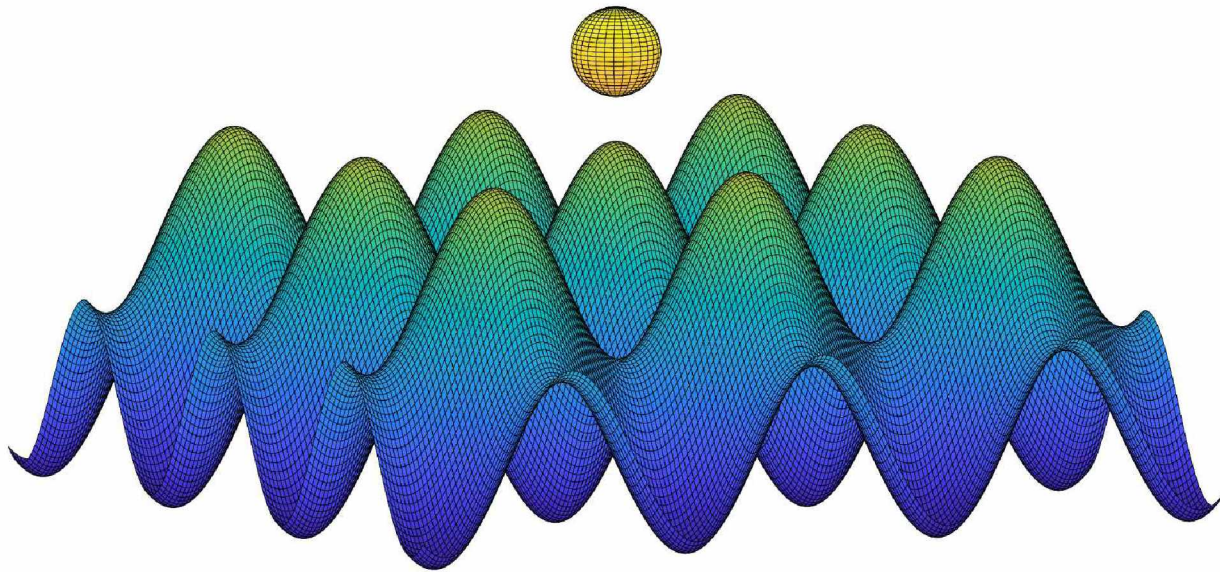


What force causes particles to stick to surfaces?



Siddharth Rajupet¹

Adriaan Riet¹

Qizan Chen¹

Mamadou Sow²

Daniel J. Lacks¹

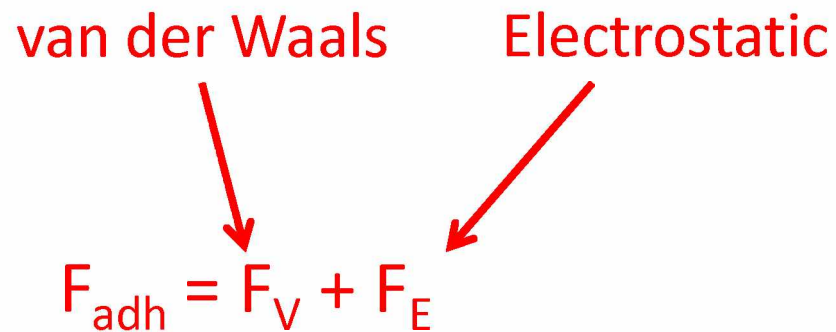
¹Case Western Reserve University, Cleveland OH, USA

²Institut de Radioprotection et de Sûreté Nucléaire,
Gif-sur-Yvette, France

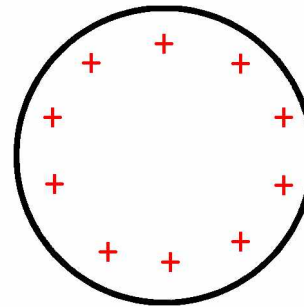
What force dominates in particle adhesion?

van der Waals Electrostatic

$F_{adh} = F_V + F_E$

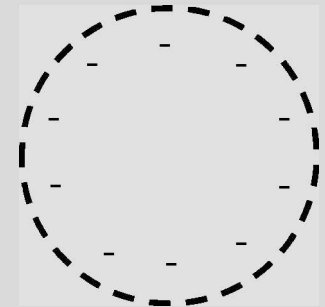


Charged particle



F_E

Image charge on
conducting surface



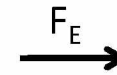
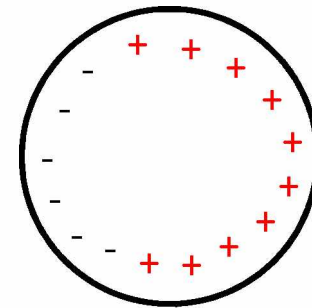
The grounded conductor induces charge to balance charge from the particles. The image charge causes an attractive electrostatic force

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Polarizable
charged particle



Polarized image charge
on conducting surface

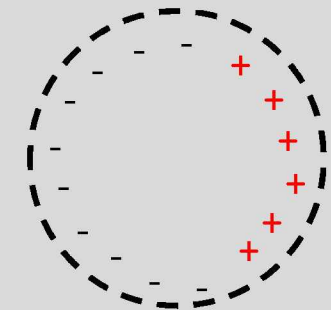


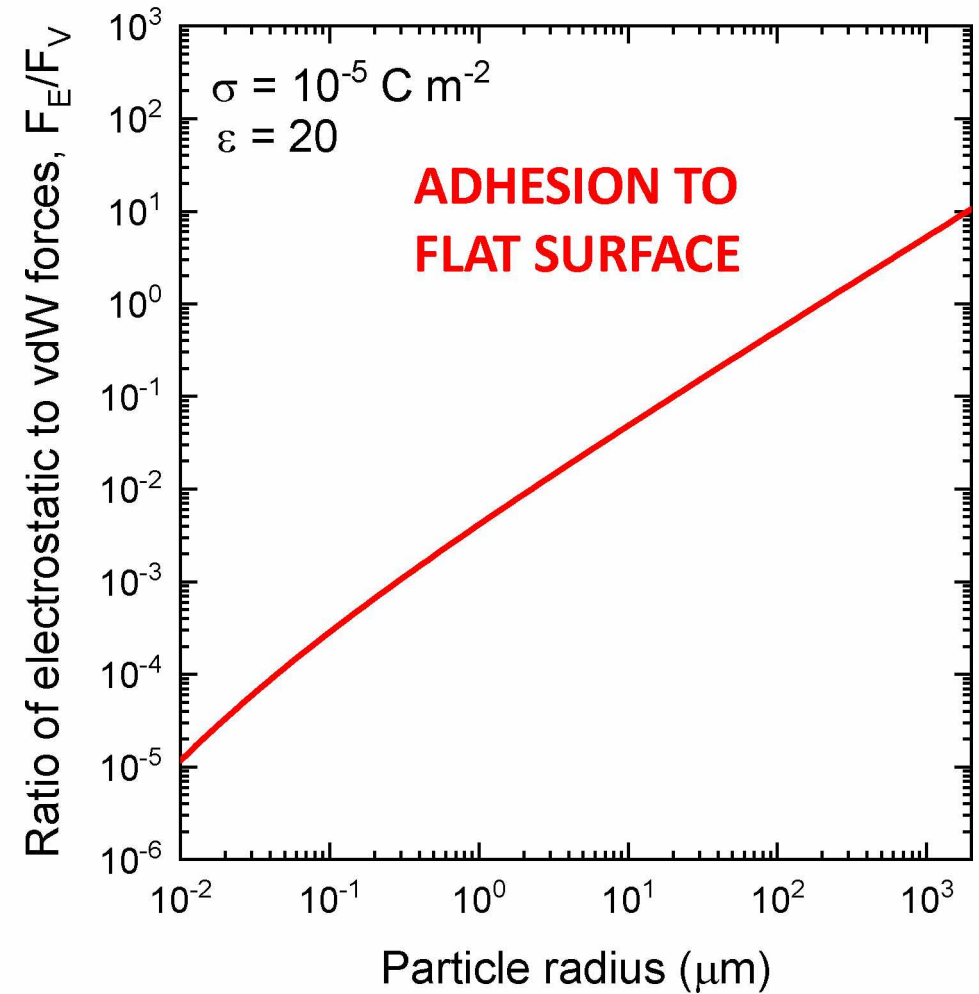
Image charge on conducting surface creates
higher order polarizations increasing adhesion

