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The Role of Water on the Tribological Performance of Molybdenum Disulphide

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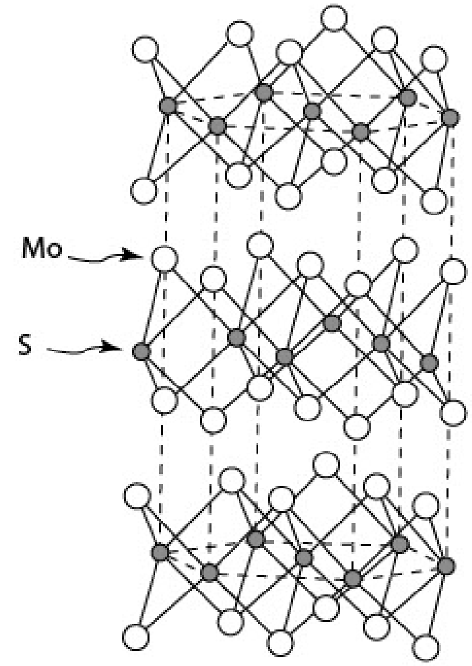
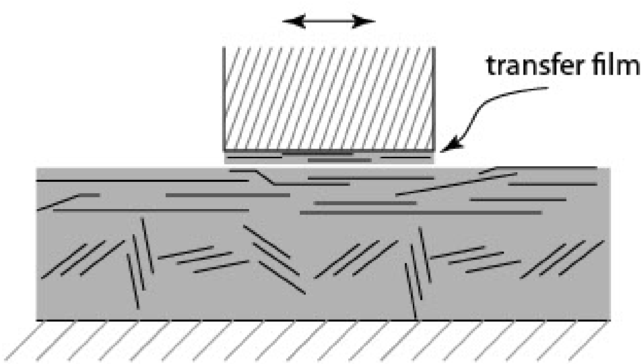
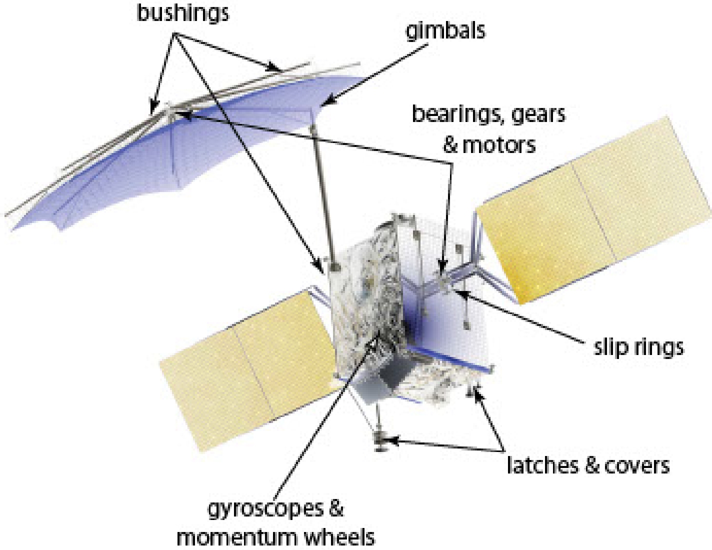
Molybdenum disulphide has a hexagonal, layer-lattice structure in which there is covalent bonding between the S-Mo-S, but van der Waals attraction between each tri-layer. This layer-lattice structure in conjunction with the van der Waals allows for the easy slip between the tri-layers providing the low friction properties.



Amorphous MoS_2 coatings are known to form crystalline layers which orient themselves upon sliding leading to the low friction characteristics.



Satellites



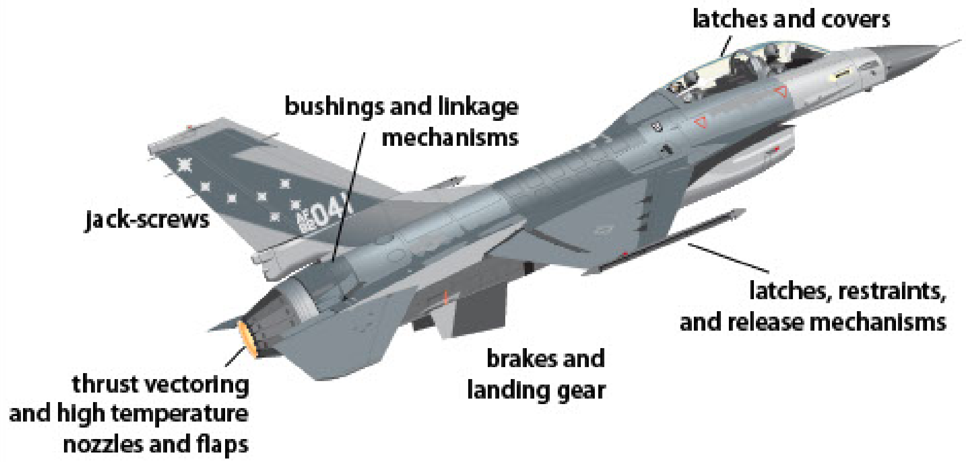
Operating Environments

Environmental Extremes:

extraterrestrial deployment (UH vacuum, -150°C to 100°C)
terrestrial testing (ambient lab air)

Packaged antennas must survive extended cycled deployment in ambient conditions prior to deployment in space.

Aircraft Actuators



Operating Environments

Environmental Extremes:

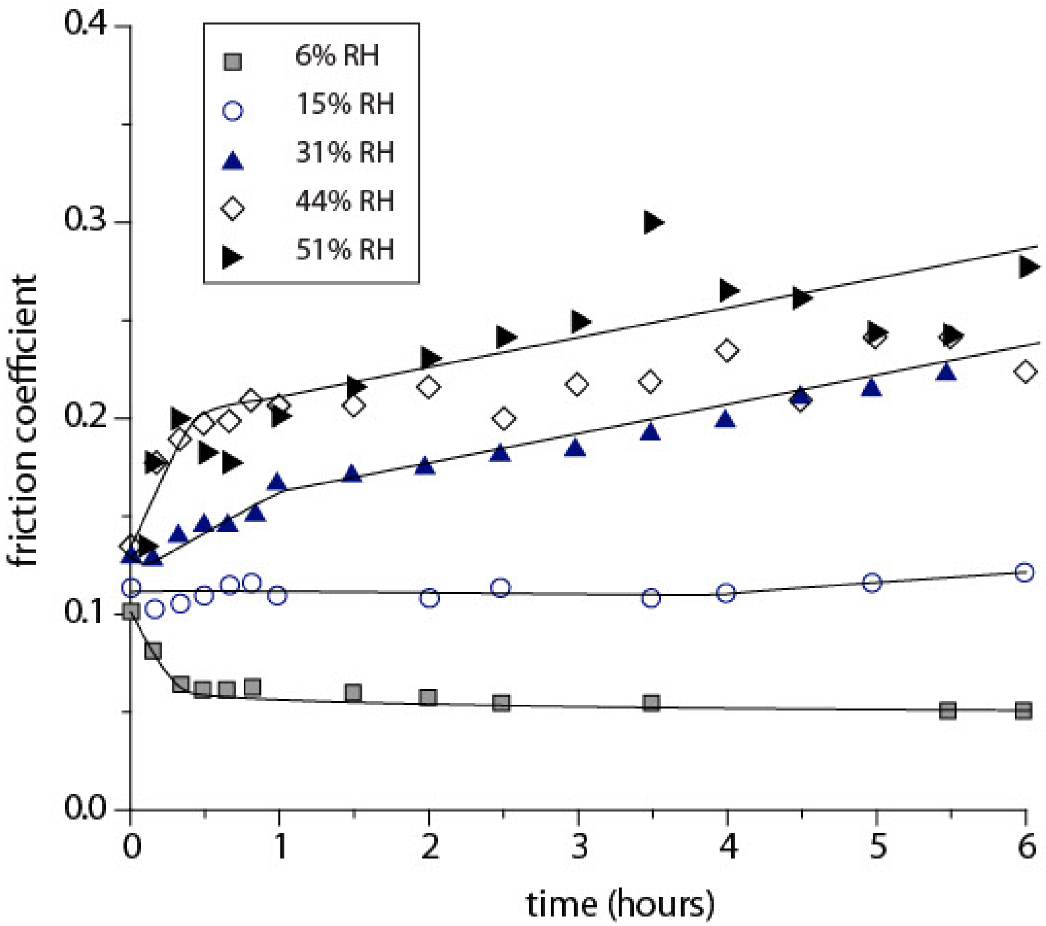
high altitude dog fights (-50°C, low humidity)
equatorial carrier operations (>35°C, >90% humidity)

Devices must function for 1000's of cycles between environmental extremes.

Studies of Water Vapor Effects on MoS_2

Since 1951 over 1,000 papers have been published on the topic of MoS_2 Tribology.

