Particle Transport, Deposition and Removal

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Particle Removal From Rough Surfaces

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Outline

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- van der Waals/Pull-off Force for Rough Surfaces
- Rolling and Sliding Removal of Rough Particles
- Hydrodynamic Forces and Torque
- Critical Shear Velocity for Detachment

JKR Adhesion Model

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Pull-Off Force

$$F_{po}^{JKR} = \frac{3}{4}\pi W_A d$$

Contact Radius at Separation

$$a = \left(\frac{3\pi W_A d^2}{8K}\right)^{1/3}$$

$$a = \left(\frac{F_{Po} d}{2K}\right)^{1/3}$$

$$K = \frac{4}{3}\left[\frac{(1-\nu_1^2)}{E_1} + \frac{(1-\nu_2^2)}{E_2}\right]^{-1}$$

Rough Surfaces

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Pull-Off Force

$$F_M = \pi a^2 N f_{Po} e^{-0.6/\Delta_c}$$

Number of Asperities per Unit Area

Pull-Off Force for each Asperity

$$\Delta_c = \frac{\delta_c}{\sigma}$$

Max Asperity Extension

Roughness Height Standard deviation

Contact Radius — Estimated →

$$a = \left(\frac{F_M d}{2K}\right)^{1/3}$$

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JKR Model → $\delta_c = \left[\frac{f_{Po}^2}{3K^2\beta}\right]^{1/3}$

Greenwood-Williamson → $\sigma\beta N \approx 0.1$

Contact of Rough Surfaces

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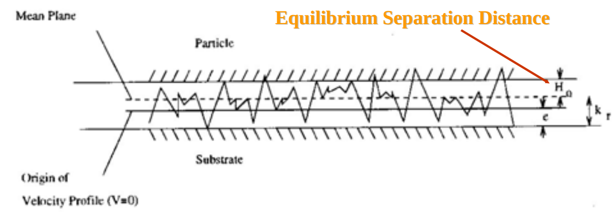

Average Roughness Height

$$k_r = 5.9\sigma$$

Displaced Origin of Velocity Profile

$$e = 0.53k_r$$

Hydrodynamic Forces

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Drag Force → $F_t = \frac{3\pi f\mu d}{C_c} V$

Lift Force → $F_l = 1.61 d^2 V (\rho\mu)^{1/2} \frac{dV/dy}{|dV/dy|^{1/2}}$

Hydrodynamic Torque → $M_t = \frac{2\pi\mu f_m d^2 V}{C_c}$

Sublayer Model

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$$u^+ = y^+$$

$$v^+ = -\beta_o {y^+}^2, \; y^+ \le 1.85$$

$$w^+ = 2\beta_o y^+ z^+$$

$$\beta_o = 0.01085$$

Velocity at Particle Centroid

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$$u^+ = \frac{d^+}{2} + 2.76\sigma^+ + H_0^+ - \alpha^+ = L^+$$

$$w^+ = \beta\frac{\Lambda^+}{2}\left(\frac{d^+}{2} + 2.76\sigma^+ + H_0^+ - \alpha^+\right)$$

$$L = \frac{d}{2} + 2.76\sigma + H_0 - \alpha$$

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Hydrodynamic Forces

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Drag Force → $$F_t = \frac{5.8\pi\rho d u^{*2} L}{C}$$

Lift Force → $$F_L = \frac{1.95\rho d^2 u^{*3} L}{\nu}$$

Hydrodynamic Torque → $$M_t = \frac{2.14\pi\rho u^{*2} d^2 L}{C}$$

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Particle-Surface Contact

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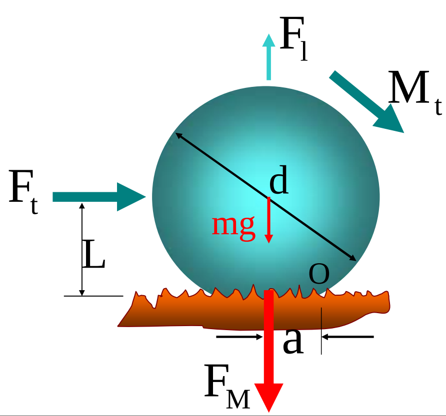

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Rough Particle

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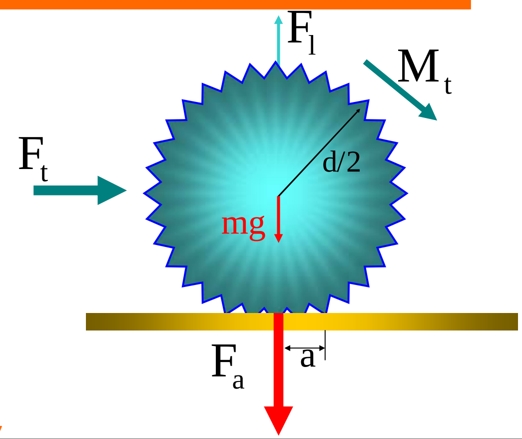

