SAND2016-10040C

How Much Is Enough? Lubricant Thickness Vs. Life In A Plain Journal Bearing

Exceptional service in the national interest

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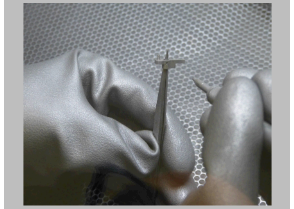

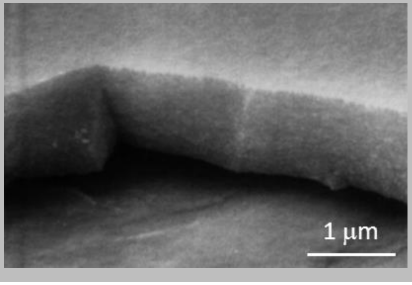

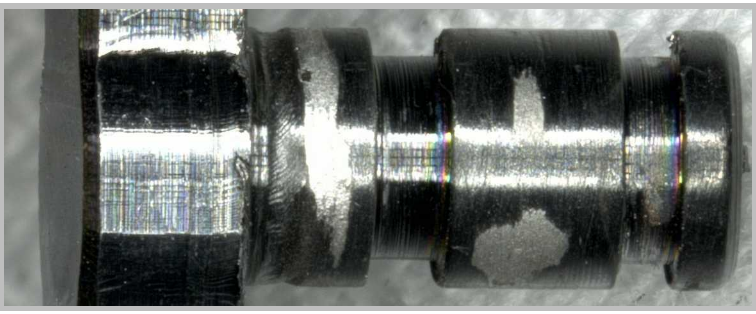

Brendan L. Nation,

Michael T. Dugger

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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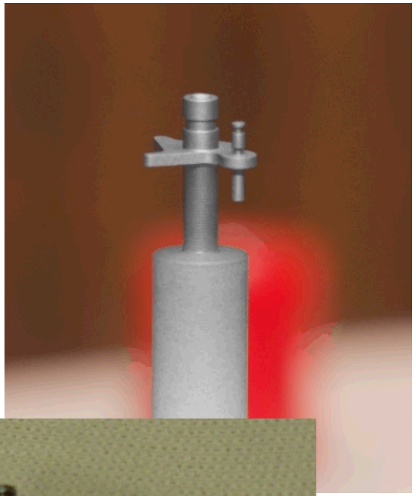
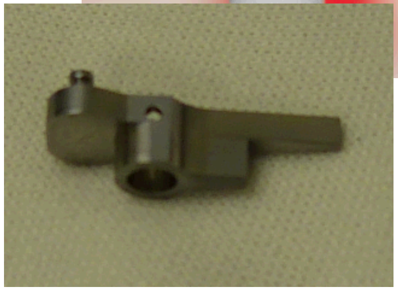
SAND No. 2011–XXXXP.

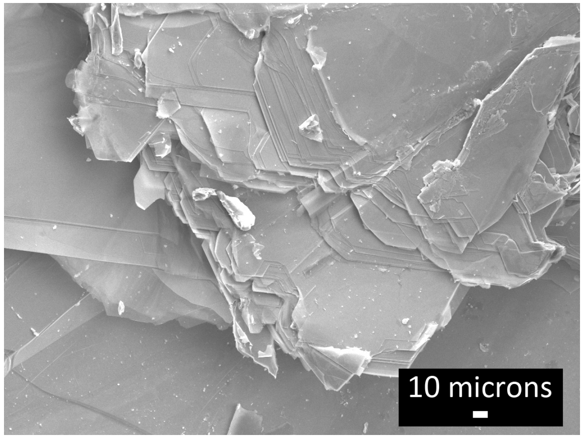
Materials used in Electromechanical Device Lubrication

- Resin-bonded MoS_2
  - Phenolic Binder w/ MoS_2+graphite particles
- **Impingement Coatings**
  - **“N_2-Sprayed MoS_2”**
  - “Harperized MoS_2”
- Silicone Fluids
  - polydimethylsiloxane (PDMS), 0.65 – 20 cSt

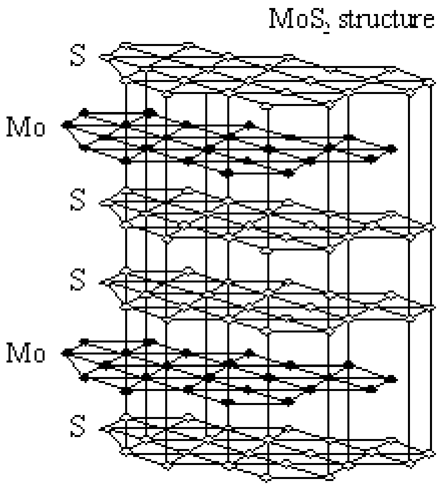




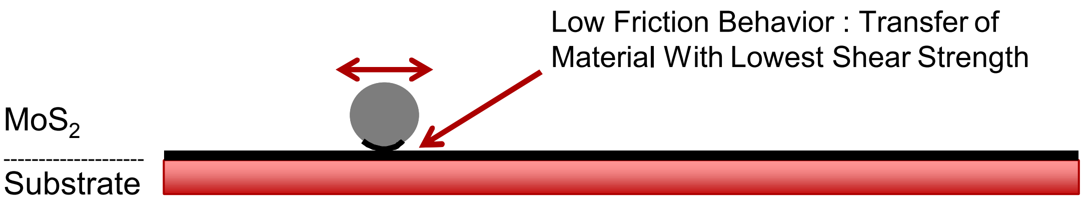
MoS_2 As A Lubricant

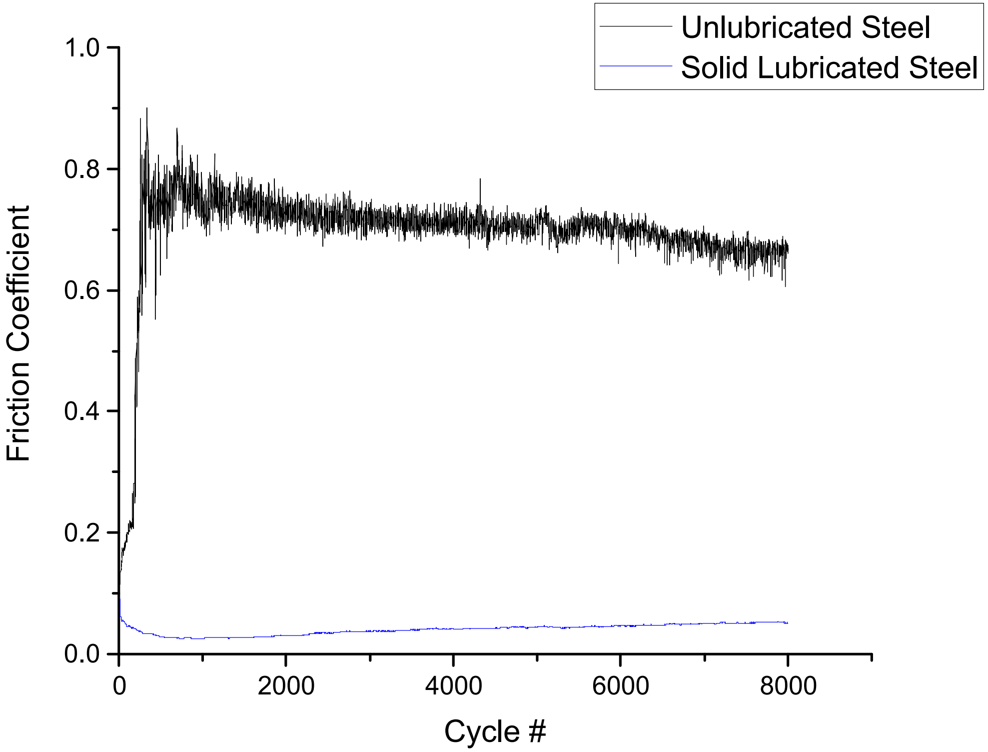


graphene-supermarket.com/MoS2-Crystal.html



wearcotetechnologies.in/2014/06/wct-mos-cote.html

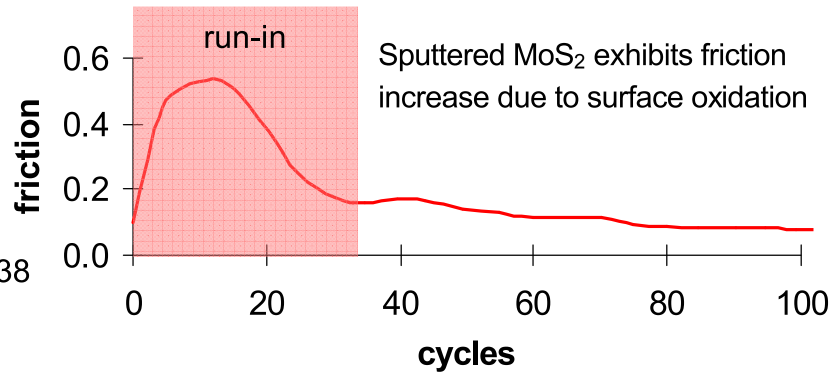


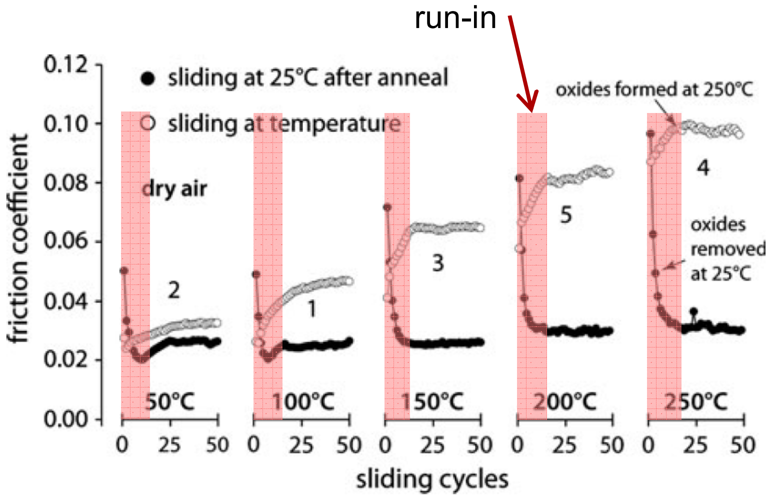


Environmental Effects on MoS_2 Aging

- Surface oxidation can dramatically increase the initial friction coefficient
  - exposure to atomic oxygen oxidizes upper ~100 nm

M.T. Dugger, T.W. Scharf and S.V. Prasad, *Adv. Mat. and Processes* **172** (2014) p.35-38





- Oxidation increases start-up and dynamic friction at elevated temperature
  - at low T or non-oxidizing atmosphere, oxidized layer is rapidly worn through

H. Khare and D. Burris, *Tribology Letters* **53** (2014) p.329-336

- *Surface oxidation increases friction during run-in*
- *Oxidized layer is rapidly worn through at RT : low COF*

