Characterization of Thermoset and Thermoplastic Polyurethane Pads, and Molded and Non-Optimized Machined Grooving Methods for Oxide CMP Applications

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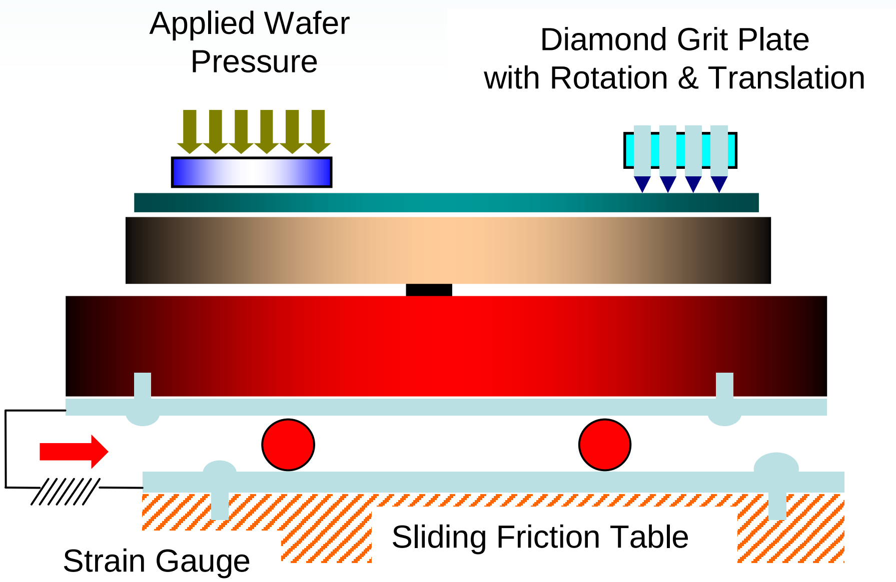
Objectives

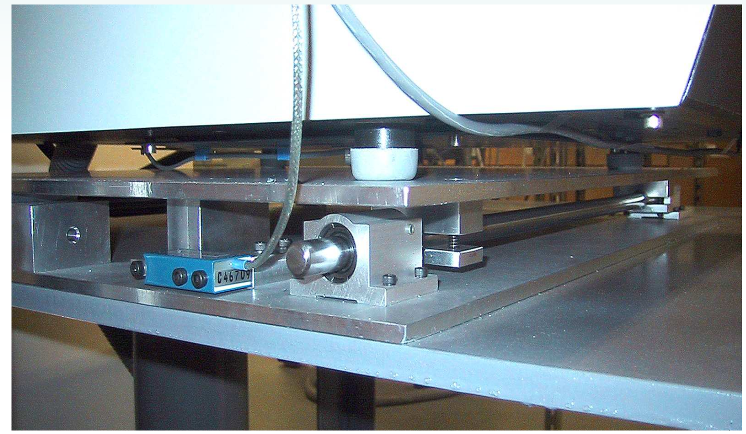
- **Investigate the effect of PU pad synthesis methods (i.e. thermoplastic and thermoset), grooving methods (i.e. molded and non-optimized machined grooving) and groove types (i.e. concentric and 'logarithmic – positive – spiral – positive') on:**
  - **Dynamic Mechanical Analyzer (DMA)**
  - **Coefficient of friction (COF)**
  - **Variance of shear force**
  - **Removal rate (RR)**
  - **Removal rate model**

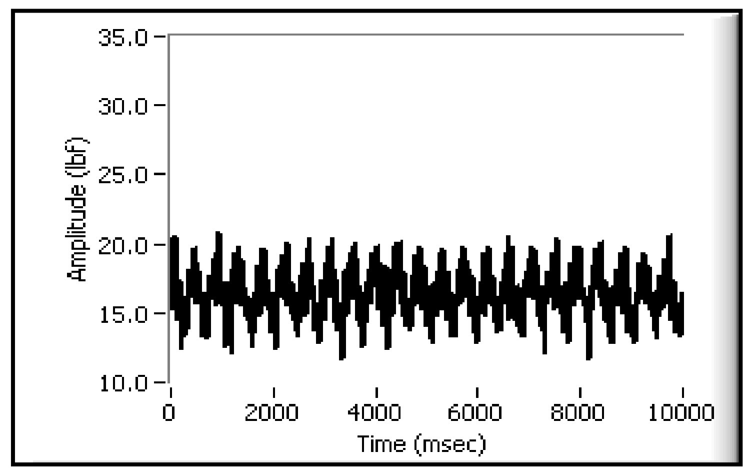
- **Perform simulations using a two-step removal rate mechanism to estimate the chemical and mechanical rate constant**

Polisher & Tribometer



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



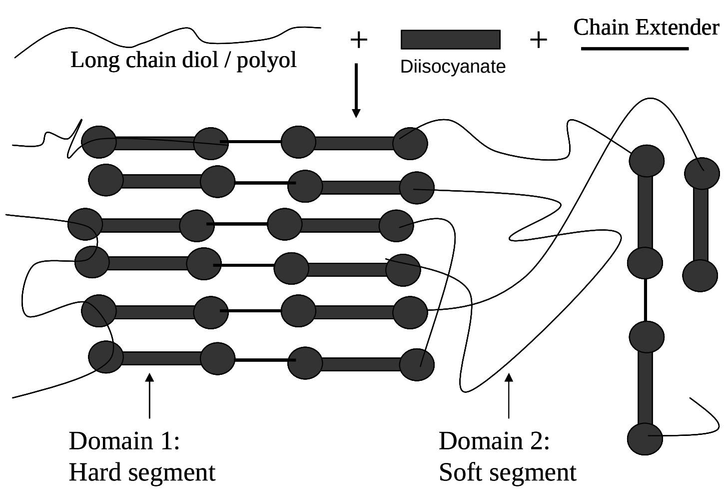


Experimental Conditions

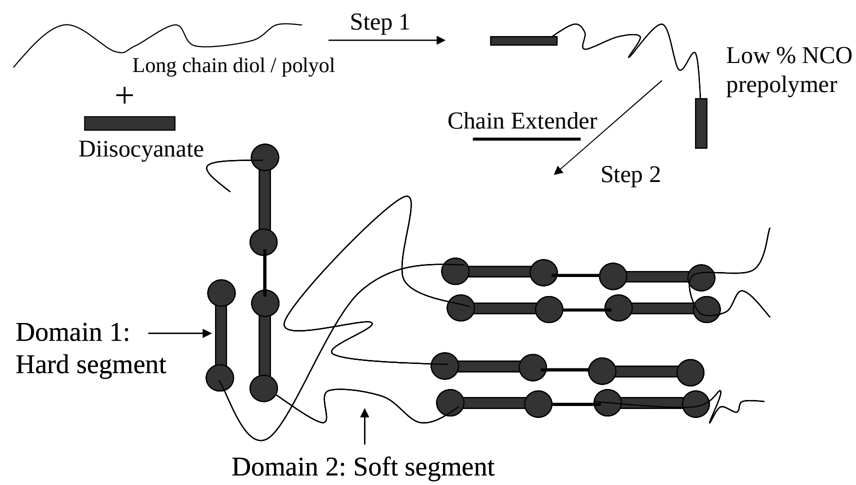
- **Diamond disc conditioner : TBW Industries 100 grit**
- **Conditioning pressure : 0.5 PSI**
- **Conditioning : *In-situ* at 30 RPM disc speed & 20 per minute sweep frequency**
- **Break-in time : 30 minutes**
- **Wafers : 100 mm blanket oxide**
- **Wafer pressure : 2, 3 and 4 PSI**
- **Sliding velocity : 0.32, 0.64, 0.96 and 1.24 m/s**
- **Slurry : Fujimi PL-4217**
- **Slurry flow rate : 80 cc/min**
- **Pad :** **- Thermoplastic non-optimized machined concentric groove**
  - Thermoplastic molded concentric groove
  - Thermoset non-optimized machined concentric groove
  - Thermoset non-optimized machined logarithmic spiral positive groove
- **Polishing time: 60 seconds**

