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Wear and subsurface damage in fretting: the key role of debris formation and transport

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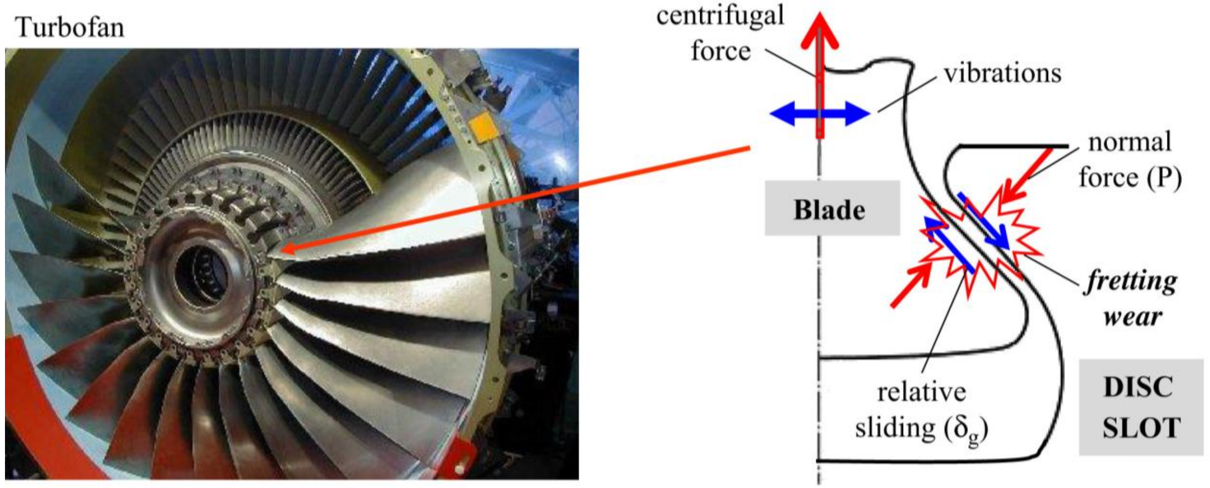
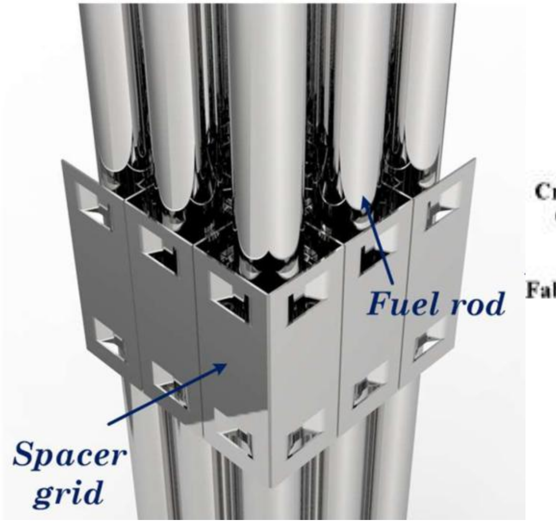
Fretting

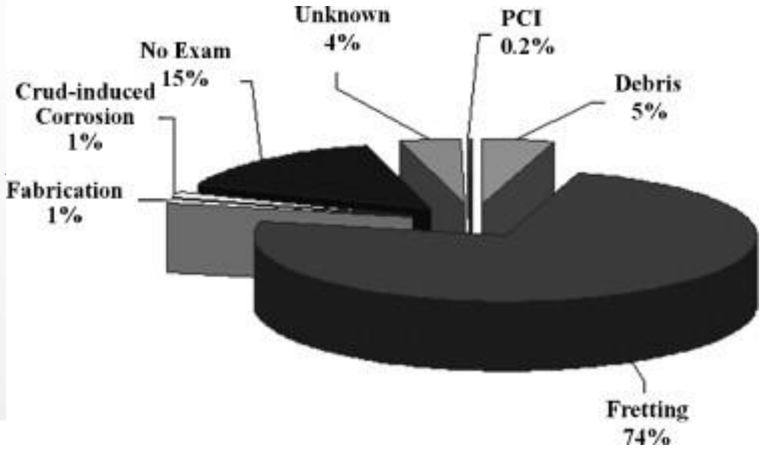
- Small amplitude motion in mechanical contacts



S. Fouvry, C. Paulin (2014) https://doi.org/10.1016/j.wear.2014.07.009



Huang, T. Liu, P. Li, Y.R. Yang (2024) https://doi.org/10.1016/j.net.2023.11.045

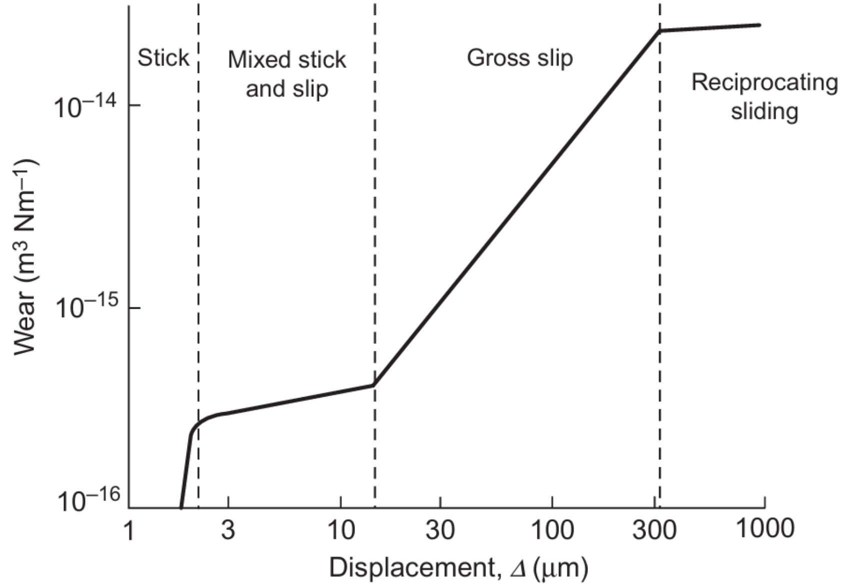


Kyu-Tae Kim (2009) https://doi.org/10.1016/j.nucengdes.2009.08.018

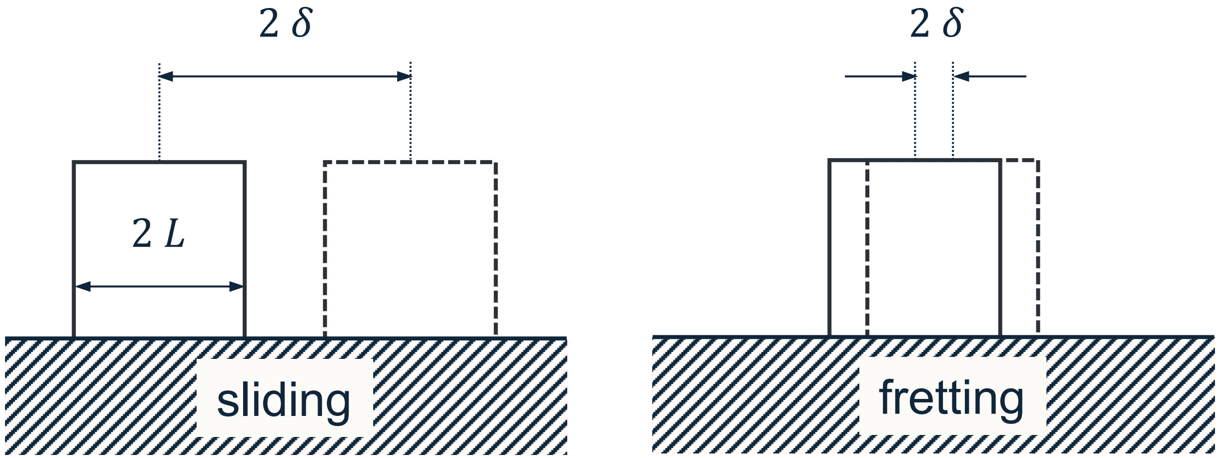
Errichello, R and Muller, J (2012) https://doi.org/10.2172/1036039

