Argonne NATIONAL LABORATORY

... for a brighter future

U.S. Department of Energy

THE UNIVERSITY OF CHICAGO

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by The University of Chicago

# *Friction and Wear Properties of Materials used in Hydrogen Service**

*Robert Erck, George Fenske, and Osman Eryilmaz*

*Energy Systems Division*

*Argonne National Laboratory*

Materials Innovations in an Emerging Hydrogen Economy
The American Ceramic Society and ASM International
Cocoa Beach, FL
Feb 26, 2008, 9:20 am

*Work supported by the Department of Energy / Office of Energy Efficiency and Renewable Energy / Hydrogen, Fuel Cells and Infrastructure Program / Hydrogen Delivery, under Contract DE-AC02-06CH-11357

# Challenges

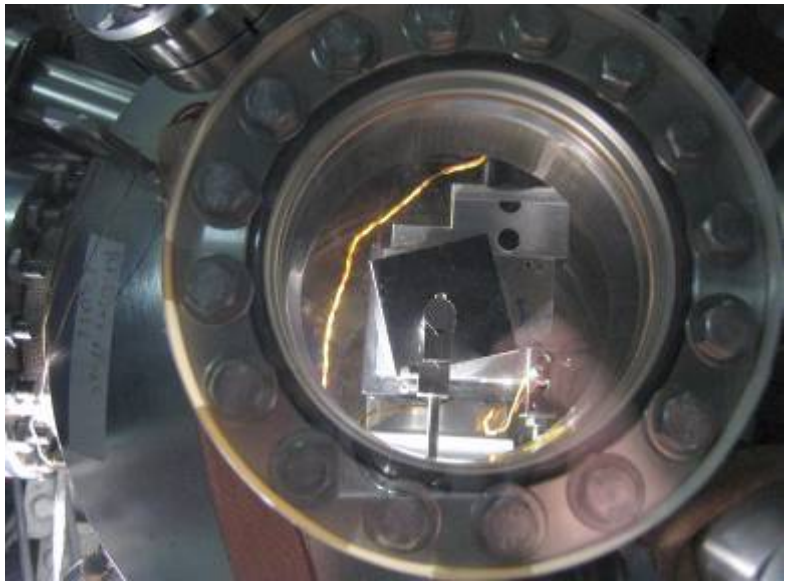
- Moving/sliding mechanical components used in hydrogen service can be subject to excessive wear, have poor reliability, or may require the use of lubricants that can contaminate the hydrogen
- Conventional lubrication of compressor components/bearings with oil or grease may not be possible or desirable - contamination issue for PEM fuel cells
- Hydrogen is a reducing environment, preventing formation of protective oxide layers on metal surfaces
- Some metals susceptible to hydrogen embrittlement - significant reduction in reliability and durability

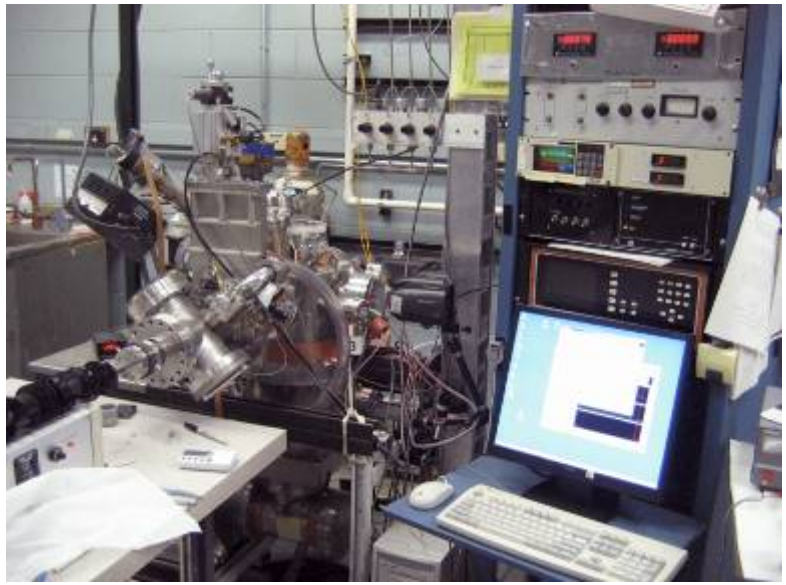
# *Tribological Tests*

- Goal: Undertake experiments to assess the friction and wear properties of test materials and coatings
- Present activities: modify existing tribological test rigs for 1) ball-on-disk sliding at low speed in air and $H_2$, and 2) thrust-washer configuration sliding at medium speed in $N_2/H_2$ ($H_2$ future)
- Materials - SS, Ti, Ni, Al, DCL; $MoS_2$ coatings
  - future: carbide-derived carbons, fluorides, solid lube coatings

# *Preliminary Tests - slow speed*

- Controlled environment/vacuum ball-on-disk tribometer





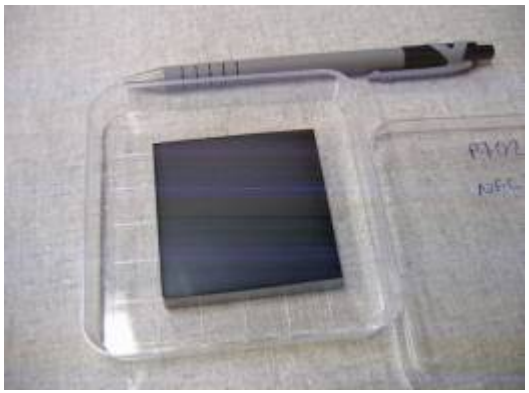
# Preliminary Tests - slow speed

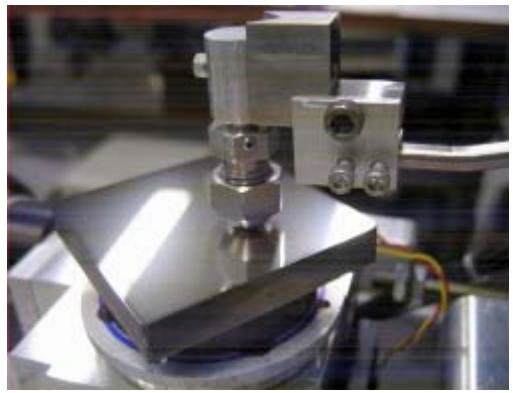
- Ball-on-flat test geometry
- X-750 nickel-base alloy flats, M-50 balls
  - Metal/metal or DLC/DLC
  - DLC - PACVD using 25% $CH_4$/ 75% $H_2$ gases at RT

**Alloy**: Inconel X-750

**Nominal Composition in Percent**:

| | |
|---|---|
| Ni | 70.00 |
| Co | 1.00 |
| Cr | 15.50 |
| Fe | 7.00 |
| Si | 0.50 |
| Mn | 1.00 |
| C | 0.080 |
| Al | 0.700 |
| Ti | 2.500 |
| Cu | 0.50 |
| S | 0.010 |
| Cb+Ta | 0.95 |

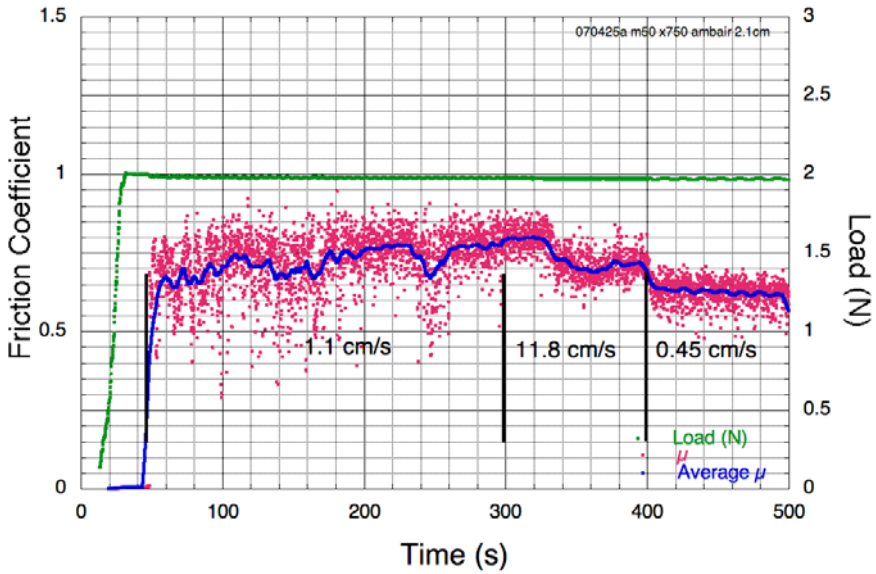




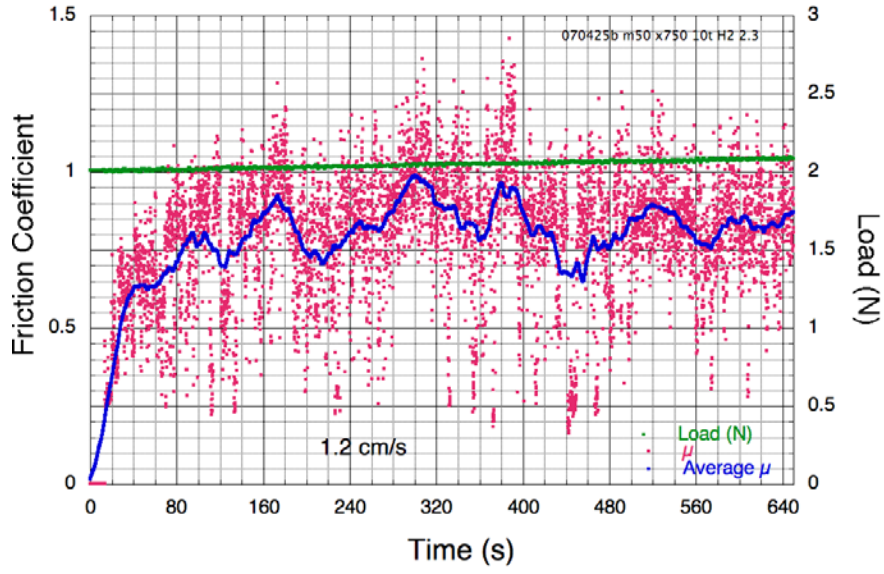
# *Steel/X-750 in air*

- Graphs shows friction as function of testing time for steel against X-750 in air or $H_2$
  - High friction in ambient air, more erratic in $H_2$

AMBIENT AIR

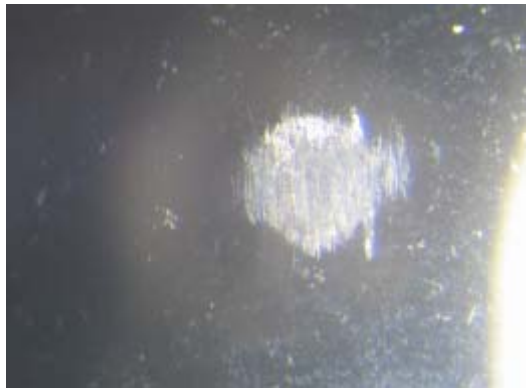


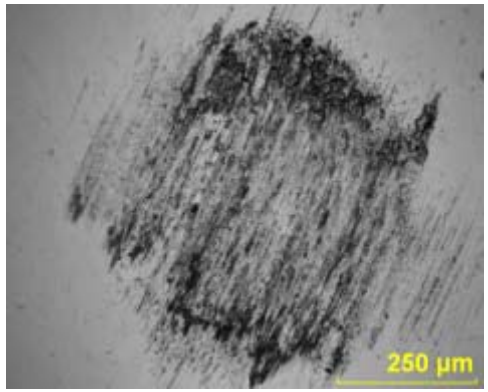

HYDROGEN

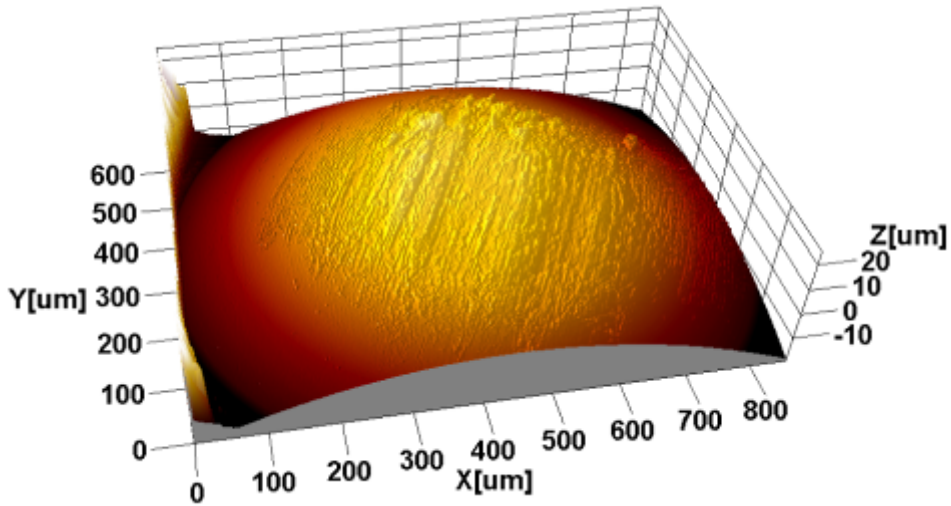


# *Steel/X-750 in air*

- Ball wear
  - Moderate wear scar with debris
  - Ball scar consists of roughening and fine parallel grooves

