Monitoring Pad-Wafer Interfacial Conditions via Real-Time PMC, SF and NF Measurements in ILD, Tungsten, Copper, Cobalt, and STI CMP

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Motivation, Proposed Solution and Approach

- For almost 2 decades, direct measurements of shear force (SF), normal force (NF), and coefficient of friction (COF) on Araca's highly-instrumented 300-mm R&D polishers and tribometers have provided valuable information regarding the thermal, tribological, kinetic and pad-microtextural aspects of CMP.

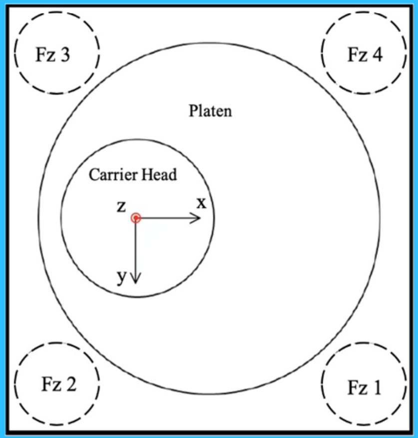
- Such sensors are expensive to implement in new HVM polishers, and even more expensive (or sometimes impossible) to retrofit onto older HVM tools.

- Since PMC is already measured with most HVM polishers (including ours), it will benefit IC Makers if it could be used as real-time indicator for certain tribological phenomena in CMP.

We investigate whether there exists a relationship between SF (and COF) vs. PMC in non-steady-state data sets – 24 cases (STI, ILD, Co, Cu, and W) involving different discs (3M, Morgan, Saesol and Shinhan), slurries (CMC, Versum, FujiFilm and Ferro) and pads (Dow, Fujibo and CMC).

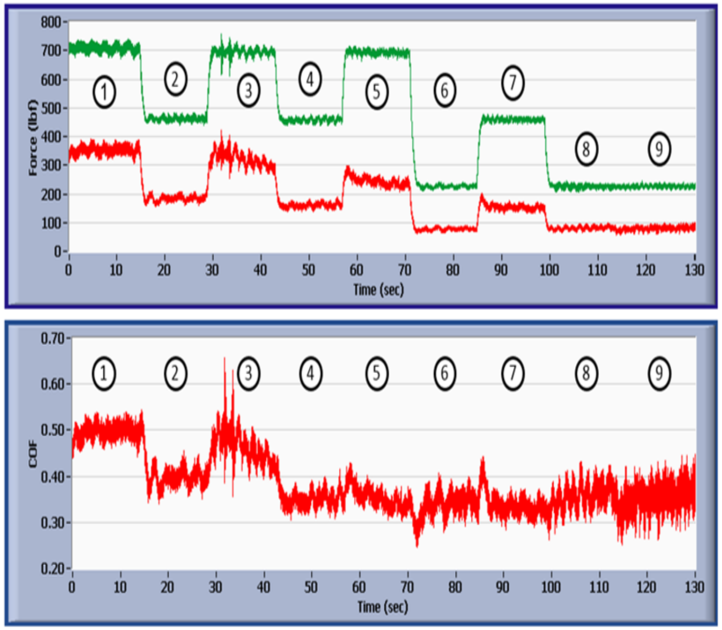
We carefully look at 132 different steady-states from the above 24 cases to determine whether PMC is sensitive enough to replace SF and COF.

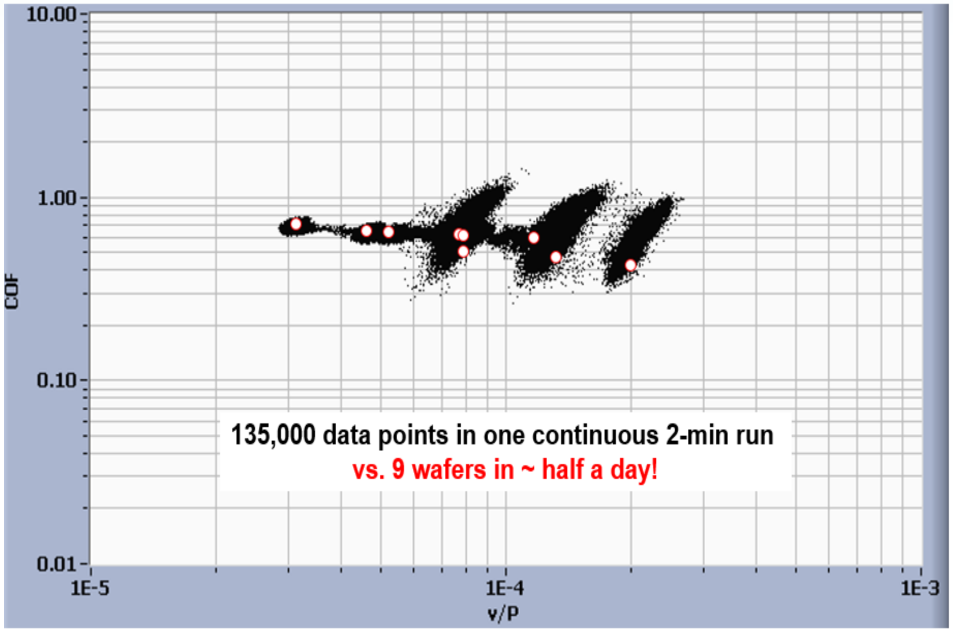
Araca's APD-800® Polisher and Tribometer for 300-mm Wafers



SF, NF and COF vs. Time (L) and vs. V/P (R) in a Continuous Run with 1 Wafer

Step	v (m/s)	P (PSI)
1	0.6	6.0
2	0.6	4.0
3	1.0	6.0
4	1.0	4.0
5	1.5	6.0
6	0.6	2.0
7	1.5	4.0
8	1	2.0
9	1.5	2.0





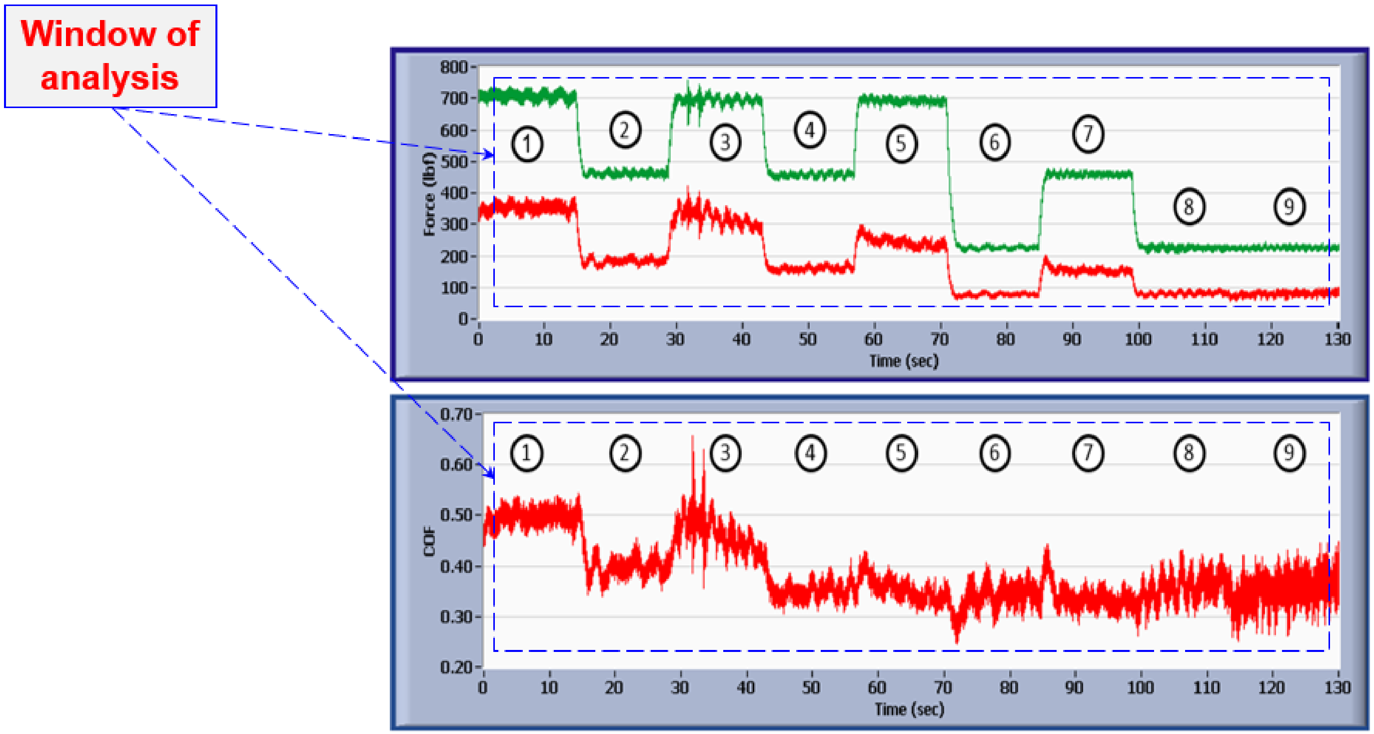
<u>Non-Steady-State</u> Analyses Procedure

- **Twenty Four Stribeck+ data sets were gathered over a six-year period and left mostly unanalyzed.**

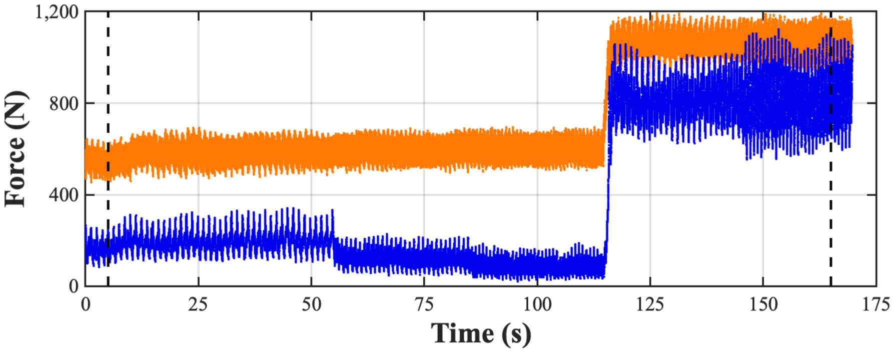
- **All experiments were conducted on the Araca APD-800® polisher and tribometer at a sampling frequency of 1,000 Hz.**

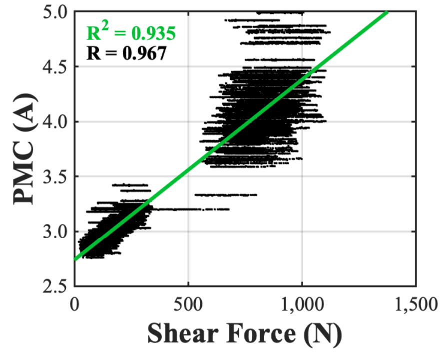
- **We looked at raw PMC, SF, and COF data.**

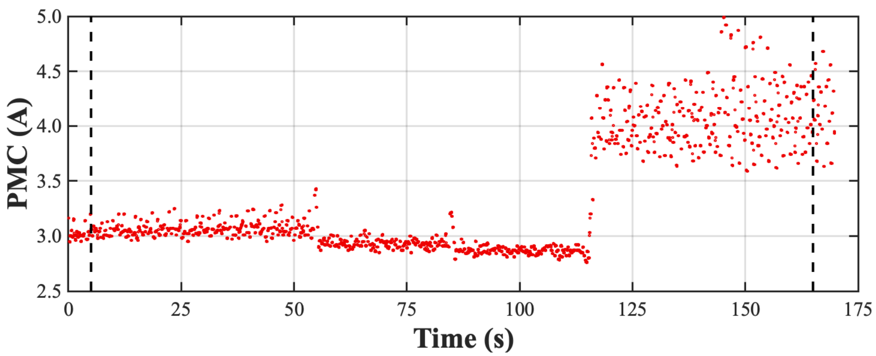
- **Shifted all PMC data by 250 ms to account for a known delay in the data acquisition clock of the polisher.**

