Performance Assessment of Solid Polymer Lubricants and Hard Coatings for Dust-Contaminated Bearing Applications

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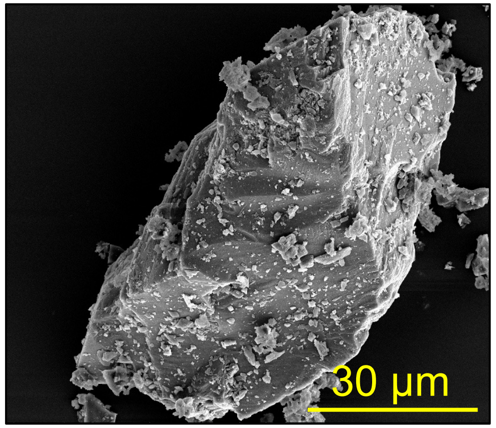
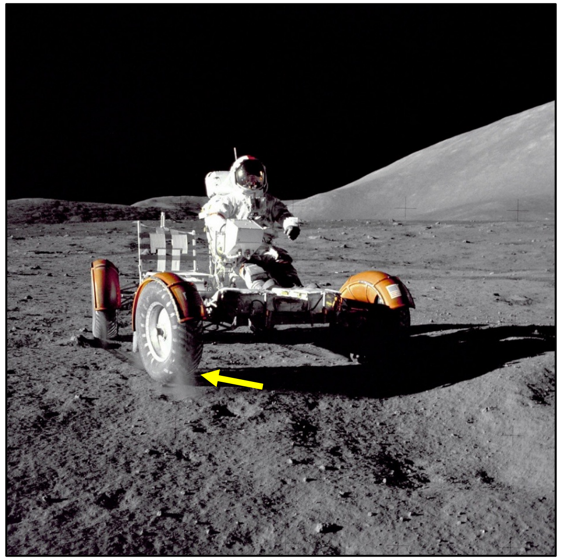
Why Bearings Fail on the Moon



Regolith (Lunar Dust)

- Abrasion
- Seizure

LRV Regolith Perturbation



Thermal Extremes

- Cryogenic Temperatures

Vacuum

- Lubricant Evaporation

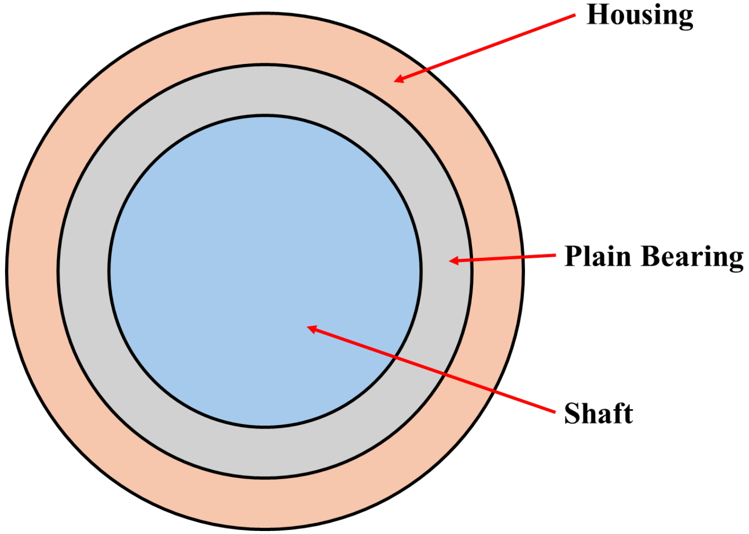
Temperatures: -246°C ⬇

Electrostatic Adhesion

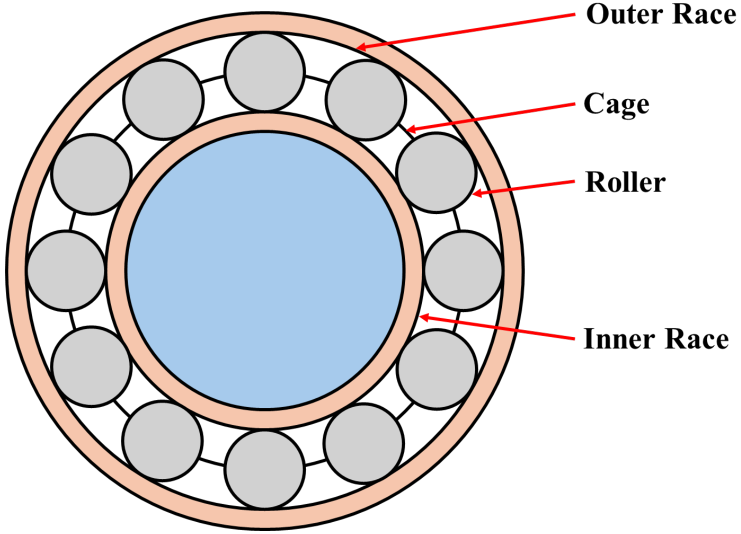
Once dust enters the contact, failure is inevitable.

Lunar Bearing Fundamentals

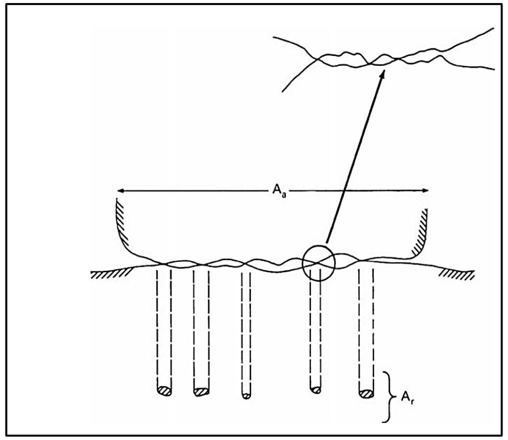
Plain Bearing



Roller Bearing



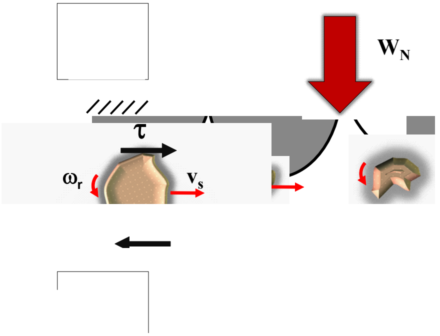
Real Contact Surfaces are Rough:



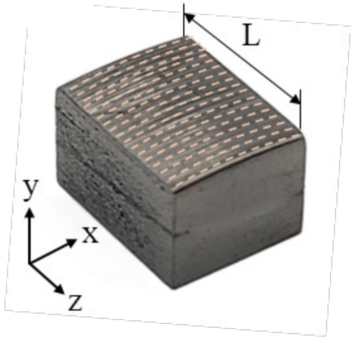
Bearings in a lunar environment are <u>unsolved</u> failure points.

How Dust Causes Bearing Failure

Three Body Abrasion

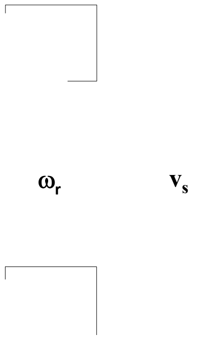


Particles roll and slide → continuous wear and surface degradation

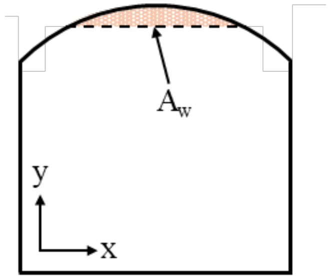


Transition between these modes determines failure rate.

