SAND2019-6087C

DLC from Thin Air: In Situ Formation of Diamond-like Carbon on Ultralow Wear Metals



PRESENTED BY

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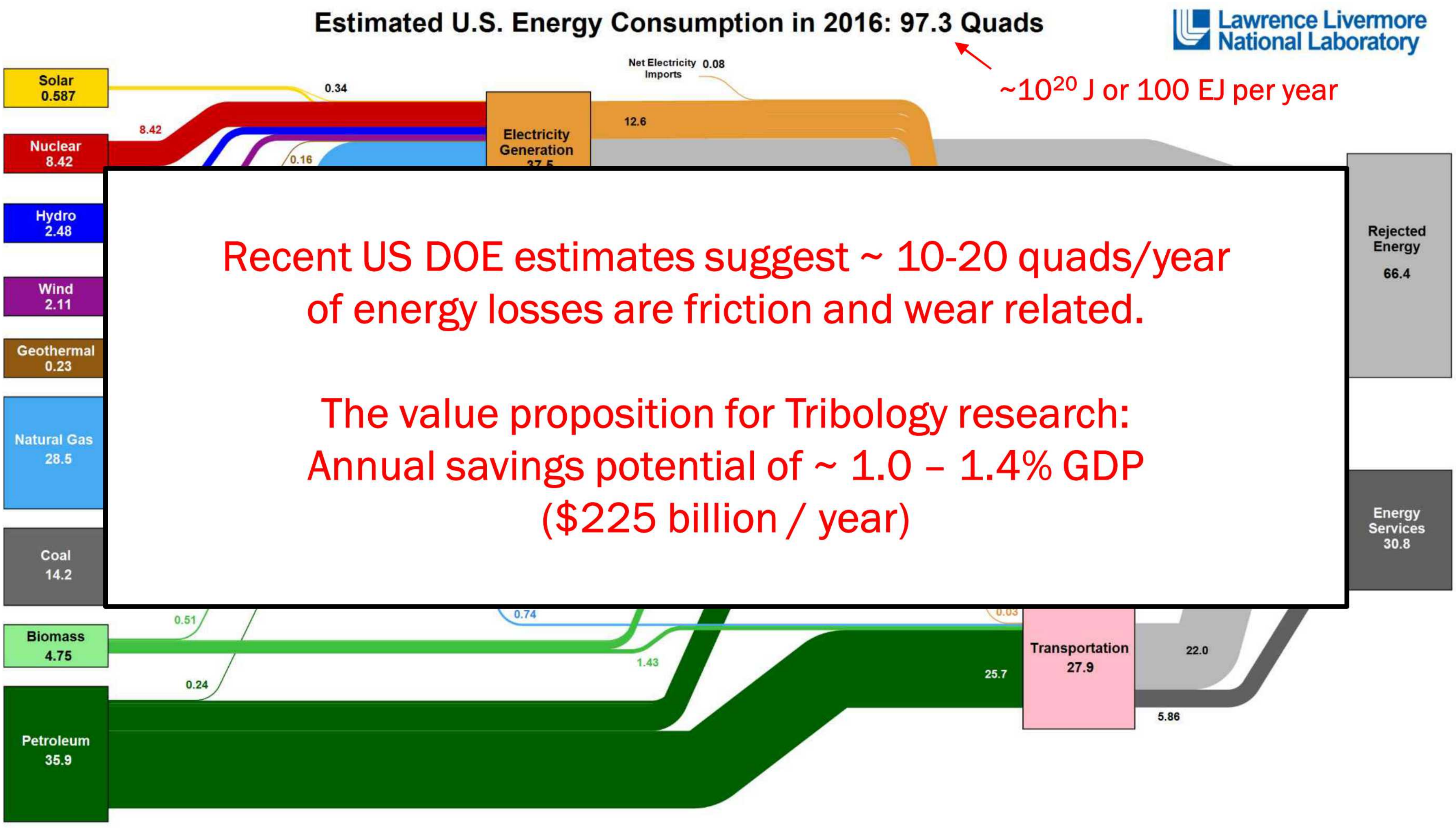
Some Perspective on the Value Proposition of Tribology Research



Recent US DOE estimates suggest ~ 10-20 quads/year of energy losses are friction and wear related.

The value proposition for Tribology research: Annual savings potential of ~ 1.0 – 1.4% GDP ($225 billion / year)

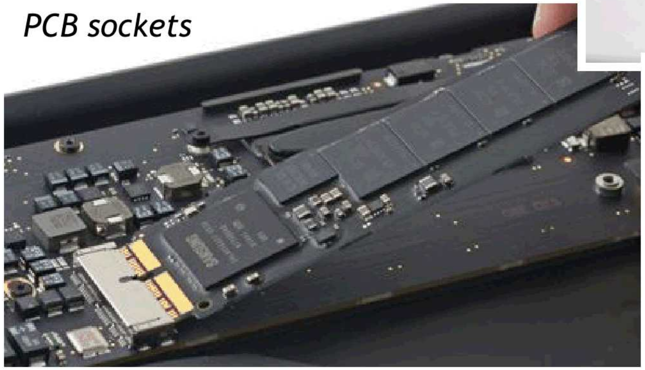
Source: LLNL March, 2017. Data is based on DOE/EIA MER (2016). If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. This chart was revised in 2017 to reflect changes made in mid-2016 to the Energy Information Administration's analysis methodology and reporting. The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential sector, 65% for the commercial sector, 21% for the transportation sector, and 49% for the industrial sector which was updated in 2017 to reflect DOE's analysis of manufacturing. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Motivation for Metals Tribology Research

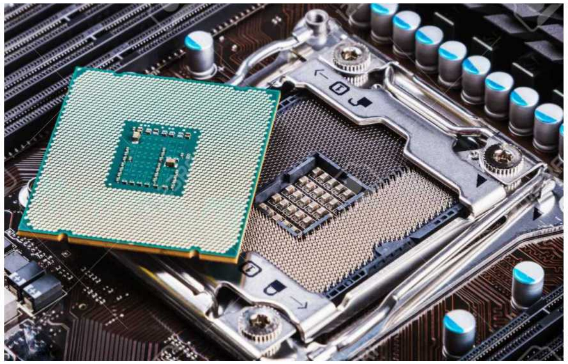
cell phones

wind turbine slip-rings
(sensors and blade pitch motors)

PCB sockets



CPU sockets



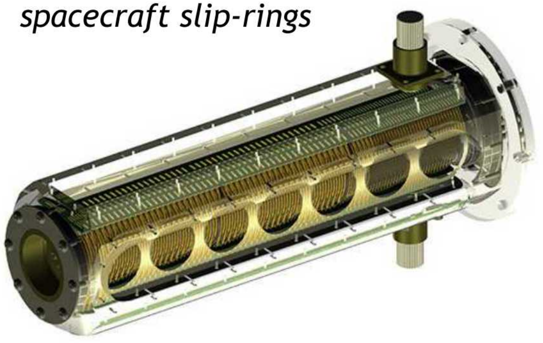
Estimated 150 Metric Tons ($6.9B) of Au used in Electrical Contacts per Year:

Refs: Gold Survey, Gold Fields Mineral Survey Ltd, 2011
Gold Bulletin 2010, Vol. 43-3, C. Hagelüken and C.W. Corti,
Gold Bulletin 1986, Vol. 19-3, T.D. Cooke