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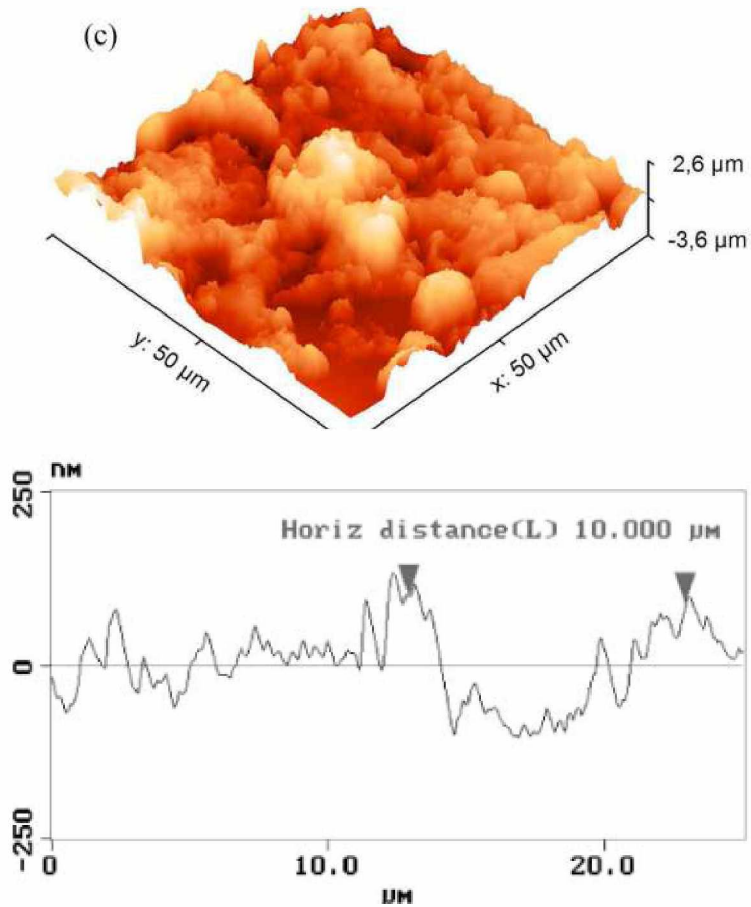
$$F_{adh} = F_V + F_E$$

Generally assumed van der Waals dominate



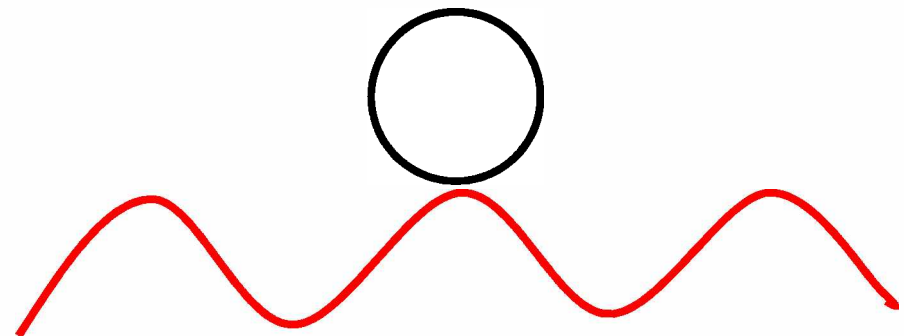
Simplifying surface roughness

Complex roughness in real systems



Model system:

- Spherical particle positioned directly above an asperity of a sinusoidal surface



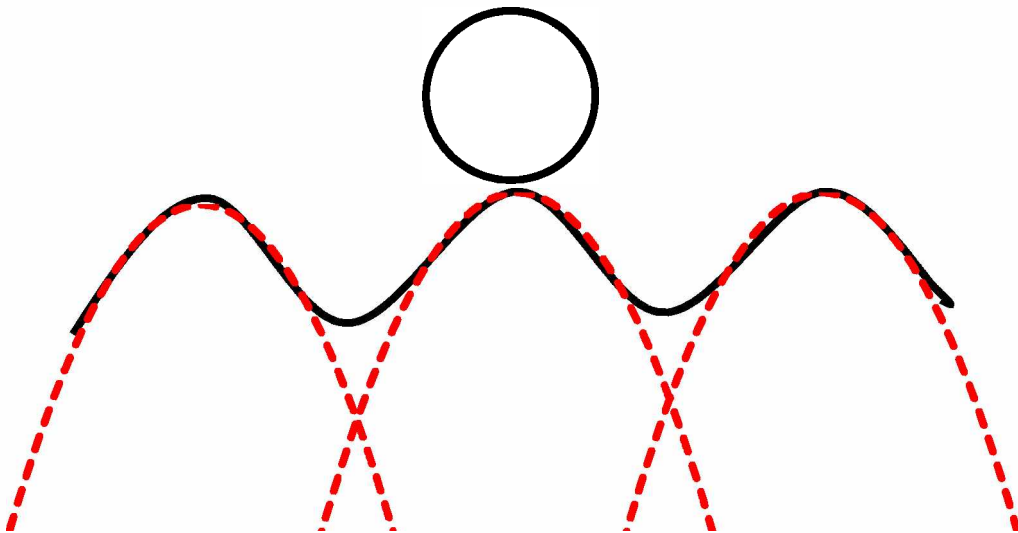
van der Waals force calculations

Start with fundamental vdW relation:

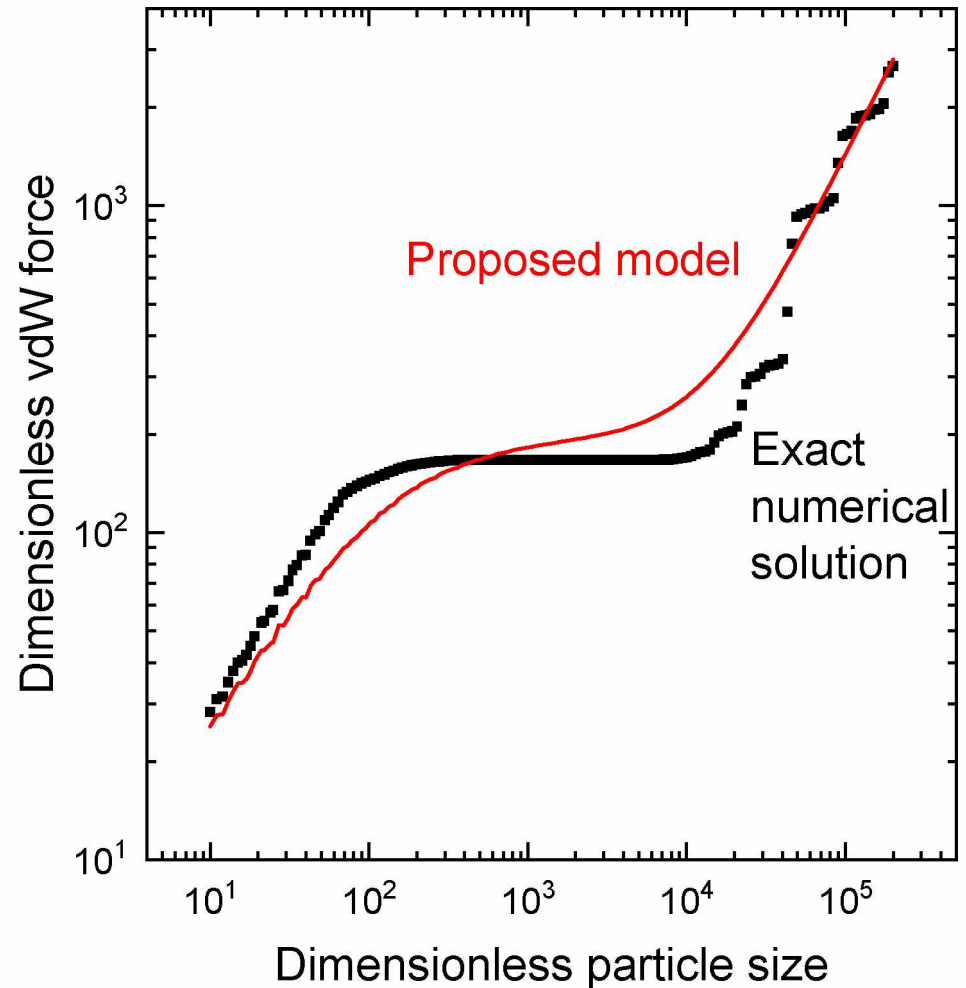
$$F_V = \sum_j \sum_k \frac{6Cz_{jk}}{r_{jk}^8}$$

↓ Use Taylor series to derive analytic expression

$$F_{V,model} = \frac{HR}{6d^2} \left(\frac{1}{1 + R/R_a} + \frac{16\pi d_c^2 (R + R_a + d)^2}{\lambda^2 (1 + R/R_a) (\lambda^2 + 8d_c (R + R_a + d))} \right)$$