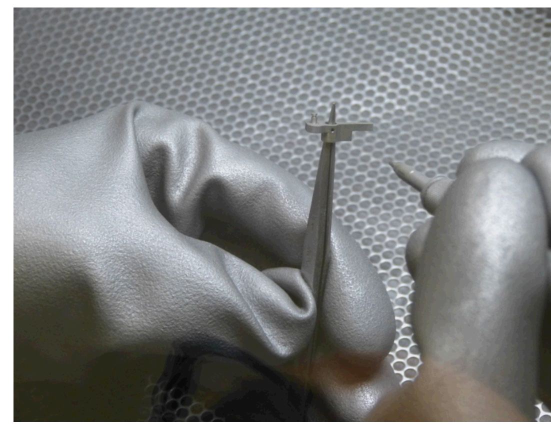
N_2-Sprayed MoS_2 Processing

Clean

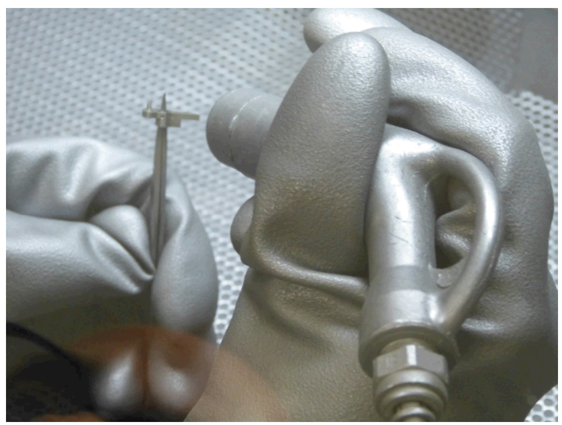
Load Parts in Spray Cabinet

Load MoS_2 in Powder Feeder

Spray

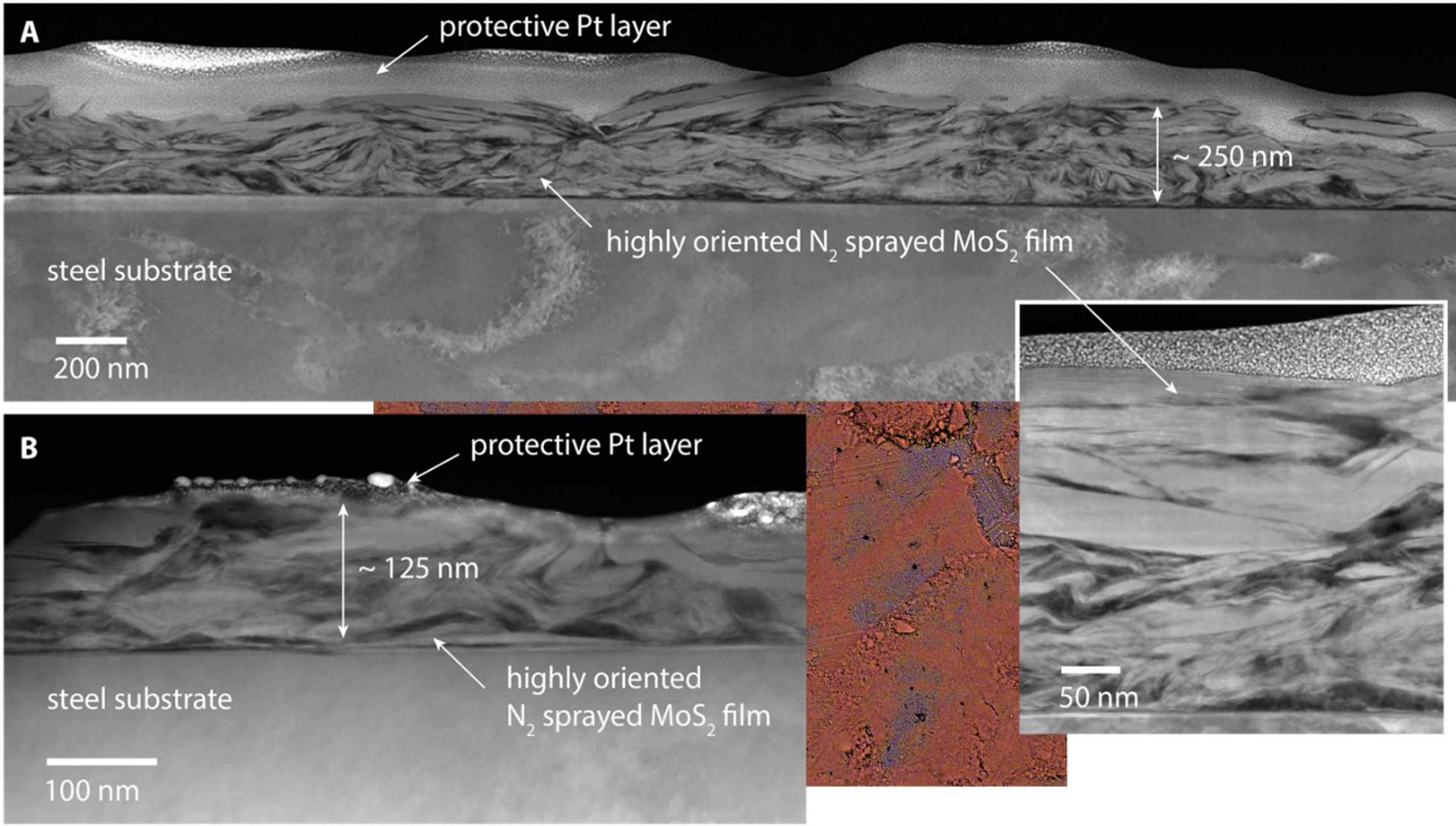


Blow Off Excess MoS_2



- thickness not adjustable; maximum ~100 nm thick, limiting operating life
- coat by hand, one fixture at a time

Ideal Coupons – Heterogeneous Coverage

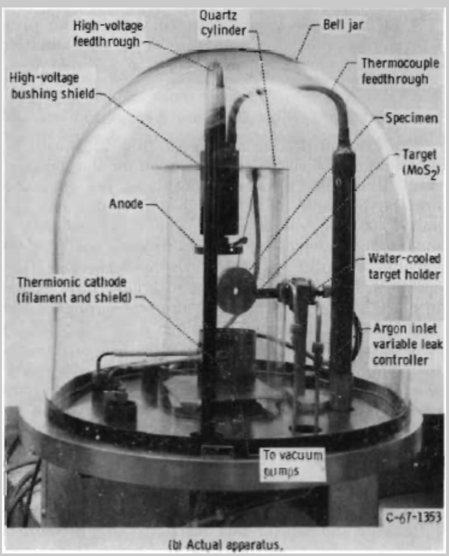


“Ideal” flat coupons exhibit inconsistent coverage

Highly Oriented MoS_2 Coatings: Tribology and Environmental Stability *Tribology Letters (Submitted, Under Review)*
John F. Curry et. al.

Advent of Sputtering Improved Consistency

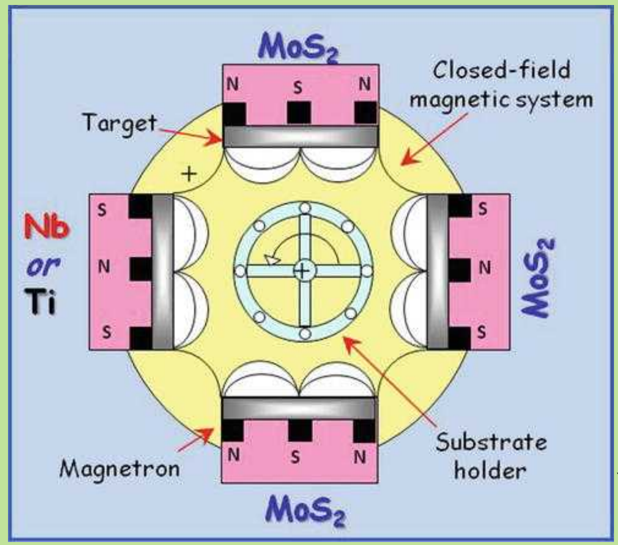
- A process is needed that is compatible with precise, small, complex parts, and which facilitates quantitative quality assurance monitoring
- Synthesize coatings via Physical Vapor Deposition (PVD)



T. Spalvins, *ASLE Transactions* **12** (1969) p. 36-43

sputtered MoS_2 has been investigated for lubrication for almost 50 years

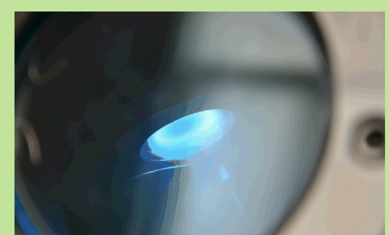
- initially DC sputtering in low vacuum
- developed by NASA for use in US space program



modern deposition systems result in improved properties

- RF magnetron, arc discharge, etc. allow for densification, doping, tailored structures, etc.
- several variants commercially available

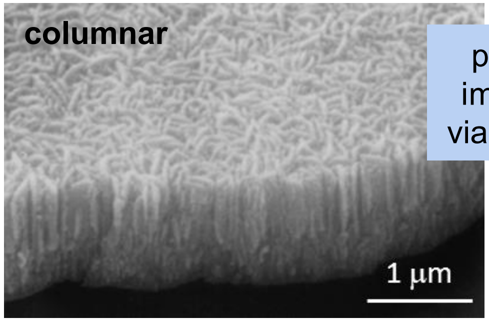
I. Efeoglu, in *Encyclopedia of Tribology*, Q. Wang and Y.-W. Chung, eds. (2013) Springer, p. 3233-3252



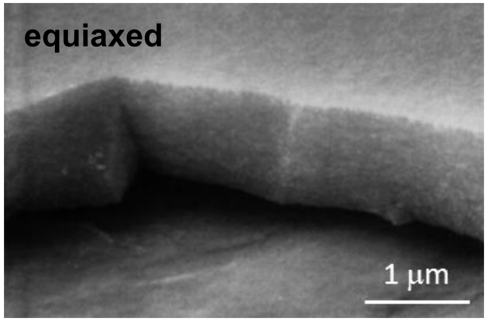
Controllable film structure/composition

- Tailored film structures improve performance in a range of atmospheres
- Expect dense films to resist long-term oxidation/environmental effects
- May be possible to reduce or eliminate "run-in"
- Controllable thickness
- Batch Processing

M.R. Hilton, et al., *Surf. Coatings Tech.* **53** (1992) p.13-23

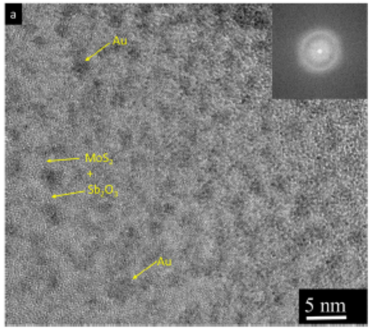


performance improvements via densification

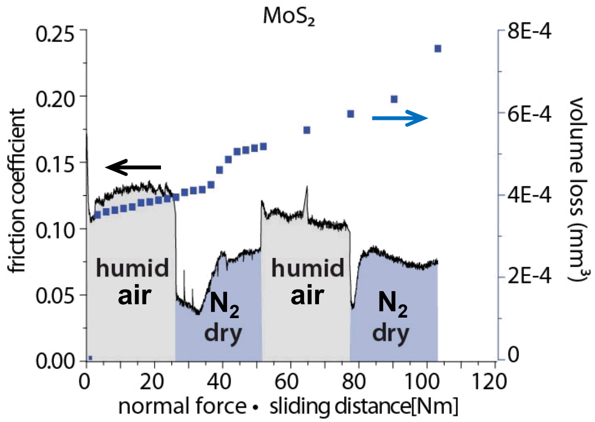


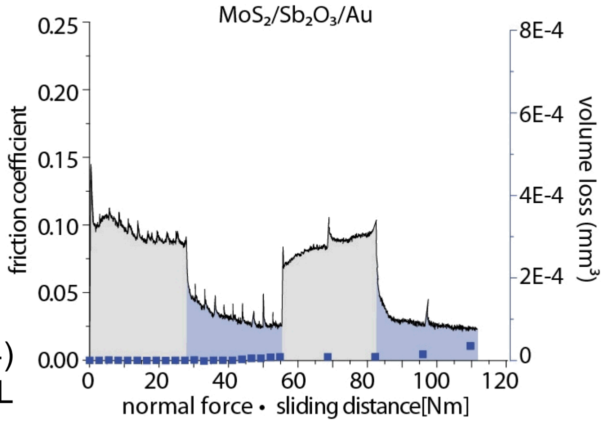
performance improvements via doping

$MoS_2+Sb_2O_3+Au$



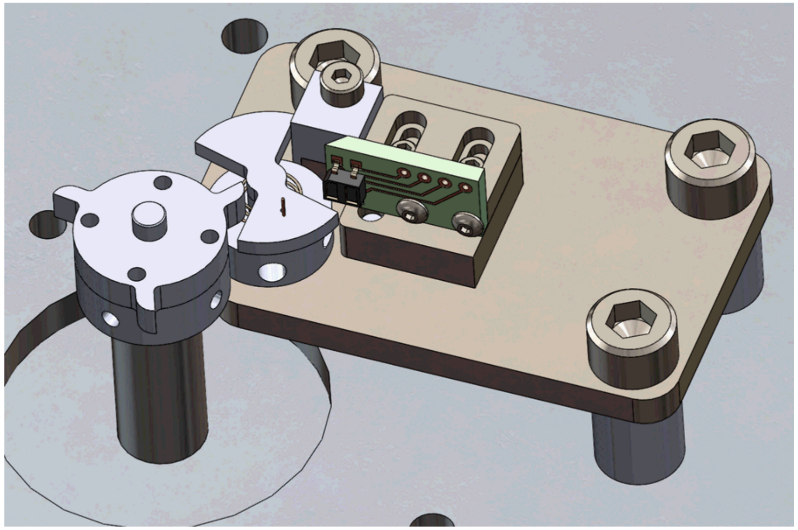
H. Singh et al., *Surf. Coating Tech.* **284** (2015) p. 281-289





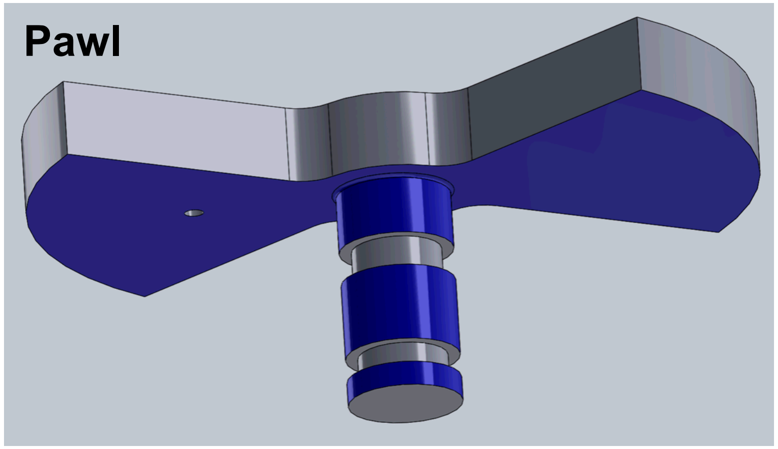
R.S. Colbert, *Ph.D. Dissertation* (2014)
U. of Florida, Gainesville, FL