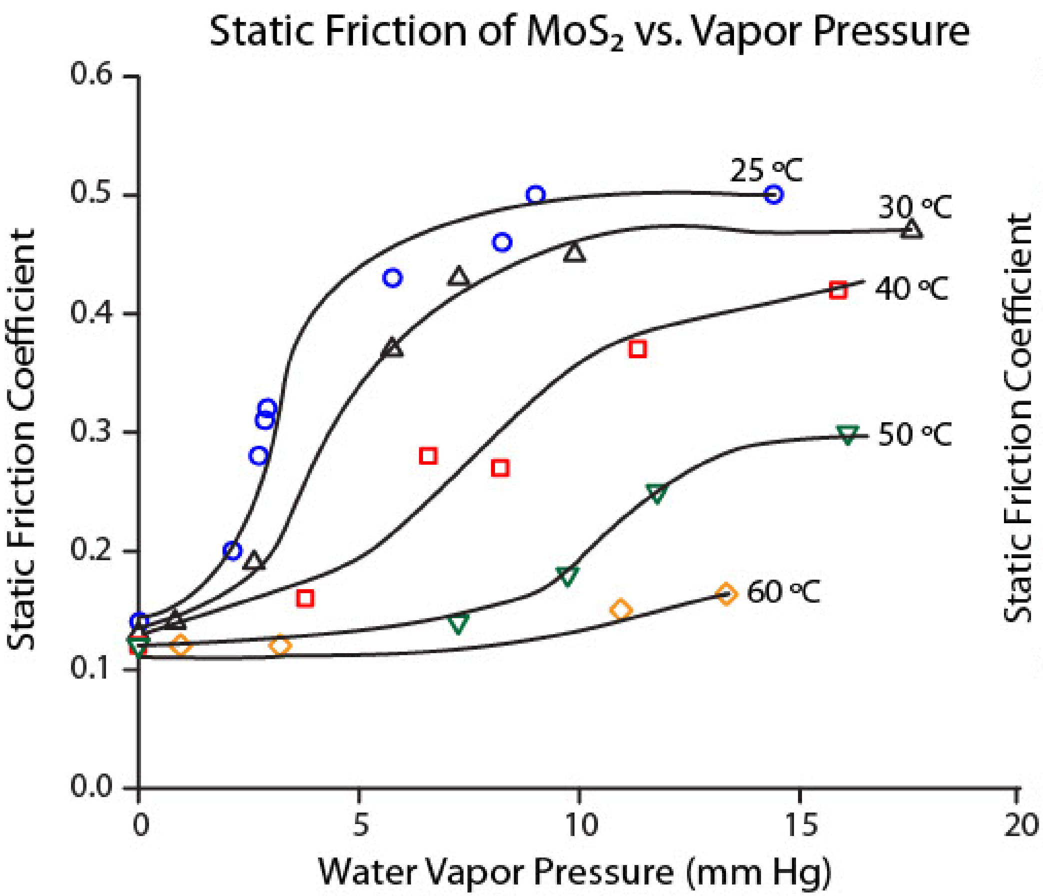
The first report on the effect of relative humidity on the friction and wear of MoS_2 is from at NACA publication in 1953 by M. B. PETERSON & R. L. JOHNSON.

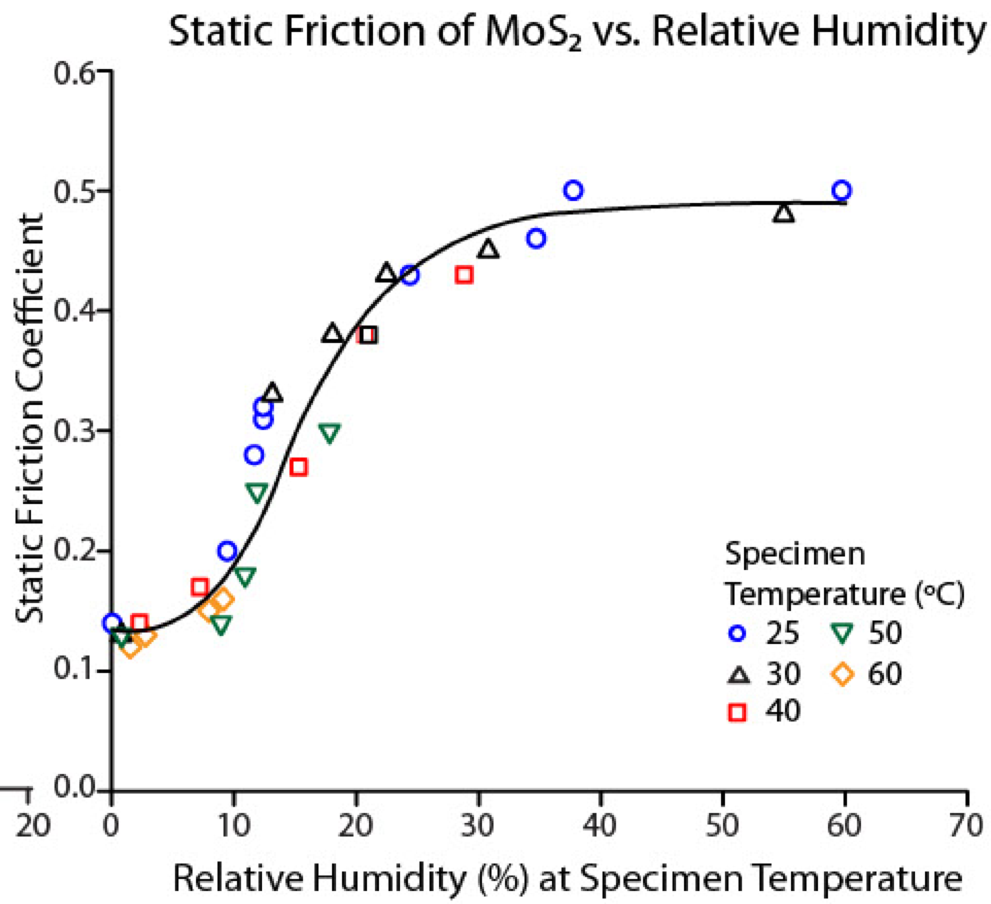


The effect of various relative humidities on the run-in of the coefficient of friction of steel specimens coated with molybdenum disulphide powder. Constant loads of ~180 N and ~30 mm/s.

Data adapted from Peterson, M.B. and Johnson, R.L., Friction and wear investigation of molybdenum disulfide I - effect of moisture, NACA, 1953