Two Body Abrasion



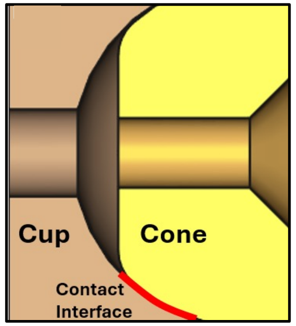
Particles are embedded → abrasive pad



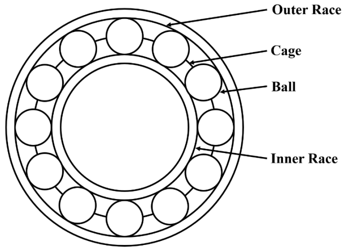
Material Strategies for Delaying Failure

Mitigation = controlling how regolith interacts with the contact

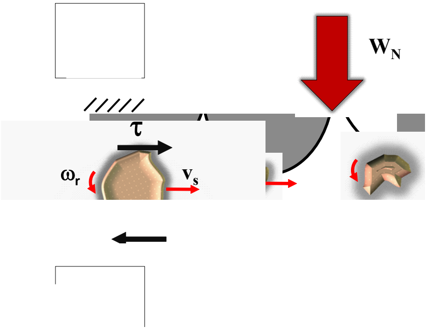
Hard Coatings
- Resist abrasion
- Maintain surface integrity

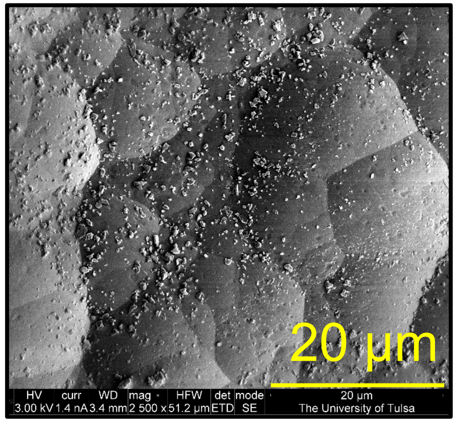


High Performance Polymers
- Absorb debris
- Stabilize contact during run-in

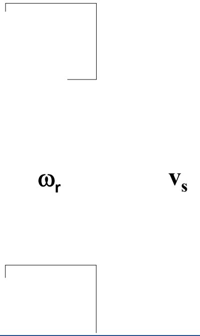


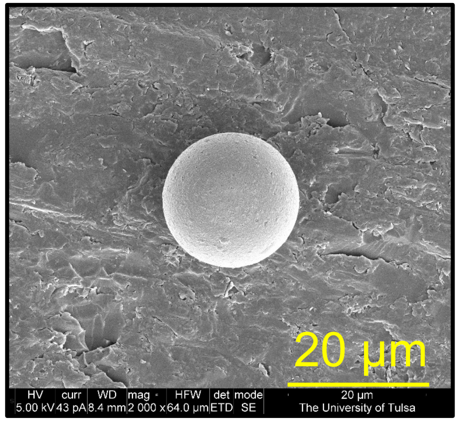
Three Body Abrasion





Two Body Abrasion





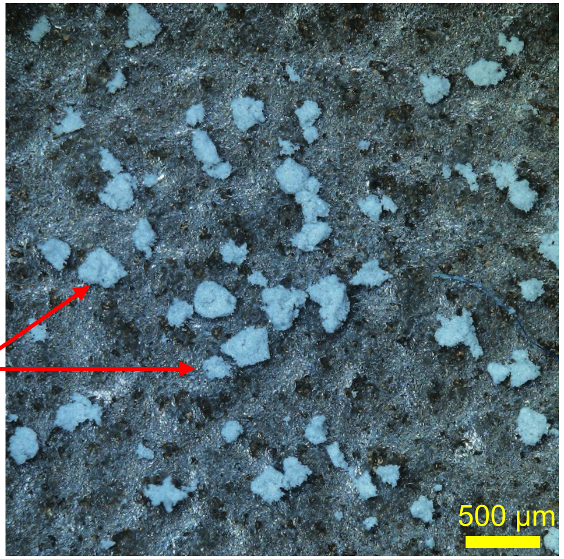
Lunar Regolith Morphology

LHS-1D Simulant

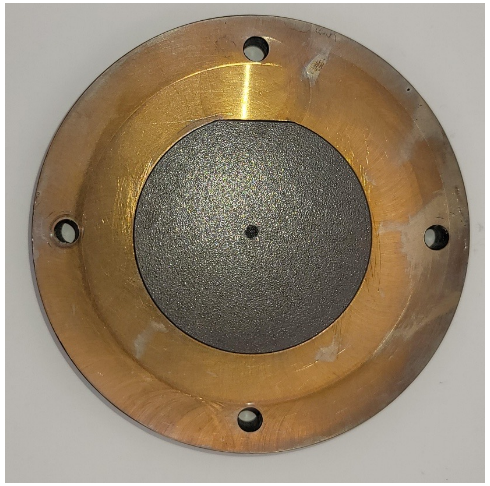
- **Angular particles** → abrasive
- **Fine size** → easily ingestible

This combination makes lunar dust uniquely destructive to bearings.

Clusters of Simulant on Polymer

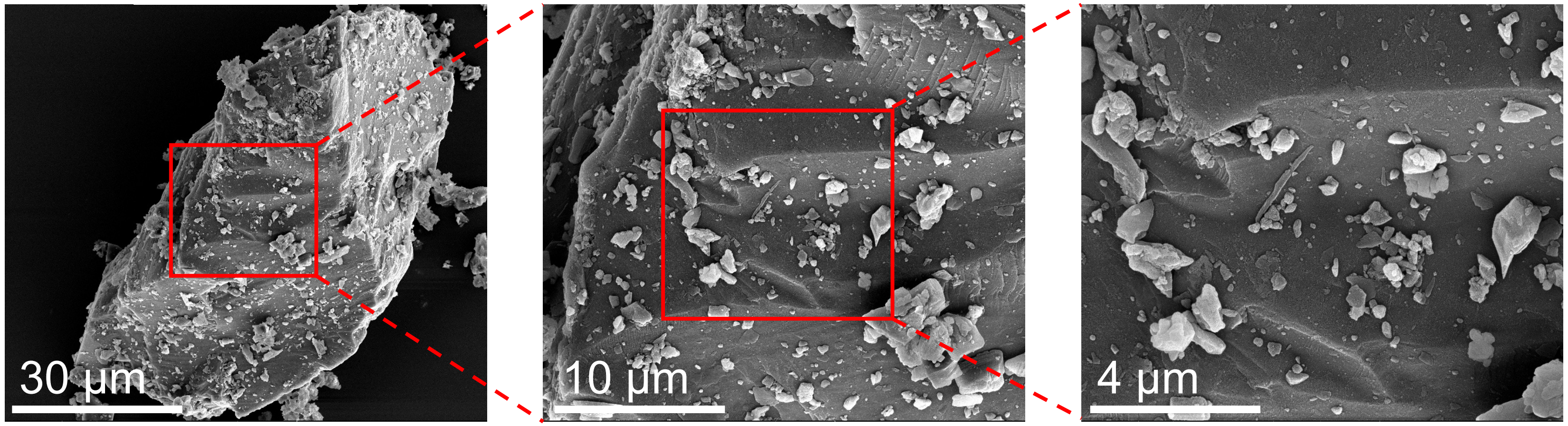


No Dust



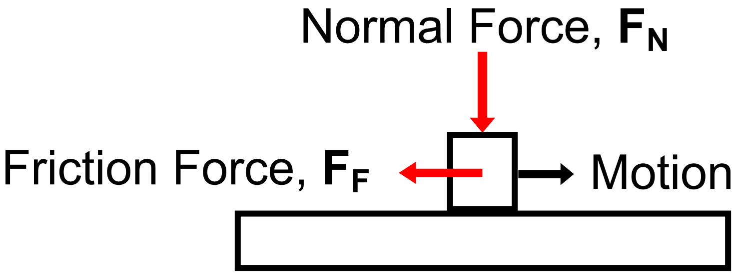
5 (g/m^2) Dust

1,500X 5,000X 10,000X



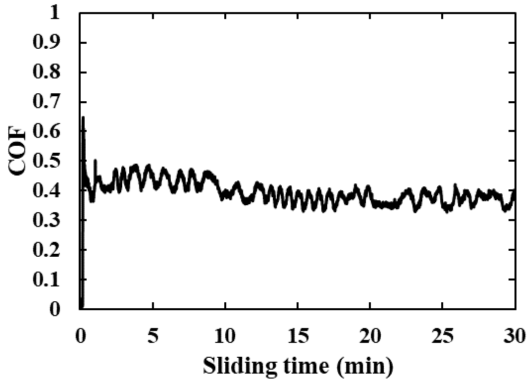
LHS-1D Lunar Dust Simulant: Extra fine lunar highlands simulant with mean particle size of 7µm and max size of 35µm.