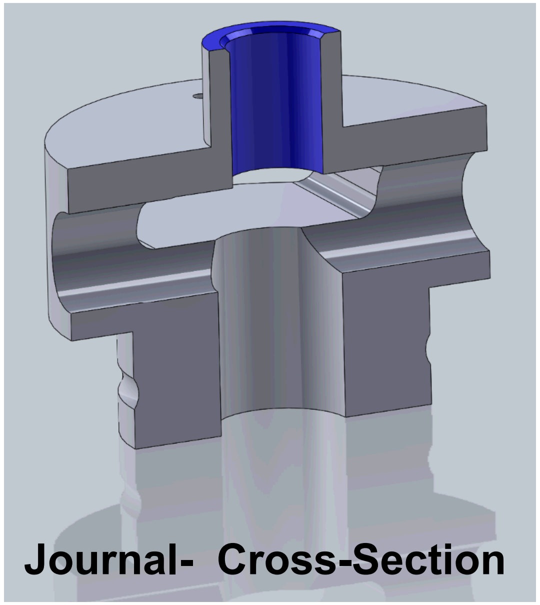
Reciprocating Plain Journal Bearing:



Mission Requirements Summary

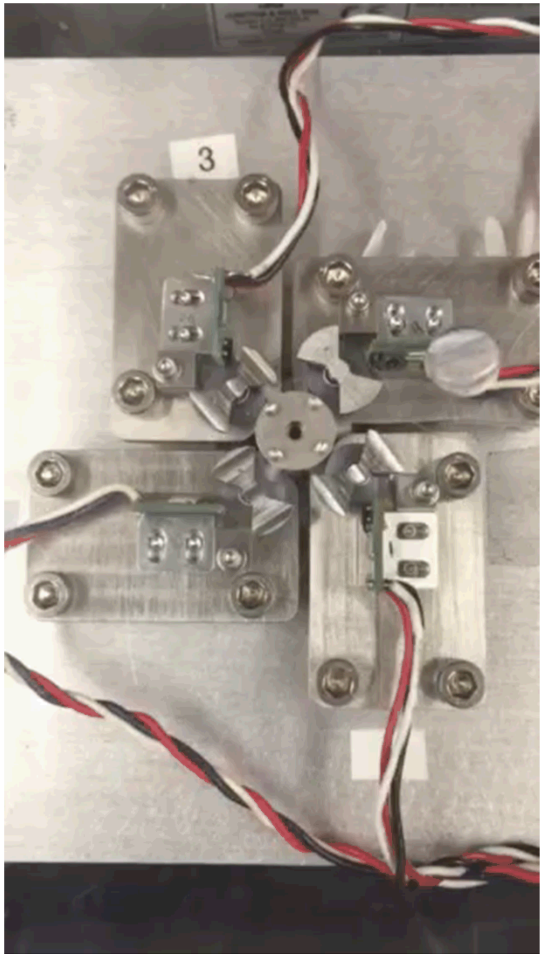
- >100K actuations
- Assembled in Open Air/Stored In Inert Atmospheres
- Not used for decades
- Must be predictable in terms of aging and functional performance





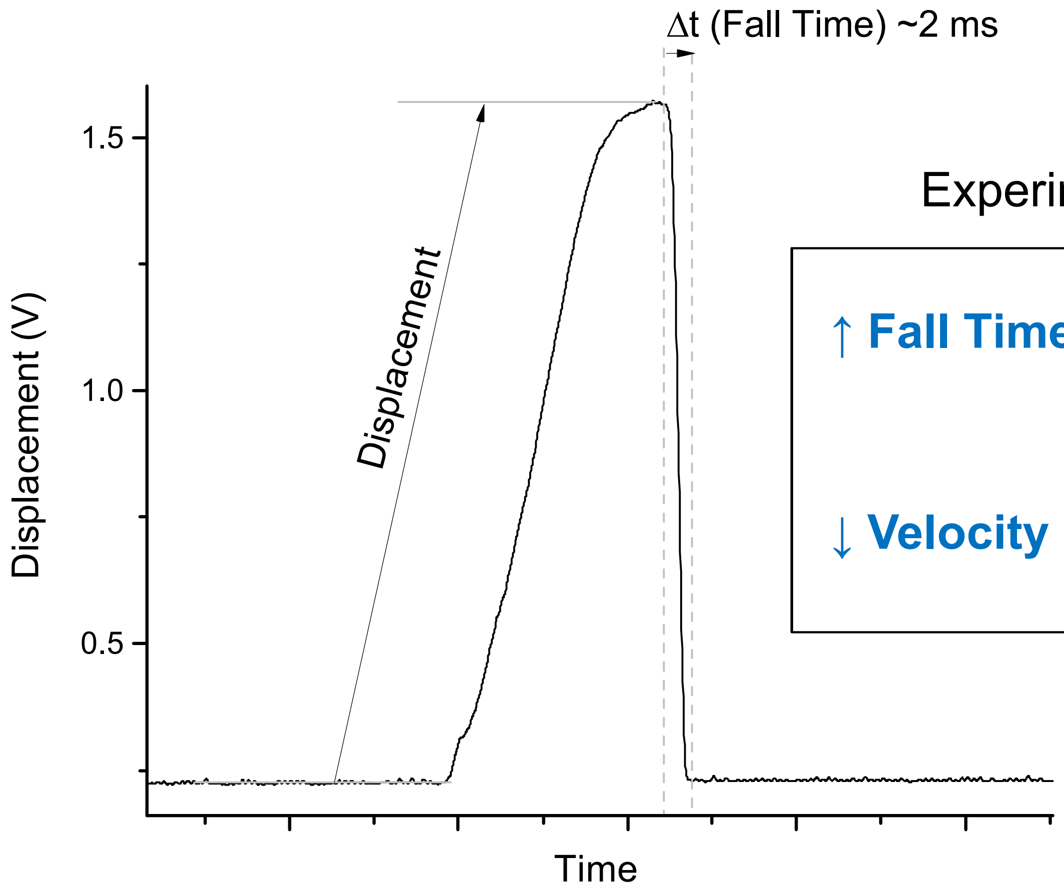
Setup Summary

Video - Operation



- Reciprocating Journal-Shaft Contact Pair
  - Pawl shaft and journal ID coated with test lubricant
  - Protective environment established via flow-thru and positive pressure
    - Dry nitrogen, <20 PPM O2,-60˚C Dew Point
  - Lift-off force set at 40gf at start of test
  - Cyclically loaded 0-10 degrees, snaps to resting position
  - 3 actuations per second
    - Fall Time and Displacement calculated for each actuation, displayed and saved before next iteration.

Simulated Raw Data + Real Time Analysis



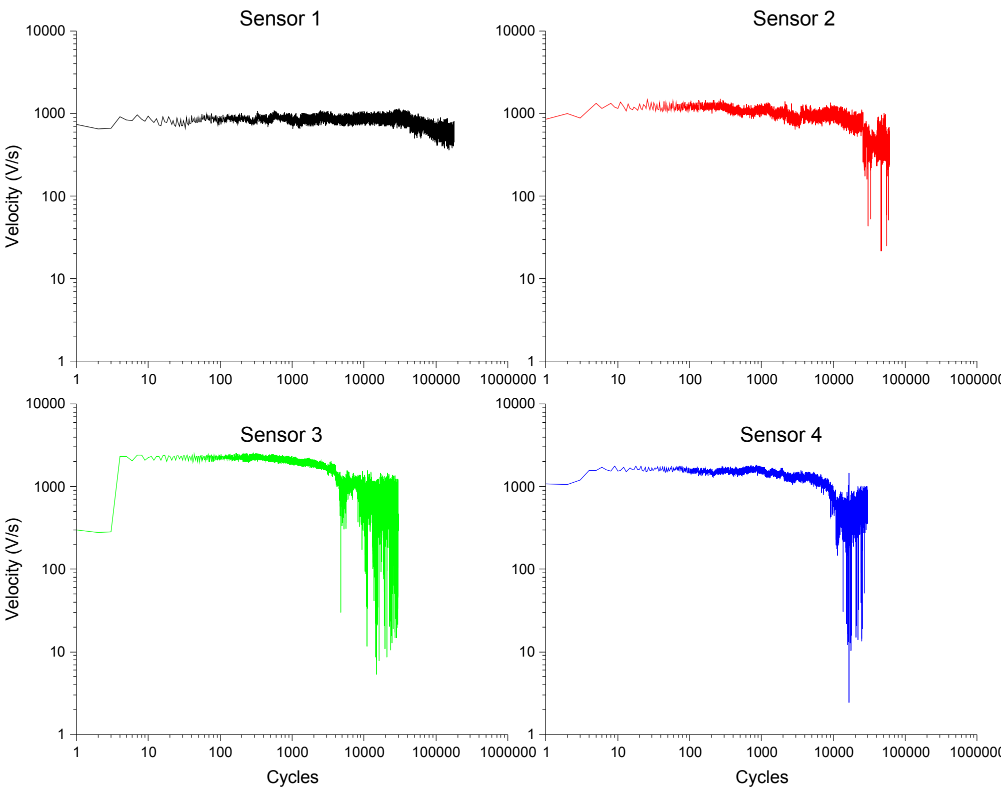
Experimental Theory

↑ **Fall Time** ≡ ↓ **Velocity**

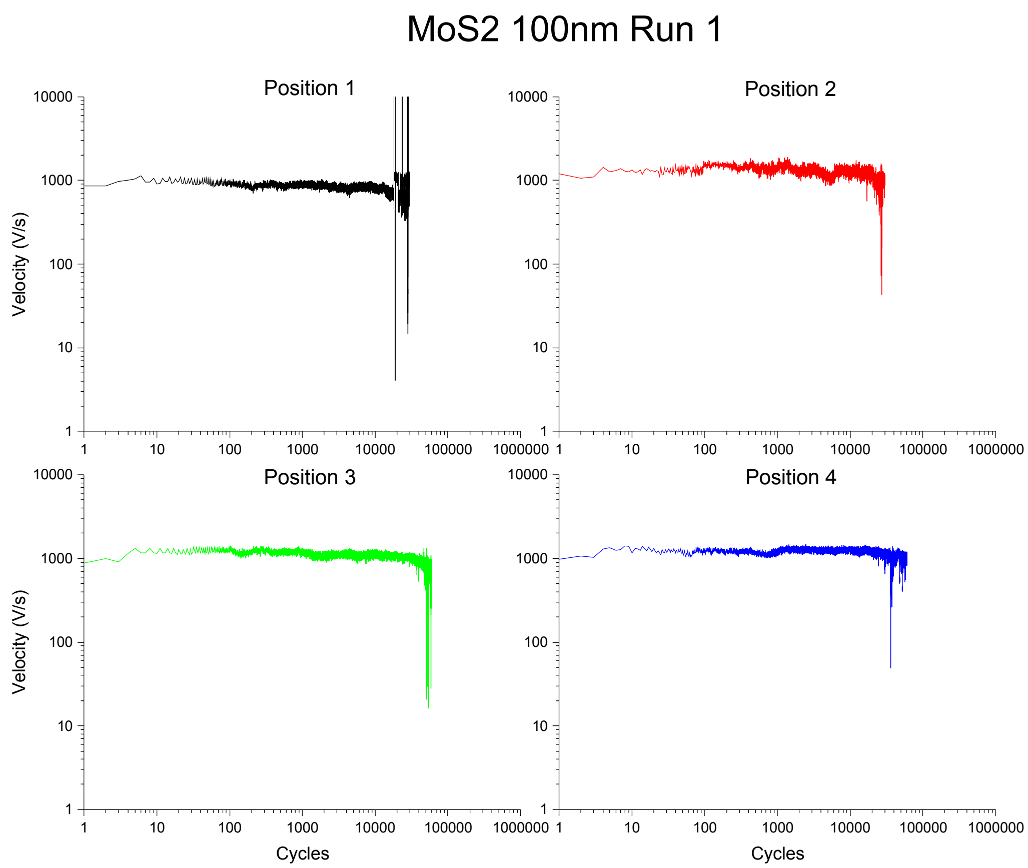
↓ **Velocity** ≡ ↑ **Friction Losses**

How does friction change for various thicknesses over many repetitive tests?