Studies of Temperature and Humidity Effects on MoS_2

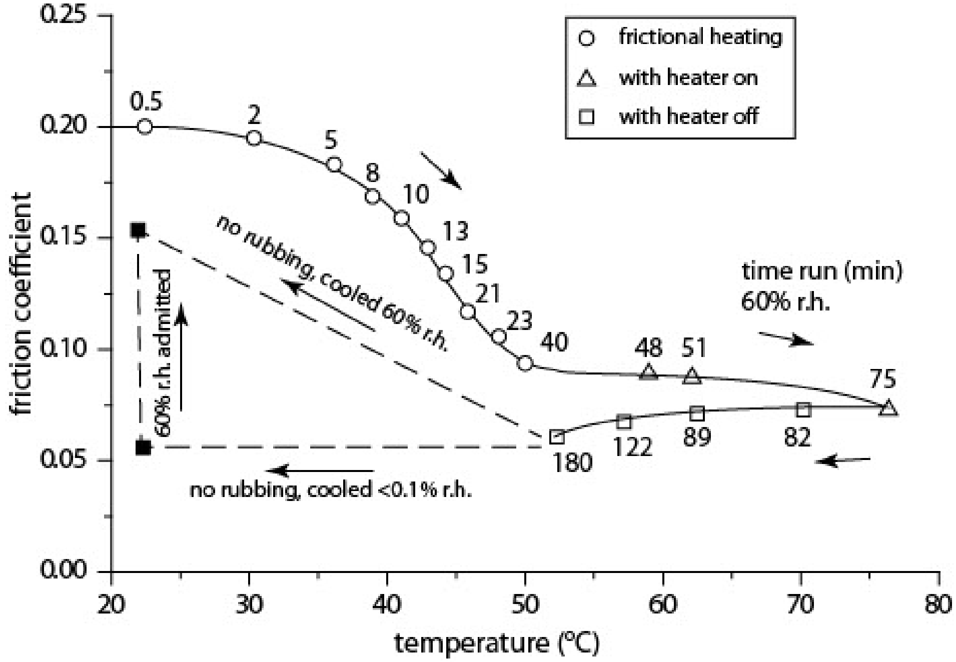




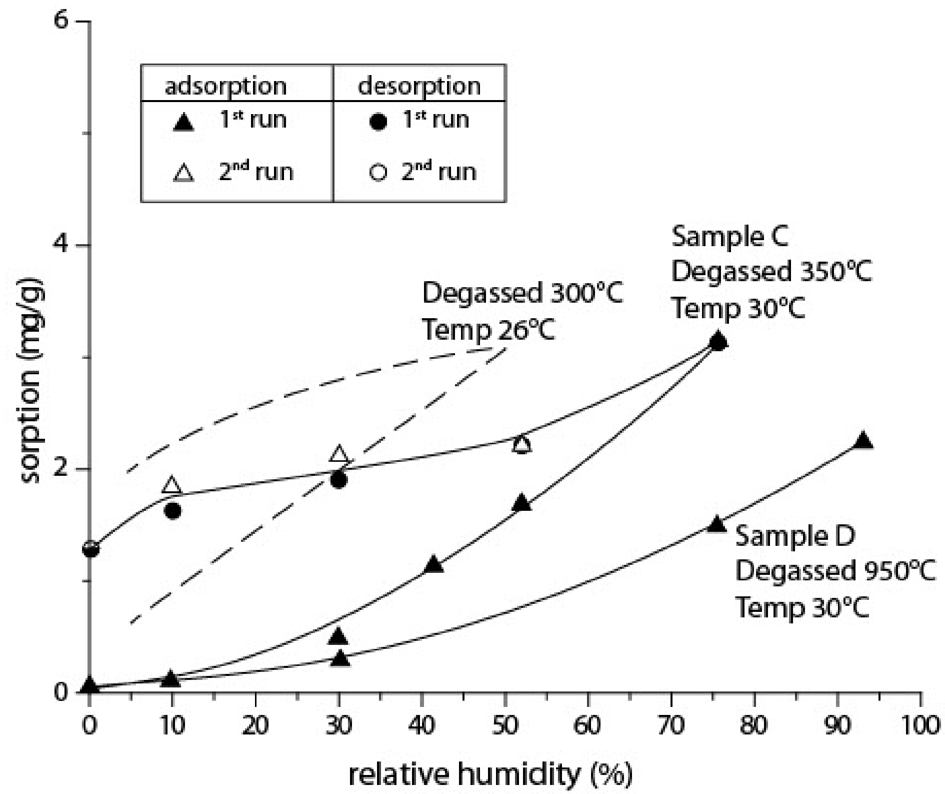
Water vapor pressure is increased while static friction is measured. The experiments were repeated five times at five different temperatures. The trend of low friction with high surface temperature indicates that water is a likely culprit.

Here the results are plotted as a function of relative humidity. The data points all adhere closely to one curve illustrating good agreement between experiments.

Pritchard, C. and J.W. Midgley, The effect of humidity on the friction and life of unbonded molybdenum disulphide films. Wear, 1969. 13(1): p. 39-50.



The reversible effect of moisture on the coefficient of friction for a rubbed molybdenum disulphide film.



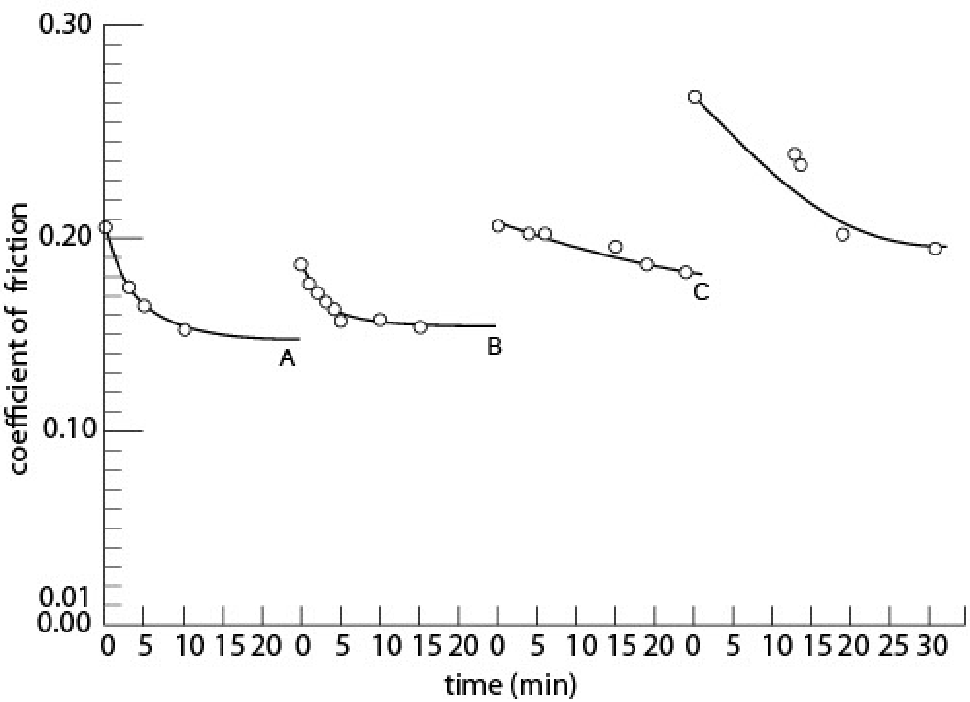
The reversible sorption and desportion of water vapor on MoS_2 after various degassing methods.

Midgley's results from Lansdown, A.R., Molybdenum Diuslphide Lubrication, D. Dowson (ed.), Elsevier Press, Amsterdam, 1999

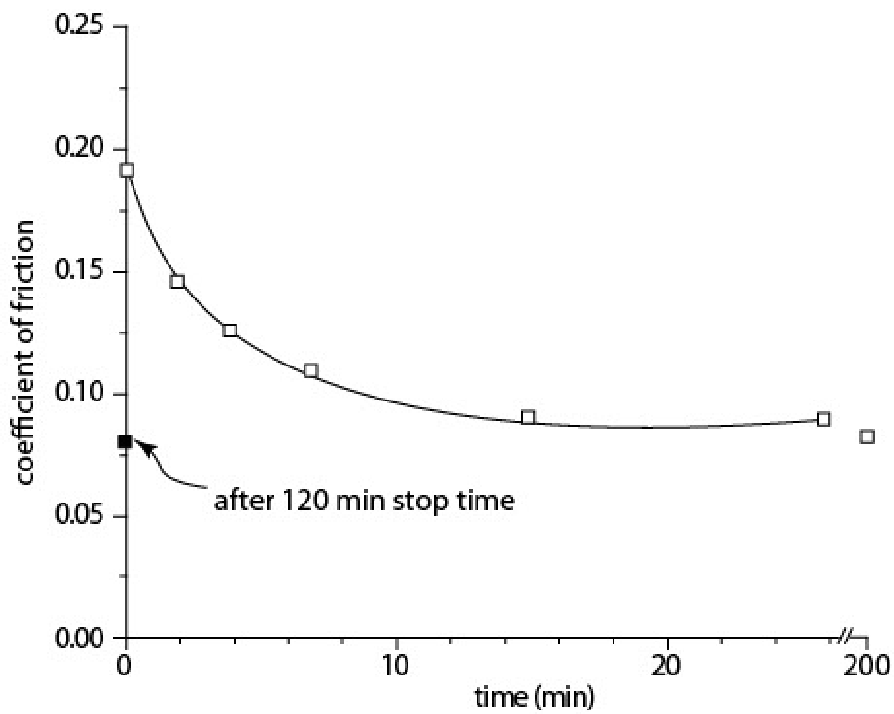
Johnston, R.R.M. and Moore, A.J.W., Water adsorption on molybdenum disulfide containing surface contaminants, Journal of Physical Chemistry, 1964, 68(11): p. 3399-3406

Studies of Exposure Times on MoS_2

In the late 1950's and early 1960's the response of MoS_2 to varying exposure time was explored. Haltner studied this effect in air and dry nitrogen environments.



Transient frictional behavior of MoS_2 in air: ... After reaching µ level at A, film and rider stood for 4 hours after sliding for 80 min; at B they stood overnight after sliding for 135 min; at C they stood overnight after sliding for 420 minutes.



