Adhesive wear and interaction of tangentially loaded micro-contacts

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Introduction

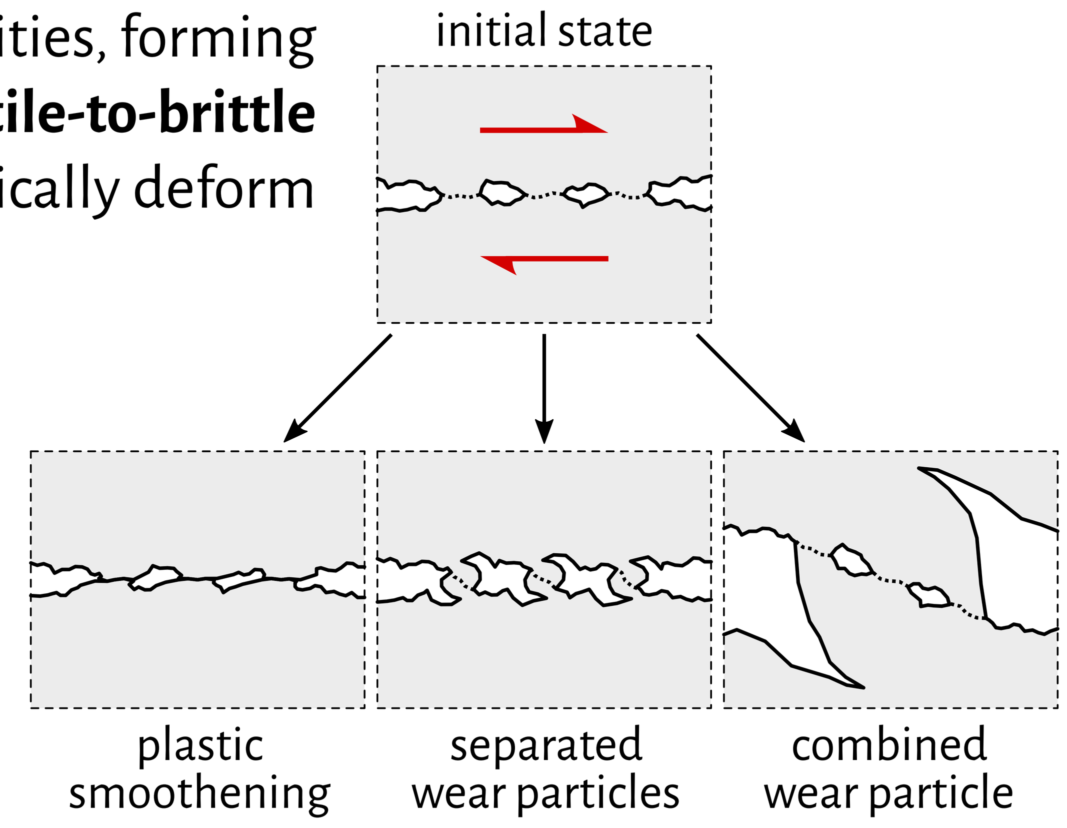
The tribological interaction between two rough surfaces comes down to the contact of microscale asperities, forming micro-contacts. Recent work [1] demonstrated the existence of a **critical asperity size** d^* governing a **dutile-to-brittle transition** for a given material in an adhesive wear situation. A *single* micro-contact of size d will plastically deform under shear if $d < d^*$ or create a wear particle if $d \geqslant d^*$.

Objective - An analytical theory for the **interaction of multiple micro-contacts** is derived in 2D, predicting the transition between a mild wear regime (formation of separate wear particles) and a severe wear regime (combined wear particles) at the scale of the micro-contacts.

Critical length scale [1]

$$d^* = \Lambda \frac{4\gamma G}{\sigma_j^2}$$

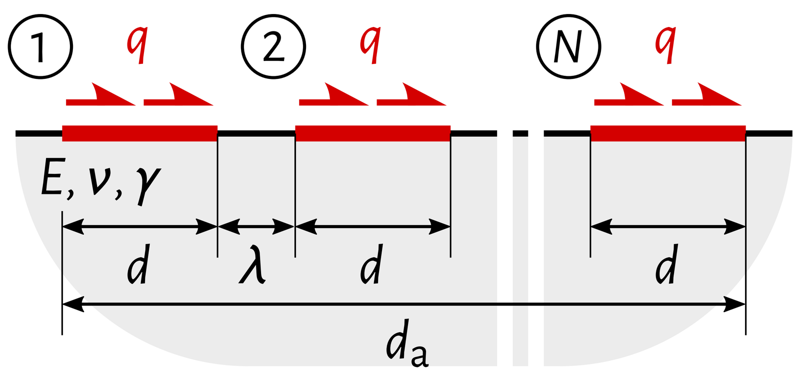
Λ: geometrical shape factor ~ 1
γ: surface energy
G: shear modulus
σ_j: shear strength



Theoretical model

Elastic energy

Micro-contacts are modeled by ***N* uniform loads** of magnitude q acting on a semi-infinite solid of thickness B. Only the bottom solid is considered because of symmetry.