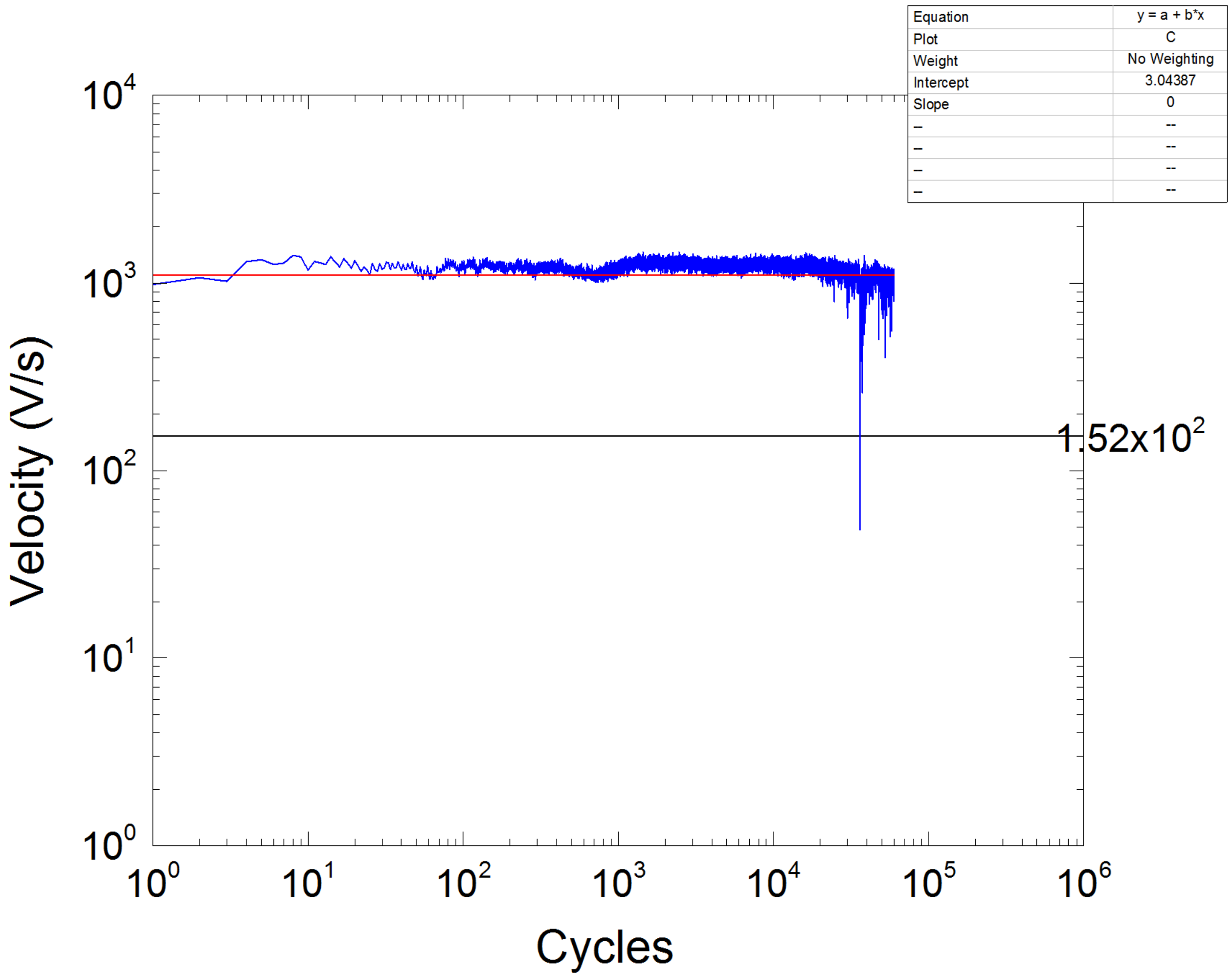
Impingement Coating – N2 Spray



Sputtered – 100nm

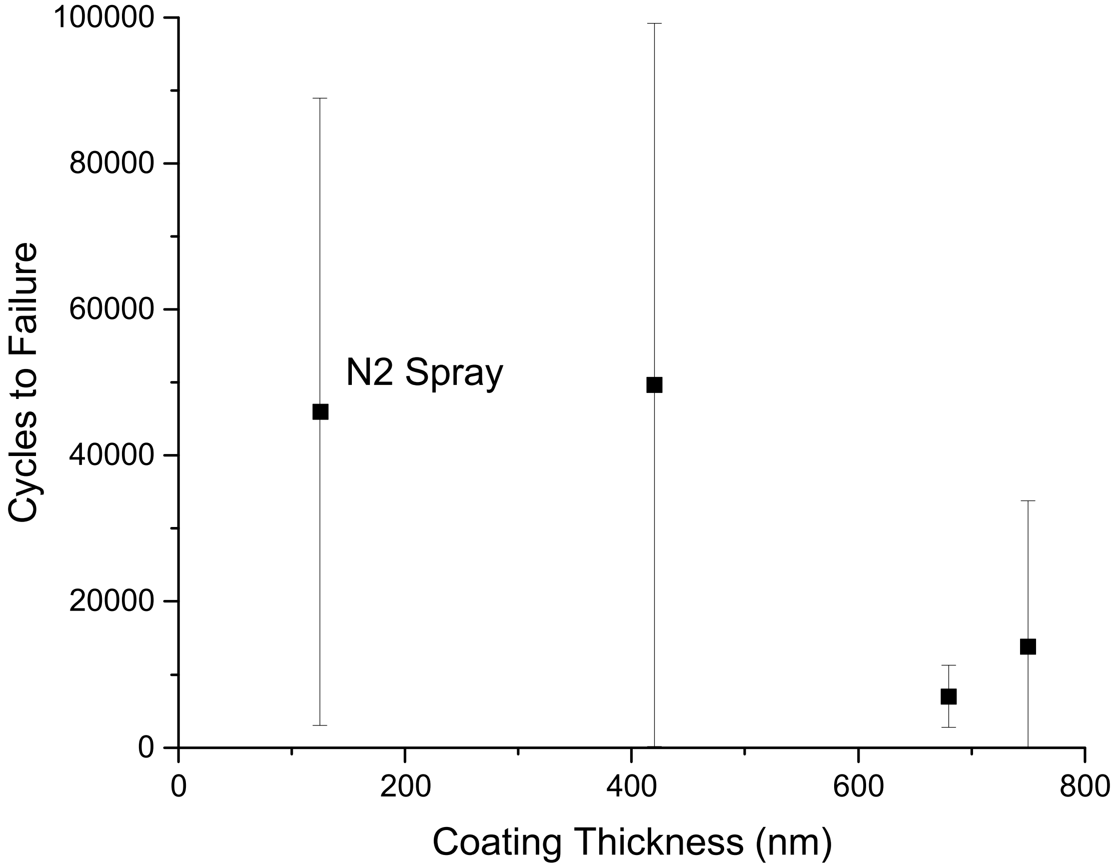


Analysis Method



Failure Threshold Setting: 50% of Average Initial Velocity

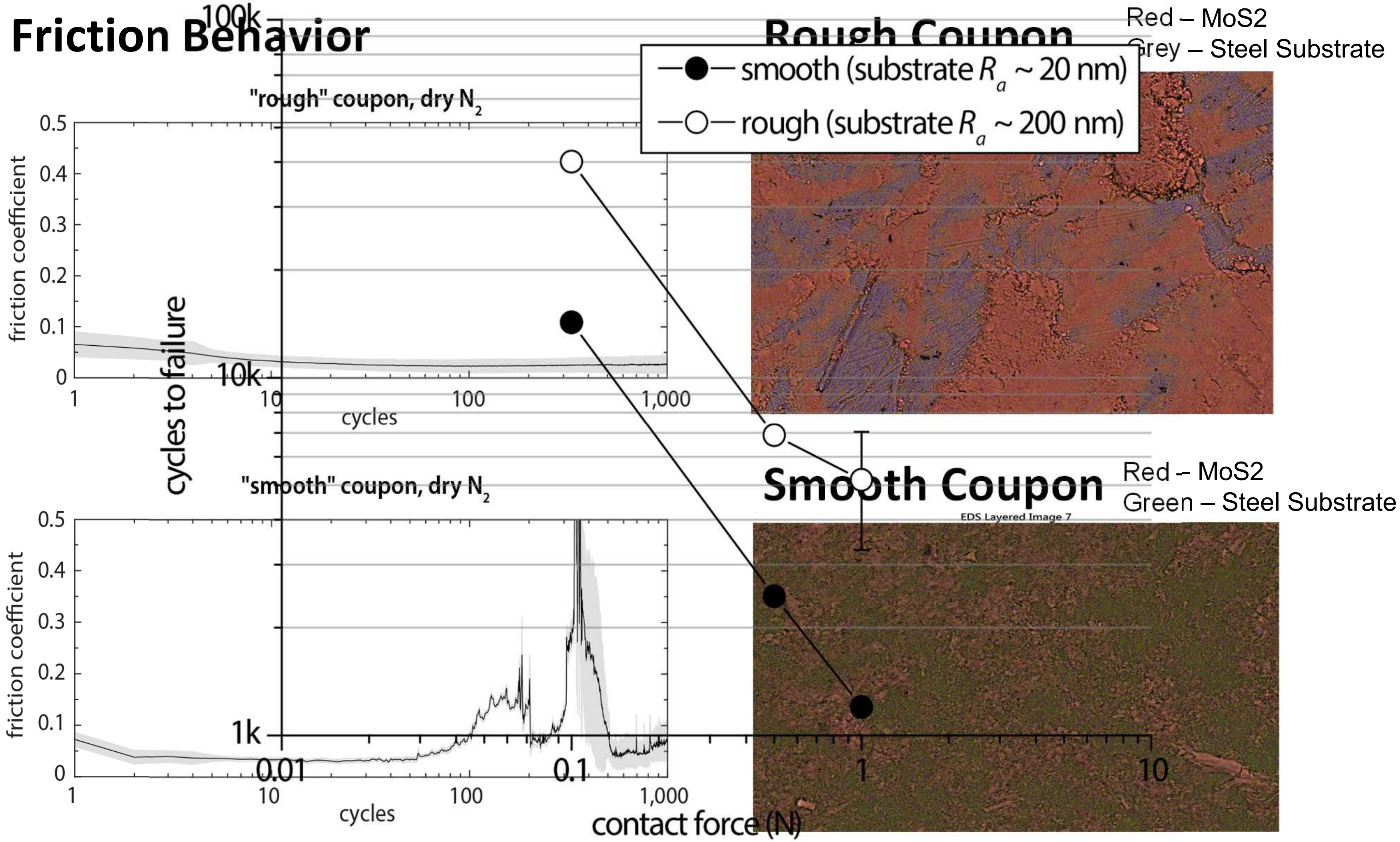
Results/Comparison



High standard deviations complicates drawing a conclusion

Impact of Surface Roughness

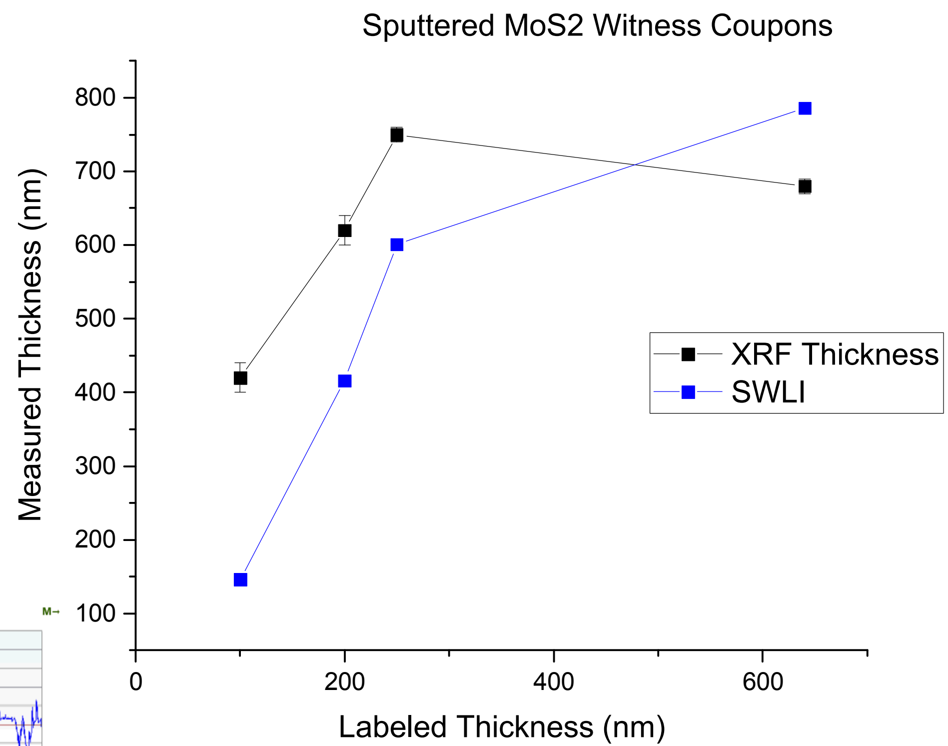
Friction Behavior

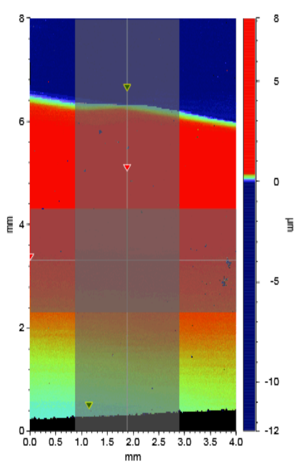


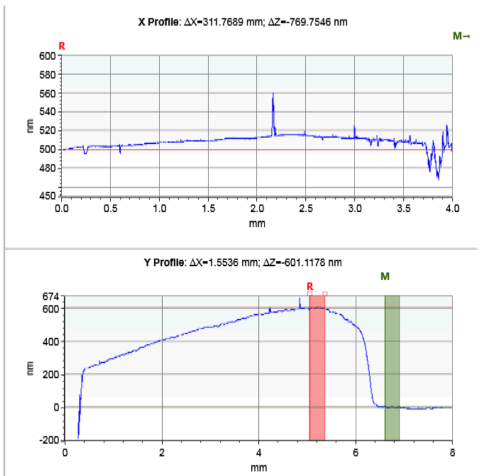
Surface Roughness actually helps friction/wear behavior