Thermoplastic and Thermoset Synthesis

Single shot synthesis



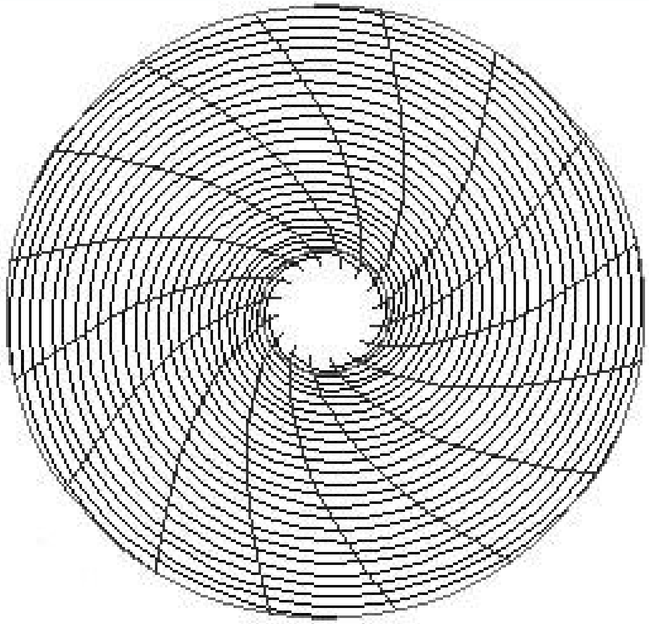
Prepolymer process (Two step synthesis)



Thermoplastic

Thermoset

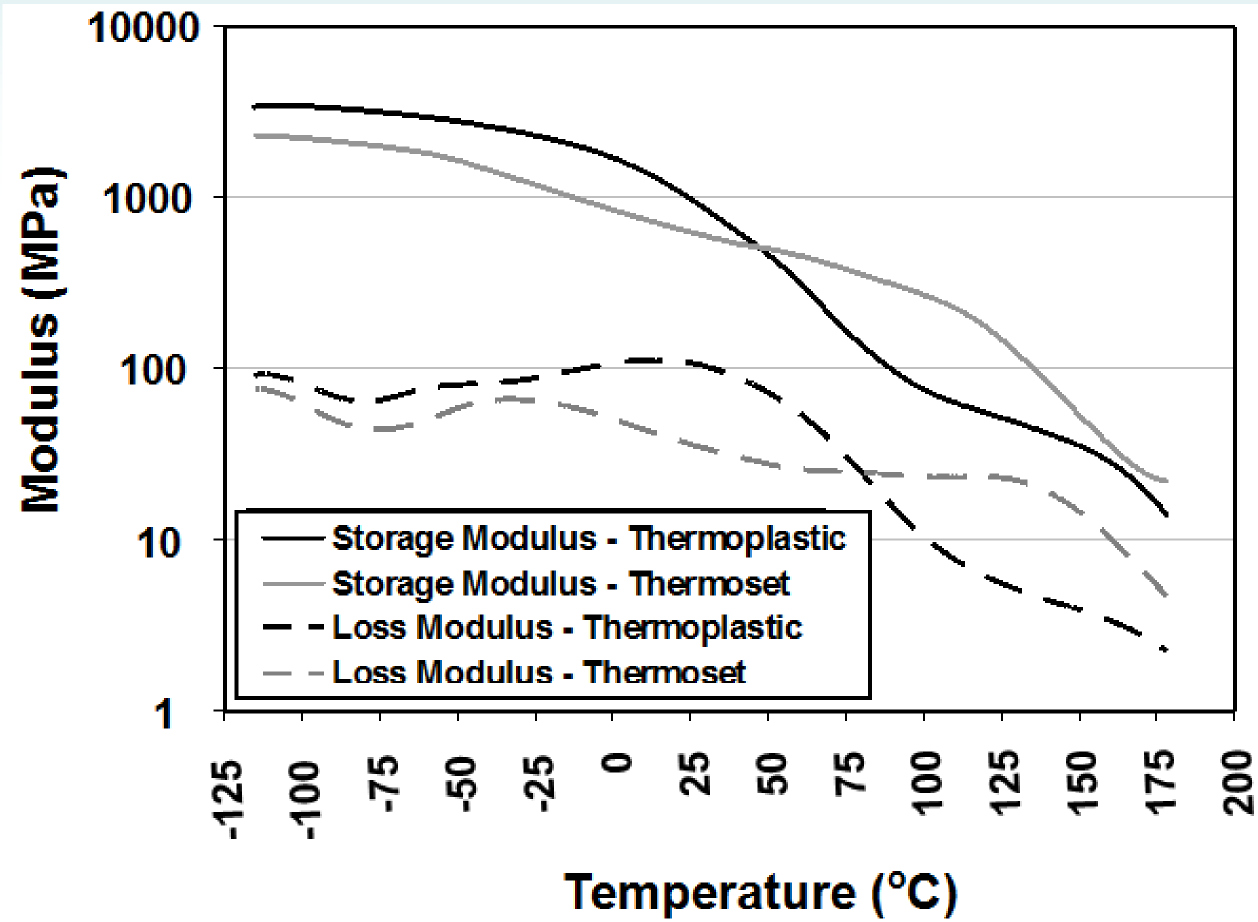
Pad Grooving Types



Logarithmic Positive Spiral Positive (LPSP)