E: Young's modulus
ν: Poisson's ratio
γ: surface energy
d: micro-contact size
λ: micro-contact spacing
d_a: aparent contact size

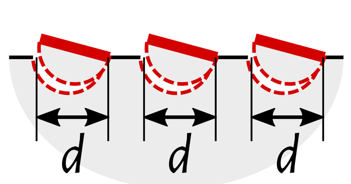
Elastic energy (*N* uniform loads) [2]

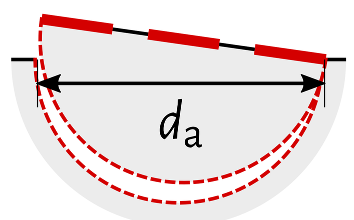
$$E_{el,Nq} = \frac{(1-\nu^2)BN^2d^2q^2}{\pi E}\mathcal{M}$$

In a 2D semi-infinite medium, $\mathcal{M}$ is infinite. In a 2D system of finite size, $\mathcal{M}$ is finite but depends on the size of the system. In a more realistic 3D system, E_{el} is independent of system size.

Adhesive energy

The creation of a debris particle under a micro-contact assuming brittle failure involves the **creation of new surfaces**. To detach a semi-circular particle of diameter d, two surfaces of area $B\pi d/2$ have to be created, which requires an adhesive energy of $E_{ad} = \pi\gamma Bd$.





Adhesive energy (separated)

$$E_{ad,sep} = \pi\gamma Bd_r$$

$d_r = Nd$: real contact size

Adhesive energy (combined)

$$E_{ad,comb} = \pi\gamma Bd_a$$

$d_a = Nd + (N-1)\lambda$: apparent contact size

Energy criterion for debris formation

Energy ratio

$$\mathcal{R} = \frac{E_{el}}{E_{ad}}$$

The formation of debris particles is possible if the stored elastic energy is greater than the adhesive energy required to create the particles, or in other words, if the energy ratio $\mathcal{R}$ is larger than one.

With $N = 1$, we get the system's critical length scale: $d^* = \dfrac{\pi^2\gamma E}{(1-\nu^2)q^2\mathcal{M}}$

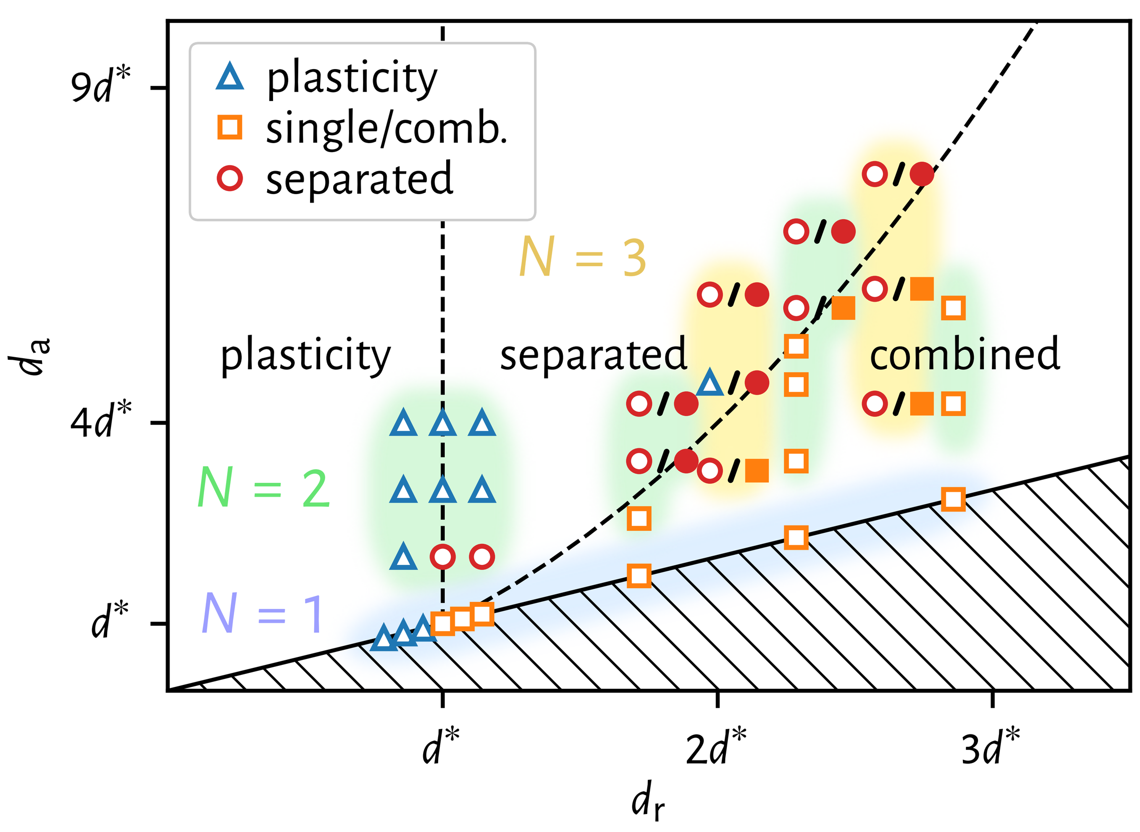
With $N > 1$, we get the **criteria for debris formation**:

- separated debris particles: $\mathcal{R}_{sep} = \dfrac{E_{el,Nq}}{E_{ad,sep}} = \dfrac{d_r}{d^*} \rightarrow d_r \geqslant d^*$
- combined debris particle: $\mathcal{R}_{comb} = \dfrac{E_{el,Nq}}{E_{ad,comb}} = \dfrac{d_r^2}{d_a d^*} \rightarrow d_a \leqslant \dfrac{d_r^2}{d^*}$

Validation using simulations

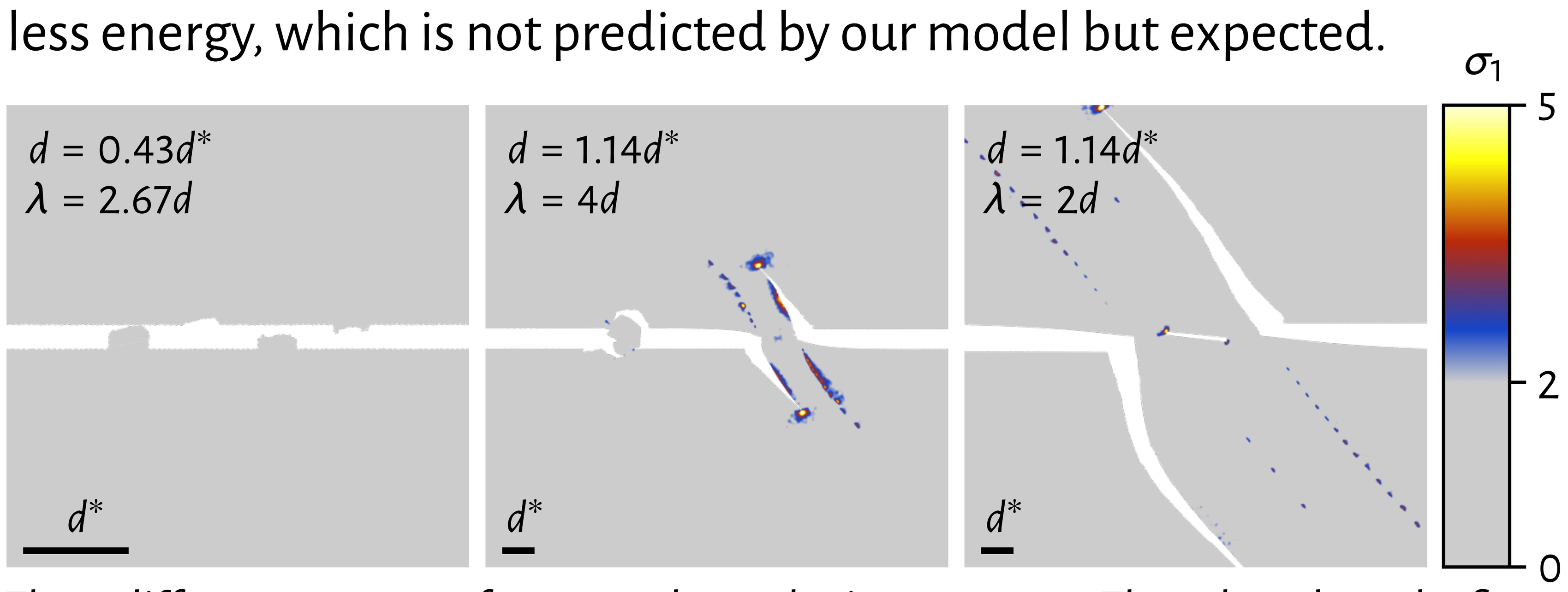
Molecular dynamics

Quasi-2D MD simulations of sheared perfect junctions were performed to check the validity of the predictions for debris formation. A model pair potential was used [1].



Distribution of the MD simulations on a wear map of the different outcomes of the system. The two dashed lines represent the theoretical debris formation criteria. White-filled and color-filled symbols represent simulations with sharp corners and rounded corners respectively.

Simulations near the $d_r = d^*$ dashed line show effects of the finite size of the system, neglected in our model. The other simulations with $N = 2$ and $N = 3$ are in good agreement with the predictions. Separated debris particles can form even in the "combined" region because it consumes less energy, which is not predicted by our model but expected.



Three different outcomes from two sheared micro-contacts. The colors show the first principal stress σ_1 in reduced dimensionless Lennard-Jones units.

Conclusion

- We derived and validated a **wear map** for the **formation of separated or combined debris particles** in an adhesive wear regime at the microscale.
- The **emergence** of a regime of **severe wear** can be physically explained by the energetic feasibility of forming combined debris particles under multiple micro-contacts.
- Future work will generalize these findings in a 3D setting (fractal rough surfaces).

References

[1] R. Aghababaei, D. H. Warner & J.-F. Molinari. Critical length scale controls adhesive wear mechanisms. Nature Communications 7, 11816 (2016).
[2] S. Pham-Ba, T. Brink & J.-F. Molinari. Adhesive wear and interaction of tangentially loaded micro-contacts. arXiv:1907.08183 (2019).

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