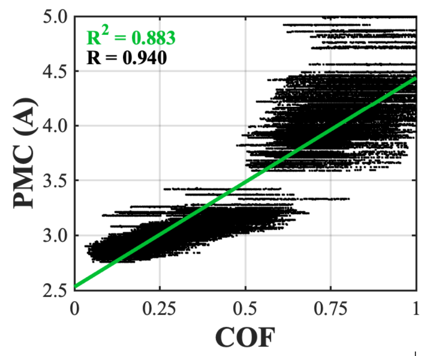


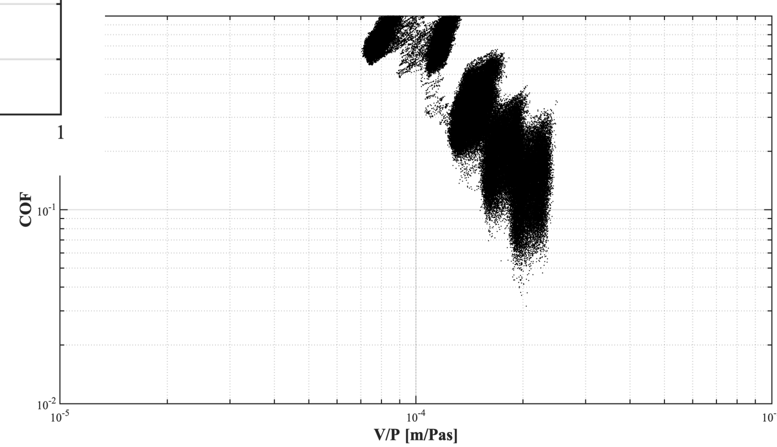
Case A (Cu) – SF, NF and PMC vs. Time (L) and COF vs. V/P (R)



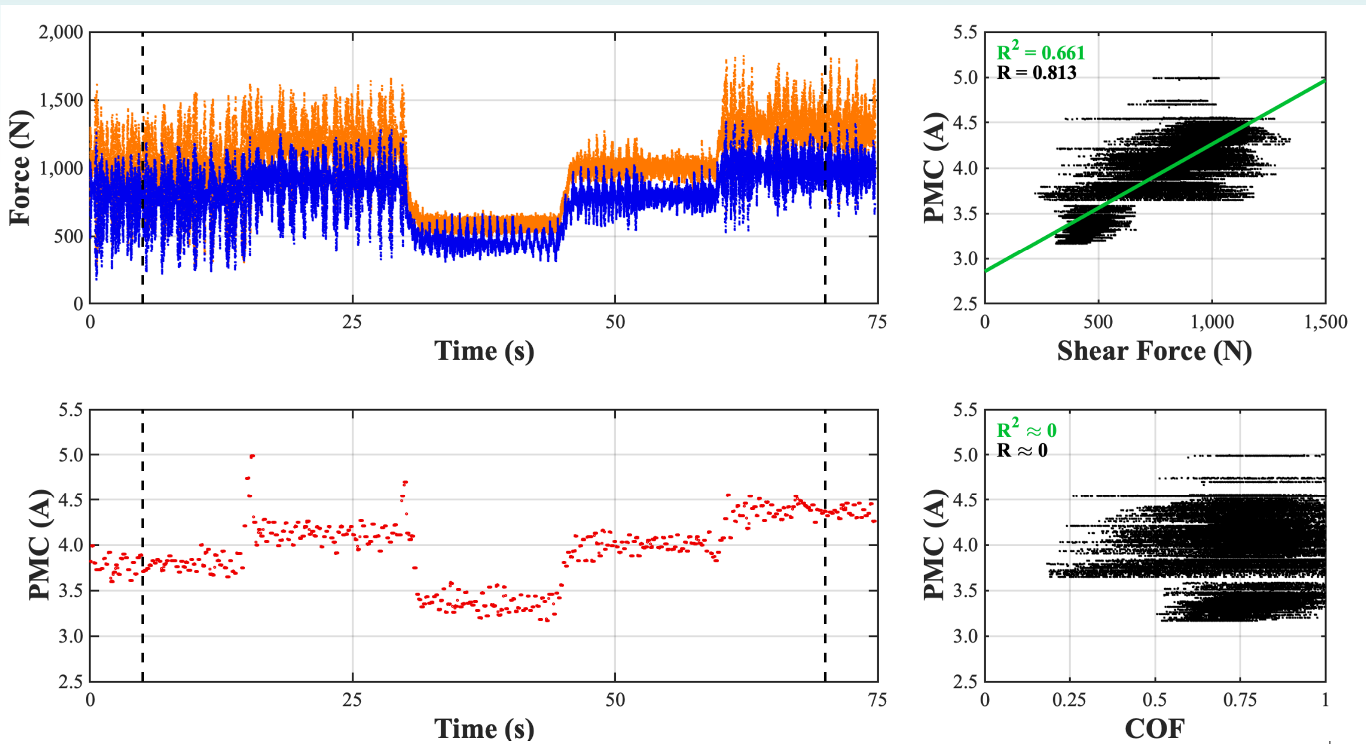


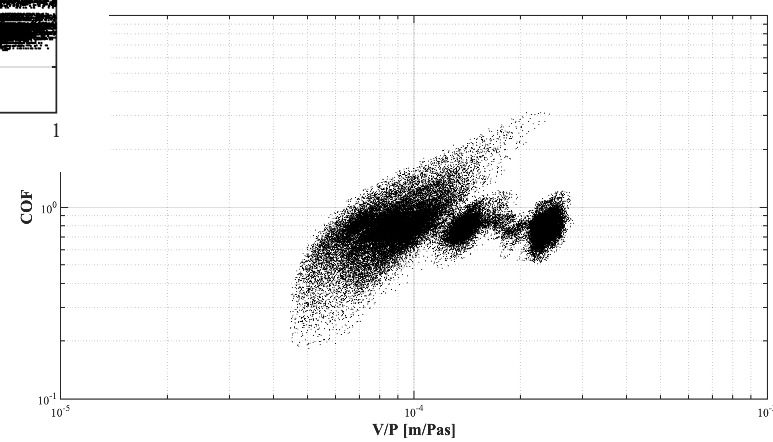




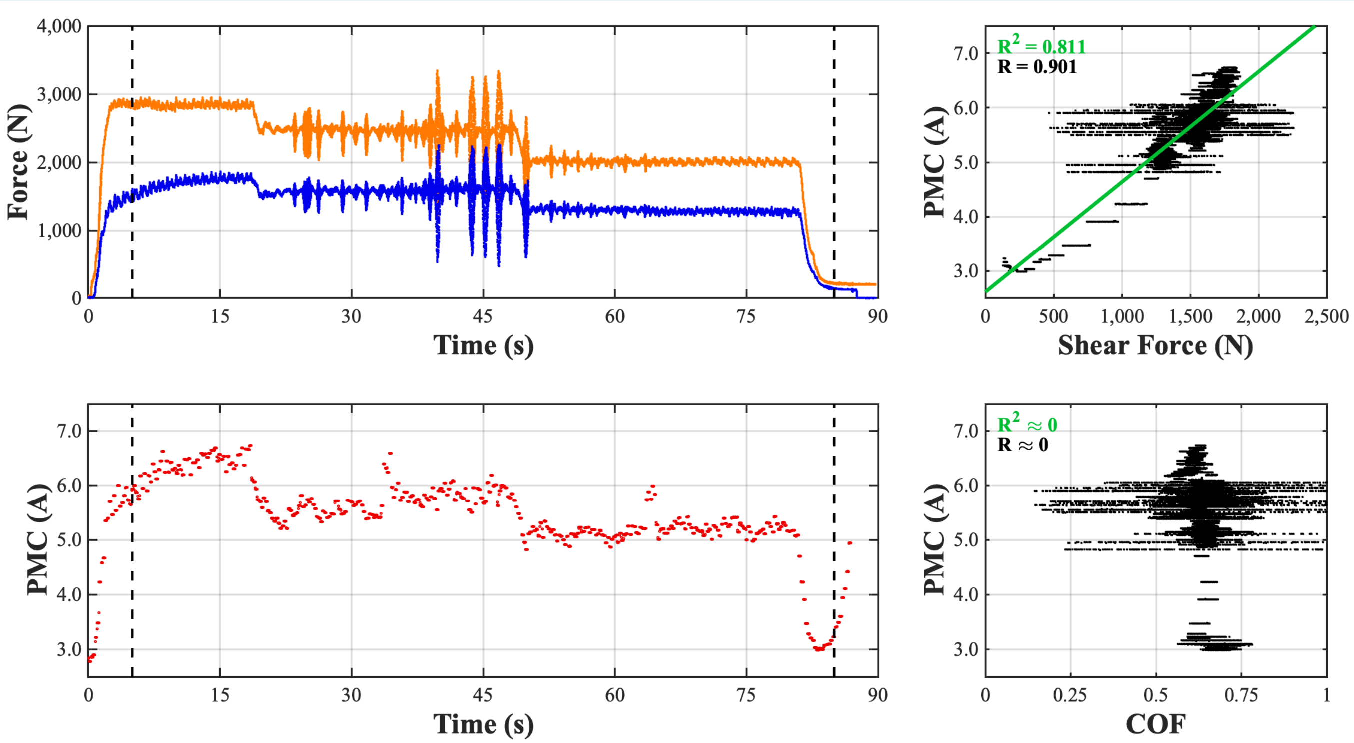


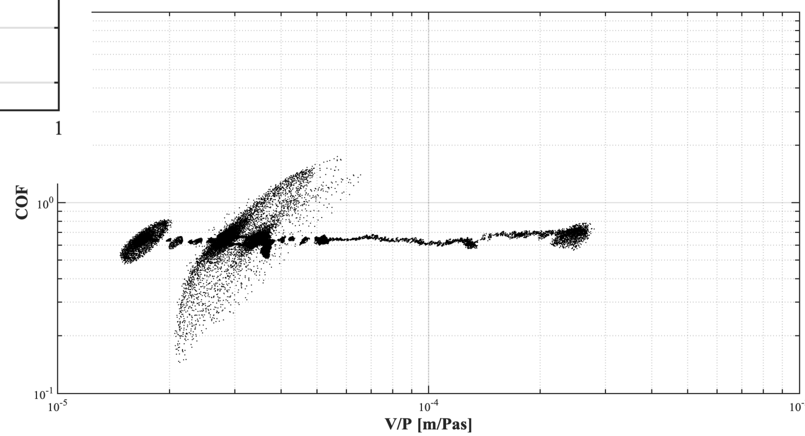
Case H (STI) – SF, NF and PMC vs. Time (L) and COF vs. V/P (R)





Case K (ILD) – SF, NF and PMC vs. Time (L) and COF vs. V/P (R)