Thickness Measurements

- Confounds ability to correlate life with thickness due to uncertainty in thickness measurement
- Poor quality witness coupons yielded inconsistent thicknesses
- Pointed out stark differences between commonly used thickness measurements
- FIB sectioning/ TEM is in progress and will settle the dispute







Summary

- Coatings have a wide life variability
  - Variety of possible sources: Bearing Tolerances, Load on Contact, Setup, etc.
  - Thickness measurements varied significantly from targets

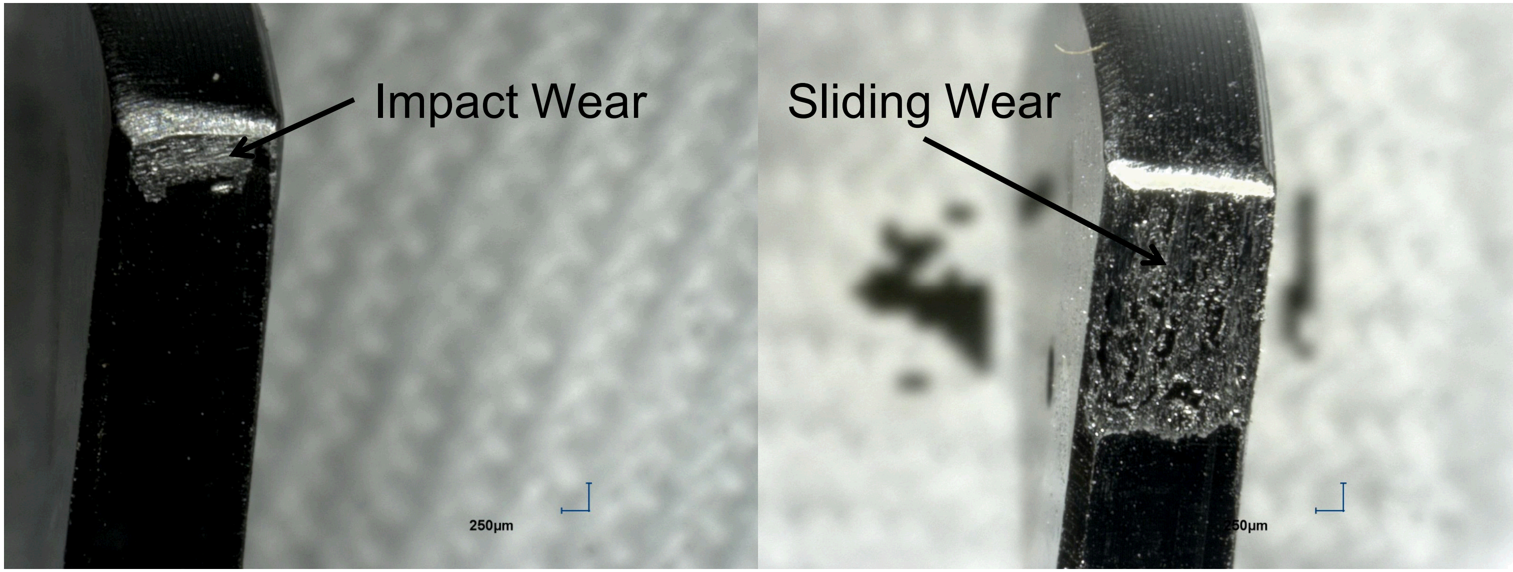
- Testing of more parts may be required
  - Weibull analysis may be more appropriate for life prediction

Special Thanks

- John Curry (Lehigh University/Sandia National Labs)
- Nicolas Argibay (Sandia National Labs)
- Paul Kotula (Sandia National Labs) TEM/EDS

Future Work/Improvements

- Sputtered coatings and vary thickness
  - Three different thicknesses and one to match impingement coatings
  - Should see much more consistent results compared to impingement coatings
- Investigate ability to extract other data from experiments



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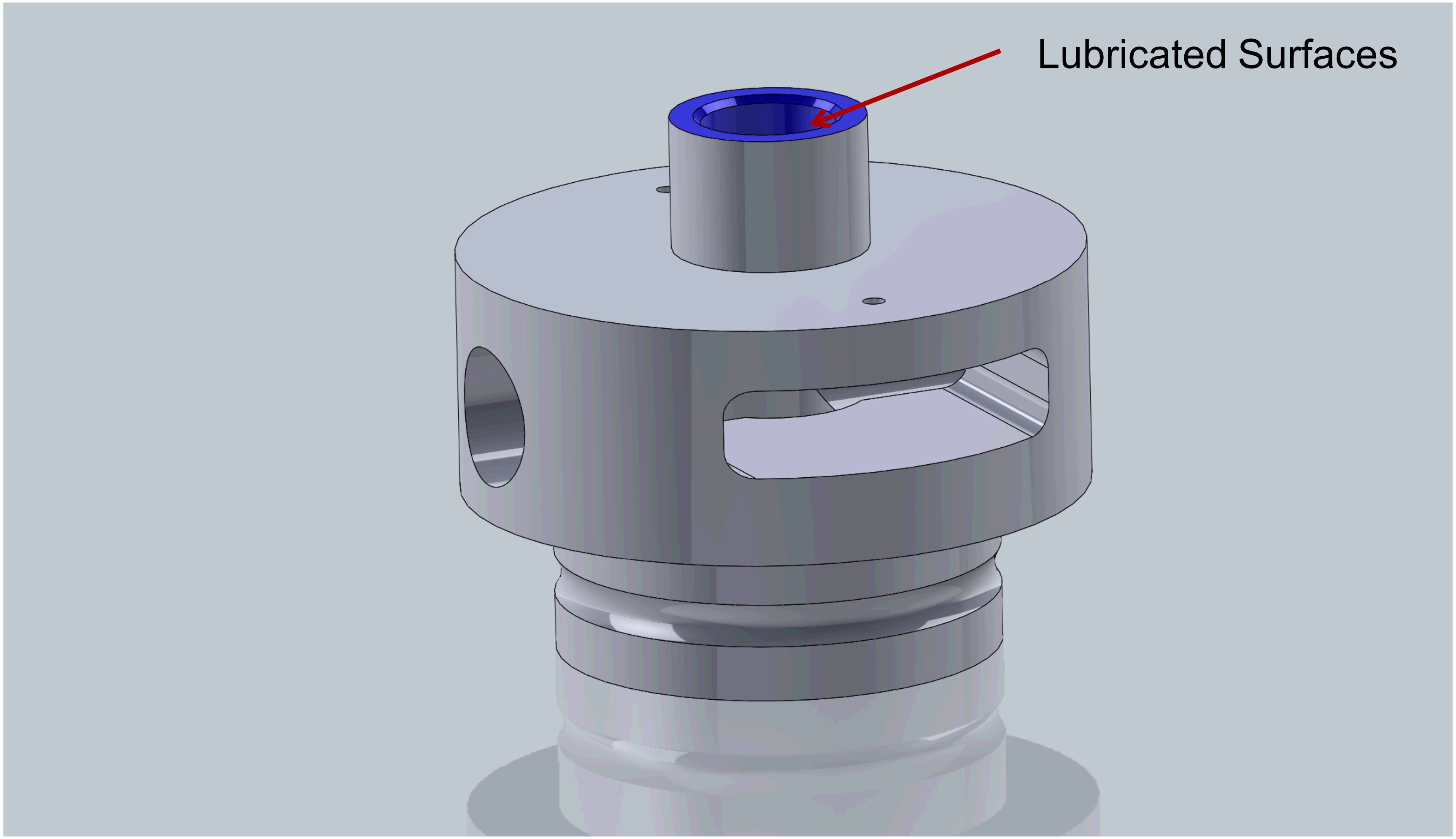
Performance of Impingement Solid Lubricants In A Plain Journal Bearing

