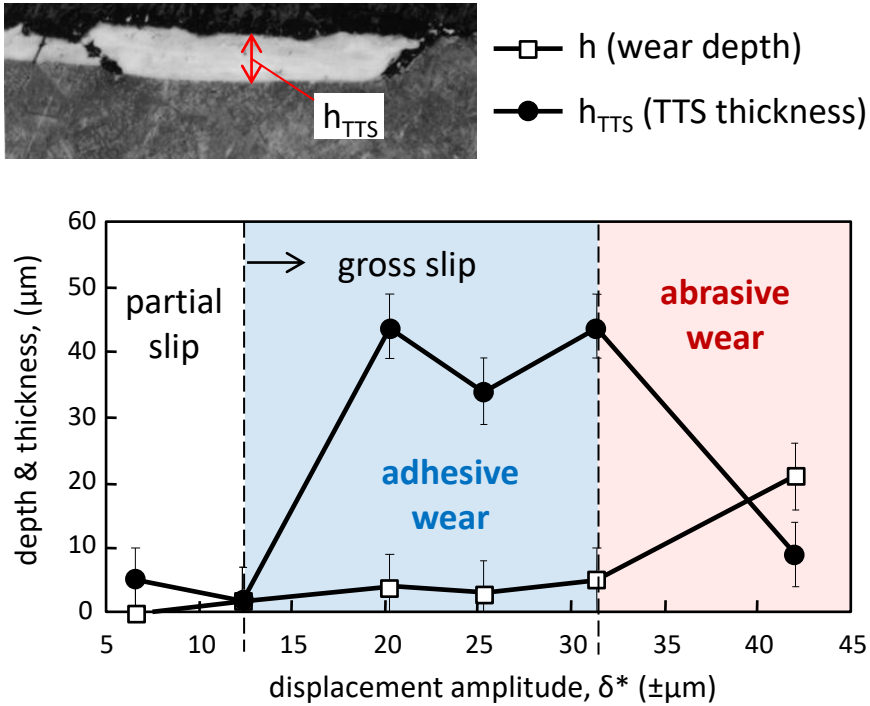
WTO model and TTS activation

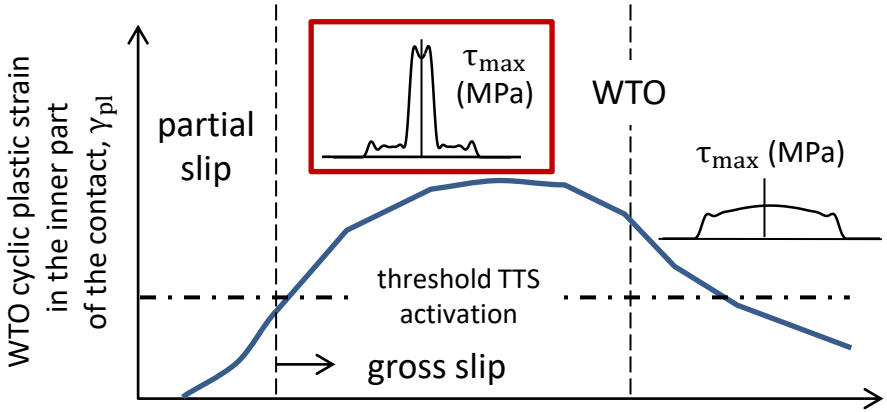
In mixed adhesive-abrasive wear

- Discontinuous wear rate
- Discontinuous surface geometry

overpressure at the contact center

Activation of plastic deformations & tribologically transformed structures (TTS)





