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

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Materials Innovations in an Emerging Hydrogen Economy
The American Ceramic Society and ASM International
Cocoa Beach, FL

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U.S. Department
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Challenges

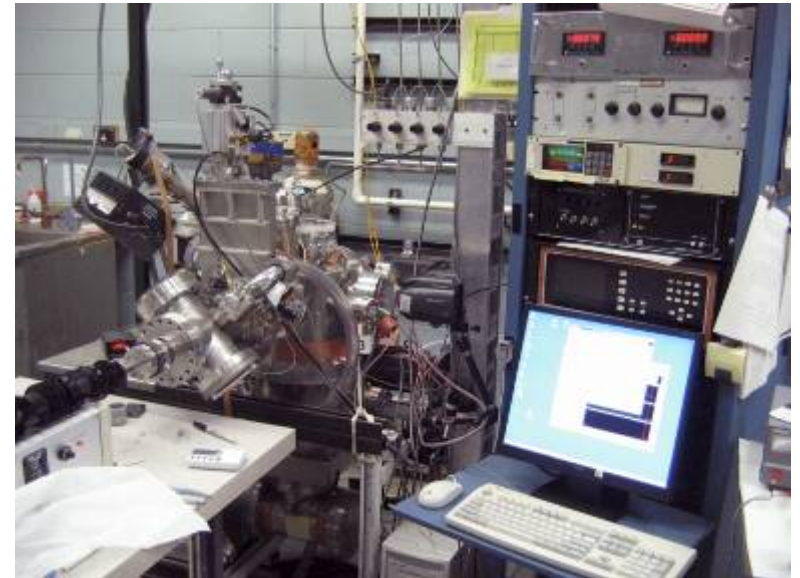
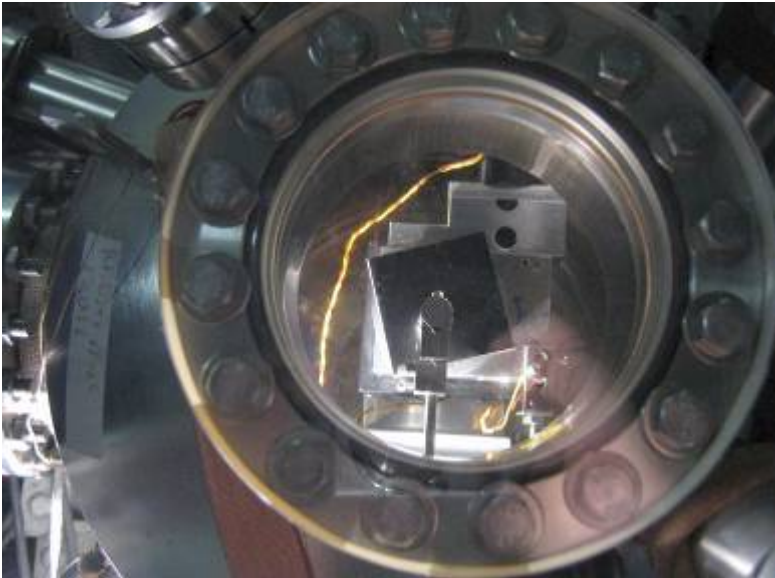
- Moving/sliding mechanical components used in hydrogen service can be subject to excessive wear, have poor reliability, or may require the use of lubricants that can contaminate the hydrogen
- Conventional lubrication of compressor components/bearings with oil or grease may not be possible or desirable - 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 H₂, and 2) thrust-washer configuration sliding at medium speed in N₂/H₂ (H₂ future)
- Materials - SS, Ti, Ni, Al, DCL; MoS₂ coatings
 - future: carbide-derived carbons, fluorides, solid lube coatings

Preliminary Tests - slow speed

- Controlled environment/vacuum ball-on-disk tribometer



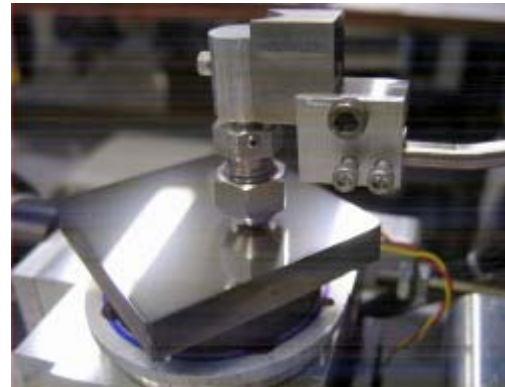
Preliminary Tests - slow speed

- Ball-on-flat test geometry
- X-750 nickel-base alloy flats, M-50 balls
 - Metal/metal or DLC/DLC
 - DLC - PACVD using 25% CH₄/ 75% H₂ gases at RT

Alloy: Inconel X-750

Nominal Composition in Percent:

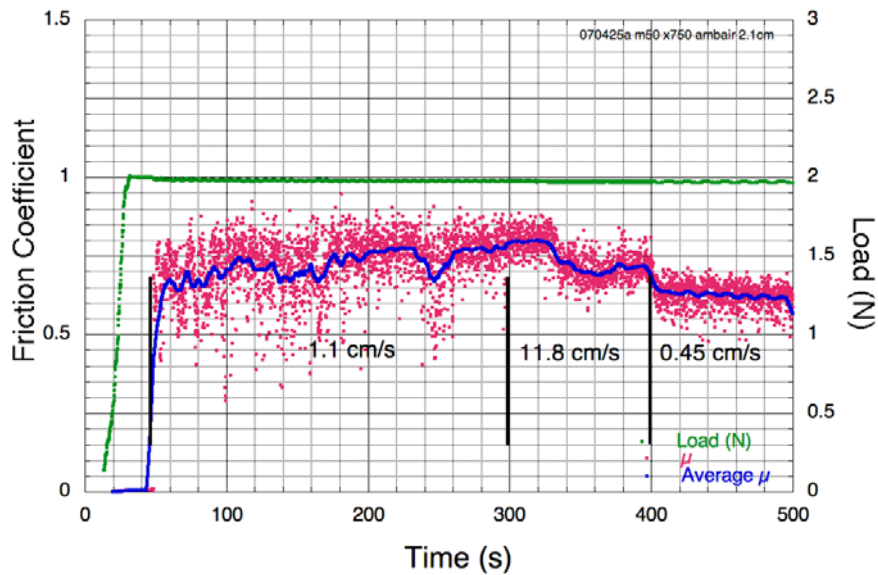
| | |
|-------|-------|
| Ni | 70.00 |
| Co | 1.00 |
| Cr | 15.50 |
| Fe | 7.00 |
| Si | 0.50 |
| Mn | 1.00 |
| C | 0.080 |
| Al | 0.700 |
| Ti | 2.500 |
| Cu | 0.50 |
| S | 0.010 |
| Cb+Ta | 0.95 |



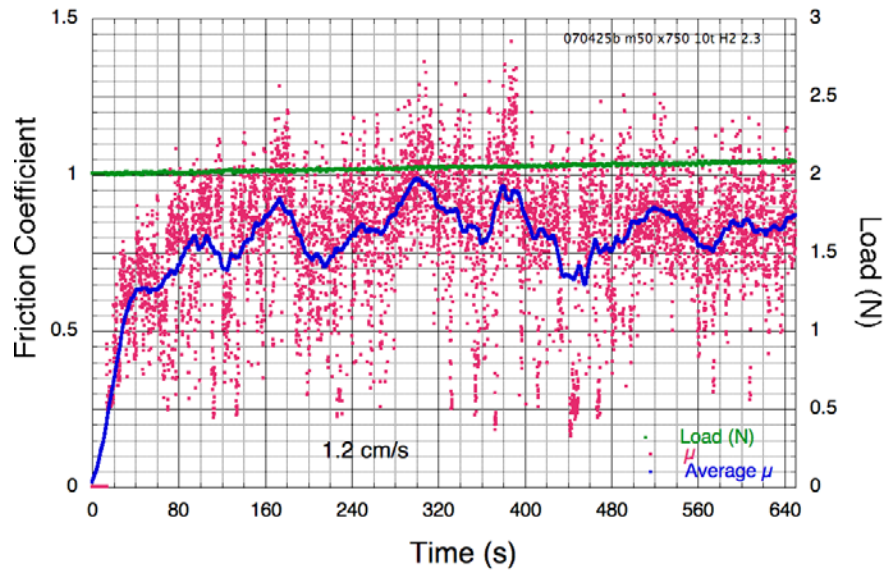
Steel/X-750 in air

- Graphs shows friction as function of testing time for steel against X-750 in air or H₂
 - High friction in ambient air, more erratic in H₂

AMBIENT AIR



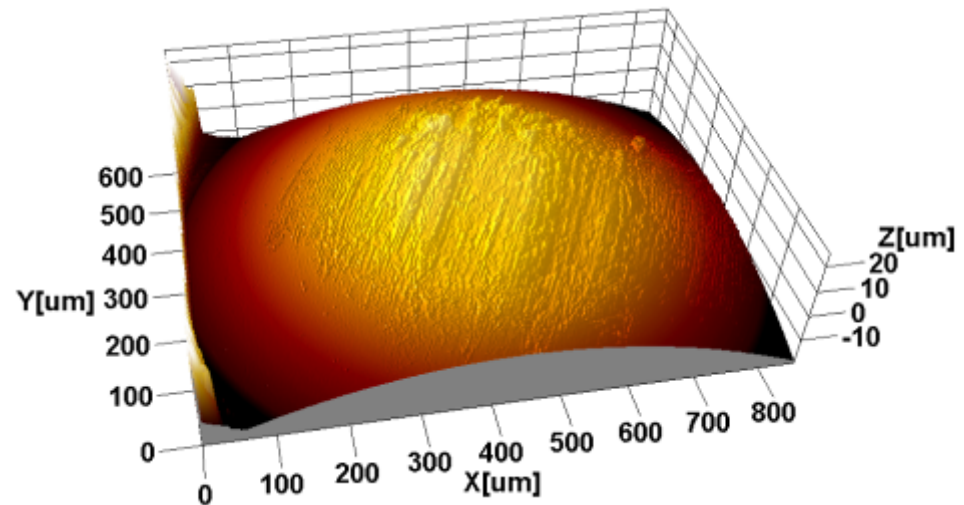
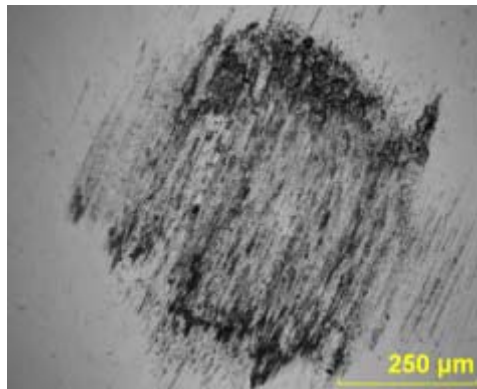
HYDROGEN



Steel/X-750 in air

■ Ball wear

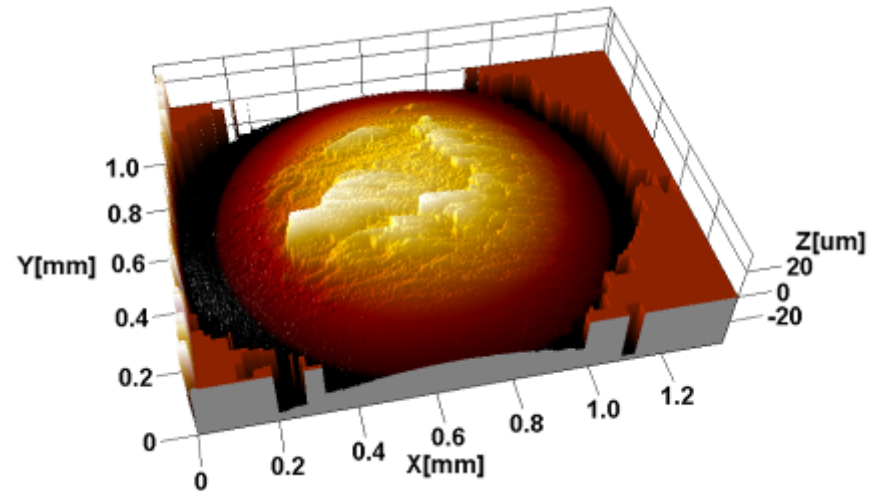
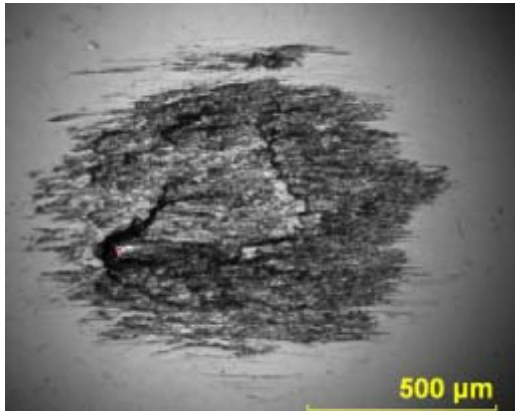
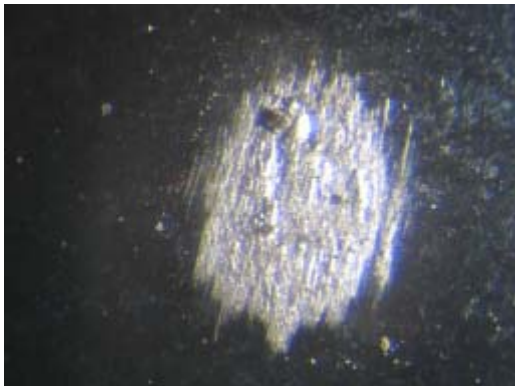
- Moderate wear scar with debris
- Ball scar consists of roughening and fine parallel grooves



