Post-CMP Cleaning Mechanisms- An Experiment-Combined-Numerical Analysis Approach

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❖ Forces calculation

Hypothesis:

- Assume the wafer with contaminating particles is flat
- The contaminating particle is represented by a sphere
- The roughness of the particle is represented by some uniformly distributed hemispherical hard asperities
- The substrate possesses infinite volume
- The molecule to molecule interactions is pair wise additive van der Waals interaction potential
- The separation between the particle and the substrate surface is less than 10 nm

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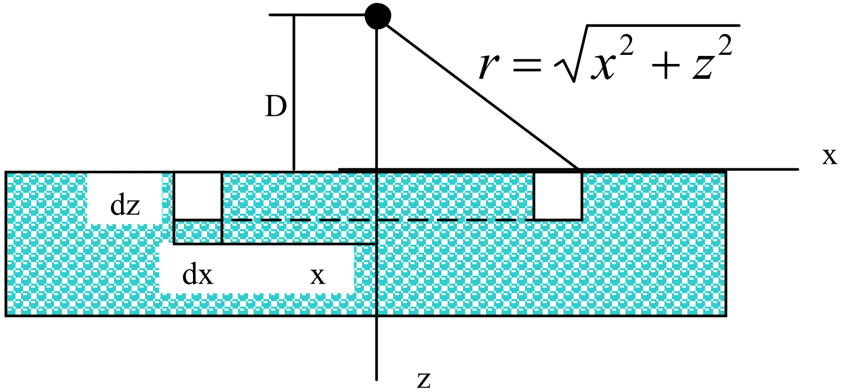
- Particle to particle van der Waals interaction potential is defined as

$$w(r) = -\frac{C}{\sqrt{x^2+z^2}}$$



- van der Waals interaction potential between particle and a flat substrate is given by the infinitive integration

$$W(D) = -2\pi C\rho_2 \int_D^{\infty} dz \int_0^{\infty} \frac{xdx}{\sqrt[n]{x^2+z^2}}$$

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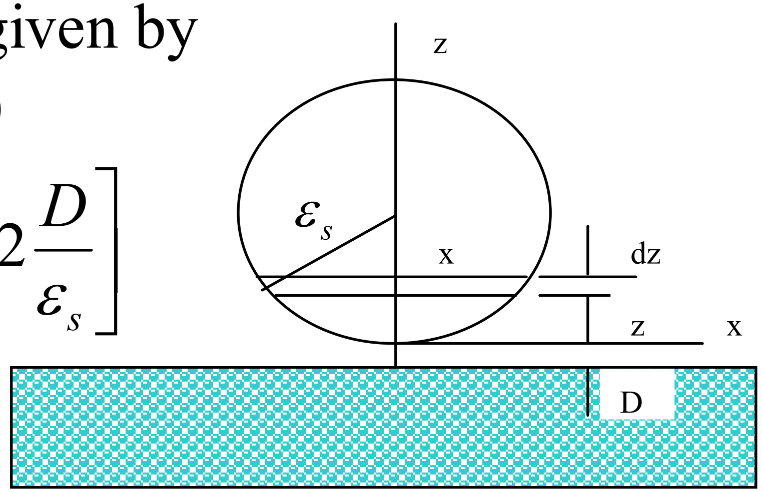
- Adhesion force for a hemispherical asperity on the surface of a particle is obtained by differentiating W(D) with respect to z and is given by (A is Hamaker constant)

$$F_z = -\frac{A\varepsilon_s^4}{6(D+\varepsilon_s)^3 D^2}\left[1 + 2\frac{D}{\varepsilon_s}\right]$$



- Adhesion force for a smooth spherical particle with radius R is given by

$$F_{sz}(D) = -\frac{AR}{6(D+\varepsilon_s)^2}$$

- Frictional force for a hemispherical asperity on particle surface is obtained by differentiating W(D) with respect to x and is given by

$$F_x = -\frac{\pi A \varepsilon_s^4}{32(D+\varepsilon_s)^3 D^2}\left[1+2\frac{D}{\varepsilon_s}\right]$$

- Frictional force for a smooth spherical particle with radius R is

$$F_{sx}(D) = -\frac{\pi AR}{32(D+\varepsilon_s)^2}$$

- Adhesion force for a colloidal particle with N asperities is

$$F_N = F_{sz} + NF_z = \frac{AR}{6(D+\varepsilon_s)^2} - \frac{NA\varepsilon_s^4}{6(D+\varepsilon_s)^3 D^2}\left[1+2\frac{D}{\varepsilon_s}\right]$$

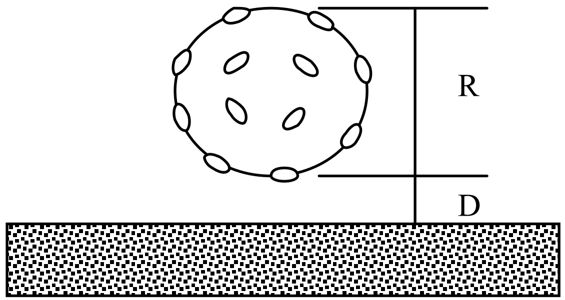
- Frictional force for a colloidal particle with N asperities is

$$F_T = F_{sx} + NF_x = \frac{\pi AR}{32(D+\varepsilon_s)^2} - \frac{N\pi A\varepsilon_s^4}{32(D+\varepsilon_s)^3 D^2}\left[1+2\frac{D}{\varepsilon_s}\right]$$

- Ratio of Frictional force to adhesion force for a colloidal particle

$$\mu = F_T / F_N = 3\pi / 16$$

A schematic of a flat, smooth surface and rough spherical colloidal particle.