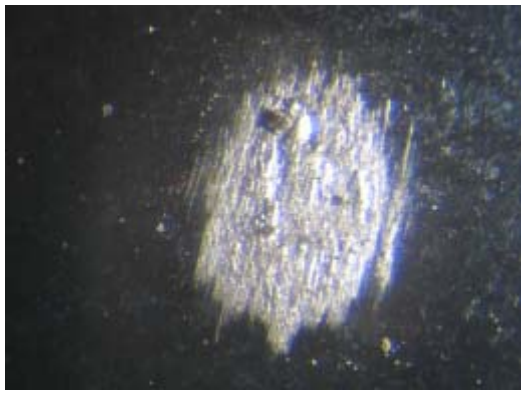


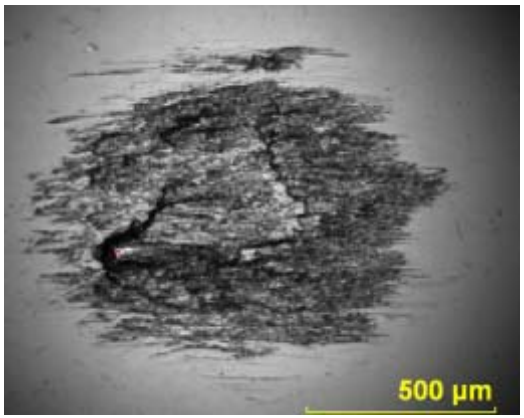


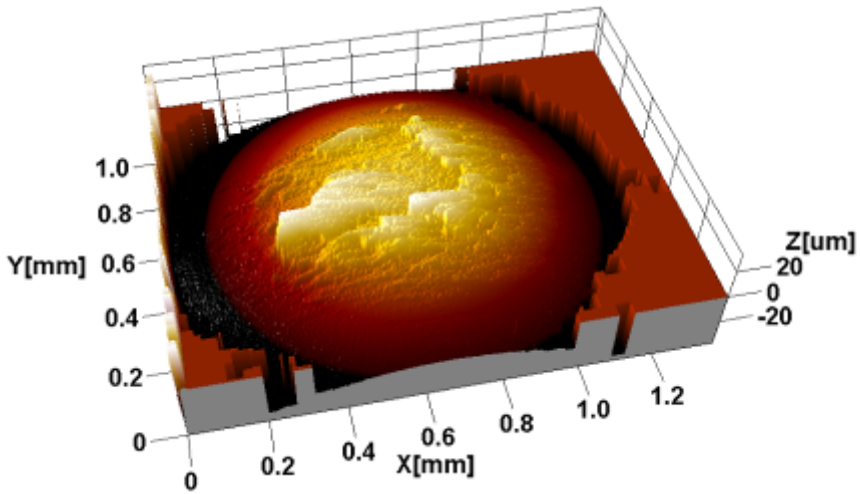



# Steel/X-750 in 10 torr hydrogen

- Ball wear
  - Wear scar on ball is very rough and shows transfer of disk material to ball



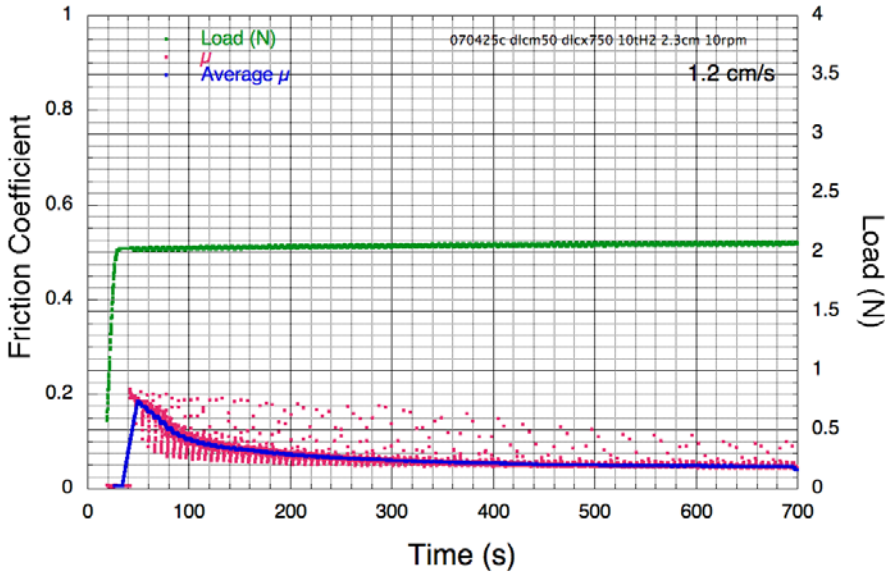


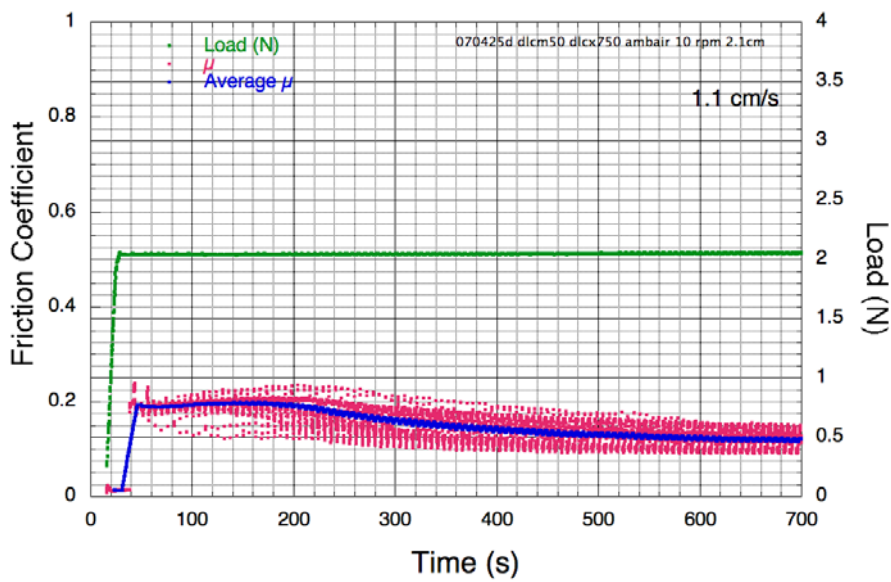
# *DLC coated materials in hydrogen or air*

- Graphs shows friction as function of testing time for DLC coated steel against DLC coated X-750
  - Friction is low, with $H_2$ giving lower friction

HYDROGEN



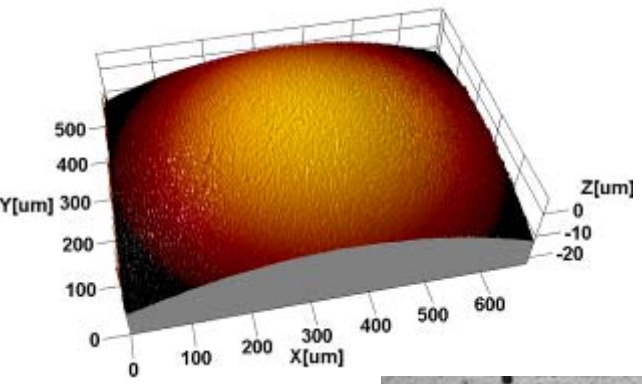

AMBIENT AIR

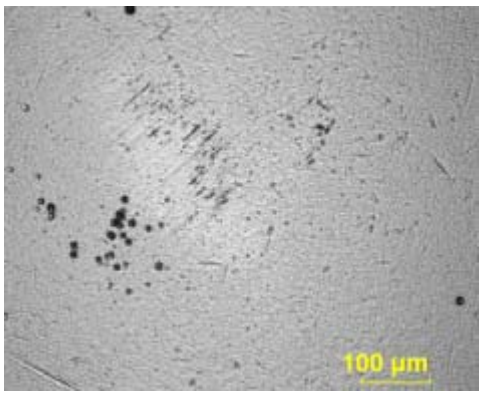


# *DLC coated steel/DLC coated X-750 in 10 torr hydrogen*

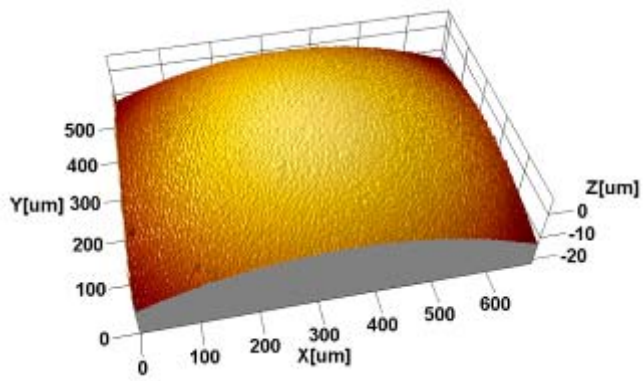
- For coated specimens, wear is negligible in either environment