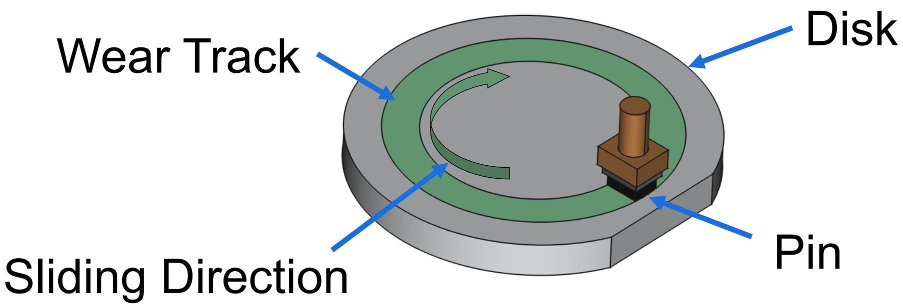
What We Measure to Understand Failure



Coefficient of Friction (COF)

$$\mu(t) = \frac{F_F}{F_N}(t)$$





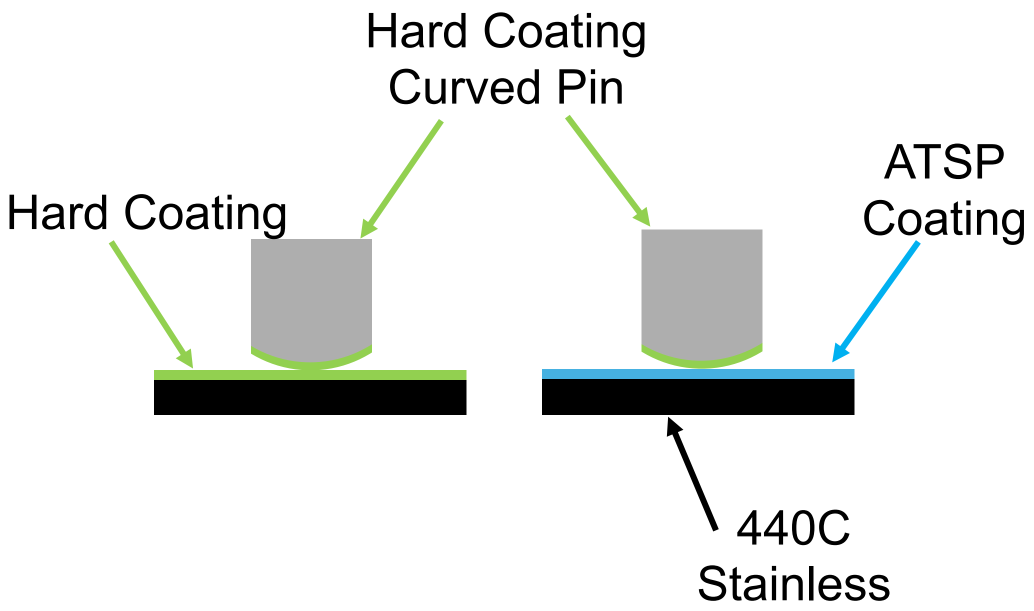
Friction → energy loss + instability

Wear → material removal

Contact Evolution → how the interface changes

These factors allow us to quantify how quickly failure develops.

Hard Coating Solid Lubricant Testing Regime



	Tribopairs		Temp. °C	Load N	Speed (m/s)	Distance (m)	Env.	Dust coverage <35μm
	Pin	Disk						
Coating vs. Coating	DLC*	DLC*	RT	5	0.25	450	N_2	5 g/m^2
	Ti-MoS2	Ti-MoS2						
	PS400	PS400						
	DLC*	ATSP						
	Ti-MoS2	ATSP						
	PS400	ATSP						

* 2 Variants of DLC coating, DLC 0701 (3-5μm thickness) and DLC 0702 (15-20μm thickness)

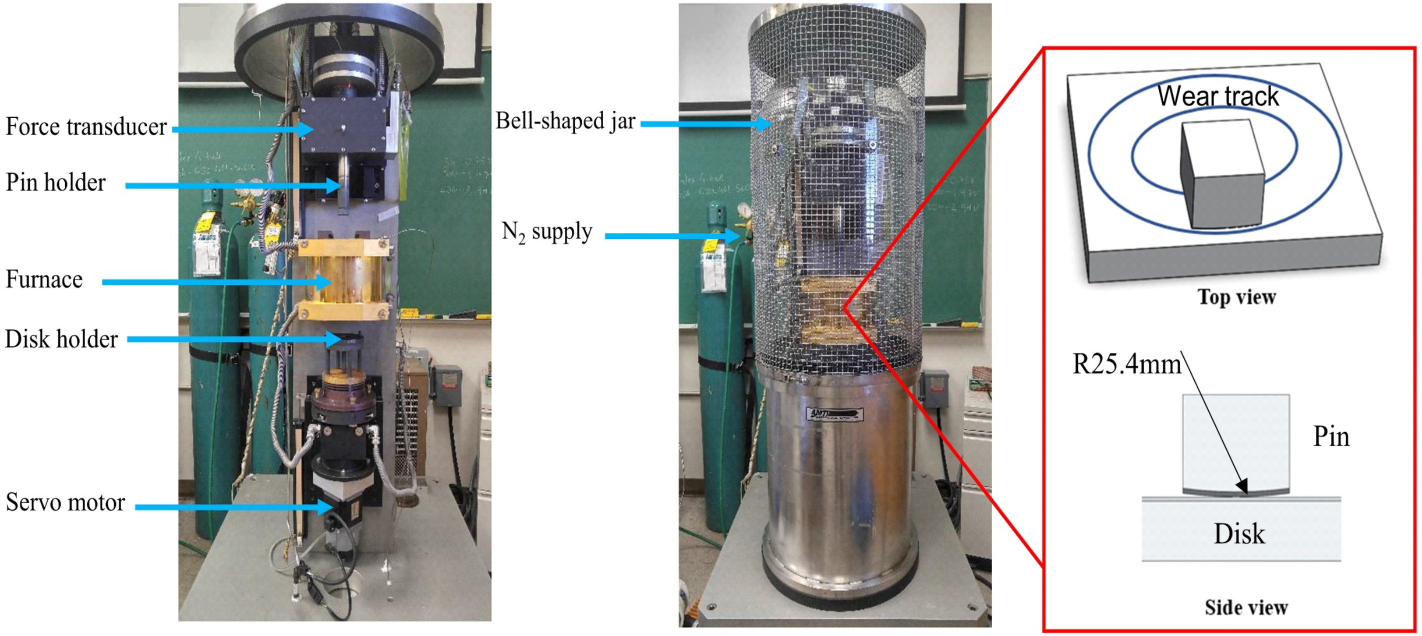
Dust Loading: Excessive dust contamination

Nitrogen Environment: Vacuum surrogate

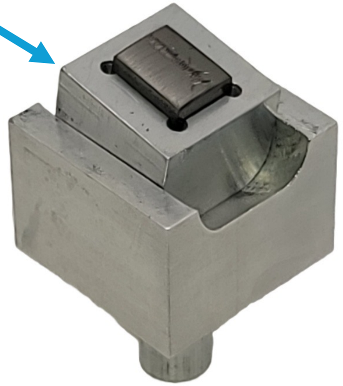
Load/Speed: Plain bearing surface simulation

Conditions selected to approximate bearing surface interactions under dust exposure.