Model agrees well with exact solution



Rajupet, Sow, Lacks, *Phys. Rev. E* 2020

Electrostatic force calculations

Model system:

- Spherical dielectric particle with uniform σ positioned directly above an asperity of a grounded sinusoidal surface

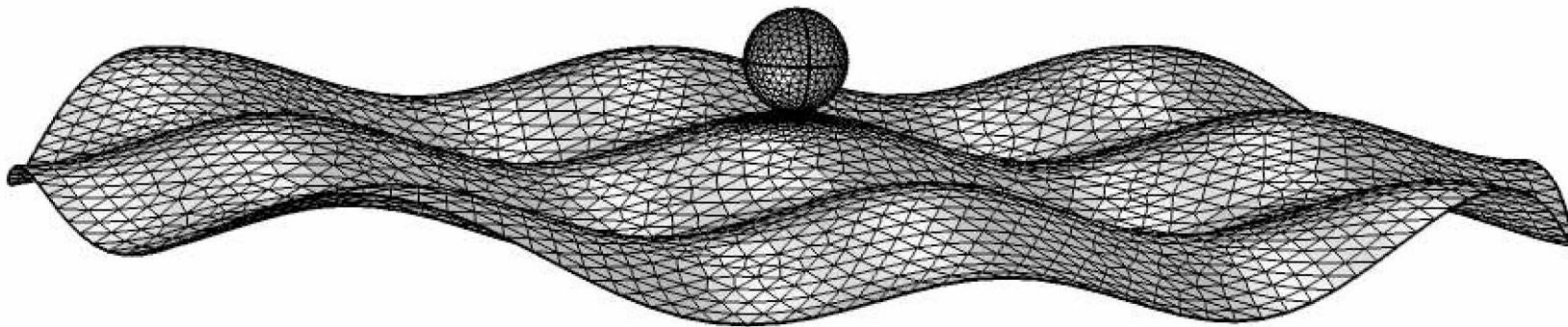
Calculations:

- Find potential distribution by solving Poisson's equation using FEA:

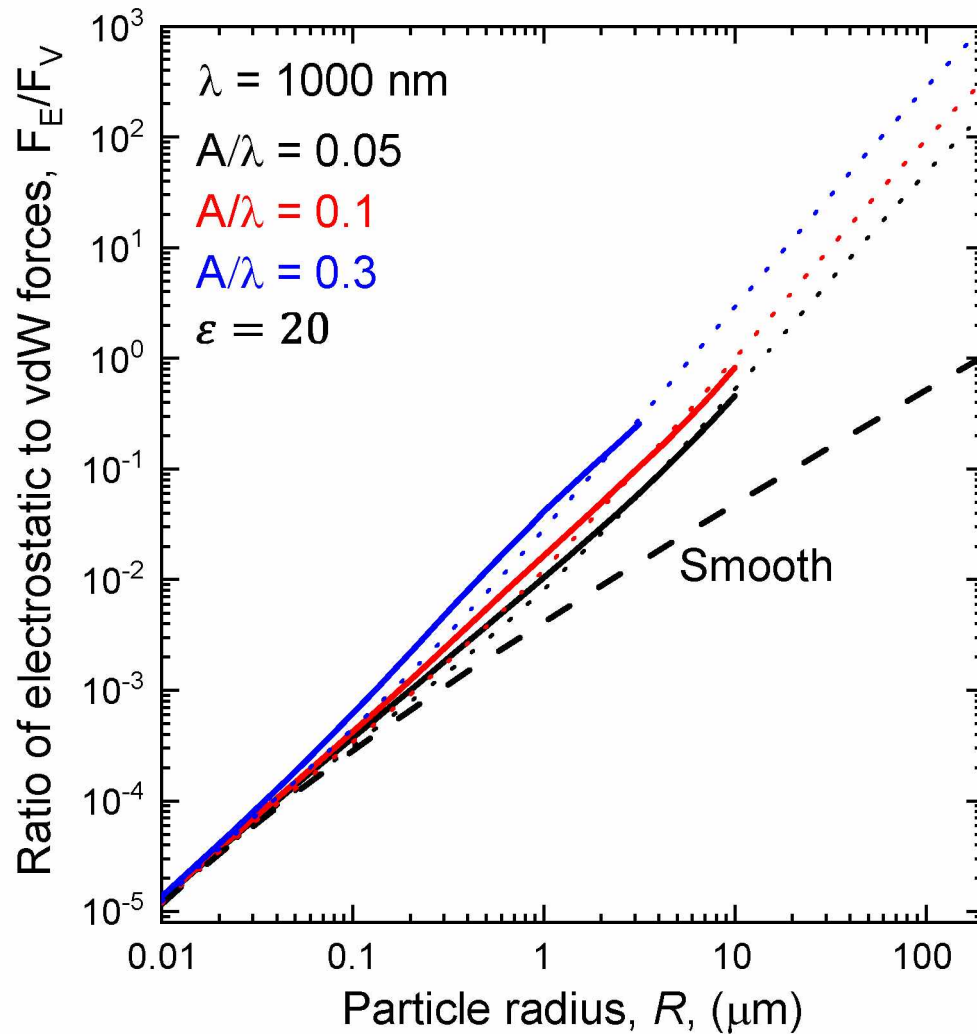
$$\nabla^2 \phi = 0$$

- Integrate Maxwell stress tensor over particle surface for the force:

$$F_E = \iint_S \mathbf{n}_z \epsilon_0 (E_z^2 - \frac{1}{2} (E_x^2 + E_y^2 + E_z^2)) dS$$



Roughness reduces R where electrostatics dominant



Roughness lowers the particle size where electrostatic forces are comparable to vdW forces by up to two orders of magnitude

Electrostatic forces should be considered in micron-sized particle adhesion

Acknowledgments



|| S N S R N

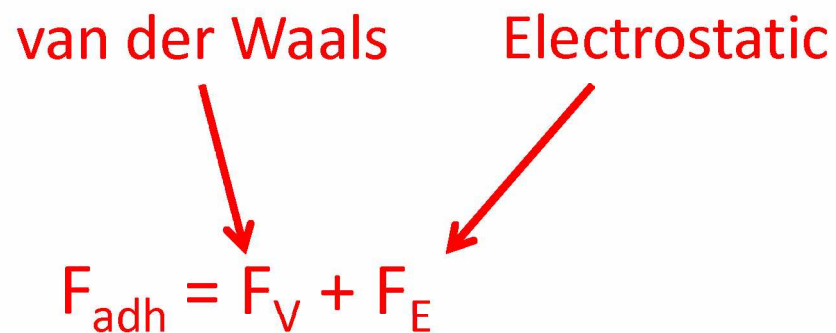
DE L O P O B T O H

Supplemental

What causes particle adhesion?

van der Waals Electrostatic

$F_{adh} = F_V + F_E$



Charged particle

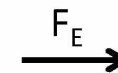
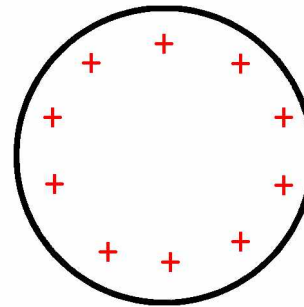
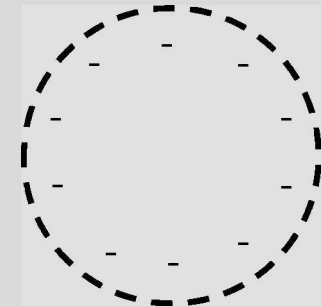


Image charge on
conducting surface



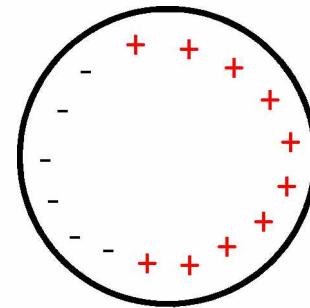
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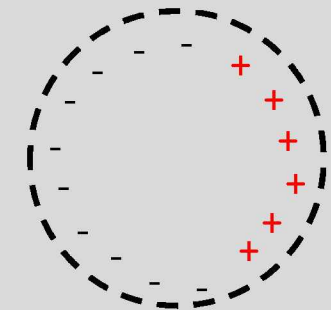


Image charge on conducting surface creates
higher order polarizations increasing adhesion