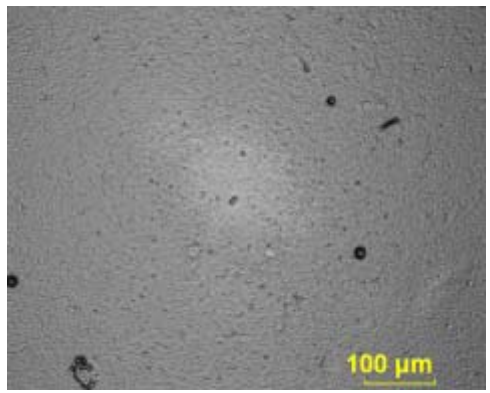
HYDROGEN



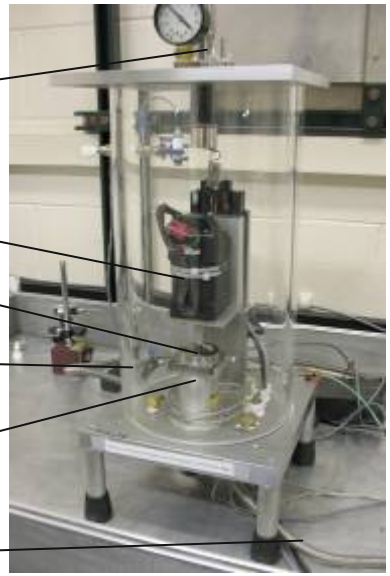

AIR

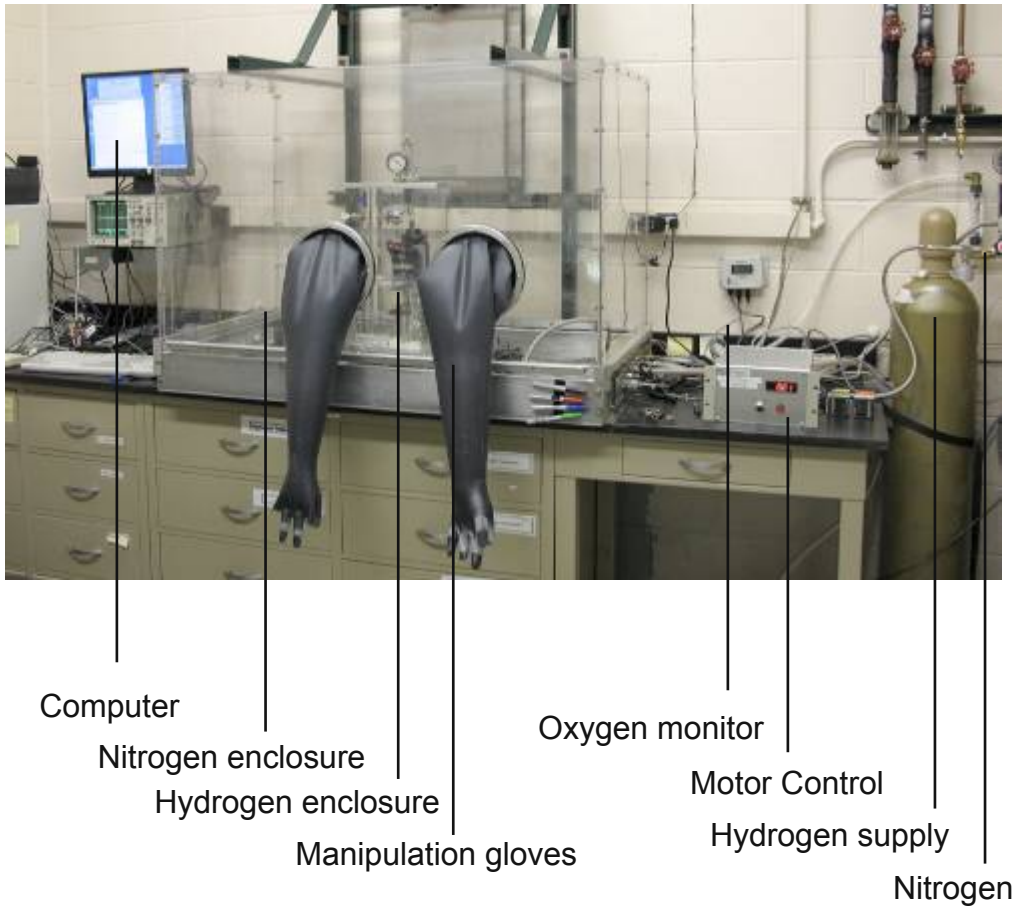


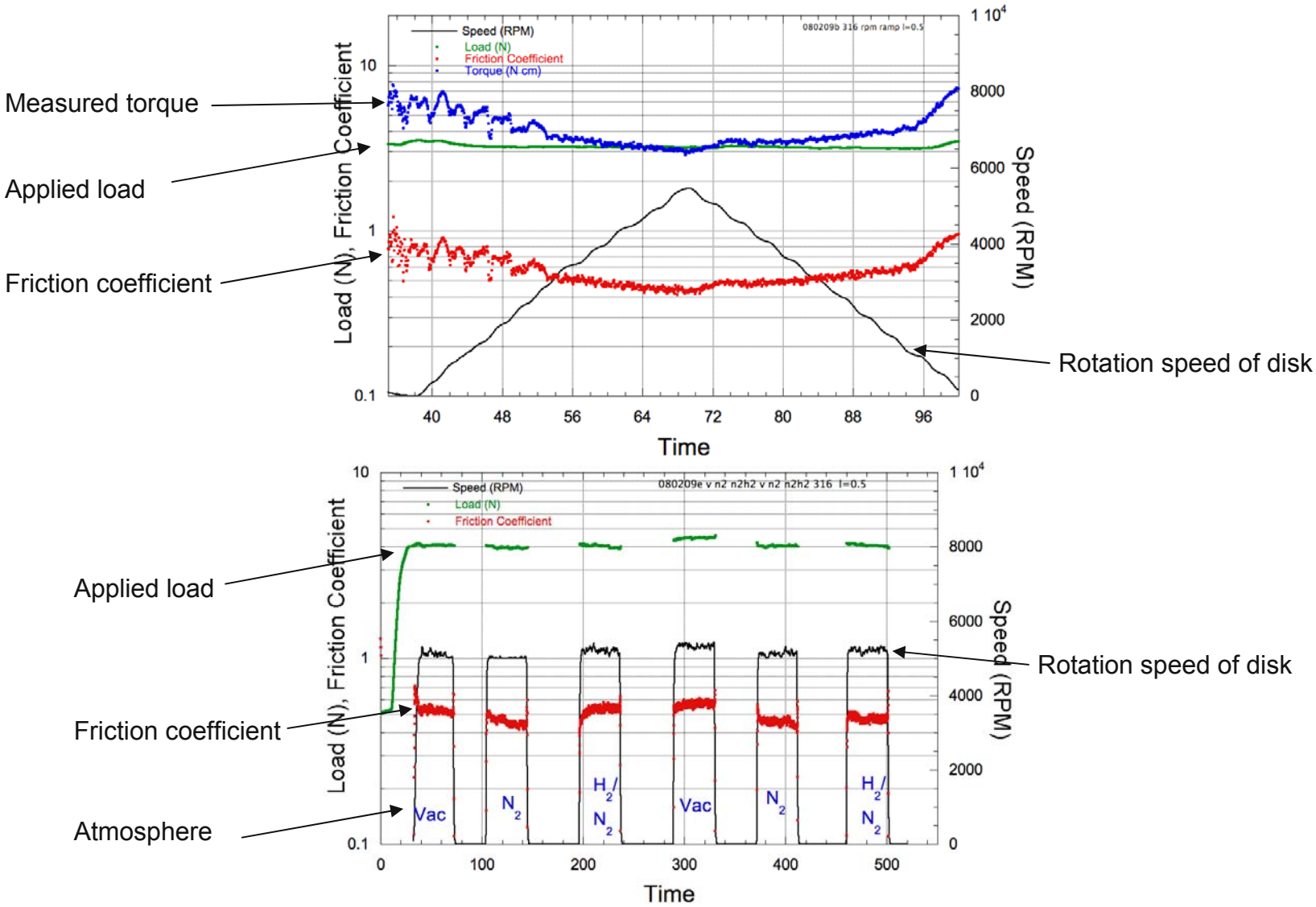
# Tests - medium speed

- Existing light-duty test machine is being modified for hydrogen testing and was used with $N_2/H_2$



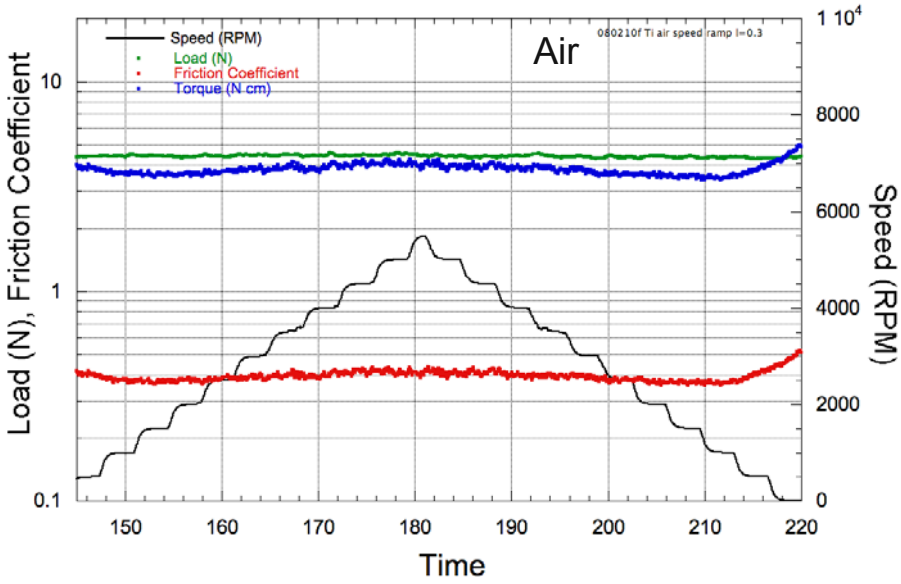



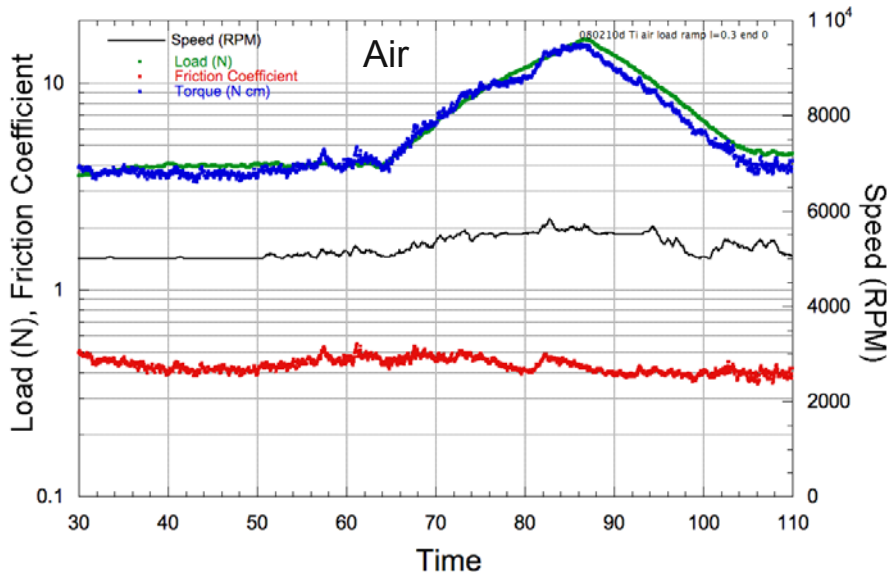
# Example - ramped speed, or load



# Ti-6AL-4V

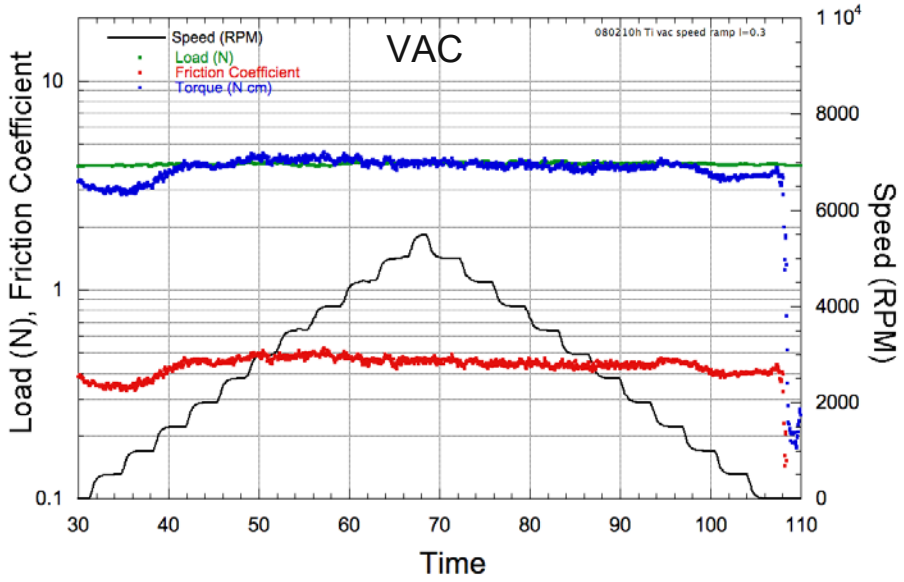
- Ti-6AL-4V / Ti-6AL-4V in air
  - Friction coefficient ~ 0.4 over range of sliding speeds
  - Very constant over range of loads (4-16 N)

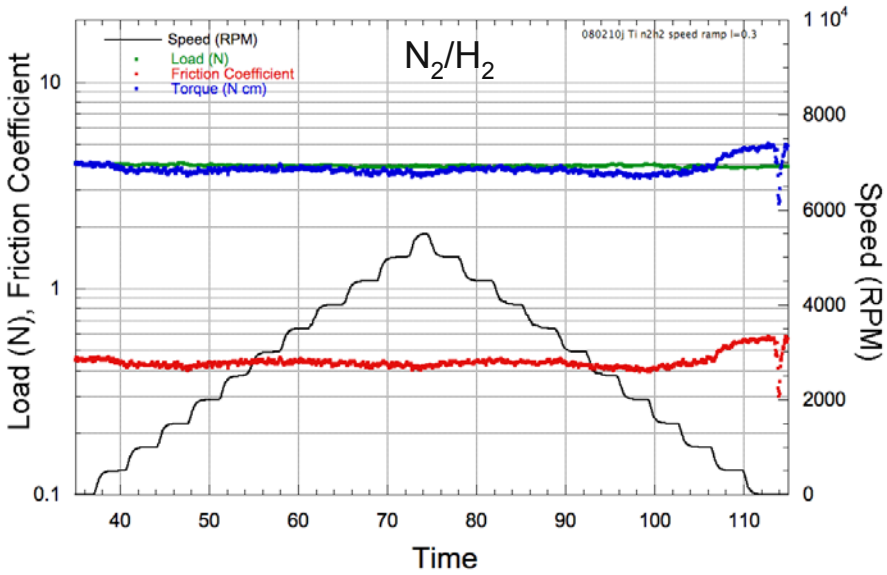


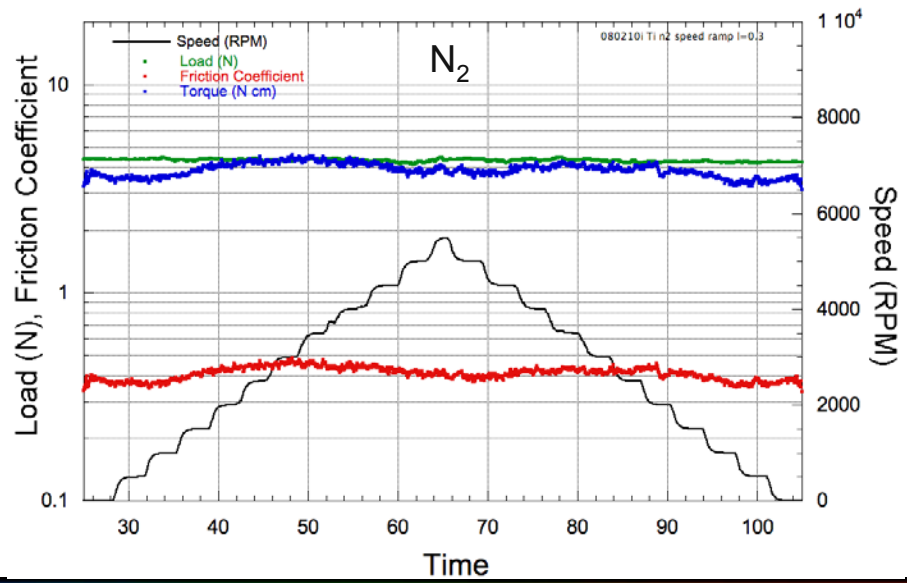



# Ti-6AL-4V

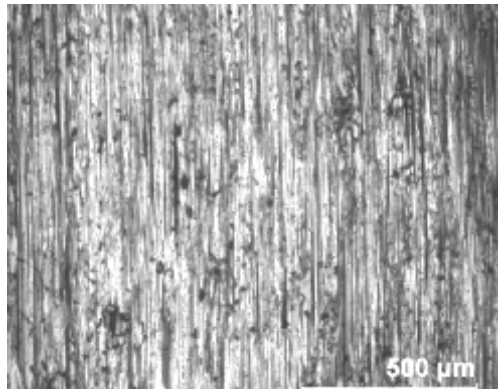
- Ti-6AL-4V sliding against itself in different environments
  - Approx constant friction over range of sliding speeds and environments