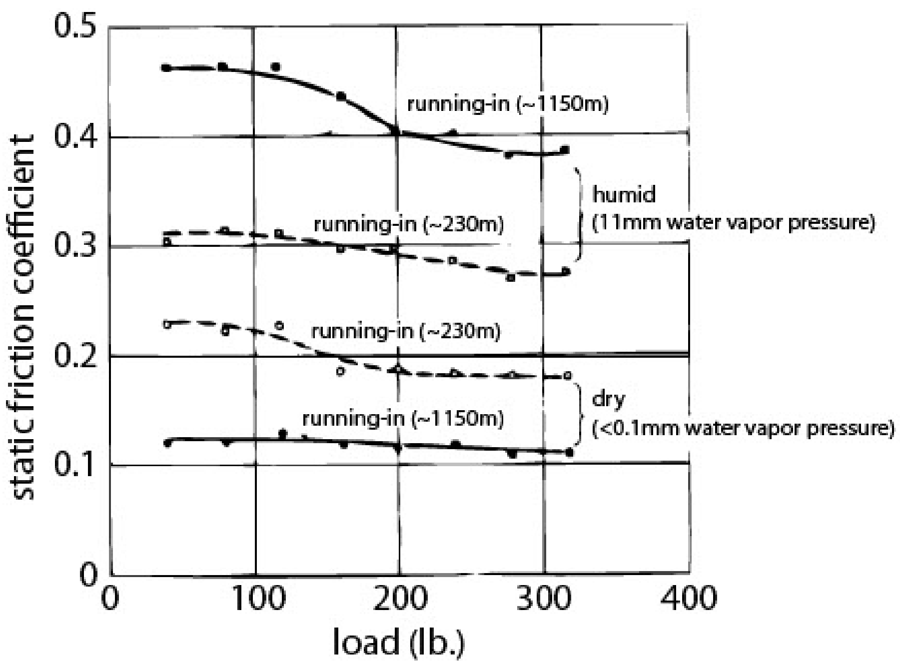
The friction coefficient of MoS_2 in a nitrogen environment at 175°C after 200 minutes of sliding is shown. The test was halted for 120 minutes and when sliding was resumed the friction value was unchanged.

Haltner, A.J., An evaluation of the role of vapor lubrication mechanism in MoS2, Wear, 7, 1964: p102-117.

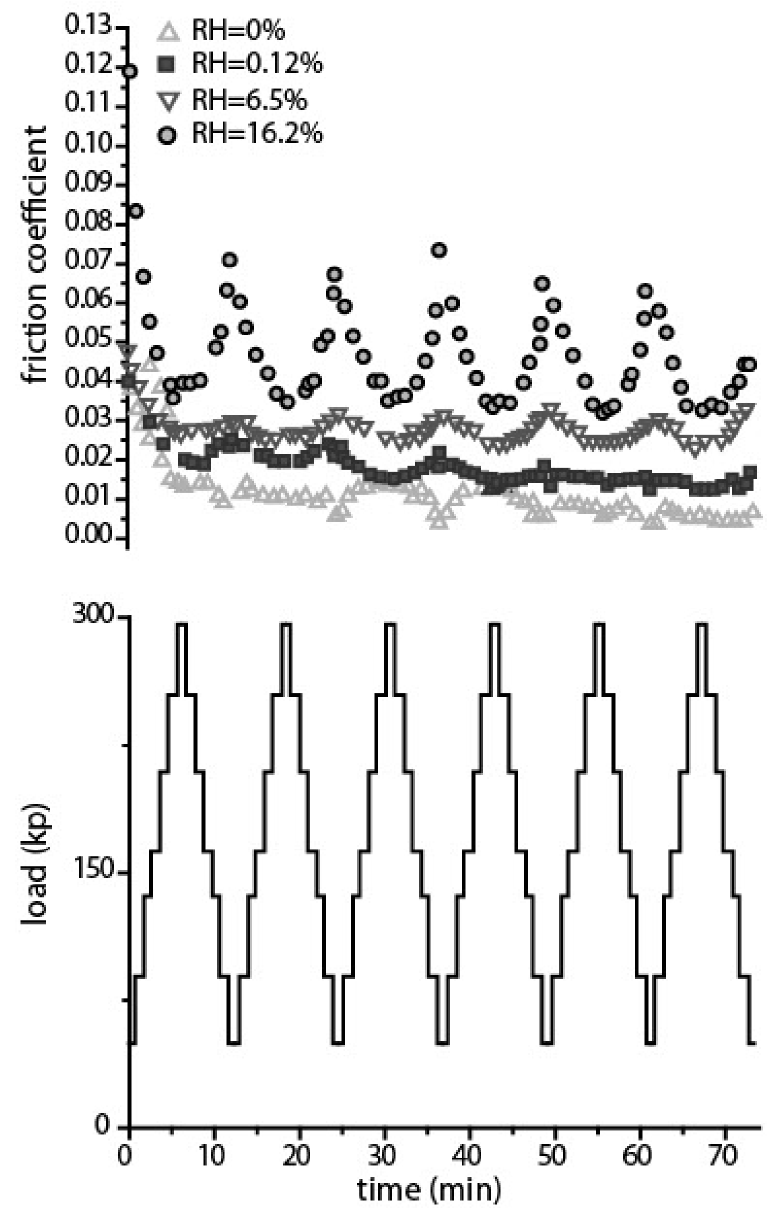
Relative Humidity Effects on Load and Friction

The effect contact pressure has on the coefficient of friction of MoS_2 has been studied since the 1960's. During this time frame, an understanding that moisture plays a role in the contact pressure effects came about.

Pritchard *et al*. and Gänsheimer analyzed the effect an increase of load had on the friction coefficient of a pure MoS_2 coating at different humidities.



Adapted From Pritchard, C., and Midgley, J.W., The Effect of Humidity of the Friction and Life of Unbonded Molybdenum Disulphide Films. Wear, 1968. 13: p. 39-50

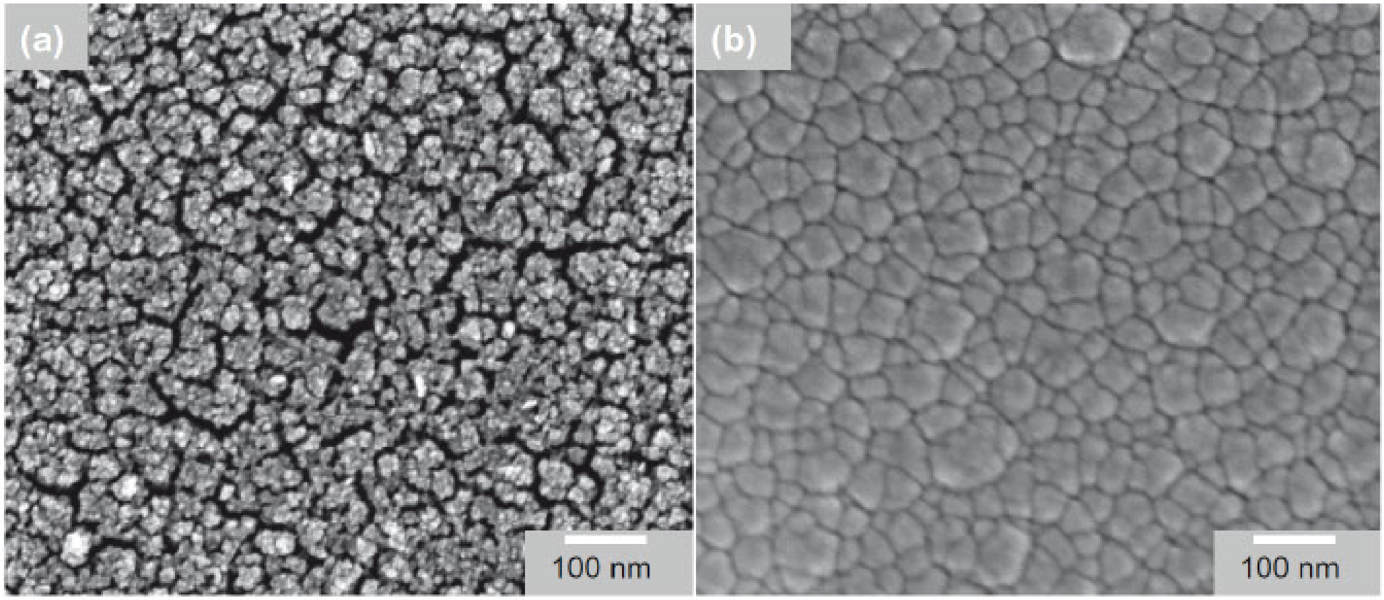


Gänsheimer's results adapted From Winer, W.O., Molybdenum disulfide as a lubricant: A review of the fundamental knowledge. Wear, 1967. 10(6): p. 422-452.

Pure MoS_2 has shown differences between its tribological behavior in dry and moist environments. A necessity for improvements of the performance in moist environments led to the development of composite MoS_2 coatings through various deposition processes. The addition of dopants was made to improve the friction, wear, and environmental stability of the coatings.