Sliding and fretting conditions

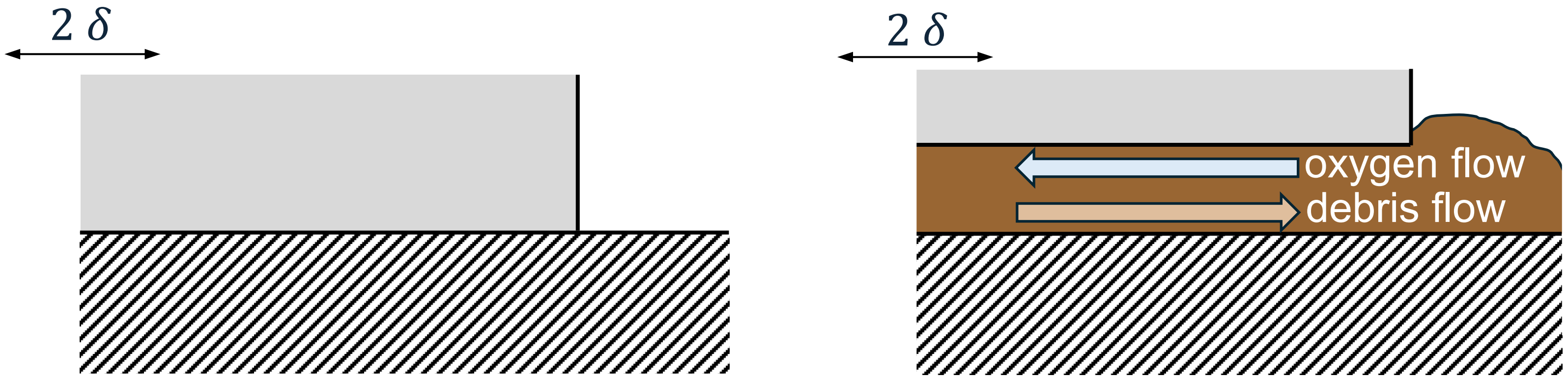
- Fretting and reciprocating sliding look very similar – with fretting having a smaller amplitude, often taken as < 300 μm after the work of Vingsbo and Söderberg (1988). https://doi.org/10.1016/0043-1648(88)90134-2



- A key feature of a fretting contact is that it remains closed throughout the cycle ($\delta < L$) and often ($\delta \ll L$).
- When the contact is closed, transport of species needs to be considered.

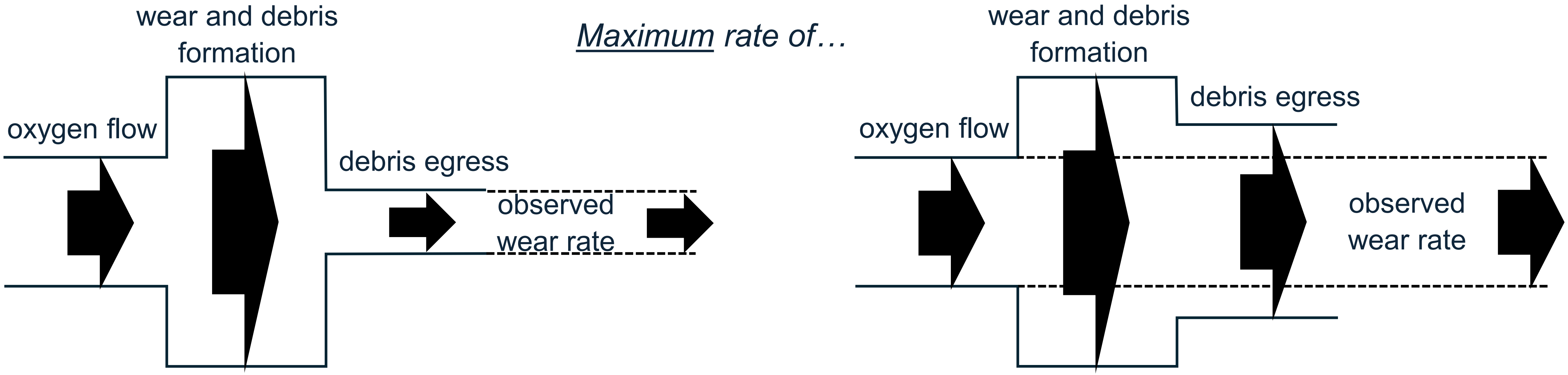


Key processes in fretting of non-noble metals

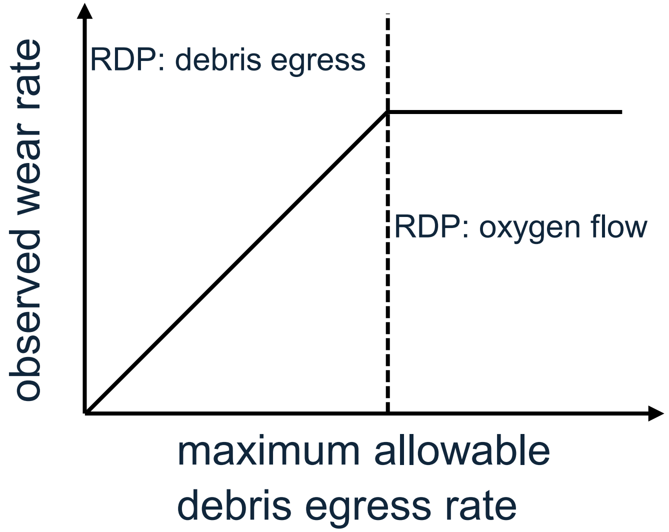


- Key processes are oxide debris formation in the contact (which requires a supply of oxygen) and expulsion of that debris from the contact to allow wear to proceed
- Oxide bed thicknesses starts at zero but reaches an equilibrium thickness under a given set of conditions – often quite thin (< 5 μm)
- From the 1980s, Godet and Berthier and their co-workers argued strongly wear is an equilibrium between debris formation and debris expulsion from the contact

The rate-determining process diagram



- The observed wear rate is the one of the slowest process. The other processes **throttle back** to the same rate (so that the rate of debris formation and egress remain the same – i.e. equilibrium).
- In the case shown here, the observed wear rate changes with the debris egress rate until the debris egress rate is no longer rate-determining.



Fouvry, Liskiewicz et al. (2003) https://doi.org/10.1016/S0043-1648(03)00117-0

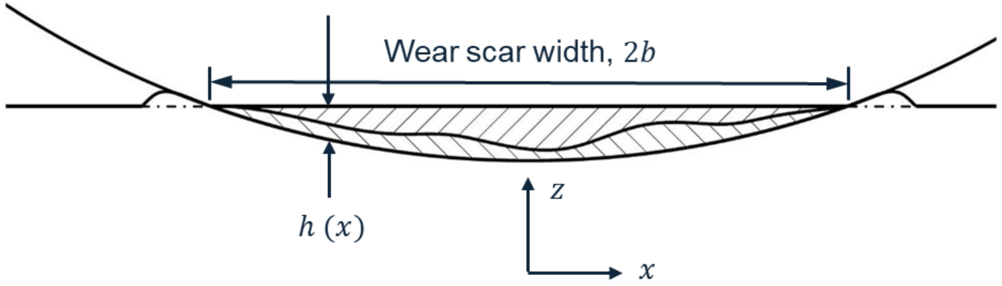
An unexplained size effect

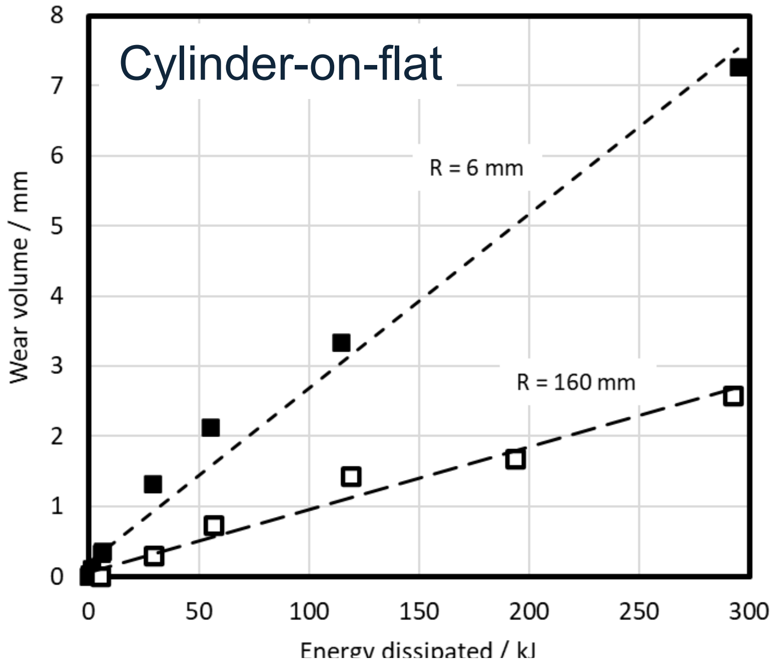
- In recent years, most fretting data is presented in a Archard-like manner:

$$V = k\,E$$

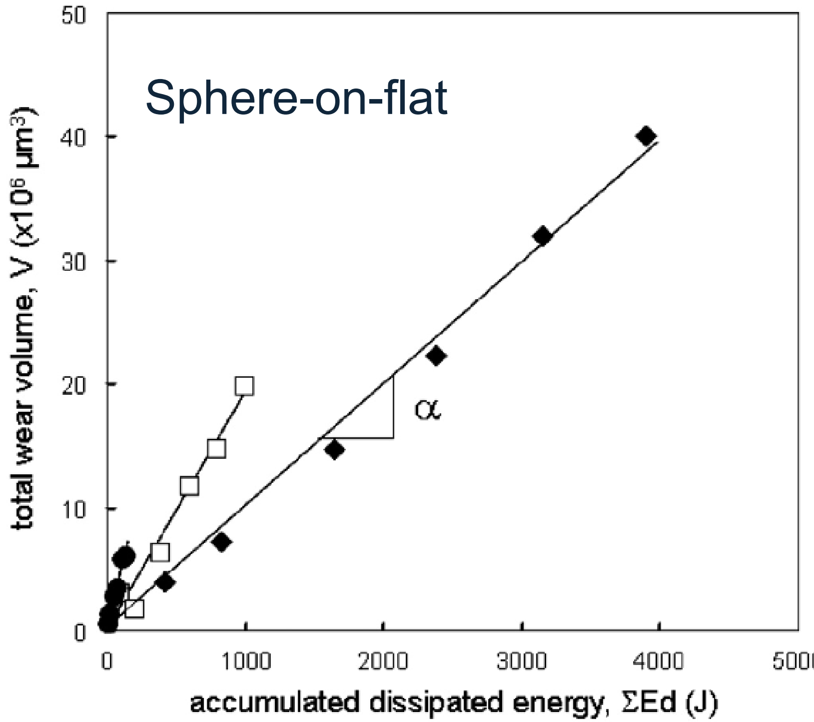
with k as the specific wear rate (typically quoted in $mm^3\ MJ^{-1}$)

- Seems to fit… but there is a dependence on geometry – a "*size effect*"
- It has been argued that this is associated with differences in debris retention, but difficult to deconvolute due to use of non-conforming contact geometries where the contact size grows as wear proceeds





https://doi.org/10.1016/j.wear.2019.203081

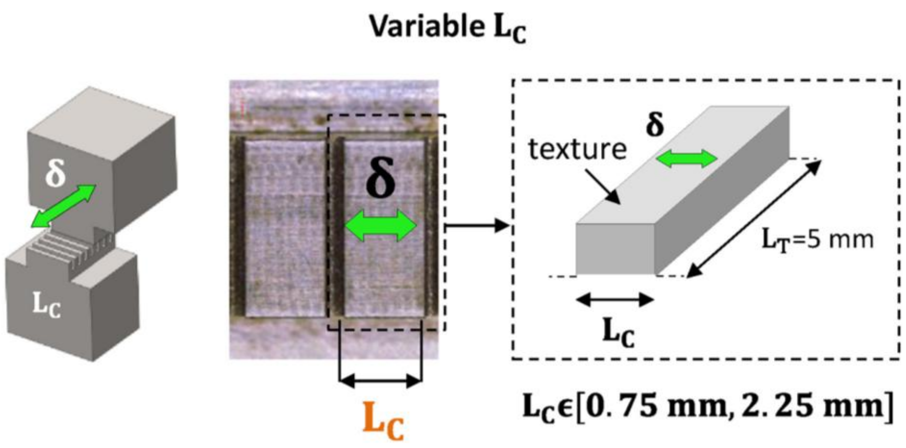


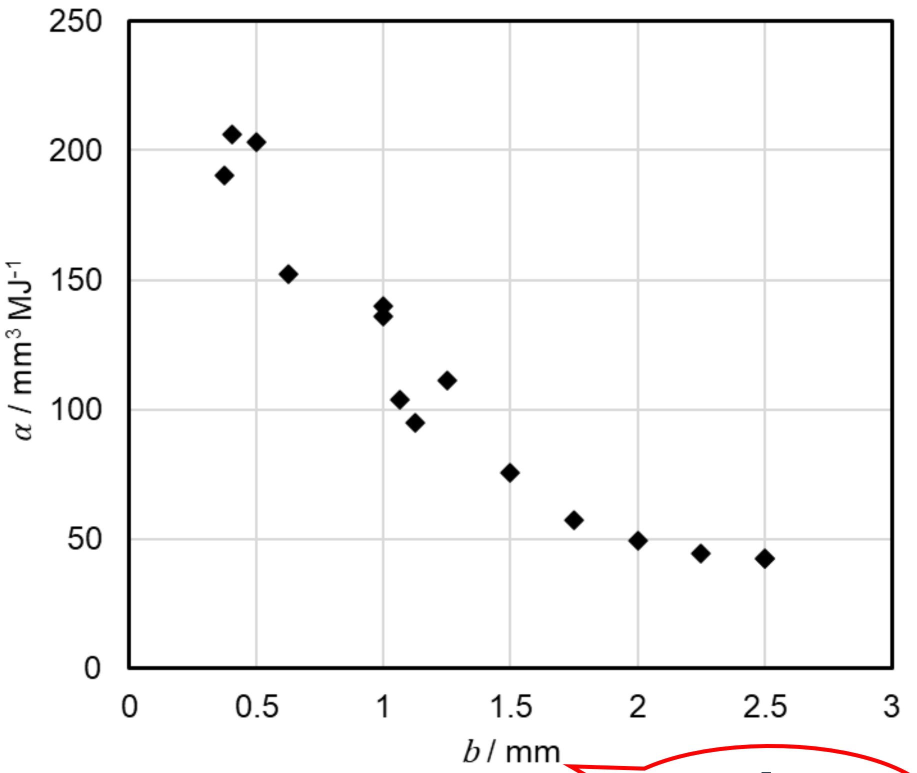
https://doi.org/10.1016/j.wear.2013.01.072

Clarity in the size effect

- In early 2022, Baydoun, Fouvry and Descartes presented some experimental work on contact size in fretting with conforming contacts.