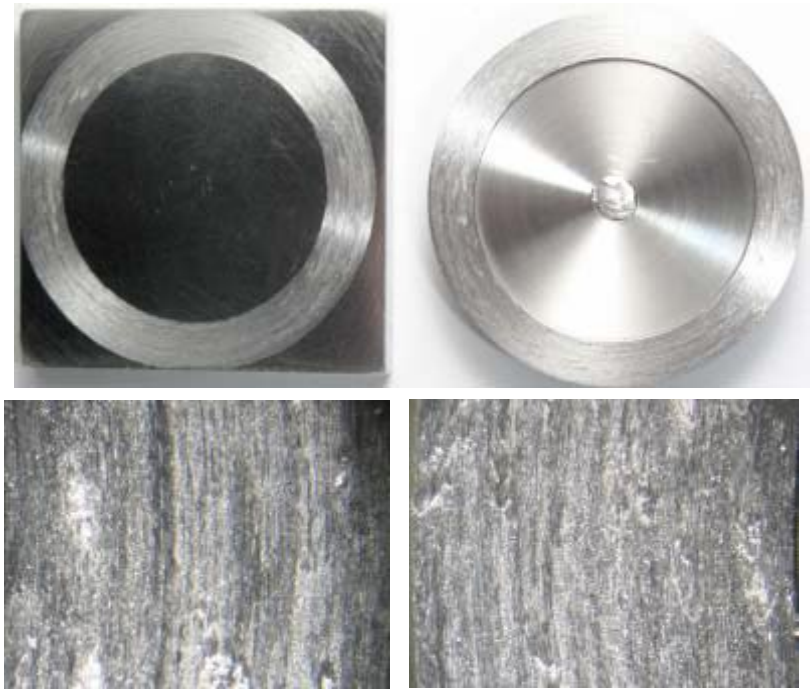



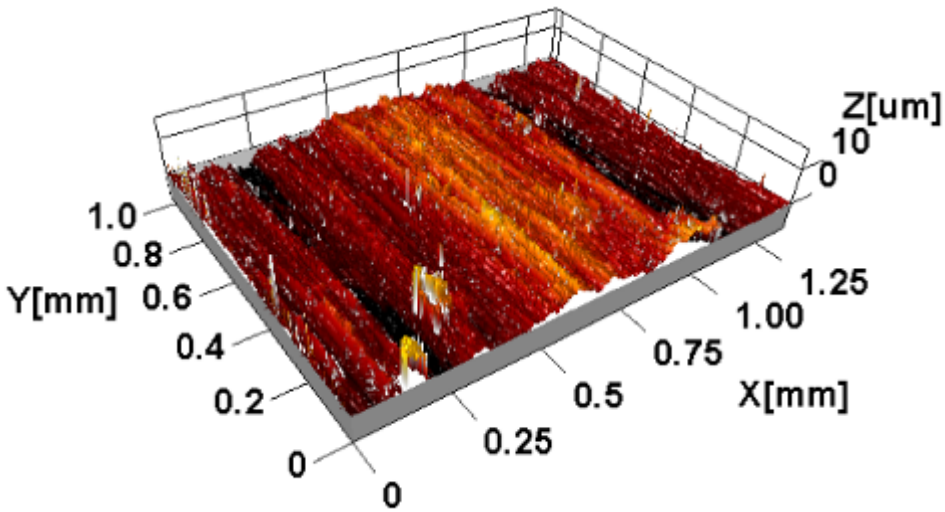



# Ti-6AL-4V



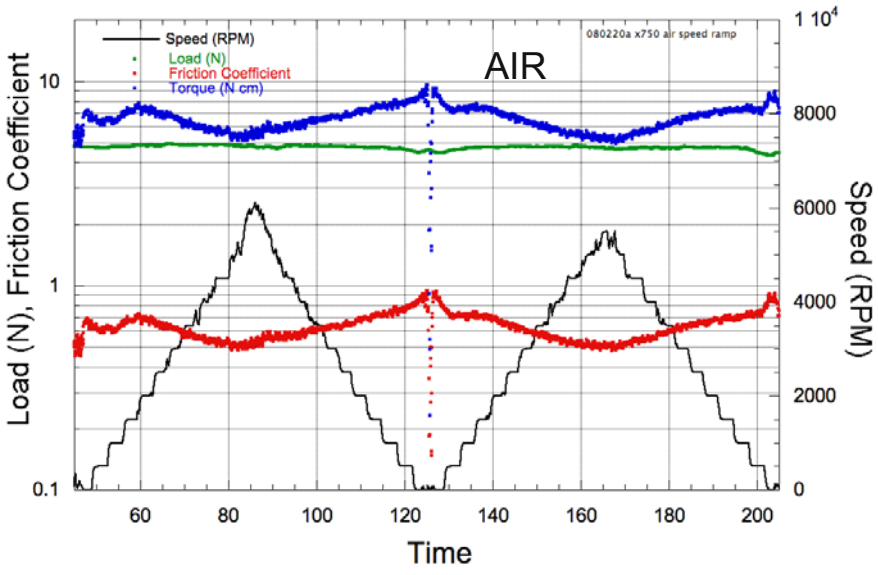

- Post test examination
  - Wear and scuffing
  - 2.1 µm Ra

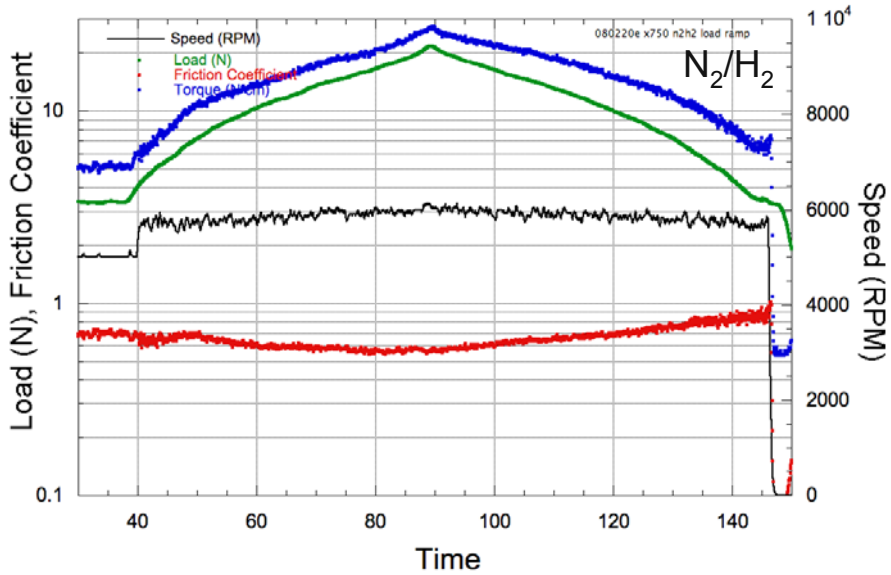




# X750/X750

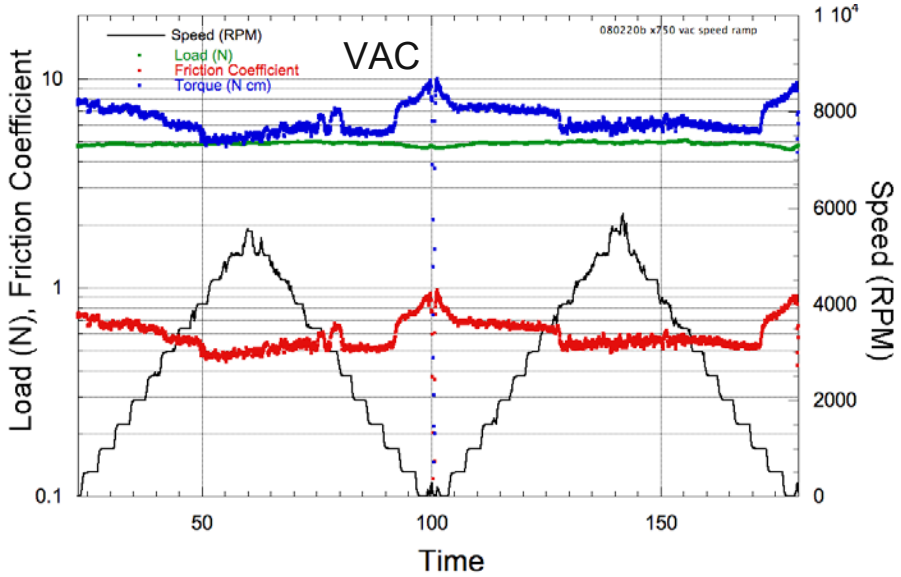
- X-750/X-750 in air
  - Lower friction at higher speeds sliding in ambient air (0.5 - 0.9)
  - Slightly lower friction at higher loads over range from 5N to 25 N in $N_2/H_2$

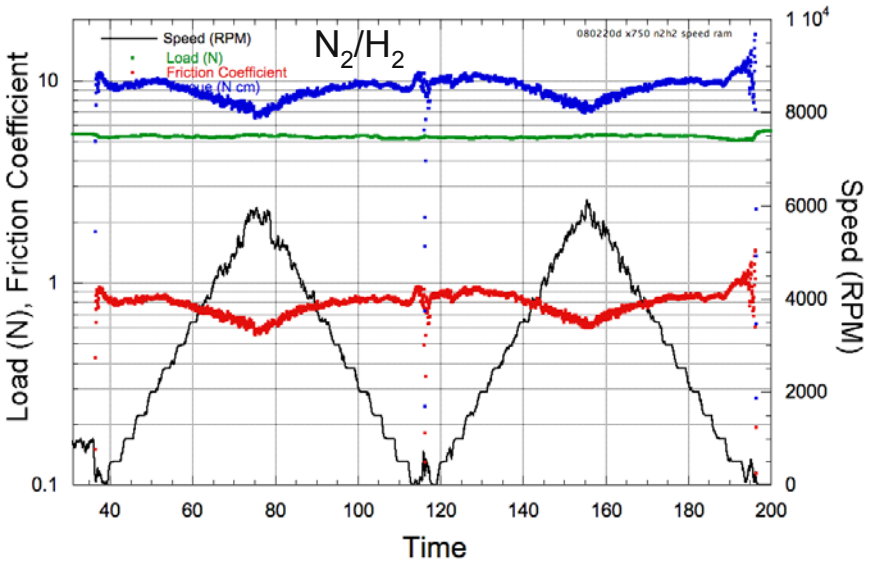


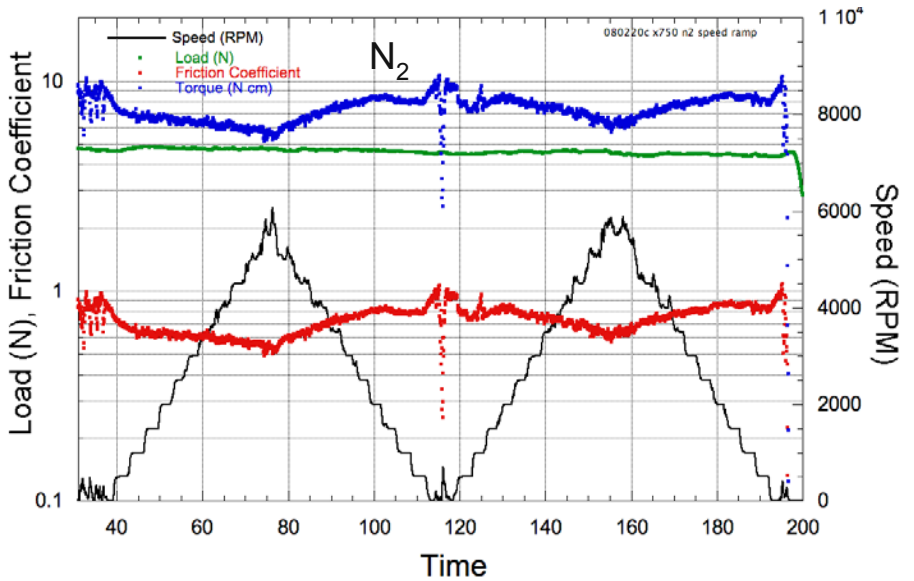



# X750/X750

- X-750/X-750 in different environments
  - High friction coefficients (0.5-0.9)

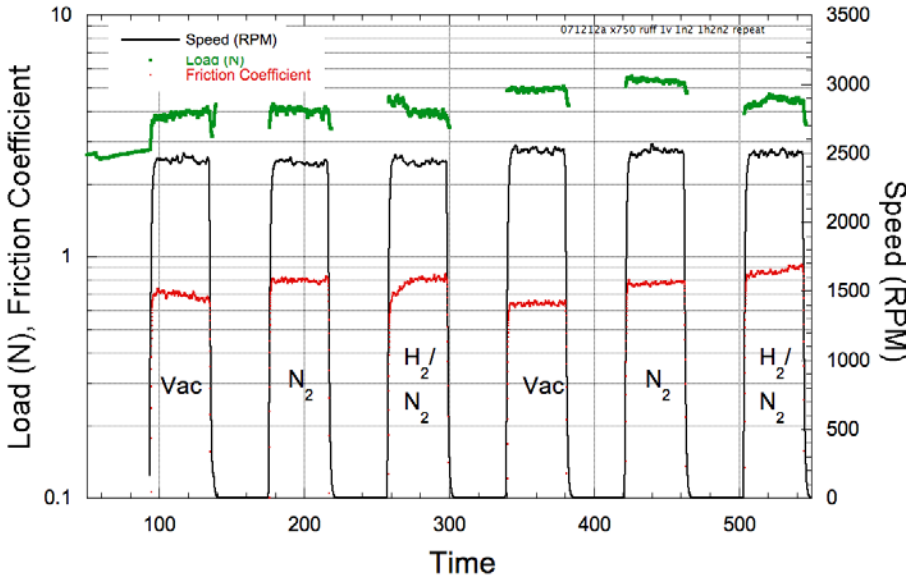


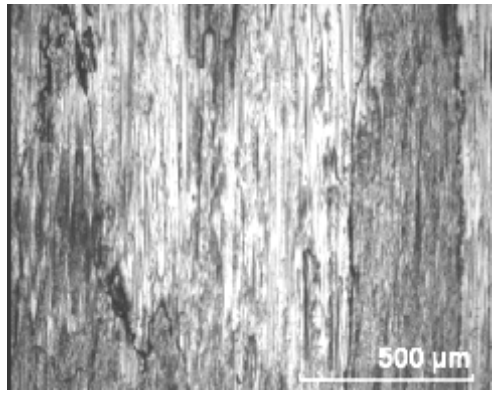
# X750/X750

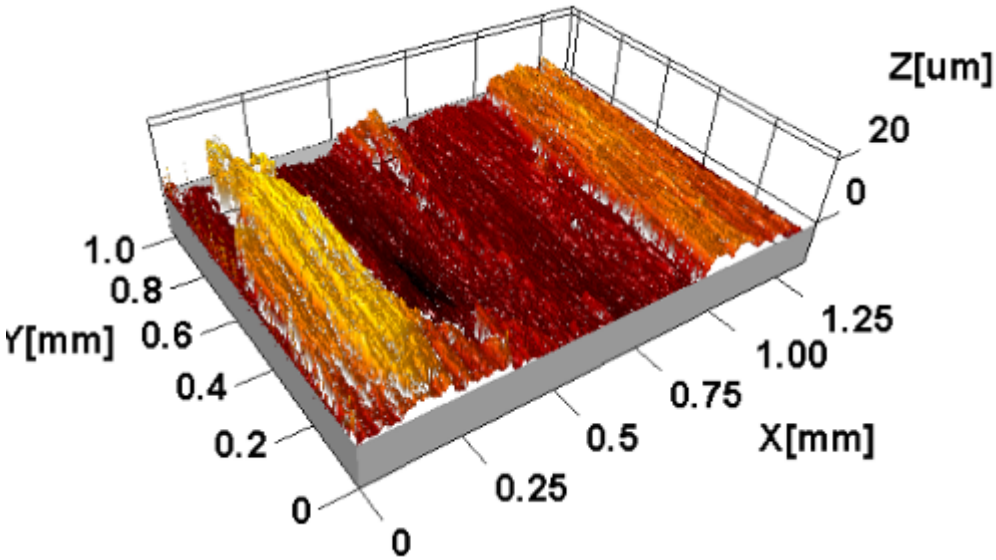
- X-750/X-750 in different environments
  - High friction coefficients (0.5-0.9), lower in vacuum and higher in $N_2/H_2$