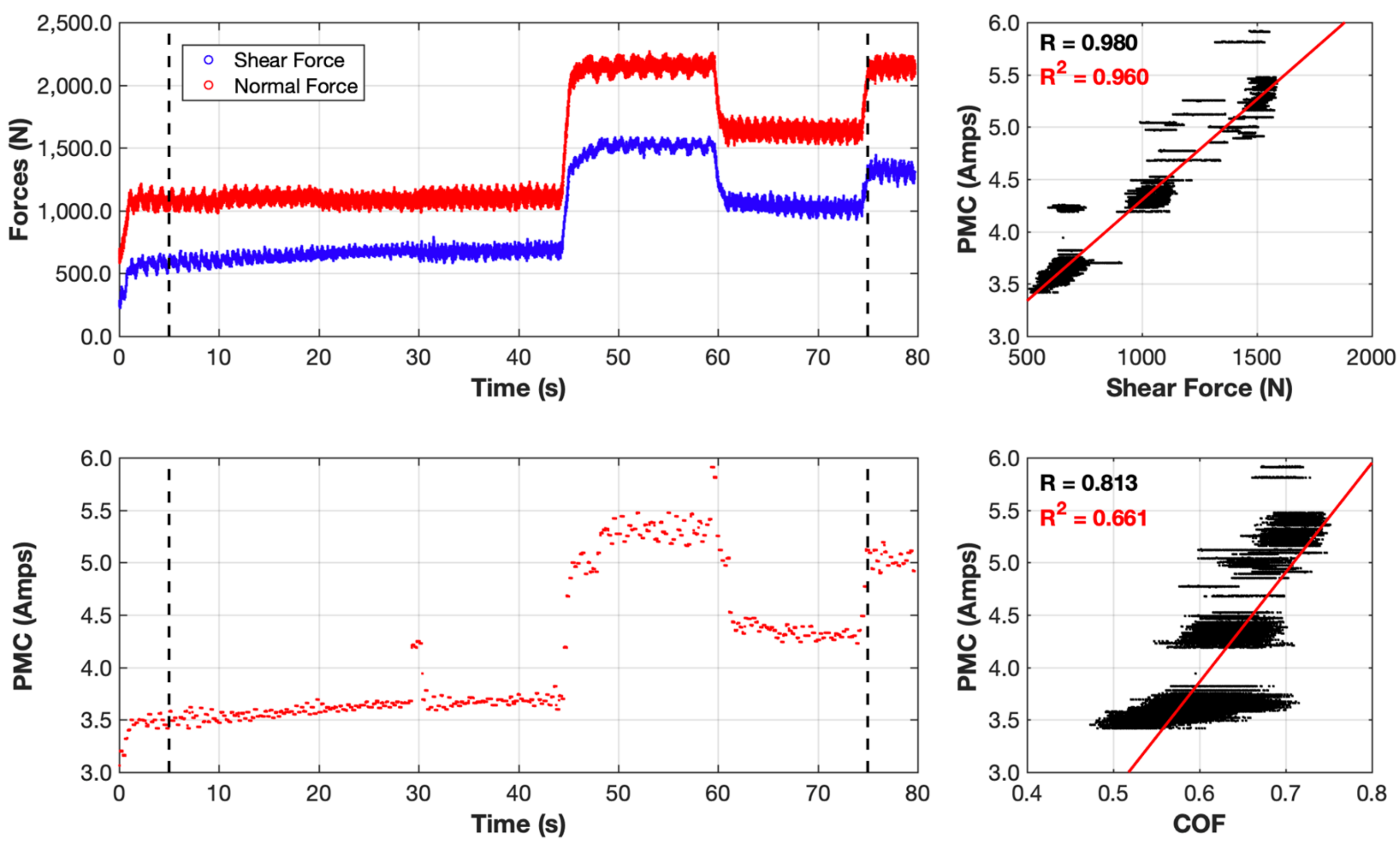




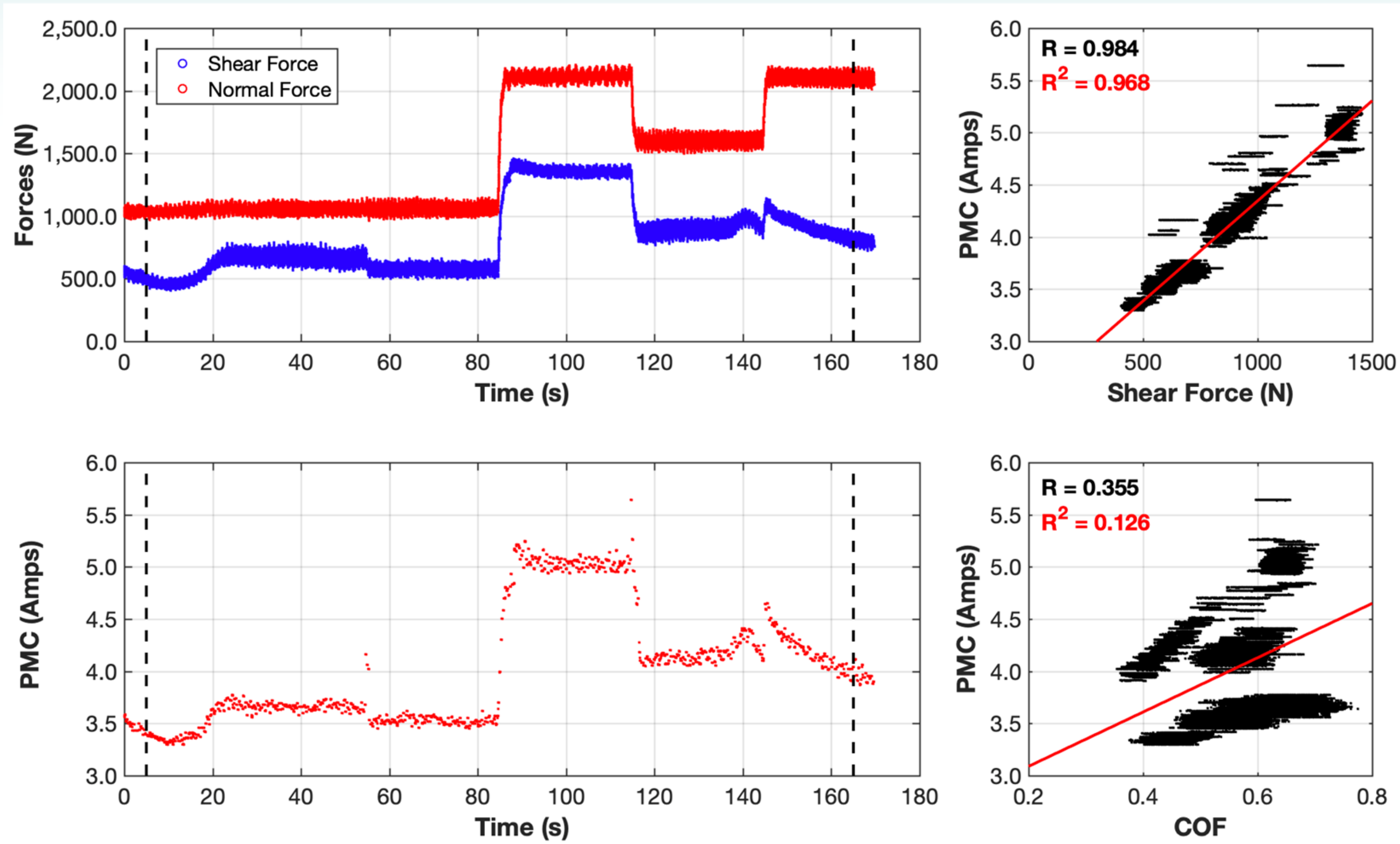
Non-SS Correlation Summary for Cases A to L

Case	Correlation Coefficient PMC vs. Shear Force	Correlation Coefficient PMC vs. COF
A – Cu	0.967	0.940
B – Cu	0.963	0.941
C – Cu	0.974 (Max.)	0.959 (Max.)
D – Cu	0.966	0.956
E – Cu	0.888	0.425
F – Cu	0.877	0.170
G – Cu	0.907	0.399
H – Cu	0.813 (Min.)	0.018
I – Cu	0.878	0.098
J – Cu	0.890	0.021
K – STI	0.901	ZERO (Min.)
L – Co	0.928	ZERO (Min.)
Average	**0.913**	**0.382**

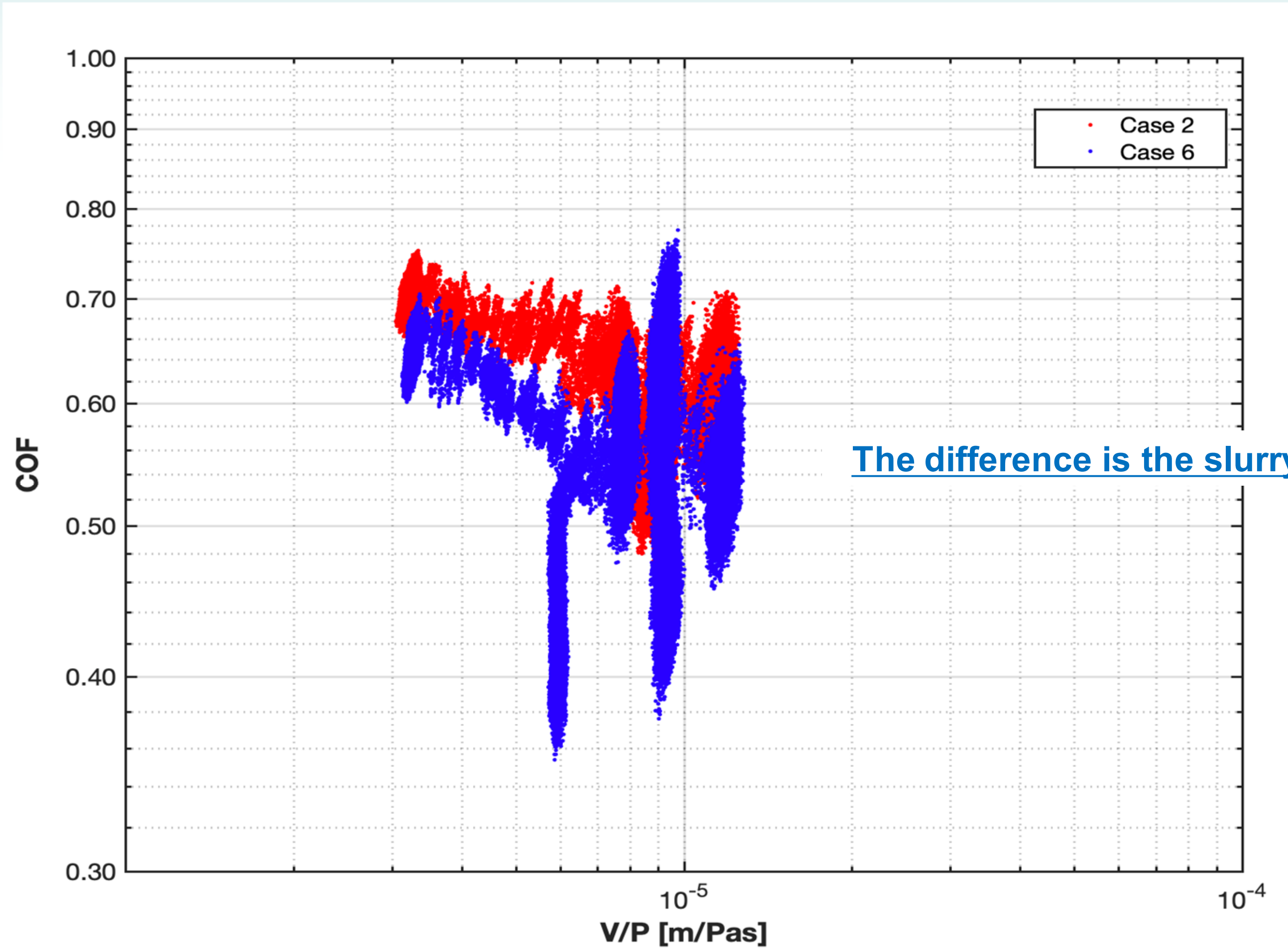
Case 2 (W) – SF, NF and PMC vs. Time



Case 6 (W) – SF, NF and PMC vs. Time

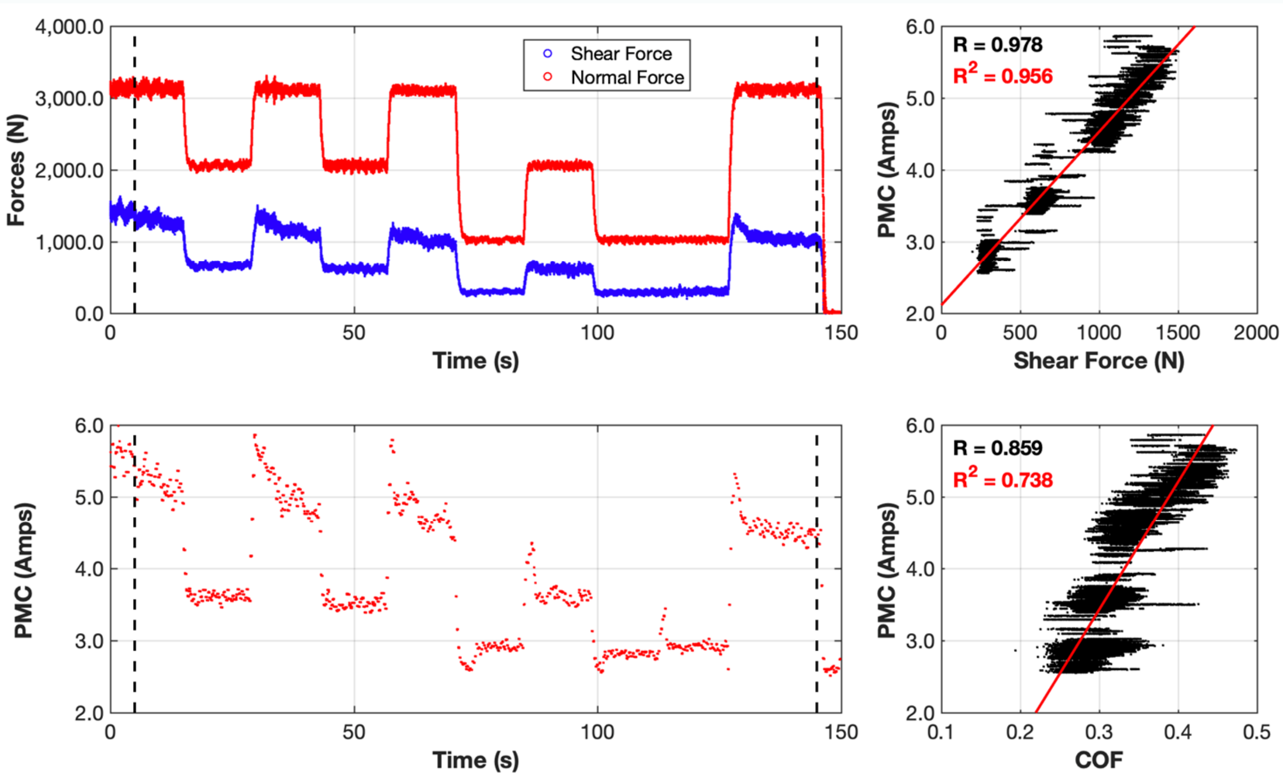


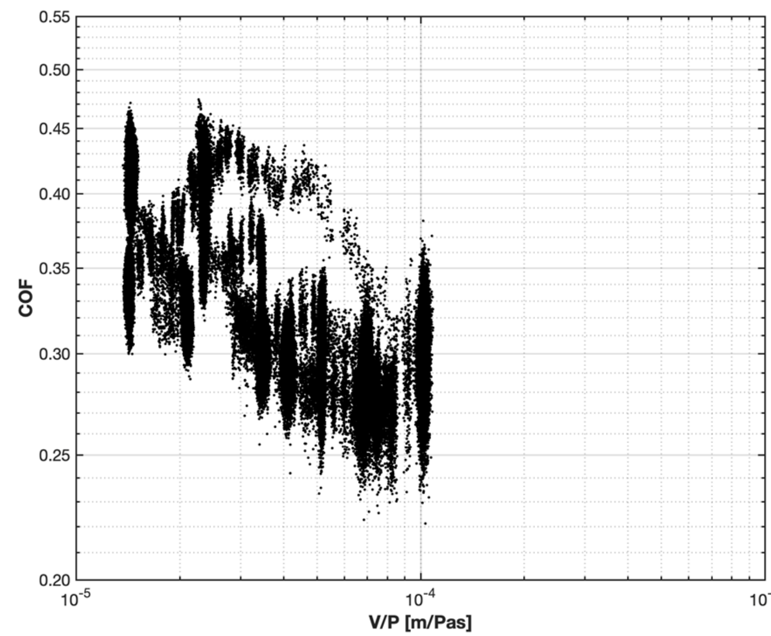
Case 2 vs. Case 6 – W CMP – Stribeck+ Curves



The difference is the slurry maker!