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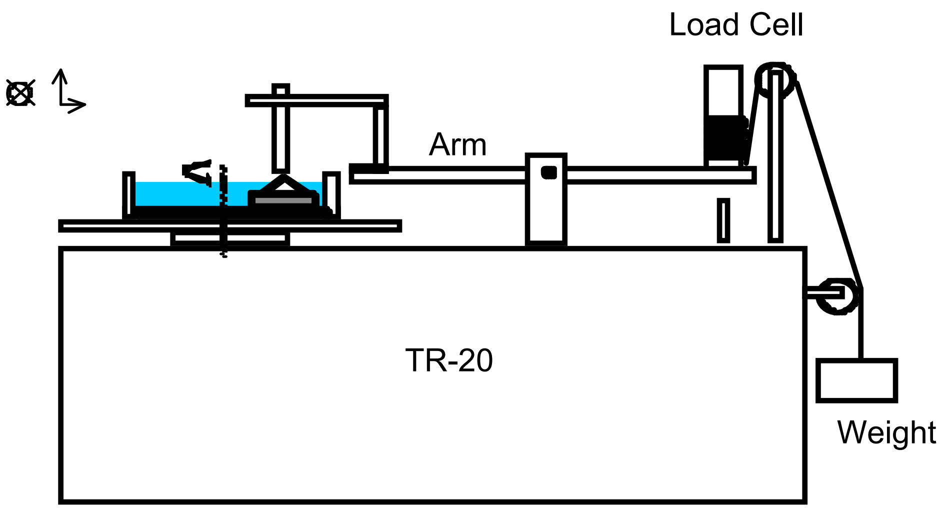
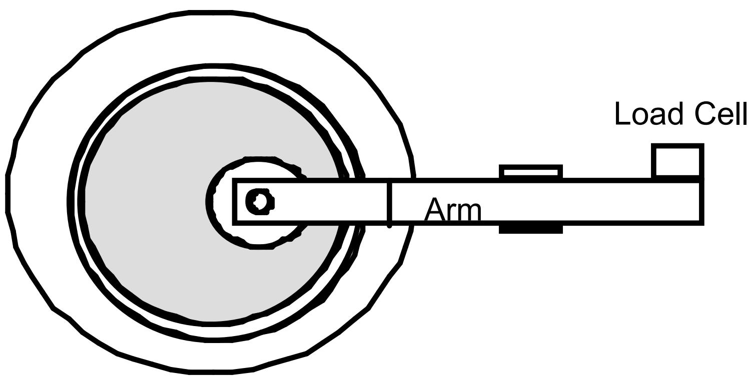
Cleaning Experiment Setup and Measurements

- Rotating Si wafer (4” dia)
- Fixed piece of smooth brush (3/8” dia)
- 5-hr soak in DI
- Friction behavior measured as function of speed and load

Schematic view of test machine



Side View



Top View

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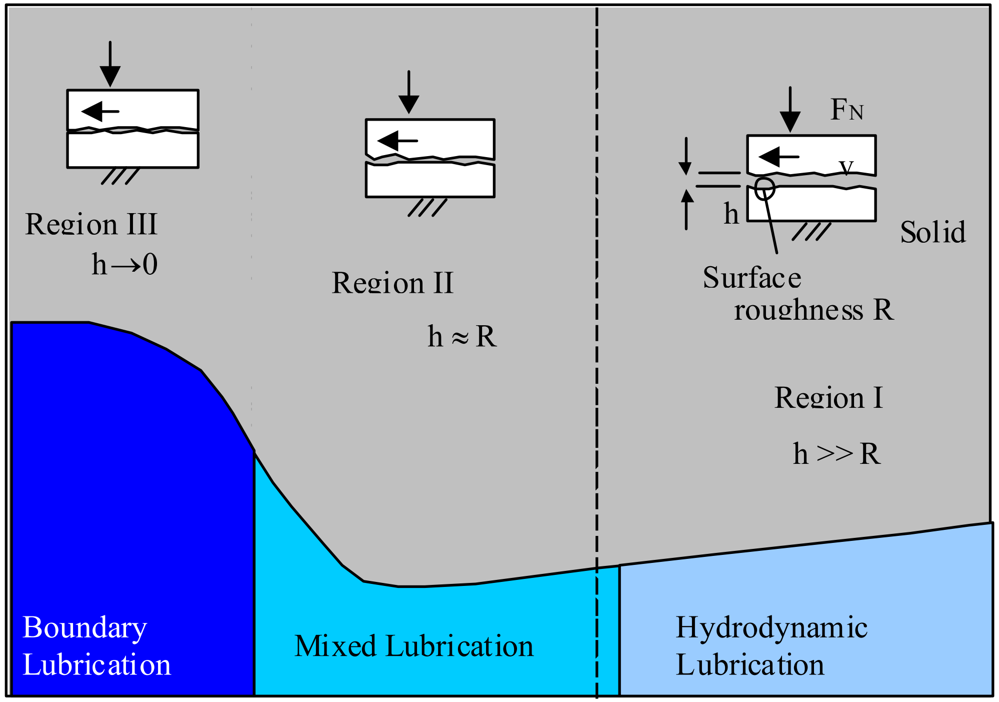
Stribeck Curve and Lubrication Regimes