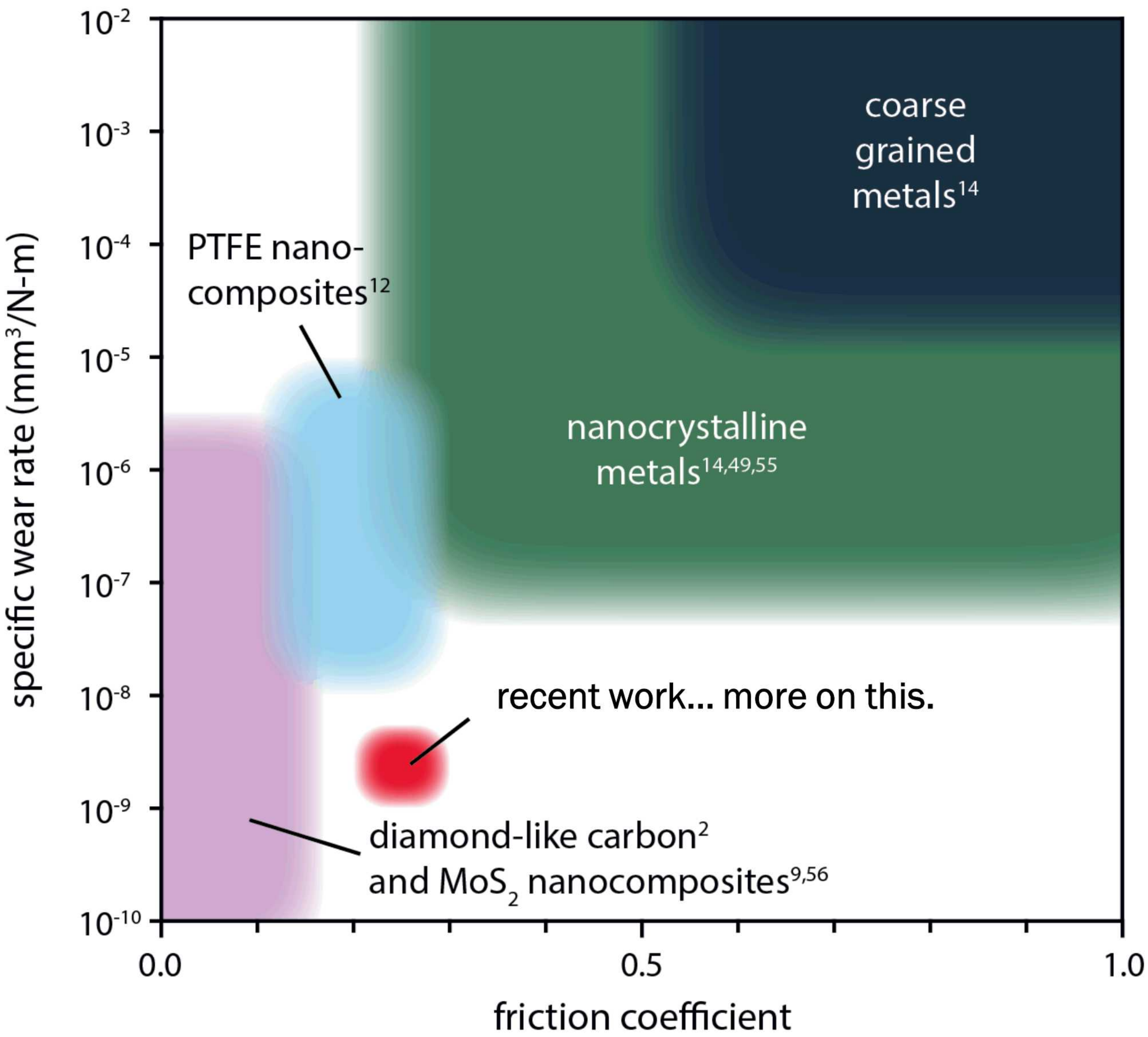
…45 connectors

EV charging

spacecraft slip-rings

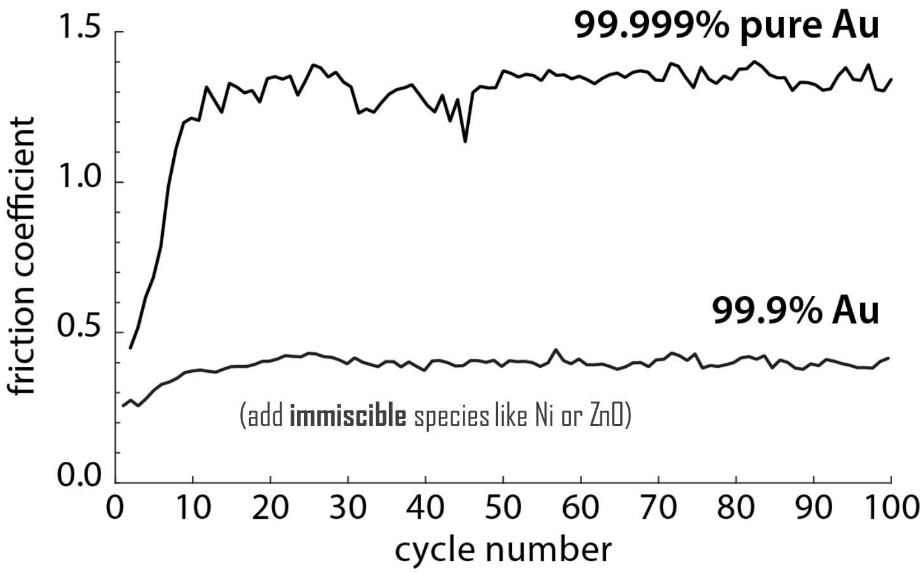


Materials Tribology Survey



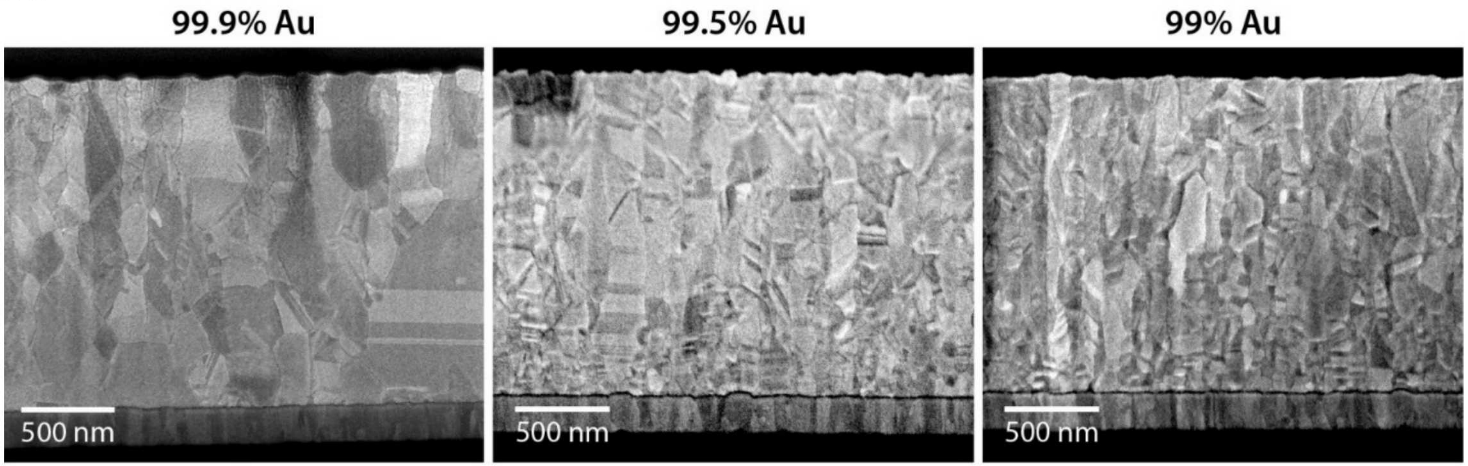
Lower friction and wear of nanocrystalline metals

Alloying reduces friction coefficient:

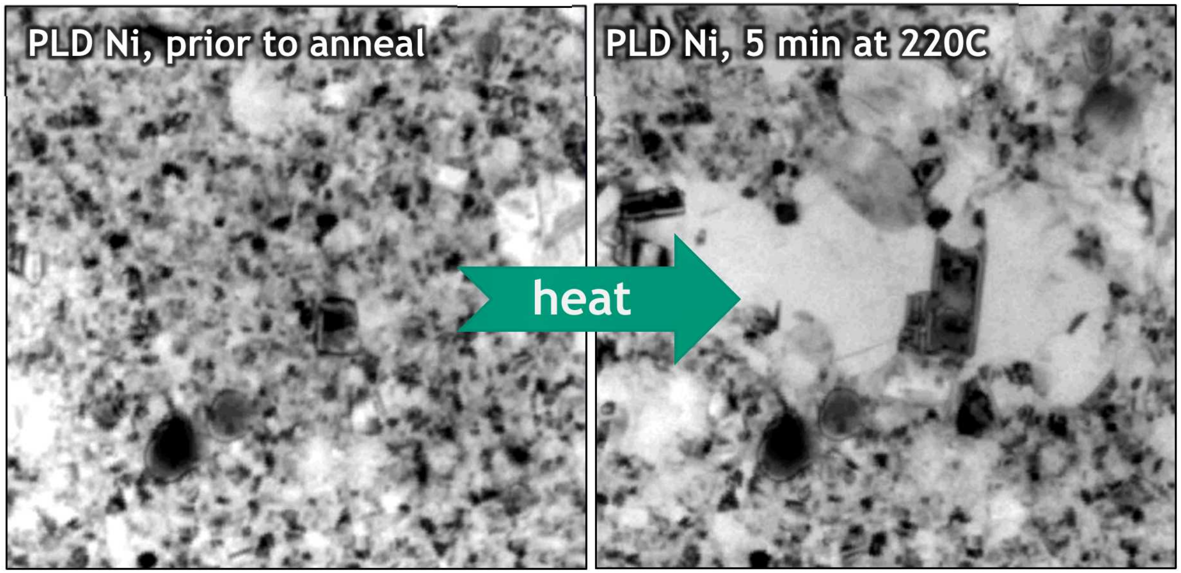


Alloying improves friction & wear performance by reducing and stabilizing grain size

