Adhesive wear of rough surfaces and interaction of micro-contacts

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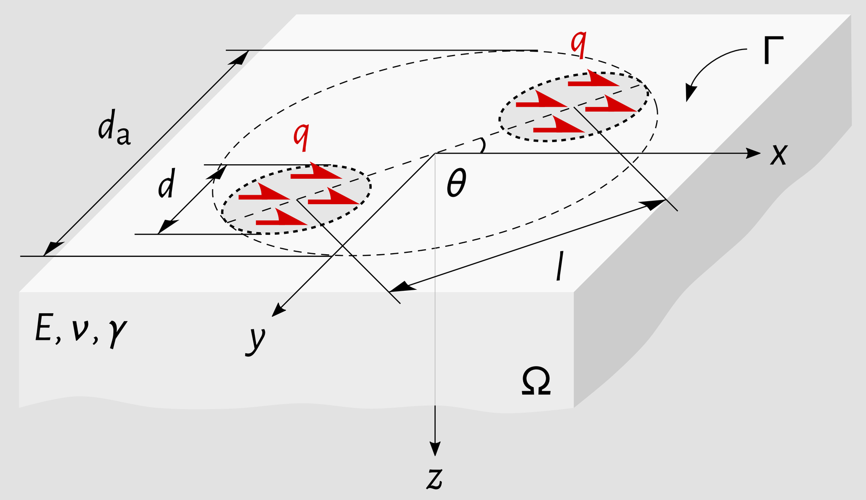
1. Introduction

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 **ductile-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 $d \geqslant d^*$.

Following a work done in 2D [2], an analytical theory for the **interaction of multiple micro-contacts** under tangential load is derived in 3D and compared to boundary element (BE) computations of **rough surfaces**.

2. Analytical theory

To study interaction, two micro-contacts are modeled by **circular uniform loads** of magnitude q acting at the surface Γ of a semi-infinite solid Ω. Only the bottom solid is considered because of symmetry.



E: Young's modulus
ν: Poisson's ratio
γ: surface energy
q: tangential load
d: micro-contact size
d_a: apparent contact size
l: distance between centers
θ: angle

Elastic energy

The stored elastic energy is:

$$E_{el} = \frac{1}{2}\int_\Gamma [u^{ker}_{x\to x} * p_x]\, p_x \, d\Gamma$$

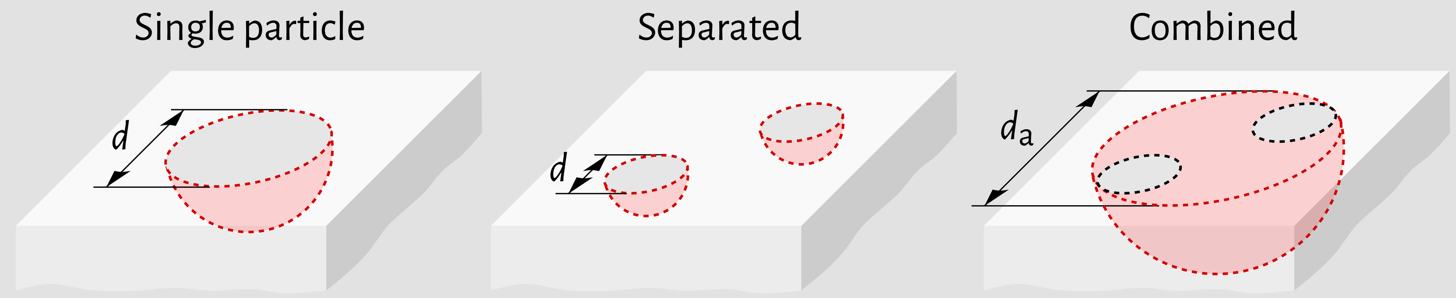
where $p_x(x, y)$ is the tangential load distribution on the surface and $u^{ker}_{x\to x}(x, y)$ is the displacement in the x direction caused by a tangential point load acting also in the x direction at the origin of Ω. The symbol $*$ denotes a convolution. The expression of the displacement kernel is:

$$u^{ker}_{x\to x} = \frac{1}{4\pi G}\left[2(1-\nu)\frac{1}{r} + 2\nu\frac{x^2}{r^3}\right]$$

where $r^2 = x^2 + y^2$.

