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

- **Abrasive wear**
  - Hard material
  - Soft material
  - $\delta$ (10 µm)

- **Adhesive wear**
  - Hard particle
  - Soft material
  - $\delta$

- **Corrosive wear**
  - Oxides
  - Material 1
  - Material 2

Debris particles

$F_n$ (N)

$\delta$ (± µm)

Collapse of Silver Bridge (1967)

Amsterdam plane crash (1992)

- Collapse of Silver Bridge (1967)
- Amsterdam plane crash (1992)
Fretting wear of flat-on-flat steel (34NiCrMo16) alloy

Optical observation

EDX map (Fe, O)
Contact oxygenation concept

Abrasive wear, $P_{O_2} \geq P_{O_2,\text{th}}$

Adhesive wear, $P_{O_2} < P_{O_2,\text{th}}$

Abrasive wear, $P_{O_2} \geq P_{O_2,\text{th}}$

$d_0$

$F_n (N)$

$\delta_g (\pm \mu m)$

asperities

debris ejection

Porous debris bed

Di-oxygen molecule ($O_2$)

Oxidation of metal surface exposed by the friction work

Adhesive interactions between metal surfaces

Continuous oxide layer

Exposed metal surface
Contact configuration

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

<table>
<thead>
<tr>
<th>Material</th>
<th>H (HV)</th>
<th>E (GPa)</th>
<th>( \nu )</th>
<th>( \sigma_{y,0.2%} ) (MPa)</th>
<th>( \sigma_u ) (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-alloyed steel</td>
<td>400</td>
<td>205</td>
<td>0.3</td>
<td>950</td>
<td>1130</td>
</tr>
</tbody>
</table>

Tribometer

- Contact geometry: crossed flat-on-flat
- Contact area: \( A = L_C \times L_T \)
- Experimental set-up

Martensite structure
Crossed-experimental strategy

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

\[ N = 20,000 \text{ cycles} \]
\[ f = 1 \text{ Hz} \]
\[ A = 5 \times 5 = 25 \text{ mm}^2 \]
\[ \delta_g = 100 \mu\text{m} \]
\[ p = 100 \text{ MPa} \]
\[ F_n = 2500 \text{ N} \]
Estimation of “Oxygen distance”

Method

Crossed oxygen EDX line scans

Calculation of oxygen distance

\[ d_{O,X} = \frac{1}{2} \cdot (d_{O,X_1} + d_{O,X_2}) \]

\[ d_{O,Y} = \frac{1}{2} \cdot (d_{O,Y_1} + d_{O,Y_2}) \]

\[ \Rightarrow d_O = \frac{1}{2} \cdot (d_{O,X} + d_{O,Y}) \]

Adhesion and abrasion areas

\[ A_{ad} = d_{ad,X} \cdot d_{ad,Y} \]

\[ A_{ab} = A - A_{ad} \]
Effect of sliding frequency

Abrasion % $A_{ab}$

optical images

EDX maps

line scans

$\delta$

Fe

O

$d_O$ = $K_f \times d_{O,ref} \times \left( \frac{f}{f_{ref}} \right)^{n_f}$

$d_{O,ref} = 1.51 \text{ mm}$

$n_f = -0.22$

$K_f = 1.12$

$R^2 = 0.86$

$\rightarrow$ frequency $\Rightarrow$ $\rightarrow$ reaction of fresh Fe with $O_2 \Rightarrow$ $O_2$ depletion towards the contact center

$\Rightarrow$ adhesion $\rightarrow$ $\Rightarrow$ $d_O \downarrow$
Effect of contact pressure

\[ d_0 = K_p \times d_{0,\text{ref}} \times \left( \frac{p}{p_{\text{ref}}} \right)^{n_p} \]

- \( d_{0,\text{ref}} = 1.51 \text{ mm} \)
- \( n_p = -0.32 \)
- \( K_p = 1.02 \)
- \( R^2 = 0.89 \)

\[ \delta \text{ Fe} \delta \text{ O} \]

↑ pressure ⇒ ↑ reaction of fresh Fe with O\(_2\) ⇒ O\(_2\) depletion towards the contact center

⇒ adhesion ↑ ⇒ \( d_0 \) ↓
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 $O_2$ ⇒ $d_O = \text{constant}$
- Sliding amplitude ⇒ Counterbalancing effect of third body ejection process

$$d_O = K_\delta \times d_{O,\text{ref}} \pm 0.09$$
$$K_\delta = 1.04$$

$$d_O = K_N \times d_{O,\text{ref}} \pm 0.10$$
$$K_N = 0.94$$
Effect of contact size