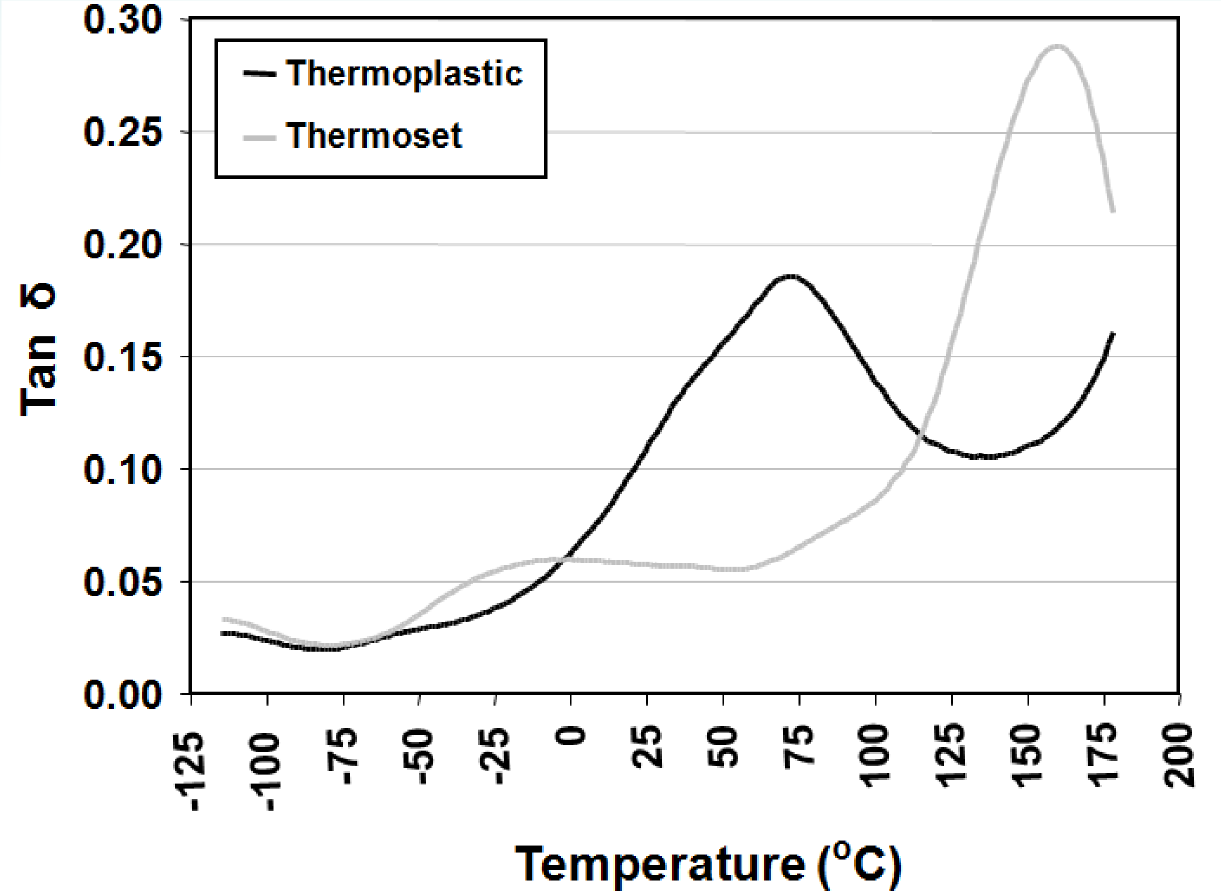
Concentric

DMA Results



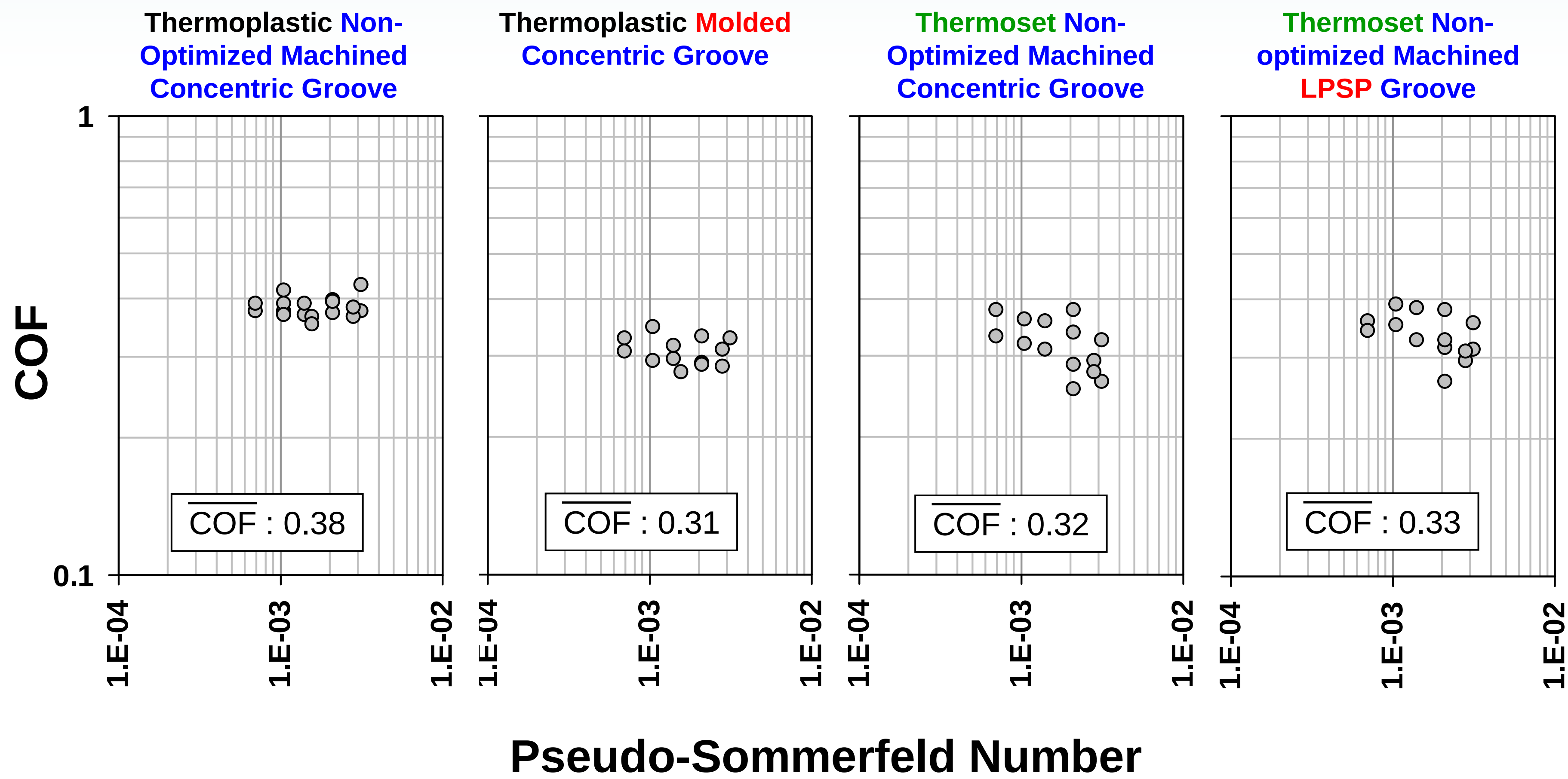
Lightly cross-linked polymers have a steeper modulus slope than more heavily cross-linked polymer. *(Rodriguez, "Principles of Polymer Systems", 1996)*

DMA Results (*cont...*)