...by reducing grain size:



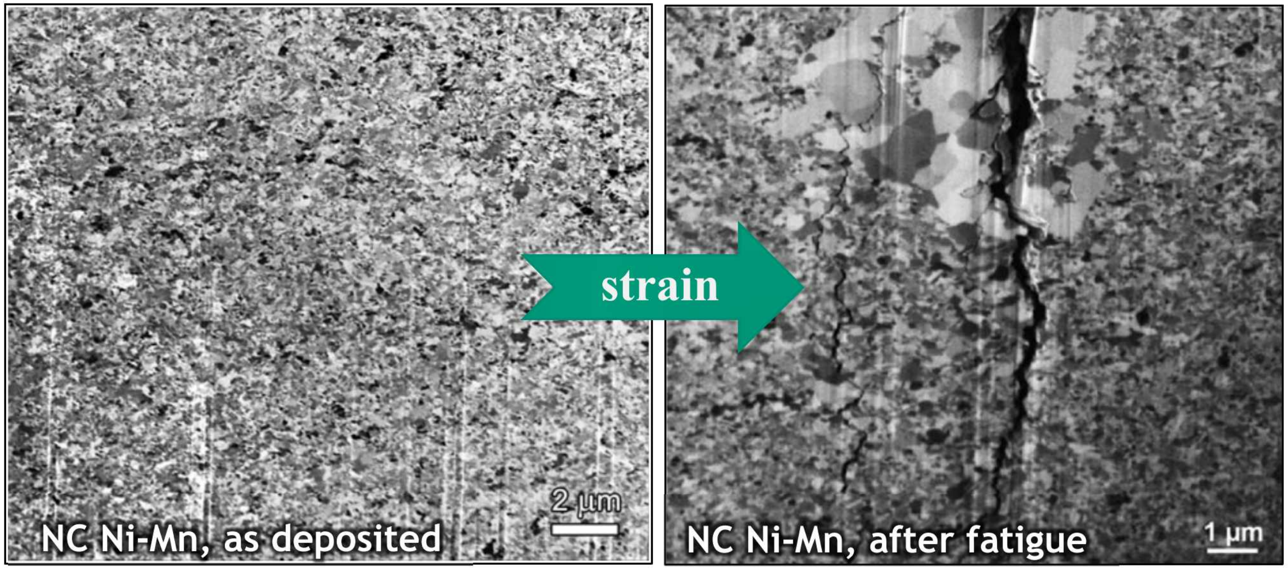
The challenge is grain size instability…



Grain growth in nanocrystalline metals is driven

Thermally…

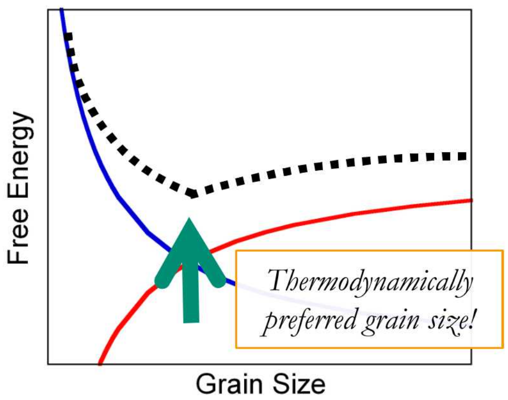
…and Mechanically



S. Rajasekhara, K. Hattar, P. Ferreira, A. Kinghorn, B. G. Clark (unpublished); H. A. Padilla and B. L. Boyce, ***Exp. Mech. (2010)***

Regular Nanocrystalline Solution Model (Schuh Group at MIT)

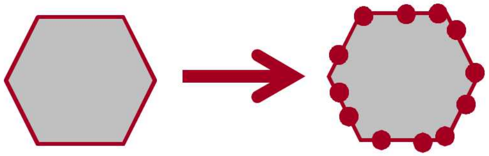
Slide courtesy of C. Schuh and H. Murdoch (MIT)



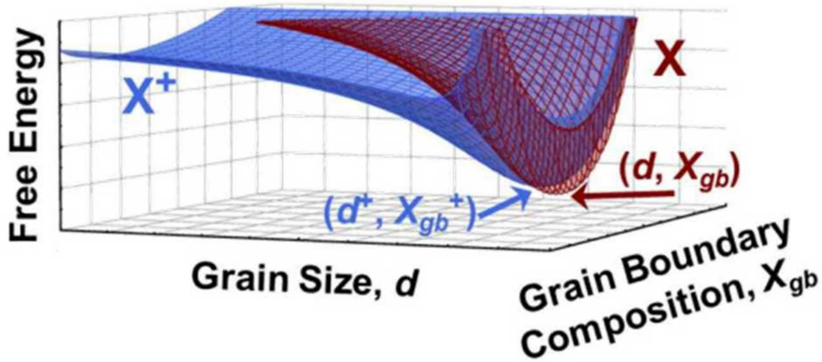
RNS Model:

Binary metal alloys exist possessing highly (intrinsically?) thermodynamically stable nanocrystallinity.

Solute segregation at grain boundaries:



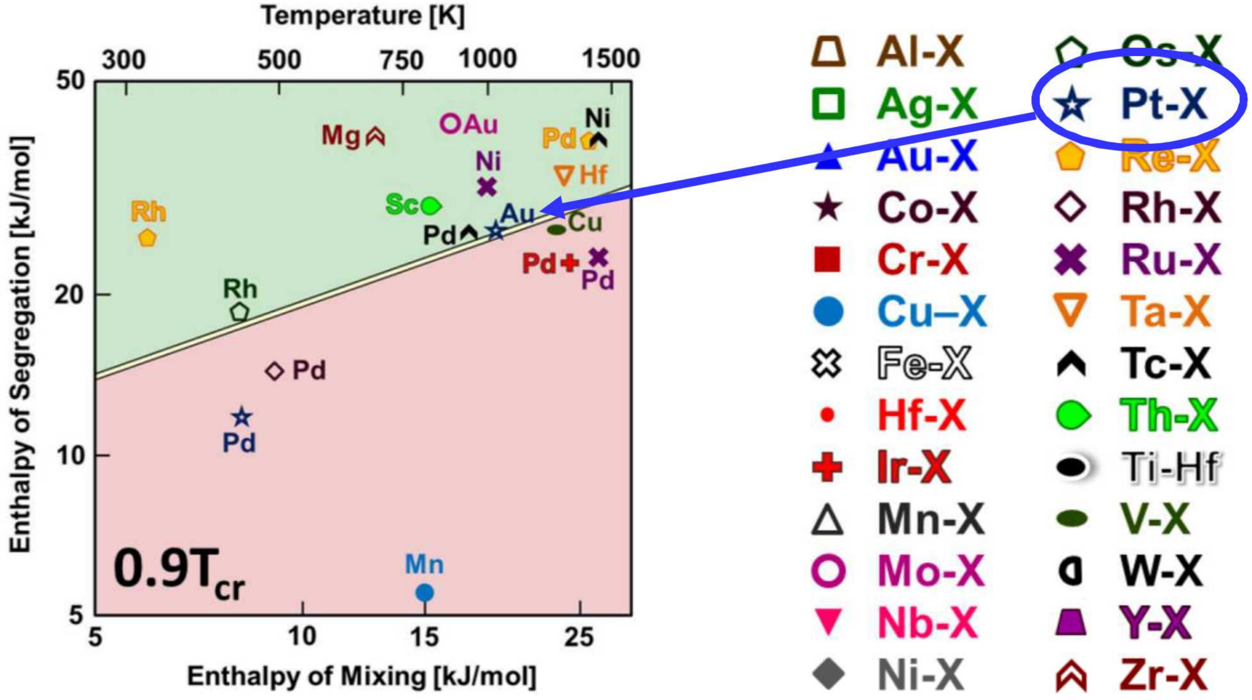
$$dG = \left[\gamma - \frac{N_\beta}{A}\Delta G_{seg}\right] dA$$