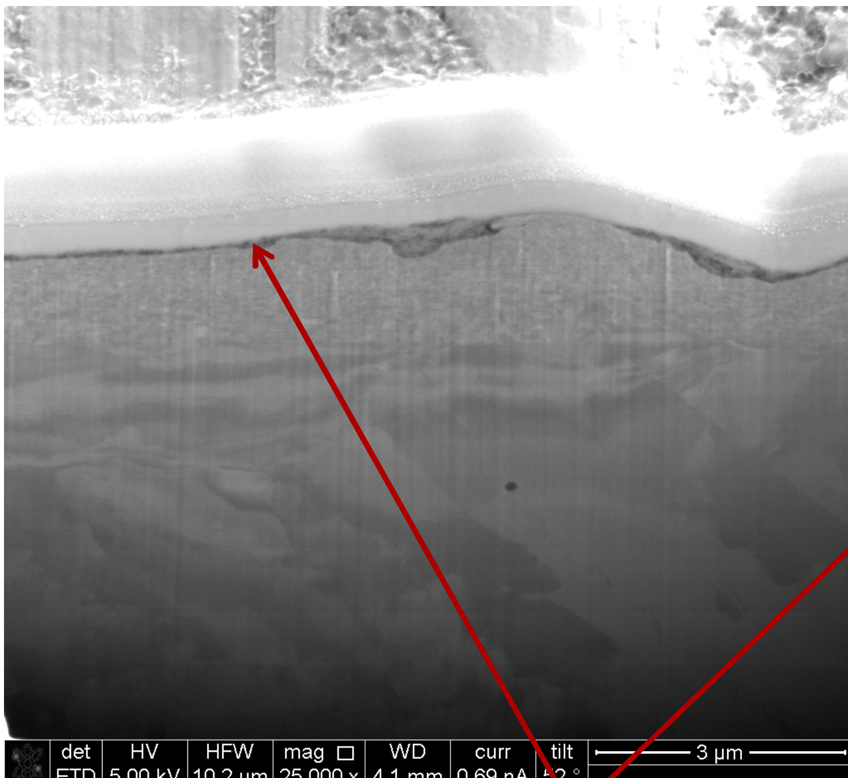
QUESTIONS

Journal

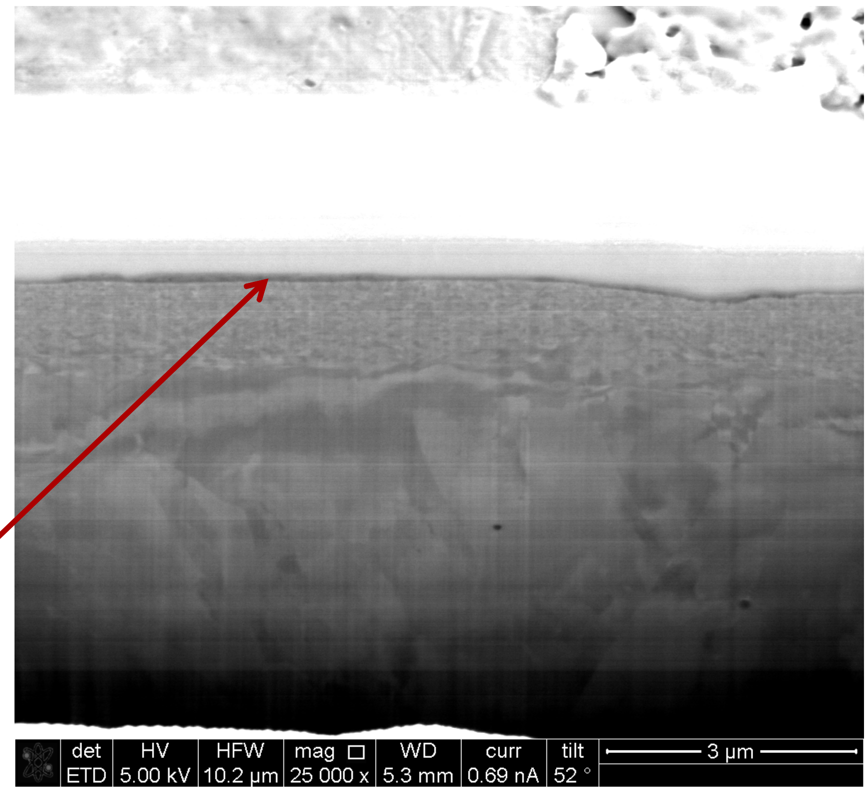


Fractional Coverage- FIB

N2 Spray

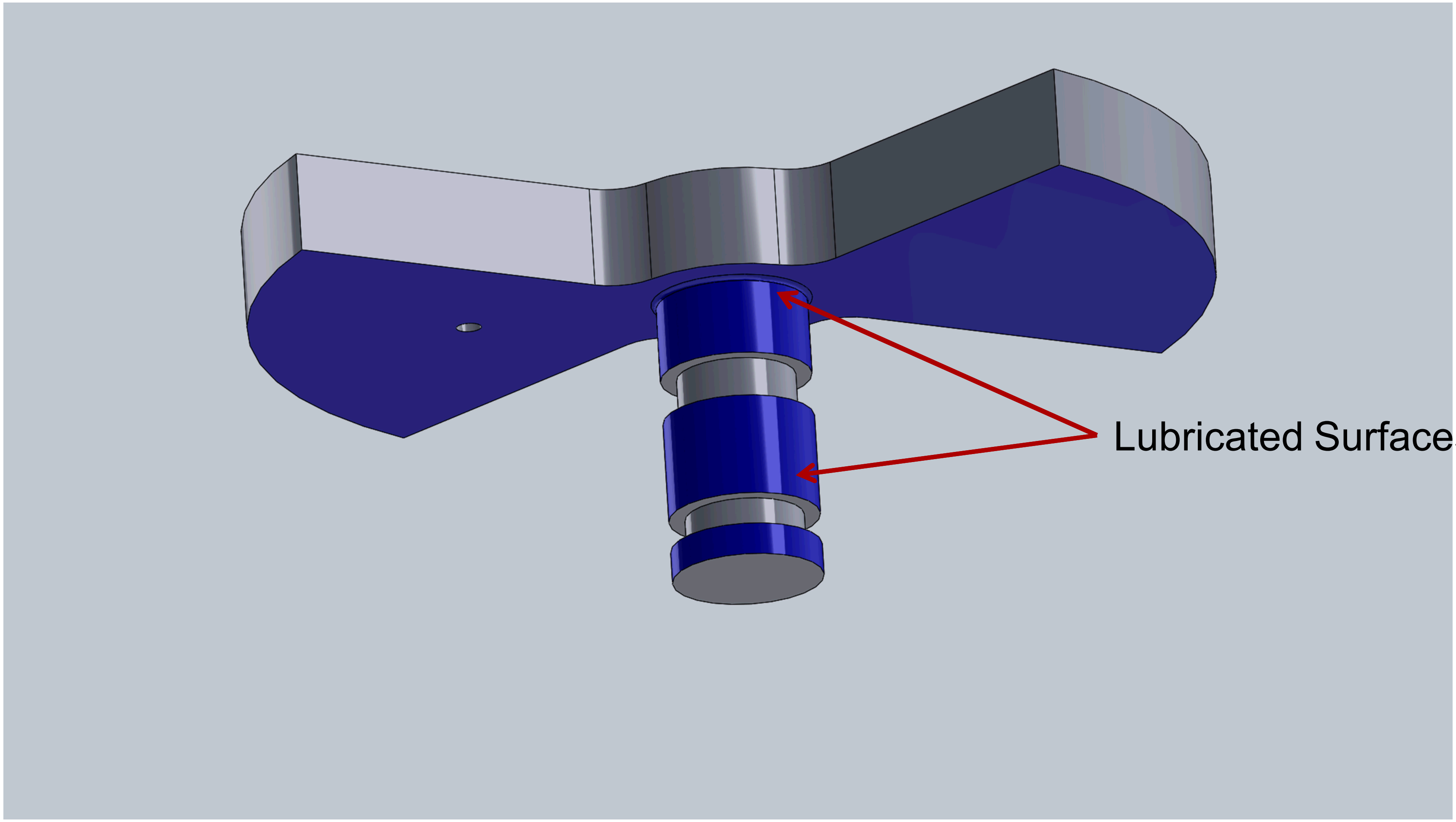


Harperized

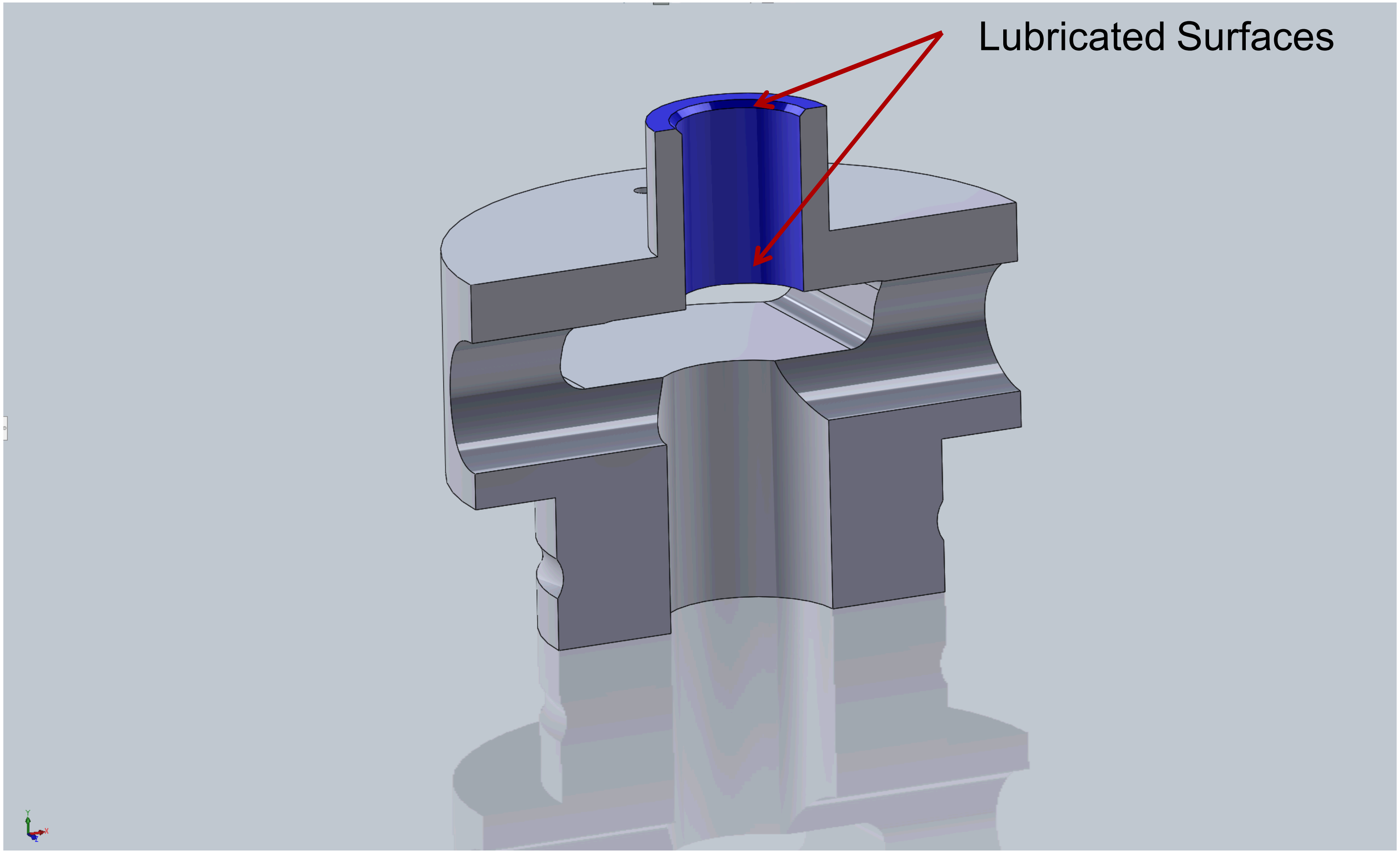


Same “thickness” different coverage

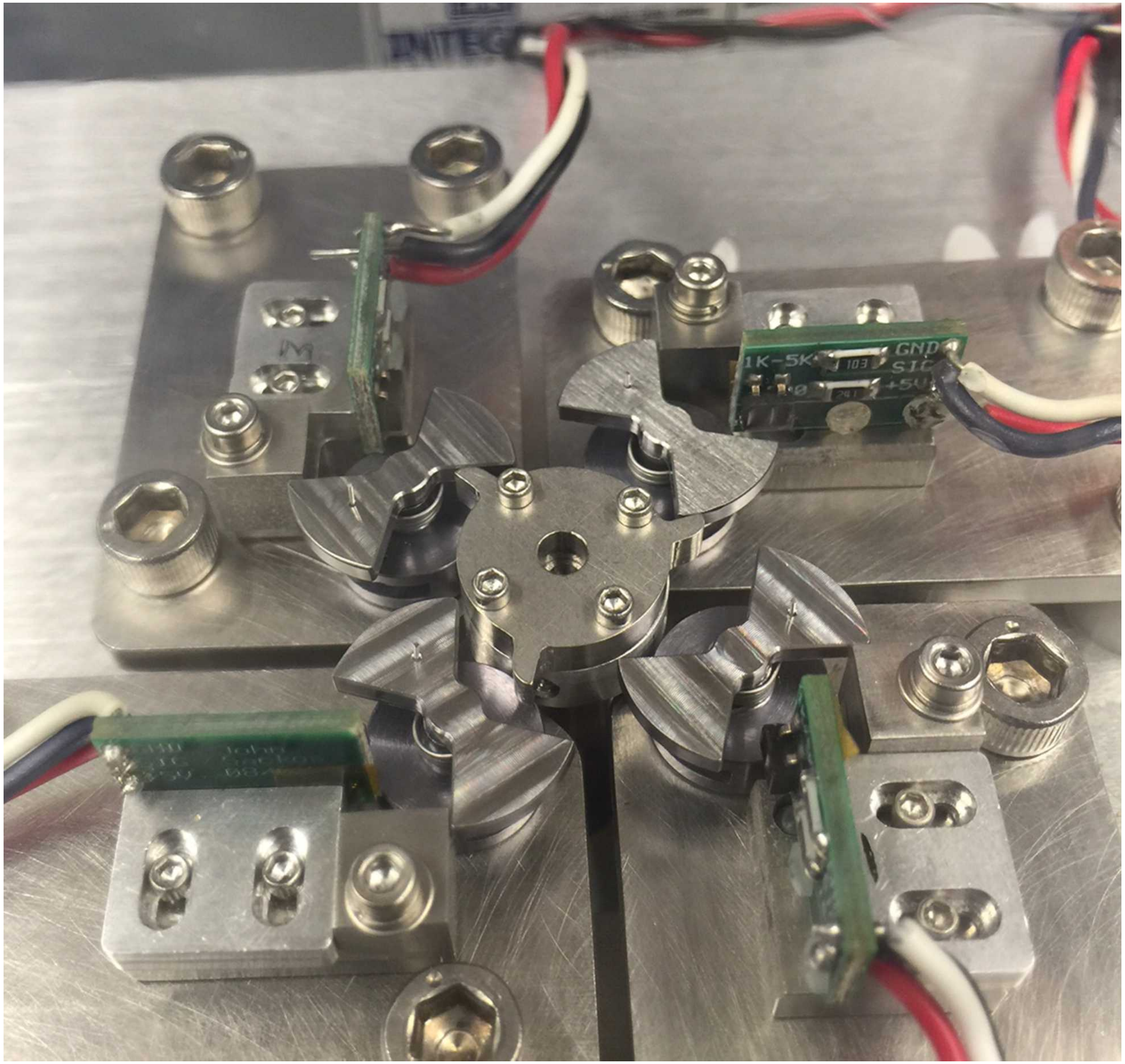
Pawl



Journal Cross-Section

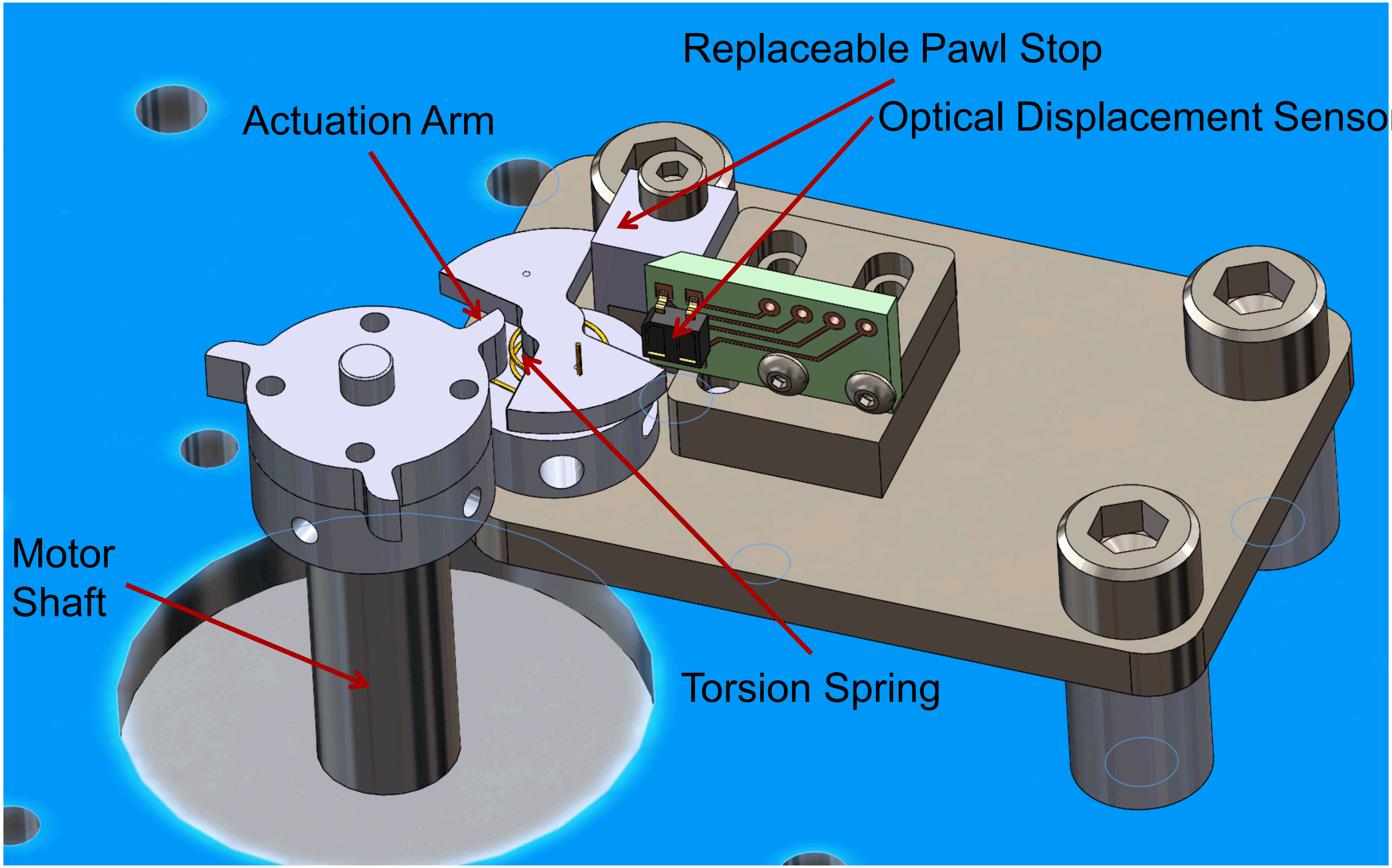


4 Modules Installed

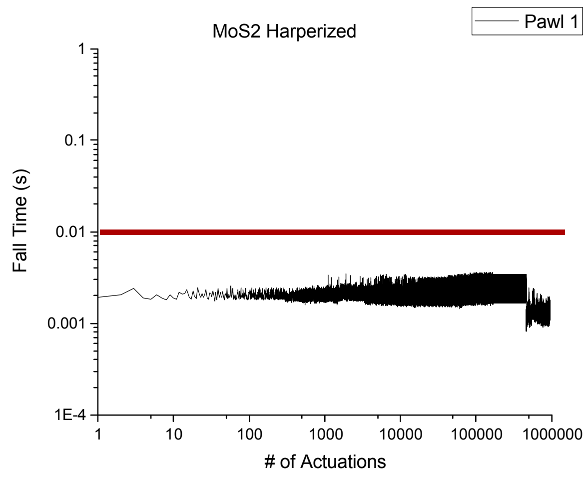


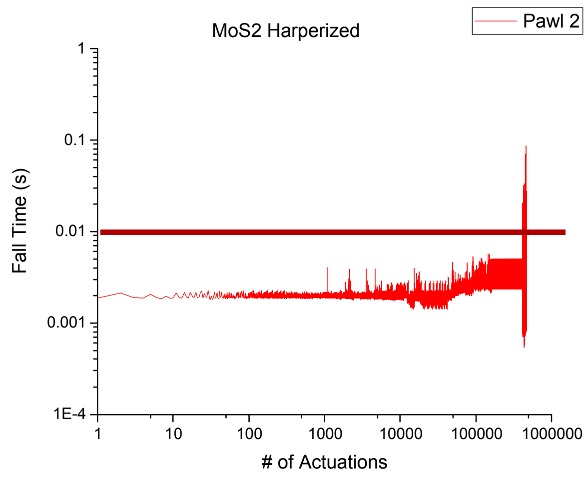
INDEX

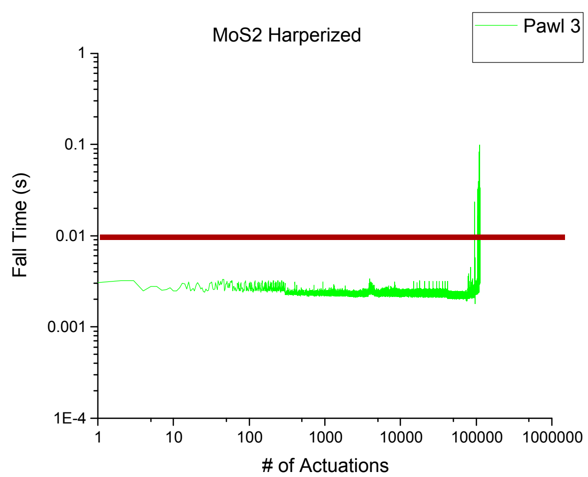
Single Test Module Installed

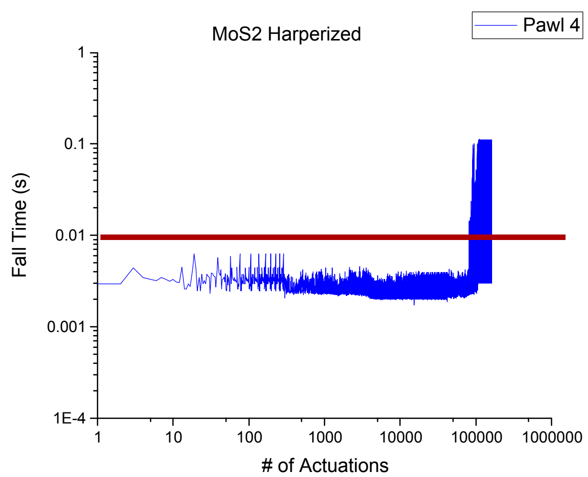


Impingment Coating - Harperized







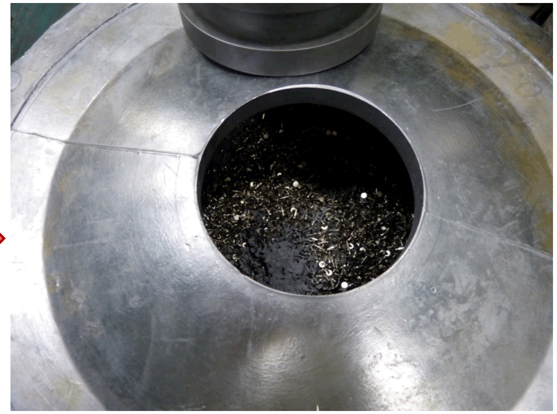


Harperized MoS_2 Processing

Sandia National Laboratories

Clean