# X750/X750

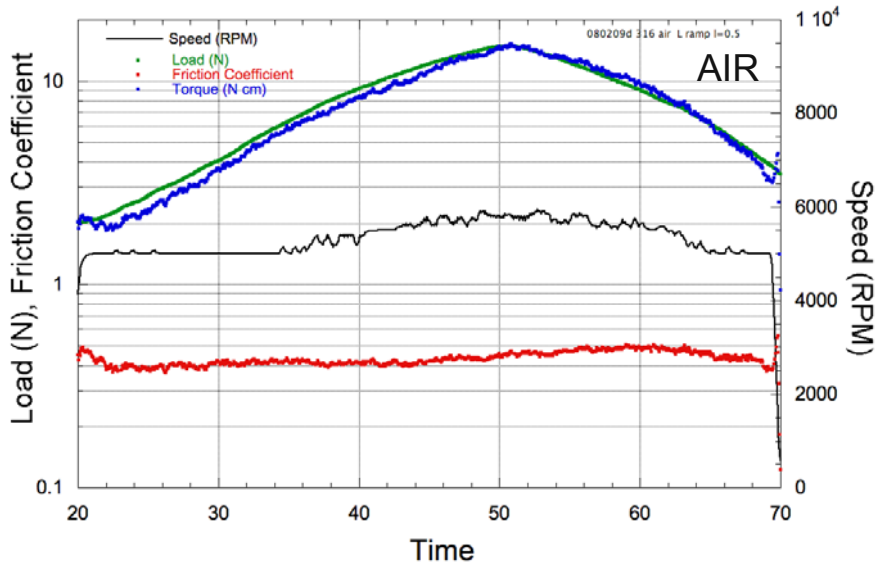
- Post test examination
  - Visible wear track, galling and material transfer
  - 3.8 µm Ra



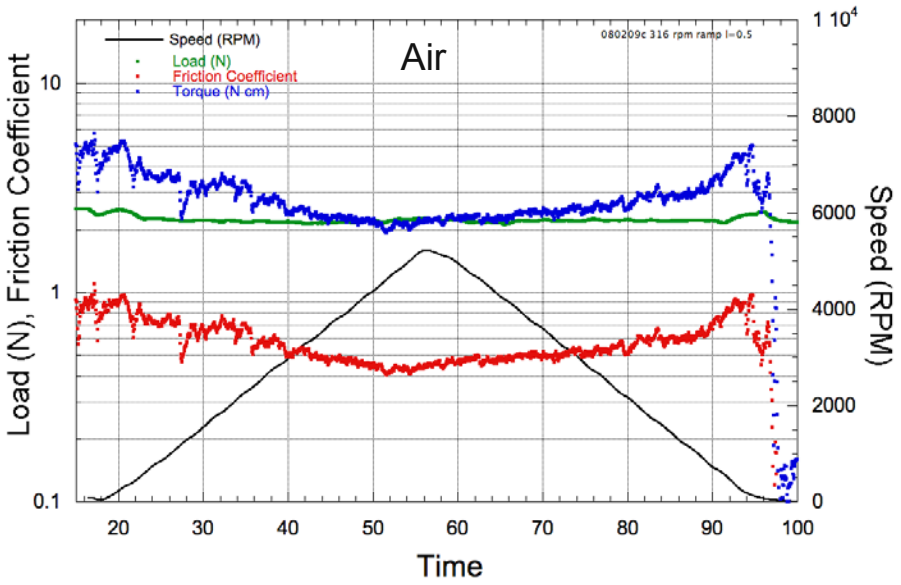
# 316 Stainless Steel

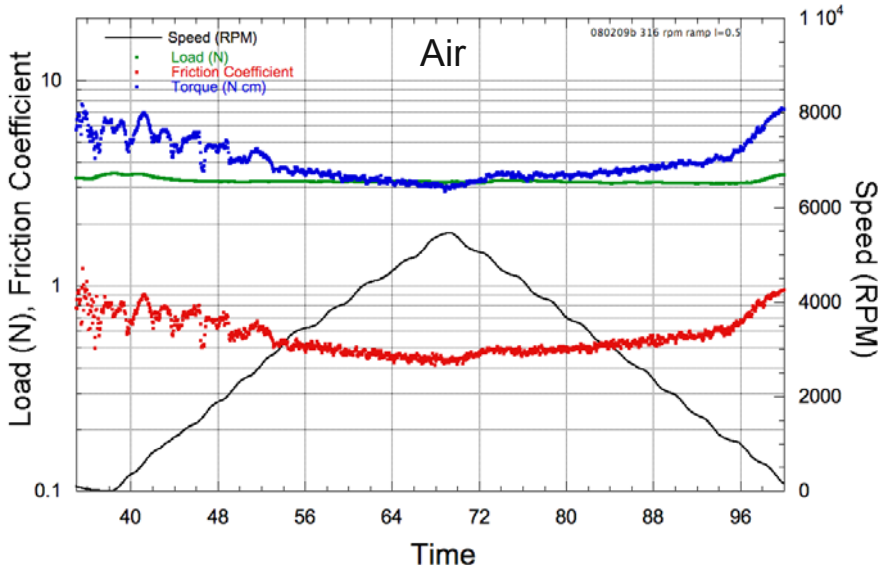
- SS316/SS316 in air has constant friction ~0.4 over loads 2 to 15 N



# 316 Stainless Steel

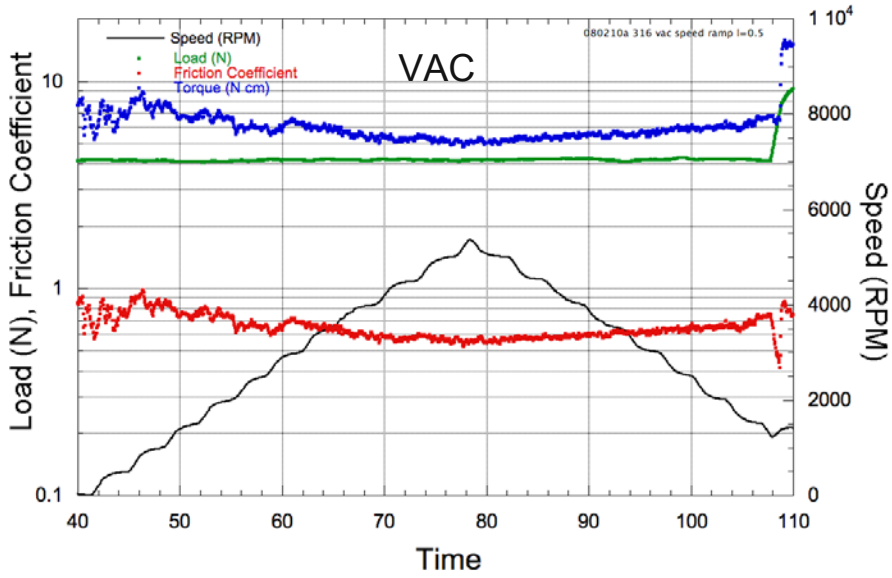
- SS316/SS316 in air (repeated)
  - Lower friction at higher sliding speeds (0.45 vs. 0.9)

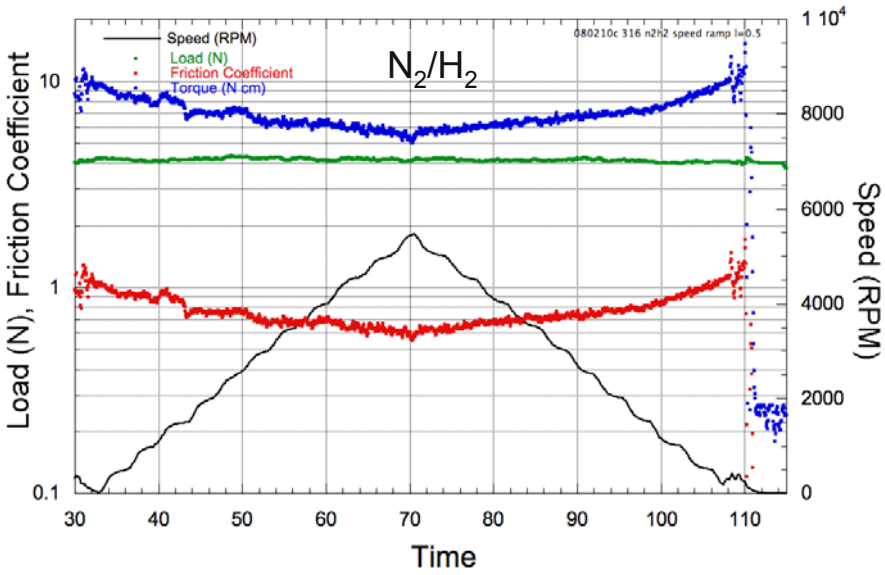


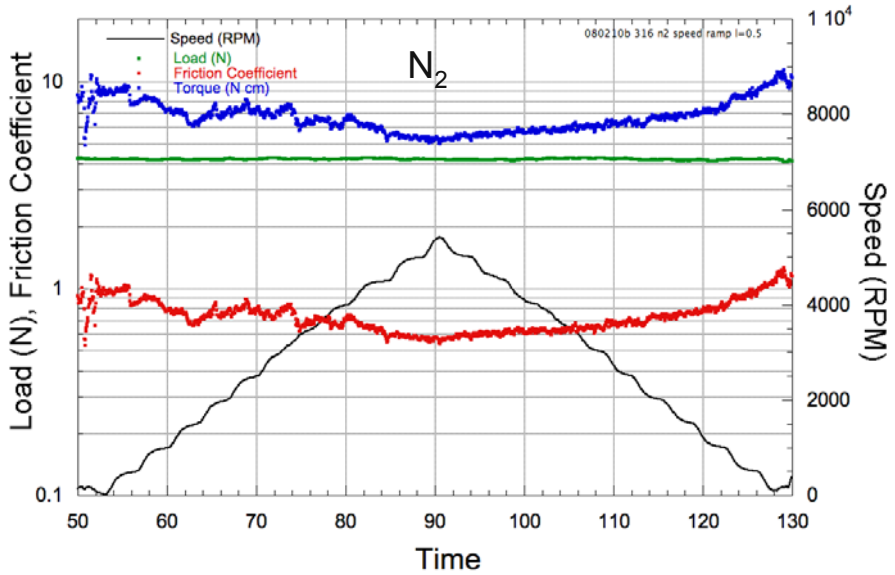



# 316 Stainless Steel

- SS316/SS316 in different environments
  - Lower friction at higher sliding speeds for all gases
  - Higher friction than in air