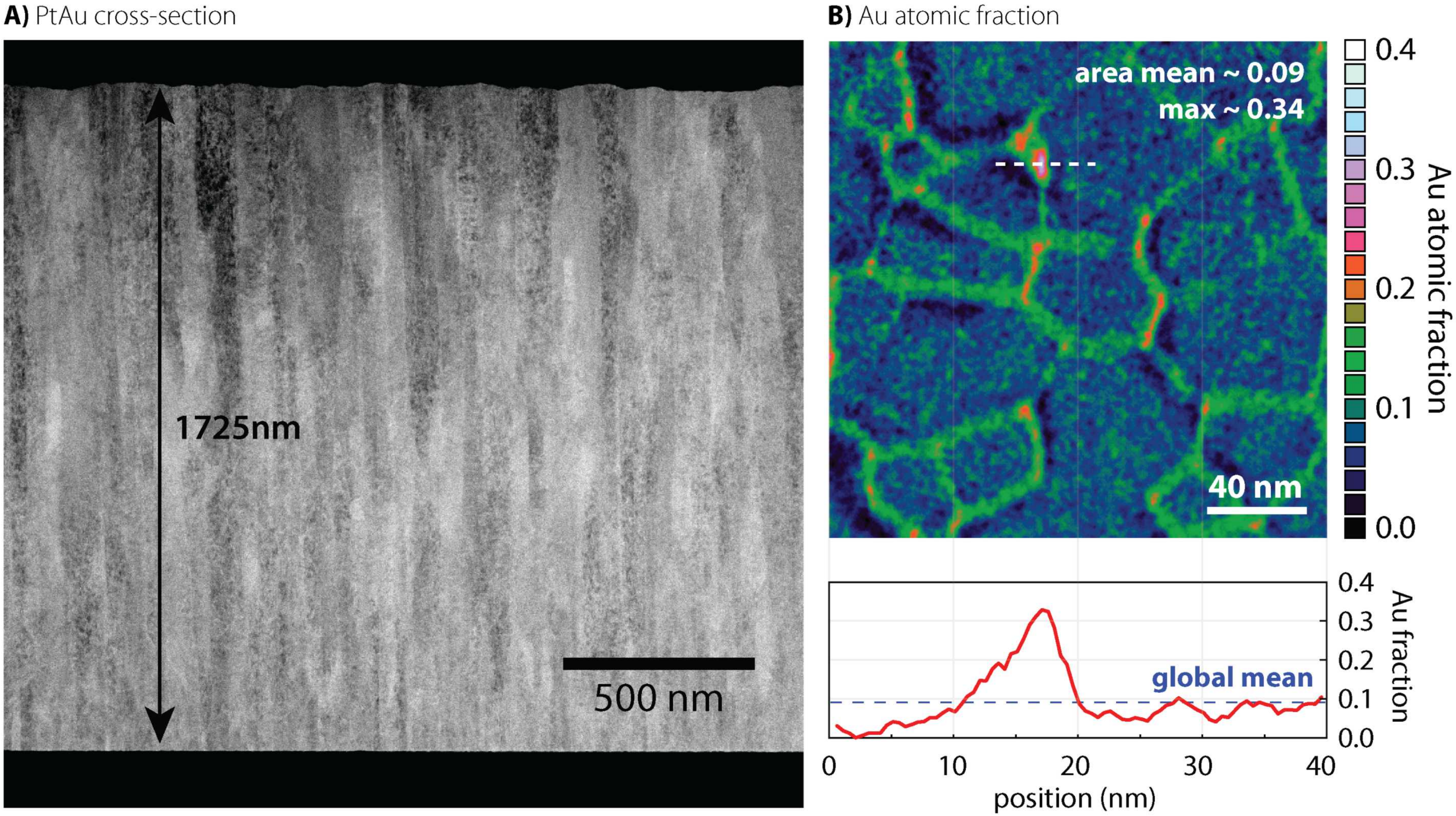
References:
*T. Chookajorn, et al., **Science, 2012***
*Kirchheim, **Acta Materialia, 2002***
*Weissmuller, J. **Materials Research, 1994***
*D.S. Gianola et al., **Acta Materialia, 2006***

Binary metal alloys with favorable segregation

Reference: Murdoch and Schuh, J. Mat. Research (2013)



PtAu alloys one of new class of highly stable nanocrystalline alloys

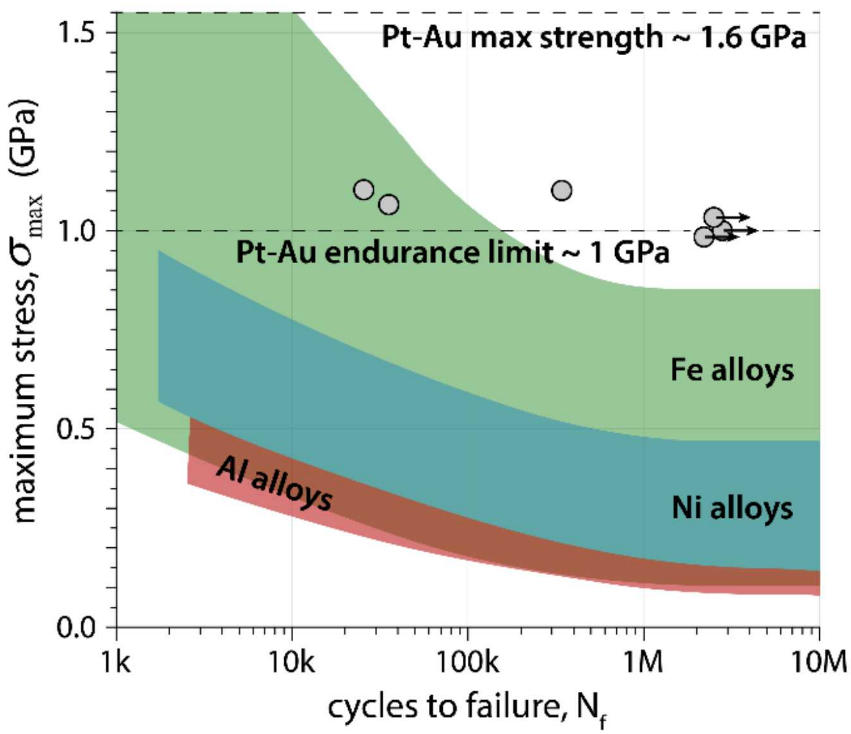


Synthesized coatings of Pt with 10 vol. % Au

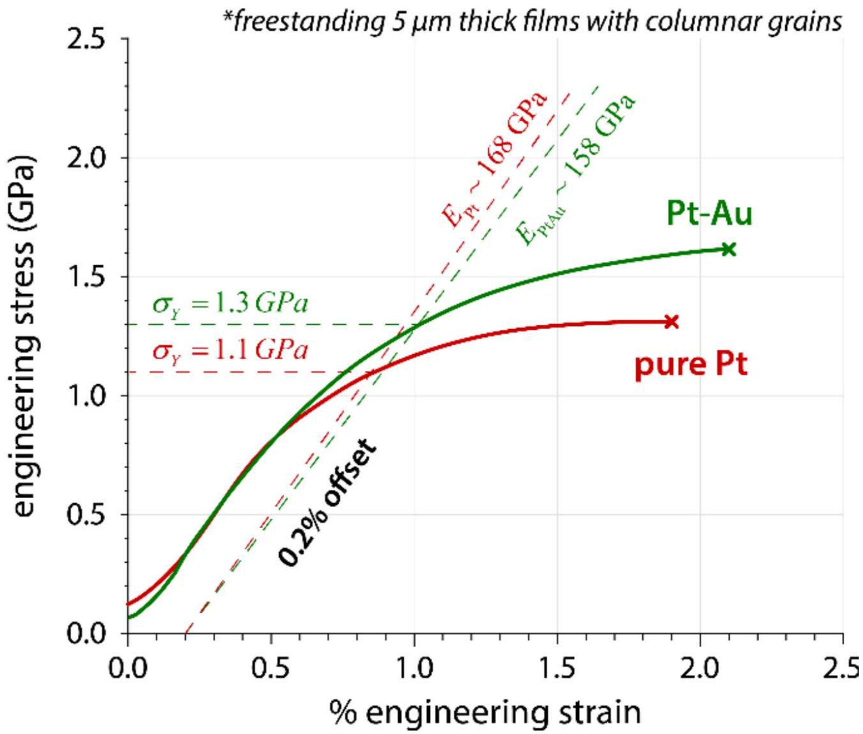
J. F. Curry, et al., ***Advanced Materials (2018)***