Parts, Pins, MoS_2 in Barrel



Barrel in Debur Tool ~20 min.

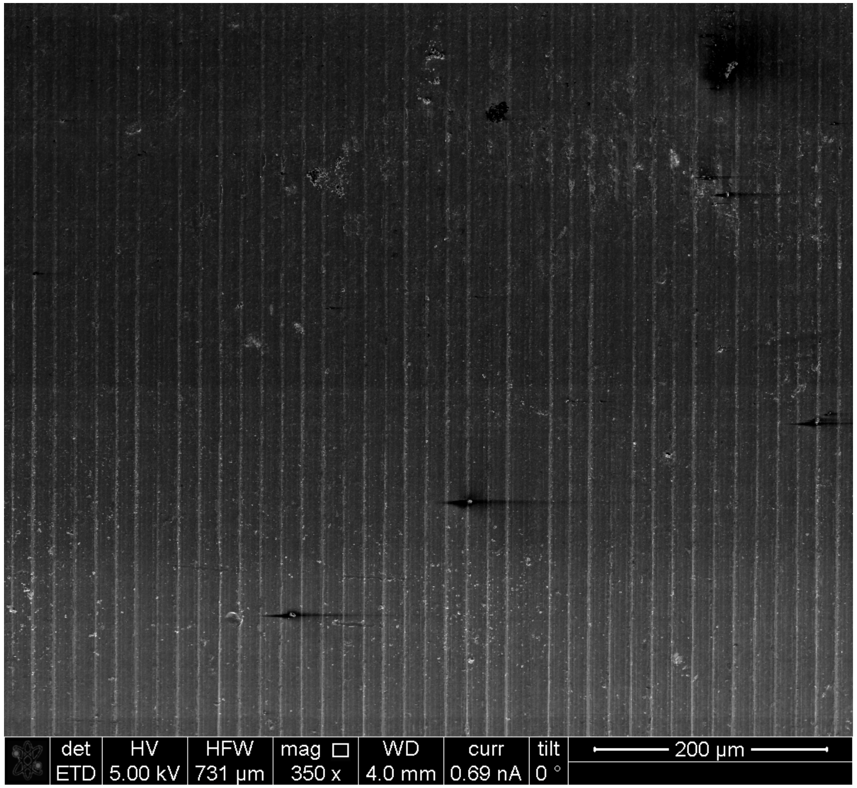
Separate Parts

Blow Off Excess MoS_2

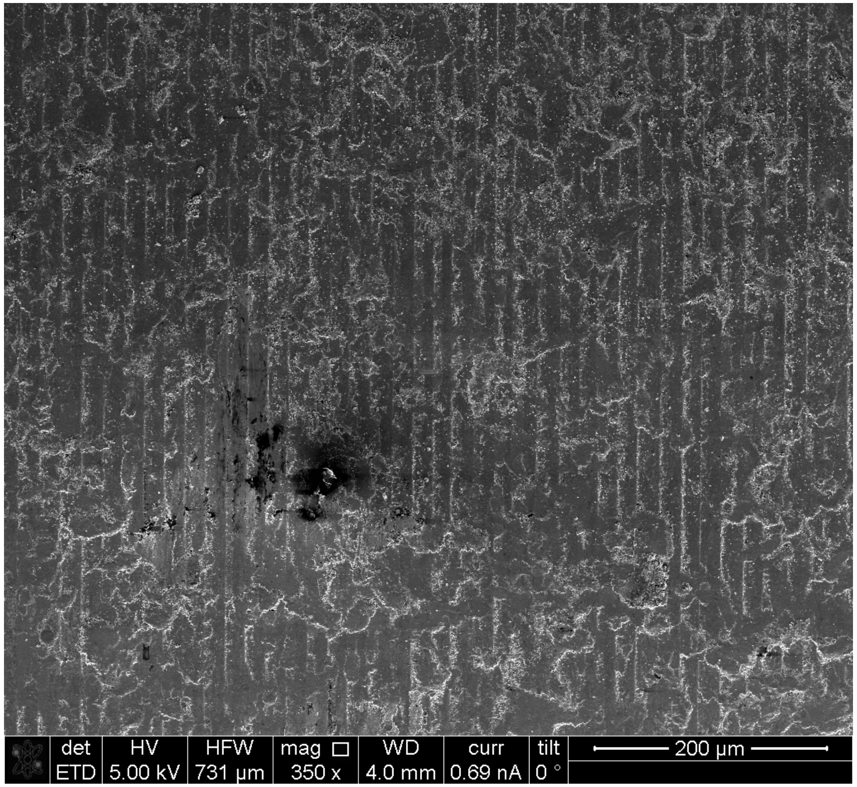
- thickness not adjustable; maximum ~100 nm thick, limiting operating life
- batch process with high impact; not appropriate for delicate/precision parts

Surface Appearance Differences

N_2 Spray



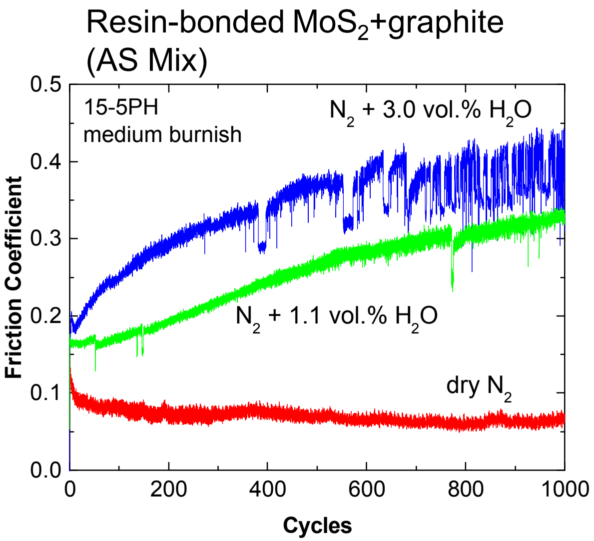
Harperized

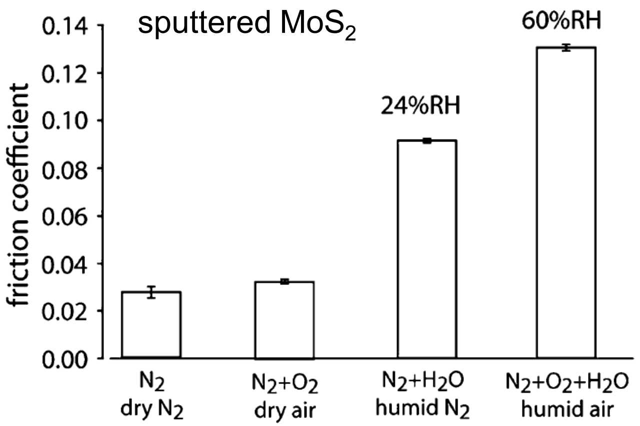


Harperized Surfaces Show Damage

Environmental Effects on MoS_2 Friction Coefficient

- Water vapor in the operating atmosphere increases friction coefficient
  - deep penetration of water into structure
  - friction increase due to alteration of transfer film adhesion and dynamics