Steel/X-750 in 10 torr hydrogen

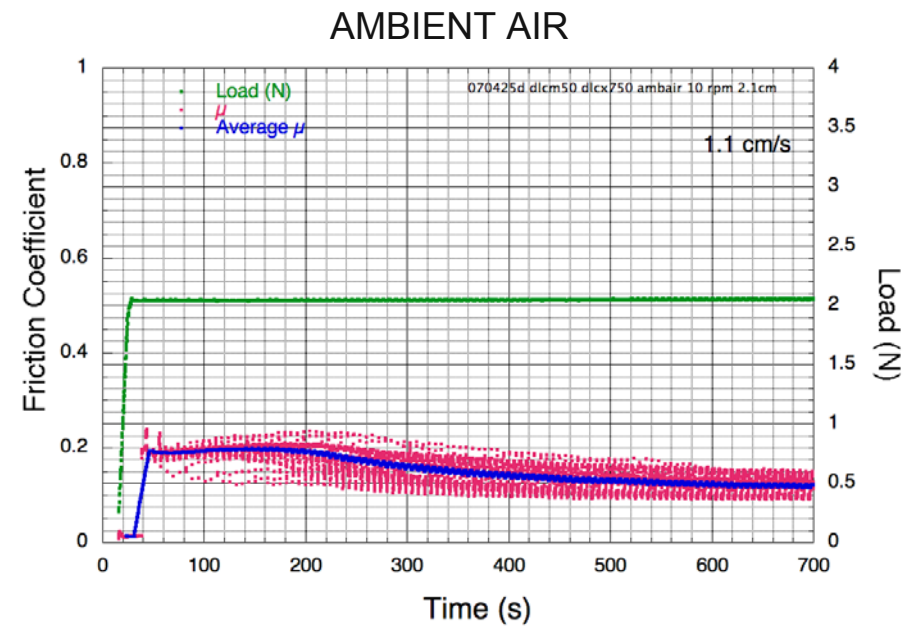
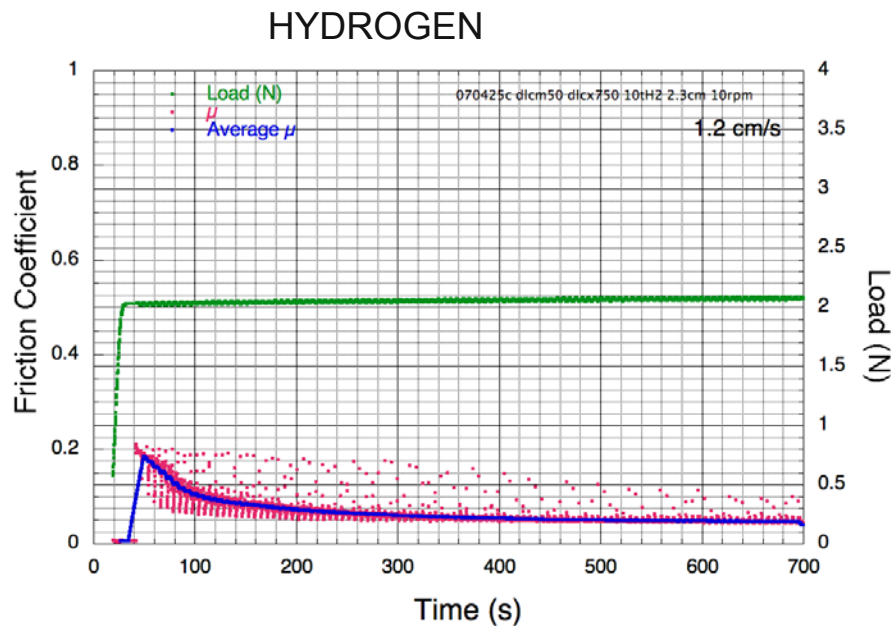
■ Ball wear

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



DLC coated materials in hydrogen or air

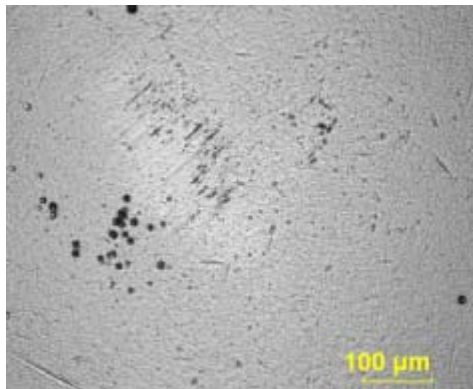
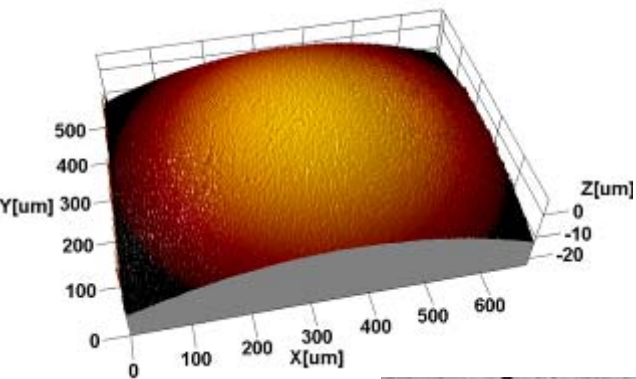
- Graphs shows friction as function of testing time for DLC coated steel against DLC coated X-750
 - Friction is low, with H₂ giving lower friction



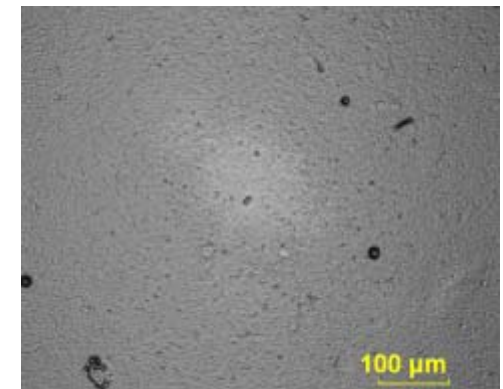
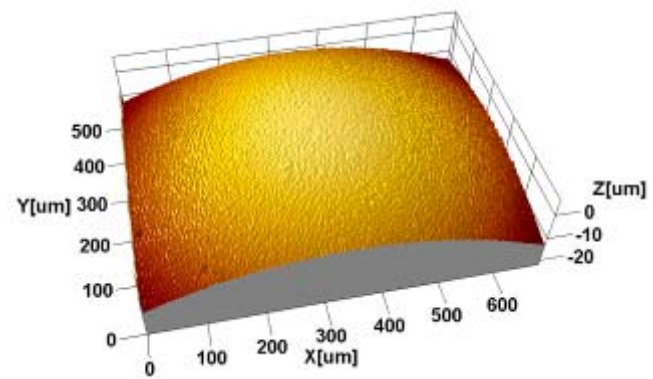
DLC coated steel/DLC coated X-750 in 10 torr hydrogen

- For coated specimens, wear is negligible in either environment

HYDROGEN

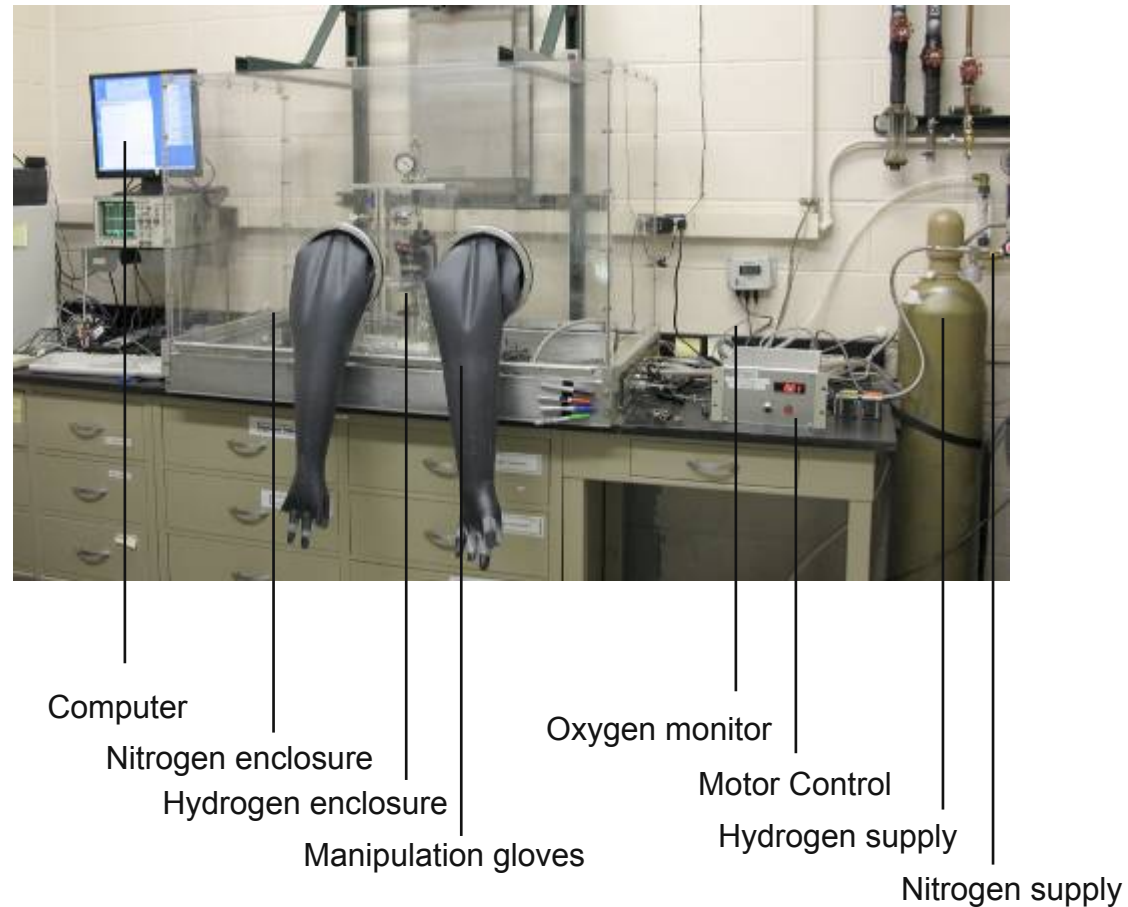
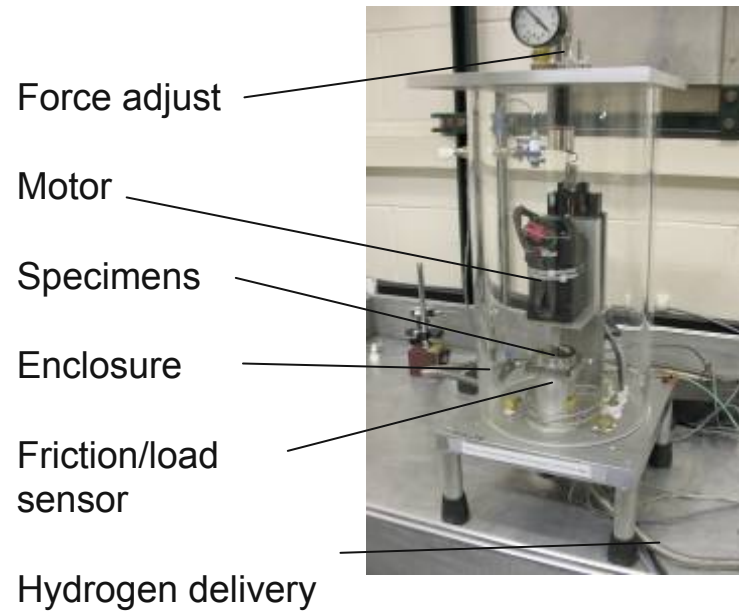