Adhesive energy

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



$E_{ad} = \pi\gamma d^2$ $\quad$ $E_{ad,sep} = 2\pi\gamma d^2$ $\quad$ $E_{ad,sph} = \pi\gamma d_a^2$

Energy criterion for debris formation

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** $\mathcal{R} = E_{el}/E_{ad}$ is **larger than one**.

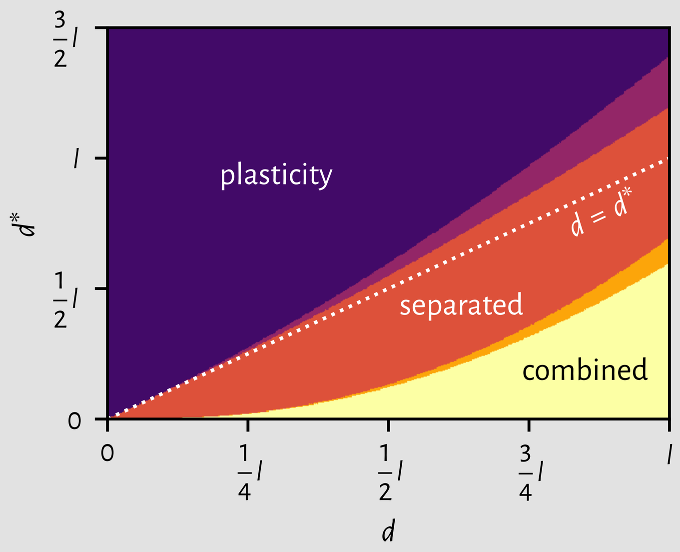
Applied to a single circular micro-contact, we get the **critical length scale**:

$$d^* = \frac{12\pi\gamma G}{(2-\nu)\sigma_j^2}$$

3. Results and discussion

Two circular micro-contacts

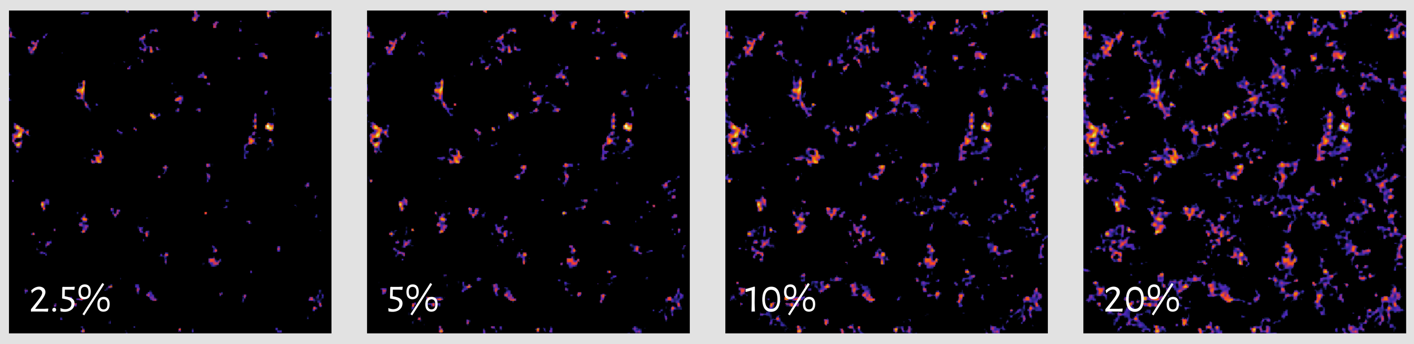
Using the energy criterion, a **wear map** can be created, indicating the possible regimes of wear particles formation as a function of the material parameters (all contained in d^*) and geometrical parameters (varying d and fixed $l = d_a - d$). For lower values of d^*, the micro-contacts can interact by forming a combined wear particle.