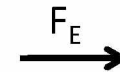
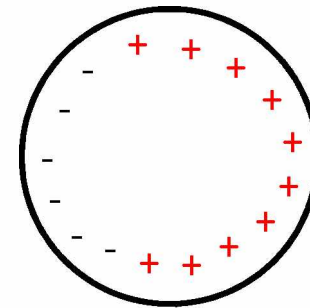
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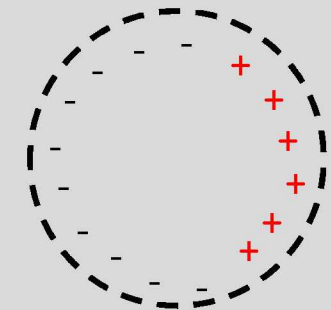


Image charge on conducting surface creates higher order polarizations increasing adhesion

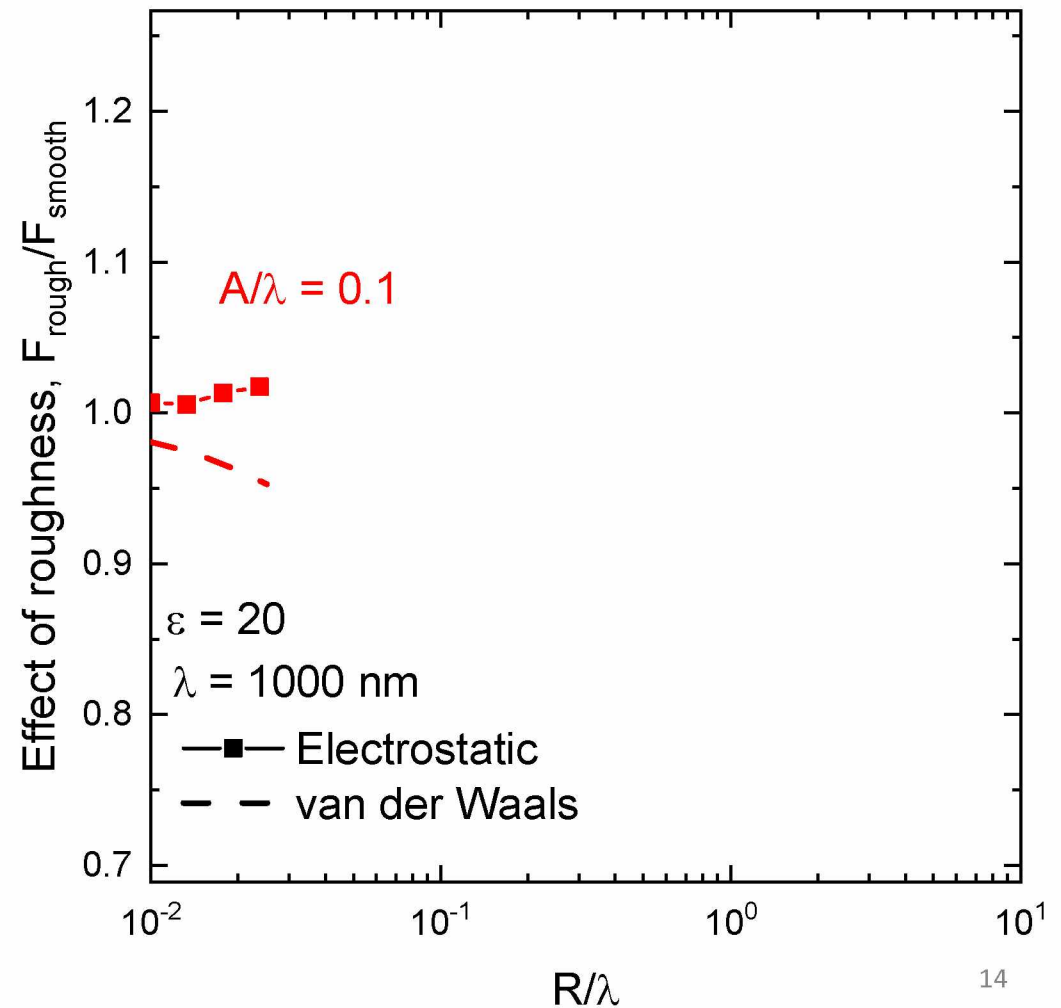
F_{rough}/F_{smooth} : effect of roughness on adhesion

F_{rough} - Force due to rough surface

F_{smooth} - Force due to smooth surface

If $F_{rough}/F_{smooth} > 1$ roughness enhances electrostatic adhesion

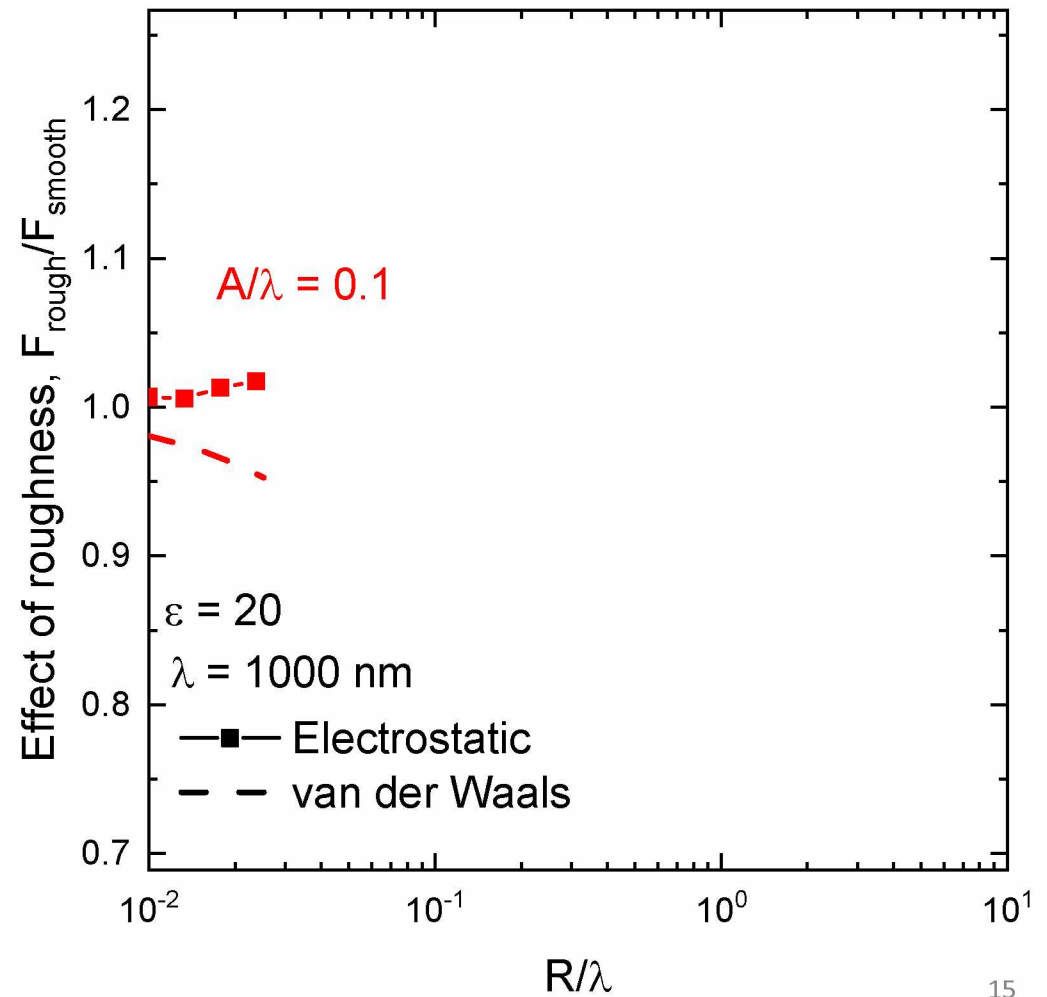
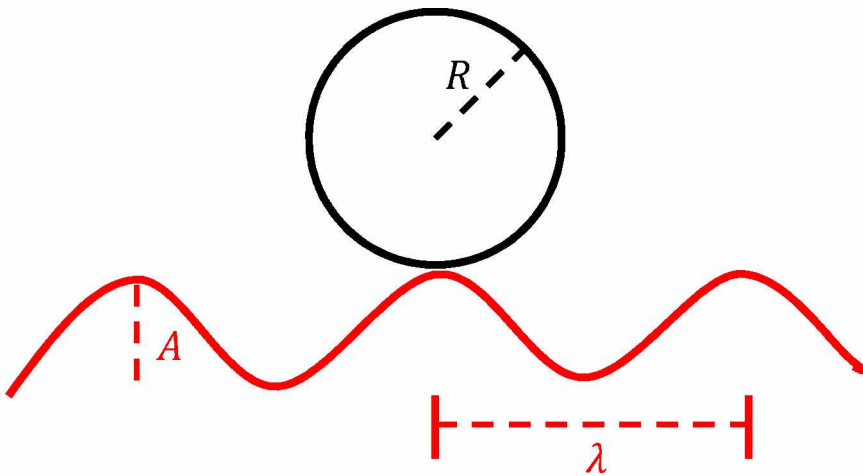
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F_{rough}/F_{smooth} : effect of roughness on adhesion