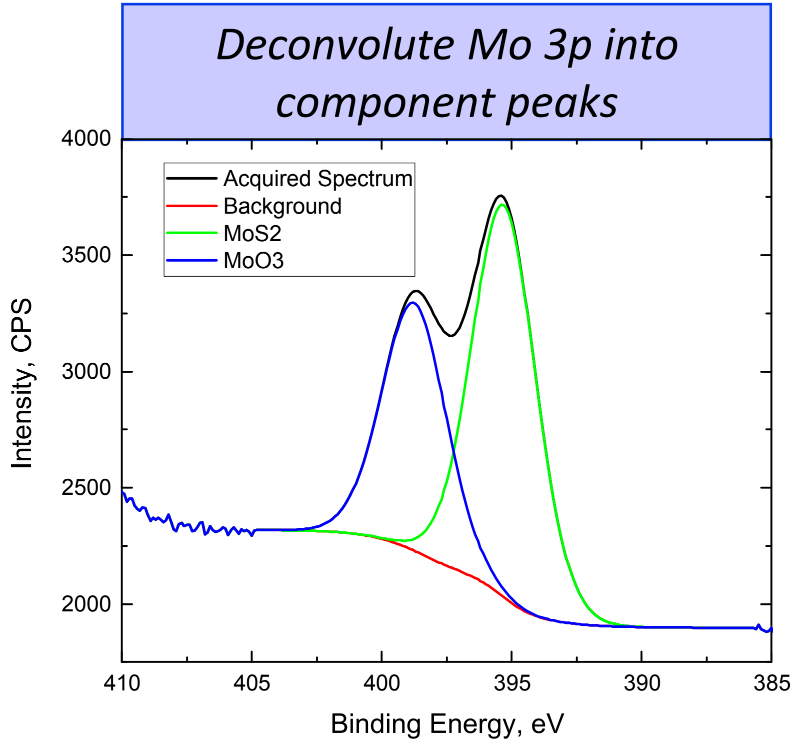


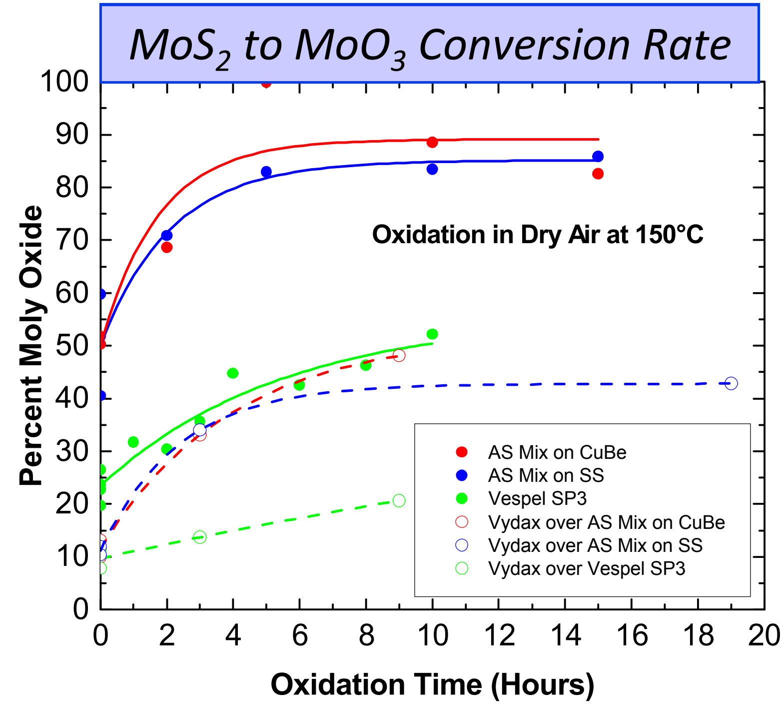
- Steady-state friction coefficient at 30°C of sputtered MoS_2
  - friction increases with water vapor content
  - far less sensitive to oxygen

H. Khare and D. Burris, Tribology Letters **53** (2014) p.329-336

O_2 has little influence on dynamic friction, while H_2O in the atmosphere significantly increases friction

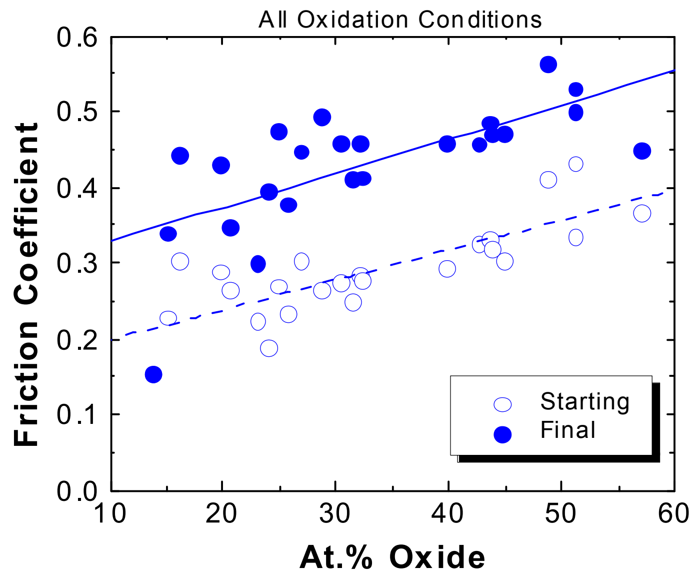
XPS Provides a Quantitative Measure of the Degree of MoS_2 Oxidation

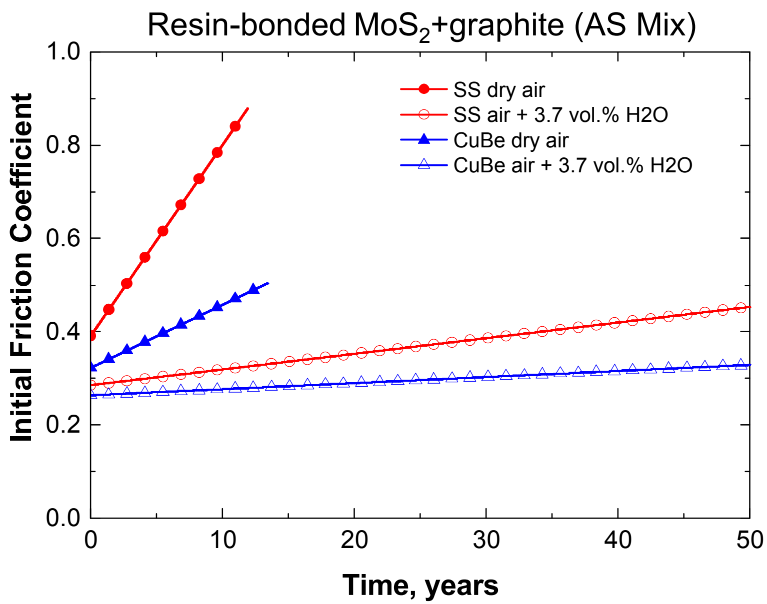




- Controlled oxidation at various times and temperatures permits kinetics to be determined
  - metal oxides accelerate MoS_2 oxidation compared to Vespel composite
  - a PTFE grease covering decreases the oxidation rate of MoS_2

Oxidation Kinetics Combined with Performance Data Yields Aging Prediction





- O_2 results in more rapid MoS_2 oxidation than H_2O
- Stainless steel promotes faster MoS_2 oxidation than copper-beryllium substrates

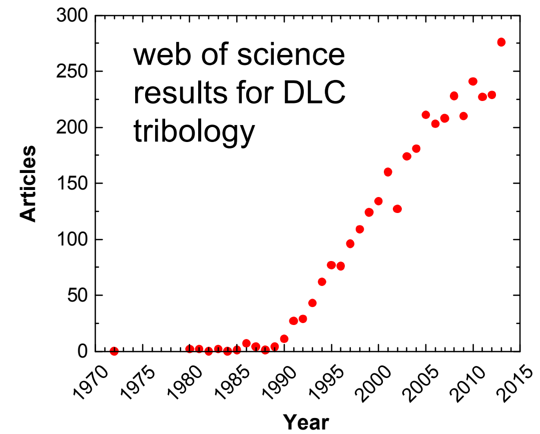
Environment and surface composition impact MoS_2 oxidation rate

Diamond-Like Carbon (DLC) Industrial Applications

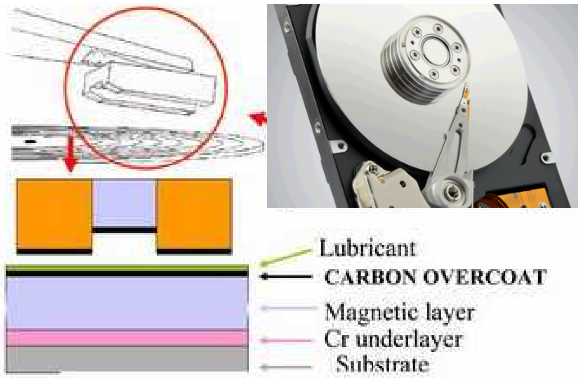
- DLC has been a technologically important material since the mid 1980's
- Adopted early for use in magnetic recording hard disks
- Presently used in many other industrial applications
  - solid lubricant
  - scratch resistant coating
  - decorative coating

Wind Turbine Gearbox Bearings

www.windsystemsmag.com



Magnetic Recording Technology



www.phys.org/news7207.html

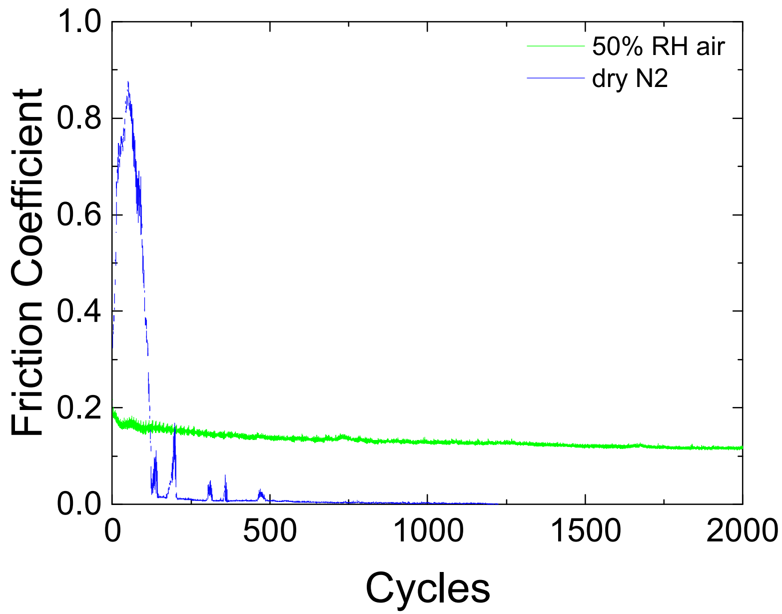
Swiss Watch (XETUM)

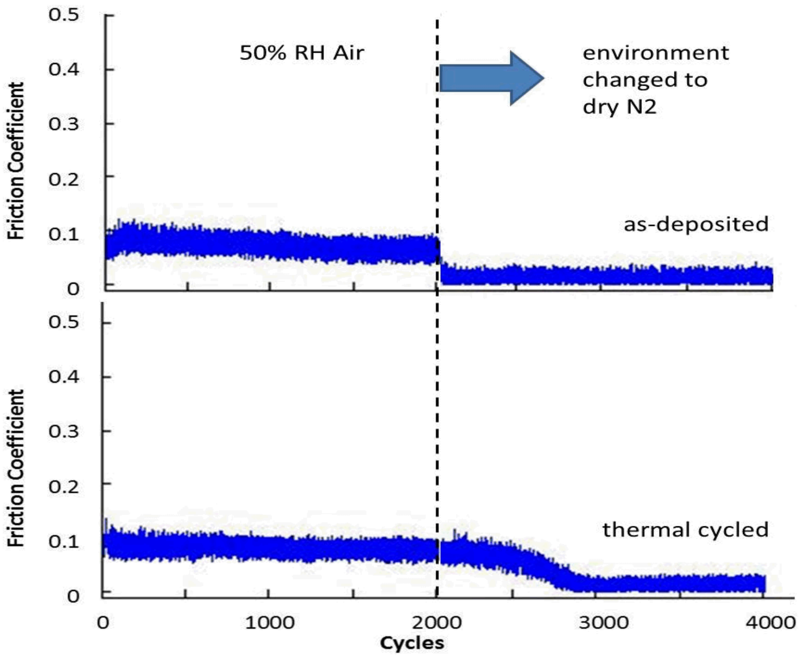
www.forums.watchuseek.com

Gears and Splined Shafts

www.sts-group.it/eng/dlc.htmll

Environmental Effects on DLC Friction





- Many films exhibit friction spike early in sliding in dry N_2 or vacuum
- Early friction spike in N_2 can be mitigated by prior running in an air (oxygen and water vapor) environment
  - facilitates transfer film formation
- Surface oxidation is not a contributor to friction changes with age