https://doi.org/10.1016/j.wear.2021.204168



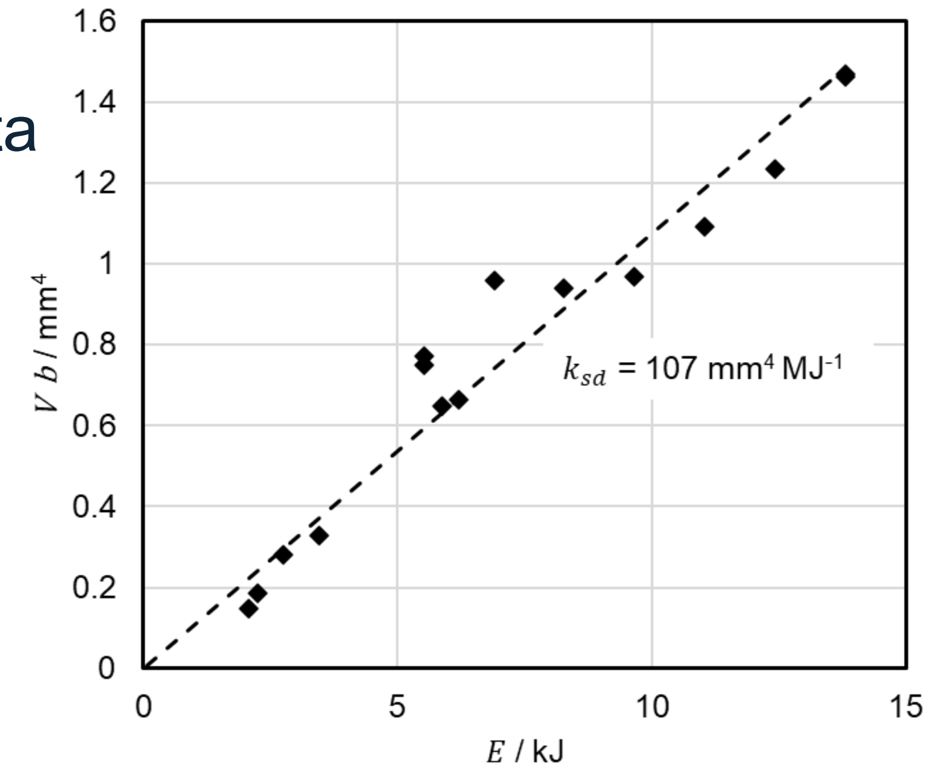


$$b = {}^{L_c}/_2$$

Replot these data

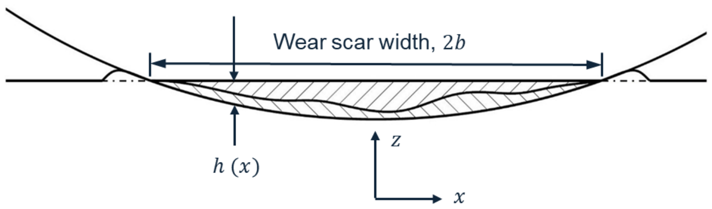
$$\frac{dV}{dE} = \frac{k_{sd}}{b}$$

$$V\,b = k_{sd}\,E$$



https://doi.org/10.1016/j.wear.2025.205783

Non-conforming contacts

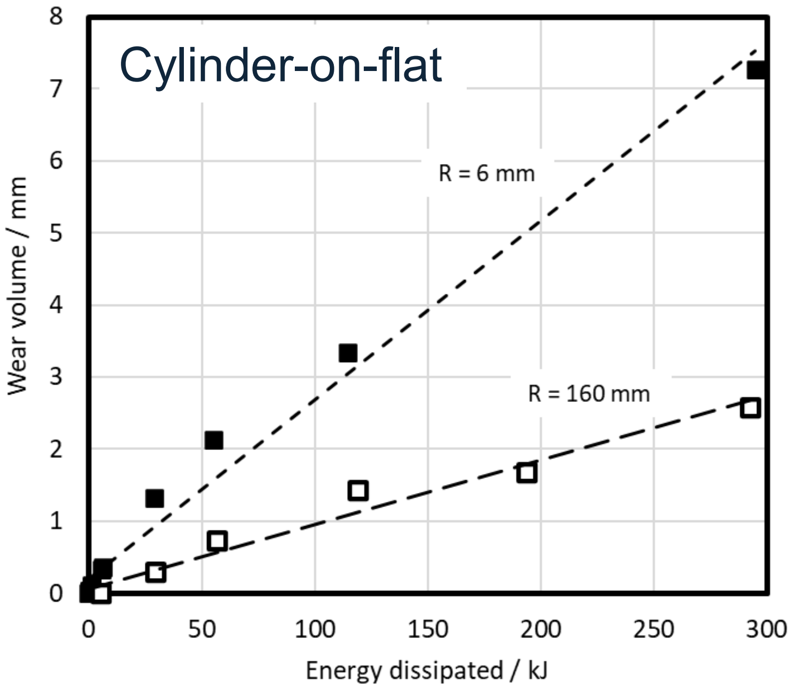


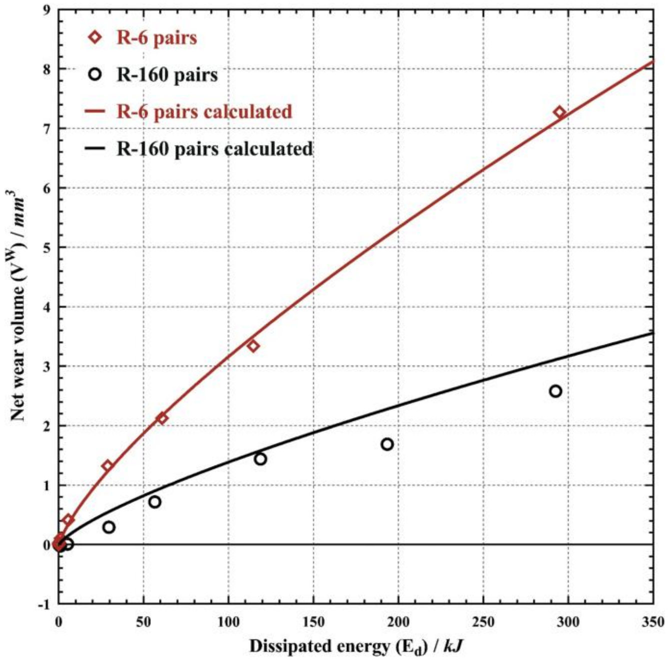
Wear rate $\frac{dV}{dE} = \frac{k}{b}$

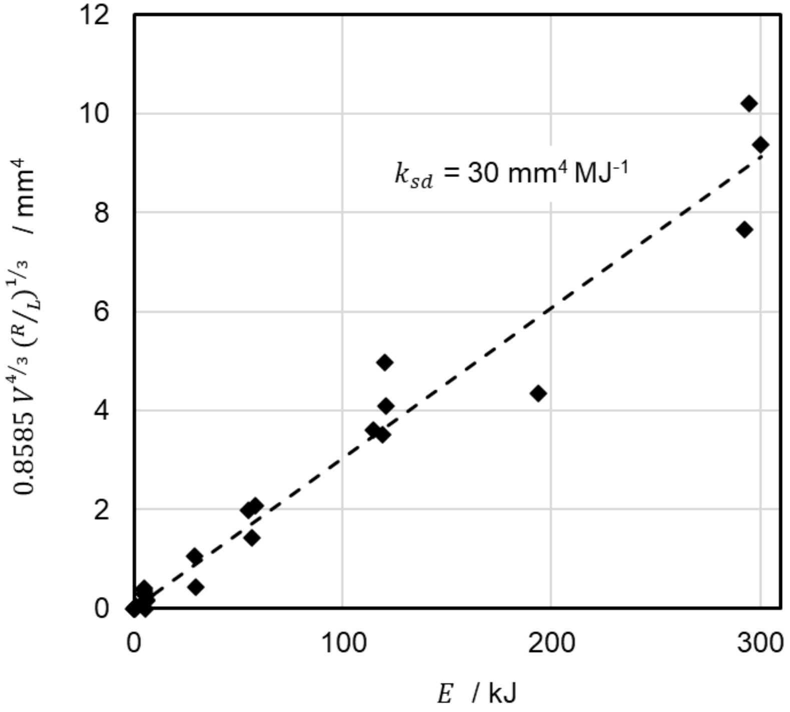
Volume $V \approx \frac{2\,b^3\,L}{3R}$