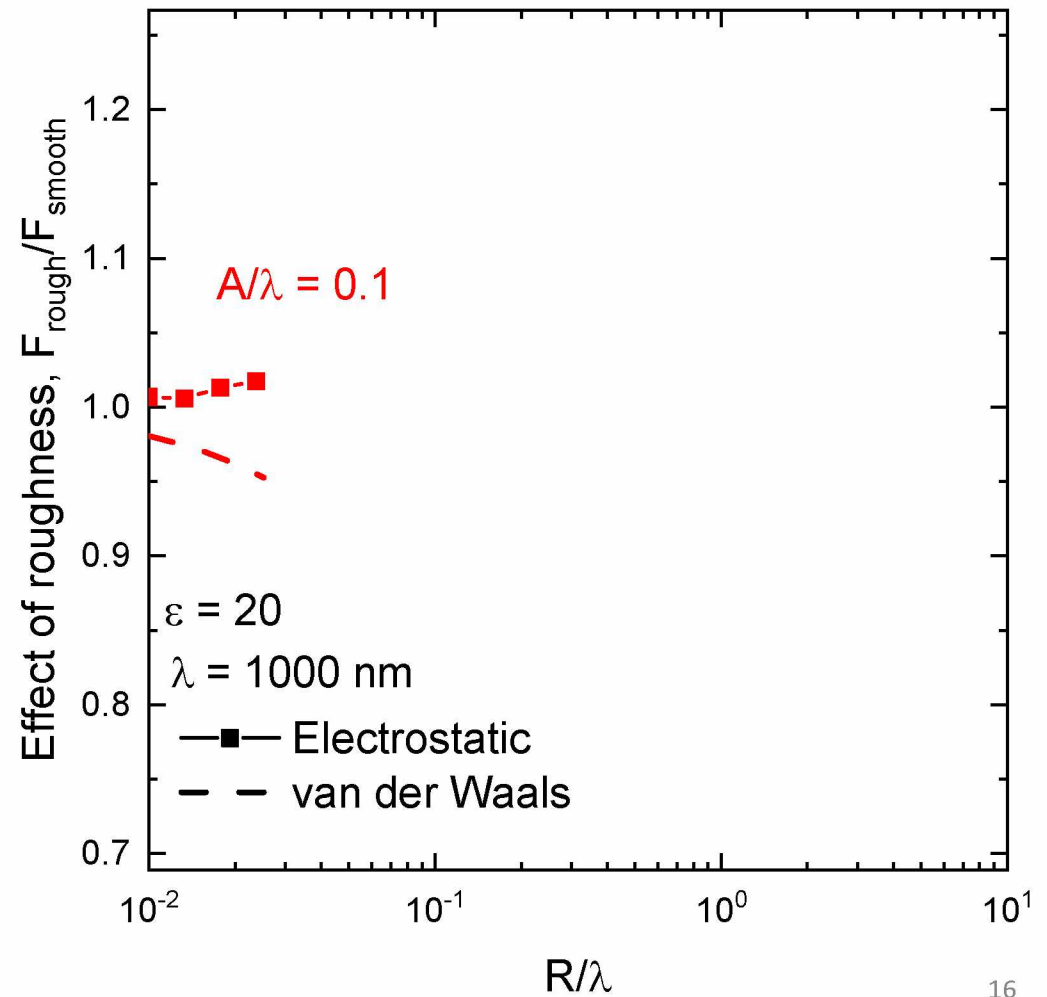
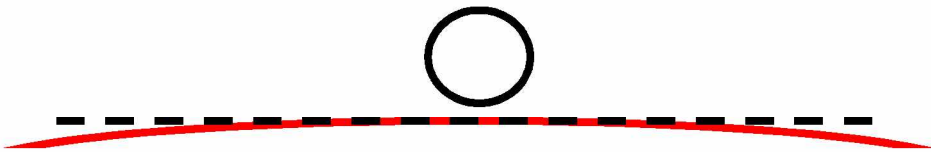
R/λ determines size of particle relative to asperities

A/λ determines “pointiness” of asperities



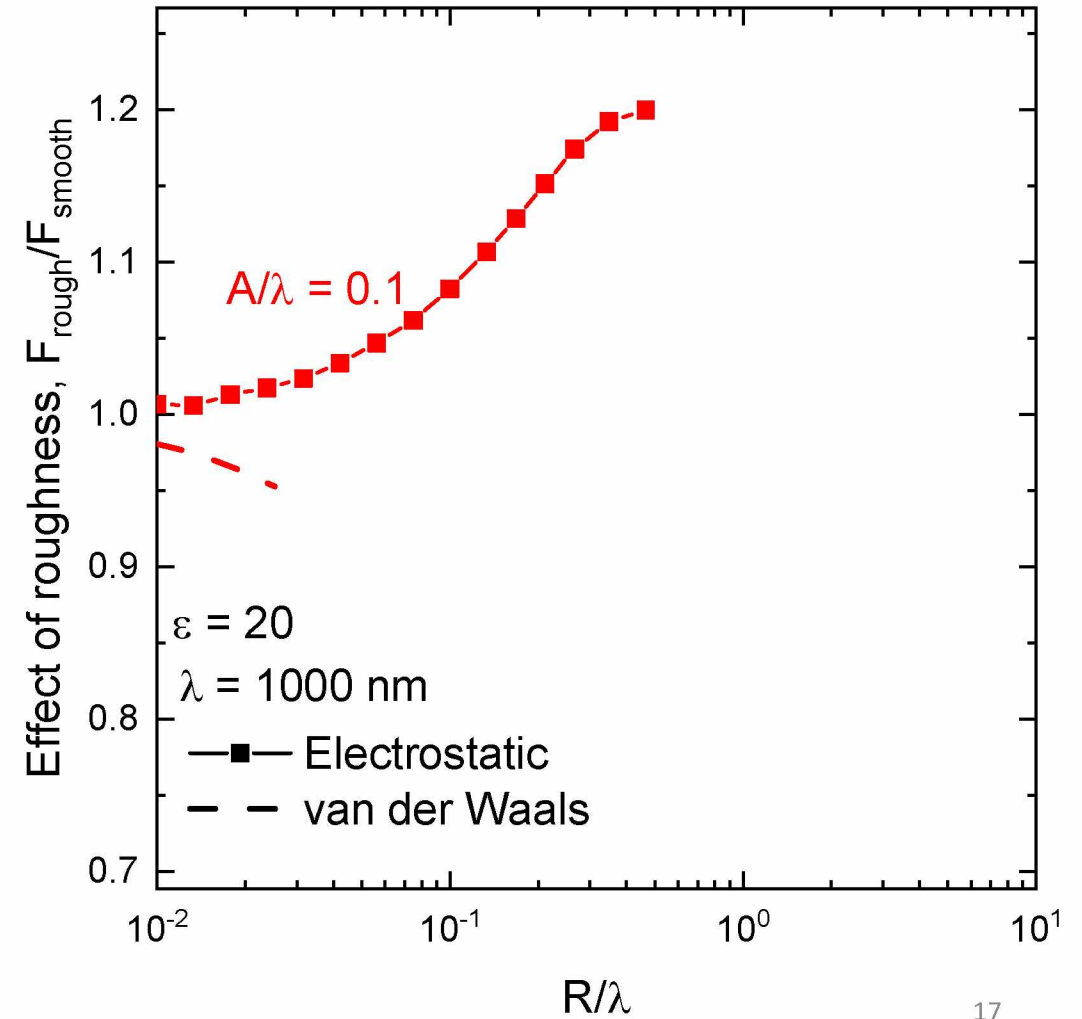
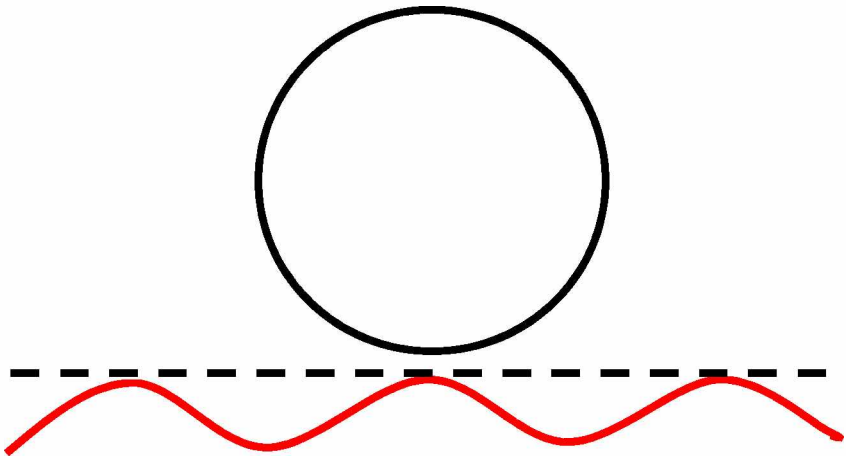
$R \ll \lambda$: roughness has no effect on F_V or F_E