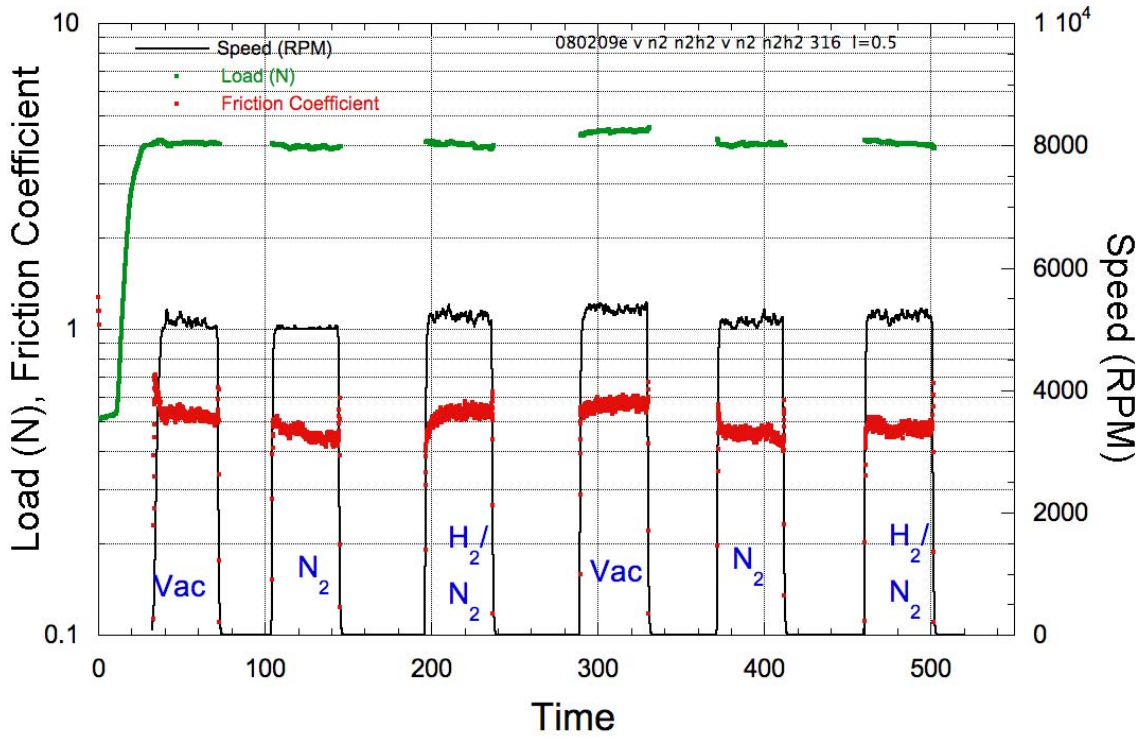


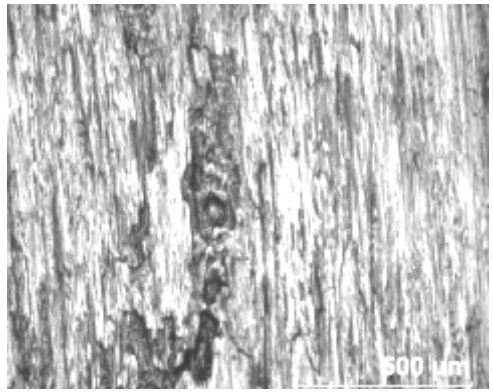
# 316 Stainless Steel

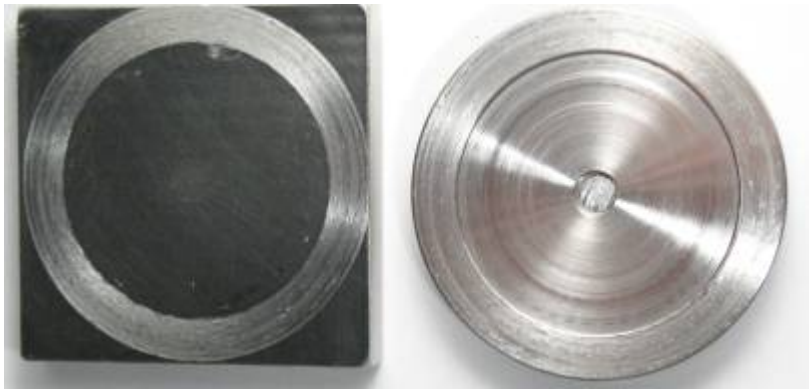
- SS316/SS316 in different environments

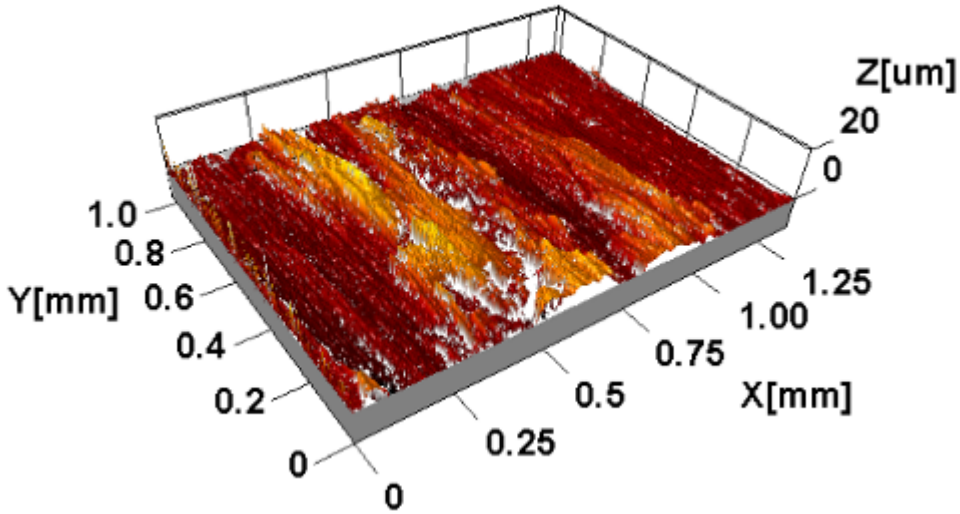


# 316 Stainless Steel

- Post test examination
  - Galling and roughening
  - 2.2 µm Ra

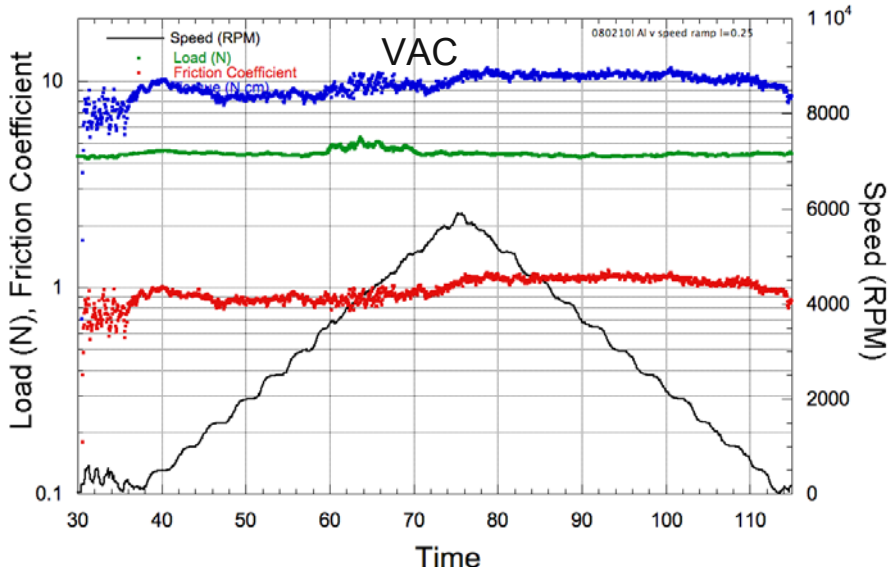


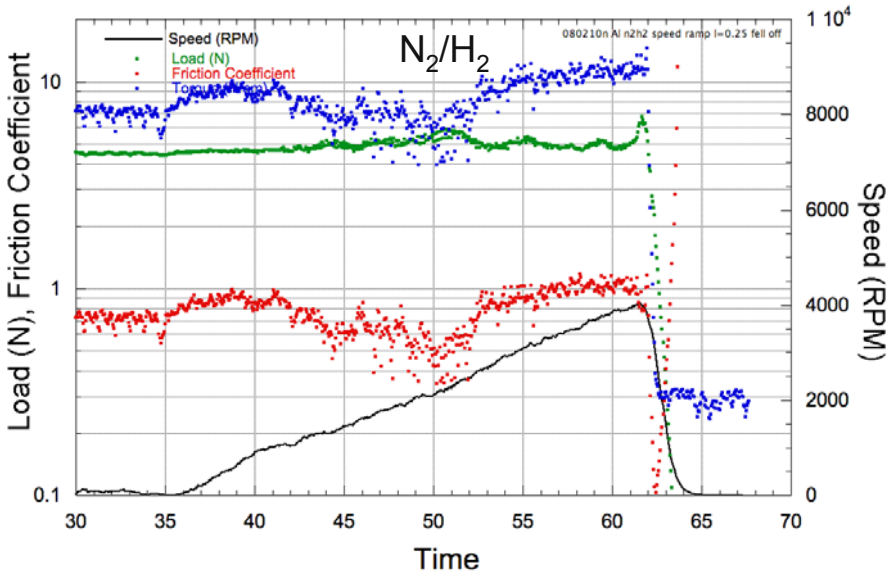



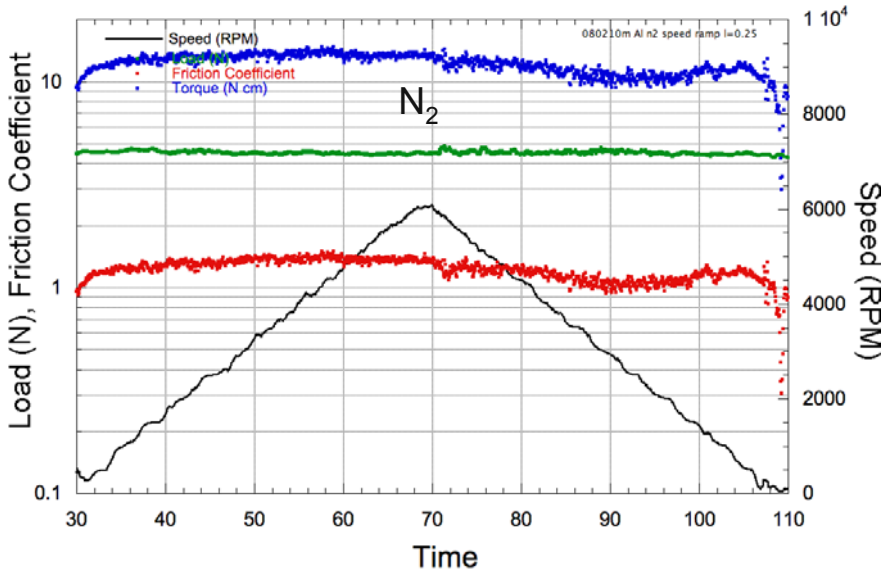


# 6061 Al

- 6061 Al / 6061 Al
  - High friction (to 1.4)
  - Seizure of sliding parts in $N_2/H_2$