AIR

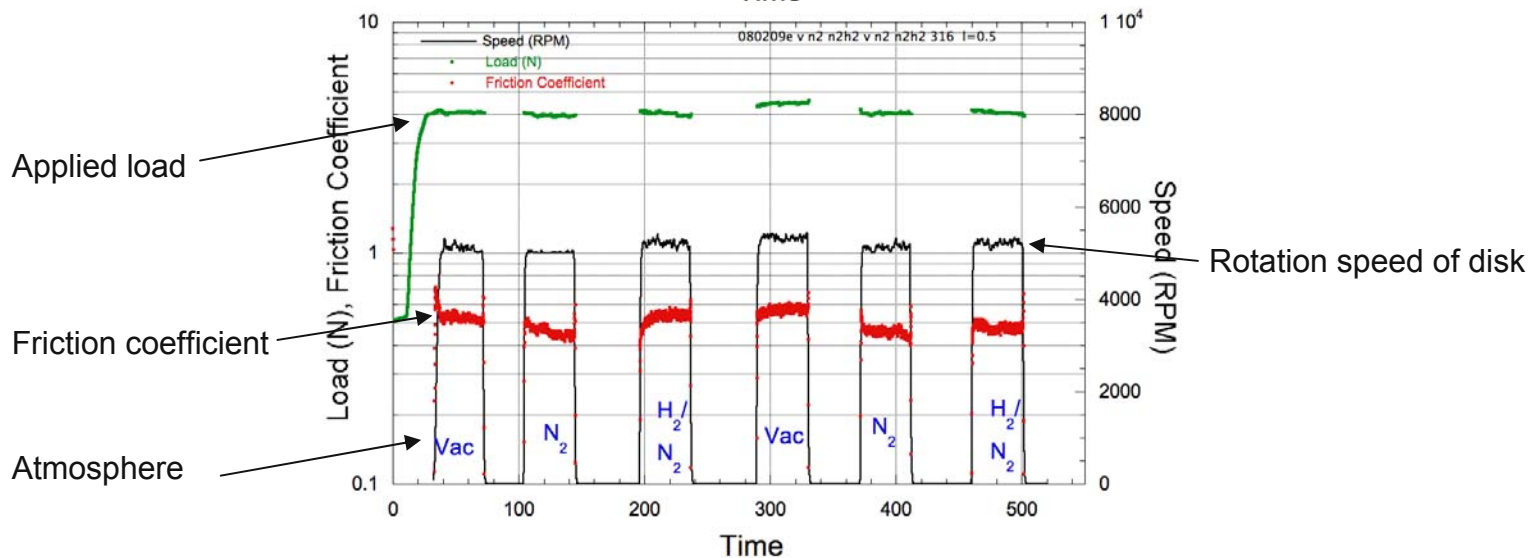
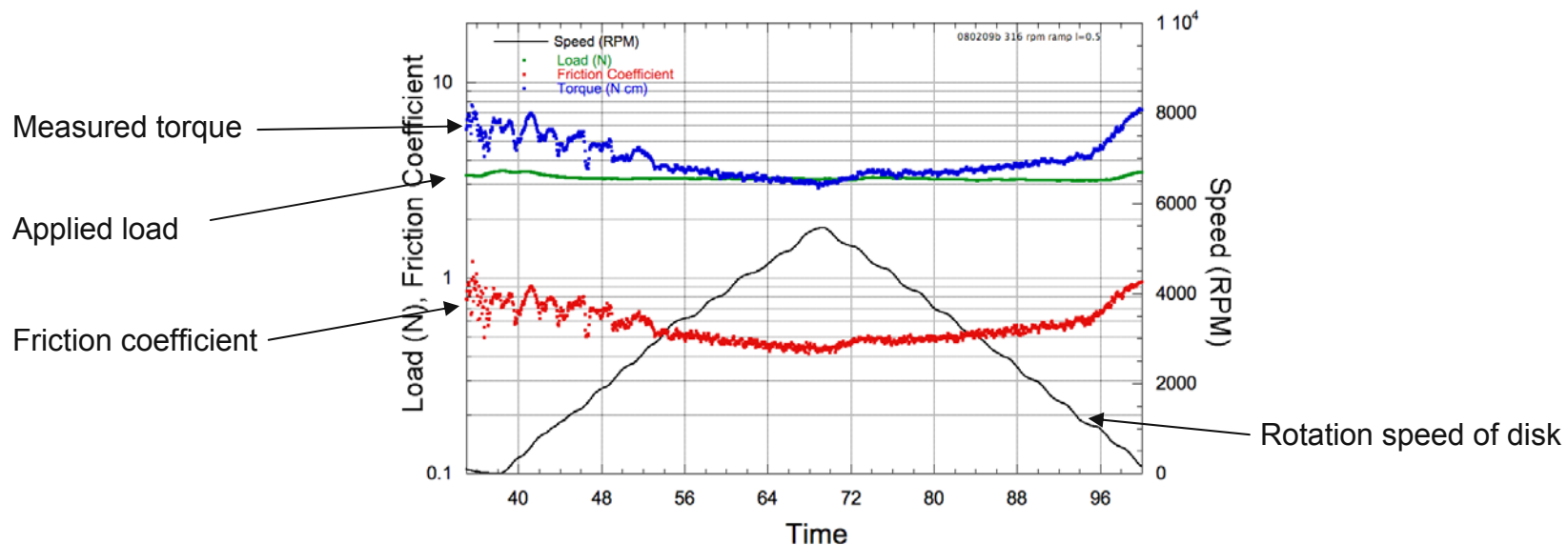


Tests - medium speed

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

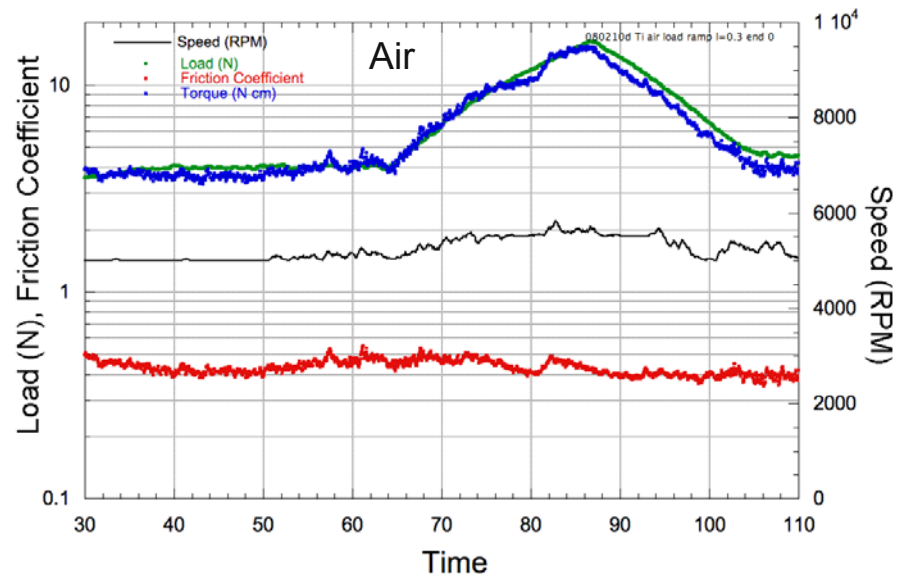
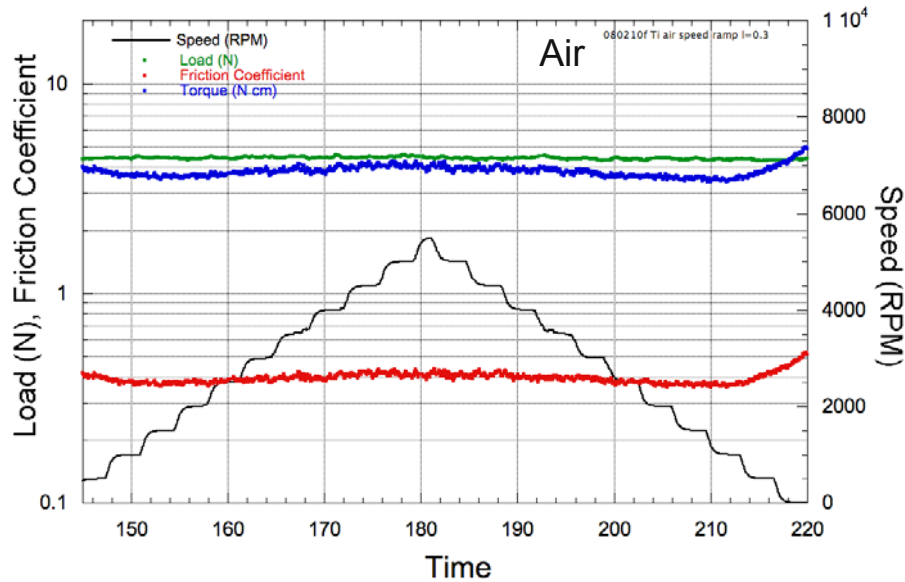


Example - ramped speed, or load



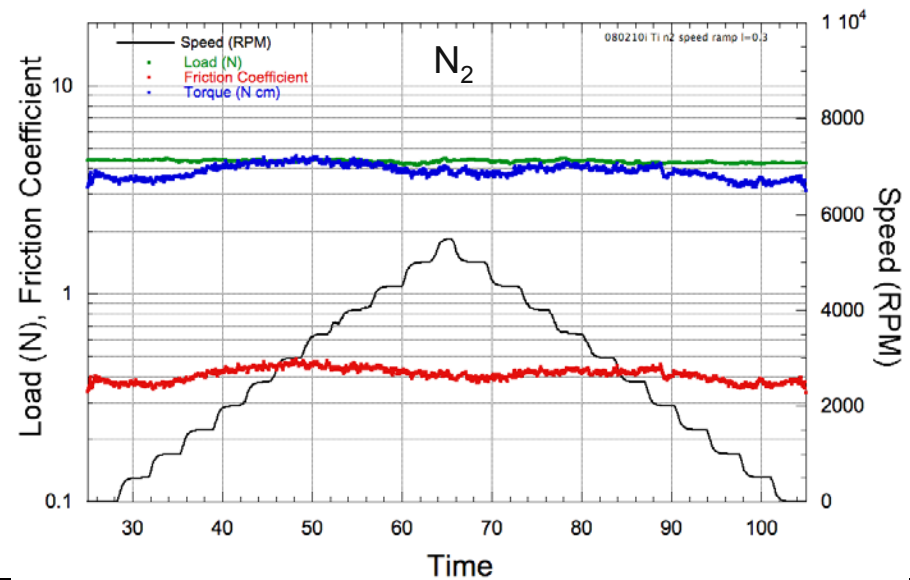
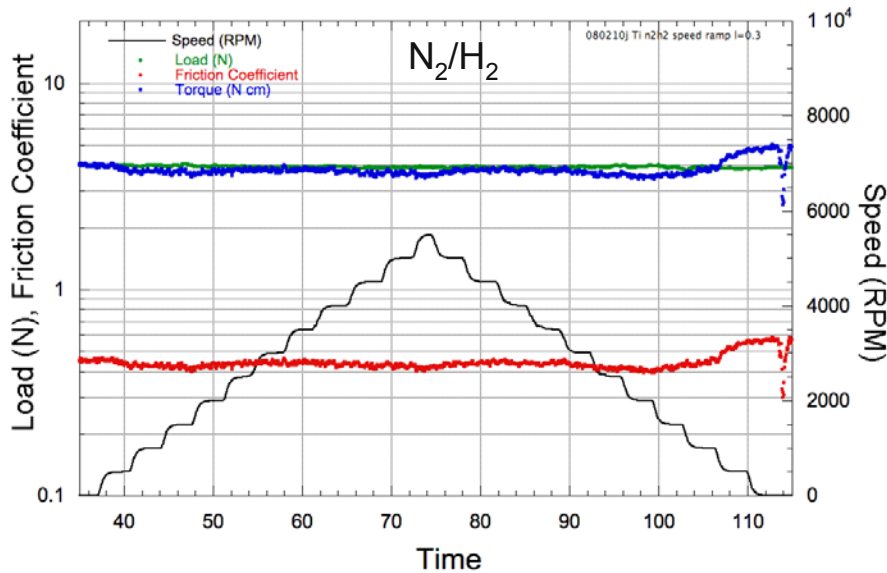
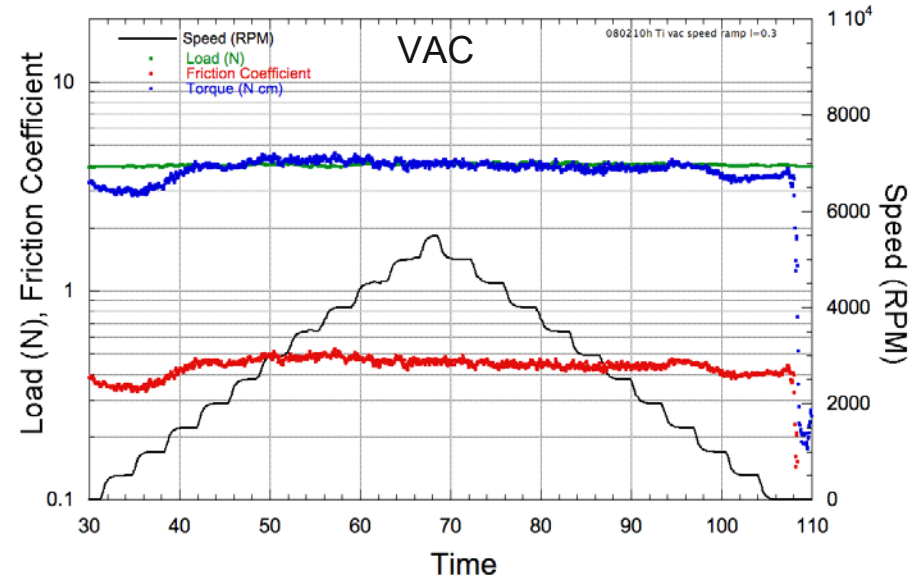
Ti-6AL-4V

- 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)