H. Czichos, Tribology, Elsevier Scientific Publishing Co., New York, 1978

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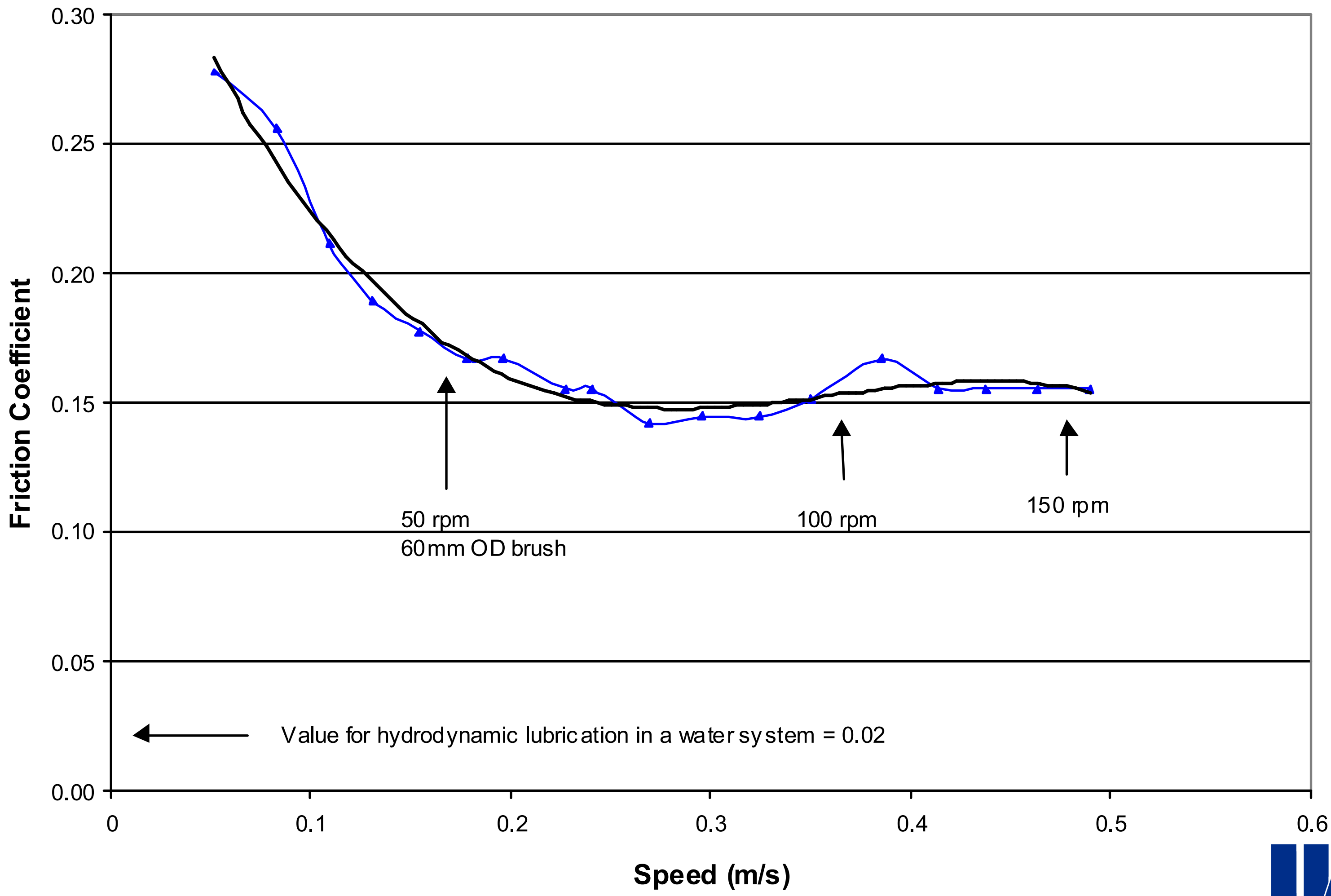
Friction Coefficient versus Speed (in water)