PtAu alloys have high yield strength and remarkable fatigue resistance

Experimental Tensile Fatigue:



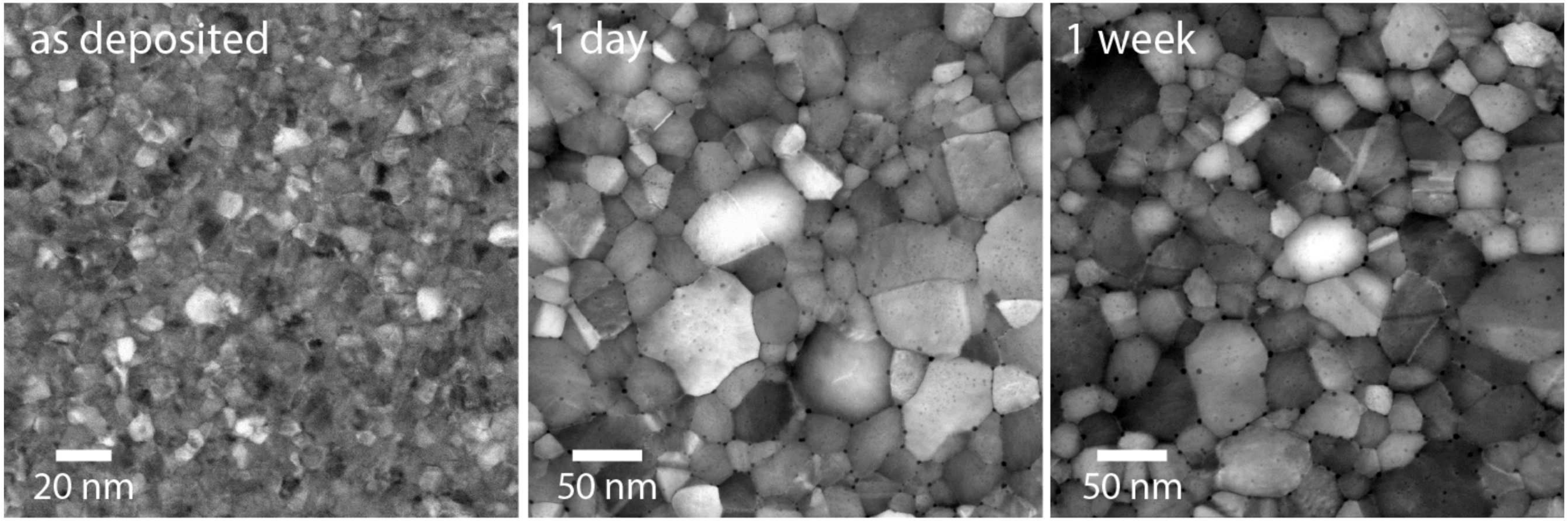
Experimental stress-strain data:

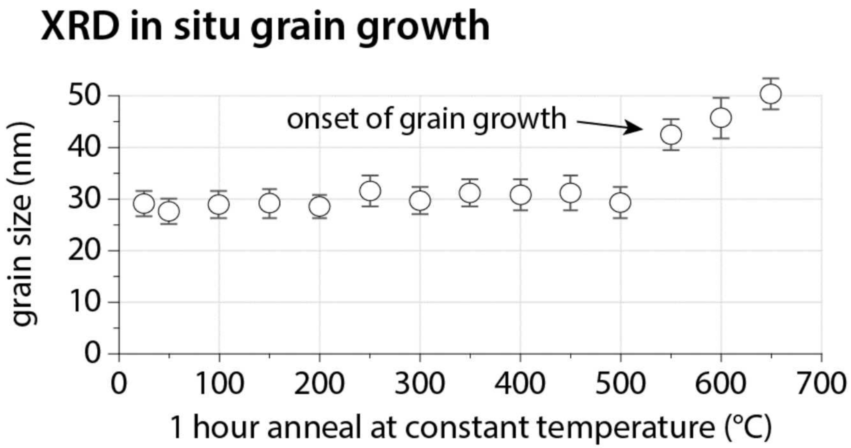


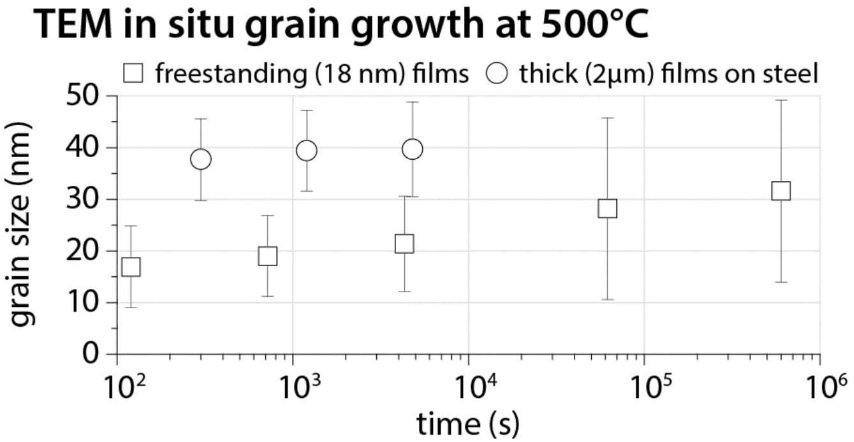
This high yield strength and fatigue resistance generated an interesting result…