Examples of composite MoS_2 coatings in use today are:

MoS_2
MoS_2 + Ni
MoS_2 + Ti
MoS_2 + Sb_2O_3
MoS_2 + Sb_2O_3 + Graphite
MoS_2 + Sb_2O_3 + Au

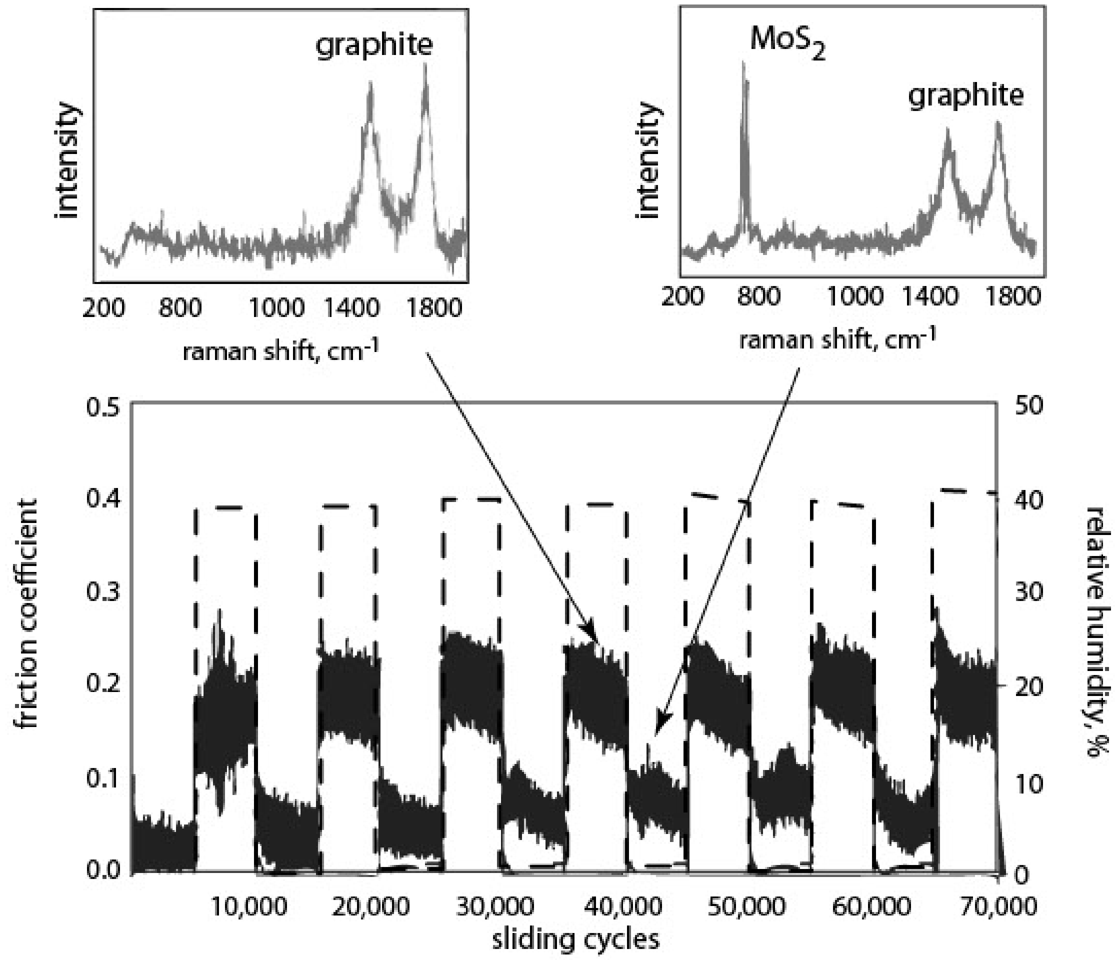


HRSEM secondary electron images of (a) pure MoS_2 film and (b) nanocomposite $MoS_2/Sb_2O_3/Au$ coating

Images adapted from Scharf, T. *et al.*, Friction and wear mechanisms in MoS2/Sb2O3/Au nanocomposite coatings, Acta Materialia, 2010, 58: p. 4100-4109

Studies of Humidity Effects on Friction

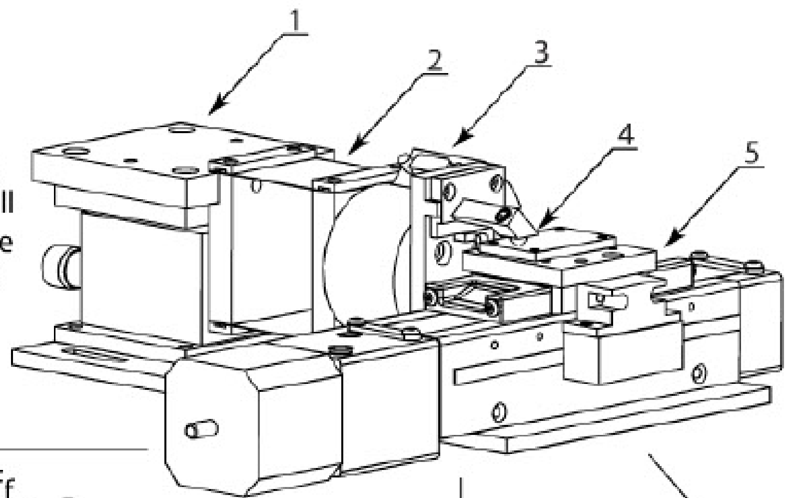
"In recent years, the concept of adaptive "chameleon" tribological coatings was developed, where coatings were designed to self-adjust their tribological contact chemistry and structure depending on the operating environment and temperature."



Variation of the friction coefficient (solid line) in sliding tests of a laser textured TiCN coating with a burnished MoS_2/graphite/Sb_2O_3 layer against a steel ball in conditions with a cycled environment humidity (dotted line). Insets show Raman analyses spectra taken from wear tracks with tests stopped during high and low humidity cycles.

A.A. Voevodin , J.S. Zabinski, Laser surface texturing for adaptive solid lubrication, Wear, 2006, 261: p. 1285–1292

In Situ Tribometer Design



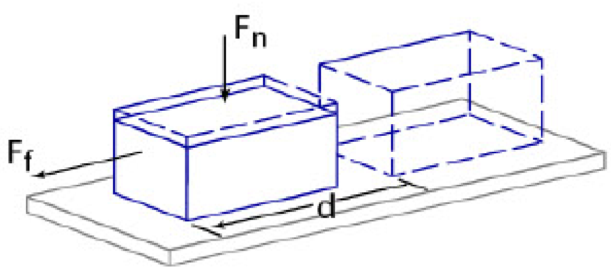
1. vertical stage
2. parallel leaf flexure
3. six-channel load cell
4. pin and counterface
5. reciprocating table

Accurate measurement of friction coefficient requires measurements of normal and frictional forces. The design philosophy is to make both measurements simultaneously with a multi-axis load-cell that is located directly in the force path to ground.

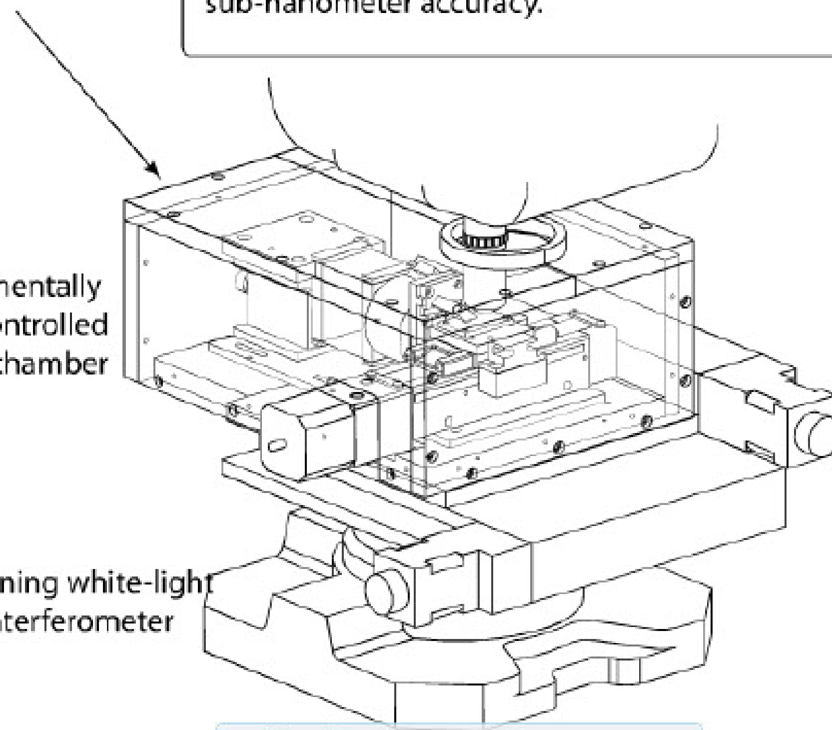
To make in-situ measurements of wear, we have implemented a scanning white-light interferometer that can measure relative displacements of surface features with sub-nanometer accuracy.

friction $\mu = \frac{F_f}{F_n}$

wear $K = \frac{Vol}{F_n\ d} \quad \left(\frac{mm^3}{N\ m}\right)$



Because the samples are consumed during tribological testing, there are no standard artifacts. Thus, following wear and progression of wear requires sensitive displacement measurements and interrupted measurements.