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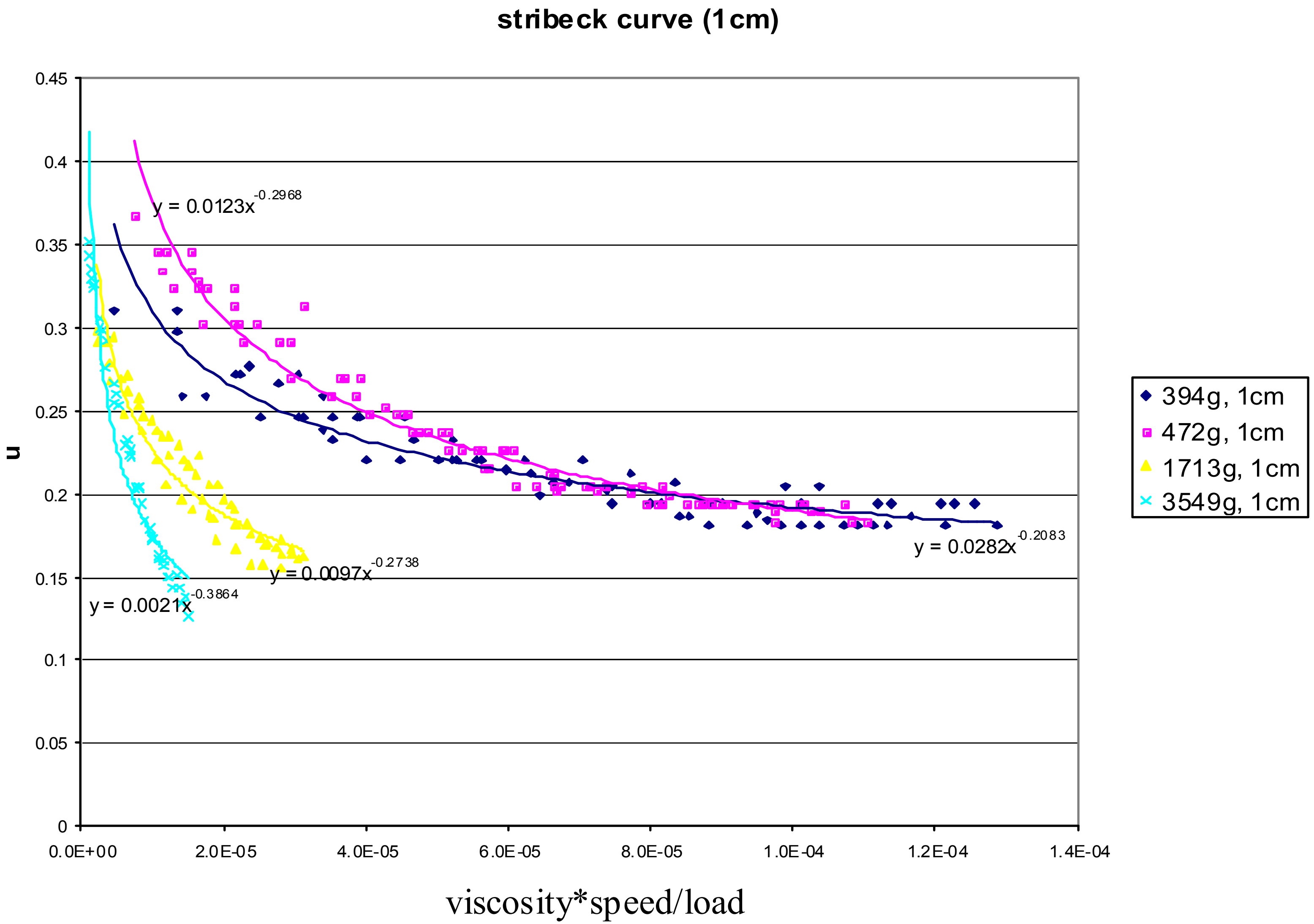

Friction curves with different loads (1 cm thick brush)