Case 12 (ILD) – SF, NF and PMC vs. Time (L) and COF vs. V/P (R)





Non-SS Correlation Summary for Cases 1 to 12

Case	Correlation Coefficient PMC vs. Shear Force	Correlation Coefficient PMC vs. COF
1 – W	0.9784	0.858
2 – W	0.9812	0.813
3 – W	0.9863 (Max.)	0.934
4 – W	0.9853	0.959
5 – W	0.9835	0.955 (Max.)
6 – W	0.9843	0.355 (Min.)
7 – W	0.8711	0.714
8 – W	0.7745 (Min.)	0.622
9 – ILD	0.9748	0.478
10 – ILD	0.9729	0.709
11 – ILD	0.9786	0.836
12 – ILD	0.9773	0.859
Average	**0.954**	**0.758**

– BUT CMP IS A “STEADY-STATE” PROCESS –

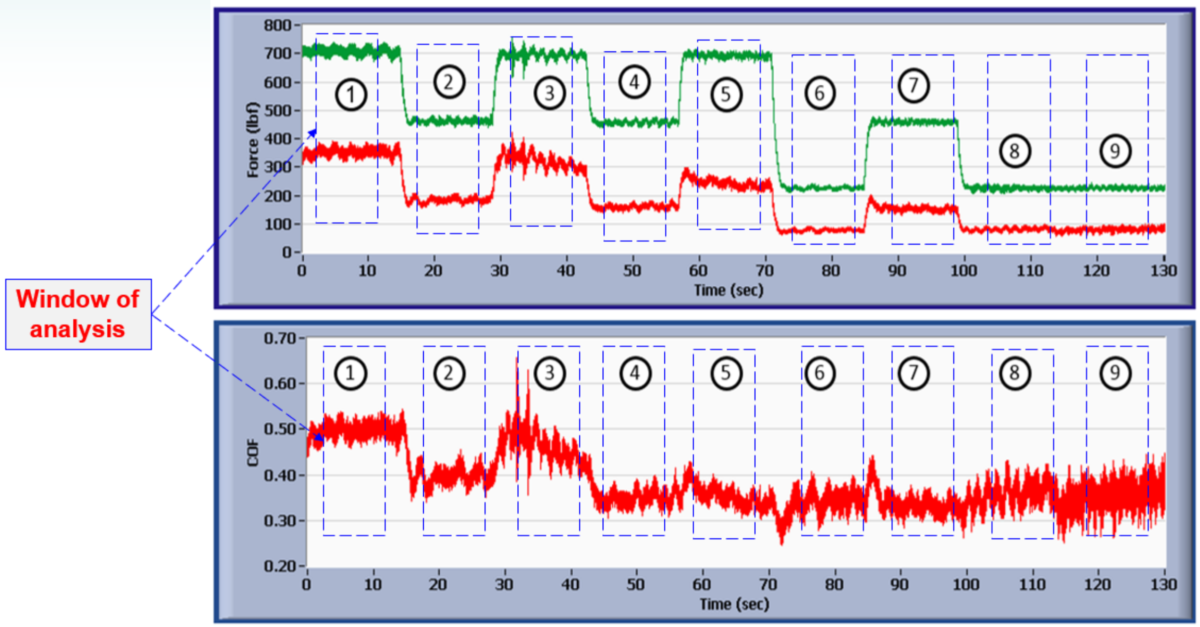
At least, that’s what one hopes!

<u>Steady-State</u> Analyses Procedure

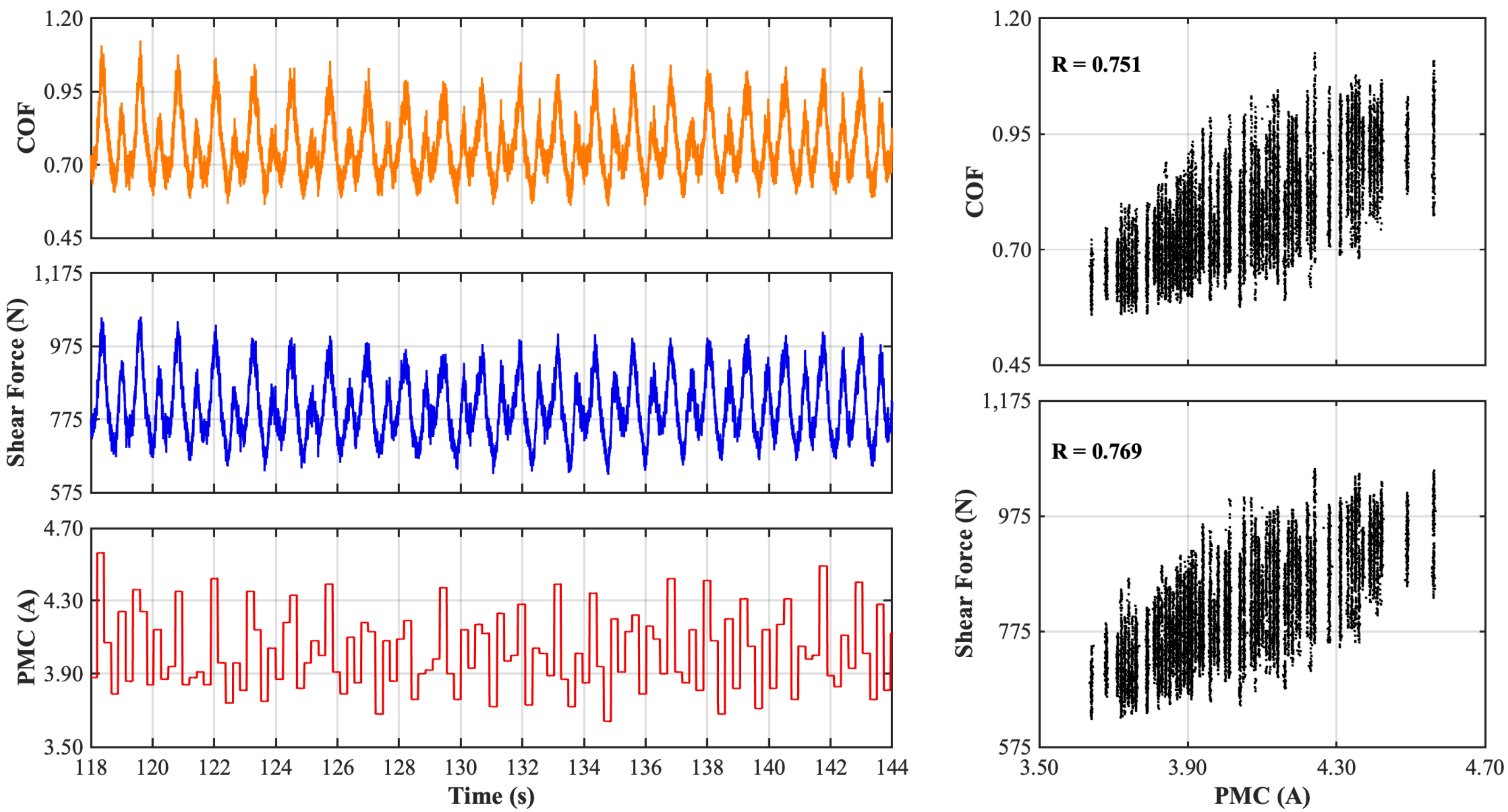
1. **Eliminated transient behavior – Removed data from 2 sec before reaching the setpoints of a new steady-state step and after reaching these setpoints (appx. 10 – 15 secs) – <u>This allowed us to examine 132 unique steady states.</u>**

2. **Investigated whether PMC was both descriptive and sensitive enough on small timescales (1 sec) to capture the myriad of stick-slip phenomena that exist at the pad-slurry-wafer interface during polishes.**

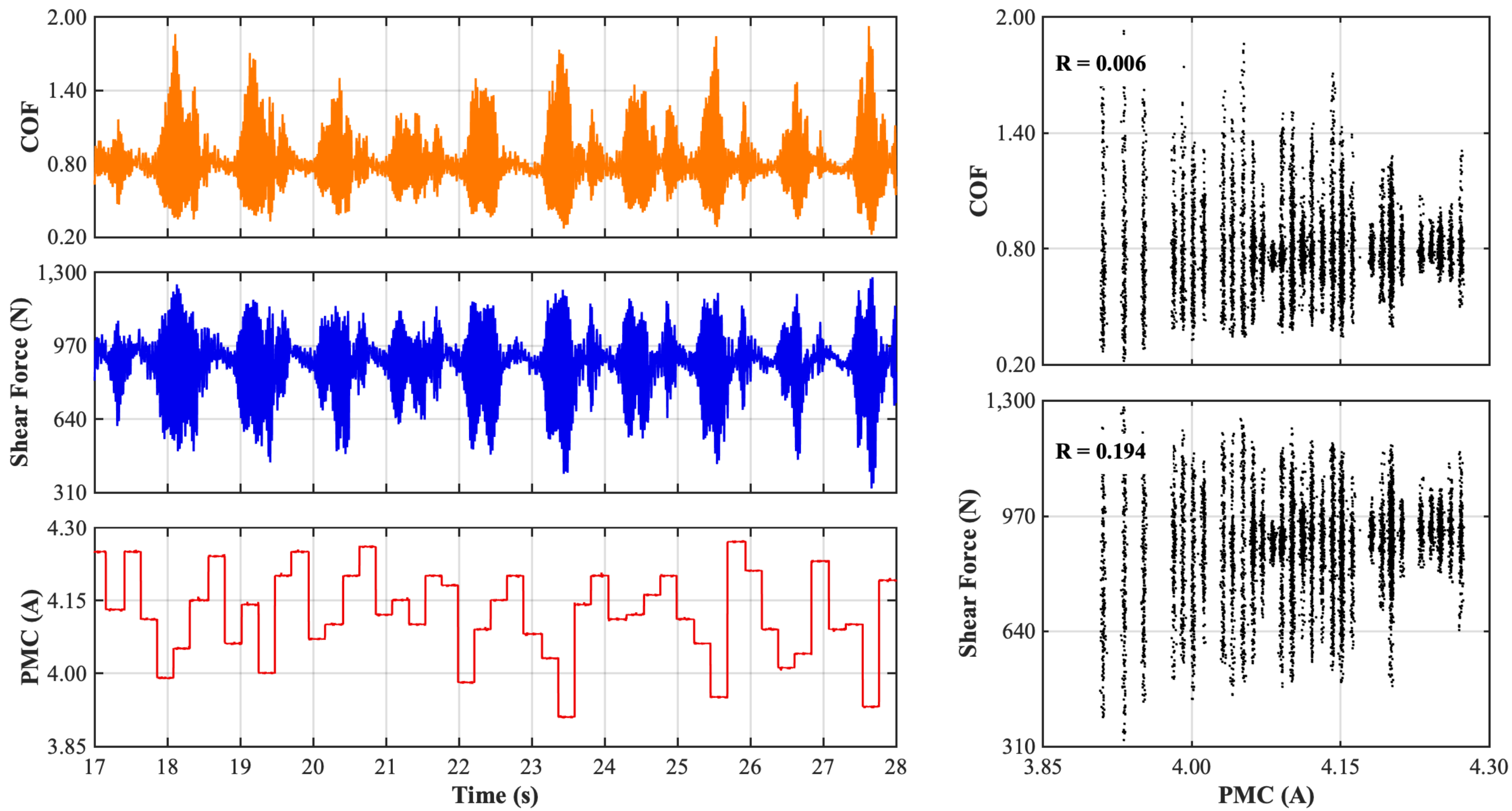
3. **Created an algorithm to determine the fraction of instances when the overall trends in these metrics were consistent with one another – This allowed us to report on the "percent match" in the SF and COF steady-state trends that were exactly echoed in the PMC data**