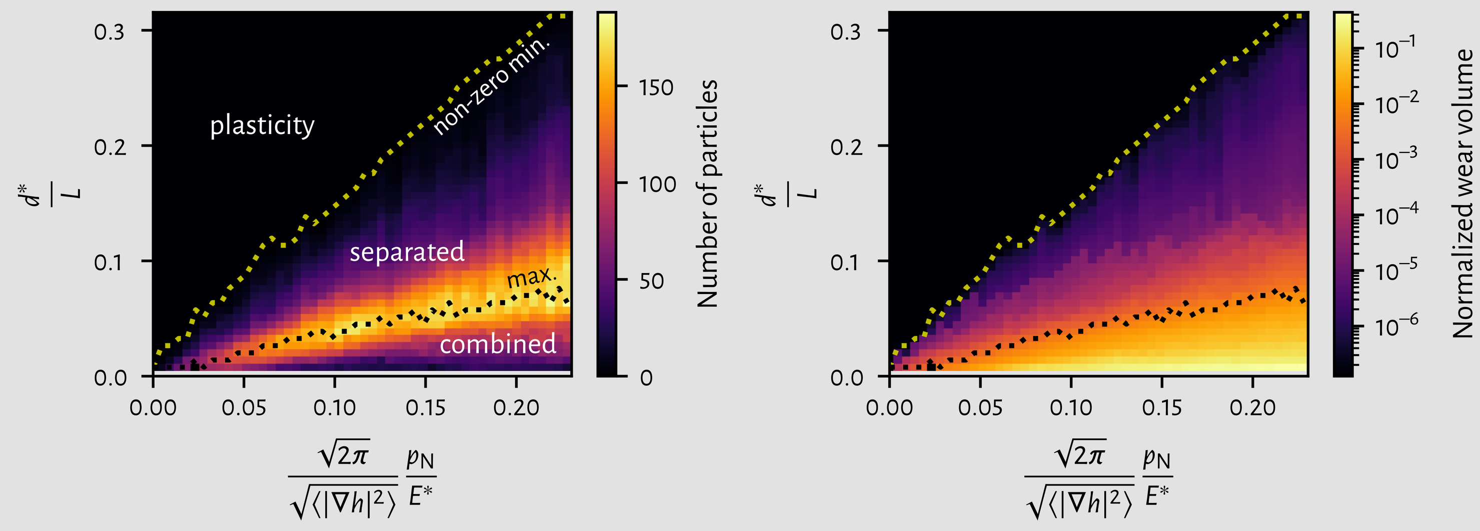
Wear map of the different outcomes of the system. The $d = d^*$ line represents the transition between plasticity and wear particle formation for a single micro-contact. The presence of a second micro-contact allows the formation of wear particles at a higher d^* (more ductile material). The thin transition bands are variations due to the possible values of ν and θ.

Contact of rough surfaces

The contact between two rough surfaces creates multiple micro-contacts of various shapes. With increasing normal load p_N, micro-contacts become bigger and more numerous, promoting interaction and leading to the possible production of a larger wear volume W.



BE simulations of the qualitative evolution of contact pressure for increasing normal load. The ratio of real contact area to apparent contact area is indicated.



The number of wear particles that can be formed and the equivalent wear volume can be evaluated for a given contact distribution (depending on p_N) and value of d^*. p_N is normalized by the RMS slope of the equivalent rough surface and by the effective Young's modulus $E^* = E/(1-\nu^2)$ to reflect an approached ratio of contact area. The map of the number of particles shows clearly distinct regimes of wear. Between the 'separated' and 'combined' regions, the number of particles decreases but the wear volume increases. The wear volume spans multiple orders of magnitude.

4. Conclusion

- **Three wear regimes** are identified in both models: **plastic** deformations, formation of **separated** wear particles, and formation of **combined** wear particles encompassing multiple micro-contacts.
- The boundaries of the three regions of the wear maps for rough contact must be analytically rationalized for a range of roughness parameters.

References

[1] R. Aghababaei, D. H. Warner & J.-F. Molinari. Critical length scale controls adhesive wear mechanisms. Nat. Commun. 7, 11816 (2016).
[2] S. Pham-Ba, T. Brink & J.-F. Molinari. Adhesive wear and interaction of tangentially loaded micro-contacts. Int. J. Solids Struct. (accepted 2019).

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