Experimental and Numerical Analysis of an Inhibitor-Containing Slurry for Copper CMP

Y. Zhuang, Z. Li and A. Philipossian (University of Arizona)

L. Borucki (Intelligent Planar)

Y. Shimazu and N. Uotani (Showa Denko K.K., Japan)

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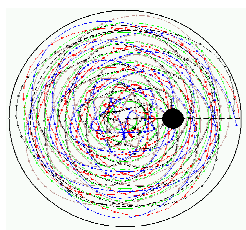

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Outline

1. Objectives
2. Experimental Apparatus and Conditions
3. Experimental Results
4. Numerical Analysis
5. Conclusions

Objectives

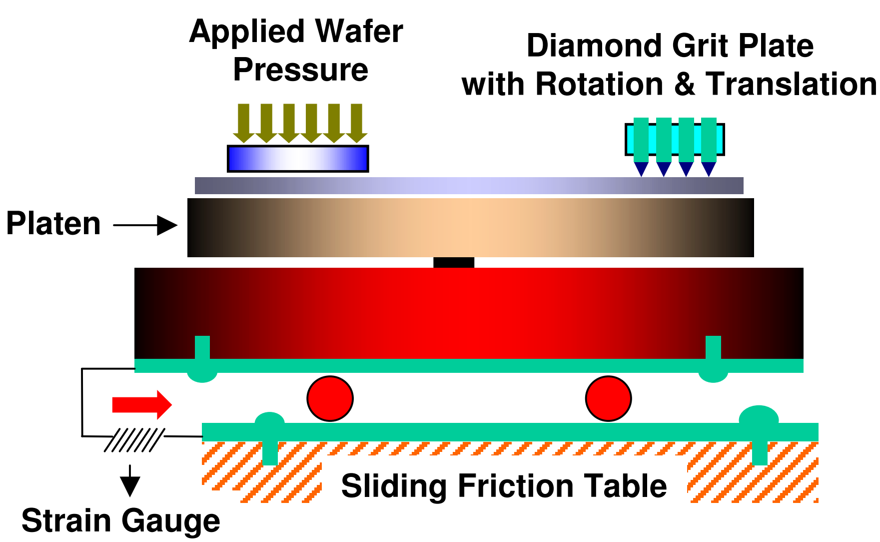
1. Investigate the tribological, thermal and kinetic attributes of an inhibitor-containing slurry for copper CMP.

2. Perform numerical analysis to simulate wafer temperature and removal rate for this inhibitor-containing slurry during copper CMP.

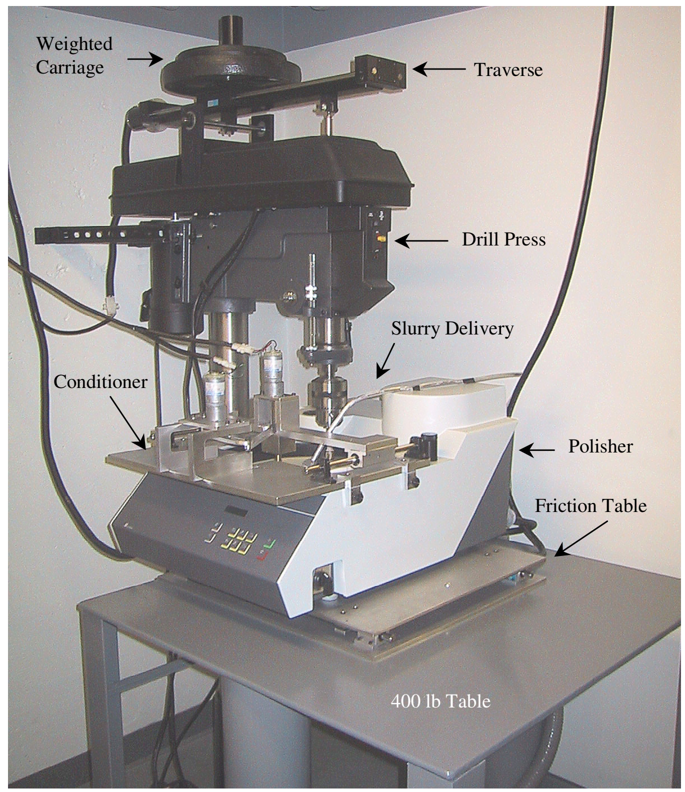
3. Determine the chemical and mechanical component dominance for this inhibitor-containing slurry during copper CMP.

Experimental Apparatus

Parameter	Scaling Factor	Speedfam-IPEC 472	Scaled Polisher
Down Pressure	1	4 PSI	4 PSI
Platen Speed	Reynolds Number	Relative pad-wafer velocity of 0.5 m per second (30 RPM)	Relative pad-wafer velocity of 0.5 m per second (55 RPM)
Platen Diameter / Wafer Diameter	D_{platen} / D_{wafer}	51 cm / 20 cm	31 cm / ~ 10 cm
Slurry Flow Rate	Platen Surface Area	220 cc per minute	80 cc per minute