Eliminate b and integrate

$$V^{4/3} = \frac{2^{7/3}}{3^{4/3}}\left(\frac{L}{R}\right)^{1/3} k_{sd}\,E$$







https://doi.org/10.1016/j.wear.2019.203081

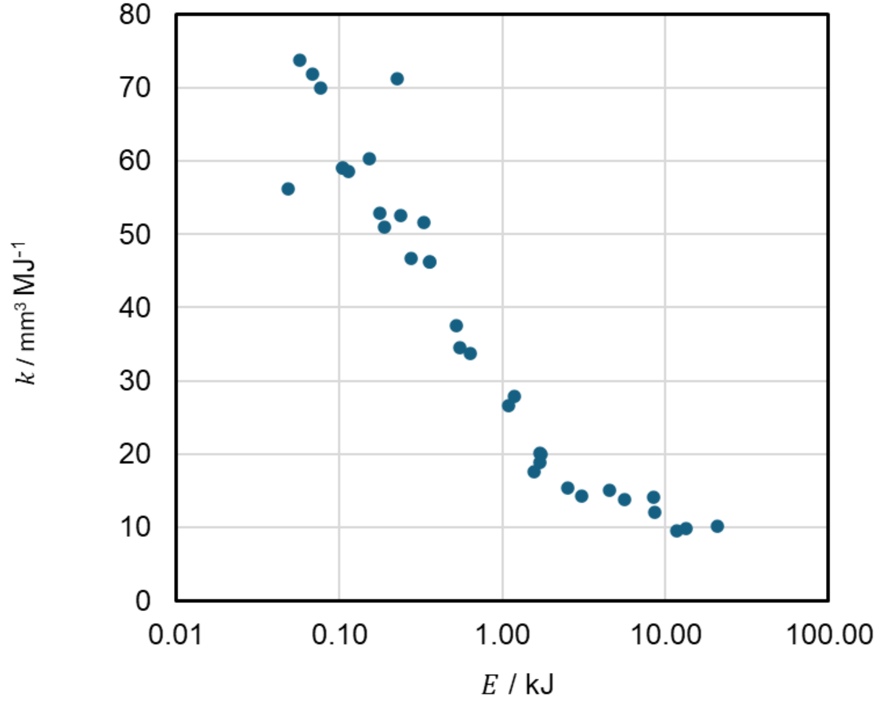
https://doi.org/10.1016/j.wear.2025.205783

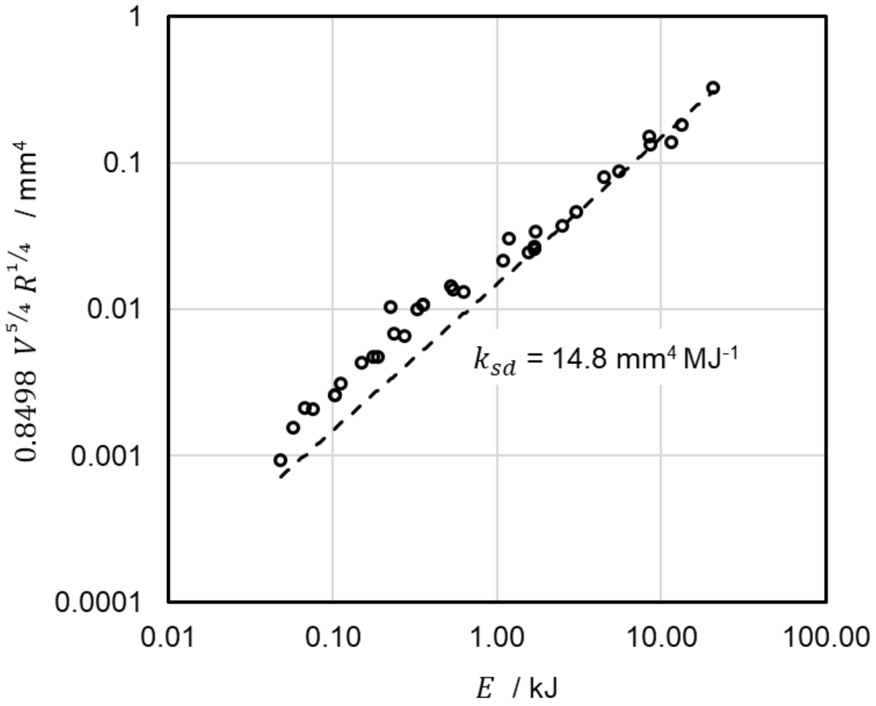
Sphere-on-flat contacts

- For the sphere-on-flat geometry, the equivalent equation is:

$$V^{5/4} = \pi^{1/4} \frac{5}{4^{5/4}} R^{-1/4} \; k_{sd} \, E$$

- Data from Fouvry and Merhej (2013) indicate the merit of the method.