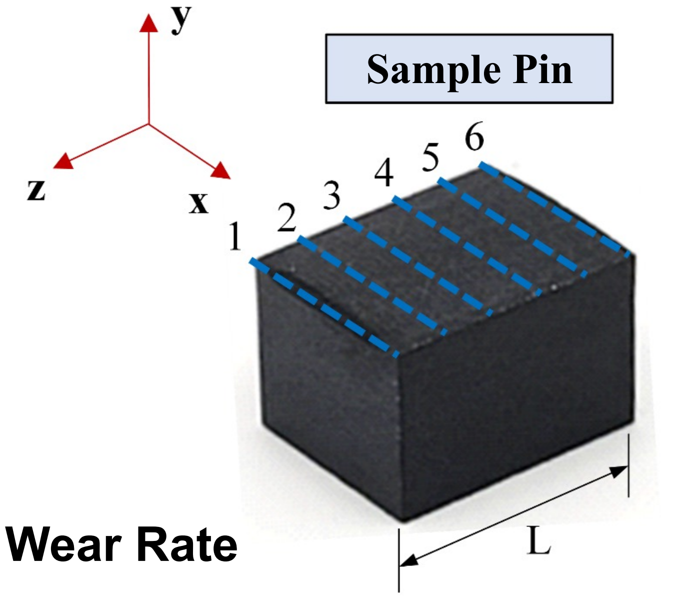
How We Actually Measure Material Failure