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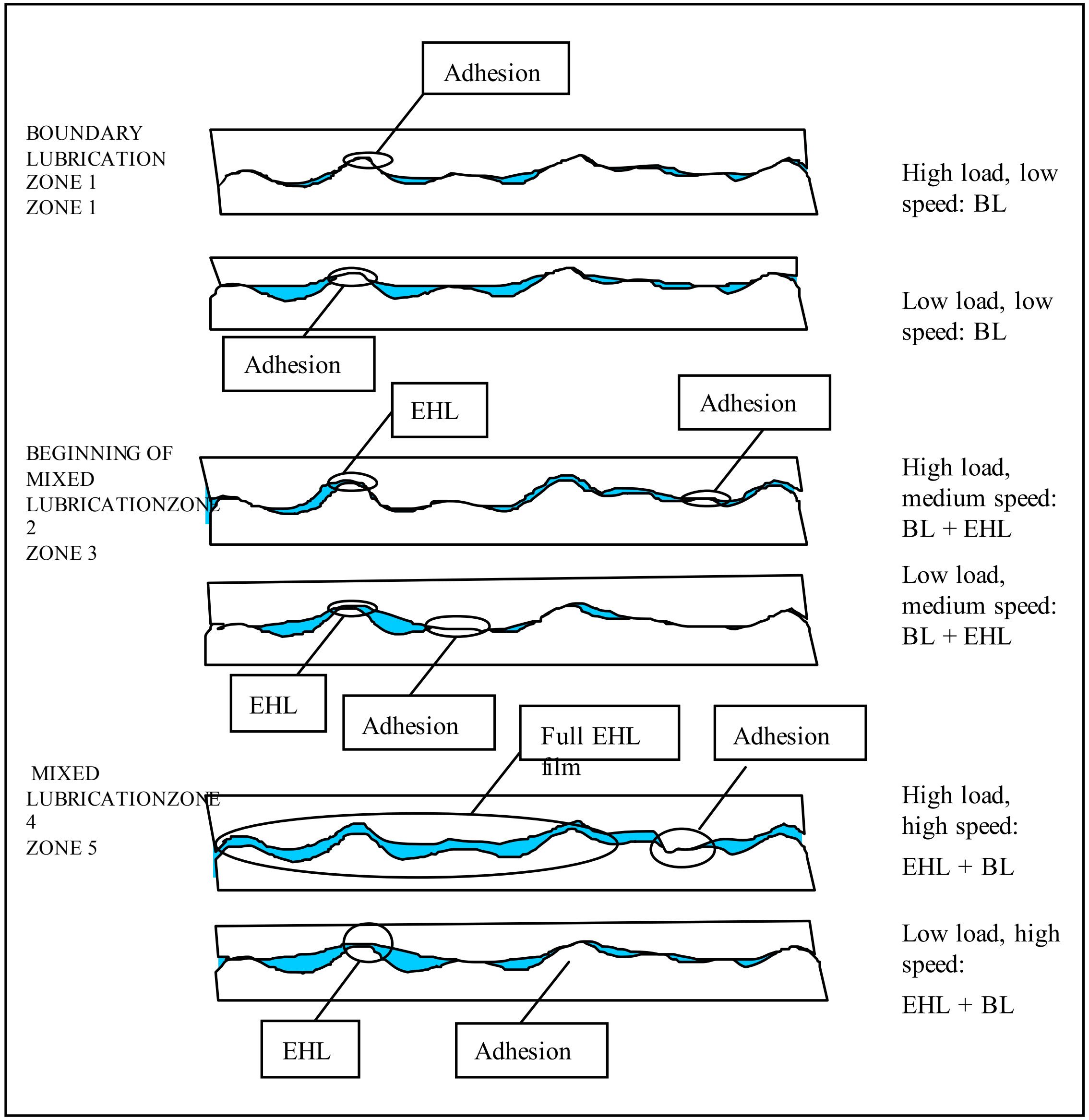
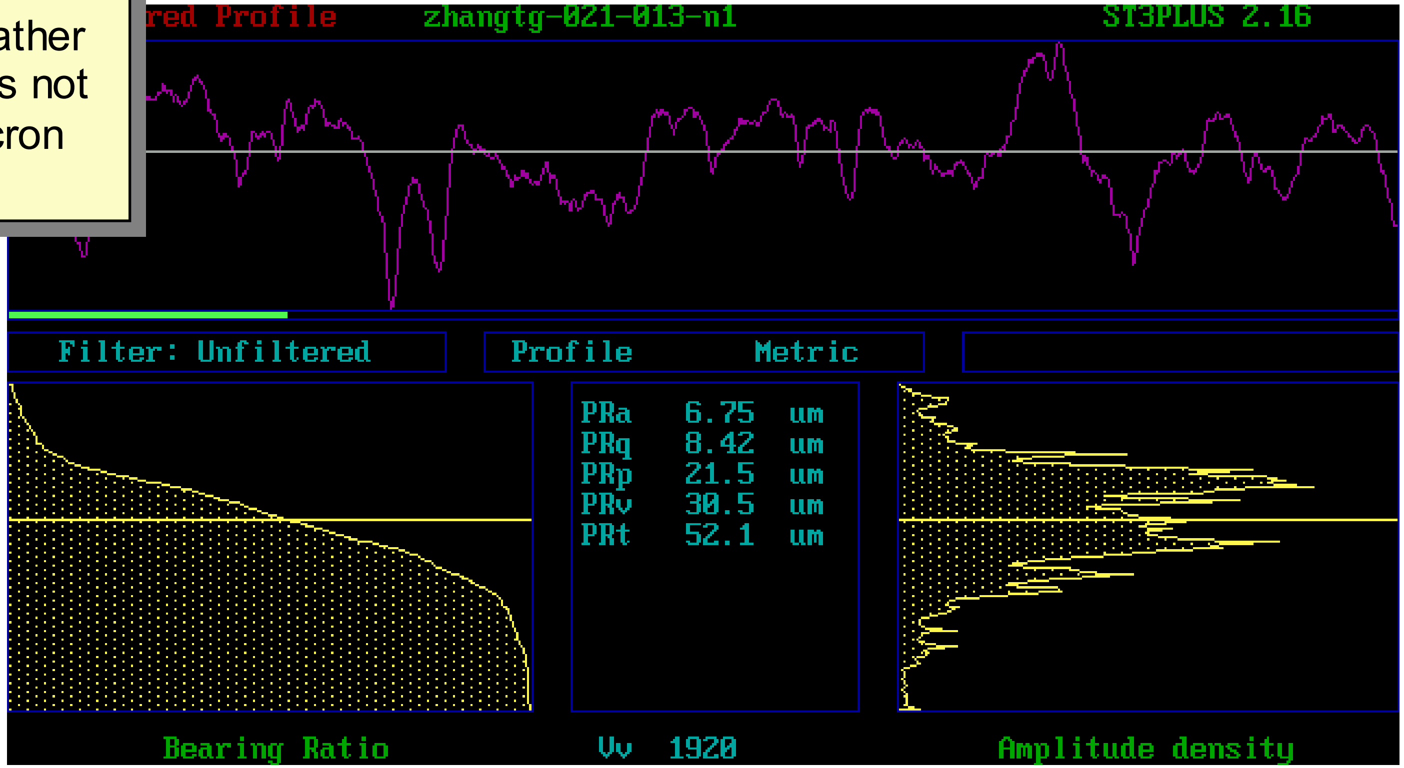
Regimes of Sliding Contact



This slide shows the surface roughness measurement on brush using the TaylorSurf Profilometer. Even through the roughness (Ra=6.75 μm) is rather large the surface is not smooth at sub micron level.