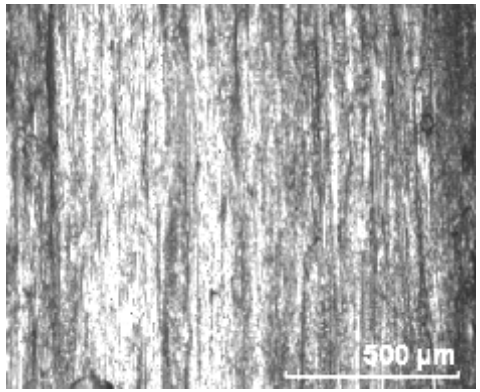


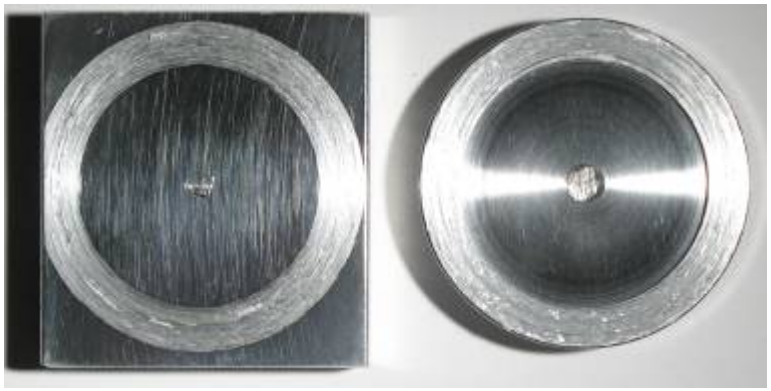



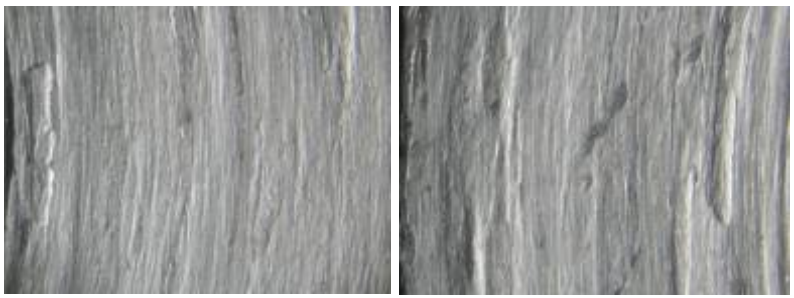



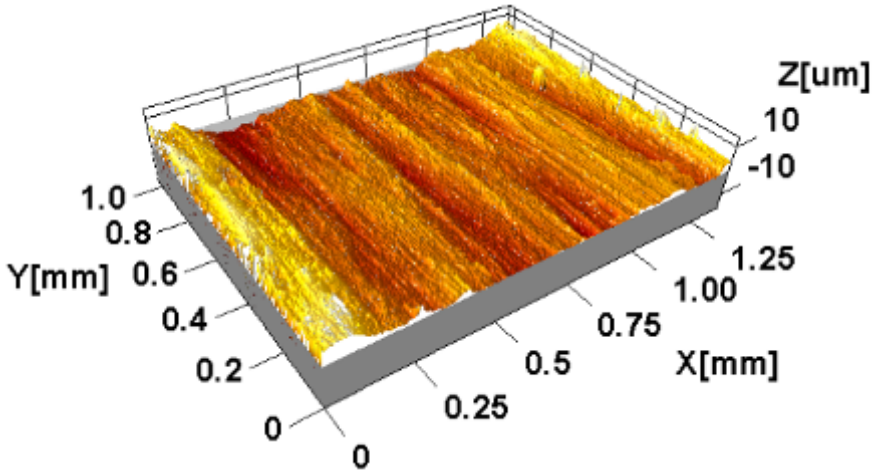
# 6061 Al

- Post test examination
  - Deformation and transfer
  - 1.8 µm Ra



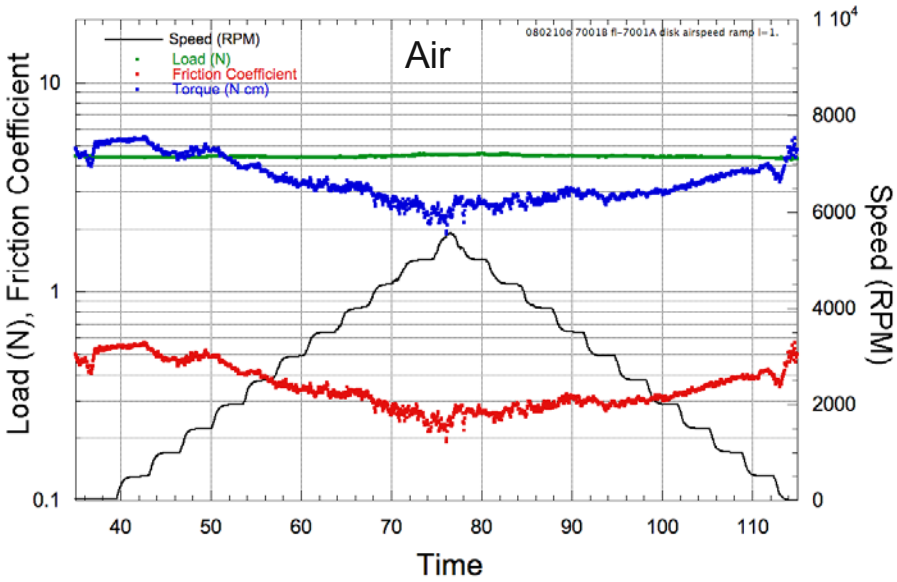



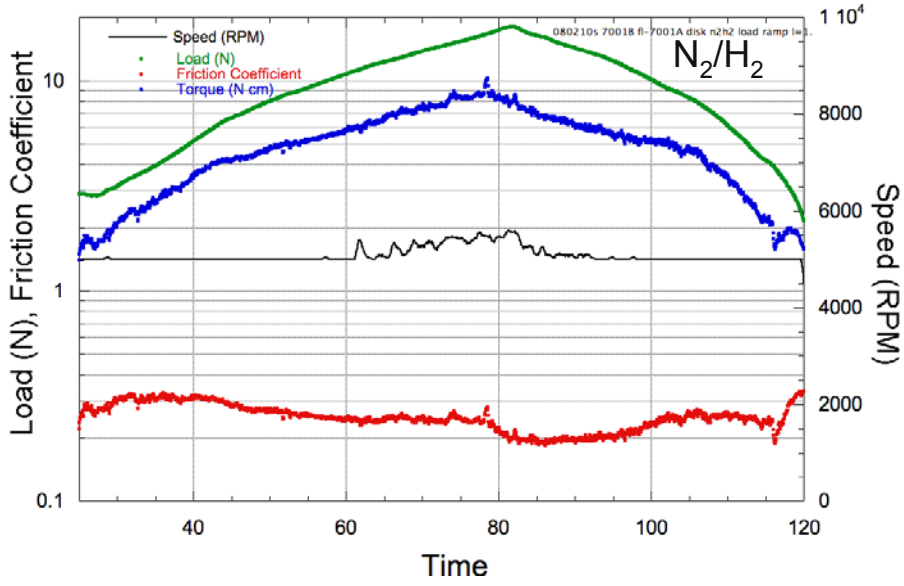




# $MoS_2$ coating

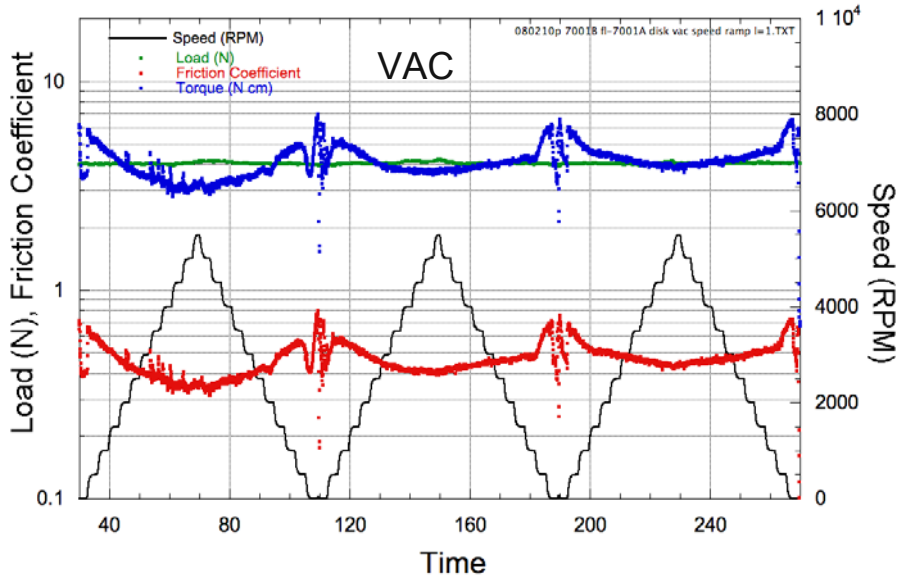
- Higher friction at lower speeds (0.25 vs. 0.5)
- Dependence on load is changing (3-18 N), due to progressive wear and wear-in

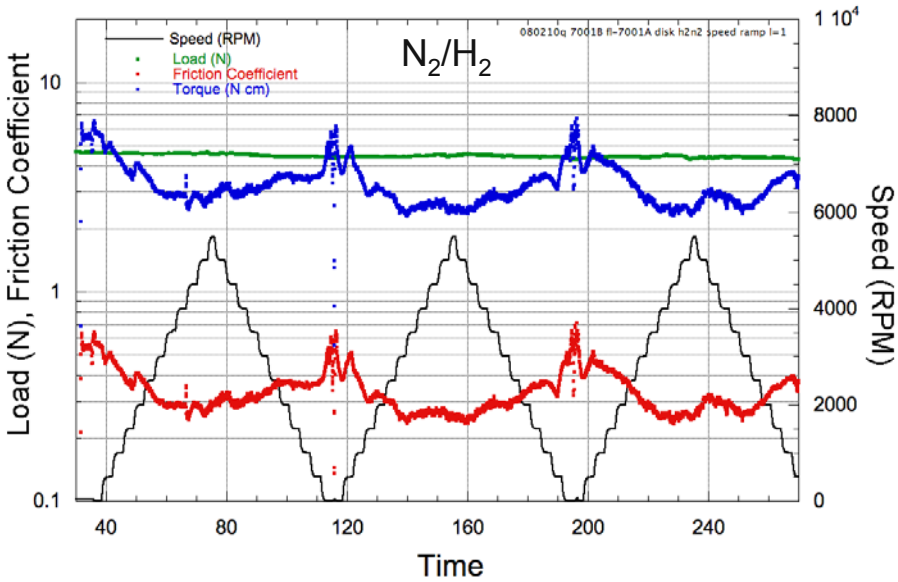


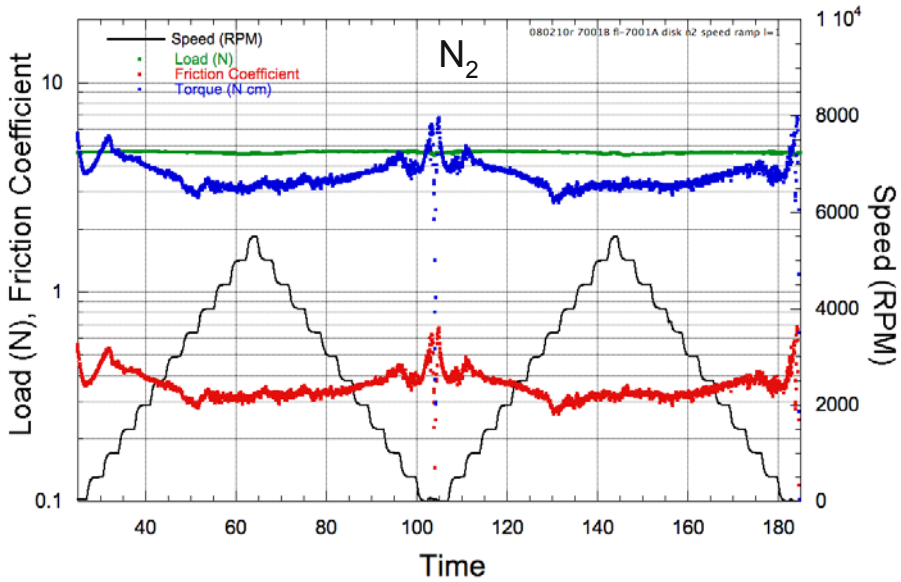



# $MoS_2$ coating

- Lower friction at higher speeds
  - Low friction (≈ 0.2-0.6)

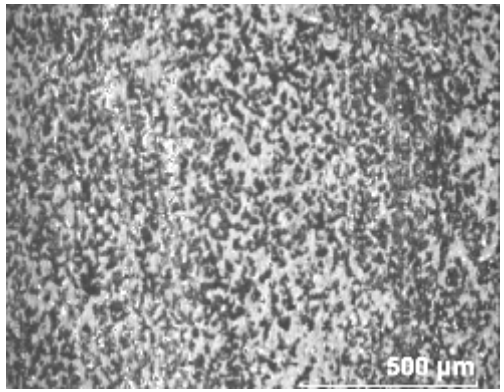


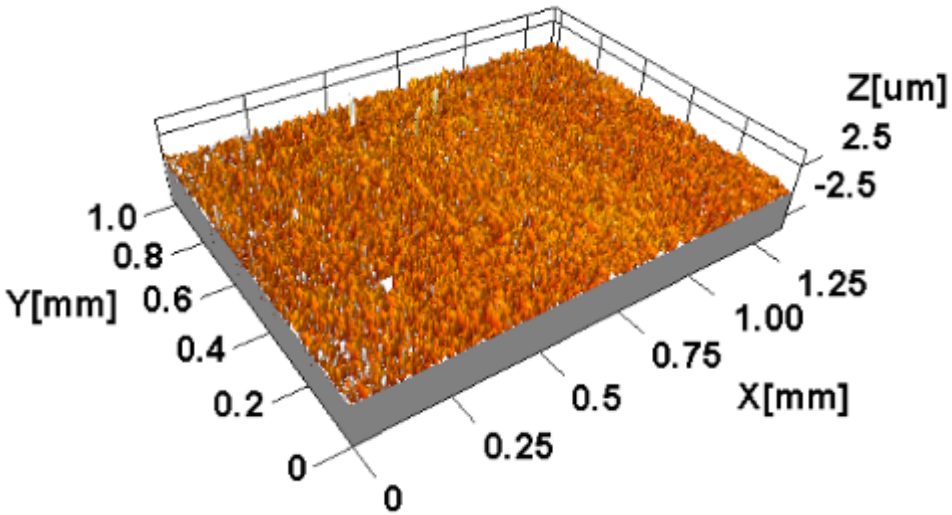



# $MoS_2$ coating

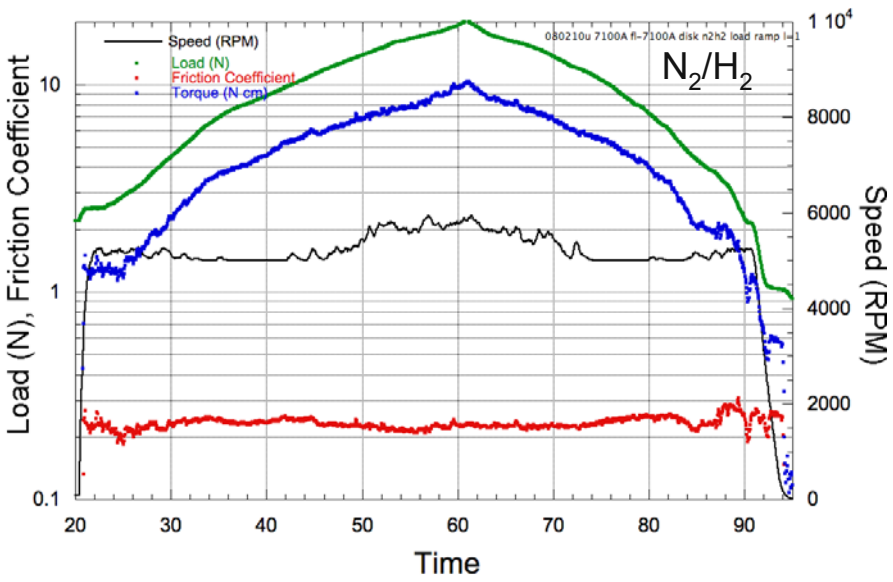
- Post test examination
  - Burnishing, removal of coating
  - 0.3 µm Ra roughness