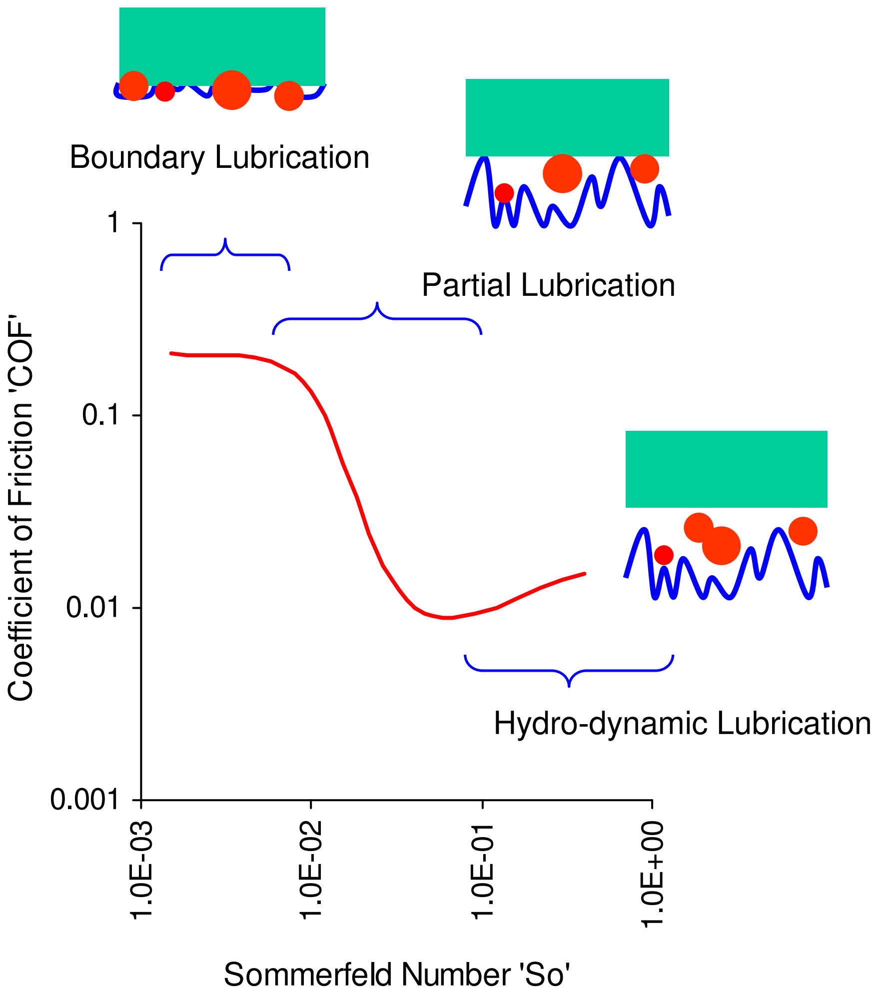
$$COF_{avg} = \frac{\overline{F}_{Shear}}{F_{Normal}}$$



Experimental Conditions

- **Constants**
  - Pad Break-In
    - IC-1000™ K-groove pad
    - Conditioned at 0.5 PSI by 100-grit diamond disk rotating at 30 rpm and oscillating at 0.33 Hz
    - 30 min with UPW
  - Pad In-situ Conditioning
    - Conditioned at 0.5 PSI by 100-grit diamond disk rotating at 30 rpm and oscillating at 0.33 Hz
  - Wafer
    - 4-inch blanket copper wafer
    - 20,000 A PVD copper film on top of a 1000 A PVD tantalum barrier layer
- **Constants (continued):**
  - Slurry
    - Inhibitor: BTA
    - Oxidizer: Hydrogen Peroxide
    - Flow rate: 80 cc per minute
- **Variables**
  - Wafer-Pad Sliding Velocity
    - 0.32 m/s (40 rpm)
    - 0.64 m/s (80 rpm)
    - 1.12 m/s (140 rpm)
  - Polishing Pressure
    - 1.5 PSI
    - 2.0 PSI
    - 2.5 PSI