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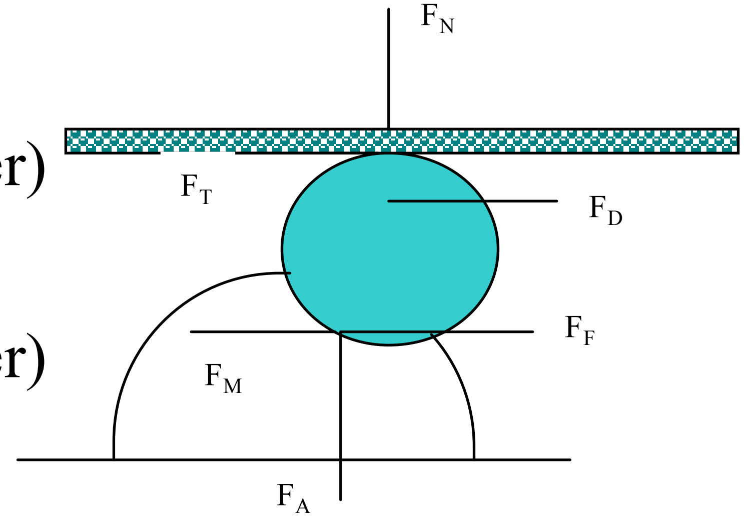
❖ Forces applied on a colloidal particle during cleaning



- F_N adhesion force between particle and substrate (wafer)
- F_T frictional force between particle and substrate (wafer)
- F_A adhesion force between particle and brush
- F_F frictional force between particle and brush
- F_D Hydrodynamic drag force
- F_M Mechanical (contact) force

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- FEA of interaction between one particle and one asperity on brush surface

The particle on the substrate surface is assumed rigid and the soft asperity represent the micro roughness of brush surface. The mechanical interaction between the particle and the brush surface is modeled as contact behavior in 2-D situation. While the asperity slides through the particle in steady state, contact forces are calculated.

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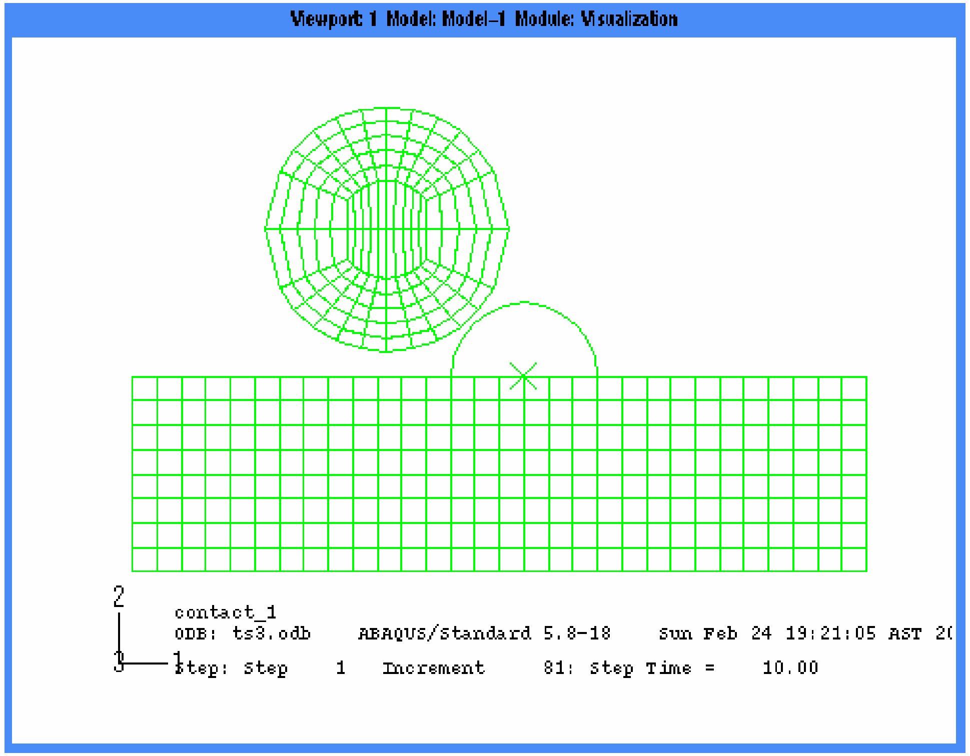
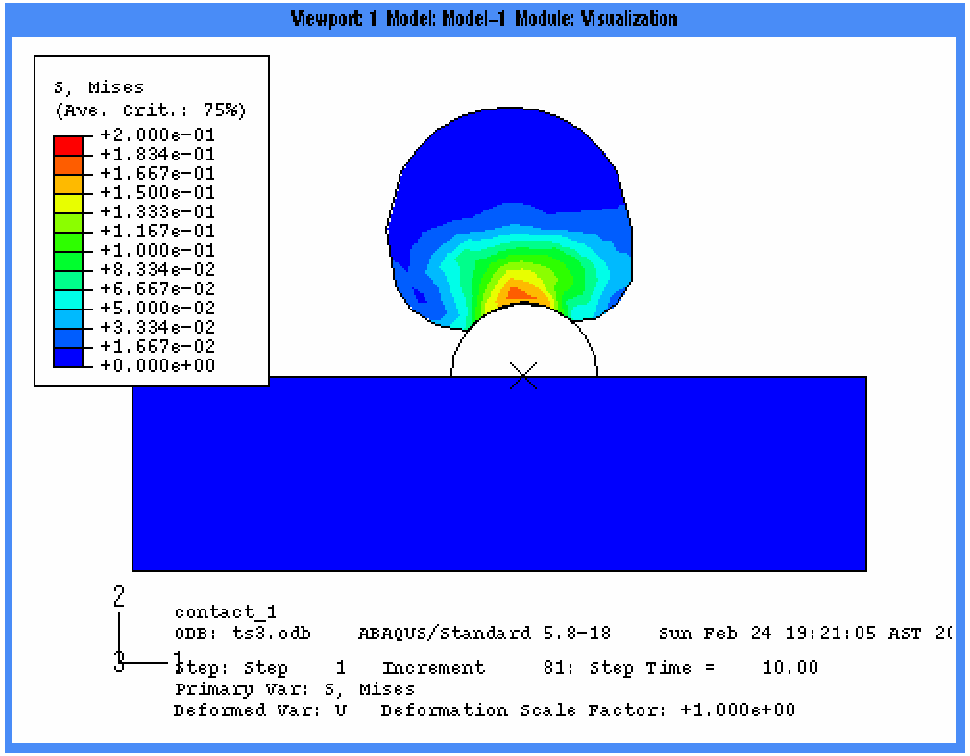
❖ FEA mesh for contact of particle and asperity of brush