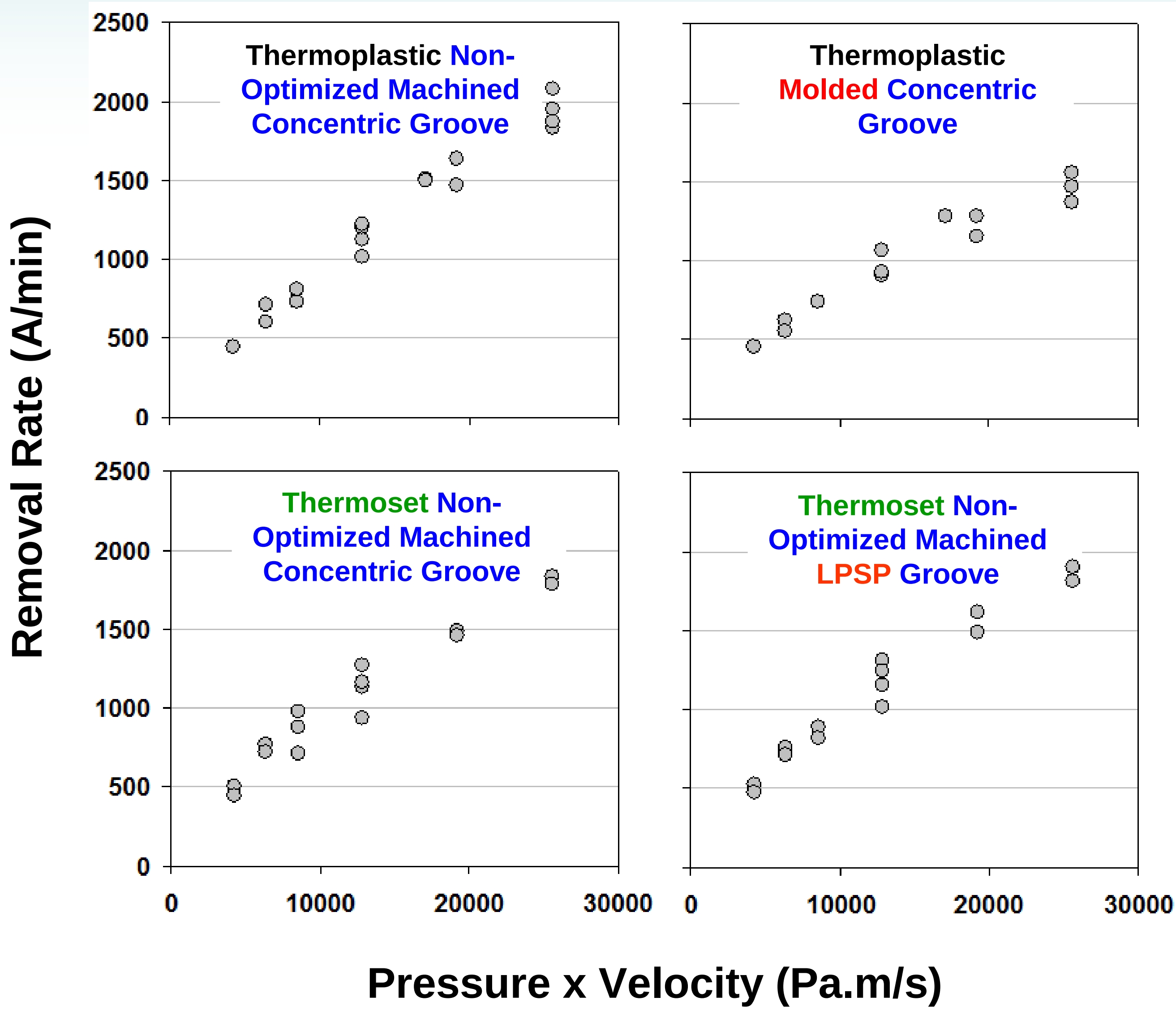


The total energy loss during a stick-slip event is proportional to the damping factor (tan δ) of the material and that this energy must be equated to the external work of friction. *(Moore, "Principles and Applications of Tribology", 1975 and Bartenev & Lavrentev, "Friction and Wear of Polymers", 1981)*