Lubrication Theory in CMP Process



$$COF = \frac{F_{Shear}}{F_{Normal}}$$

Slurry viscosity

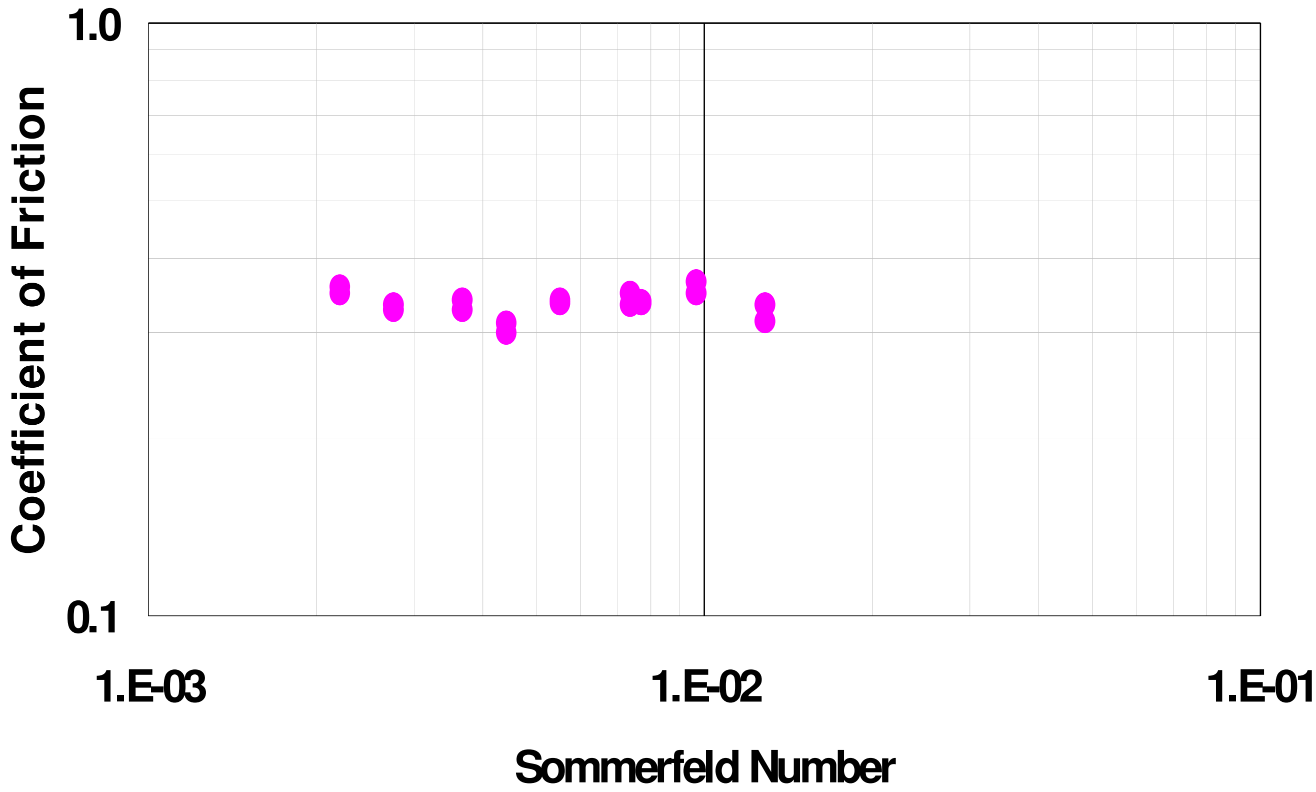
Relative wafer-pad velocity

$$So = \frac{(V) \times (\mu)}{(P) \times (\delta_{eff})}$$

Polishing Pressure

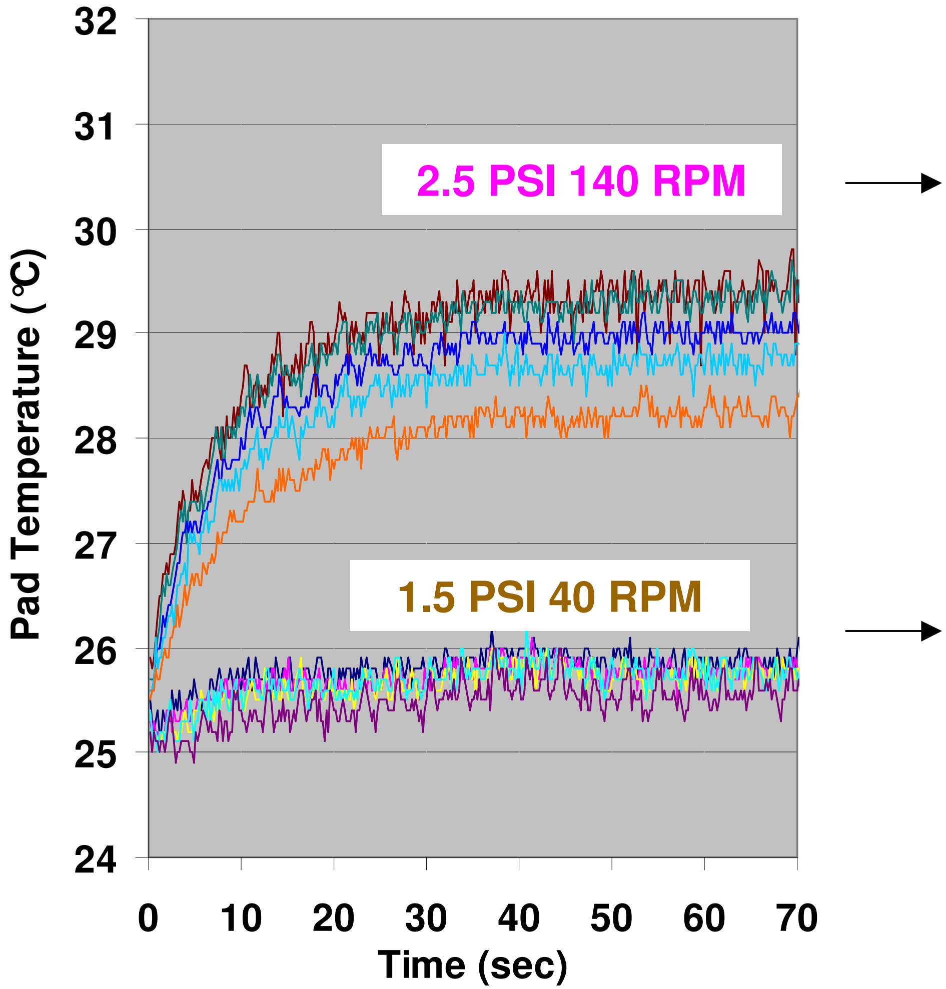
Effective slurry film thickness

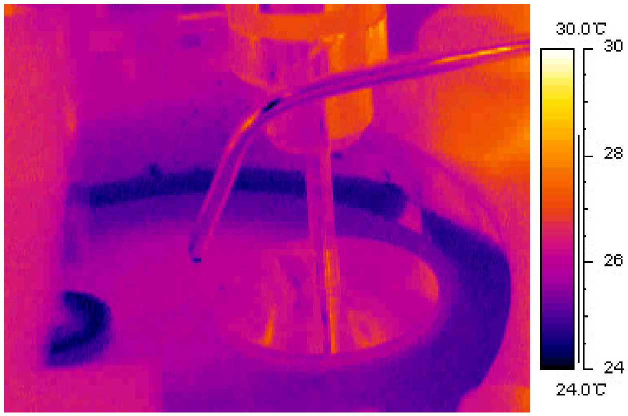
Experimental Results: Tribological Characteristics

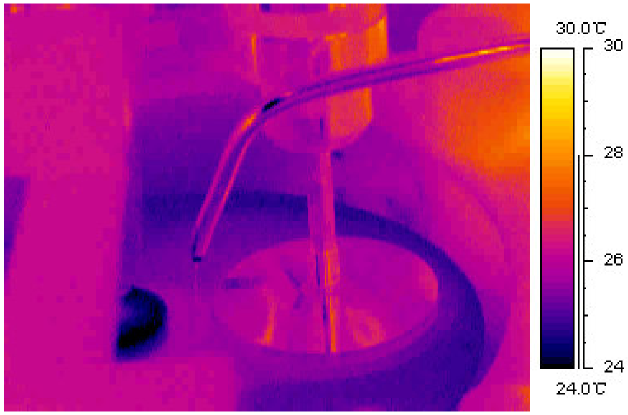


Tribological mechanism is ‘Boundary Lubrication’