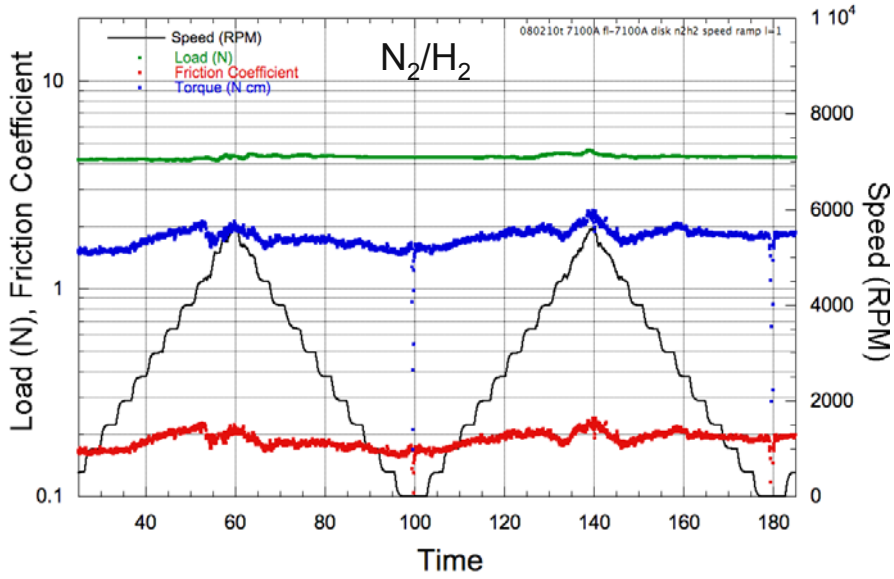


# $MoS_2$ bonded topcoat

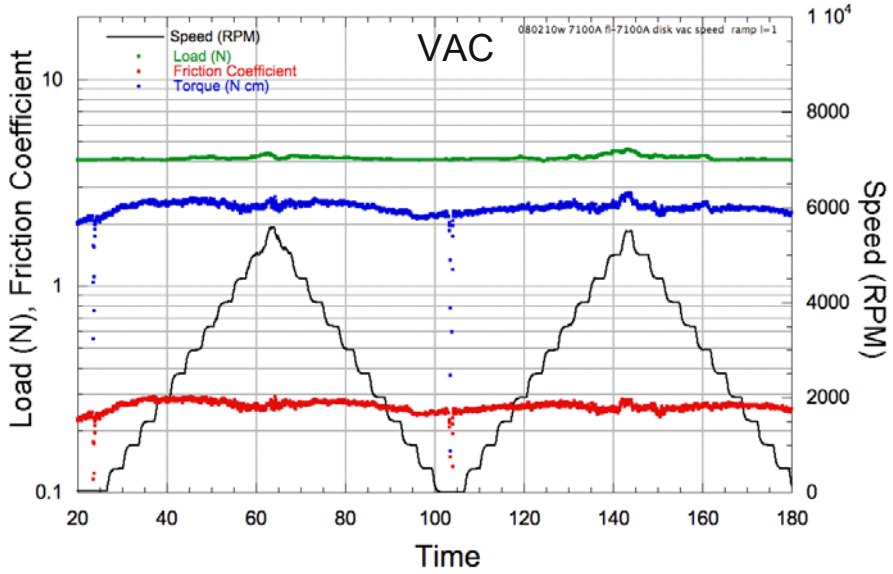
- Constant friction coefficient (≈ 0.25) over range of loads from 2-20 N and sliding speeds

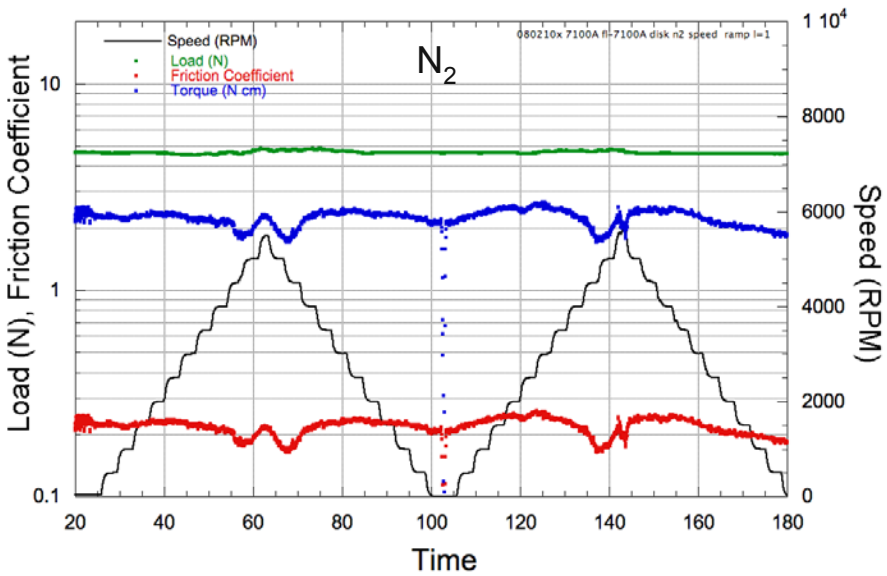


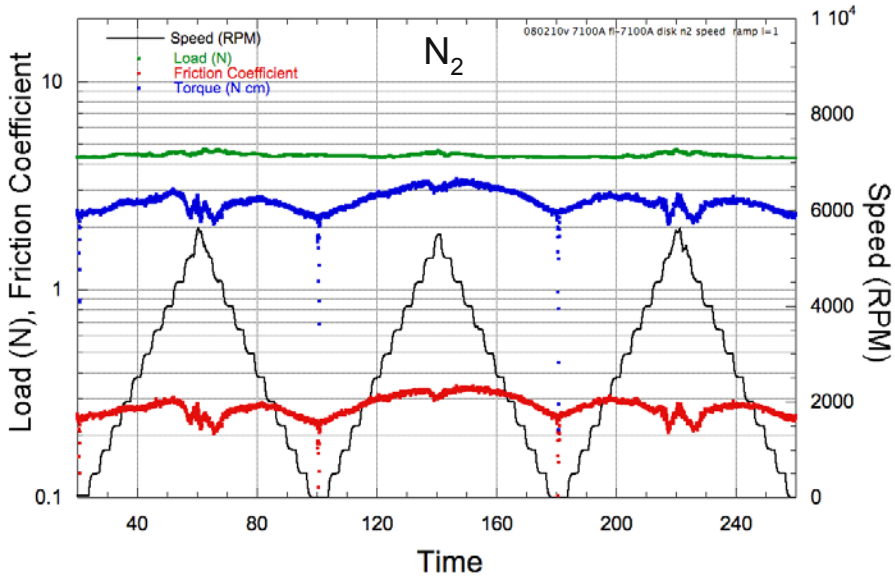



# $MoS_2$ bonded topcoat

- Friction coefficient low over range of speeds, higher in $N_2$
- Fluctuations likely due to machine vibrations

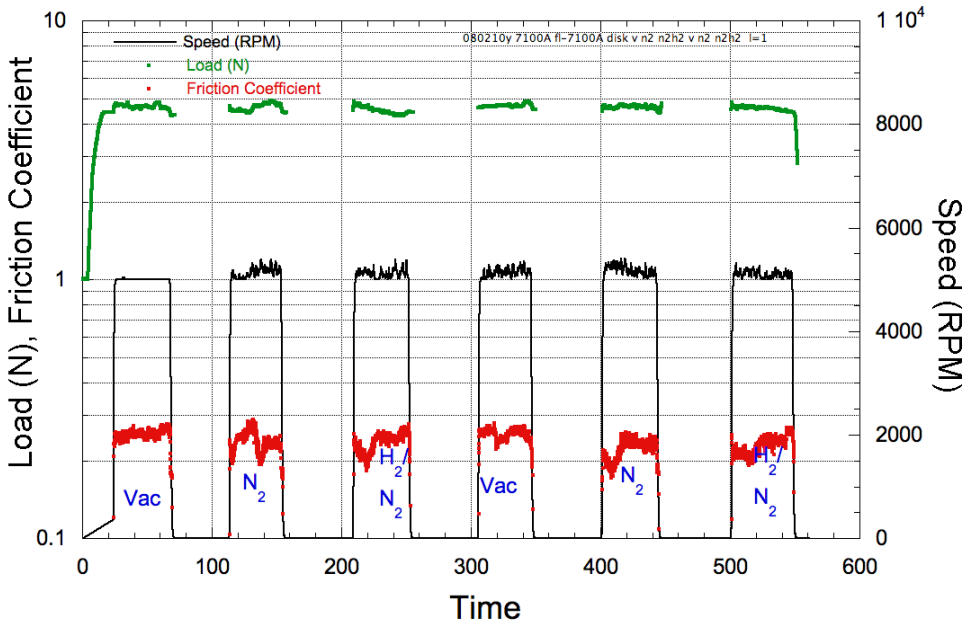


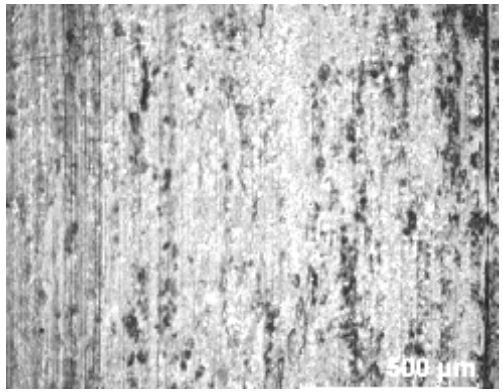



# $MoS_2$ bonded topcoat

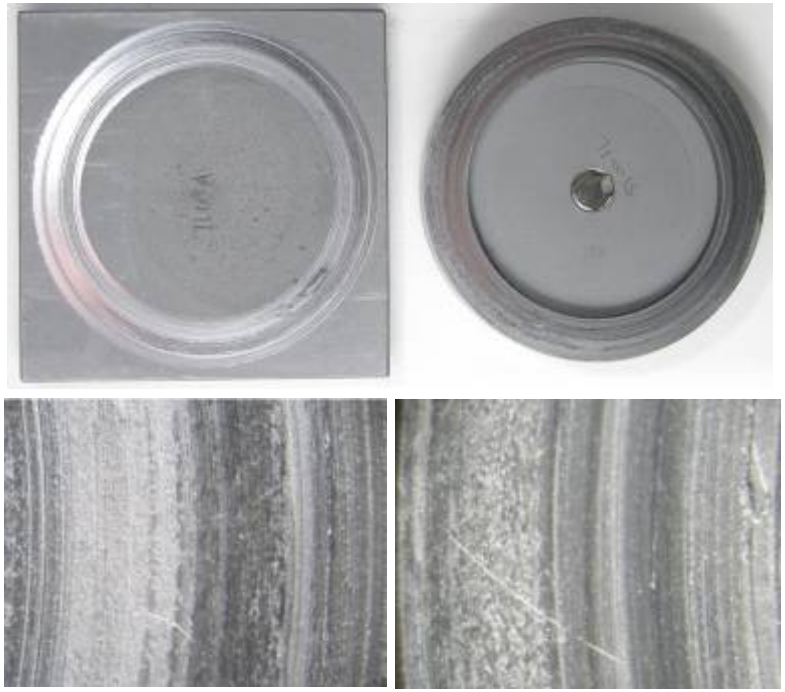
- Friction coefficient low for measured conditions

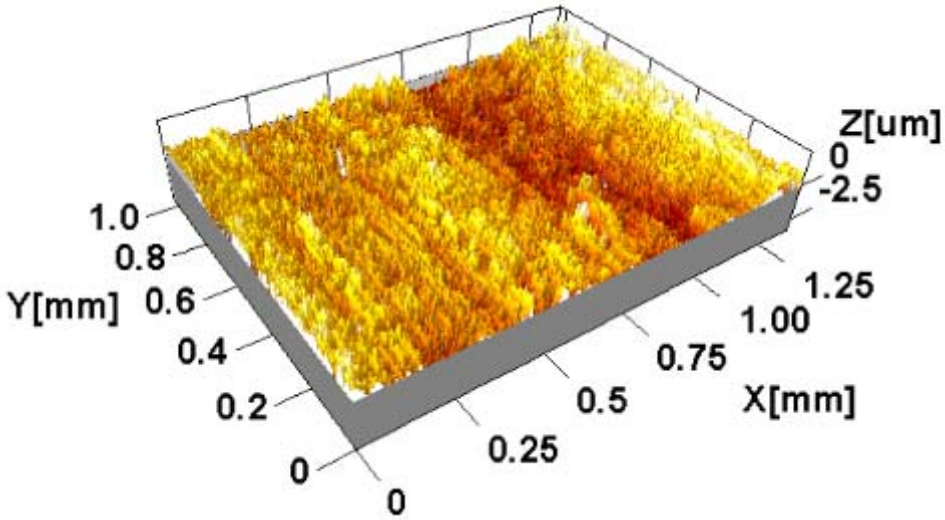


# $MoS_2$ bonded topcoat




- Post test examination
  - Burnishing, removal of coating
  - 0.5 µm Ra roughness





# Summary friction

- Friction table

| Material | Air | $N_2$ | $N_2/H_2$ | Vacuum |
|---|---|---|---|---|
| Ni alloy type X-750 | 0.5 - 0.9 | 0.5 - .9 | 0.6 - 1 | 0.5 - .9 |
| Al alloy type 6061-T6 | - | 1-1.5 | 0.5- | 0.8-1.2 |
| Ti-6Al-4V | 0.4 | ~0.5 | ~0.5 | 0.5-0.6 |
| 316 type stainless steel | 0.4-0.9 | 0.6-1 | 0.6-1 | 0.5-0.8 |
| $MoS_2$ coated X-750 | 0.25-0.5 | 0.3-0.6 | 0.25 | 0.3 |
| $MoS_2$ bonded X-750 | - | 0.2-0.25 | 0.25 | 0.3 |
| Argonne DLC type 6 | 0.1 | 0.04 | | |

# Summary

- For slow sliding, high contact stress
  - uncoated metals in air: expected high wear and friction coefficient typical of sliding metal surfaces; in hydrogen: large transfer wear and larger friction coefficient
  - DLC coated materials in air: negligible wear and low friction (equivalent to oil-lubricated surfaces); in hydrogen: negligible wear and very low friction
- For medium-speed sliding
  - Friction coefficient largely independent of load for loads used (2-20 N)
  - High friction coefficient for metal/metal sliding in all atmospheres; seizure for Al in $H_2/N_2$
  - Smallest friction coefficients for solid lube coating

# *Acknowledgements*


- Work supported by the Department of Energy / Office of Energy Efficiency and Renewable Energy / Hydrogen, Fuel Cells and Infrastructure Program / Hydrogen Delivery, under Contract DE-AC02-06CH-11357