❖ FEA results for contact of particle and asperity of brush



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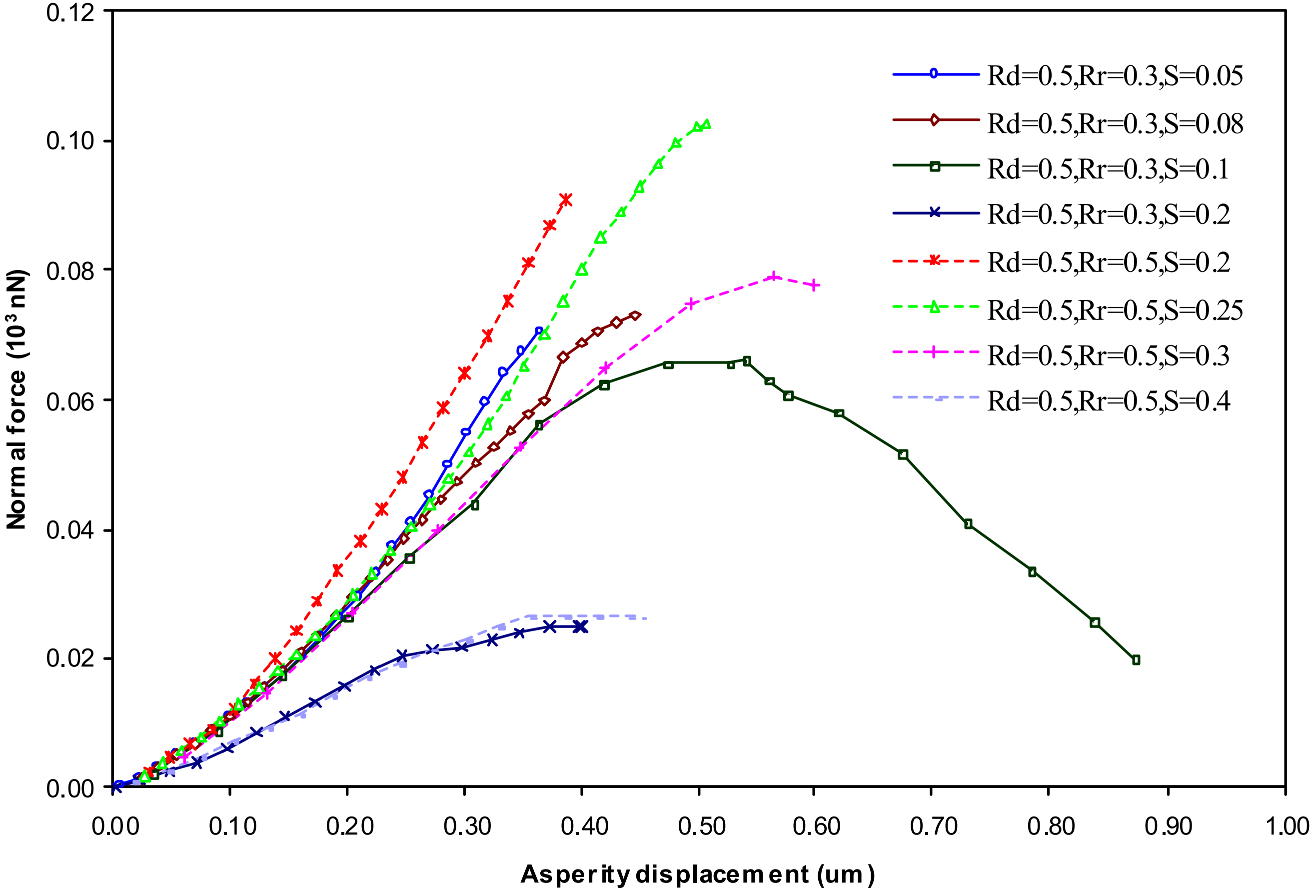
❖ Normal Force versus Displacement