1D Self Aligning Pin Holder

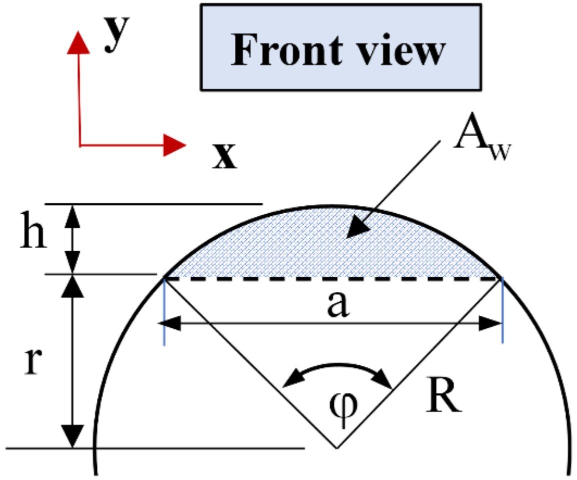


Volumetric Loss Calculations

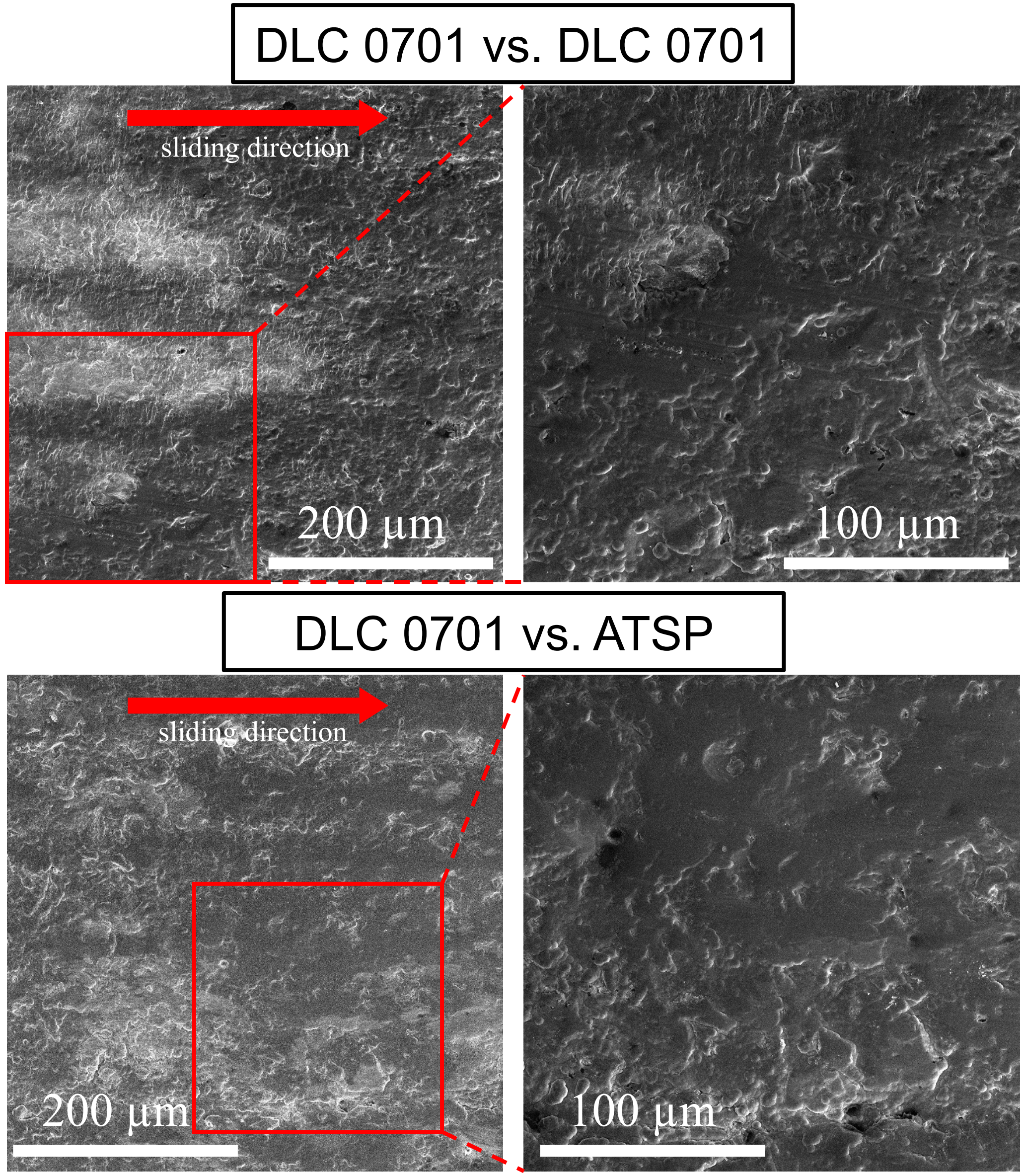


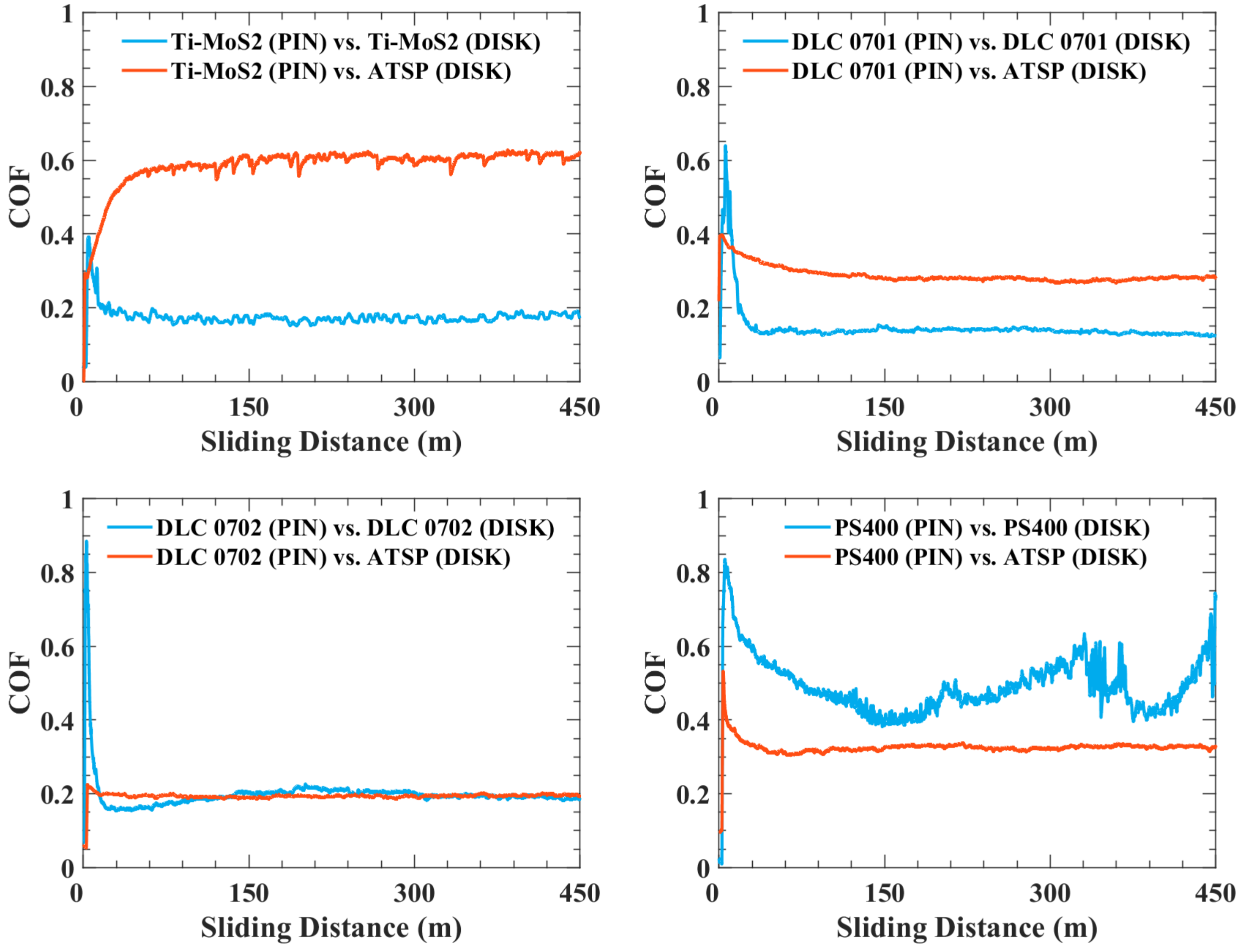
Wear Rate

$$k = \frac{\Delta V}{W_n . s}$$



Contact Instability During Testing





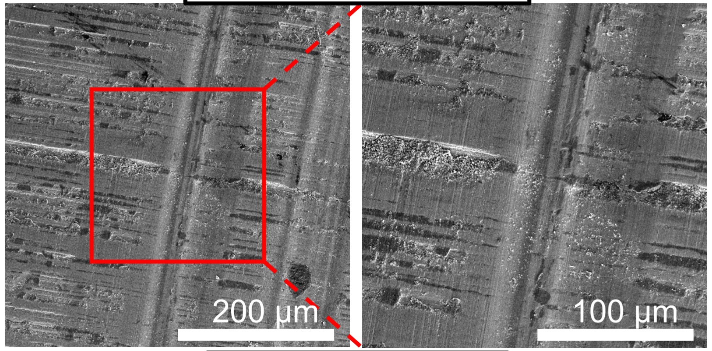
- Hard-hard → unstable run-in → high energy events (damage)
- Hard-soft → stabilized → smoother transition

Regolith-Mediated Contact Evolution

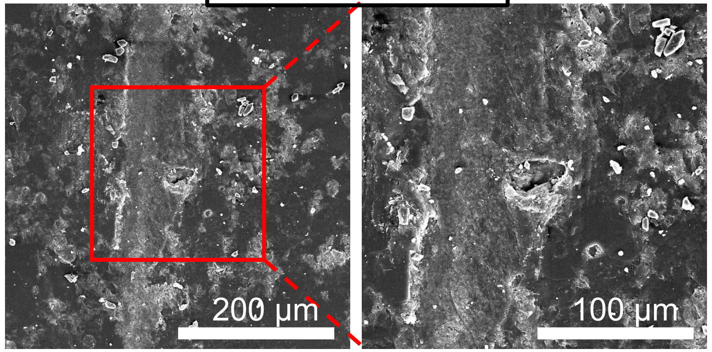
Under <u>certain</u> conditions regolith can form a protective film