J. F. Curry, et al., ***Advanced Materials (2018)***

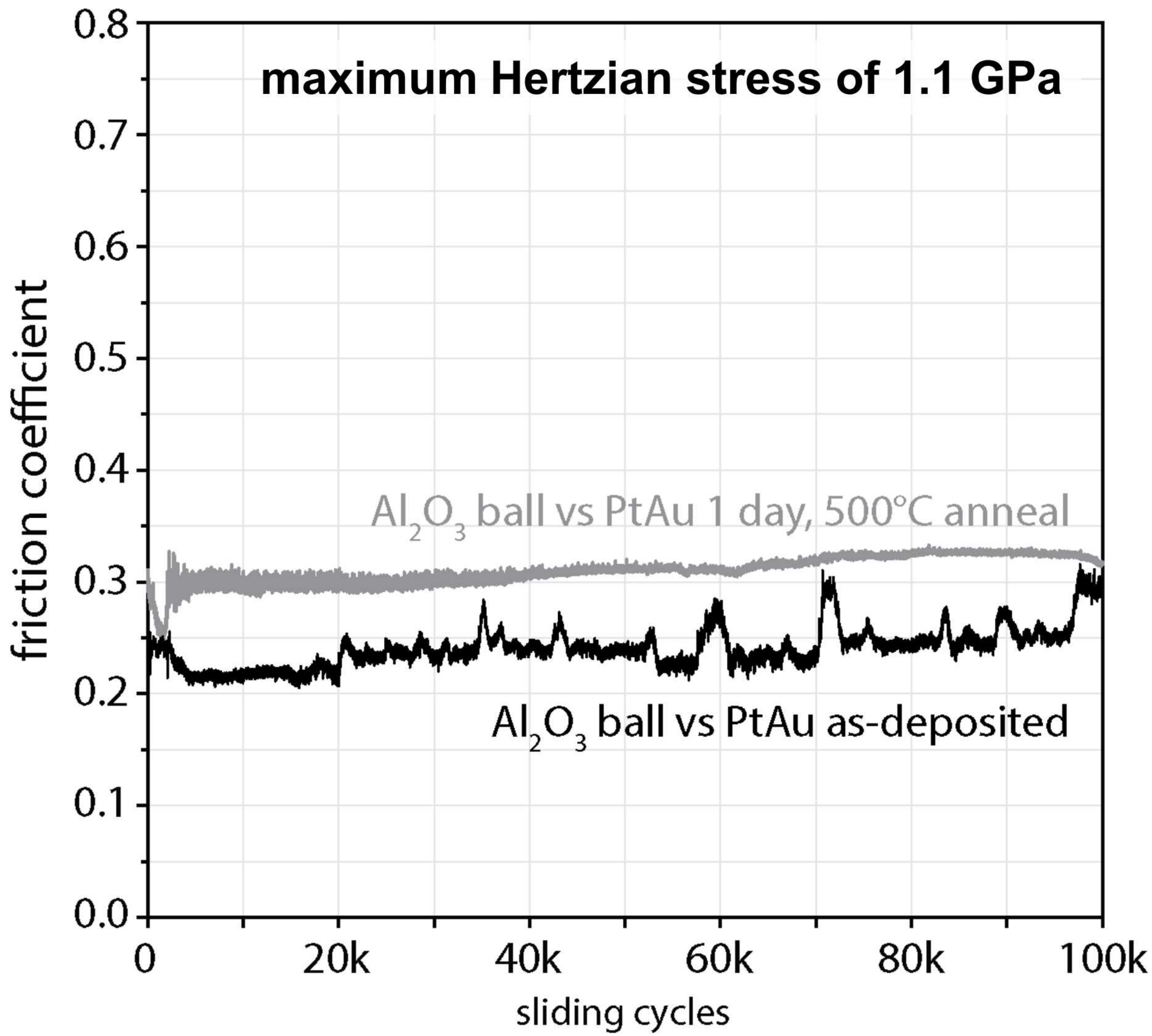
Excellent thermal stability. What about mechanical?





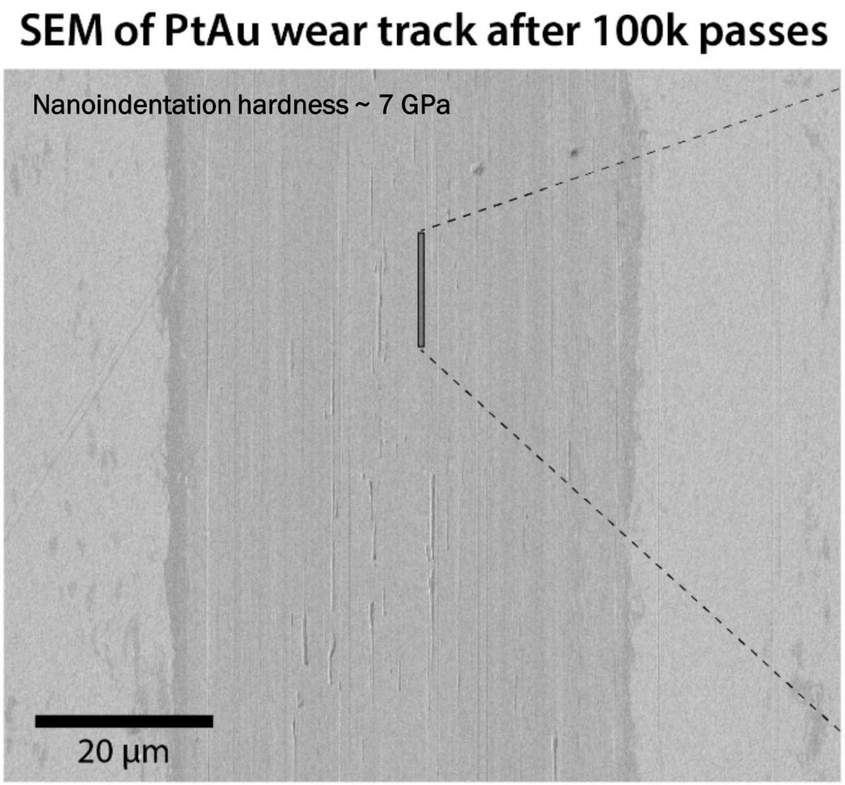


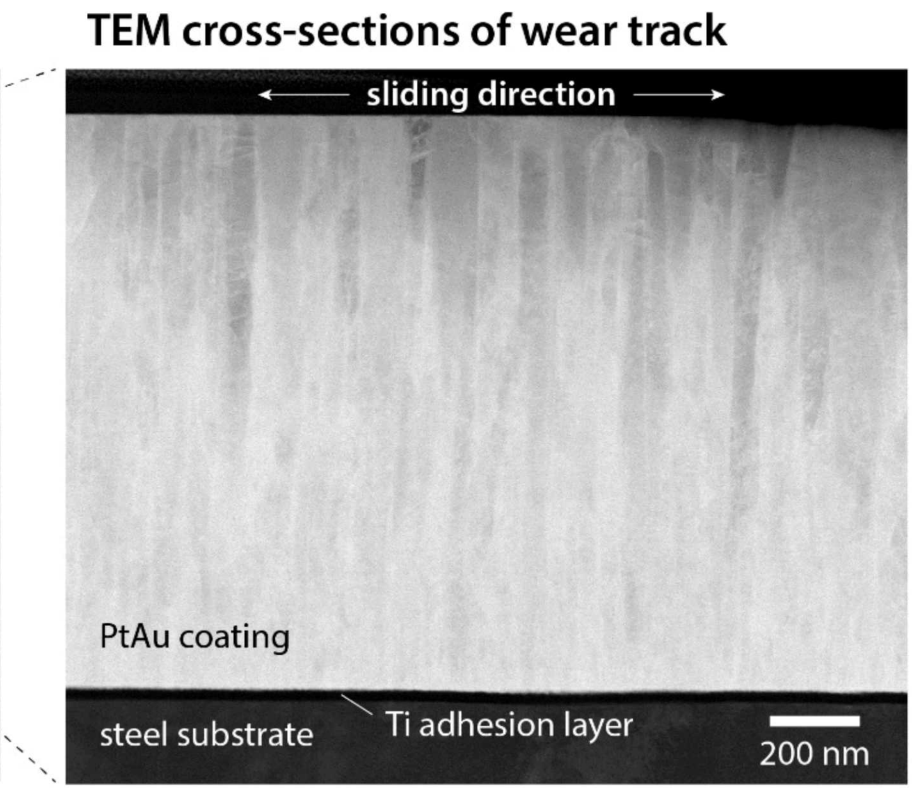
Stable nanocrystalline PtAu exhibited long-lived low friction (sliding against sapphire)