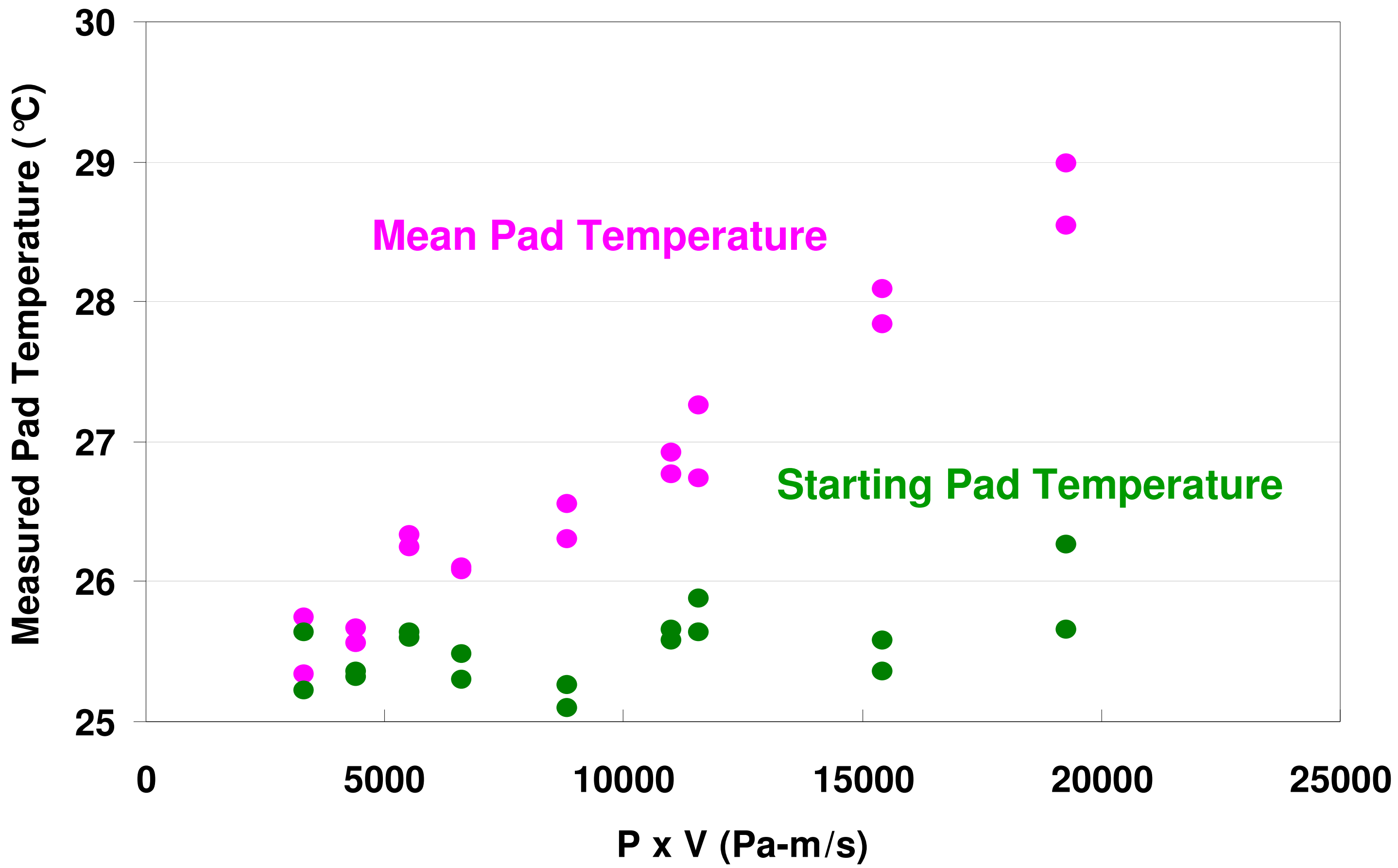
Experimental Results: Pad Surface Thermal Imaging