- Smearing + MoS_2 → protective tribolayer → reduced wear

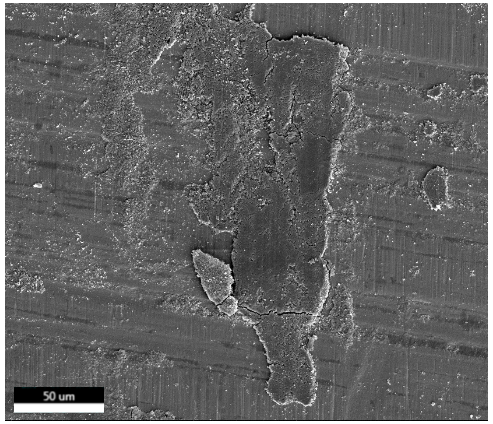
Ti-MoS_2 vs. Ti-MoS_2

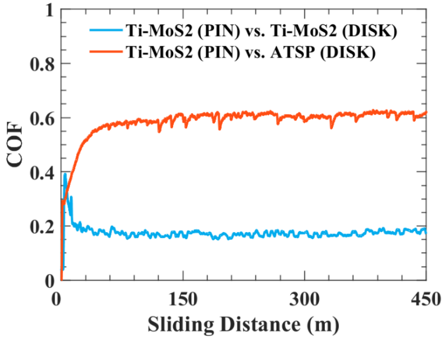


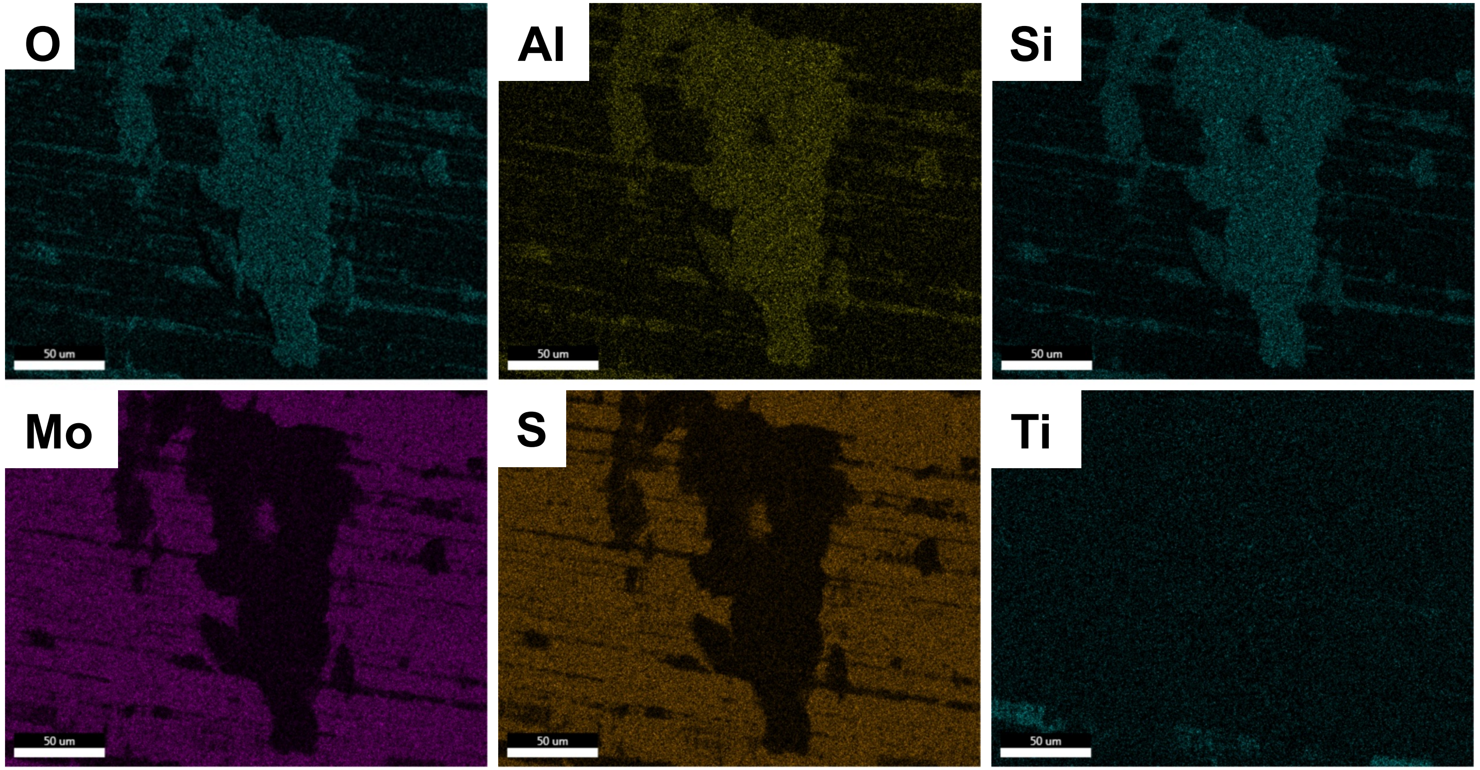
Ti-MoS_2 vs. ATSP



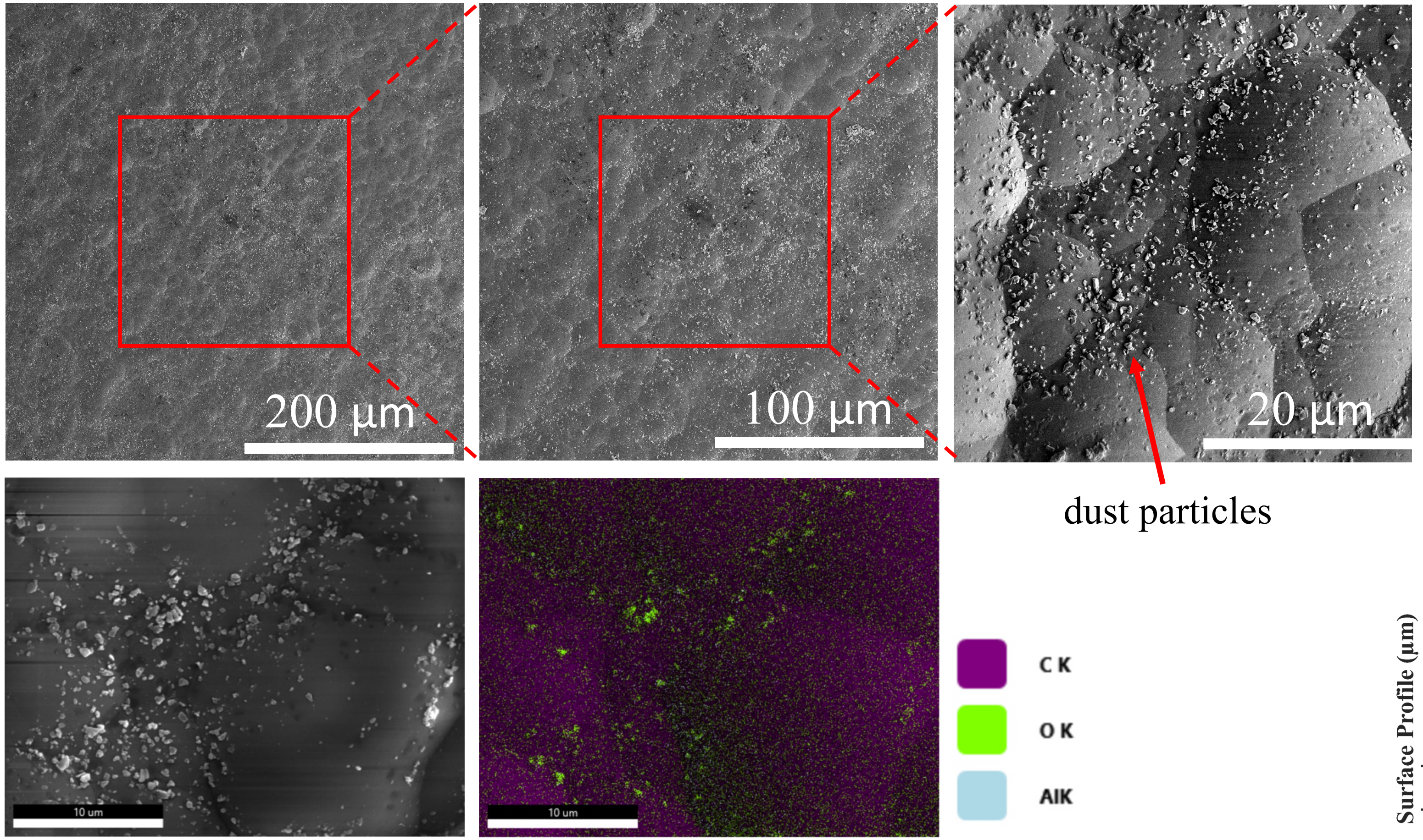
Ti-MoS_2 vs. Ti-MoS_2







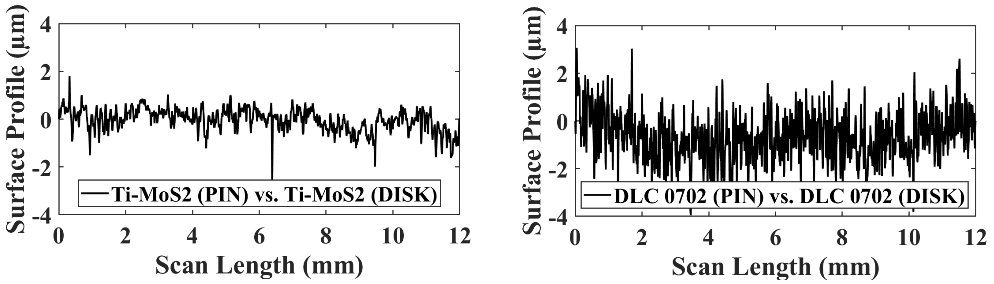
High Energy Regolith Interactions



Particle crushing → high stress → damage

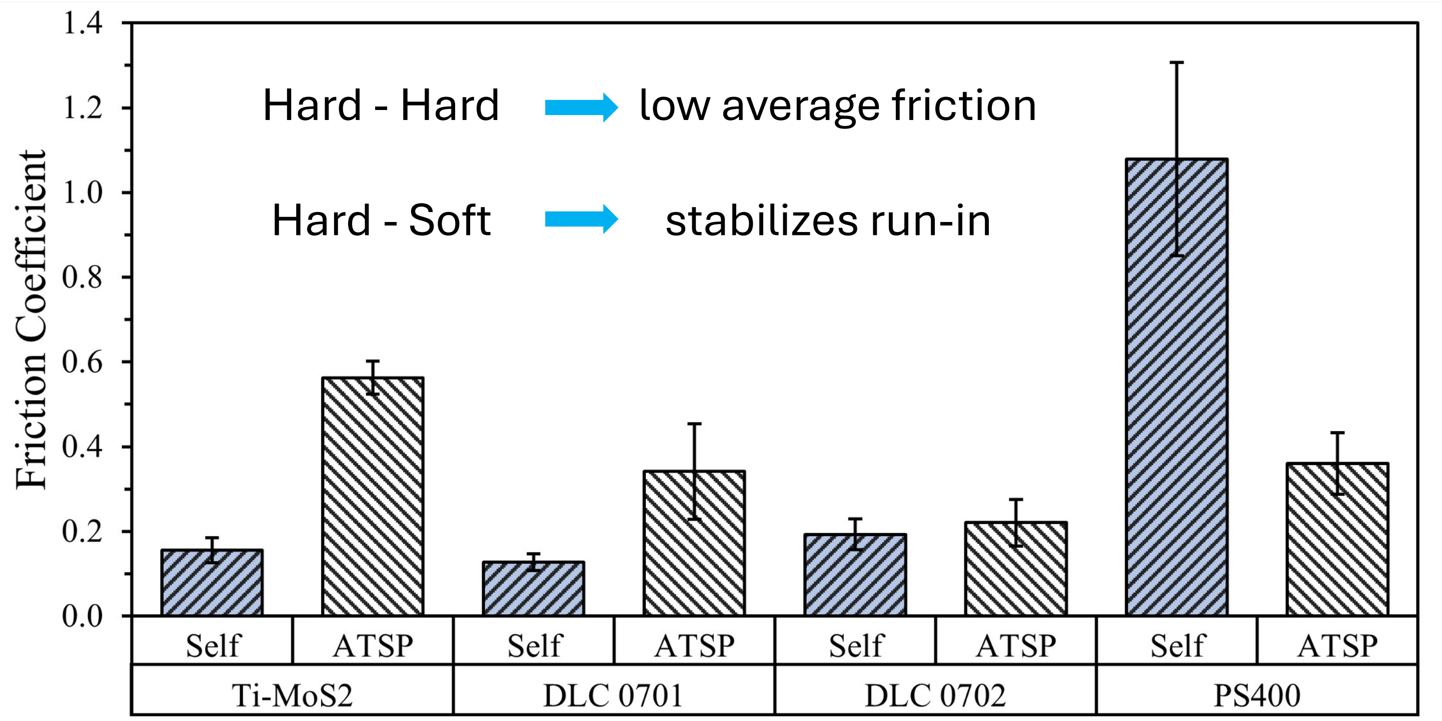
Surface “stamping” → roughness driven failure