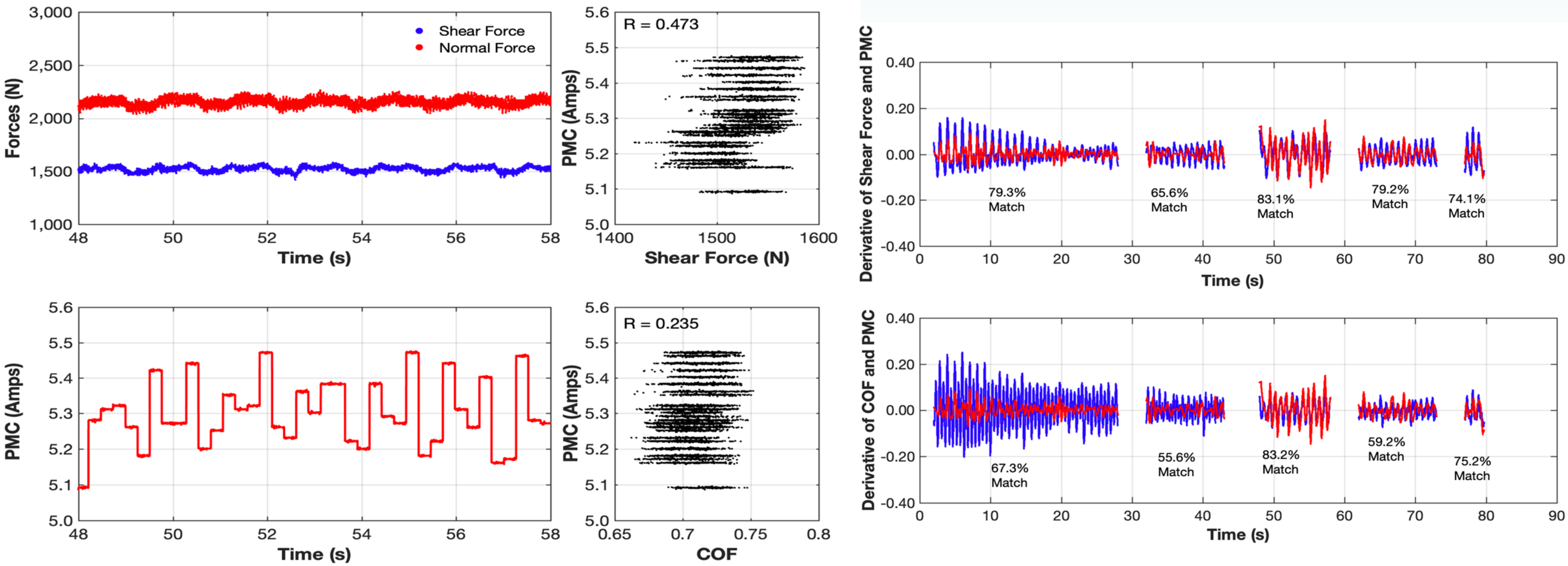
Case A Step 4 – Cu – The Entire Steady State



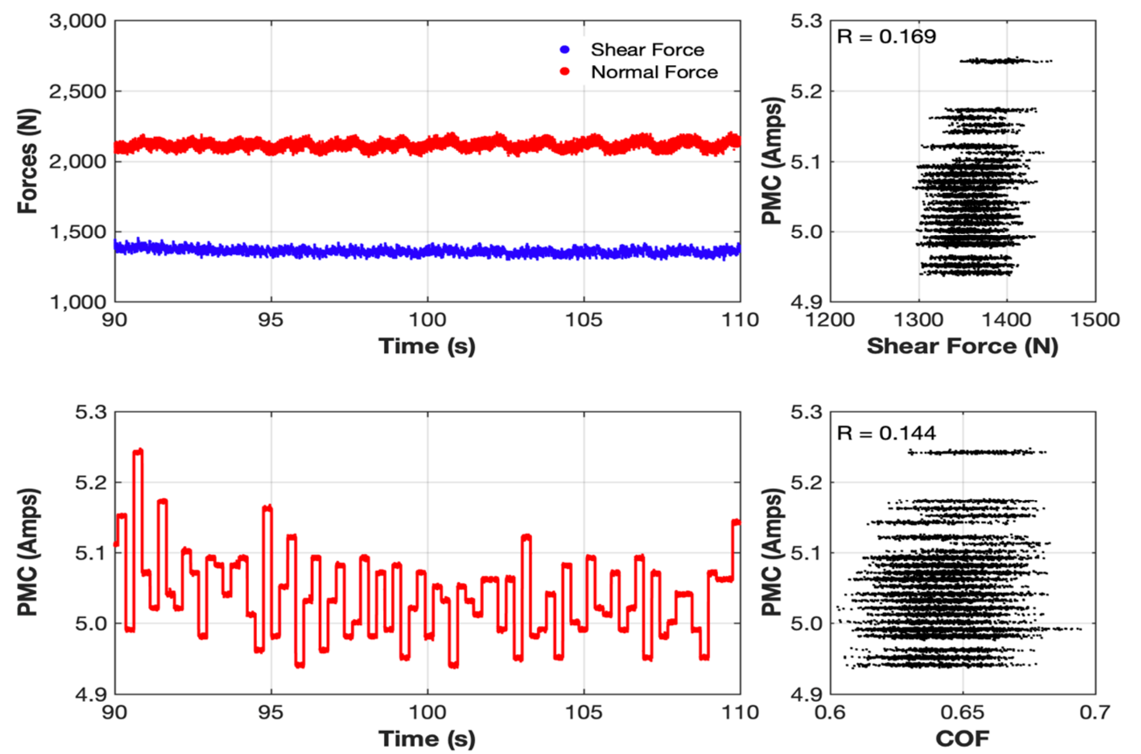
Case H Step 2 – Cu – The Entire Steady State