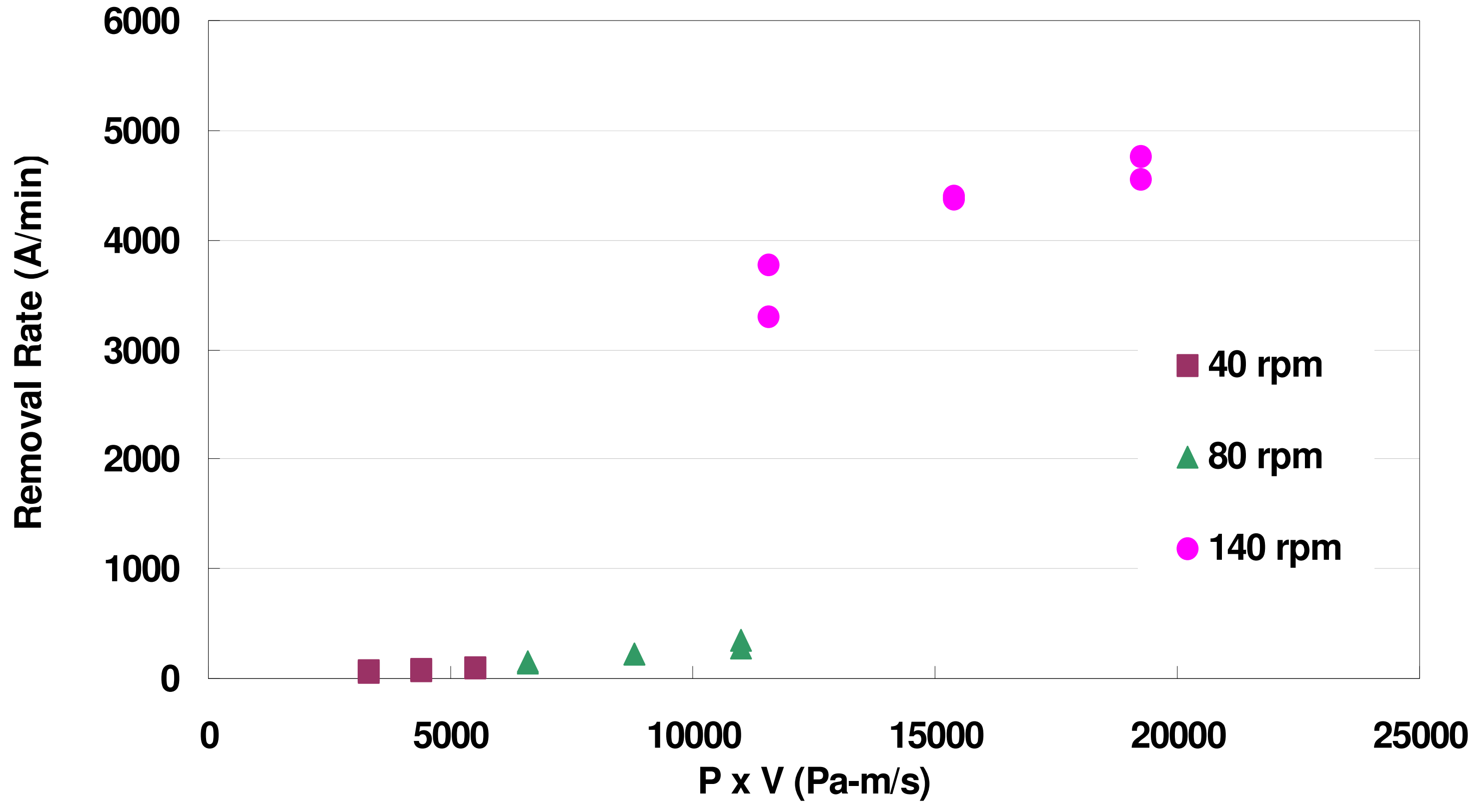




Experimental Results: Pad Temperature



Experimental Results: Removal Rate

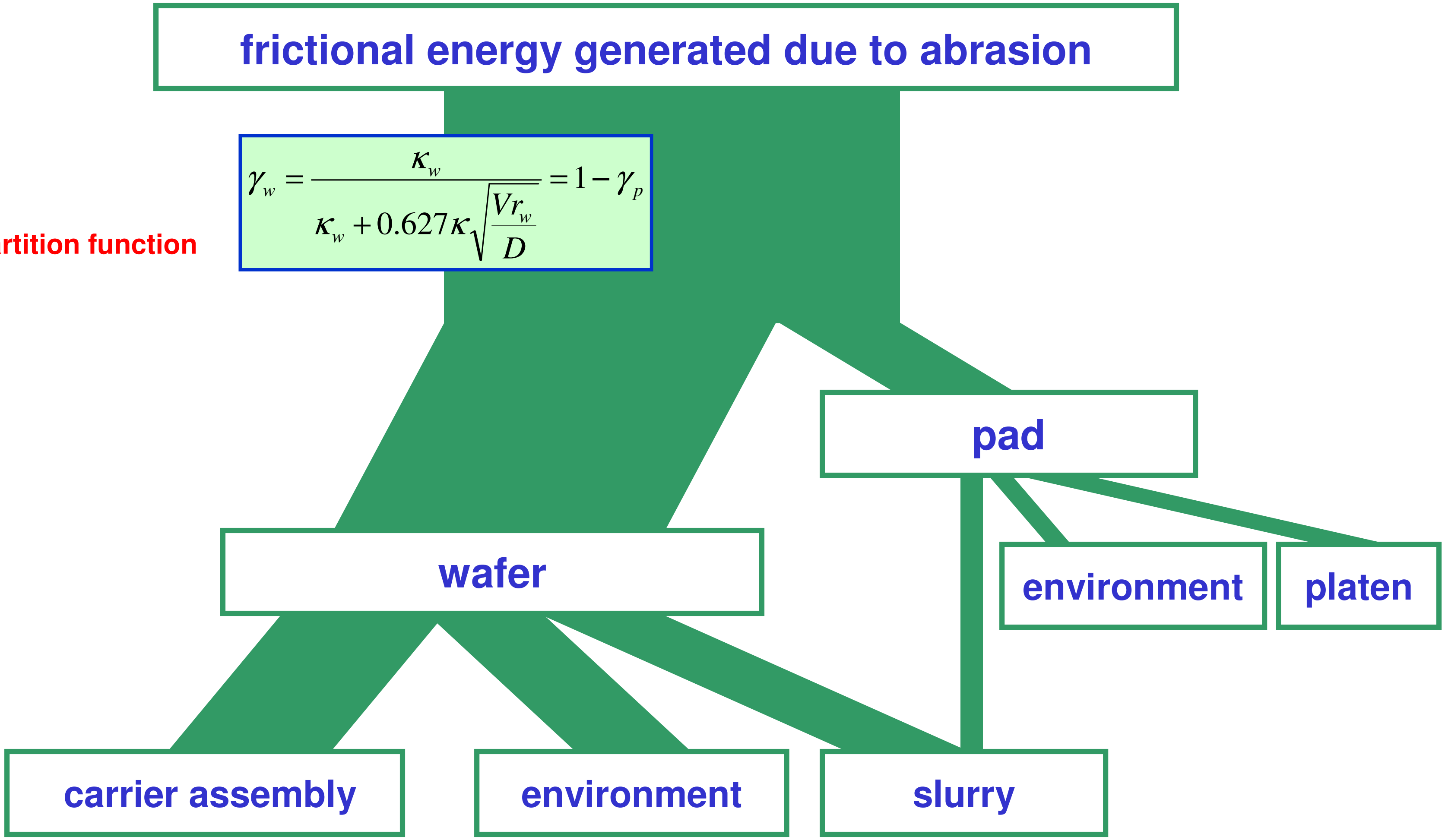


The non-Prestonian behavior is believed to be due to the presence of inhibitor in the slurry