https://doi.org/10.1016/j.wear.2013.01.072

https://doi.org/10.1016/j.wear.2025.205783

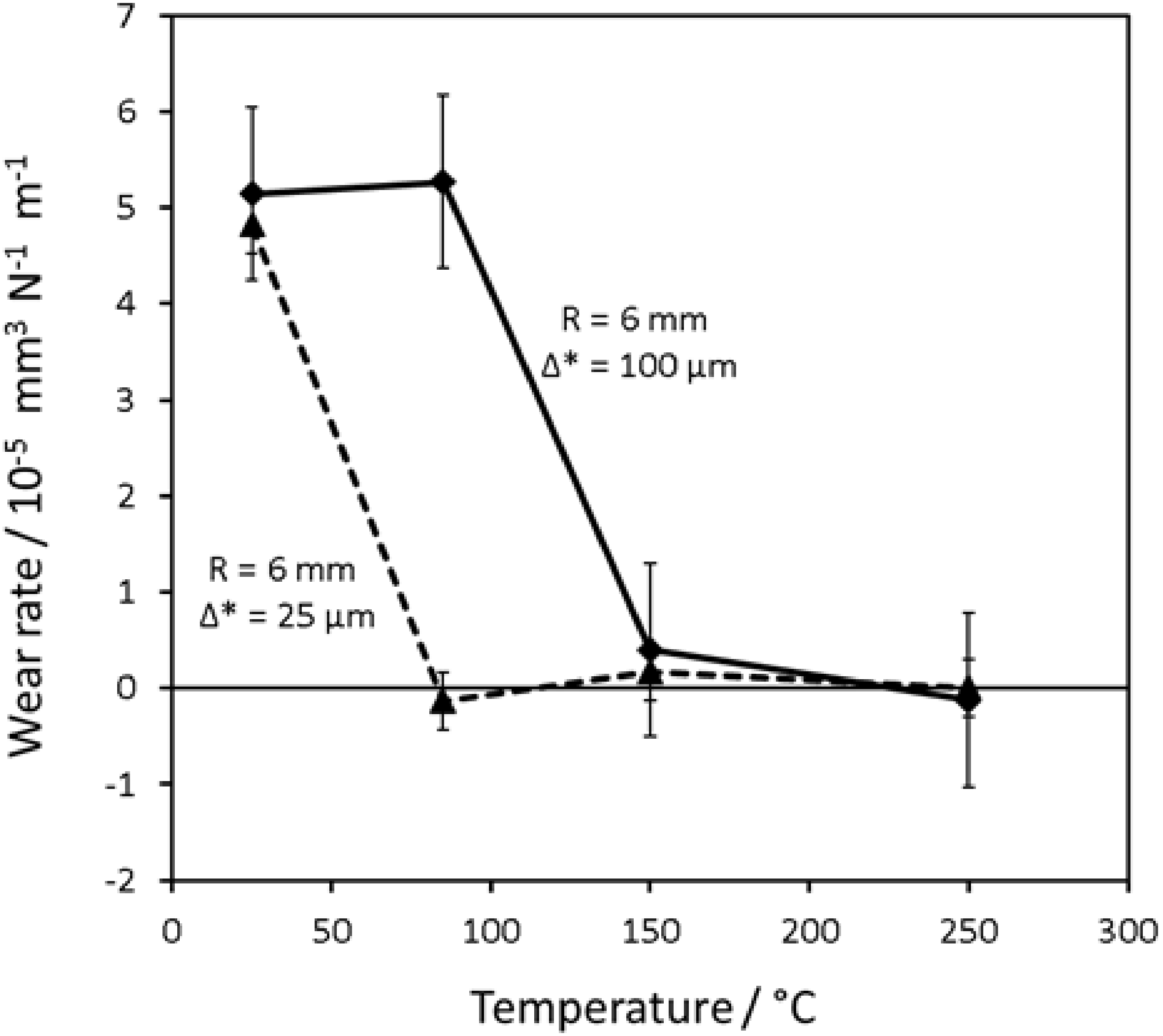
Review…

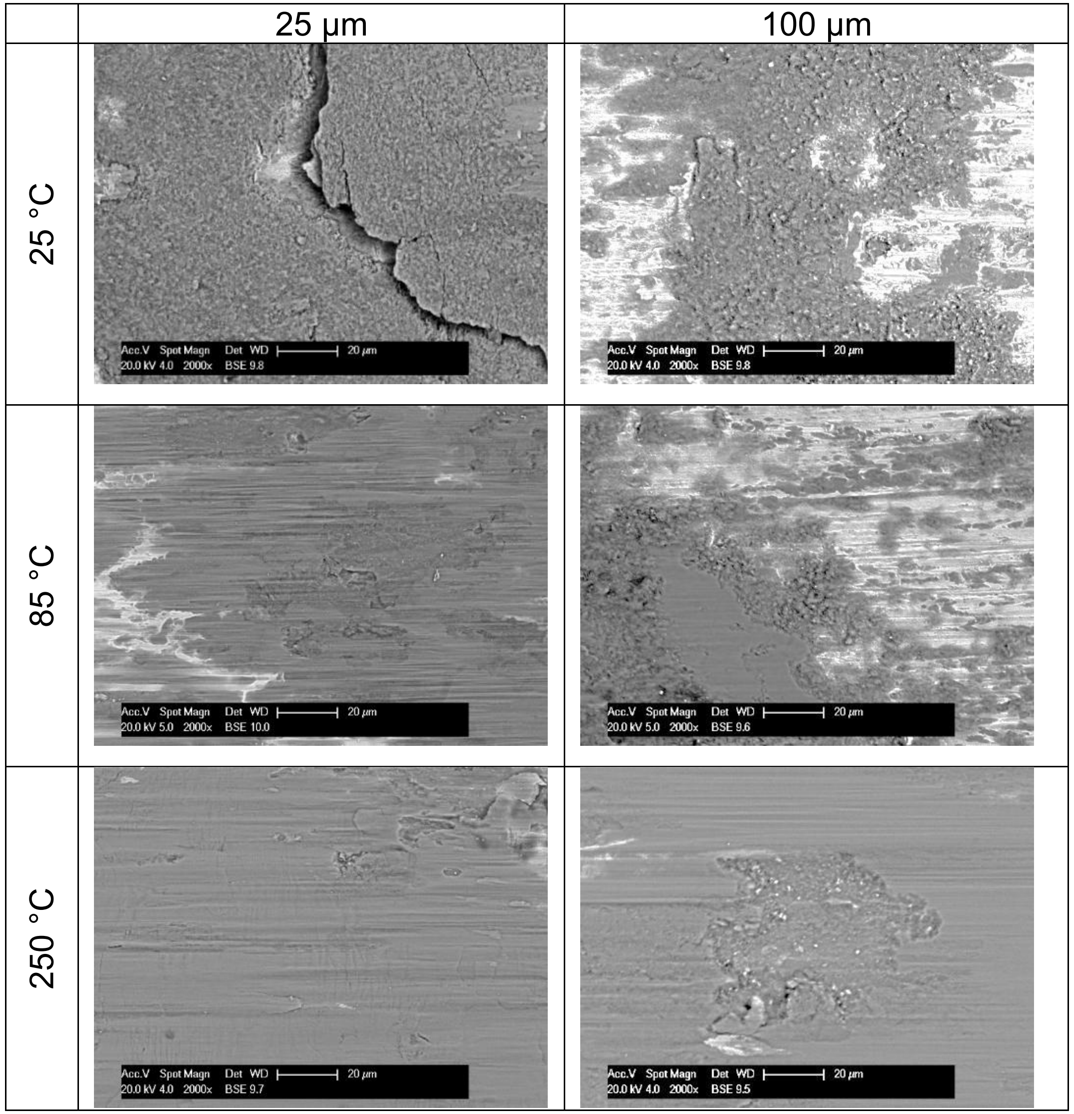
- Fretting wear of non-noble metals requires three processes:
  - oxygen flow into the contact (amount per unit time);
  - mechanical action and the formation of oxide debris across the contact (amount per cycle);
  - debris flow out of the contact (amount per cycle).

- The observed rate will be the rate of the slowest of these (since they all need to operate at the same rate).

- The rates of the transport processes are dependent upon the size of the contact. So…
  - Use of Archard’s equation is not appropriate;
  - Laboratory testing for service applications needs to take into account contact size;
  - Data from non-conforming contacts (where the contact size changes with exposure) need special care.

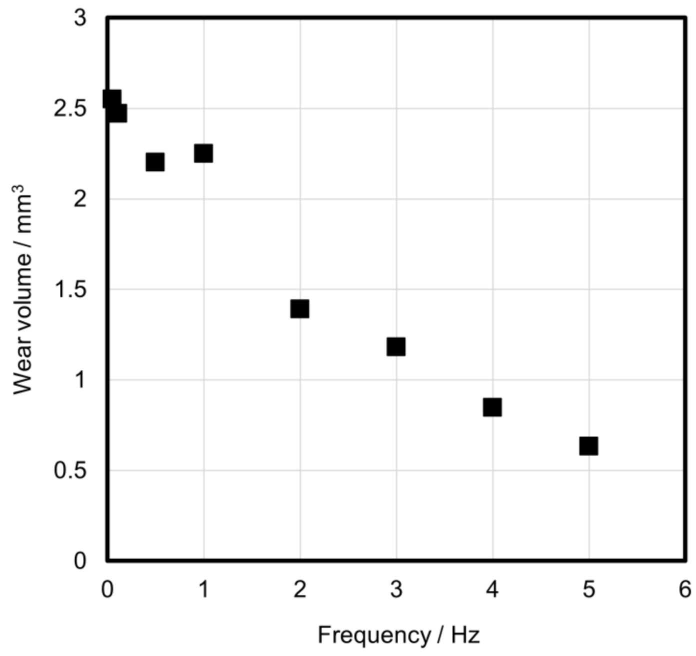
Debris egress – effects of temperature and amplitude