J. F. Curry, et al., ***Advanced Materials (2018)***

No evidence of microstructural evolution after prolonged tests

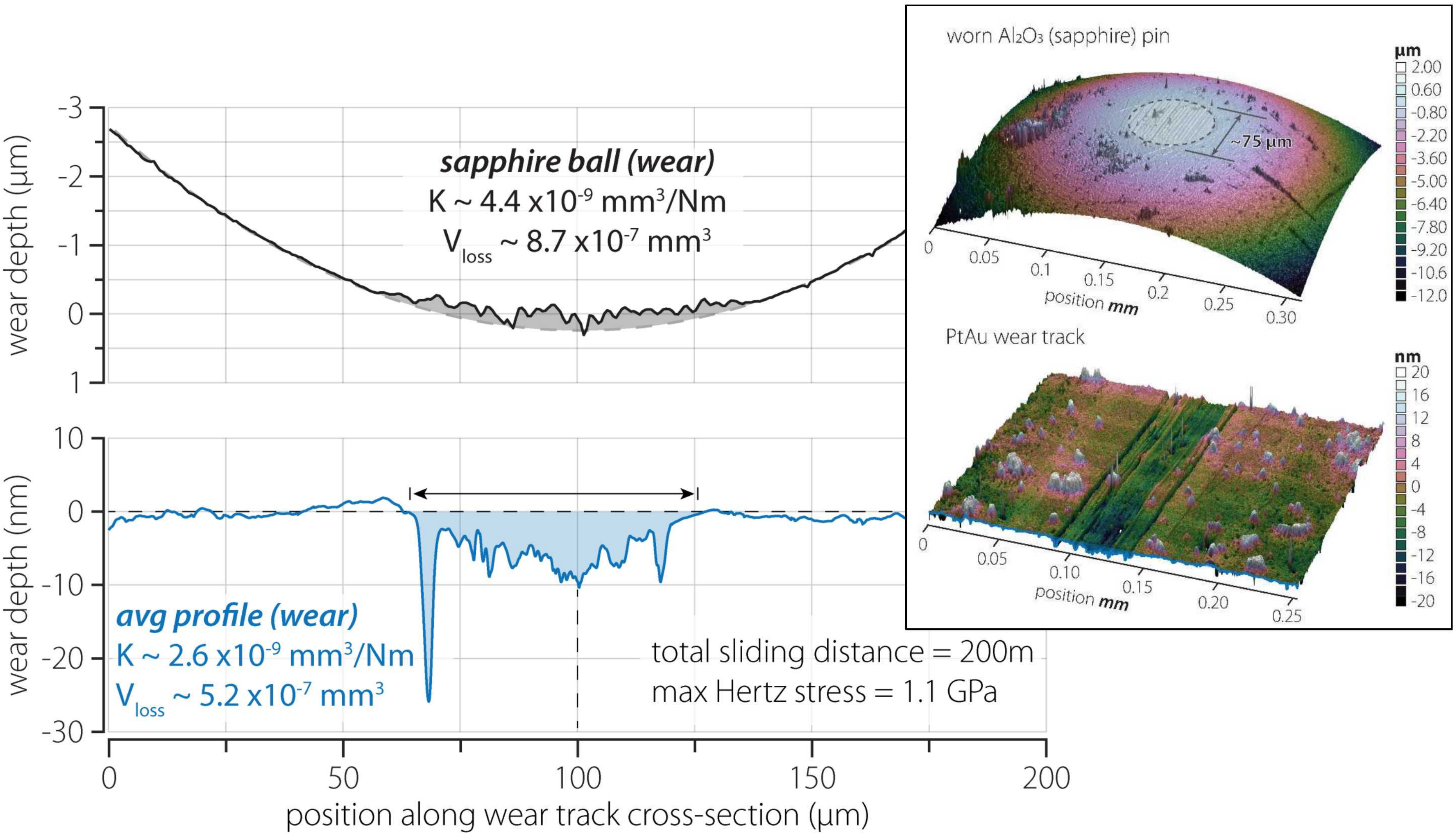




No evidence of microstructural evolution
(maximum Hertzian stress of 1.1 GPa)

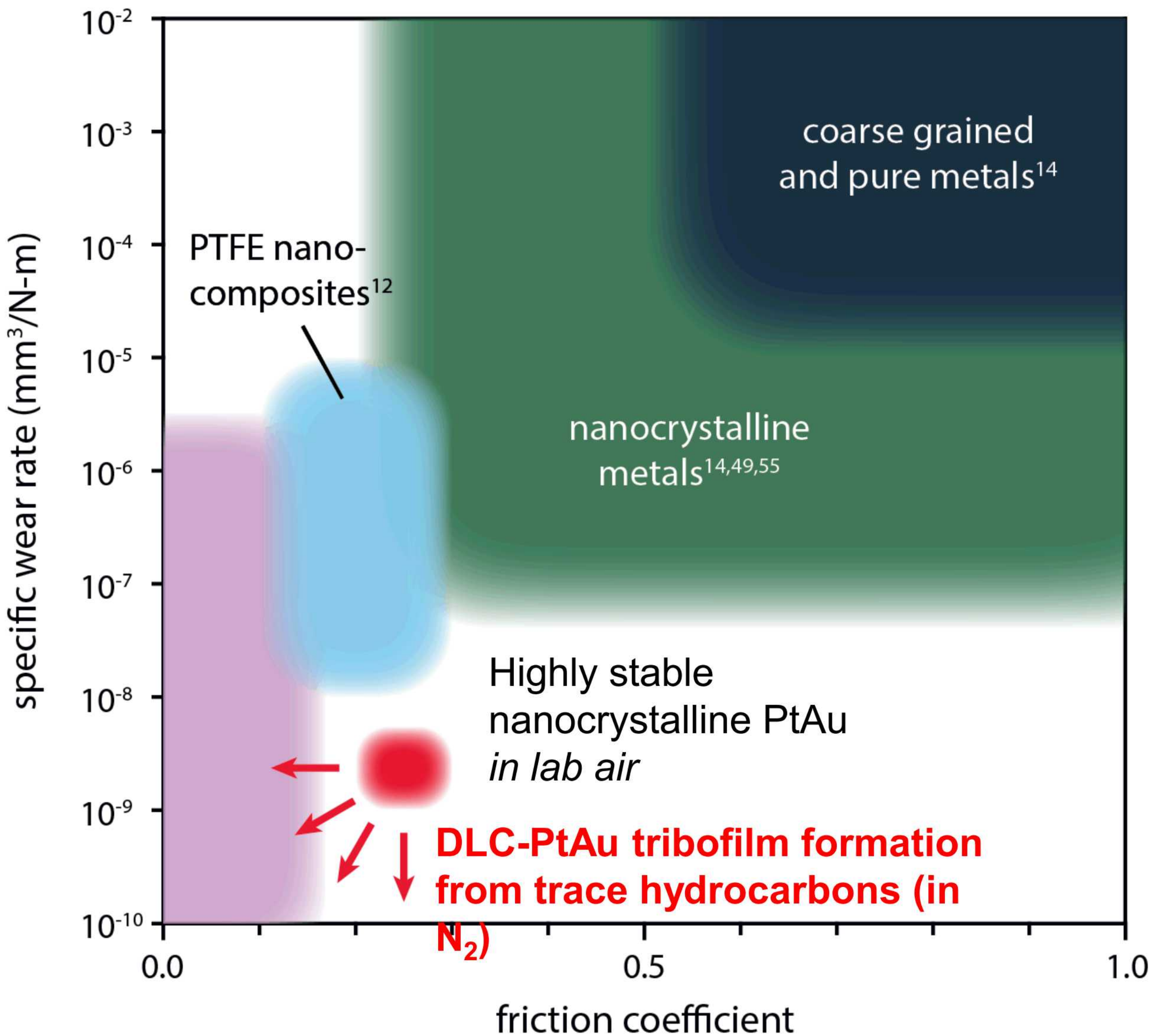
J. F. Curry, et al., Advanced Materials (2018)

Ultra-low wear rate of PtAu (3×10^{-9} mm³/N-m)



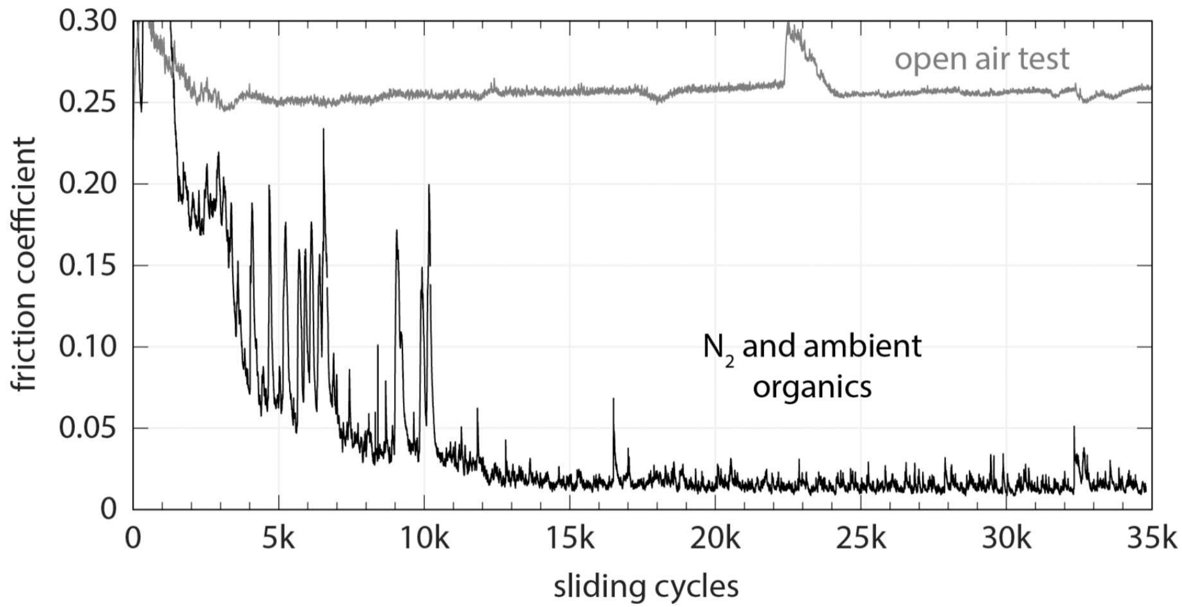
J. F. Curry, et al., ***Advanced Materials (2018)***