Numerical Analysis: Thermal Model

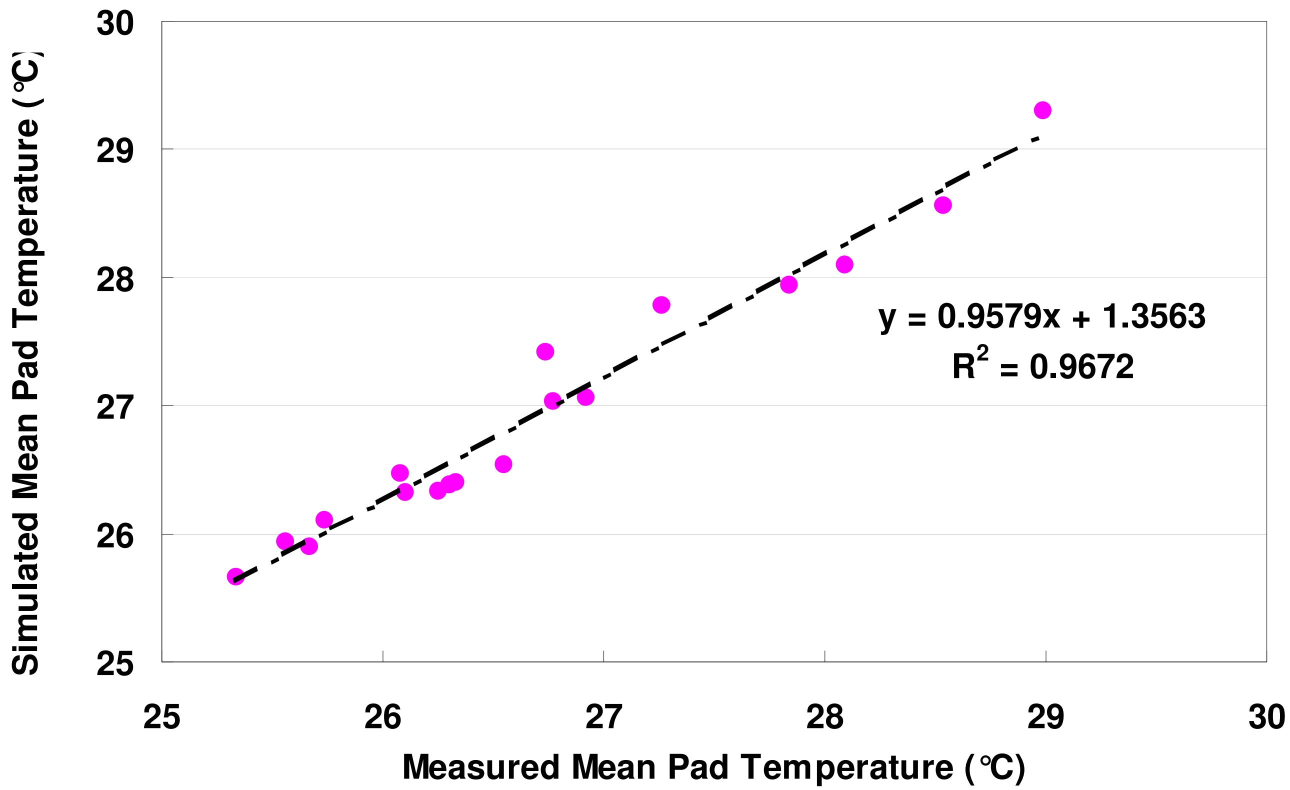
heat partition function

$$\gamma_w = \frac{\kappa_w}{\kappa_w + 0.627\kappa\sqrt{\frac{Vr_w}{D}}} = 1 - \gamma_p$$