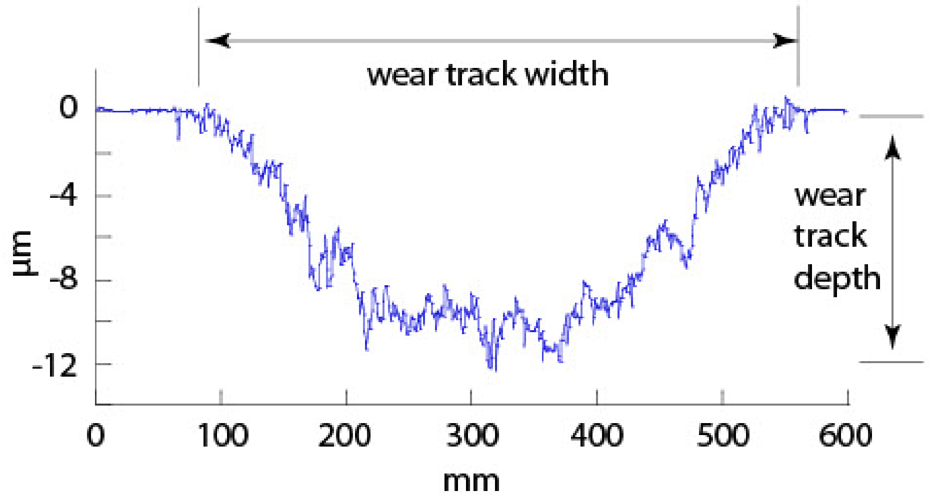
Volume loss

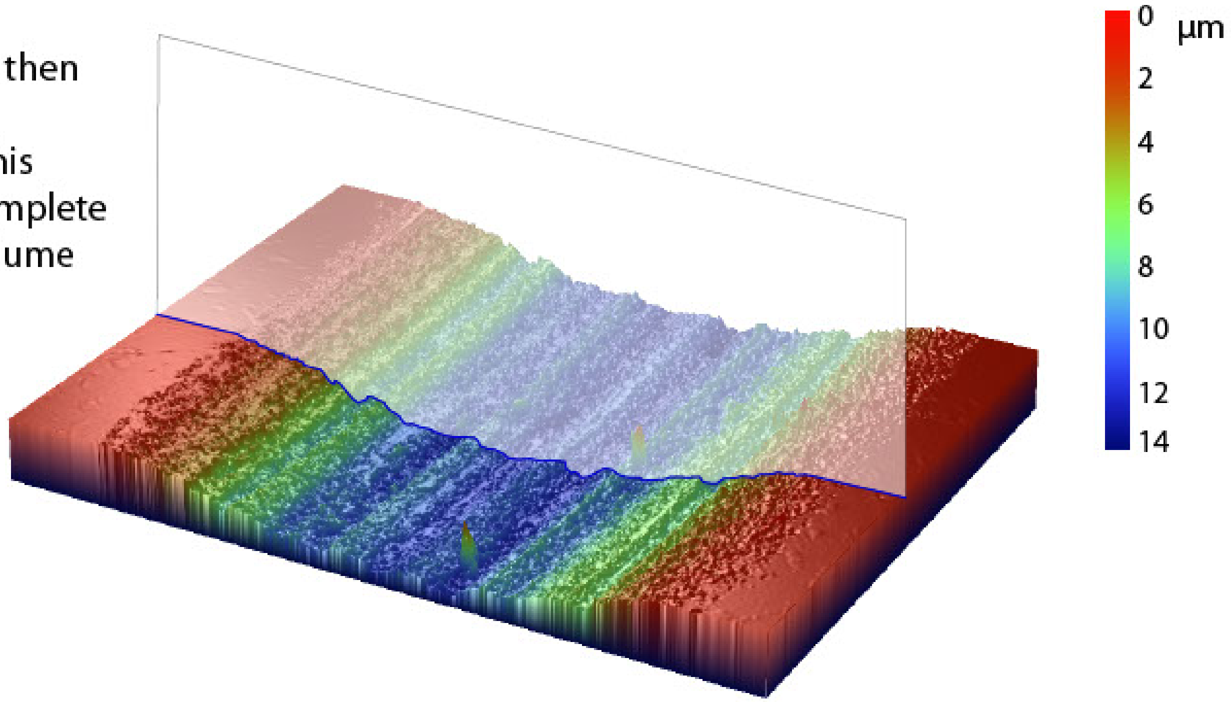
Using scanning white light interferometry, a 3D surface scan of the wear track is taken.

A representative 2D slice through the wear track is taken and analyzed for the wear track cross-sectional area.

Creep of these thin film coatings is considered negligible.

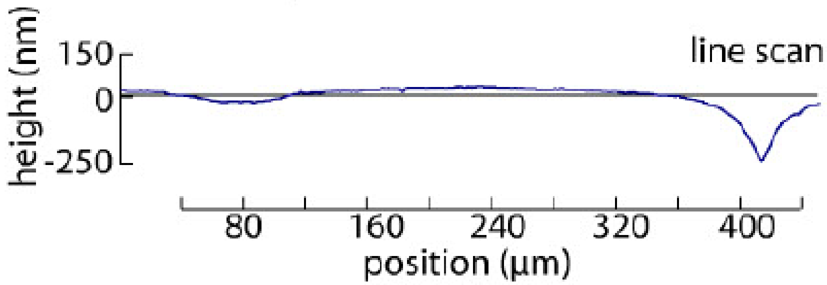
The volume of material removed is then estimated by calculating the cross-sectional area of the scans. This average area is swept along the complete wear track path to calculate the volume loss.