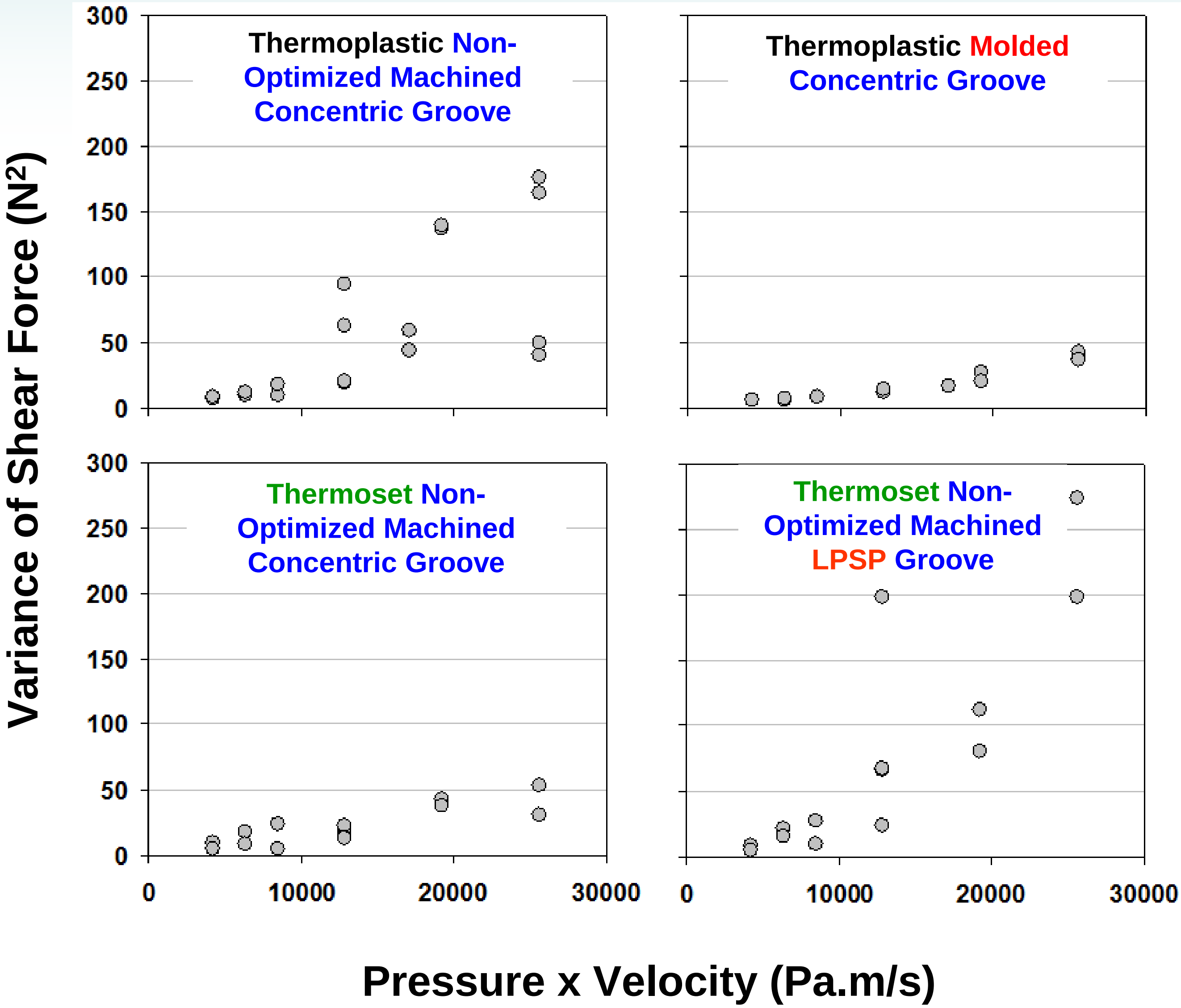
Stribeck Curves



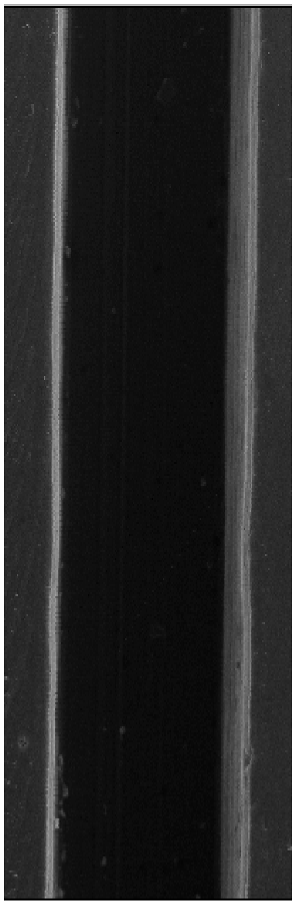
Removal Rate



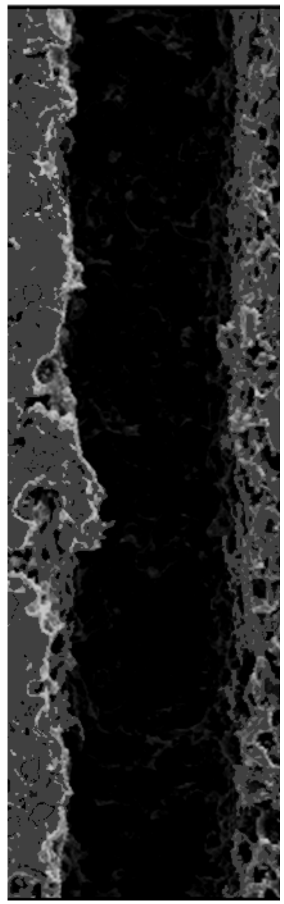
Variance of Shear Force



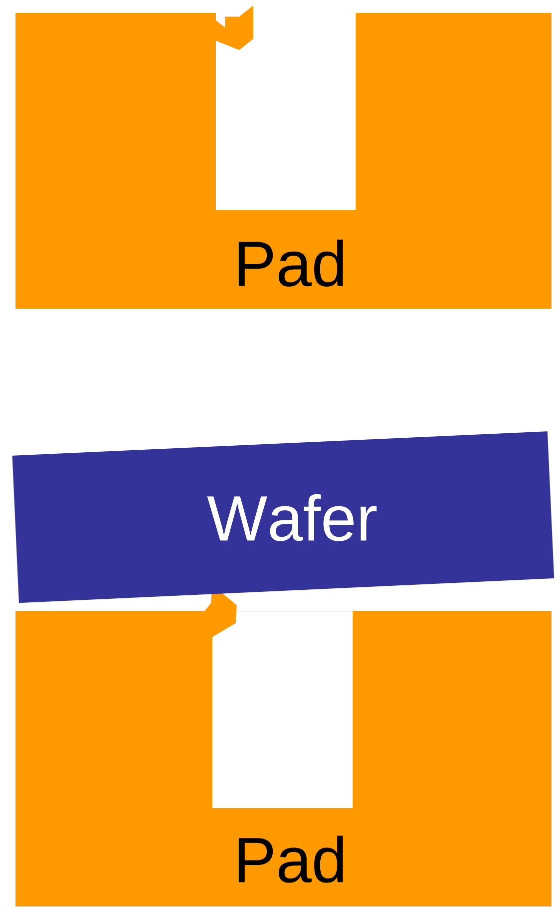
SEM Images and Conceptualization of Burrs



Molded Groove



Non-Optimized Machined Groove



Removal Rate Model

- **Oxide removal in the Langmuir-Hinshelwood model:**
  - ***n*** **moles of reactant** ***R*** **in the slurry react at rate** k_1 **with oxide film on the wafer to form a product layer** ***L*** **on the surface**

$$SiO_2 + nR \xrightarrow{k_1} \underline{L} \qquad k_1 = A \cdot \exp\left(\frac{-E}{kT}\right)$$

  - **Product layer** ***L*** **subsequently removed by mechanical abrasion with rate** k_2