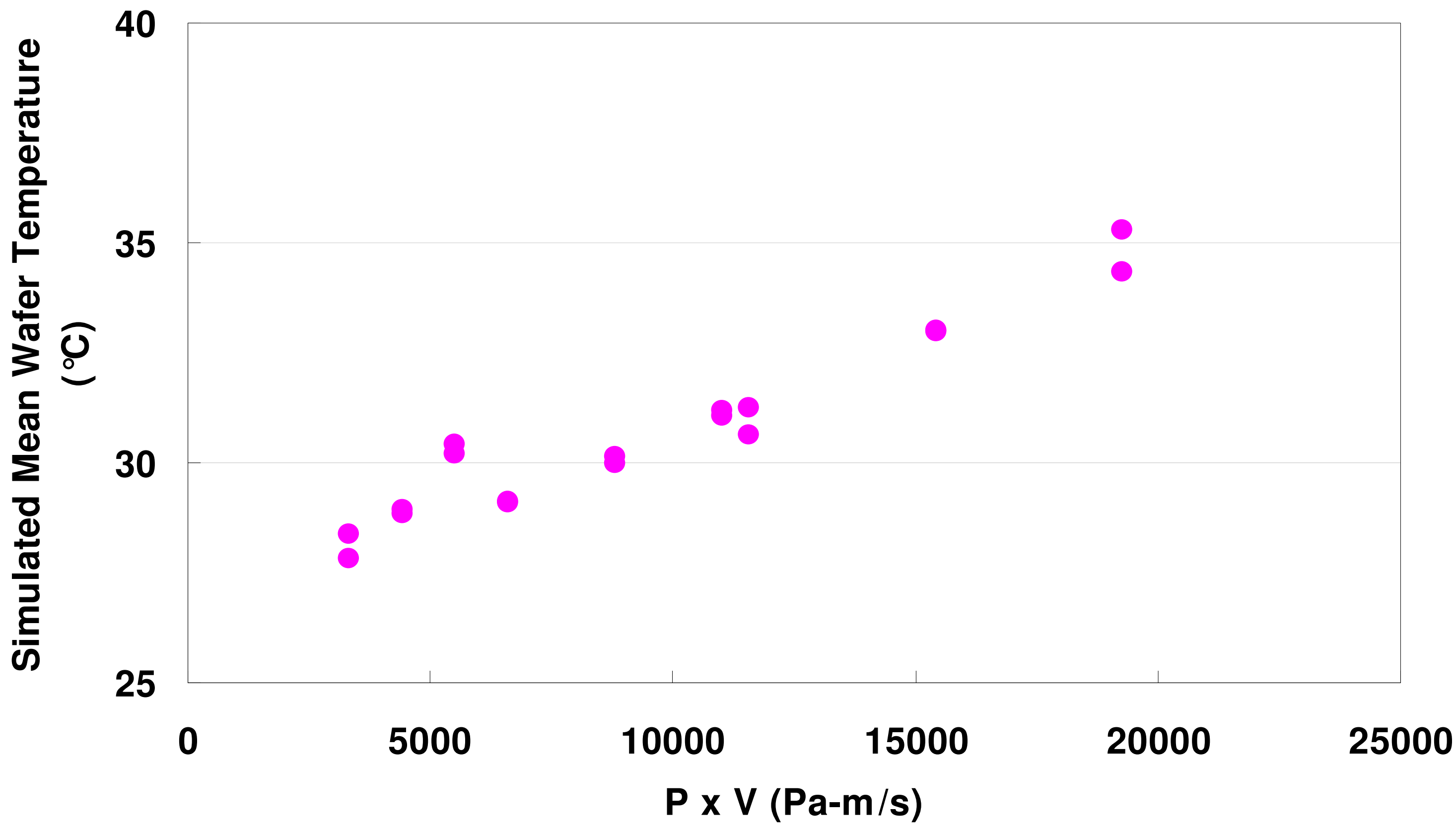
(Journal of the Electrochemical Society, 151 (7), G482, 2004)

Numerical Analysis: Pad Temperature



Simulated mean pad temperatures agree very well with the measured data.

Numerical Analysis: Wafer Temperature



Simulated wafer temperature is higher than simulated/measured pad temperature, and has minimal effect on the significant increase in RR

Numerical Analysis: Removal Rate Model

- When P x V < 11000 Pa-m/s, an inhibitor-protected layer (BTA-Cu) is formed on the copper surface. Copper RR is assumed to be determined by the mechanical removal of this surface layer as described by Preston Equation:

$$RR = \frac{M_w}{\rho} C_p PV$$

- When P x V > 11500 Pa-m/s, the adsorbed inhibitor is assumed to be removed instantly from the surface rendering minimal inhibition effect. Copper RR follows the modified Langmuir-Hinshelwood model:
  - *n* moles of reactant *R* in the slurry react at rate k_1 with copper film on the wafer to form a product layer $\underline{L}$ on the surface

$$\underline{Cu} + nR \xrightarrow{k_1} \underline{L} \qquad k_1 = A\exp(-E/kT_w)$$

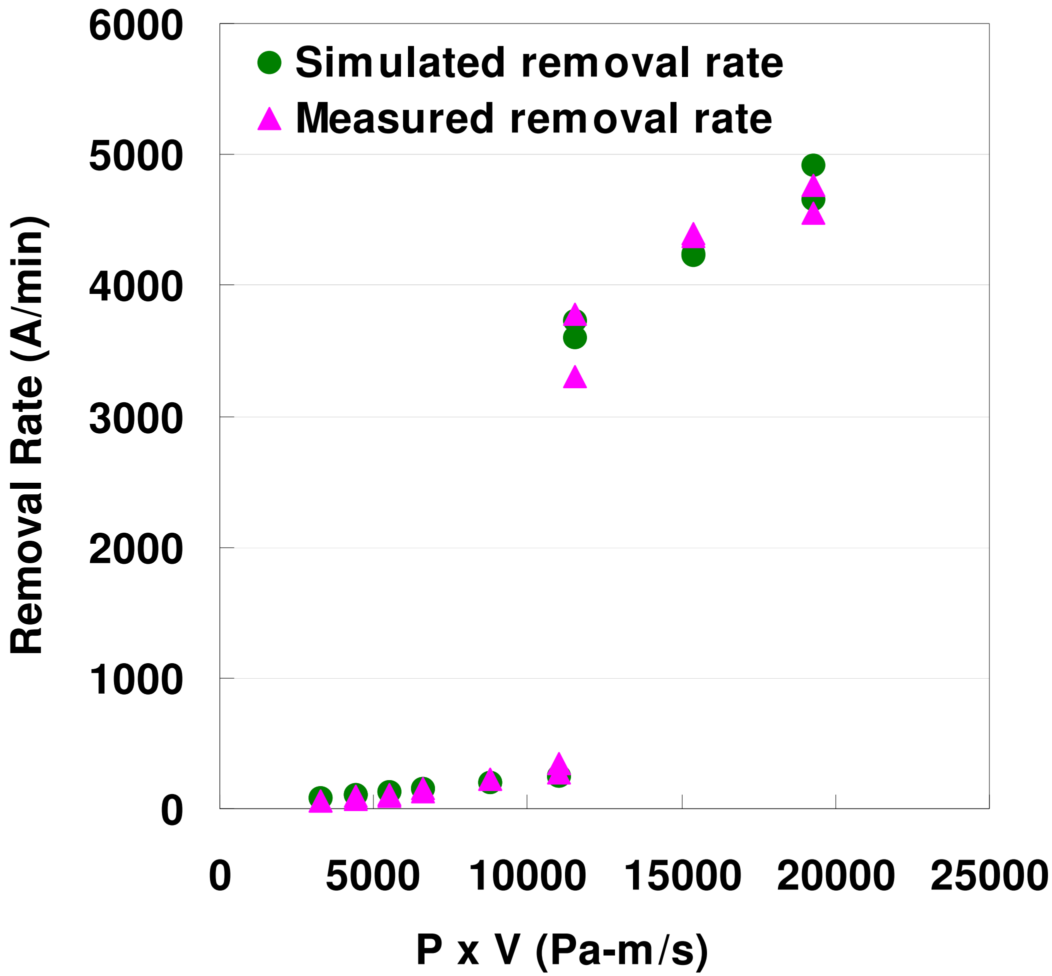
  - Product layer $\underline{L}$ subsequently removed by mechanical abrasion with rate k_2