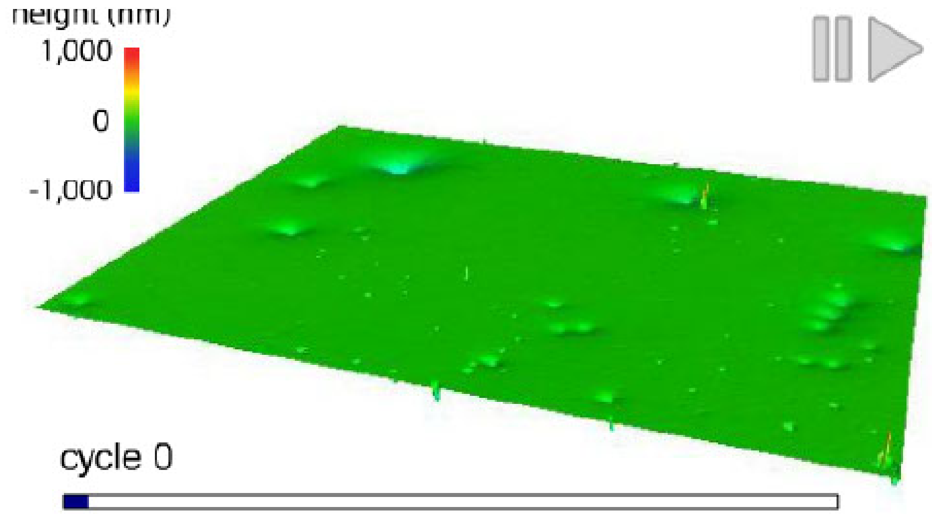


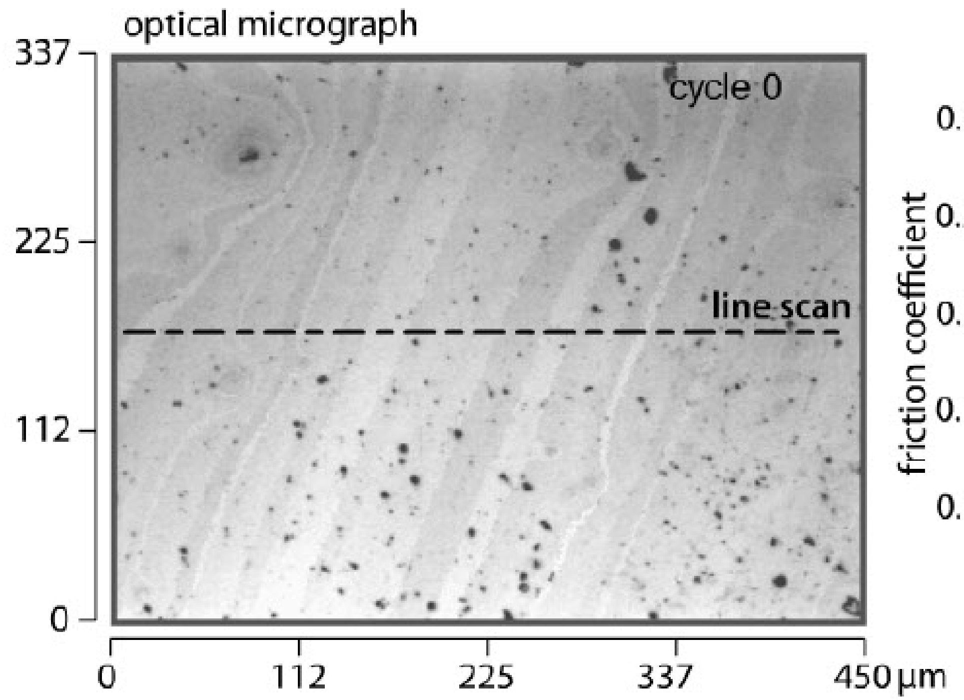


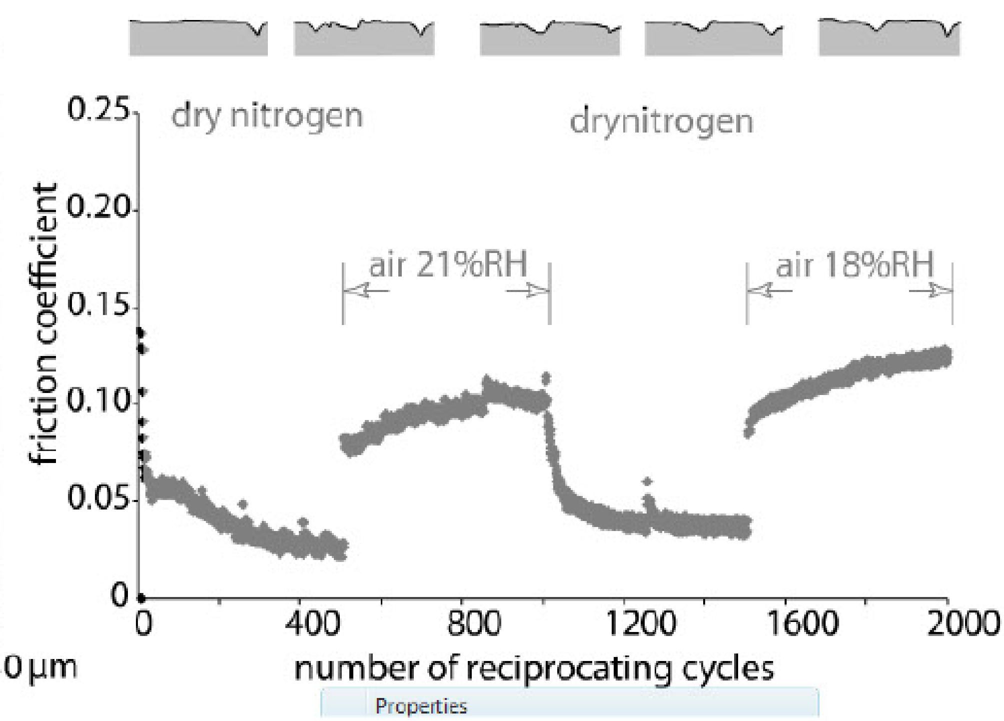
Self-Mated $MoS_2/Sb_2O_3/Au$ in Dry Nitrogen and Air

Fn = 5N
V = 10 mm/s
L = 10 mm
nitrogen <1% RH



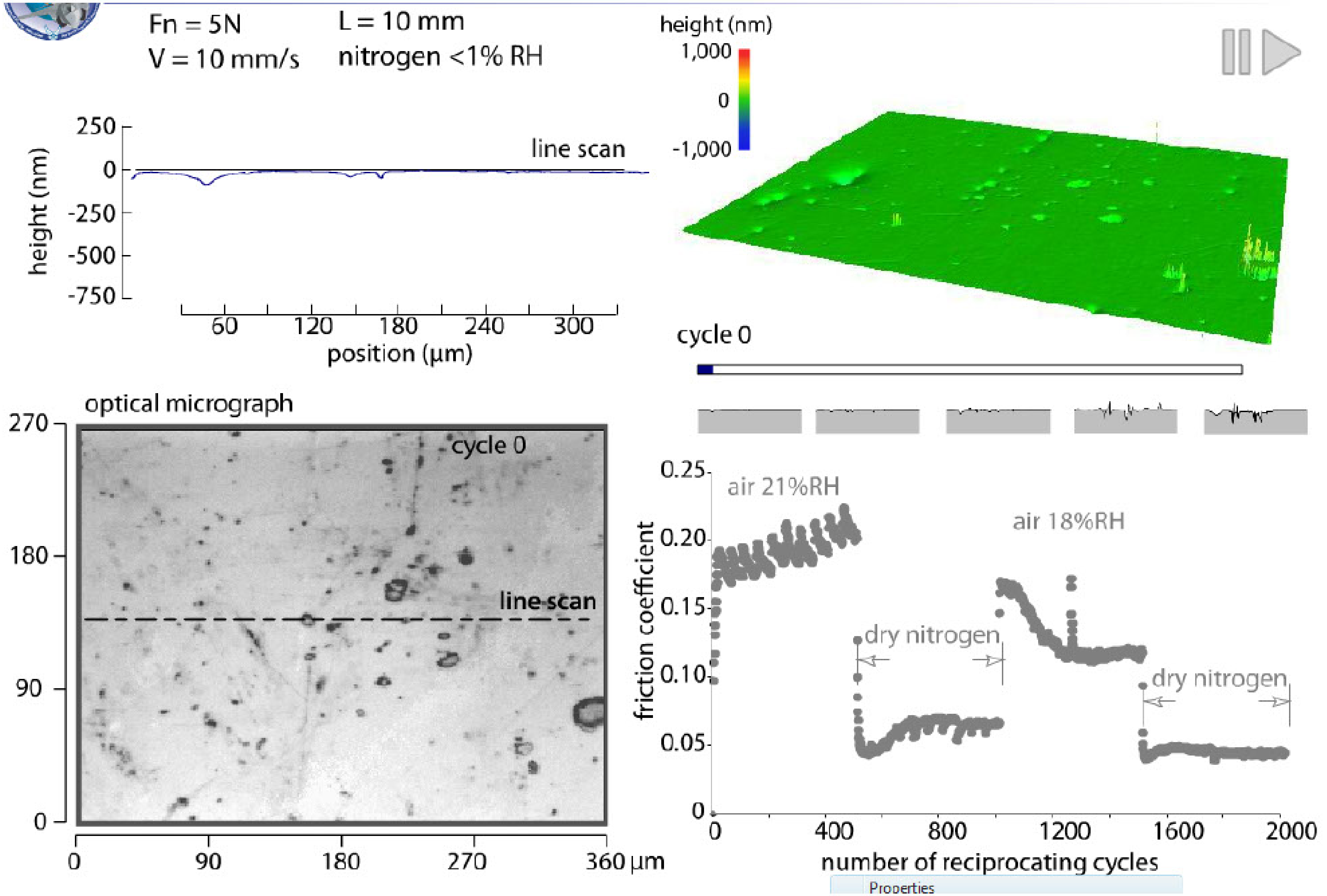






12-hohman dry N2 and air.ai

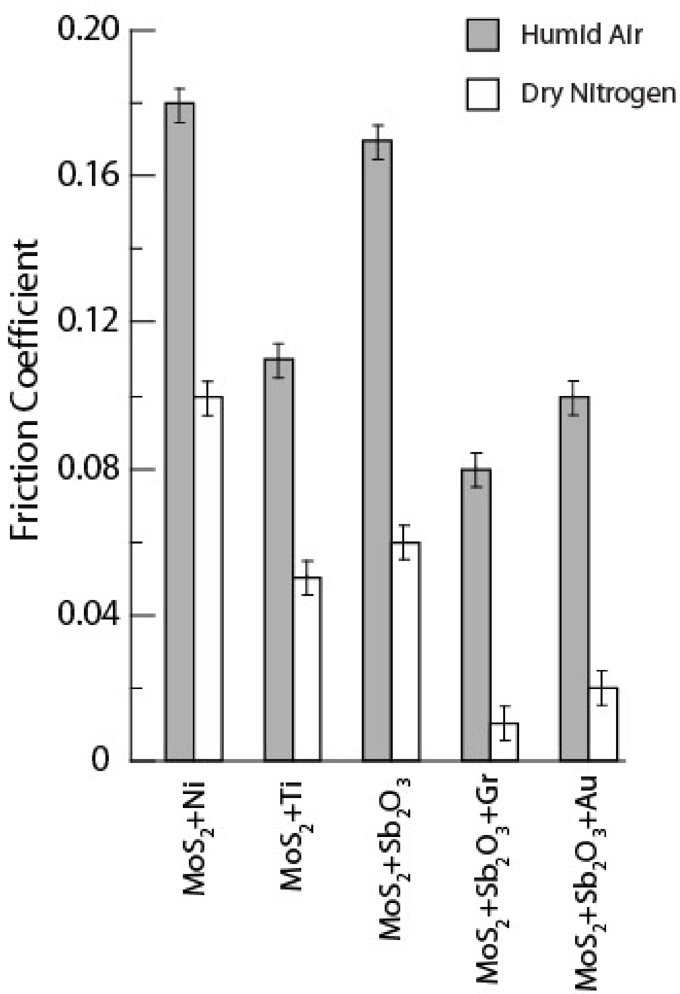
Self-Mated MoS_2/Ti in Air and Dry Nitrogen