When $R \ll \lambda$, the asperity appears like a flat surface causing $F_{rough} \rightarrow F_{smooth}$



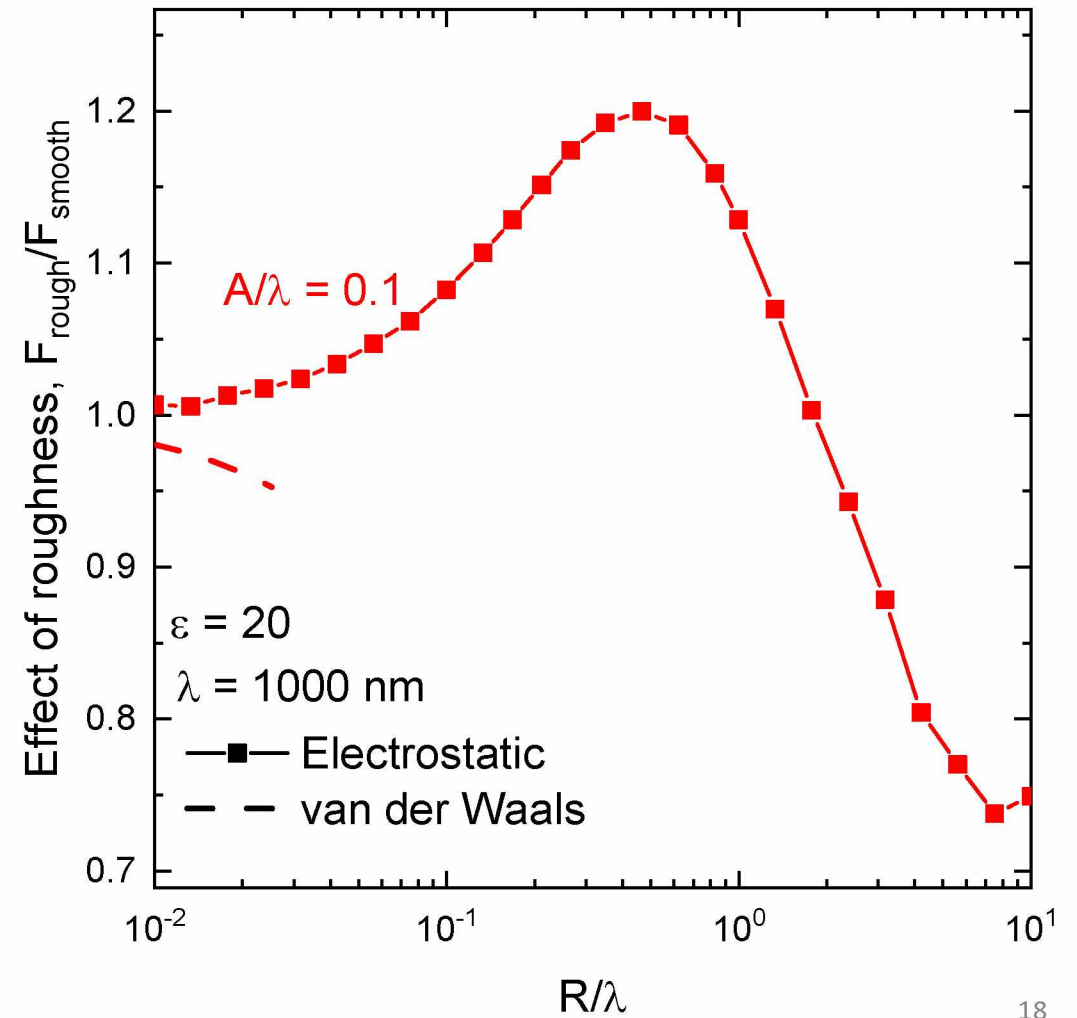
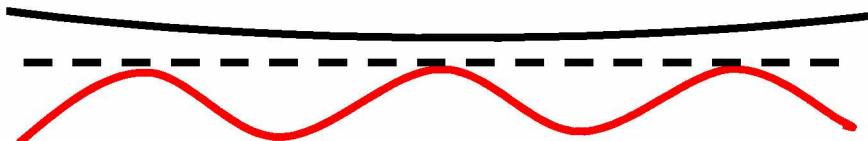
Roughness enhances F_E when $R < \sim \lambda$

Charge accumulates on peaks of the conducting surface, amplifying polarization and enhancing electrostatic adhesion



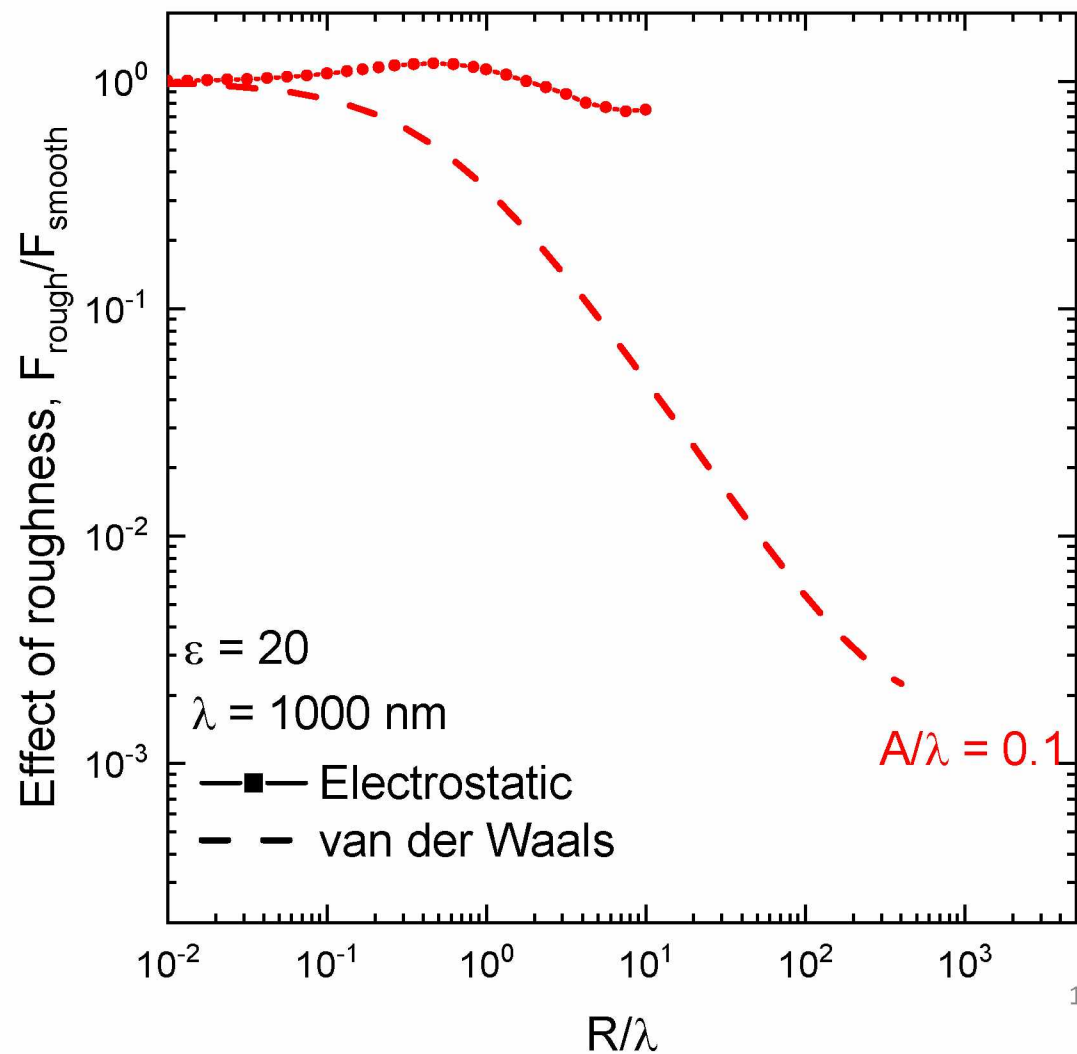
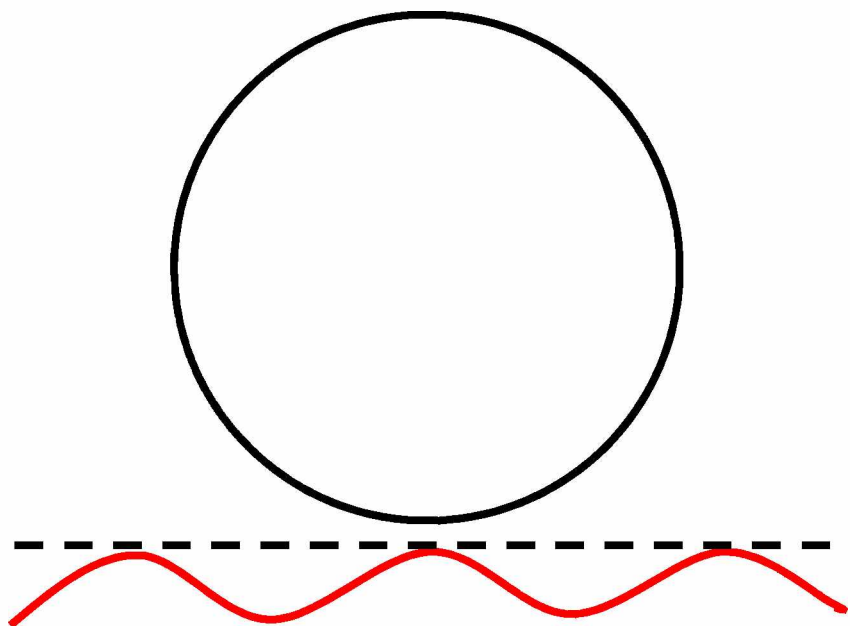
Roughness diminishes F_E when $R > \sim \lambda$