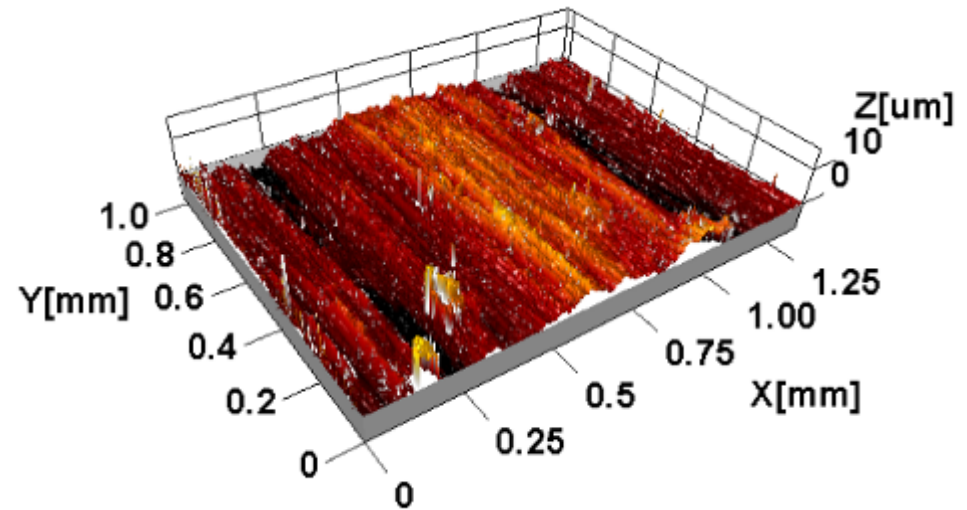
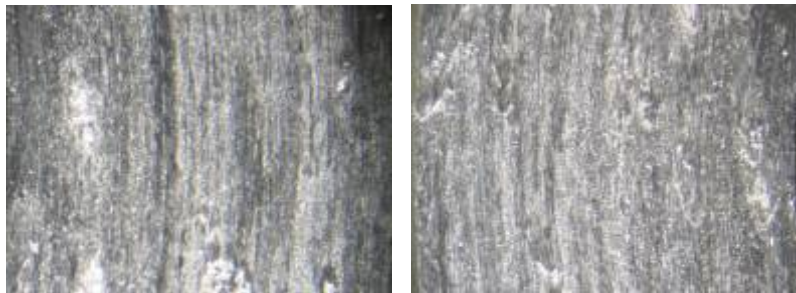
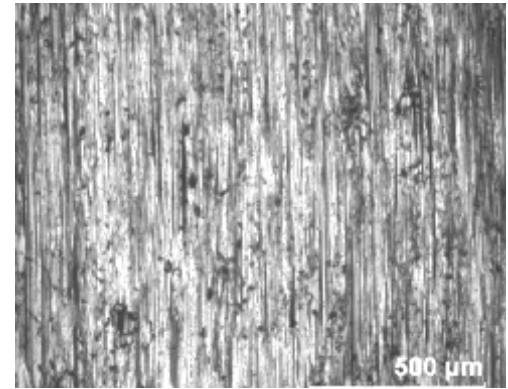
Ti-6AL-4V

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



Ti-6AL-4V

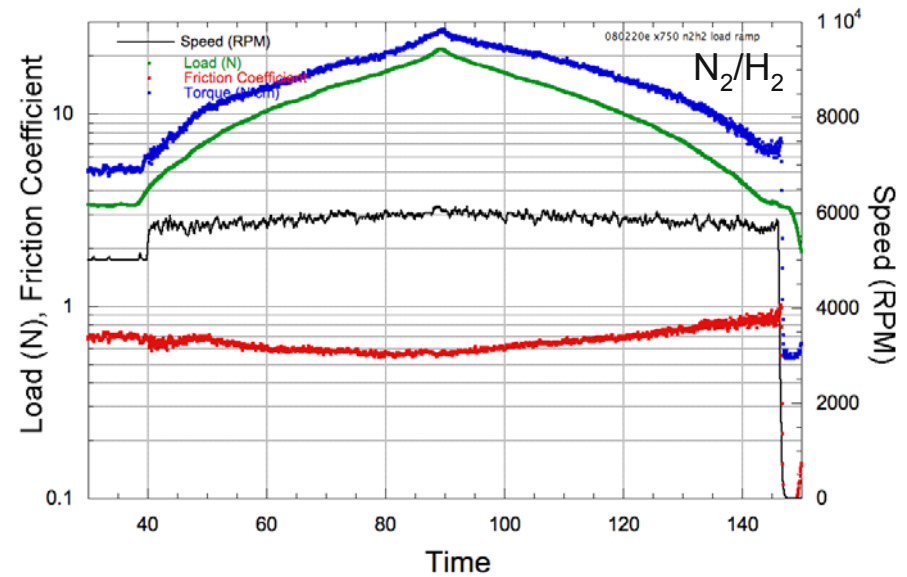
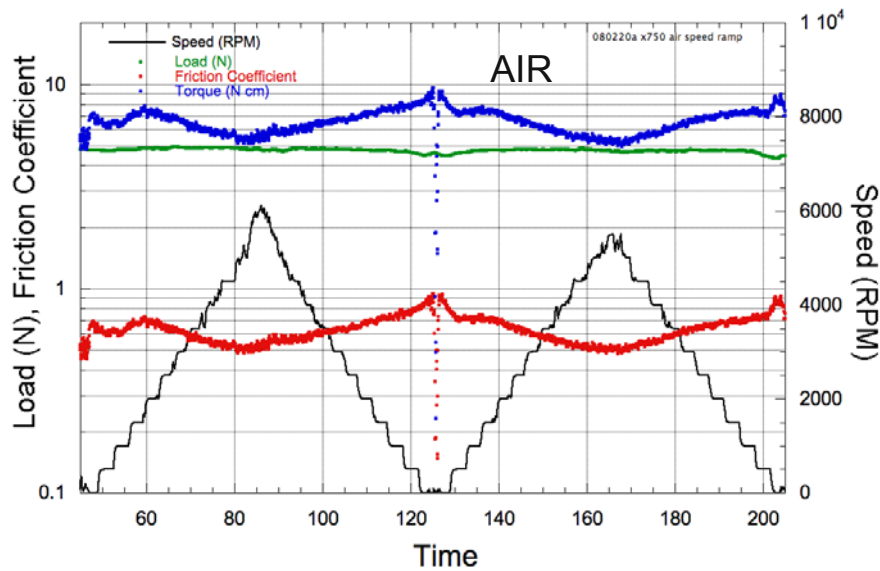
- Post test examination
 - Wear and scuffing
 - 2.1 $\mu\text{m Ra}$



X750/X750

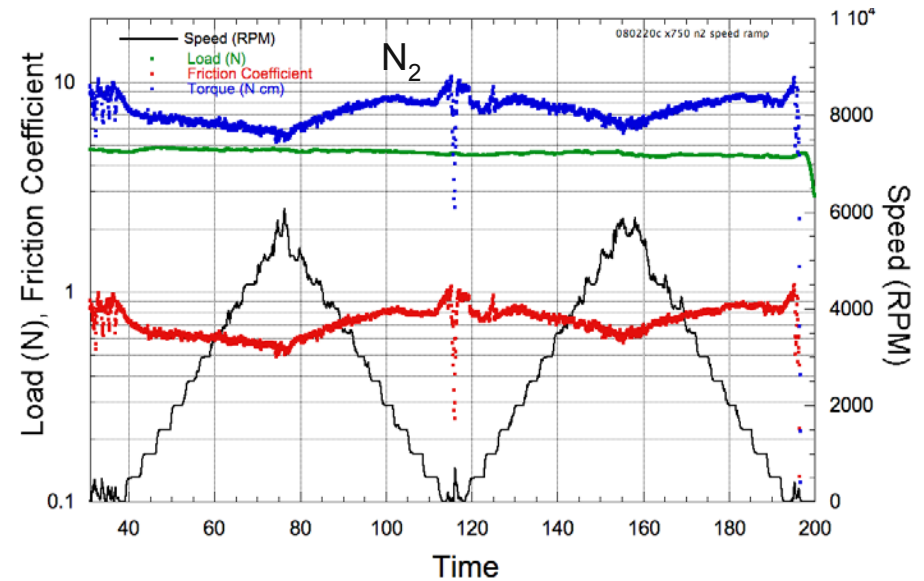
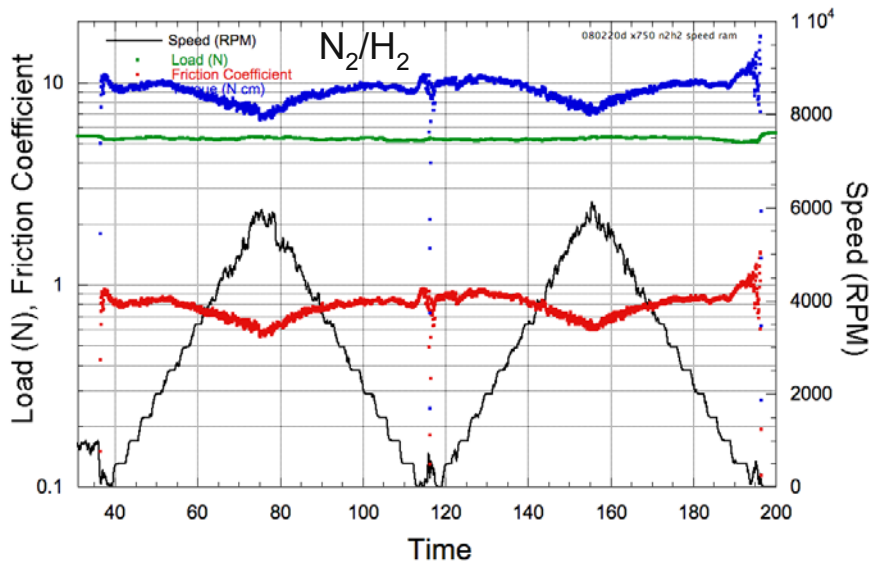
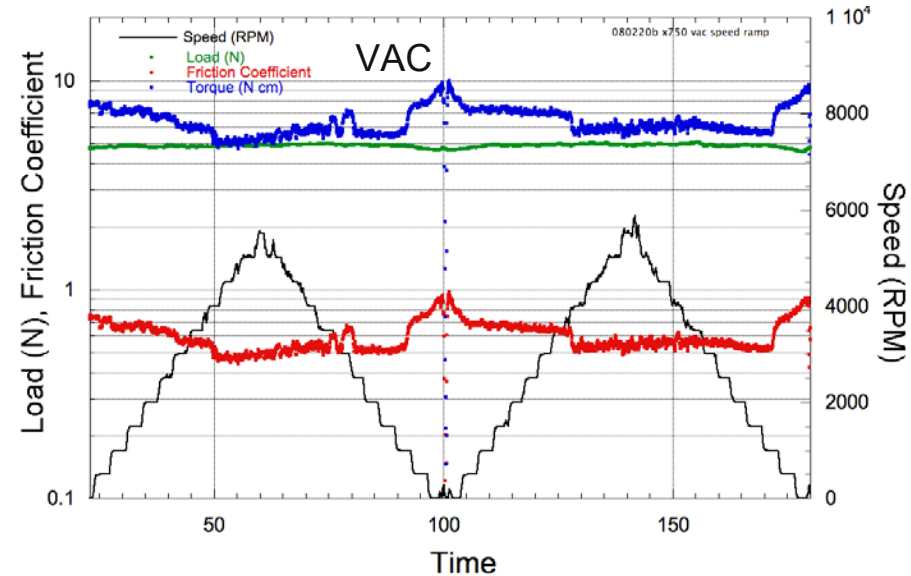
■ X-750/X-750 in air