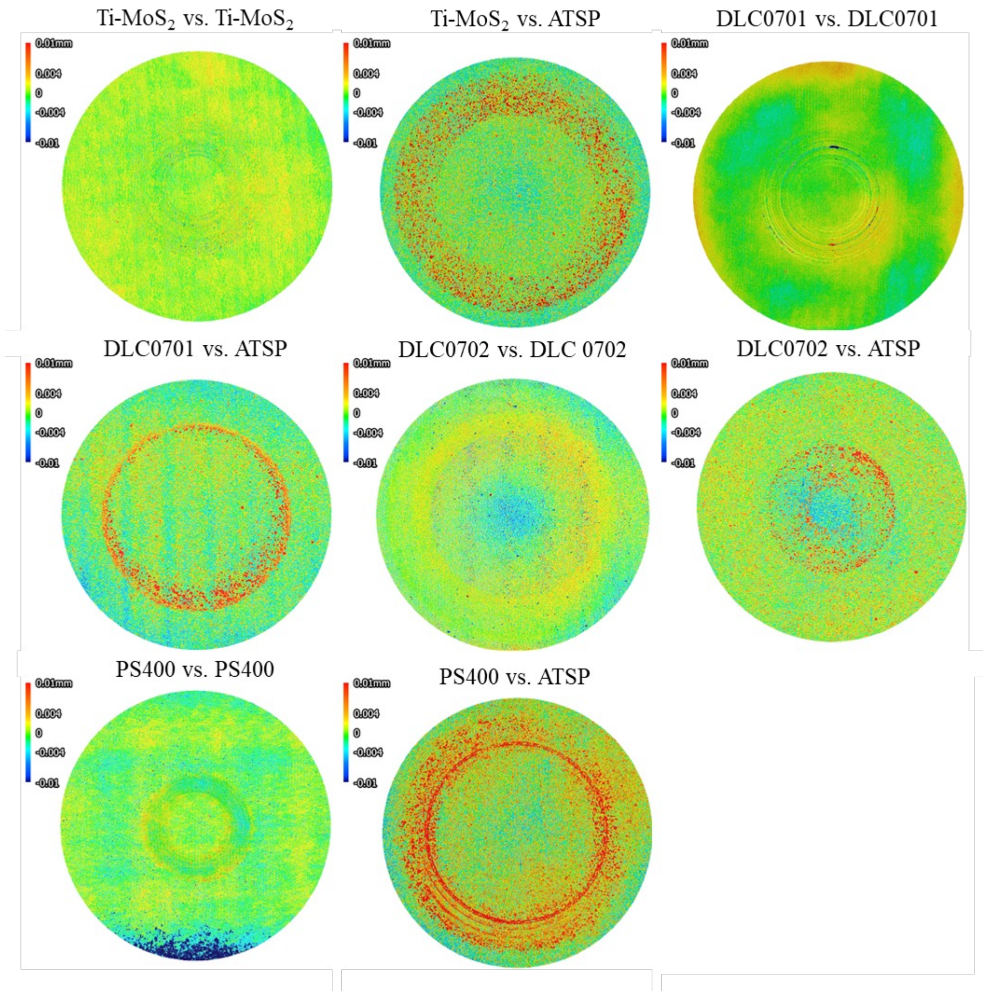
2D Profilometric Surface Comparison



Surface topography and coating thickness strongly influence failure mode.

Material Influence on Failure Progression





- Thin hard coatings → lower friction but limited wear life
- Thick hard coatings → better under abrasive loading
- Hard coatings paired with polymer → stabilizes contact and reduces harsh run-in

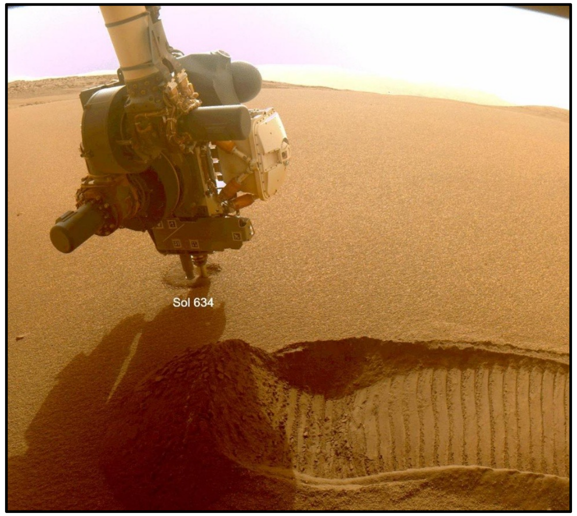
Material pairings strongly influence how quickly failure develops.