Increased interaction distance due to roughness causes electrostatic adhesion to be diminished



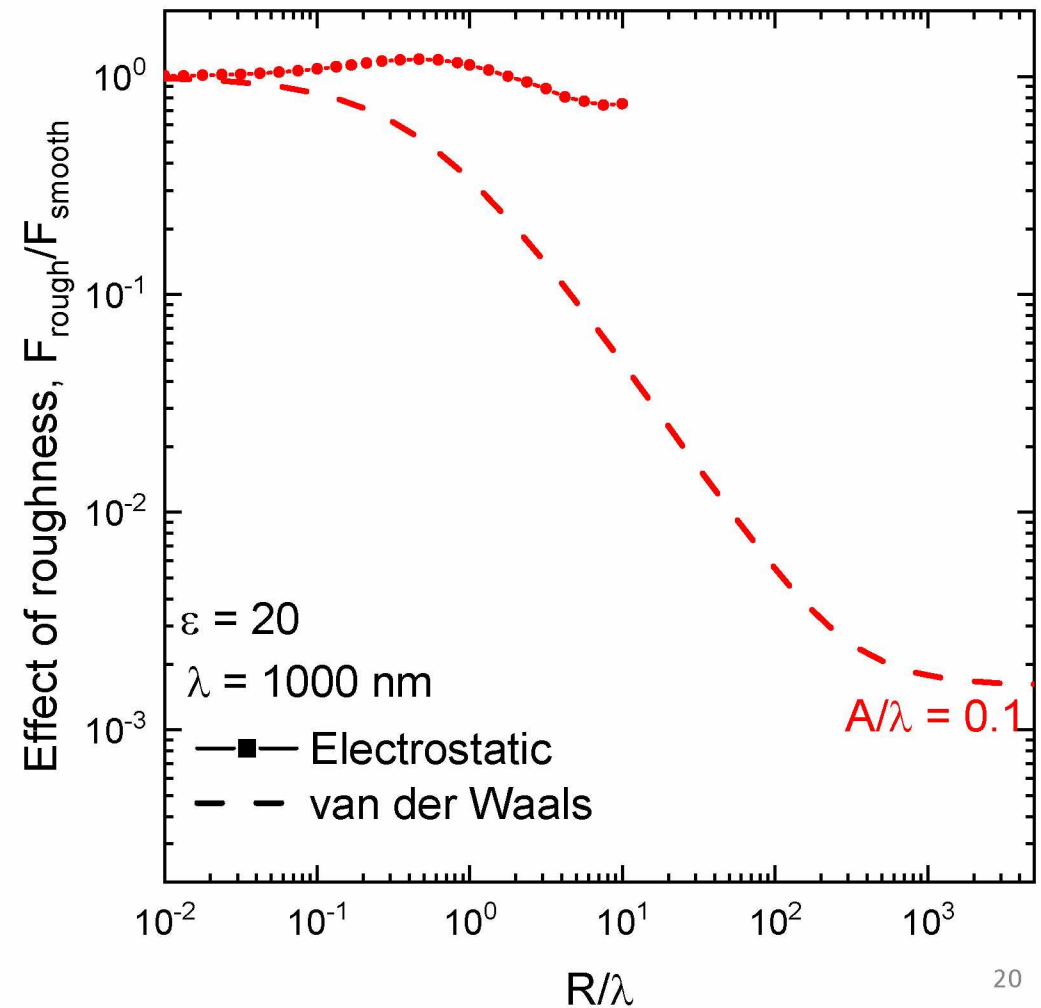
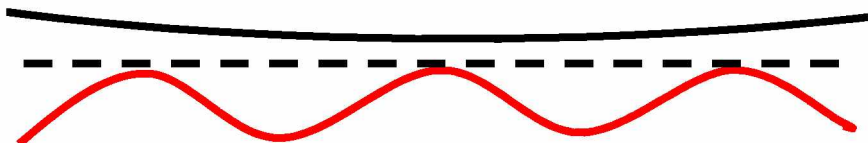
Roughness diminishes F_V when $R > \sim \lambda$