- 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 N₂/H₂



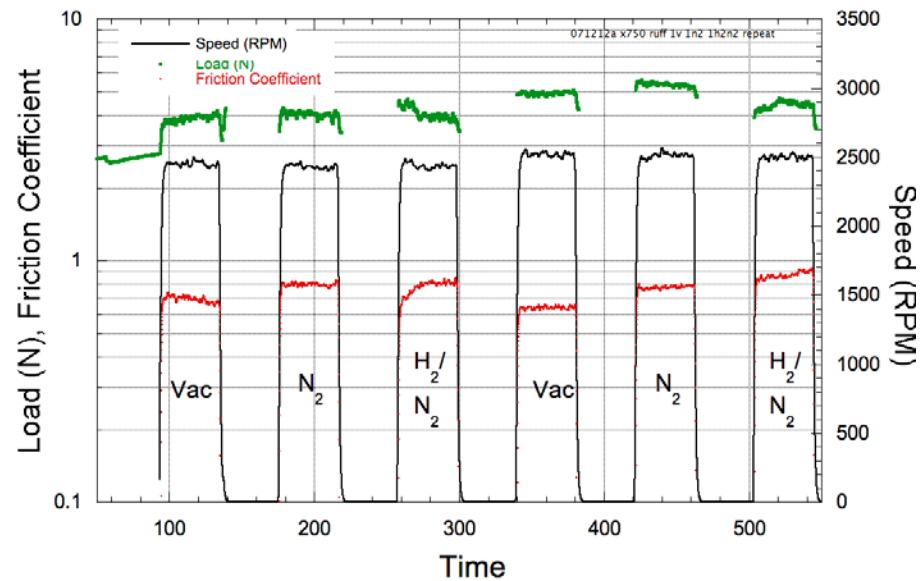
X750/X750

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



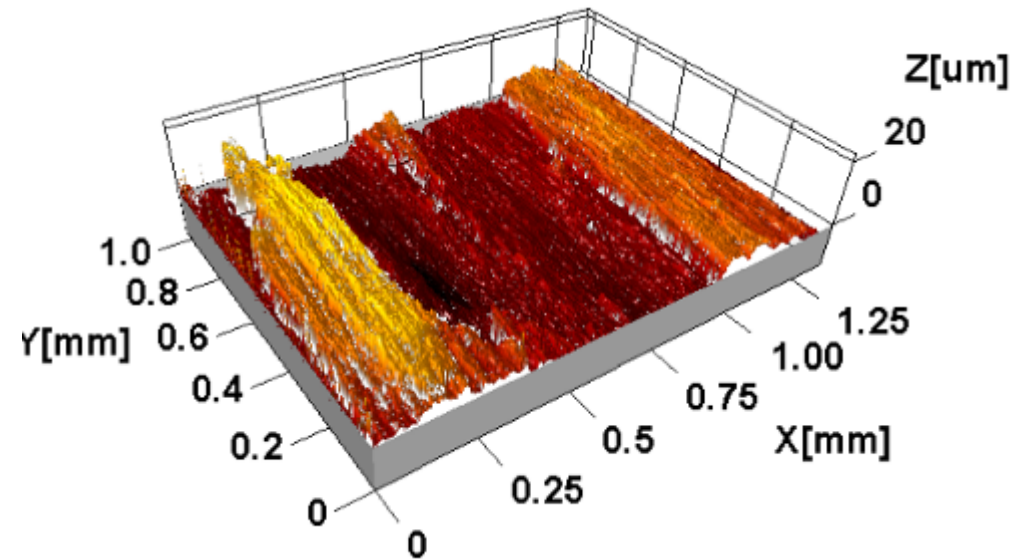
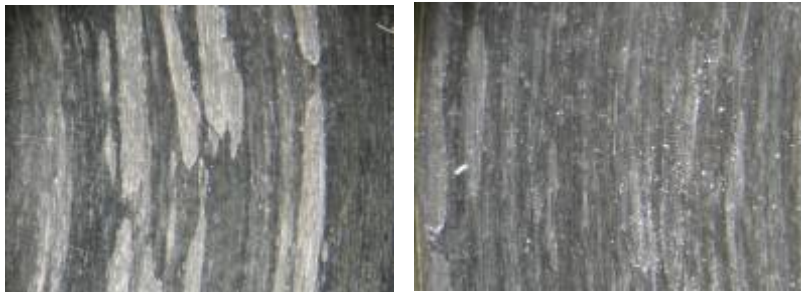
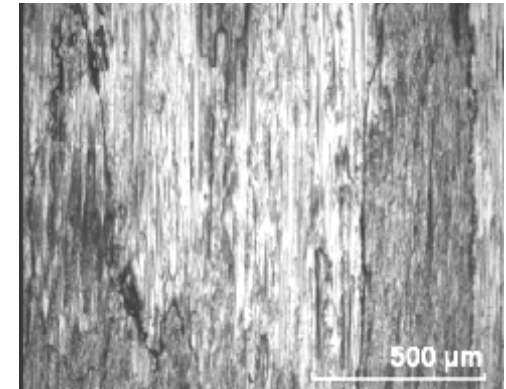
X750/X750

- X-750/X-750 in different environments
 - High friction coefficients (0.5-0.9), lower in vacuum and higher in N₂/H₂



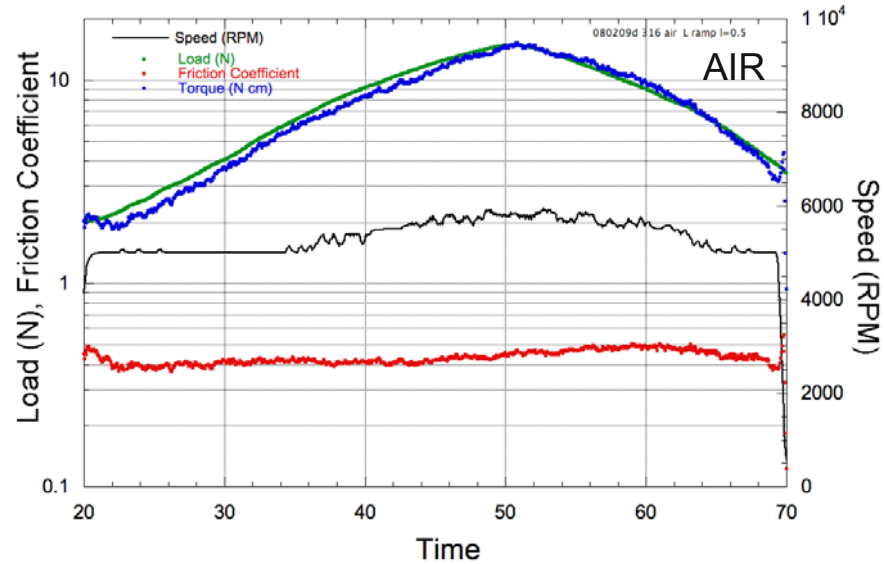
X750/X750

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



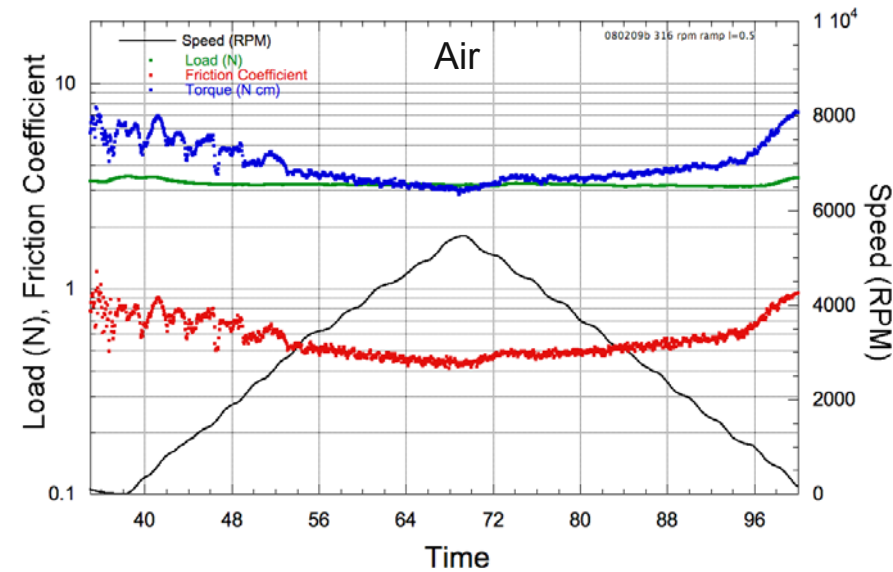
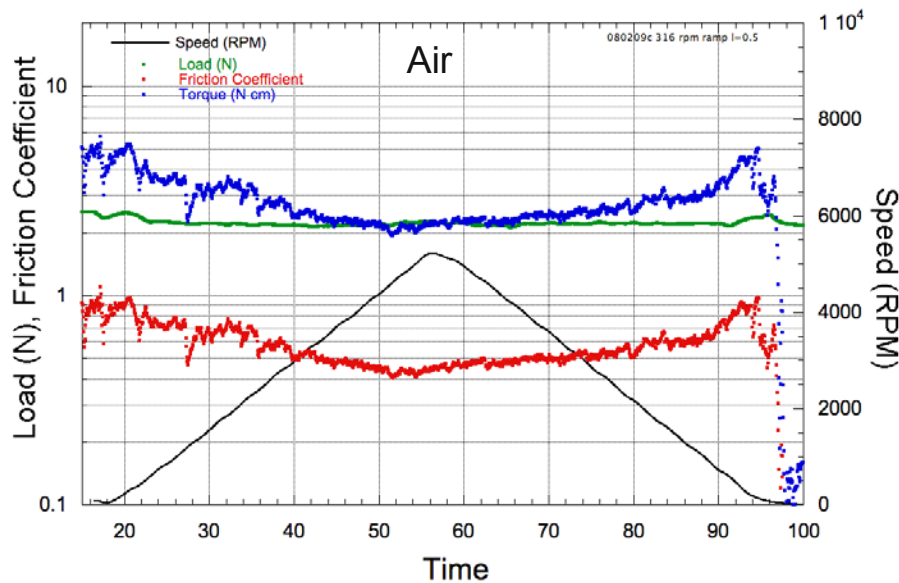
316 Stainless Steel

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



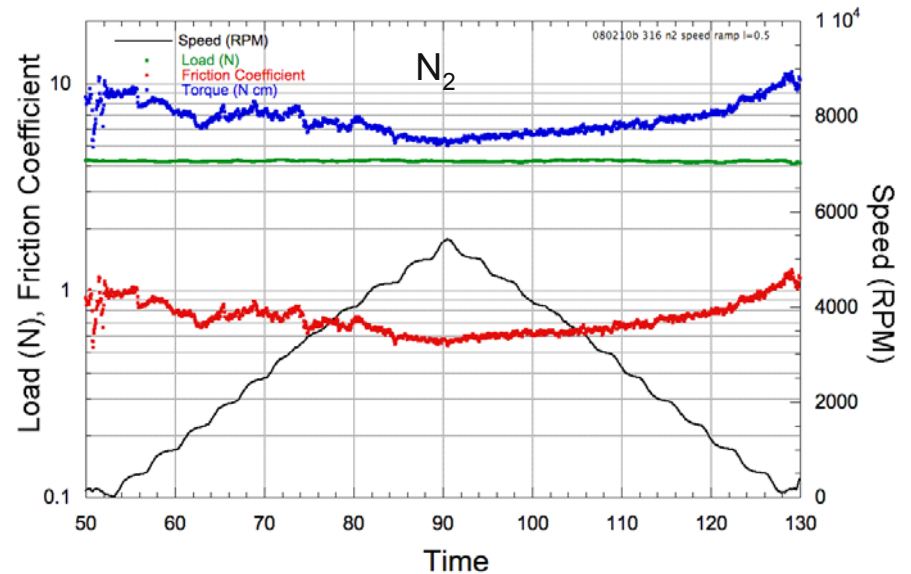
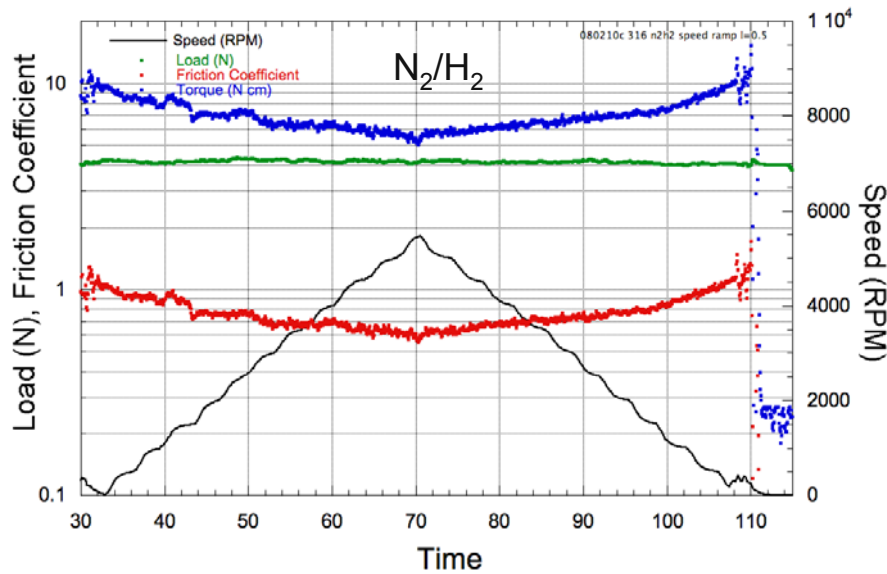
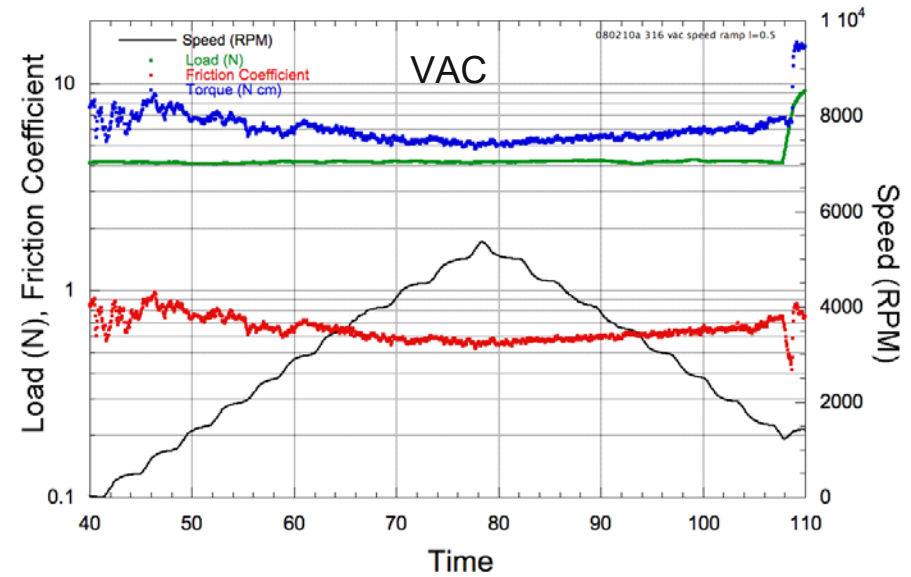
316 Stainless Steel