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Detachment Model

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MOMENT DETACHMENT

$$M_t + F_t\left(\frac{d}{2} - \alpha_0\right) + (F_L - mg)a \geq F_M a$$

SLIDING DETACHMENT

$$F_t \geq k(F_M + mg - F_L)$$

Detachment Models- Sublayer

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Rolling

$$u_c^* = \left[\frac{aC[\pi a^2 N f_{po} \exp[-0.6/(\Delta_c)^2] + mg]}{\rho L d^2 (5.04\pi + 1.95 \frac{aCu_c^*}{\nu})}\right]^{1/2}$$

Sliding

$$u_c^* = \left[\frac{kC[\pi a^2 N f_{po} \exp[-0.6/(D_c)^2] + mg]}{\rho L d (5.8\pi + 1.95 \frac{kCdu_c^*}{\nu})}\right]^{1/2}.$$

Detachment Models-Burst

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Rolling

$$u_c^* = \left[\frac{aC\left(\pi a^2 N f_{po} \exp[-0.6/(\Delta_c)^2] + mg\right)}{\rho L d^2 (1.72 + 0.1\frac{u_c^* L}{\nu})\left(5.04\pi + 1.95\frac{aCu_c^*}{\nu}(1.72 + 0.2\frac{u_c^* L}{\nu})^{1/2}\right)}\right]^{1/2}$$

Sliding

$$u_c^* = \left[\frac{kC[\pi a^2 N f_{po} \exp[-0.6/(\Delta_c)^2] + mg]}{\rho d L (1.72 + 0.1\frac{u_c^* L}{\nu})\left(5.8\pi + 1.95\frac{kCdu_c^*}{\nu}(1.72 + 0.2\frac{u_c^* L}{\nu})^{1/2}\right)}\right]^{1/2}$$

Critical Detachment Shear Velocity

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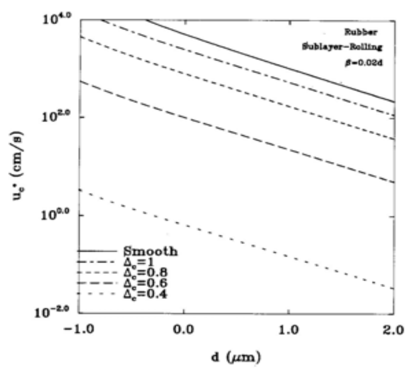
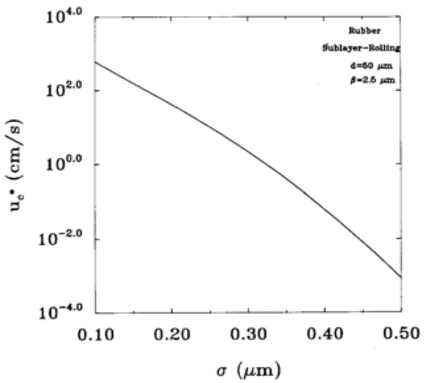


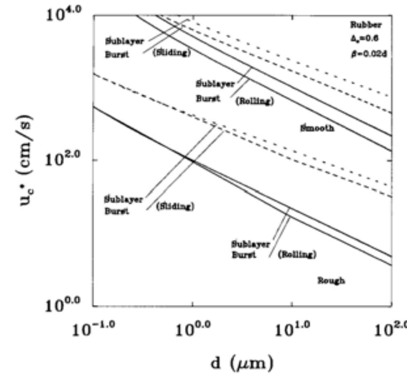
Critical Detachment Shear Velocity

Clarkson University



Critical Detachment Shear Velocity

Clarkson University



Critical Detachment Shear Velocity

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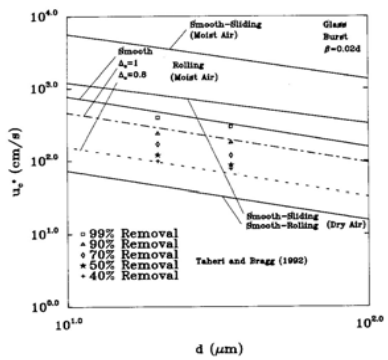

Comparison with Zimon

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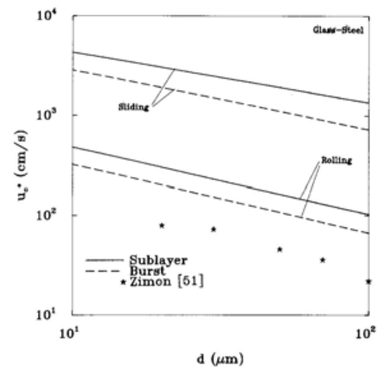

Critical Detachment Shear Velocity

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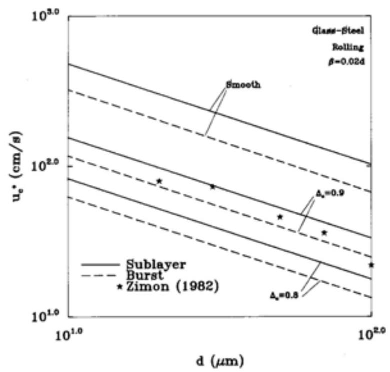

Conclusions

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- **Rolling detachment is the dominant mechanism for detachment of rough spherical particles.**
- **Roughness significantly reduces the adhesion pull-off force.**
- **Turbulence near wall flow structure plays an important role in particle detachment process.**
- **Accounting for surface roughness improves the agreement between the model prediction and experimental data**

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Thank you!

Questions?