Increased interaction distance causes roughness to diminish F_V

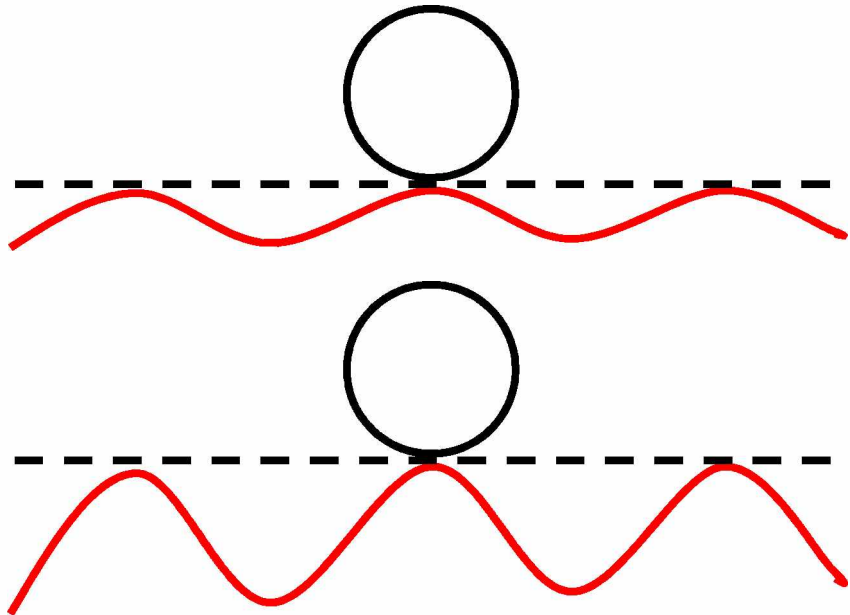


When $R \gg \lambda$, effect of roughness on F_V stabilizes

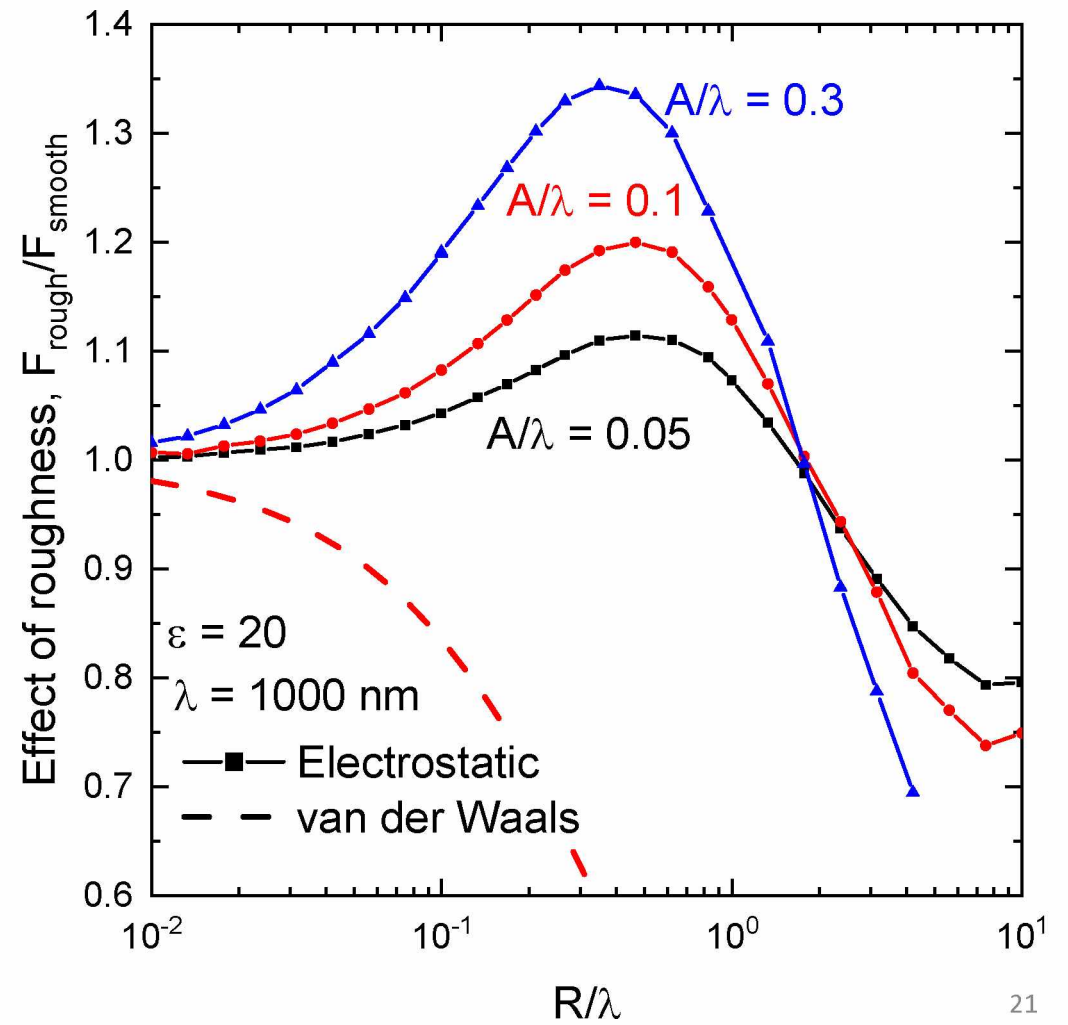
At very large particle sizes, the particle interacts with several asperity and the effect of roughness on the vdW force stabilizes



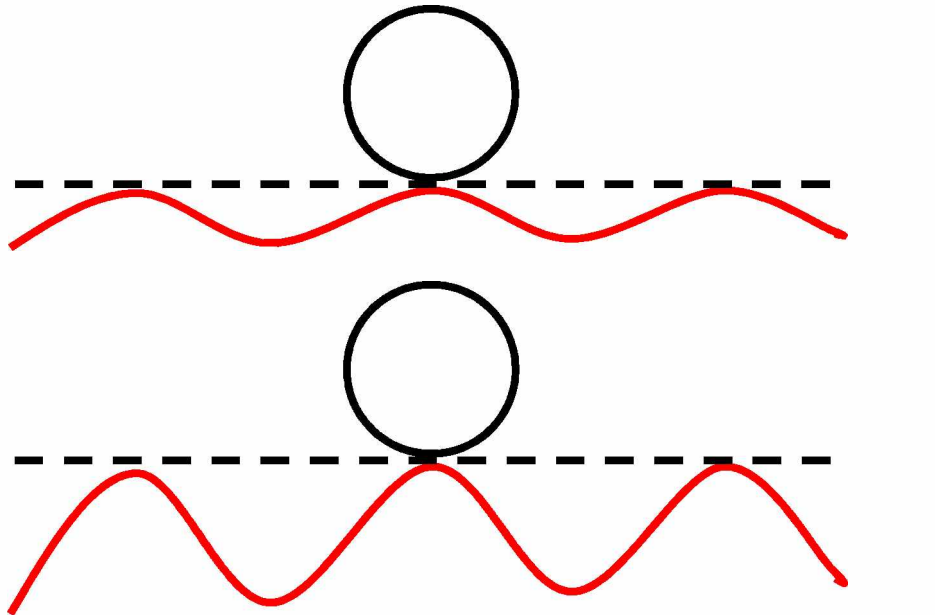
Increasing amplitude amplifies effect of roughness



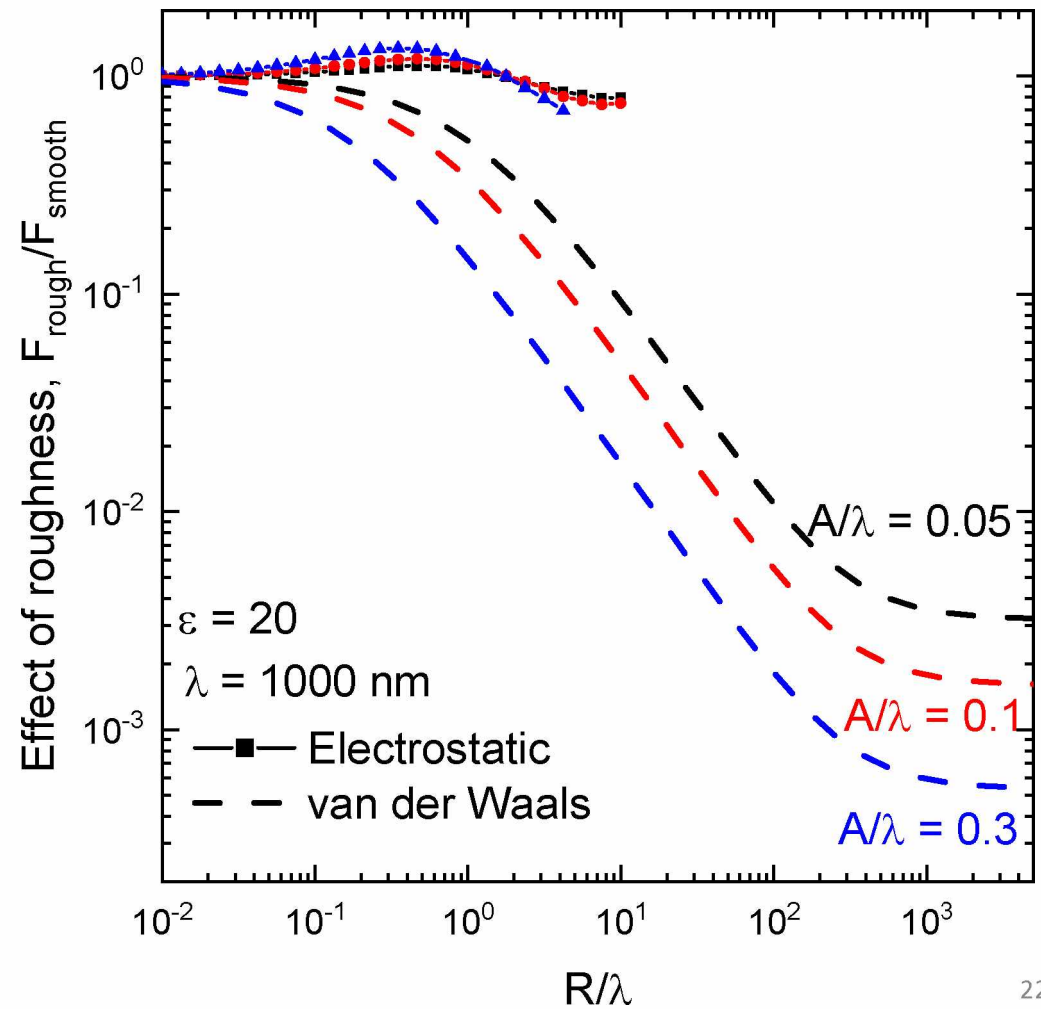
Larger A/λ makes asperities more “pointy”. More charge accumulates at peaks, causing more enhancement of F_E . Valleys of the surface are further from the particle, causing greater diminishment of F_E .



Increasing amplitude amplifies effect of roughness



Larger A/λ diminishes the vdW force more significantly since the interaction distance is increased.



Roughness diminishes vdW more than electrostatic

Roughness diminishes vdW forces by several orders of magnitude but scales the electrostatic force by less than a factor of 2