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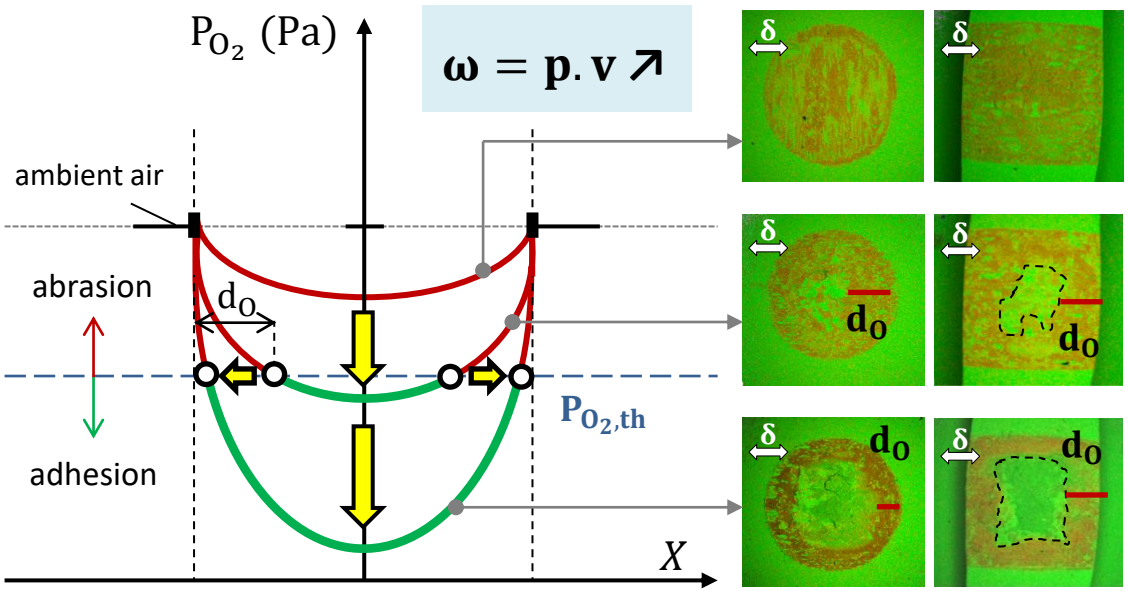
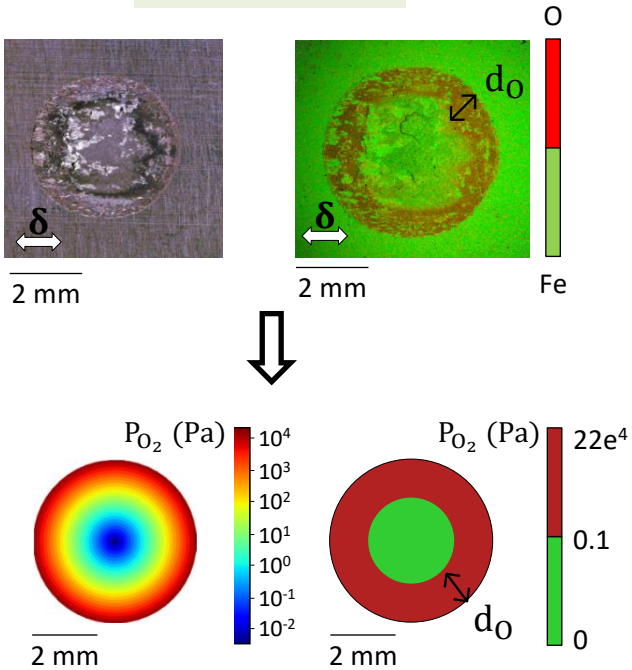
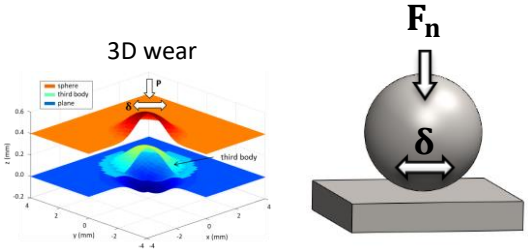
Conclusion