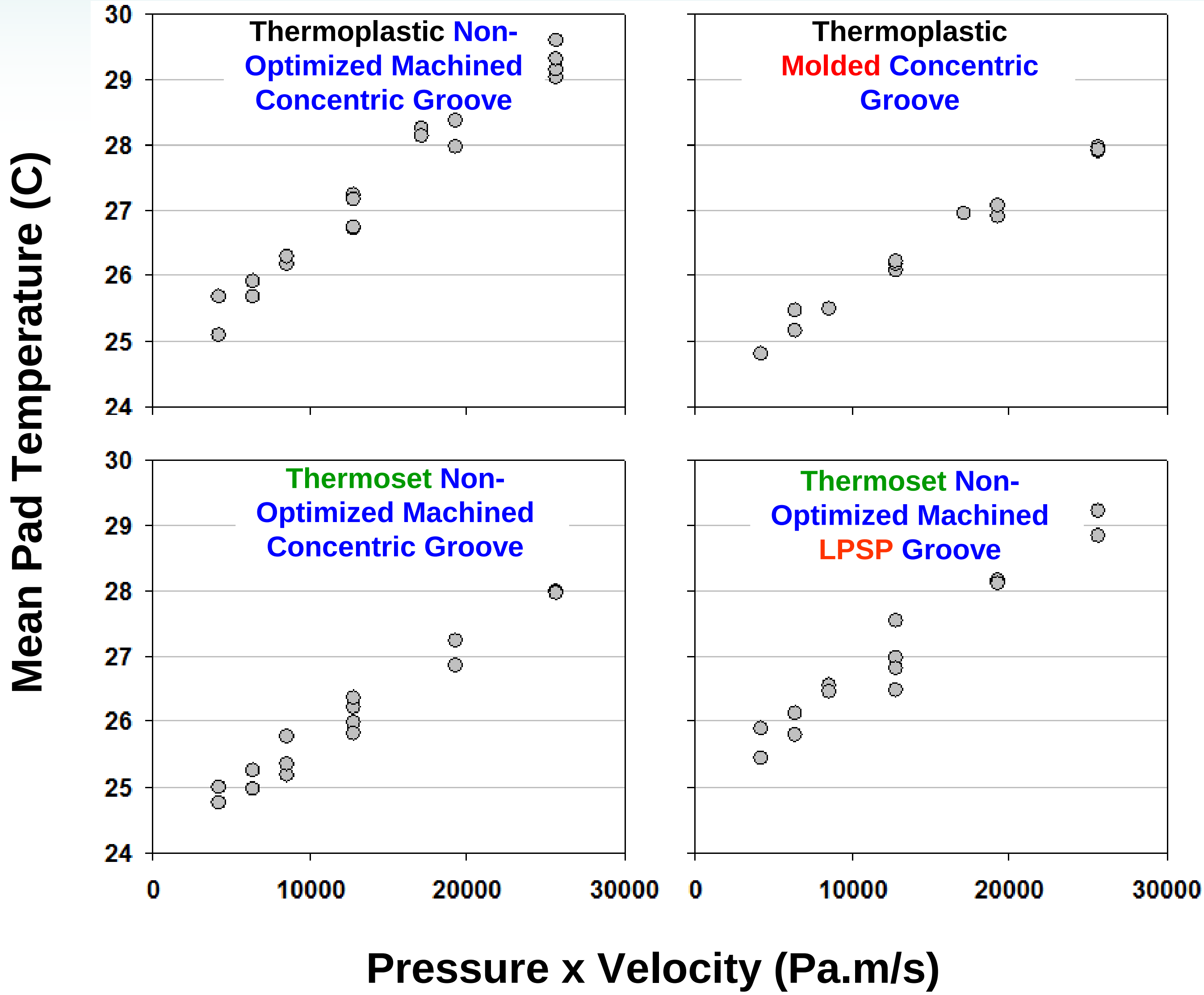
$$\underline{L} \xrightarrow{k_2} SiO_2{}^* \qquad k_2 = c_p \times p \times V$$

  - **Abraded material** ***L*** **is carried away by the slurry**

- **The local removal rate in this mechanism therefore is a function of chemical and mechanical contributions**

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

Pad Temperature



Physical Temperature Model

Fraction of heat conducted to pad

Geometric factor

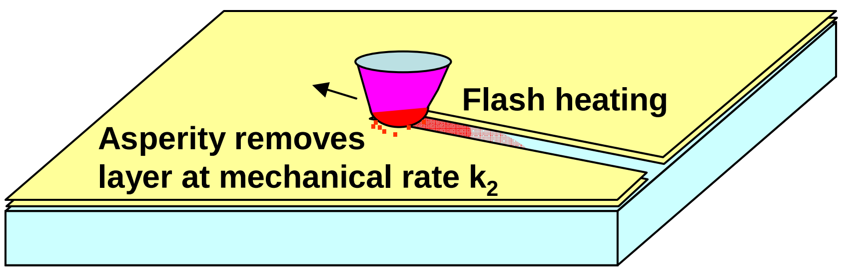
Depends on contact area

$$\bar{T} = T_p + \frac{2\zeta}{\sqrt{\pi\kappa\rho C_p}} \frac{\gamma_p (p_a / p)}{V^{1/2}} \mu_k p V$$

COF

Pad thermal properties

Mean asperity tip contact pressure



Surface layer grows at chemical rate k_1. Growth is fastest at the flash temperature

(Borucki, CMPMIC 2005)

Flash Heating Temperature

- $T \equiv$ hydrolyzed layer reaction temperature
- Reaction temperature is due to flash heating by passing slurry particle-laden asperity tips

$$T = T_p + \zeta \frac{\gamma_p \mu_k}{\sqrt{\kappa \rho C_p}} \left[\frac{(p_a / p)}{V^{1/2}} \right] pV$$

- The quantity in brackets depends on *V* due to fluid dynamic effects. Assuming a power law dependence:

$$T = T_p + \frac{\beta}{V^{1/2+e}} \mu_k pV$$

- The model has five fitting parameters: *A, E,* c_p, β & *e:*

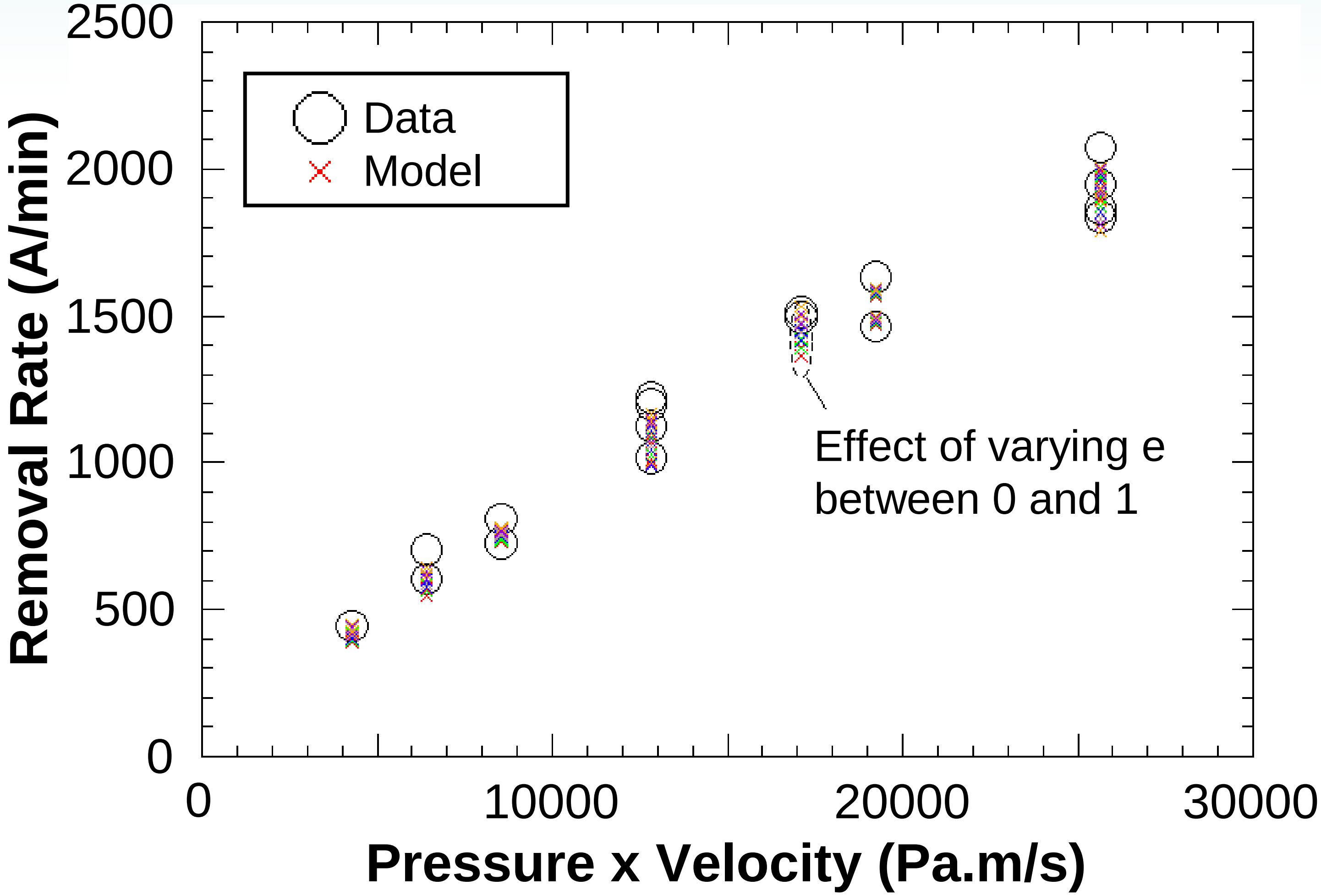
$$RR = \frac{M_w}{\rho} \frac{\left(c_p \cdot pV\right) \cdot Ae^{\left(\frac{-E}{k\left(T_p + \frac{\beta}{V^{1/2+e}} \mu_k pV\right)} \right)}}{\left(c_p \cdot pV\right) + Ae^{\left(\frac{-E}{k\left(T_p + \frac{\beta}{V^{1/2+e}} \mu_k pV\right)} \right)}}$$