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



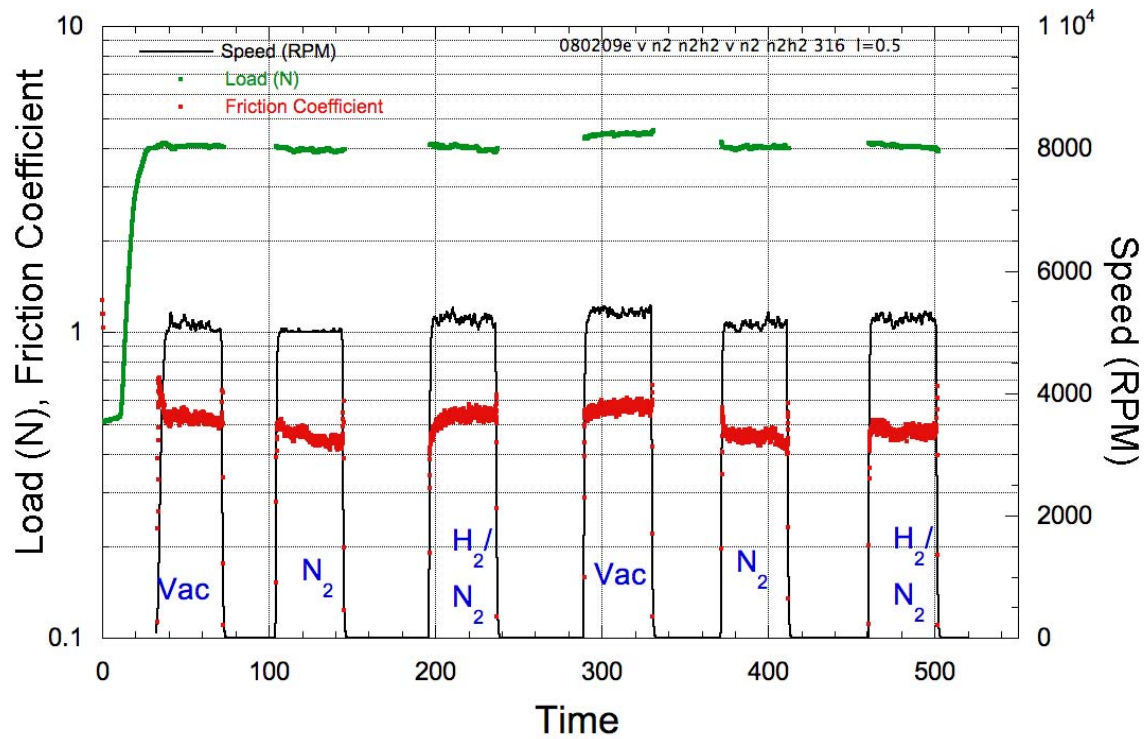
316 Stainless Steel

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



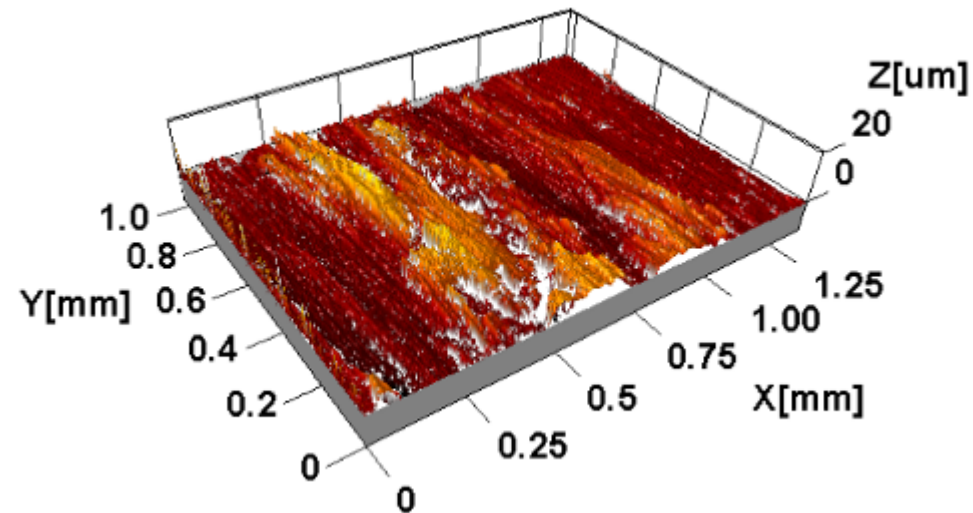
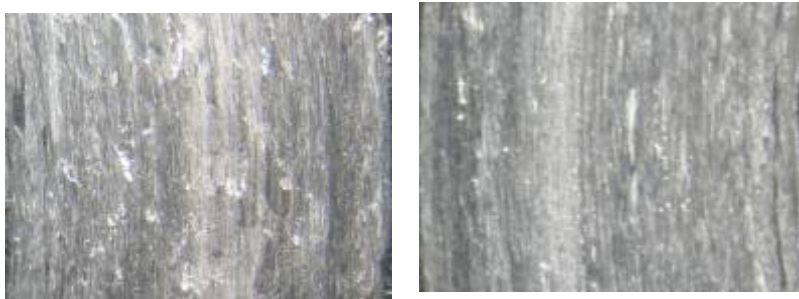
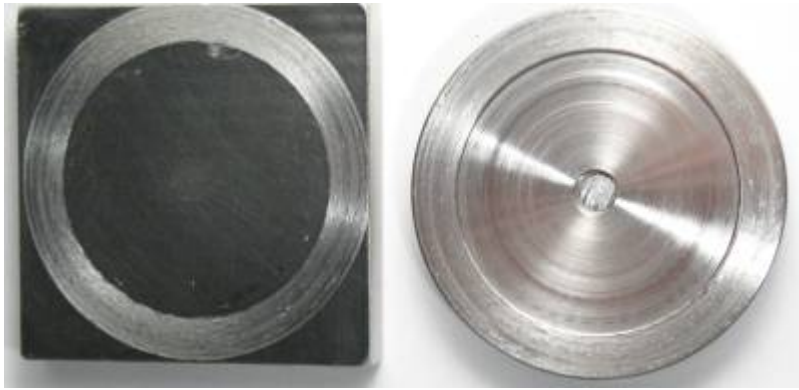
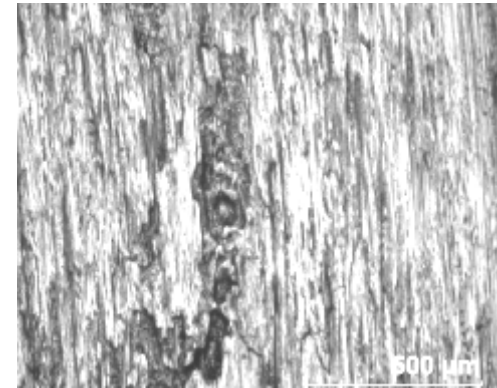
316 Stainless Steel

- SS316/SS316 in different environments



316 Stainless Steel

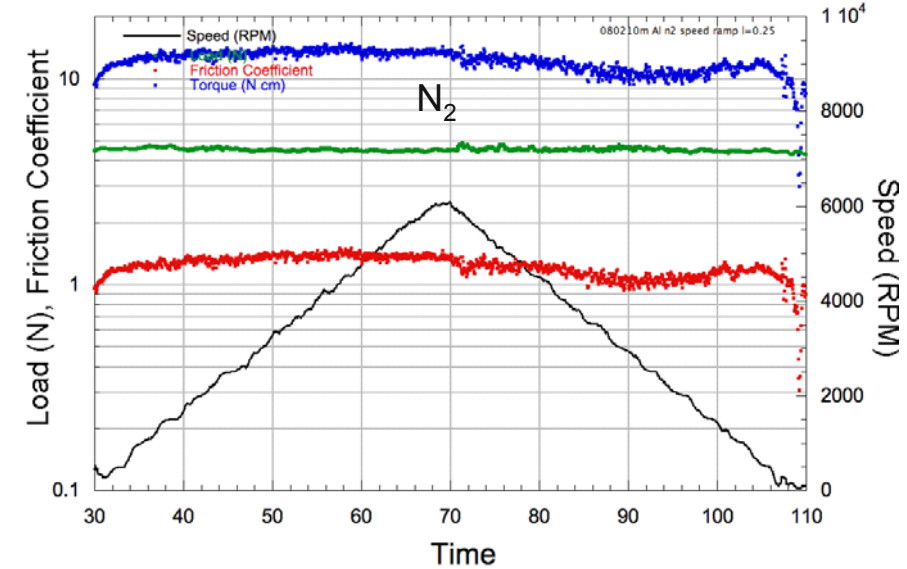
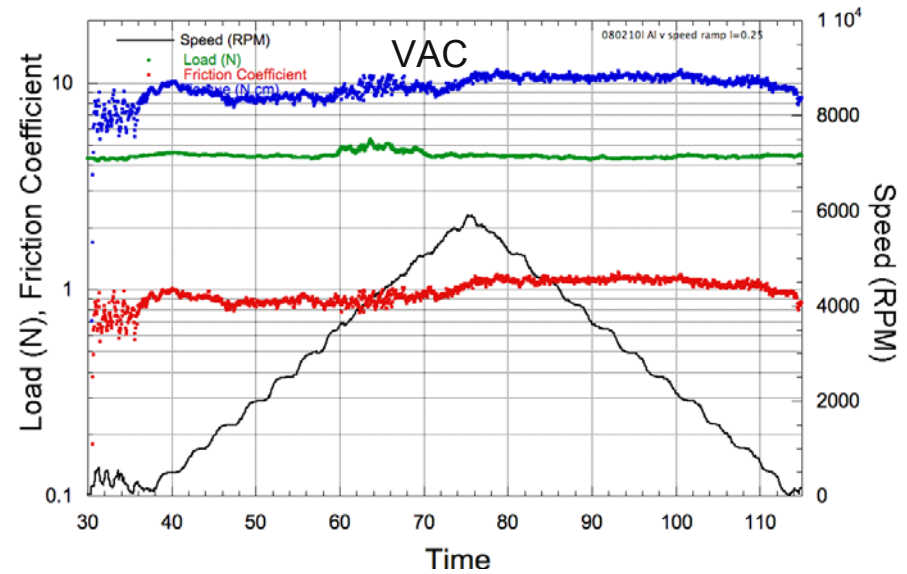
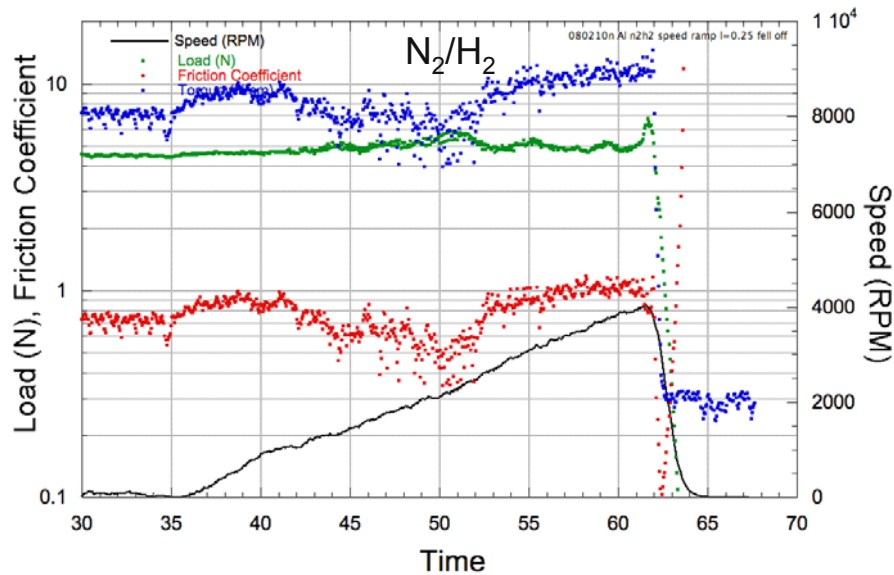
- Post test examination
 - Galling and roughening
 - $2.2 \mu\text{m Ra}$



6061 Al

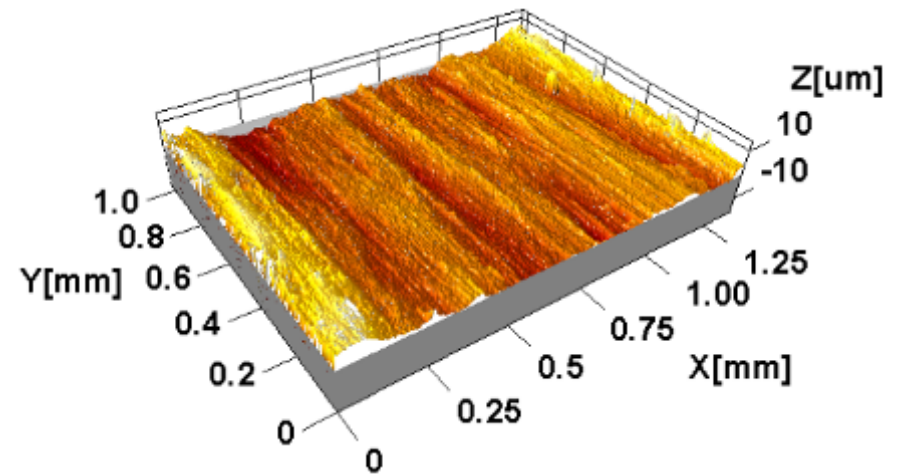
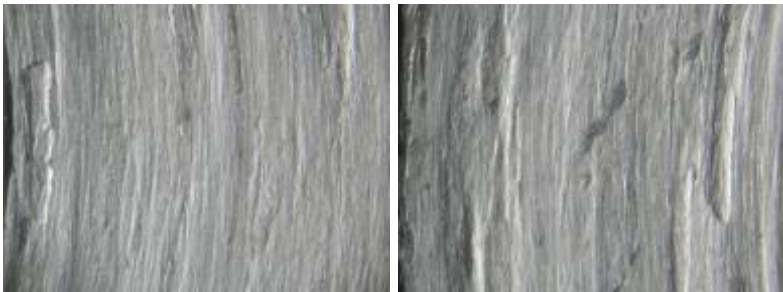
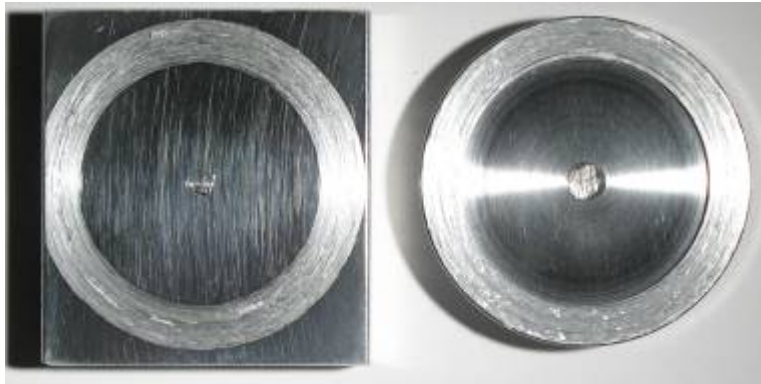
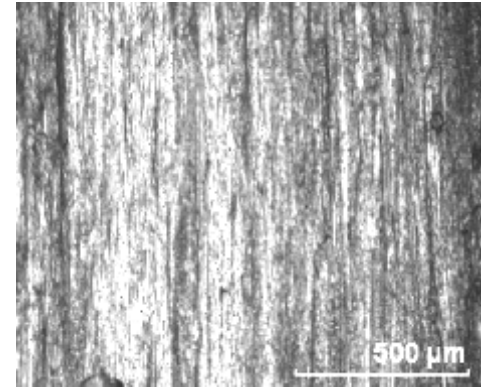
6061 Al / 6061 Al