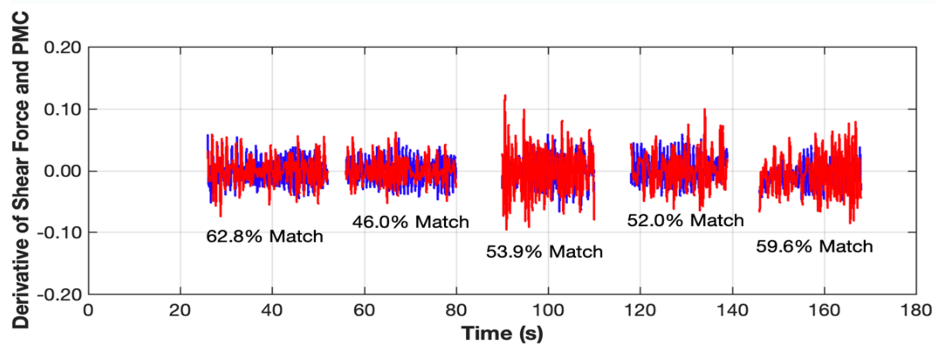


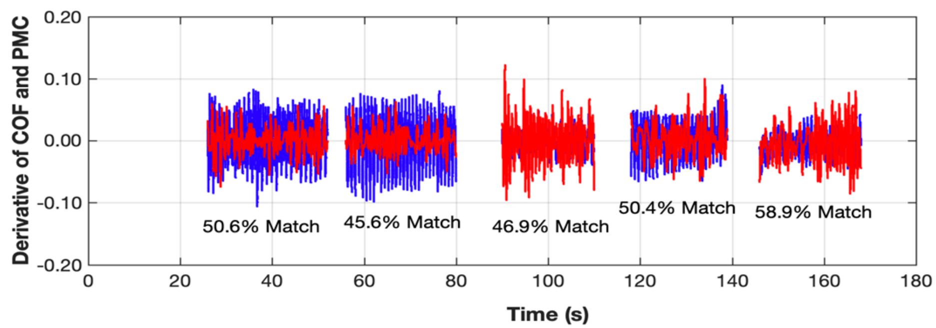
All 5 Steady-Stated Steps of Case 2 – W



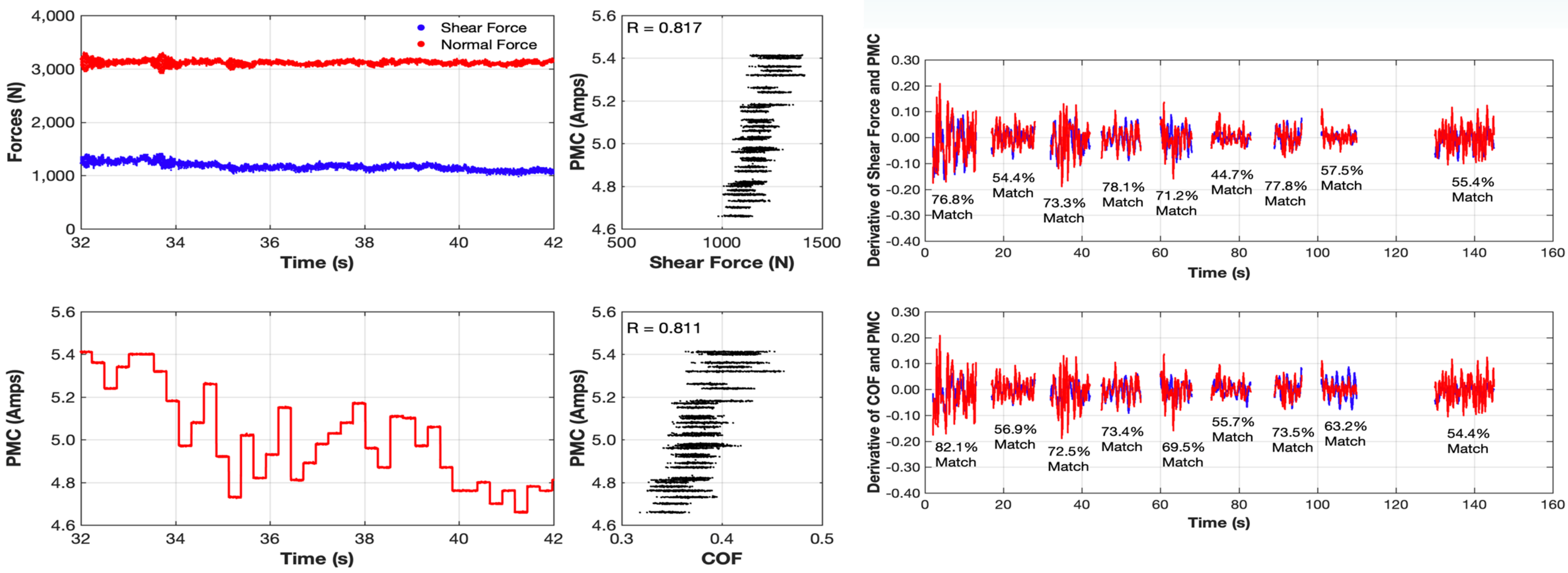
All 5 Steady-Stated Steps of Case 6 – W







All 9 Steady-State Steps of Case 12 – ILD

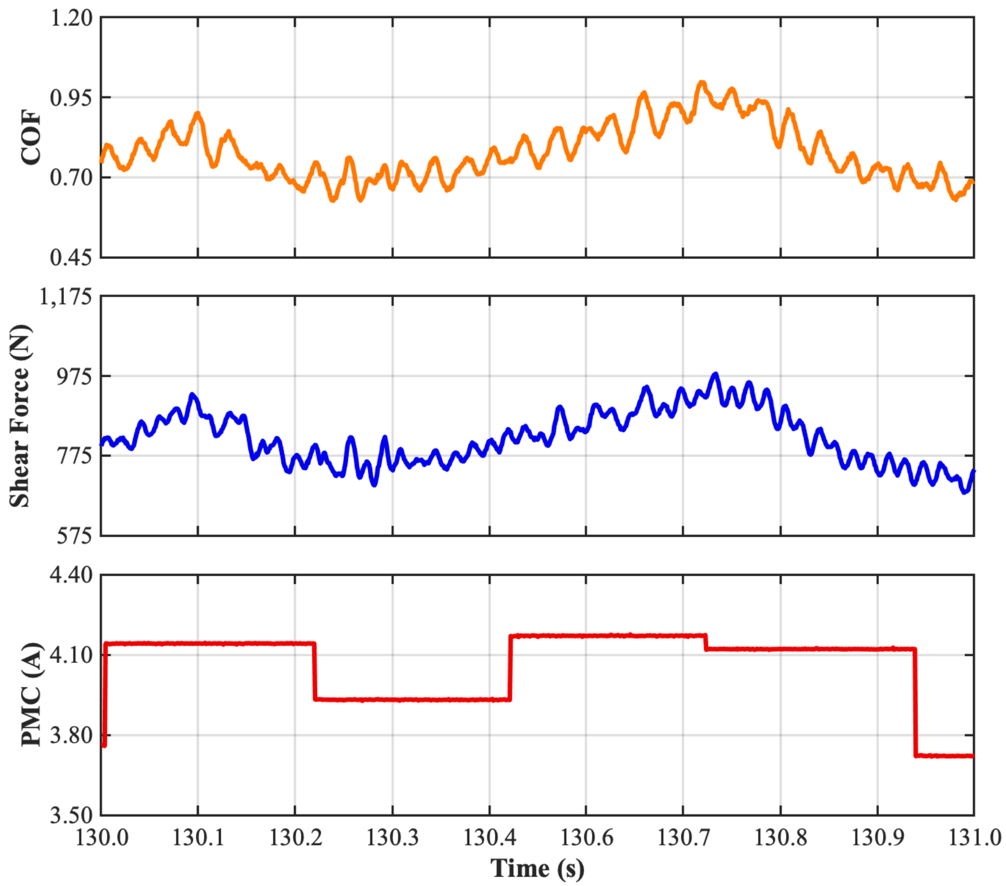


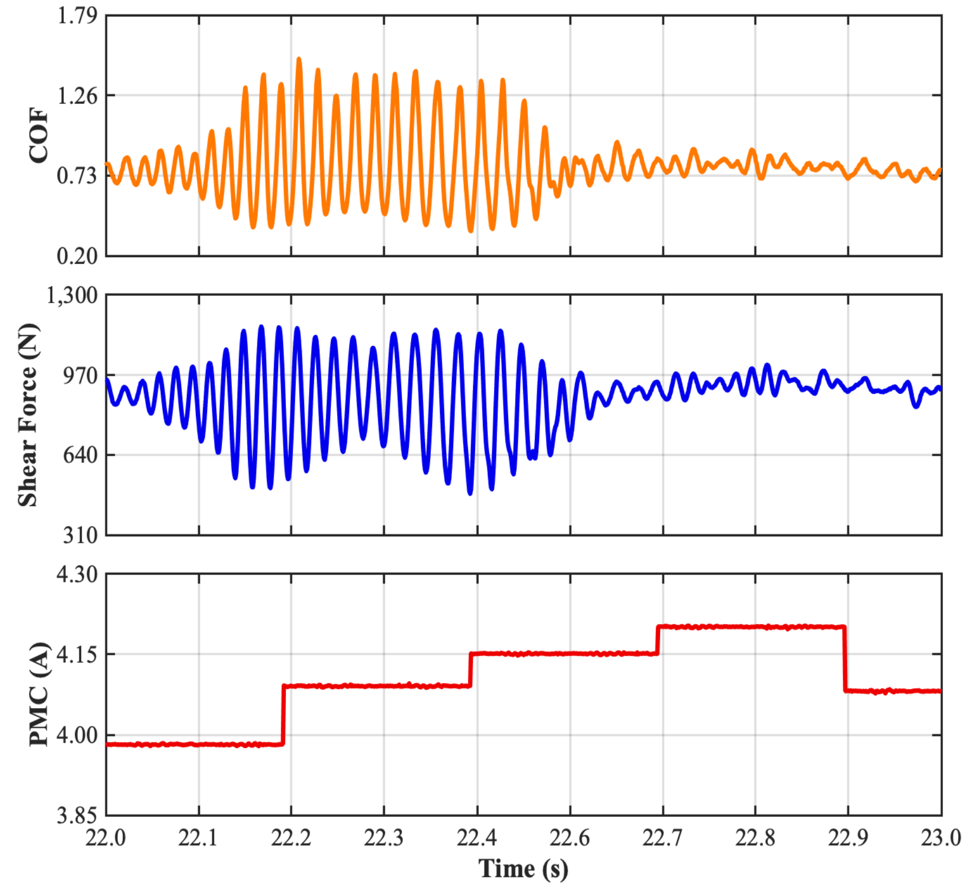
SF, COF and PMC Correlation Summary – 132 Individual SS Cases

60 Steps Cu, STI and Co	% Trend Match SF vs. PMC	R Values for SF vs. PMC	% Trend Match COF vs. PMC	R Values for COF vs. PMC
Min.	62	0.04	62	ZERO
Max.	86	0.77	85	0.75
Average	69	0.39	68	0.33

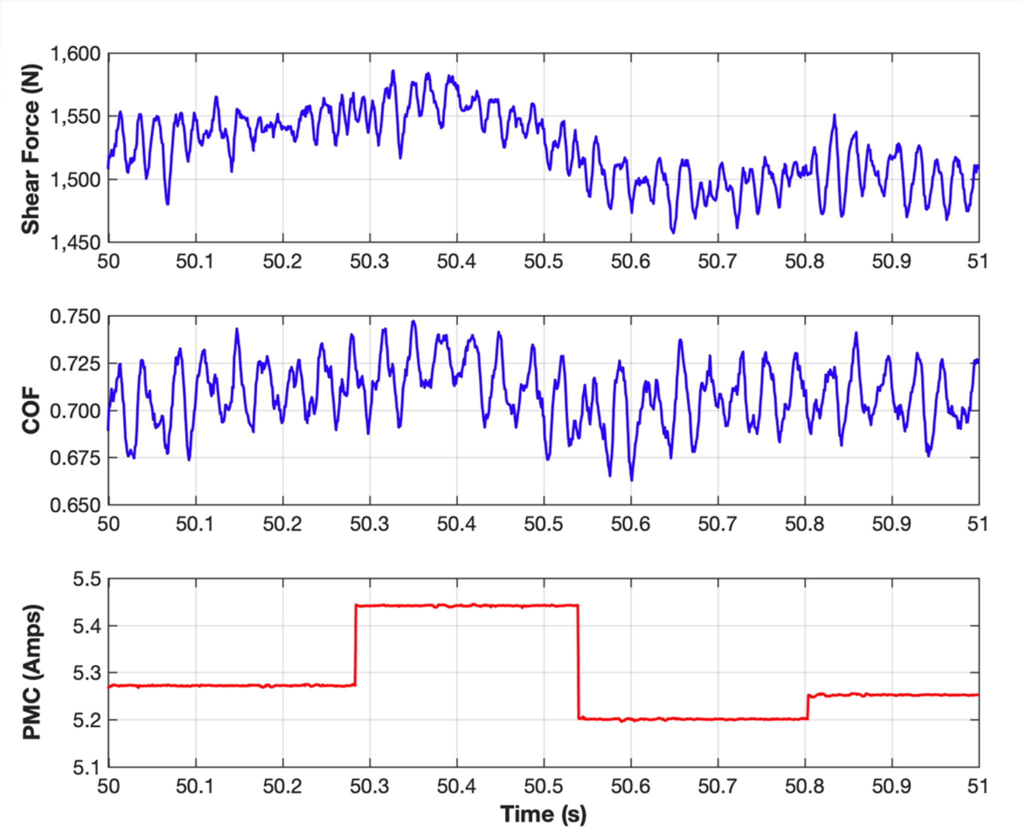
72 Steps W and ILD	% Trend Match SF vs. PMC	R Values for SF vs. PMC	% Trend Match COF vs. PMC	R Values for COF vs. PMC
Min.	45	0.03	42	0.03
Max.	85	0.92	85	0.92
Average	64	0.37	62	0.33

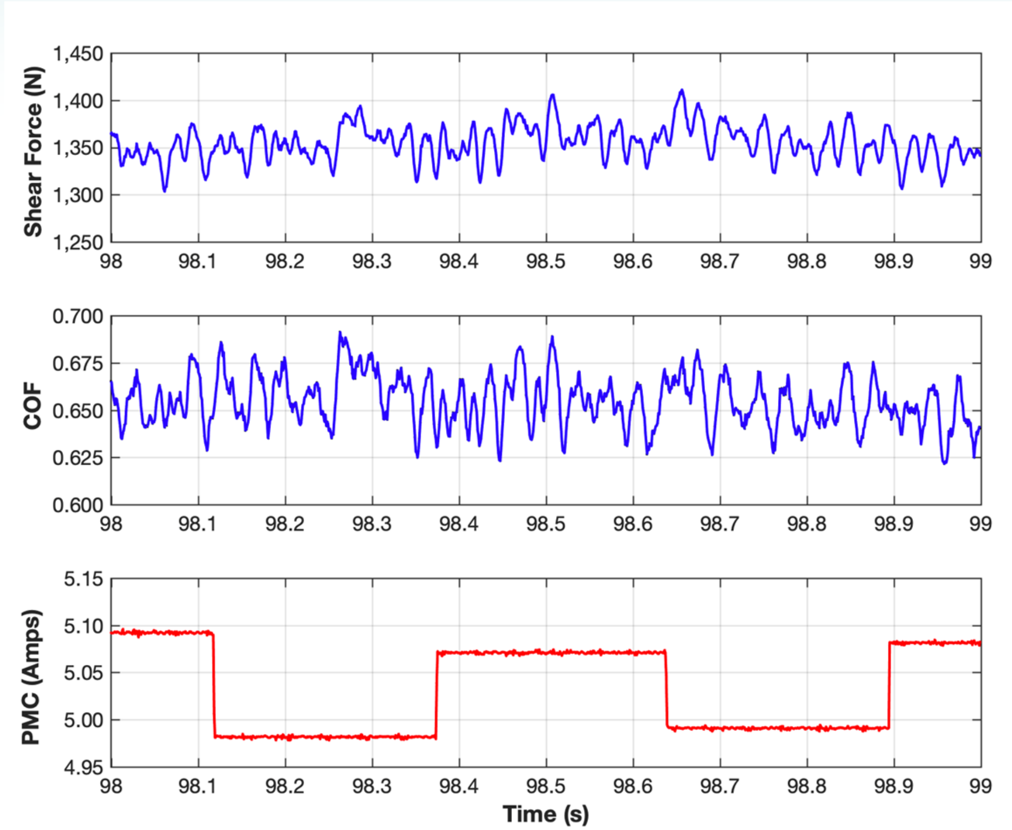
Case A Step (L) and Case H Step 2 (R) – Cu CMP – 1 sec Wavelet