Optimized Fitting Parameters

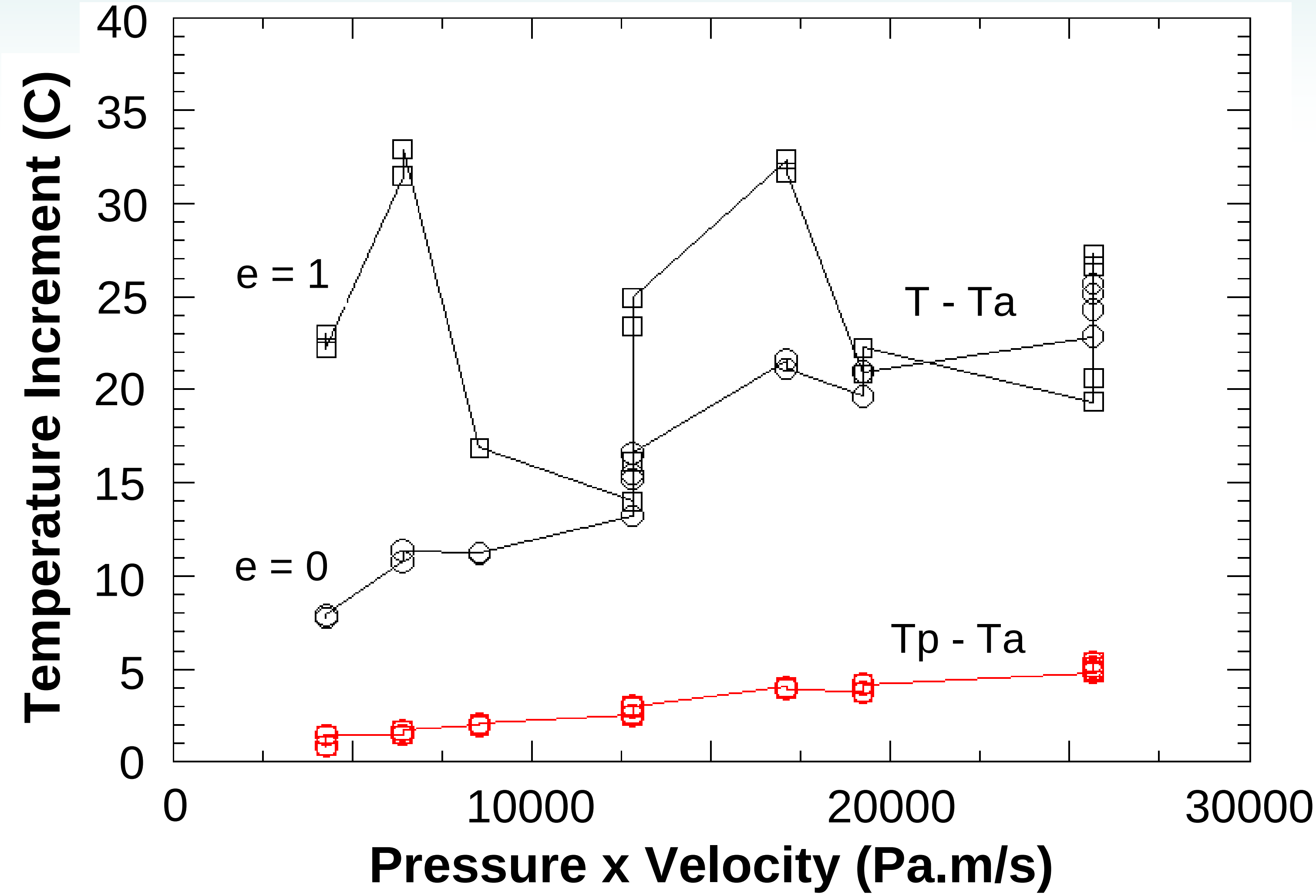
Polishing pad	c_p (moles/J)	β (K/Pa-(m/s)$^{1-a}$)	RMS Error (Å/min)
Thermoplastic machined concentric groove	1.64E-8	2.15E-3	77
Thermoplastic molded concentric groove	1.74E-8	2.15E-3	78
Thermoset machined concentric groove	2.59E-8	1.45E-3	81
Thermoset machined LSP	2.52E-8	1.45E-3	65

E = 0.53 eV *from Sorooshian et al., Journal of Tribology, 127, 639 (2005)*
e = 0.66
A = 1.02 x 10^5 moles m^{-2} s^{-1}