Effect of contact length $L_C$

- Optical images
- EDX maps

Effect of contact length $L_T$

- Optical images
- EDX maps

% Abrasion $\downarrow$

$A \uparrow$

$\% A_{ab} = -0.01 \times A + 1.07$

$R^2 = 0.59$

$d_O = K_A \times d_{O,ref} \pm 0.10$

$K_A = 0.91$
Oxygen distance prediction model

**Parametric “oxygen distance” modeling**

\[
\begin{align*}
  d_{0,\text{pred}} &= d_{0,\text{ref}} \times \left( \frac{f}{f_{\text{ref}}} \right)^{n_f} \times \left( \frac{p}{p_{\text{ref}}} \right)^{n_p} \\
  d &= \min \left( \frac{L_C}{2}, \frac{L_T}{2} \right) > d_0 \\
  A_{\text{ad}} &= L_T \cdot L_C - 2 \cdot d_0 (L_T + L_C) + 4 \cdot d_0^2 \\
  A_{\text{ab}} &= A - A_{\text{ad}}
\end{align*}
\]

- \( d_{0,\text{ref}} = 1.51 \text{ mm} \)
- \( f_{\text{ref}} = 1 \text{ Hz} \)
- \( p_{\text{ref}} = 100 \text{ MPa} \)
- \( n_f = -0.22 \)
- \( n_p = -0.32 \)
Advection-Dispersion-Reaction ADR approach

ADR Model

**Advection**

\[ J_{a,i} = v P_i \]

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

Darcy's law:

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

Carman-Kozeny model:

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

**Dispersion**

Fick's law:

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

\[ D_i = D_{\text{mech.mixing}} + D_{\text{dif},i} \]

\[ D_{\text{dif},i} = \tau \cdot D_{\text{im}} \]

\[ D_{\text{mech.mixing}} = \alpha_L |v| \]

**Reaction**

No nitriding reaction:

\[ R_{N_2} = 0 \]

Oxidation reaction:

\[ R_{O_2} = -r_{O_2} \cdot P_{O_2} \]

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

\( \omega = p \cdot v = 4 \cdot p \cdot \delta_g \cdot f \)

**ADR continuity equation:**

\[ \alpha \frac{dP_i}{dt} = -\nabla \cdot (J_{a,i} + J_{d,i}) + R_i = -\nabla \cdot (D_i \nabla P_i + v P_i) + R_i \]
Model calibration

ADR modelling $P_{O_2}$ (Pa)

Wear modelling

EDX of a steel fretting scar

Atmospheric pressure, (Pa)
adhesion oxidation

Advection-Dispersion-Reaction ADR approach
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 $d_0$ 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 $d_0$ with ADR model

\[
d_0 = 5.34 \times p^{-0.24}
\]

$R^2 = 0.97$
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 $d_0$ 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

\[ \eta = \sqrt{\frac{r_{O_2}}{D_{\text{diffusion},O_2}}} \]

square and rectangular contacts

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

\[ I_0(\eta r) = \sum_{n=0}^{\infty} \frac{1}{(n!)^2} \left(\frac{1}{2} \eta r\right)^{2n} \]

\[ \eta = \sqrt{\frac{r_{O_2}}{D_{\text{diffusion},O_2}}} \]

circular flat contacts

square flat contacts

rectangular flat contacts

circular flat contacts

ADR maps

EDX maps

Optical images

\[ \omega \] (W/mm²)
Application of ADR on other contact configurations

Good prediction of abrasion and adhesion zones

Multiphysics wear modelling including third body and contact oxygenation concepts

Tribologically transformed structure (TTS)

SEM Observations

Wear modelling?

Application of ADR on other contact configurations
WTO modelling

- Modelling Wear evolution (friction energy approach)
- Modelling Third body evolution (Third body approach - TBA)
- Model contact Oxygenation (COC ADR)

third body particles

abrasion adhesion

P. Arnaud et al., Tribol Int 161 (2021) 107077
Comparison with experiments

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

**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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P. Arnaud et al., Tribol Int 161 (2021) 107077
Conclusion and perspectives

Conclusion

Perspectives

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

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

Nitriding of the inner TTS

f=1 Hz, p=100 MPa & A=25 mm²

gas pressure, P (Pa)

length, L_c=L_T (mm)

binding energy, (eV)

references

C. Mary et al., Wear 272 (2011) 18–37

TiN (reference)

TiO_2 (reference)

TiO_2_N_y

Ti^0

inner TTS zone

external oxidized zone

worn punch
Thank you for your attention