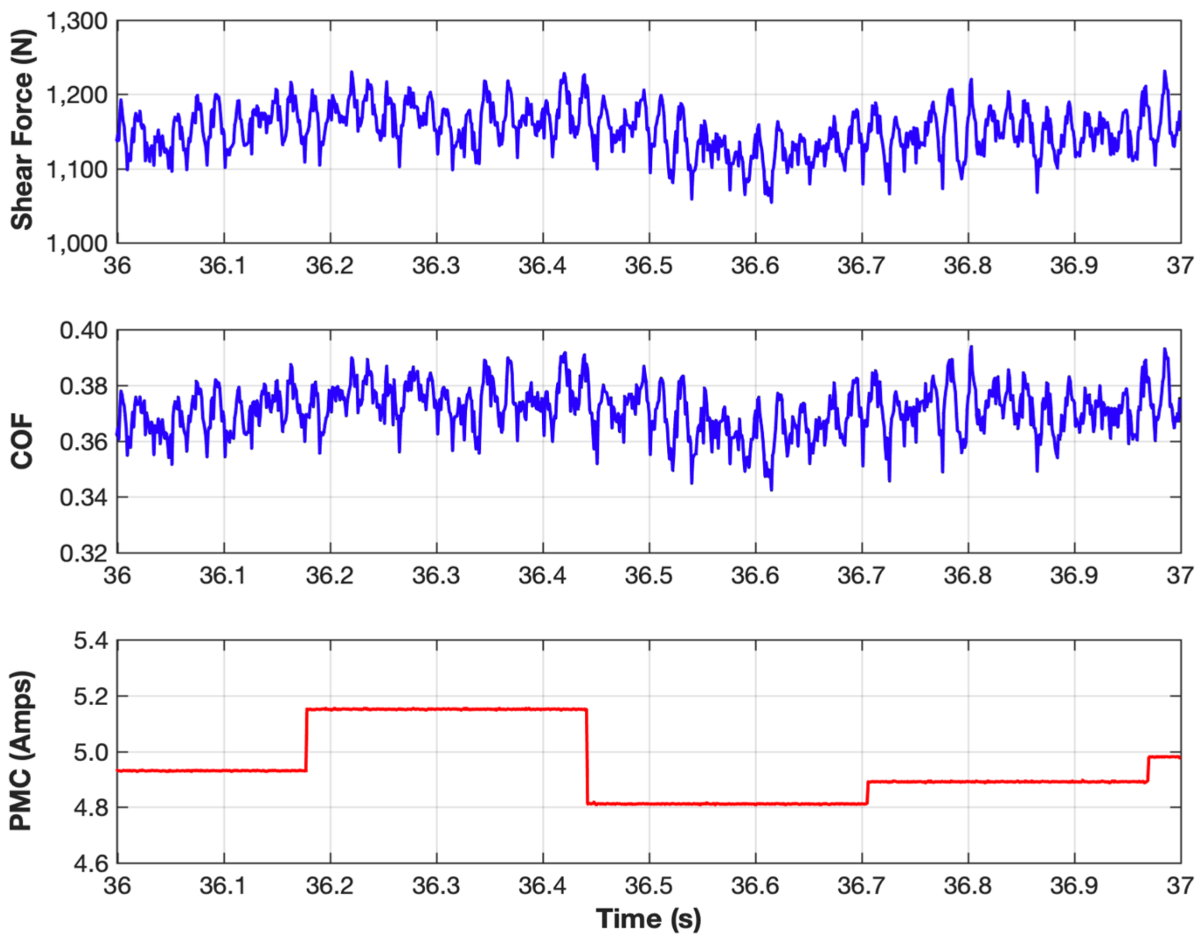


Case 2 Step 3 (L) and Case 6 Step 2 (R) – W CMP – 1 sec Wavelet





Case 12 Step 5 – ILD CMP – 1 sec Wavelet And Takeaway Messages

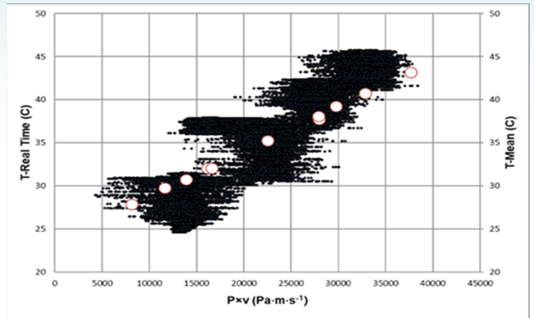


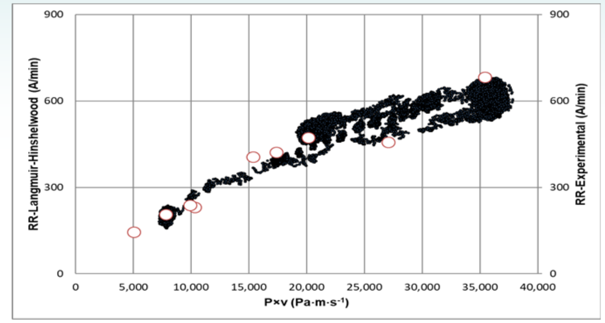
- **By relying on PMC data, we CANNOT …**
  - ❖ **Calculate SF, or COF (A. Philipossian in JJAP 2003).**
  - ❖ **Explain whether COF is governed by solid sliding contact or lubricated sliding contact (L. Borucki relied on NF and SF in JSS 2019).**
  - ❖ **Determine if a pad has been broken-in or seasoned sufficiently before use (R. Han relied on SF in JSS 2016).**
  - ❖ **Have a real-time indicator for pad EOL (based on a joint 2020 work with Versum – Still classified)!**

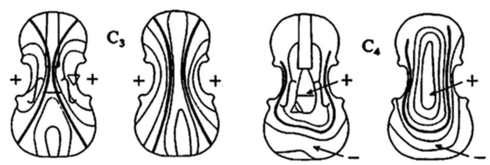
Issues Associated with Relying on PMC Data

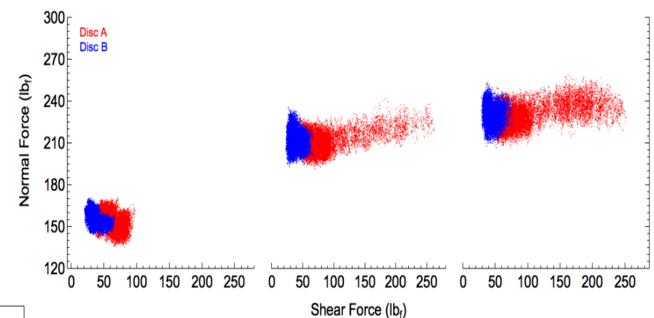
- By relying on PMC data, we CANNOT …

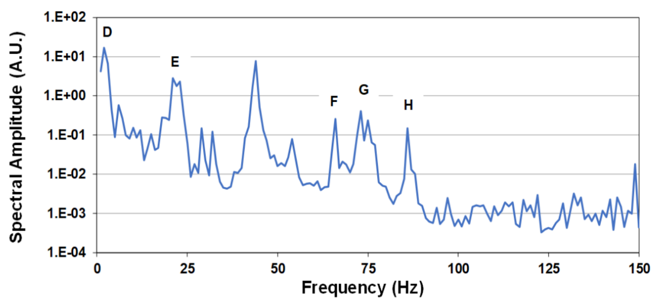
  - ❖ Construct Stribeck and Stribeck+ curves – Therefore no information on the governing lubrication mechanism (A. Philipossian in JJAP 2003, and R. Han in JSS 2017).
  - ❖ Construct and use Kinetic Plots to predict RR (G. Diaz in JSS 2018).
  - ❖ Construct and use Directivity Plots (similar to those used in violin characterization) to predict RR (A. Philipossian in MM 2018, and L. Peckler in JSS 2018).
  - ❖ Perform high-frequency force FFT analyses to fingerprint the nature or effectiveness of discuss or nano-particles (A. Philipossian in JJAP 2006).











Parameters	Cond. Disc A	Cond. Disc B
Average RR (Å/min)	1,510	934
Average COF	0.448	0.215
Average Δ	48.1	7.14
Contact Area (%)	0.075	0.028
Contact Density (#/mm²)	2,560	1,670
MHDLL Thickness (µm)	12	23

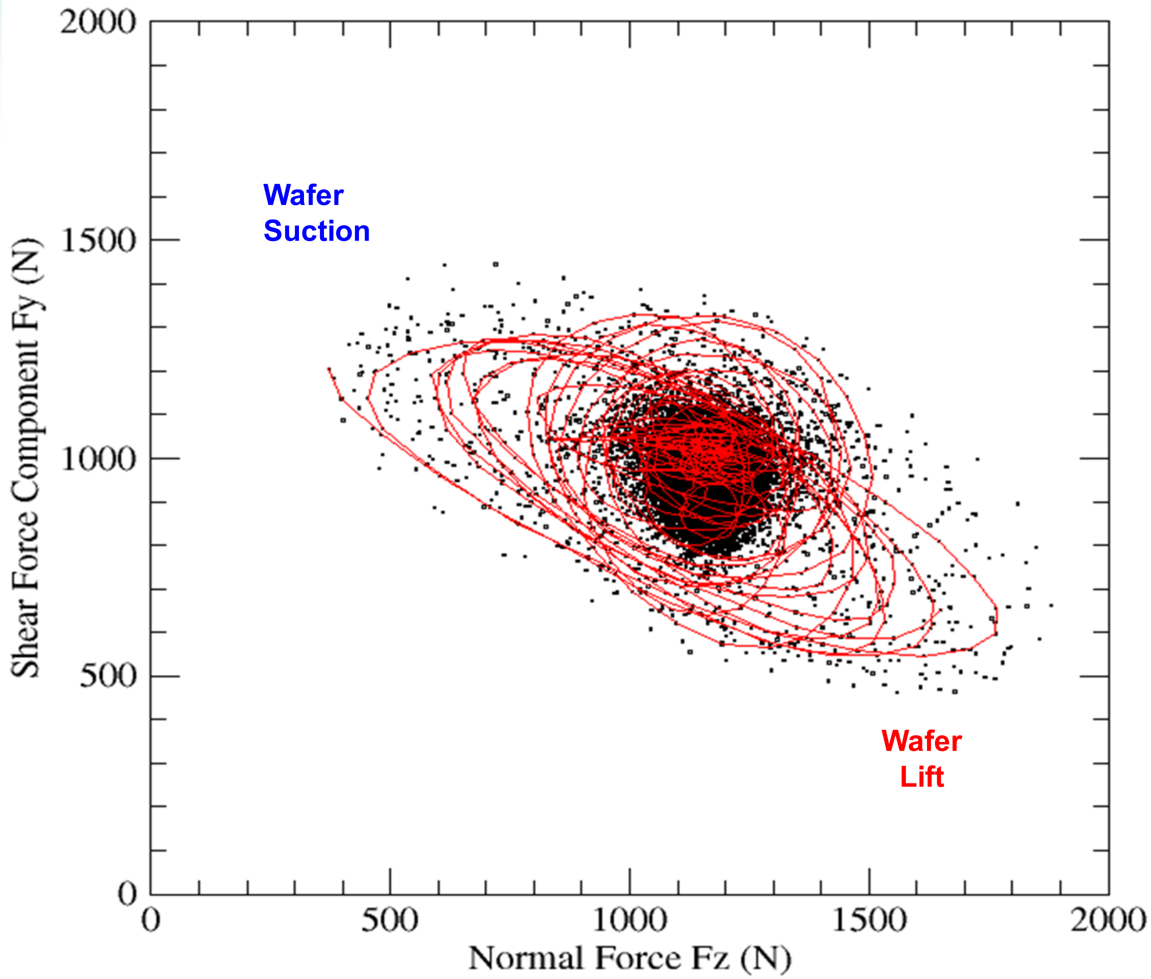
Issues Associated with Relying on PMC Data

- By relying on PMC data, we CANNOT …

  - ❖ Provide information about SF vs. NF cluster shapes – This is important because it gives information about slurry fluid dynamics and wafer altitude, pitch, and bank (L. Borucki relied on SF and NF in JSS 2019).

  - ❖ Detect abnormal vibrations – This is especially important in ceria slurries (R. Han relied on SF and NF in JSS 2017 – Same with M. Bahr in 2017).

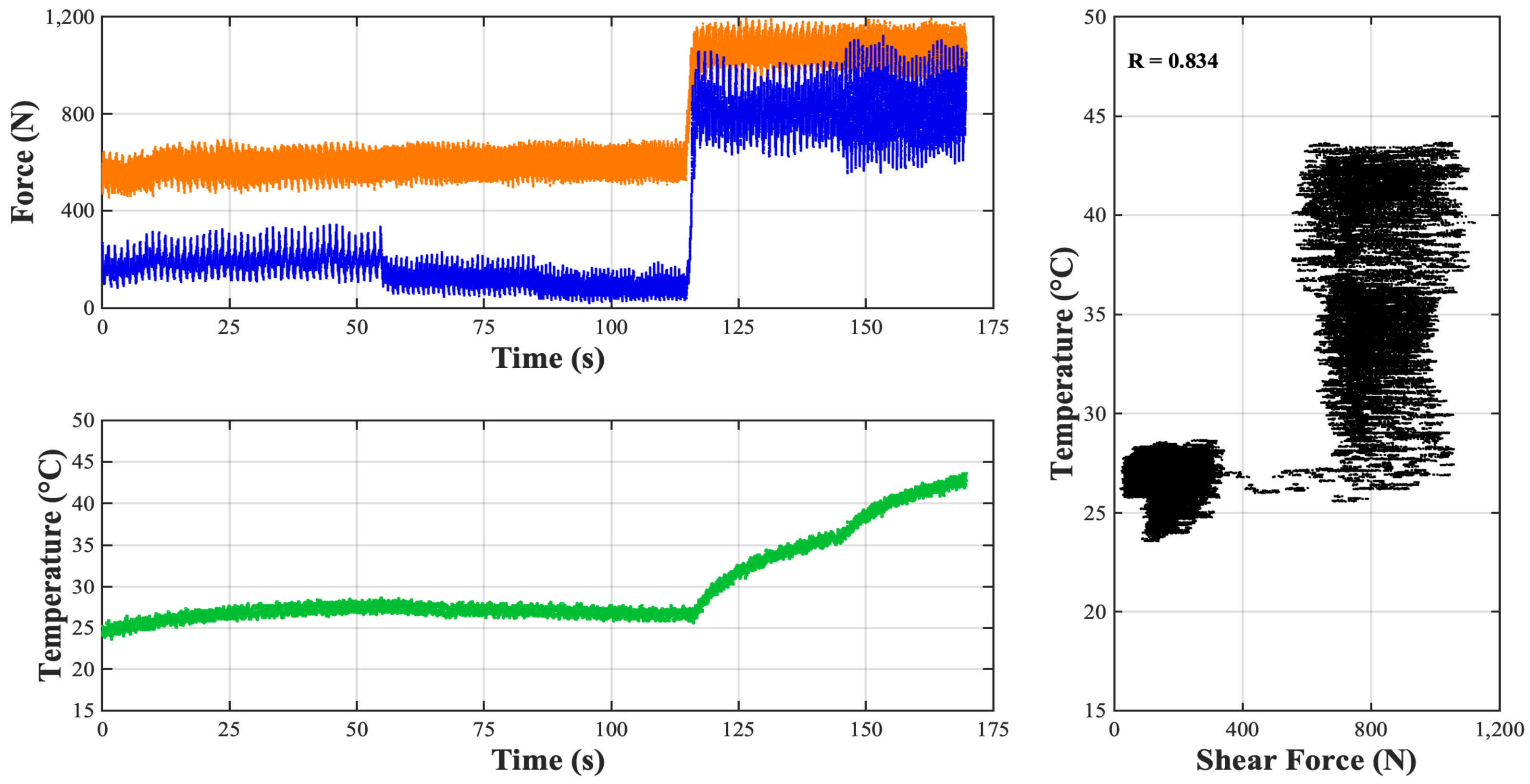
  - ❖ Detect gross vibrational bursts – This is especially important in copper CMP processes (L. Borucki relied on SF and NF in LP 2018).