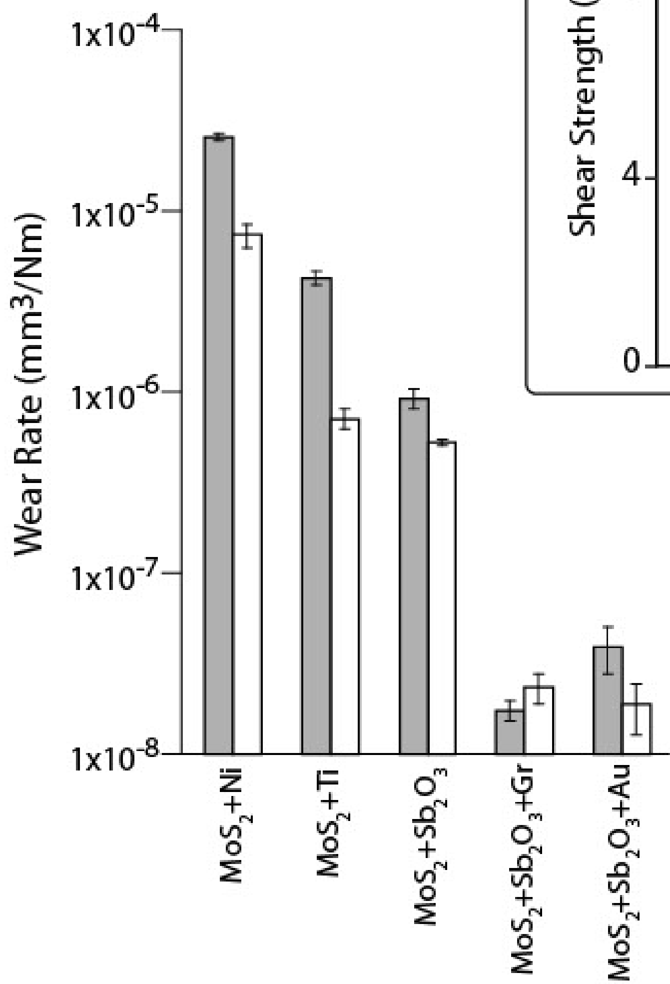


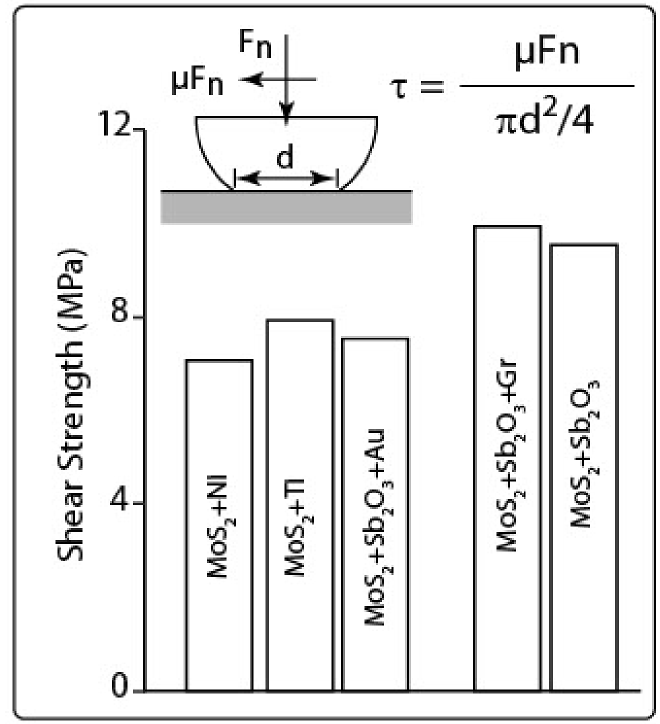
13- MoS2+Ti in air and dry N2.ai

Review of Experiments

The friction coefficient and steady-state wear rates for the various coatings along with the experimental uncertainties in the measurements are given below. The wear rates of the films varied over 3 orders of magnitude. All tests were run self-mated at 5N load, 10 mm/s sliding speed, for 10,000 cycles; the total sliding distance was 100m.







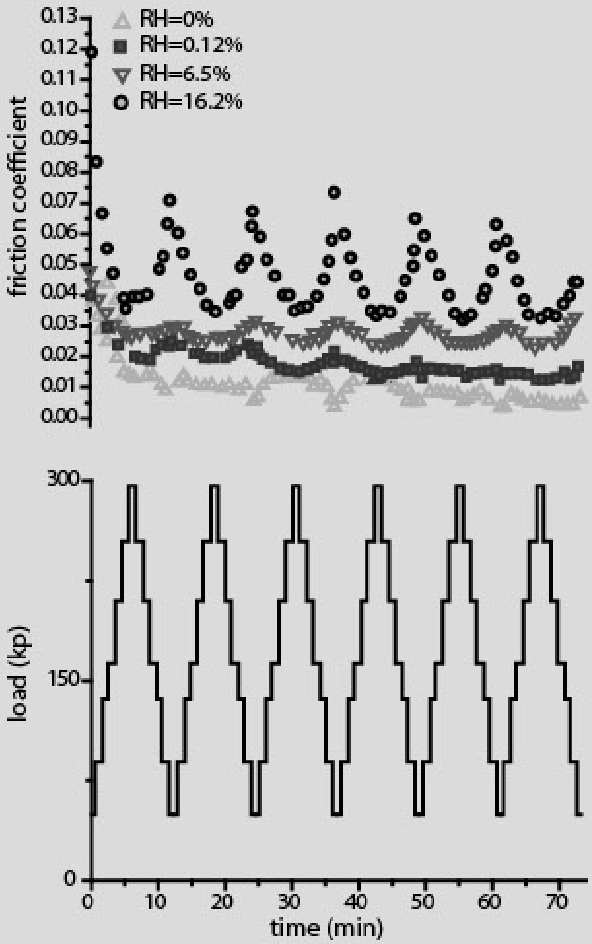
Under these experimental conditions at a wear rate of $K=1x10^{-7}$ $mm^3/(Nm)$ approximately 1nm of material is removed each pass.

Summary of Trends

Friction coefficient decreases with a decrease in water content
Friction coefficient decreases with an increasing normal force, but only with water present
Initial run-in friction coefficient values increases with increased exposure to moisture without sliding
The water sorption of MoS_2 is a reversible process once a portion of water is irreversibily sorbed

Questions to be Addressed

What is the amount of water being adsorbed into the films?
What is the critical moisture content which causes the increase in friction coefficient?
Is the water sorption affected by the density/porosity and thus surface area/volume ratio of the films?
Does orientation of the films play a role on the moisture effects?



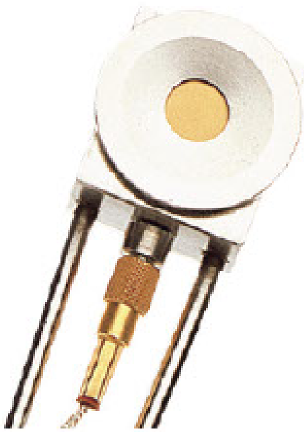
Gänsheimer's results adapted From Winer, W.O., Molybdenum disulfide as a lubricant: A review of the fundamental knowledge. Wear, 1967. 10(6): p. 422-452.

$$\mu = \frac{F_f}{F_n} = \frac{A_{real} \cdot \tau_{shear}}{F_n}$$

There is a strong interdependence between friction coefficient and applied load at high humidity. That interdependence dissapears at low partial pressure of water.

This indicates that the friction force is the factor influenced by moisture. As the friction force is defined as the real area of contact multiplied by the shear stress of the film, this would indicate that the shear stress is the variable of interest.

The friction force is hypothesized to be correlated water sorption.



Quartz Crystal Microbalance's (QCM) work using the piezoelectric effect from the quartz crystal. Alternating currents are applied to the crystal which creates a standing shear wave. The frequency of oscillation of the quartz crystal is dependent upon the mass of the crystal, thus if a change of mass occurs, the frequency will change correspondingly.

The Sauerbrey's Equation is used to calculate mass change per unit area:

$$\frac{\Delta m}{A} = -\frac{\Delta f}{2 f_0^2}\sqrt{\mu_q \rho_q}$$

QCM Studies

The mass of water sorption into a MoS_2 film per exposed area at various partial pressures of water can be studied.

As the partial pressure of water is varied, the friction can be measured as well. Allowing a correlation between mass of the water on the film and the friction coefficient to be made.

Image courtesy of Inficon

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