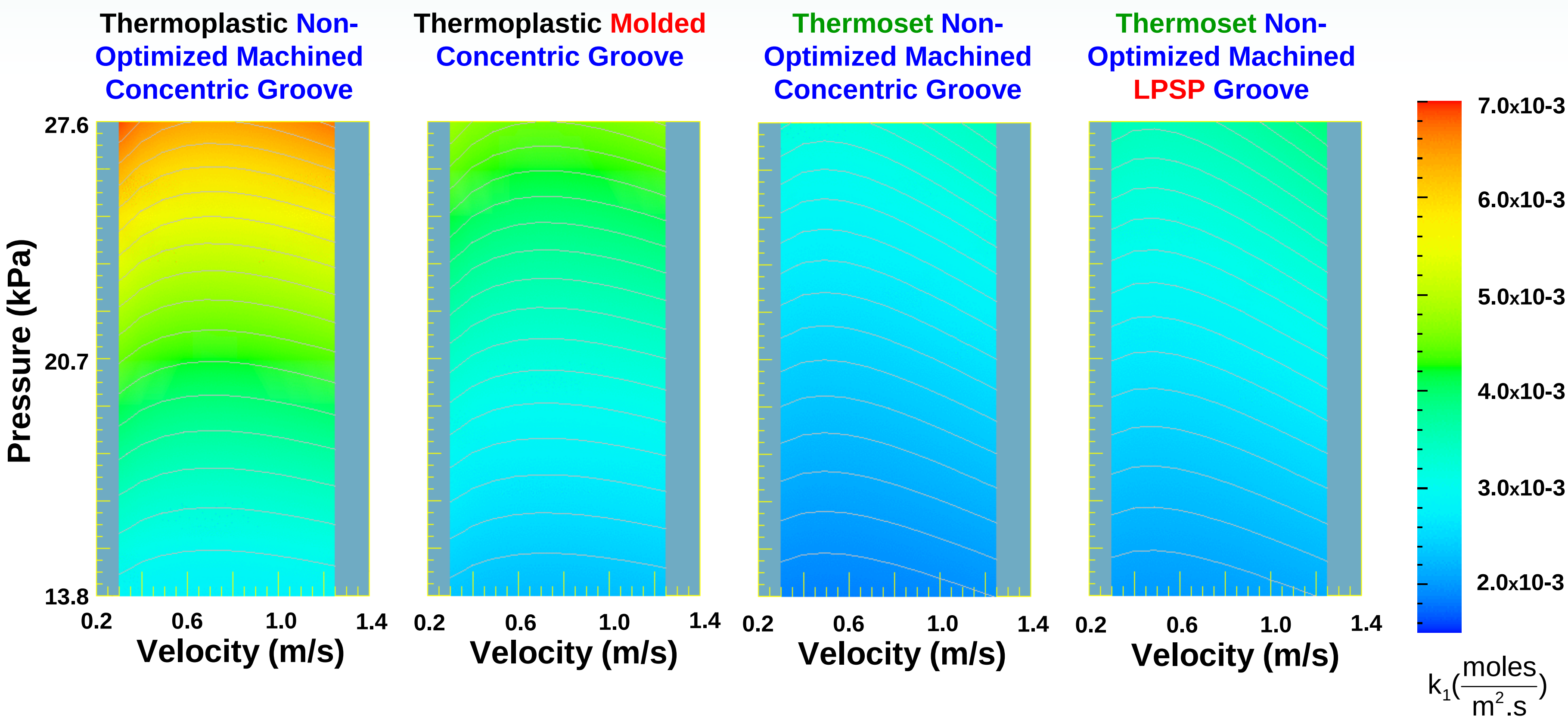
Sensitivity of 'e'



Contribution of Flash Heating Temperature

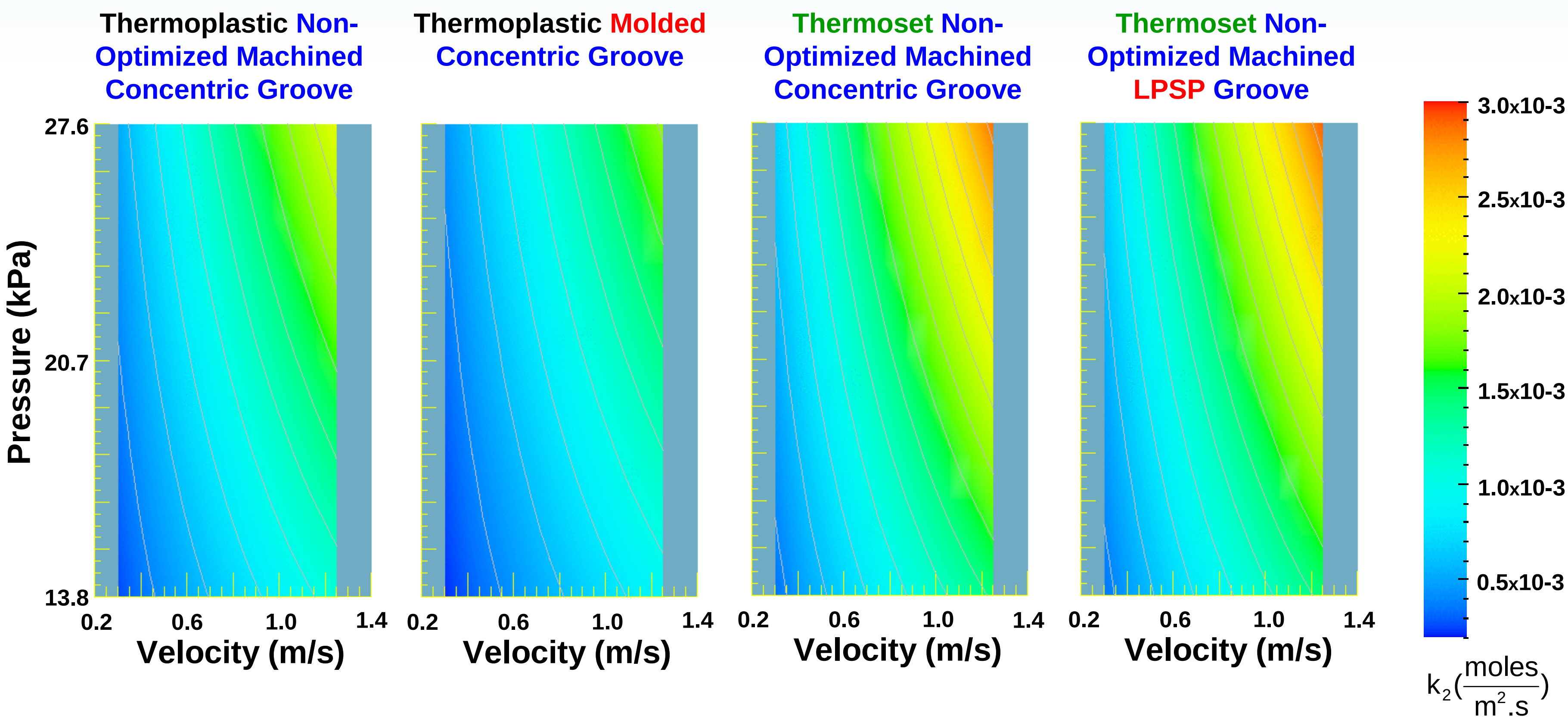


Chemical Reaction Rate Constant, k_1



Thermoplastic pads exhibit higher chemical reaction rate constant than thermoset pads

Mechanical Abrasion Rate Constant, k_2



Thermoplastic pads exhibit lower mechanical abrasion rate constant than thermoset pads

Summary

- Thermoplastic pads induce higher COFs than the thermoset pads due to their inherently higher degree of energy loss.
- Since thermoplastic pads exhibit more reduction in storage modulus, the variance of shear force associated with thermoplastic pads is higher than thermoset pads.
- Un-optimized machined grooves produce rougher edges than molded grooves, thereby inducing a higher COF and a higher shear force variance.
- LPSP groove is designed to bring slurry towards the pad center, resulting in a higher mean pad temperature. In addition, the LPSP pad induces a higher shear force variance.
- Simulation results indicate that thermoplastic pads produce a more mechanically controlled removal than thermoset pads.