Implications for Resource Utilization Systems

Conveyance Systems → fewer seizure events

Excavation Systems → reduced wear rates → longer operation cycles

Processing Equipment → improved reliability under contamination



** Images obtained from NASA Image and Video Library*

Bearing Design Conclusions

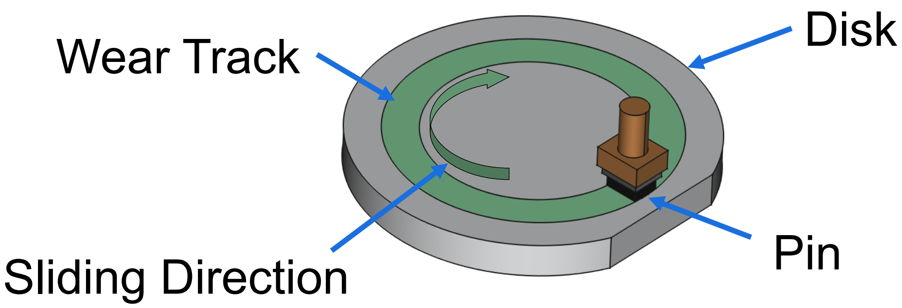
- Failure inevitable after seal breach; rate controllable.
- Hard coatings resist abrasion.
- Soft counterfaces stabilize run-in.
- Dust behavior depends on materials and surfaces.
- Material design extends bearing life.

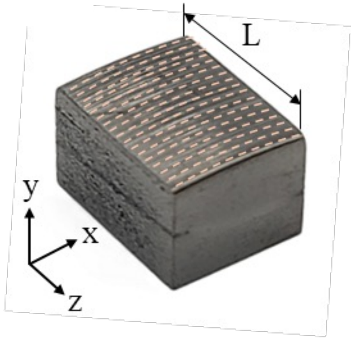
Acknowledgements

Sorrell, J., Nunez, E. E., & Polycarpou, A. A. (2025). High-performance polymer composites for dust-tolerant extreme environment bearings for lunar exploration. *Wear*, *574*, 206084.

Sorrell, J., Rahman, M. A., Tsigkis, V., Vaught, L. O., & Polycarpou, A. A. (2026). Tribological performance of hard coatings and polymer interfaces under the effect of lunar regolith. *Wear*, 206669.

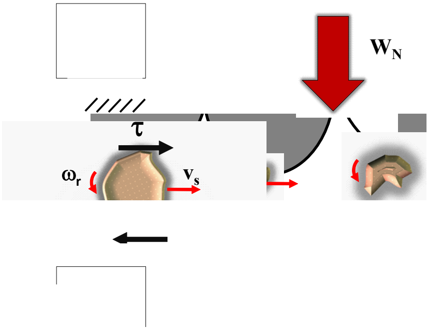
Questions?

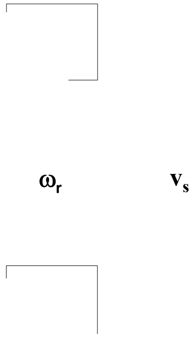


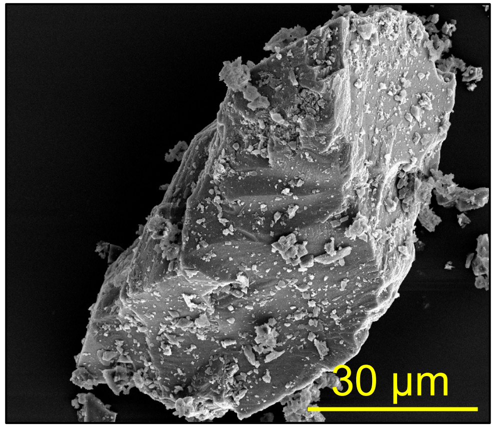


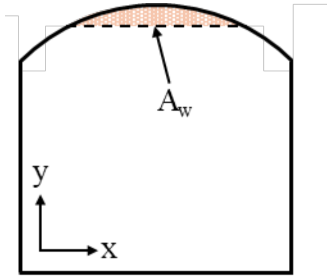
Three Body Abrasion

Two Body Abrasion

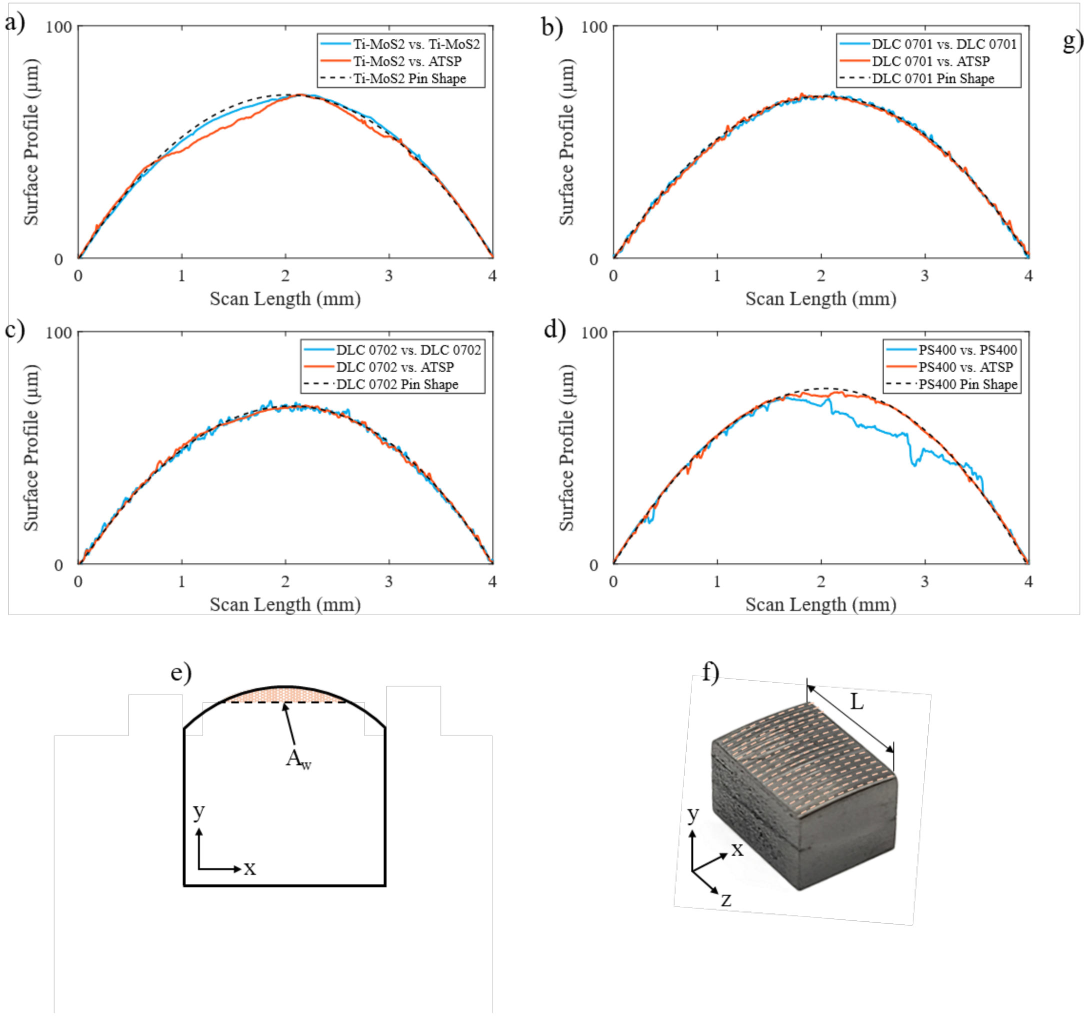








Wear Measurement Process



g)

Disk	*Pin*	*Wear Rate (mm³/Nm)*
Ti-MoS₂	*Ti-MoS₂*	--
	ATSP	$2.7x10^{-5}$
DLC0701	*DLC0701*	--
	ATSP	--
DLC0702	*DLC0702*	--
	ATSP	--
PS400	*PS400*	$5.5x10^{-5}$
	ATSP	$2.1x10^{-5}$

$$\Delta V = A_W \; L$$

$$k = \frac{\Delta V}{W_n . s}$$

LHS-1D Composition

Minerology (> 5%)

- 74.4% Anorthosite ($CaAl_2Si_2O_8$)
- 24.7% Glass-rich basalt

Composition (> 5%)

- 48.1% SiO_2
- 25.8% Al2O3
- 18.4% CaO

Hardness Testing