- High friction (to 1.4)
- Seizure of sliding parts in N₂/H₂



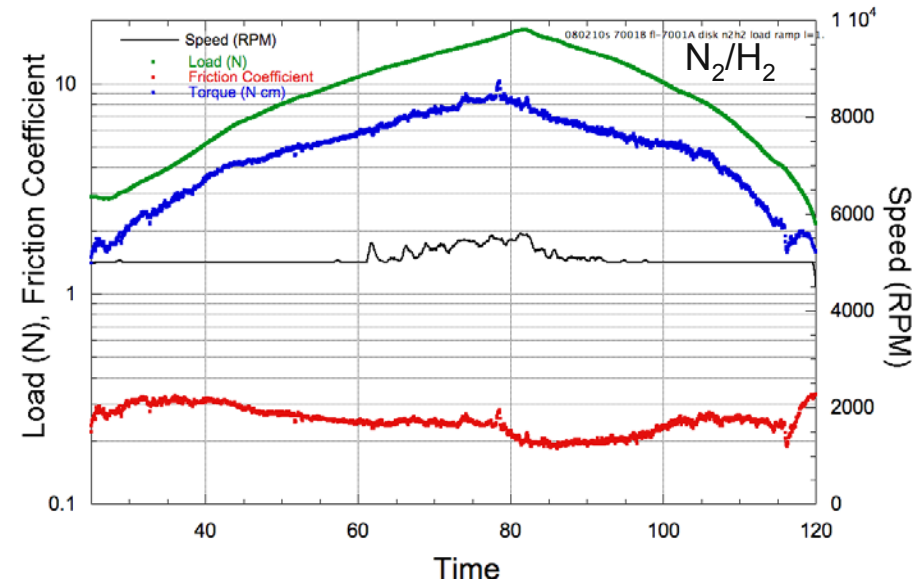
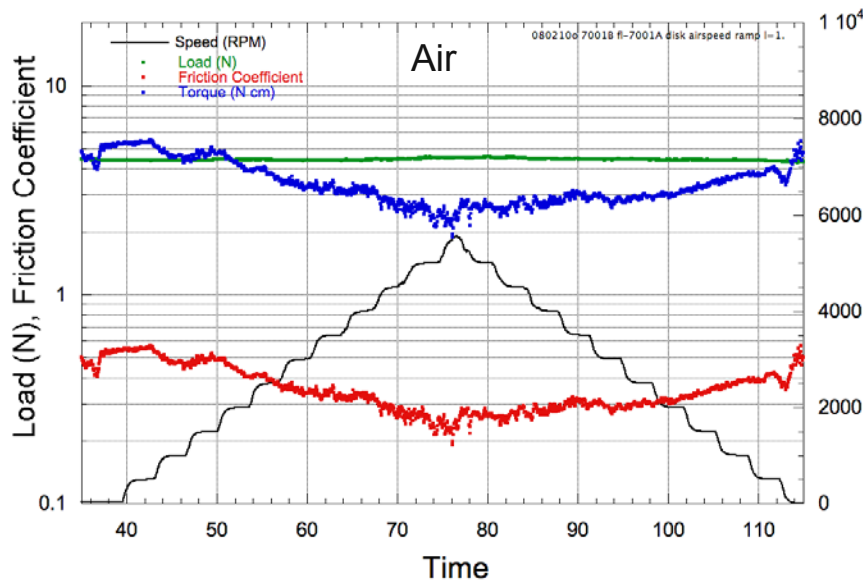
6061 Al

- Post test examination
 - Deformation and transfer
 - $1.8 \mu\text{m Ra}$



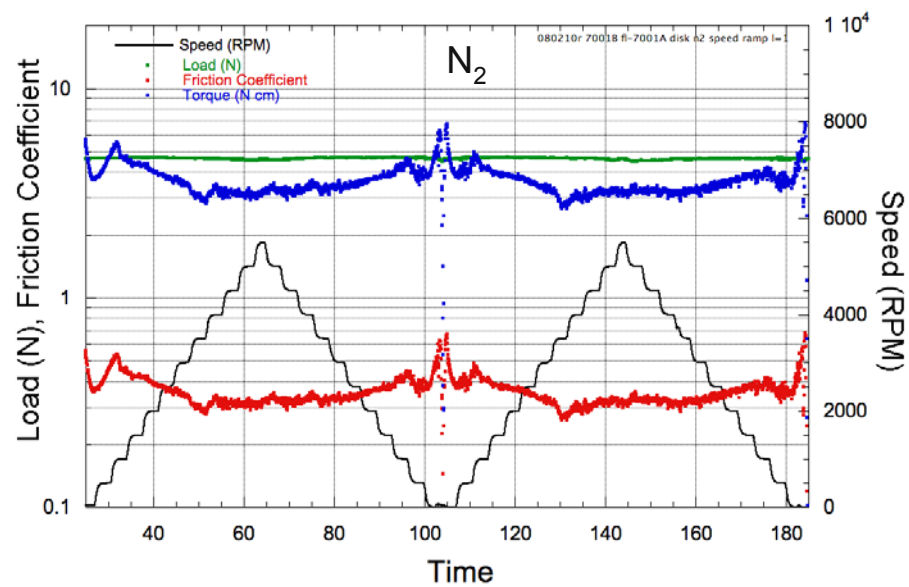
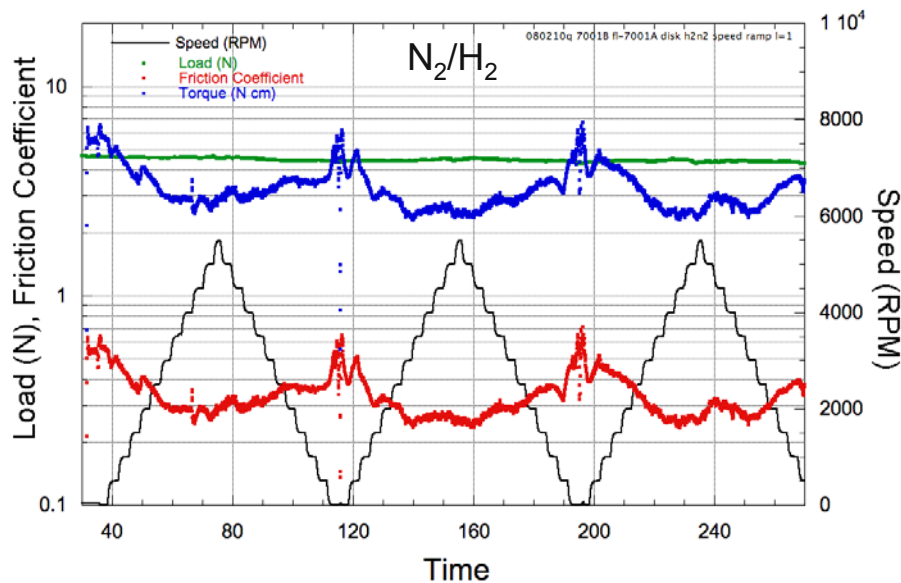
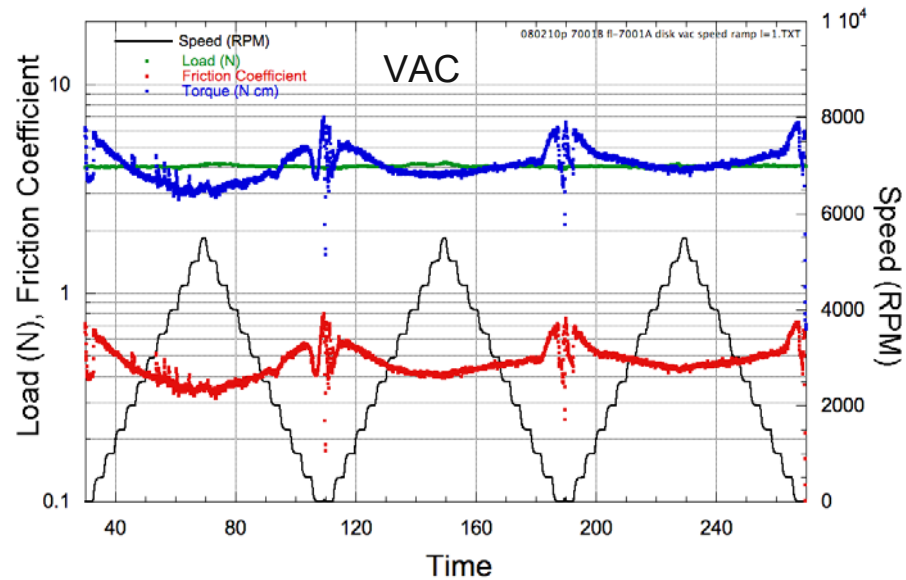
MoS₂ coating

- 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



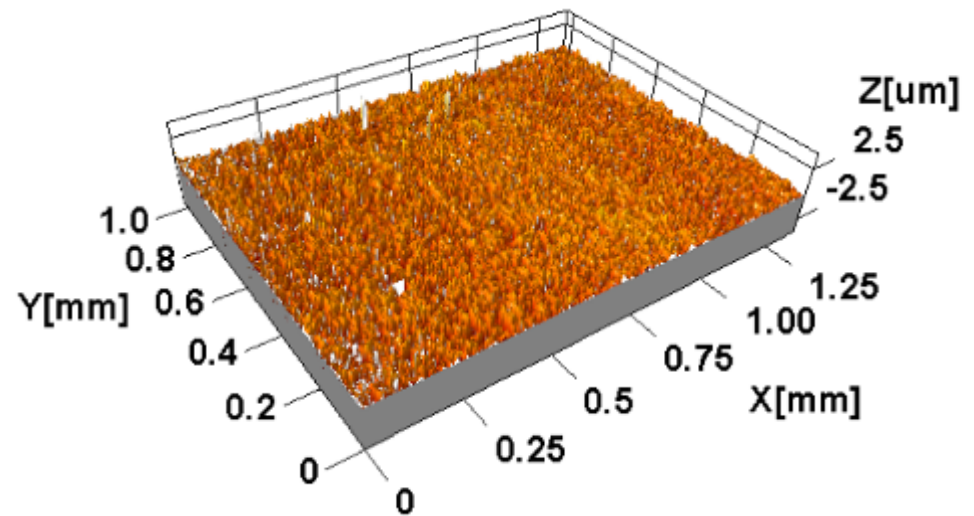
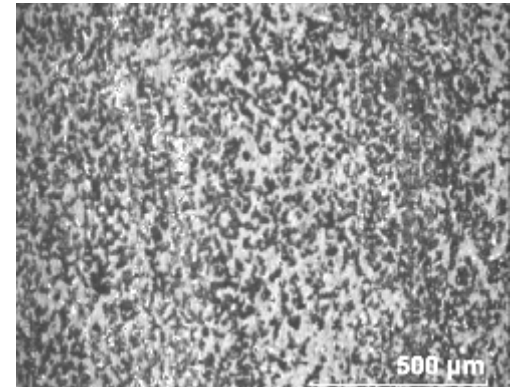
MoS₂ coating

- Lower friction at higher speeds
 - Low friction ($\approx 0.2-0.6$)