$$\underline{L} \xrightarrow{k_2} L \qquad k_2 = C_p PV$$

  - Copper removal rate

$$RR = \frac{M_w}{\rho} \frac{k_1}{1 + \frac{k_1}{k_2}}$$

Comparison of Experimental & Simulated RR



- P x V < 11000 Pa-m/s,

C_p = 5.78e-9 moles/Pa-m^3

- P x V > 11500 Pa-m/s,

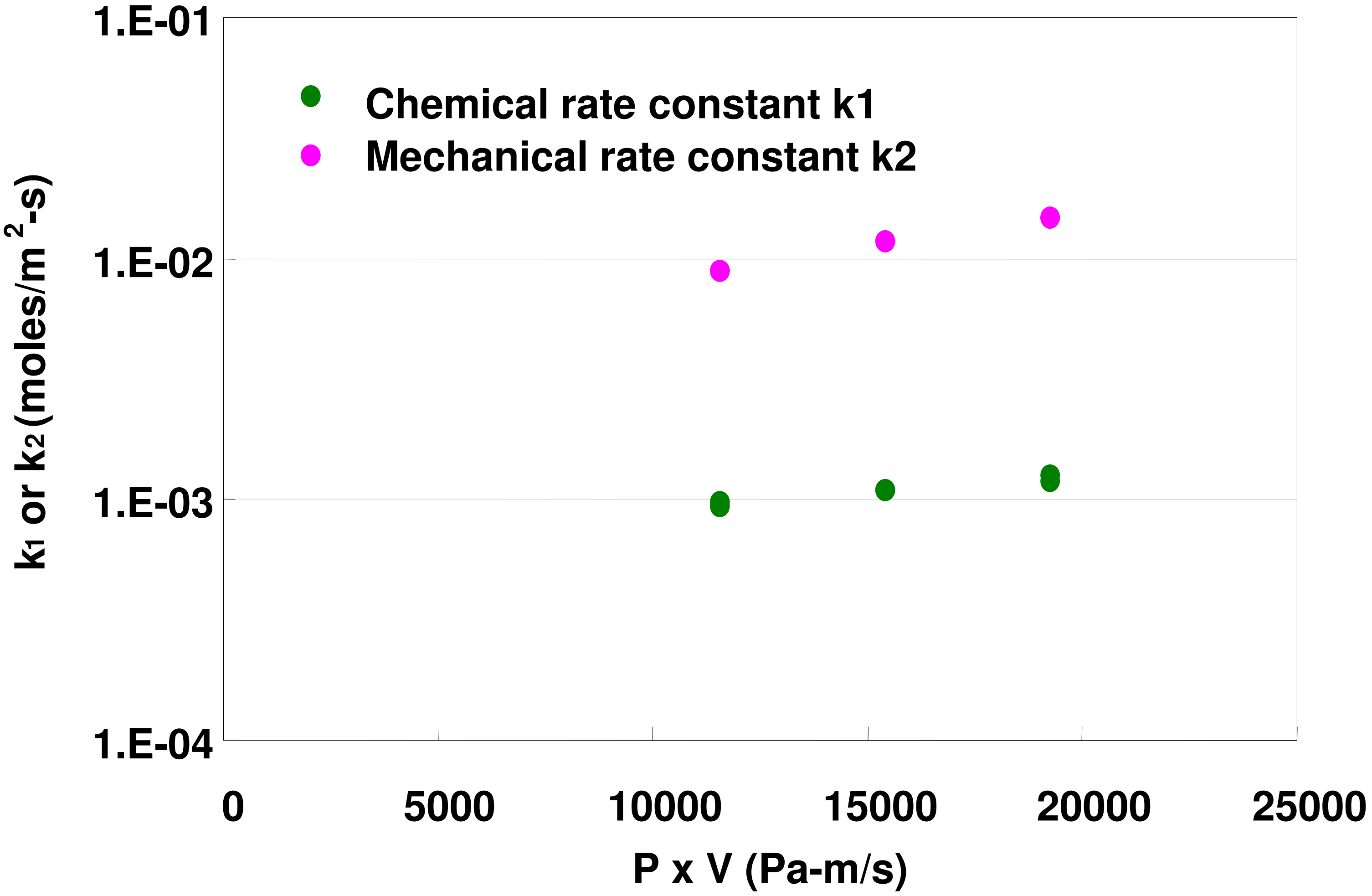
A = 2.68 moles/m^2-sec

E = 0.51 eV

C_p = 7.69e-7 moles/Pa-m^3

Simulated RR is in good agreement with experimental data

Numerical Analysis: k_1 and k_2



Conclusions

- The Stribeck curve shows that Boundary Lubrication is the lubrication mechanism in this study.

- An inhibitor-protected layer is formed on the copper surface, causing low removal rate when P x V is less than 11,000 Pa-m/s.

- When P x V increases to 11,500 Pa-m/s, the inhibitor-protected layer is abraded off rapidly from the surface, resulting in a dramatic increase of the copper removal rate. Temperature effect has minimal contribution to this significant increase of removal rate.

- The modified Langmuir-Hinshelwood model indicates that copper polishing process is chemically controlled at P x V values higher than 11,500 Pa-m/s in this study.

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