ADR Model

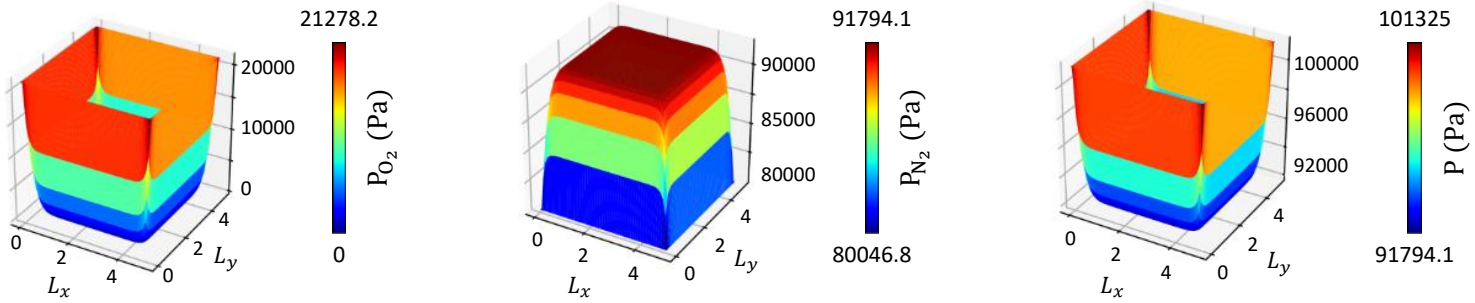


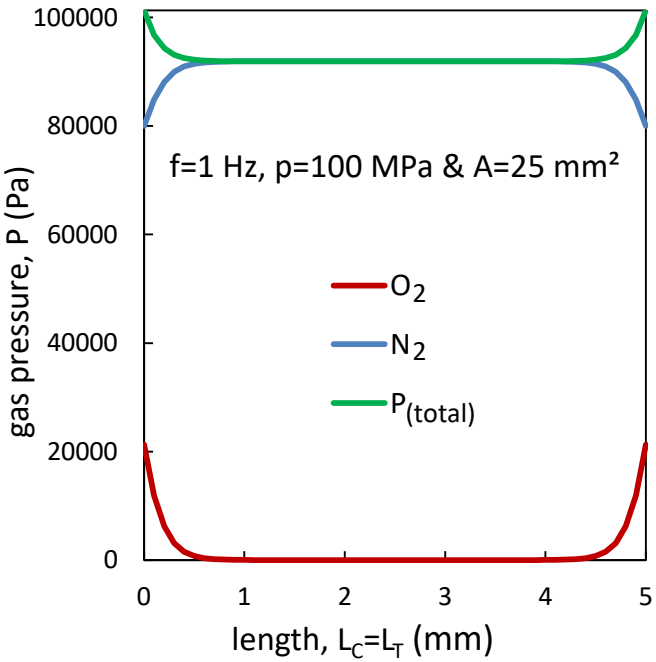
Perspectives



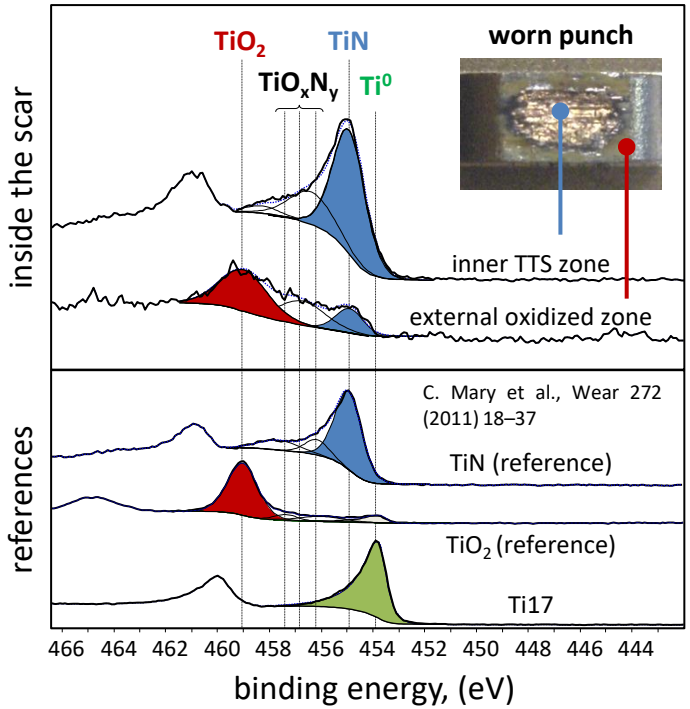
- Extension of ADR model to Hertzian sphere-on-flat contacts
- Coupling of wear damage and adhesive wear prediction in Hertzian contacts

Nitriding + Testing different materials (Ti, Cu, Fe, Al)





Nitriding of the inner TTS



Thank you for your attention