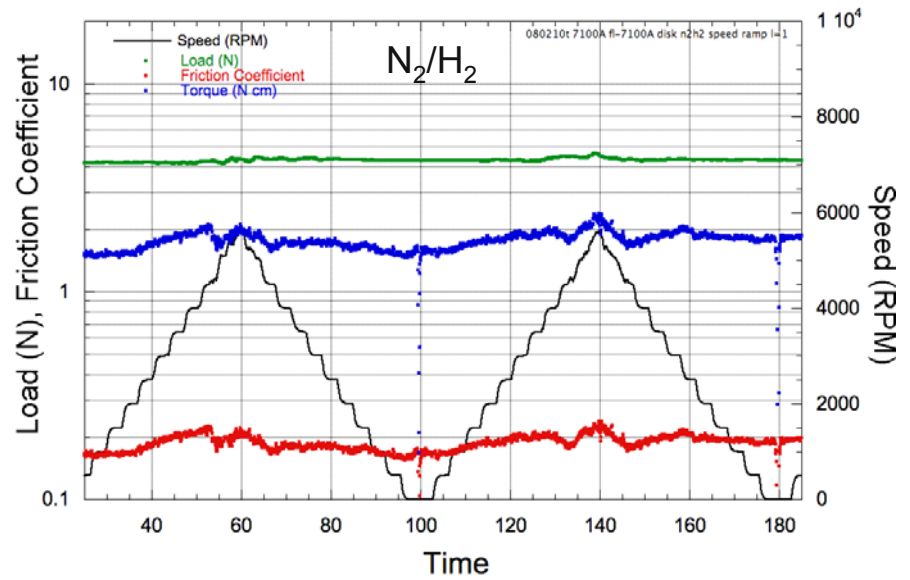
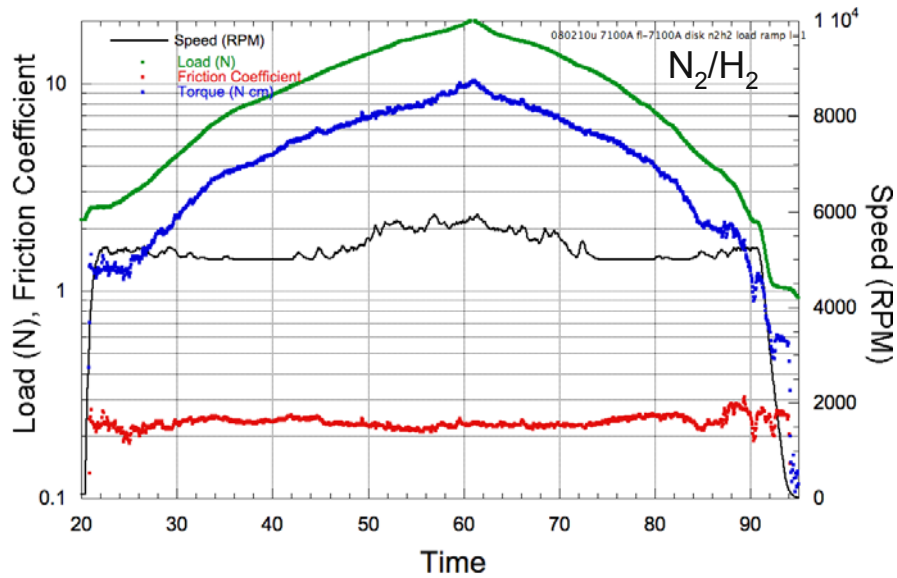
MoS₂ coating

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



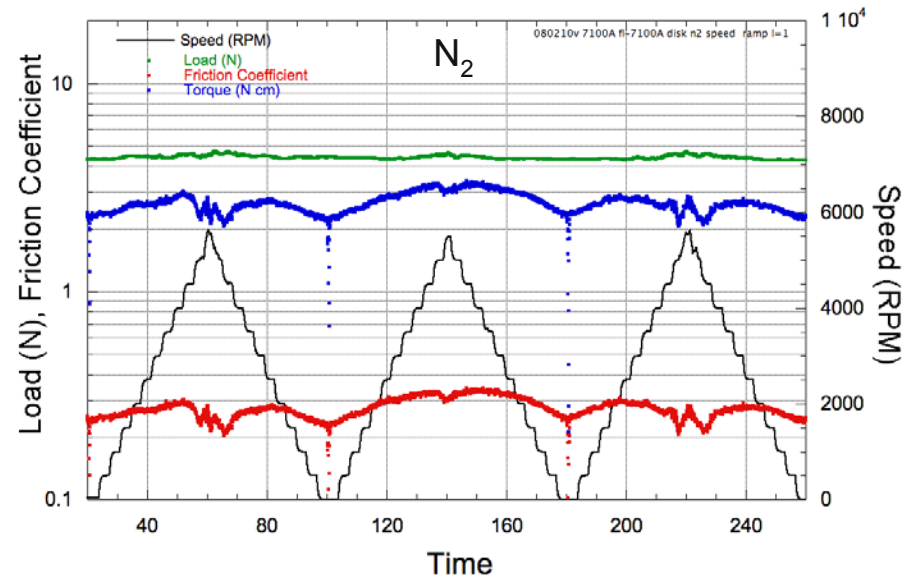
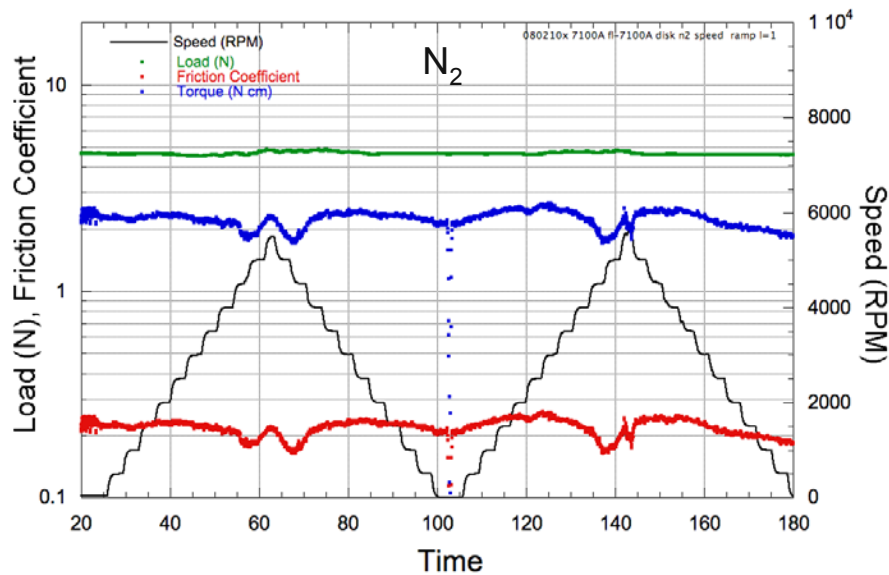
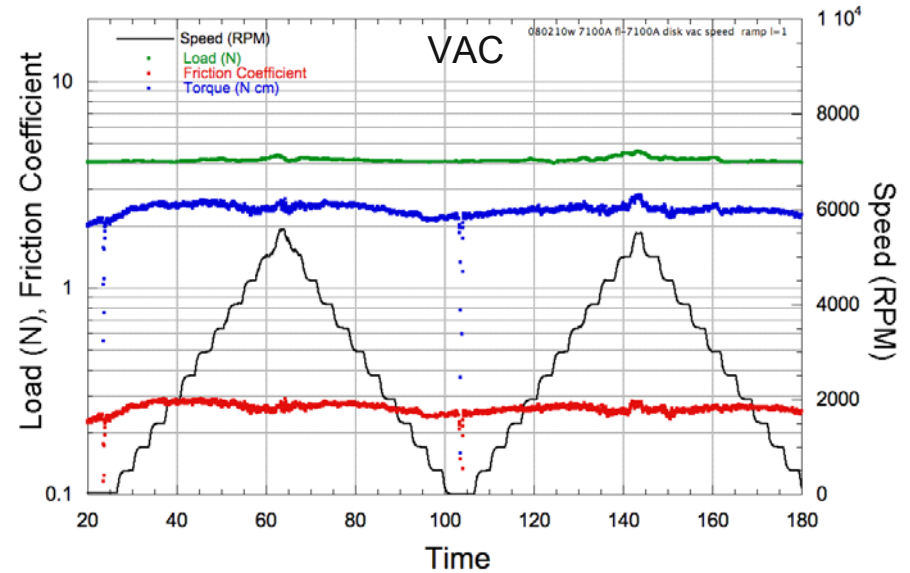
MoS₂ bonded topcoat

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



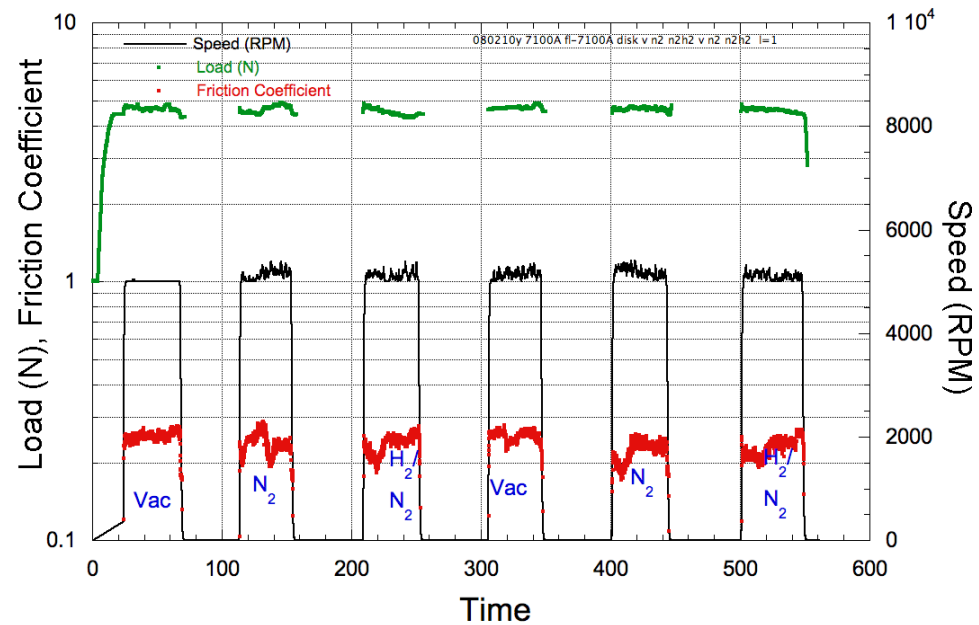
MoS₂ bonded topcoat

- Friction coefficient low over range of speeds, higher in N₂
- Fluctuations likely due to machine vibrations



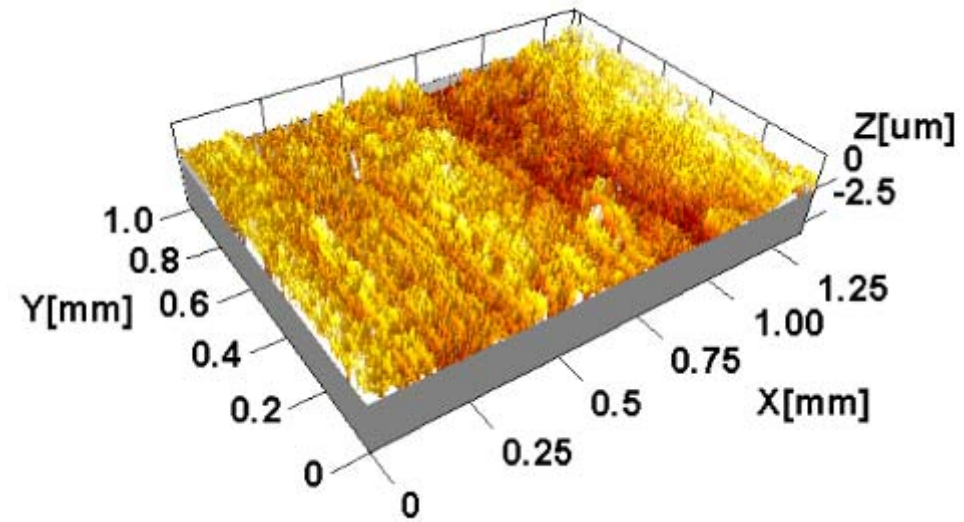
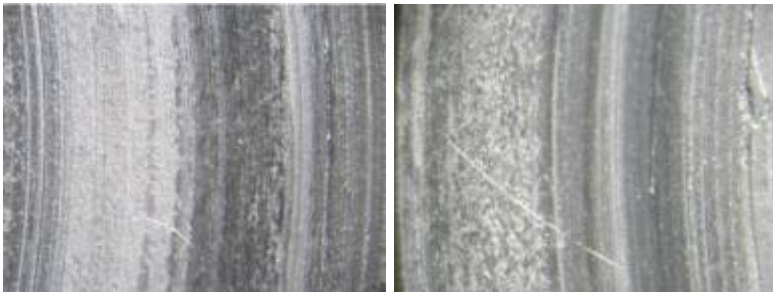
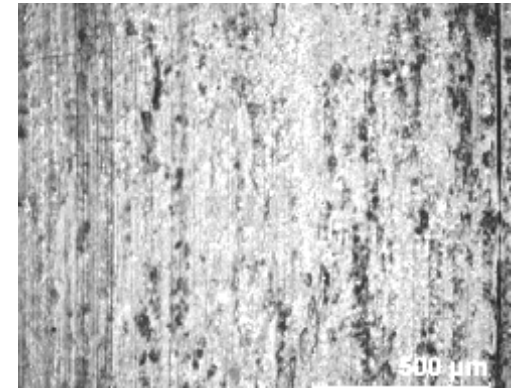
MoS₂ bonded topcoat

- Friction coefficient low for measured conditions



MoS₂ 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 H₂/N₂
 - Smallest friction coefficients for solid lube coating

Acknowledgements

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