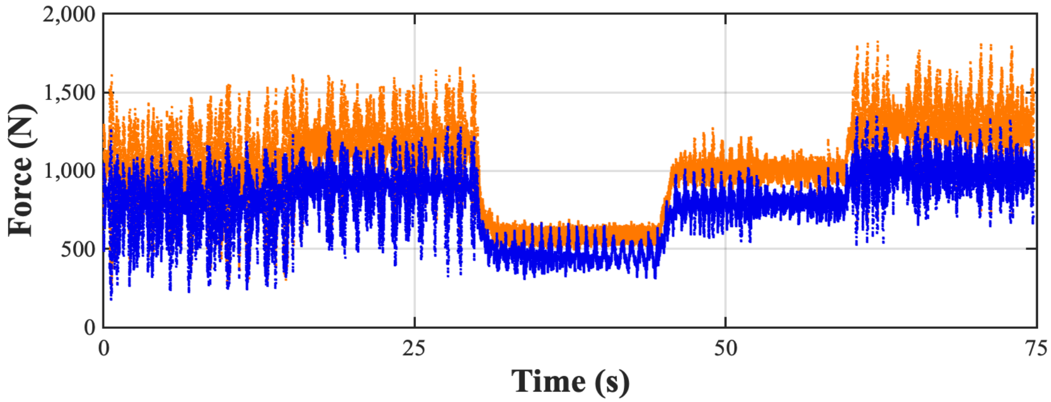
– Back-Up Slides –

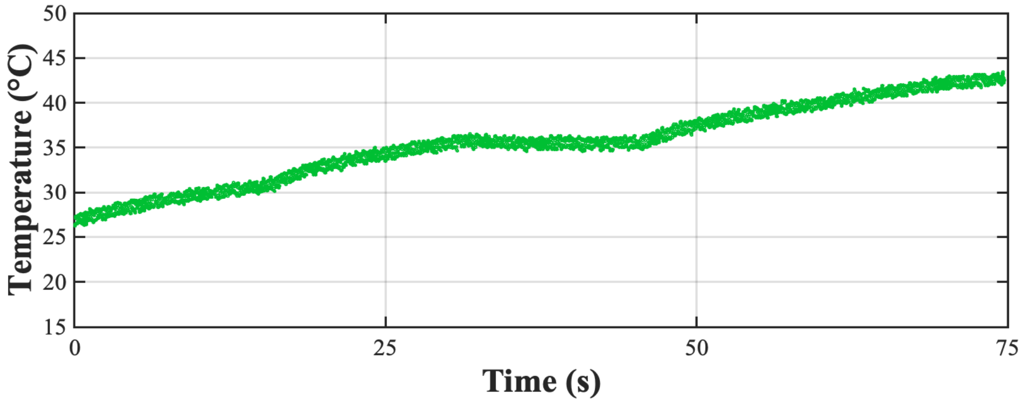
Pad Temperature vs. SF and NF Data … An Announcement … Annual “Per Student” Cost

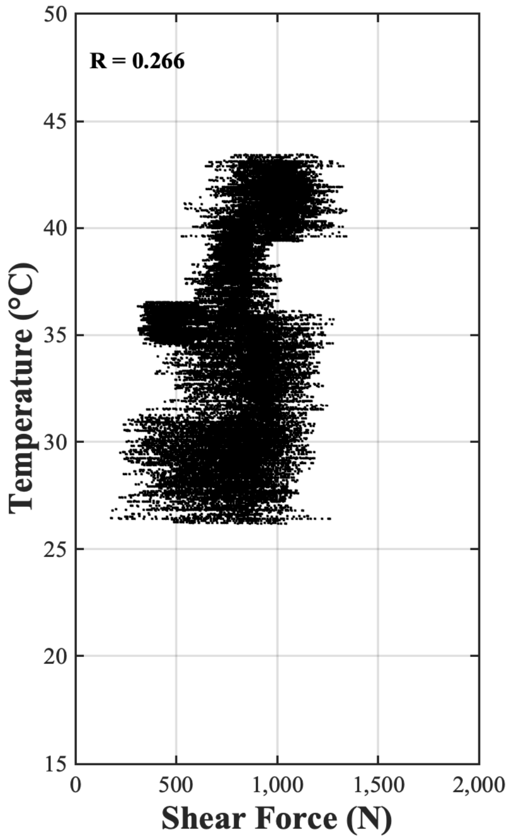
Pad Temperature Monitoring – Case A (Cu)



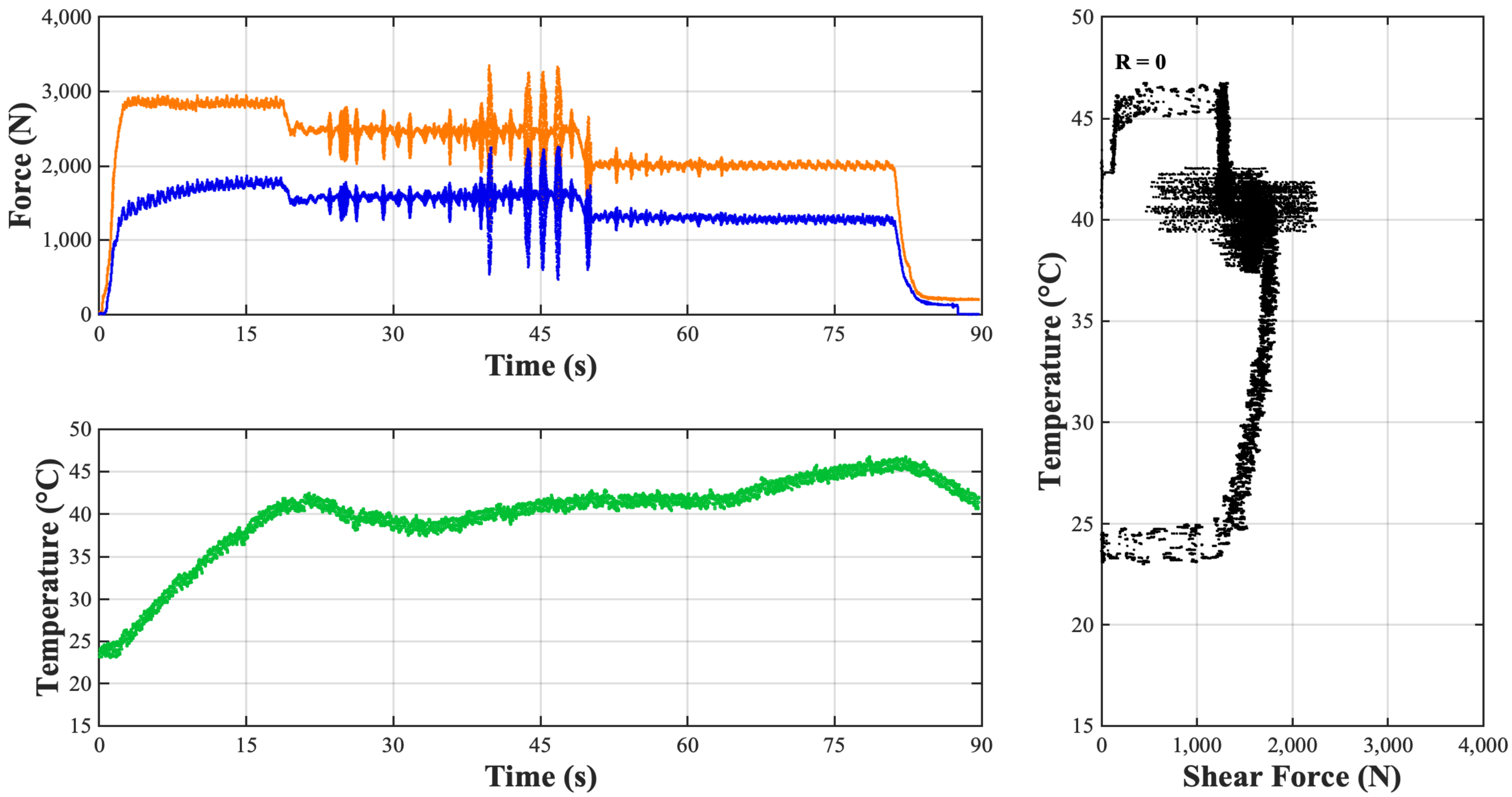
Pad Temperature Monitoring – Case H (STI)



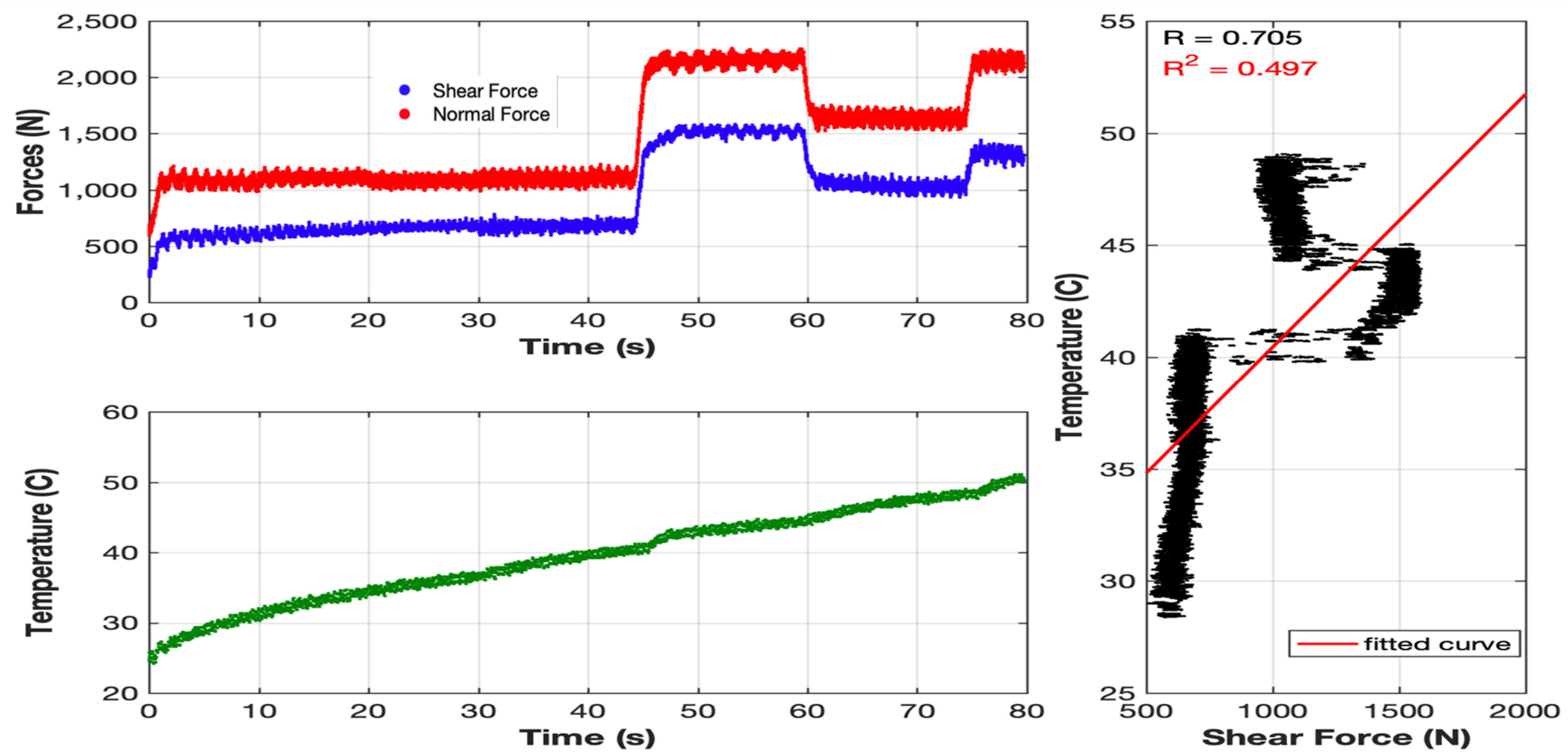




Pad Temperature Monitoring – Case K (ILD)



Pad Temperature Monitoring – Case 2 (W)



A Bit of News!

I’m quitting my job at the University of Arizona in December to focus 100+% on growing Araca, Inc.

– – – A BIG THANKS TO ALL OF YOU – – –

Especially to those who’ve financially and materially supported my research, and have hired my graduate students and undergraduate research assistants over the past 20 years!

Annual Per Student Cost of Research in the Philipossian Group at UA ~ 100K USD

Based on 29 PhD and 16 MS Graduates