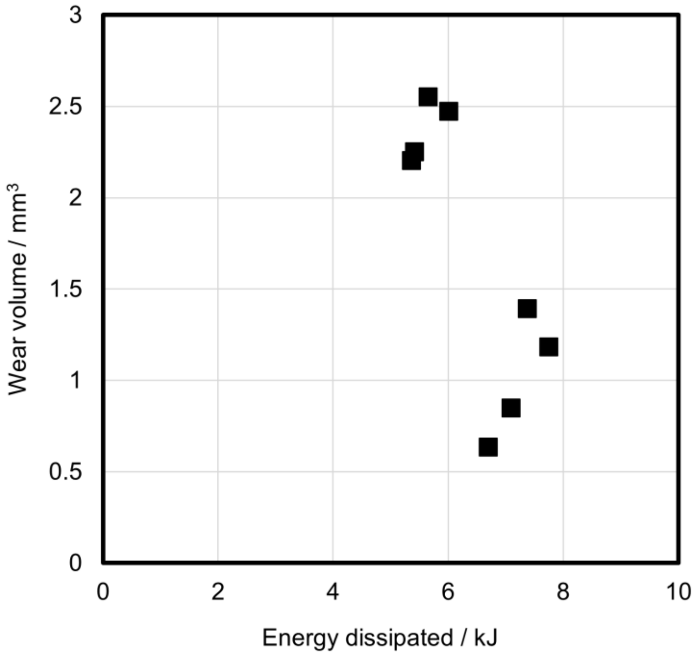


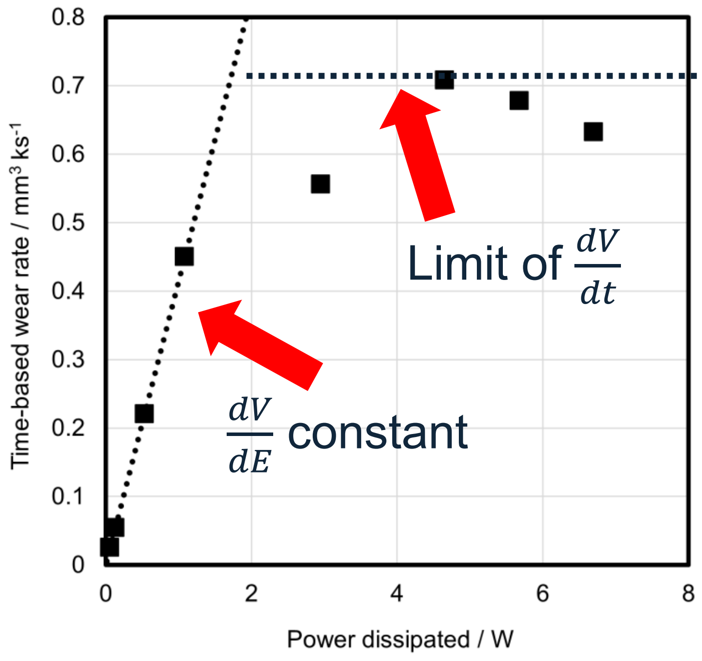


Oxygen supply – the effect of frequency

- Time-based rate of energy dissipation: $\frac{dE}{dt} = 4\,\delta\,\mu\ N\,f$
- If $\frac{dV}{dE}$ is constant, then $\frac{dV}{dt} = C\ \frac{dE}{dt}$
- Oxygen flow rate into the contact to form debris will have a maximum rate (volume per unit *time*) – once exceeded, there will be oxygen starvation.







Data from Fouvry et al. (2017)
https://doi.org/10.1016/j.triboint.2016.12.049

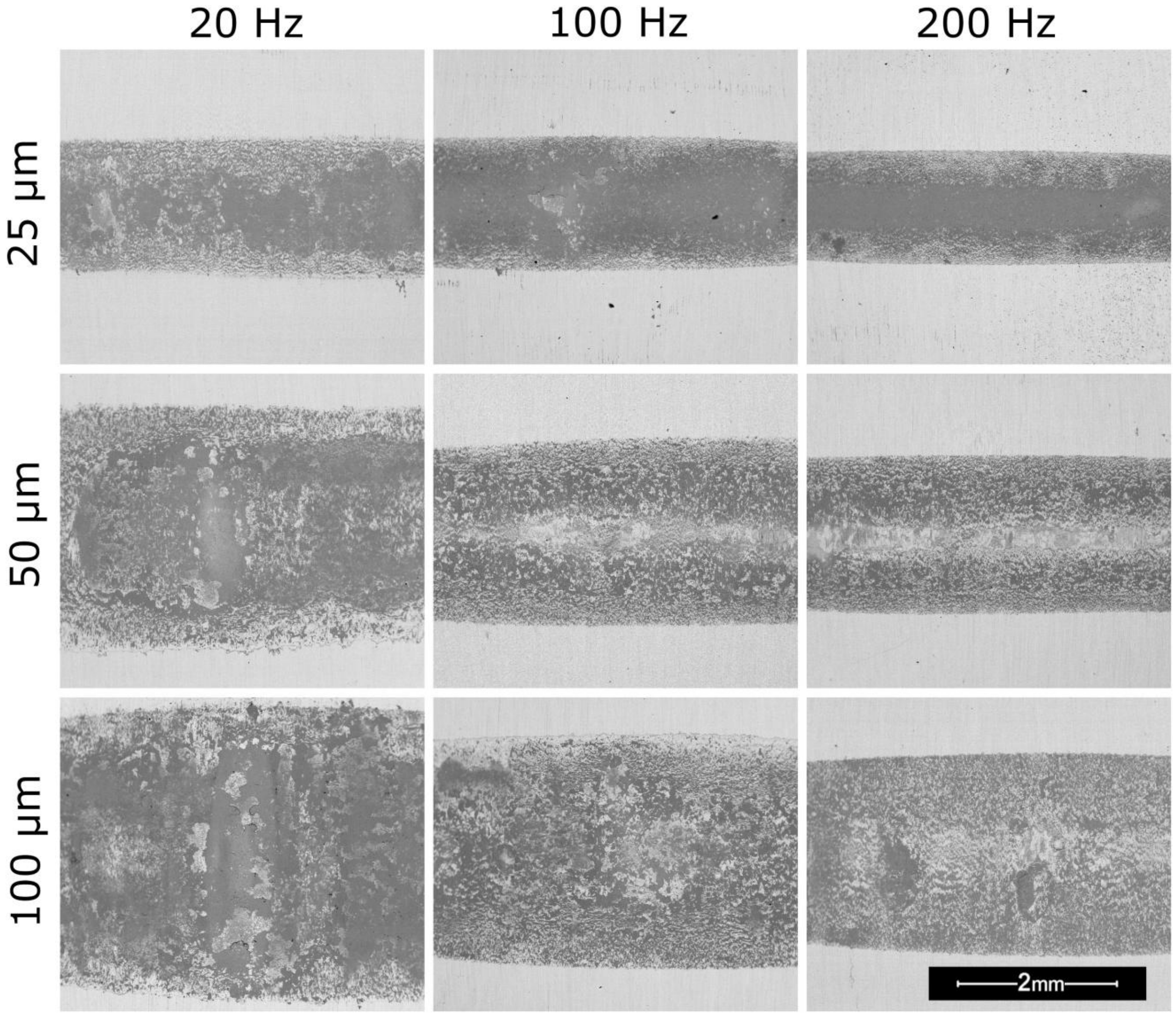
Reprocessed data (Shipway, 2021)
https://doi.org/10.1016/j.wear.2021.203826

Oxygen supply – the effect of frequency

- Rate of energy dissipated

$$\frac{dE}{dt} = 4\,\delta\,\mu\;N\,f$$

- If $\frac{dV}{dE}$ is constant, then $\frac{dV}{dt} \propto \delta \times f$
- Oxygen starvation depends both on frequency and slip amplitude
- This can lead to metal-metal contact and damage if oxygen ingress is the RDP (although frequency and slip amplitude both change debris egress too…)