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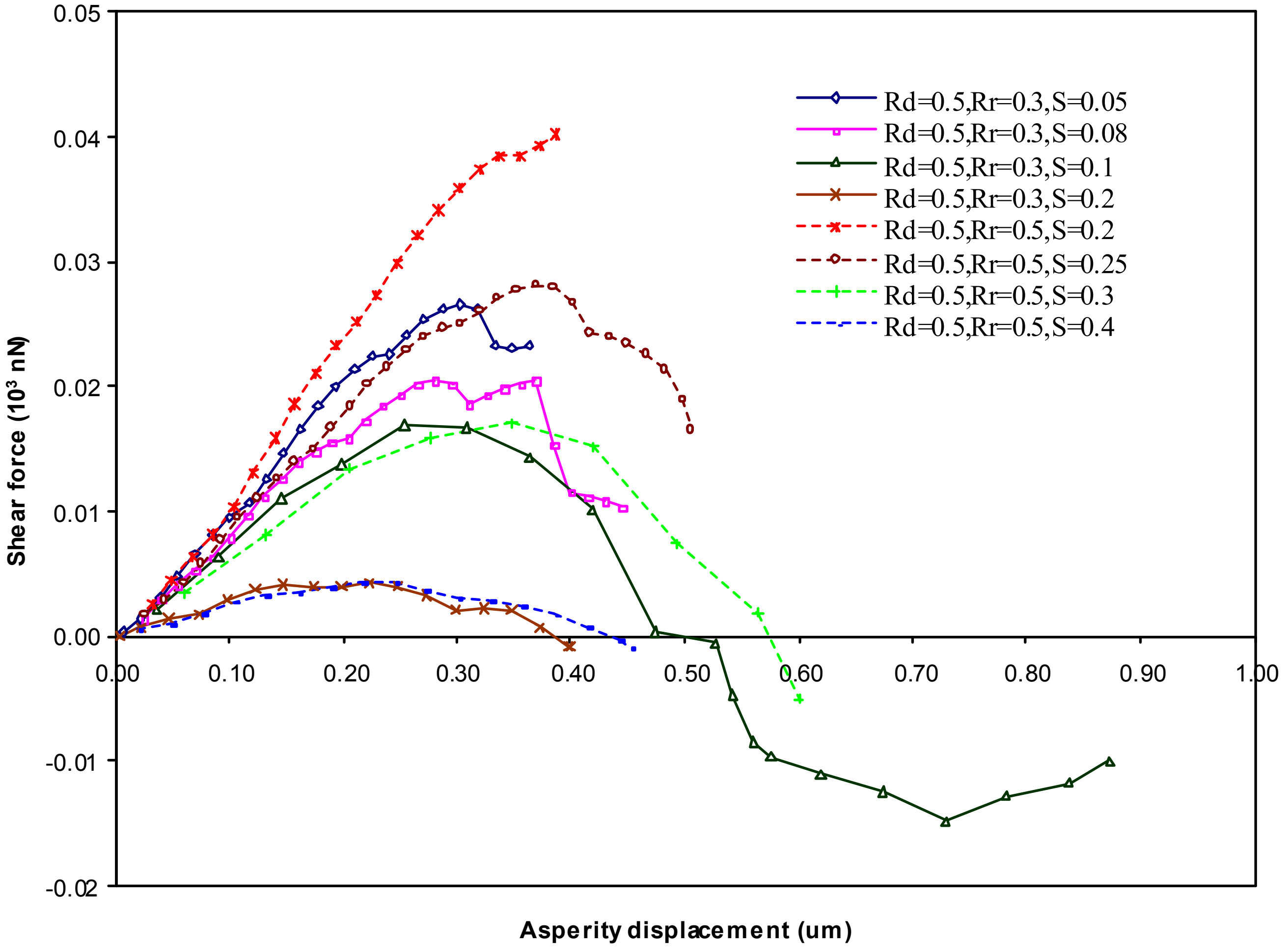
❖ Shear Force versus Displacement



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❖ Example

A colloidal particle with radius R=0.3 µm, asperity radius of 0.5 µm and a separation distance of 0.05 µm. The forces applied on the particle are calculated from the above equations using Hamaker constant $A=1.6*10^{-20}$ (J).

- $F_N = 9$ nN
- $F_T = 5.3$ nN
- $F_M = 25$ nN (Shear force from FEA results)
- $F_A = 2\pi WR(1+r^2/RD)$
- $F_F = \mu F_A$

W is thermodynamic work of adhesion, r is contact radius, and D is separation.

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❖ Cleaning Mechanisms

- Particle removal by large adhesion and friction forces F_A and F_F.
- Particle removal by the combination of mechanical force F_M and adhesion and frictional forces F_A and F_F.
- Particle removal by mechanical force F_M alone.

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❖ Conclusions:

- Frictional forces must be considered for removal force estimates.
- Total force needed to removal a particle is a combination of adhesion force and frictional force.
- For particle removal we must consider the mechanical properties of the brush asperities and the adhesion between the brush and the particle.

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