https://doi.org/10.1016/j.wear.2021.203981

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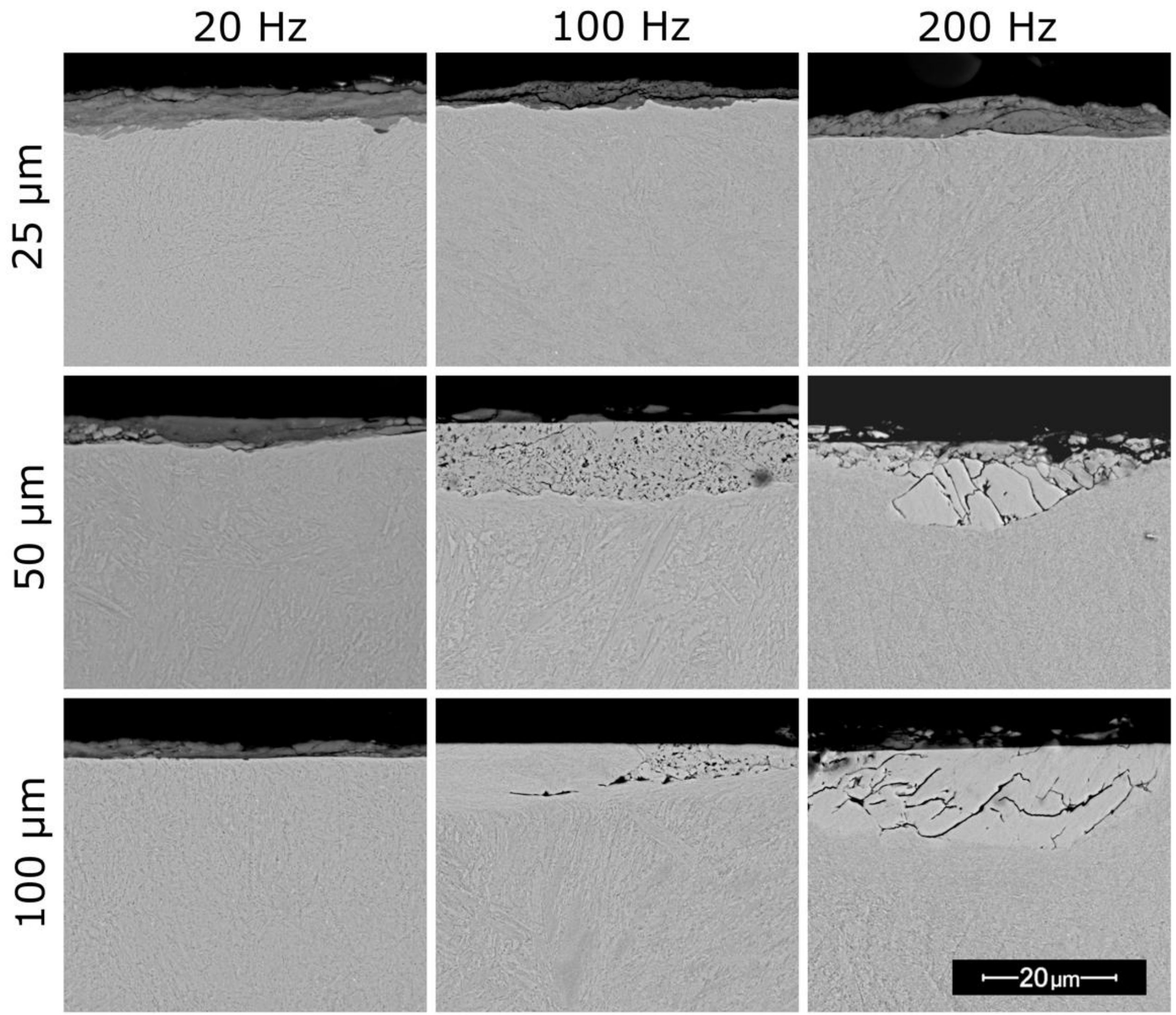
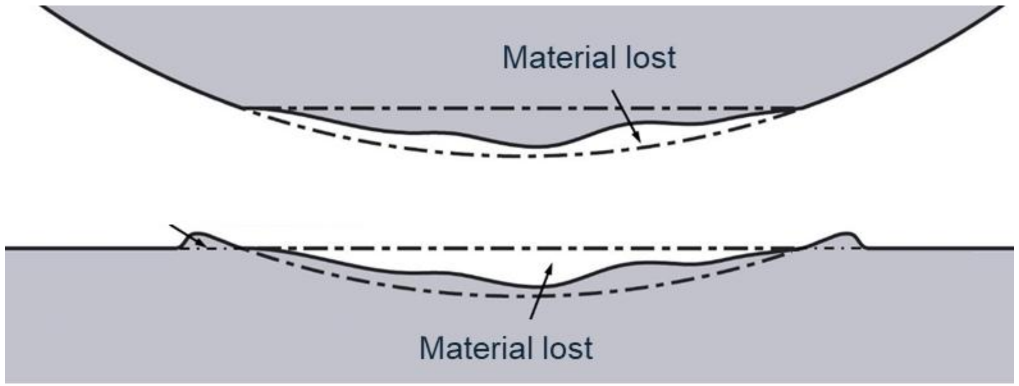


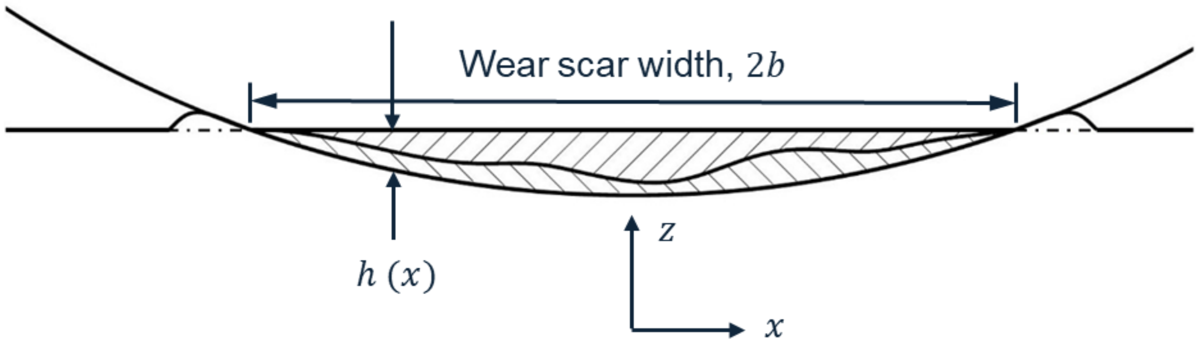
https://doi.org/10.1016/j.wear.2021.203981

Conclusions

- Fretting is different to sliding, with the key RDPs not being debris formation, but instead oxygen flow and debris elimination from the contact
- Archard’s equation derived for sliding wear is not appropriate for fretting and should be replaced by the relationship $\frac{dV}{dE} = \frac{k_{sd}}{b}$
- Data from both conforming and non-conforming geometries are in accord with this
- The concept of wear rates being determined by transport can be used to explain effects of contact size, temperature, fretting amplitude and frequency – either by considering debris egress or oxygen ingress.

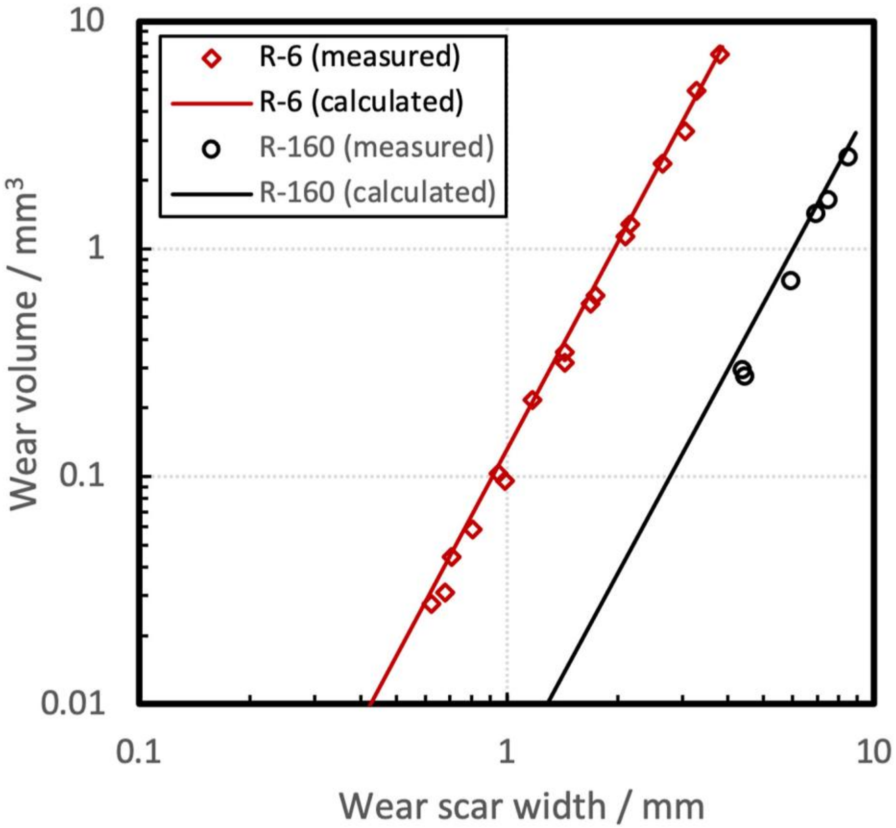
Non-conforming contacts – scar geometry





- Consider a cylinder-on-flat contact geometry*. Approximation for the wear volume:

$$V \approx \frac{2\, b^3\, L}{3R}$$



*principles apply to other geometries

https://doi.org/10.1016/j.wear.2021.204066