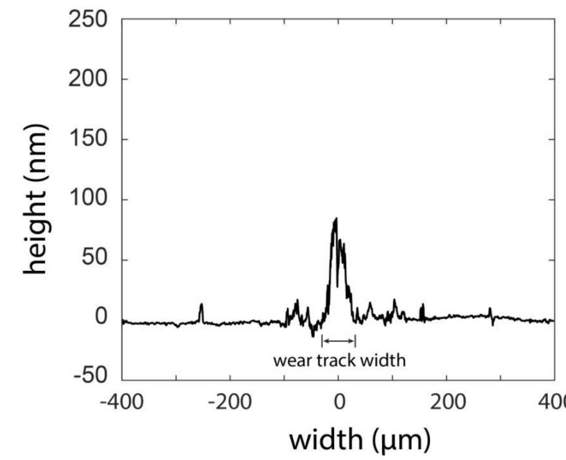
PtAu is great, but what about environment?

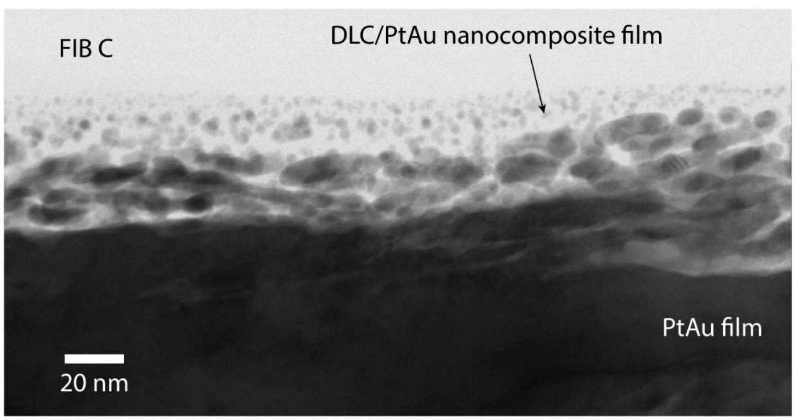


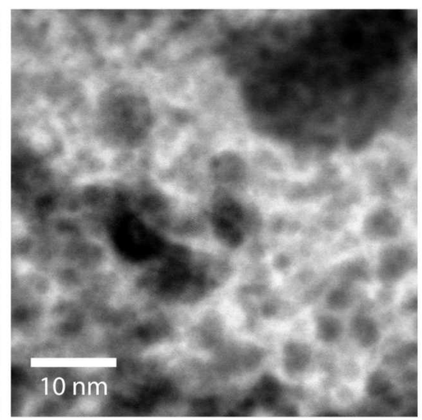
J. F. Curry, et al., ***Advanced Materials (2018)***

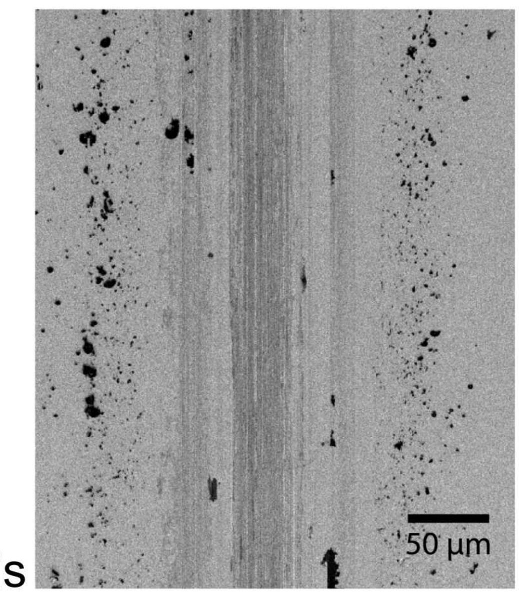
Friction Behavior in Anoxic Environments with Trace Hydrocarbons







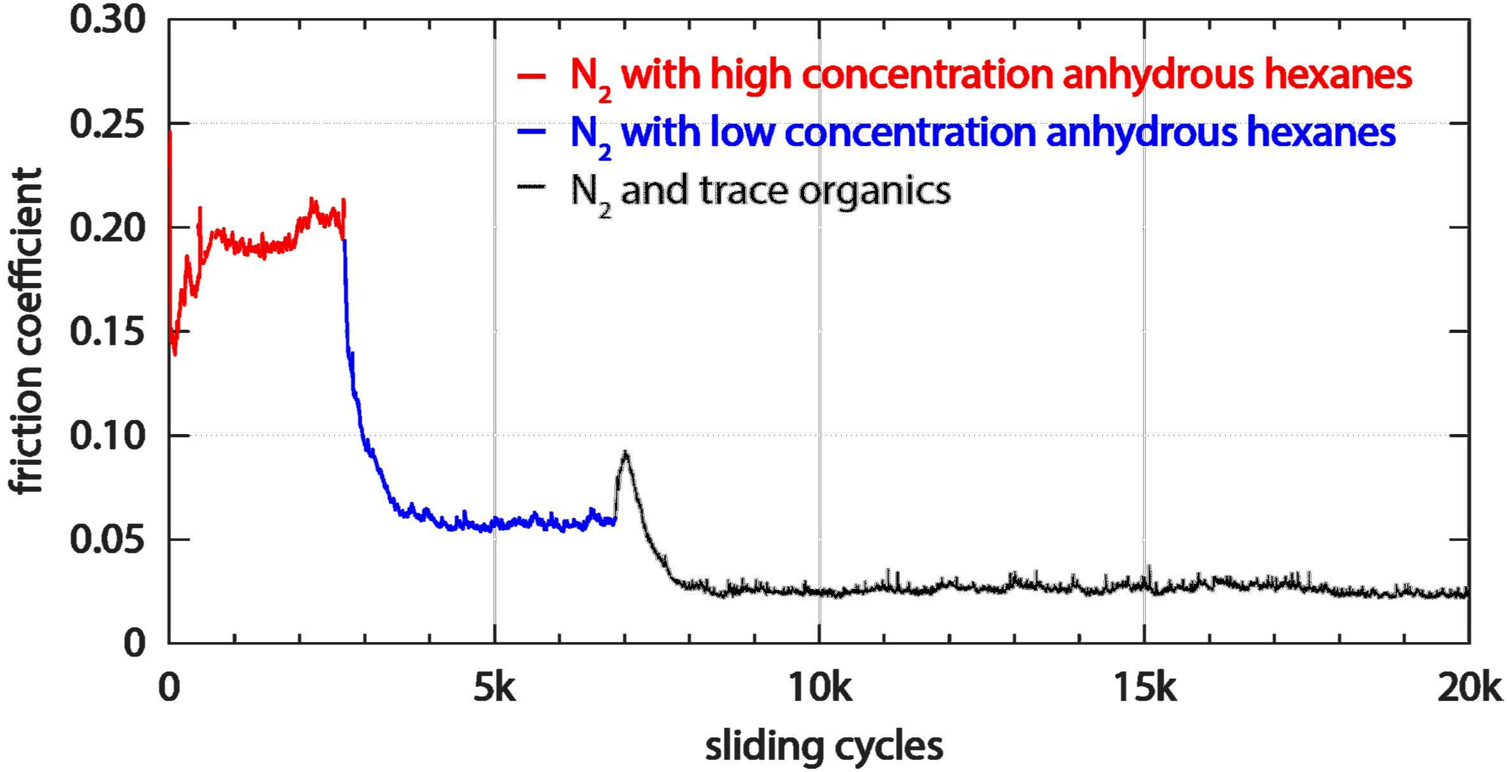




confirmed **diamond-like carbon (DLC)** using Raman analysis
with 20% hydrogenation using elastic recoil

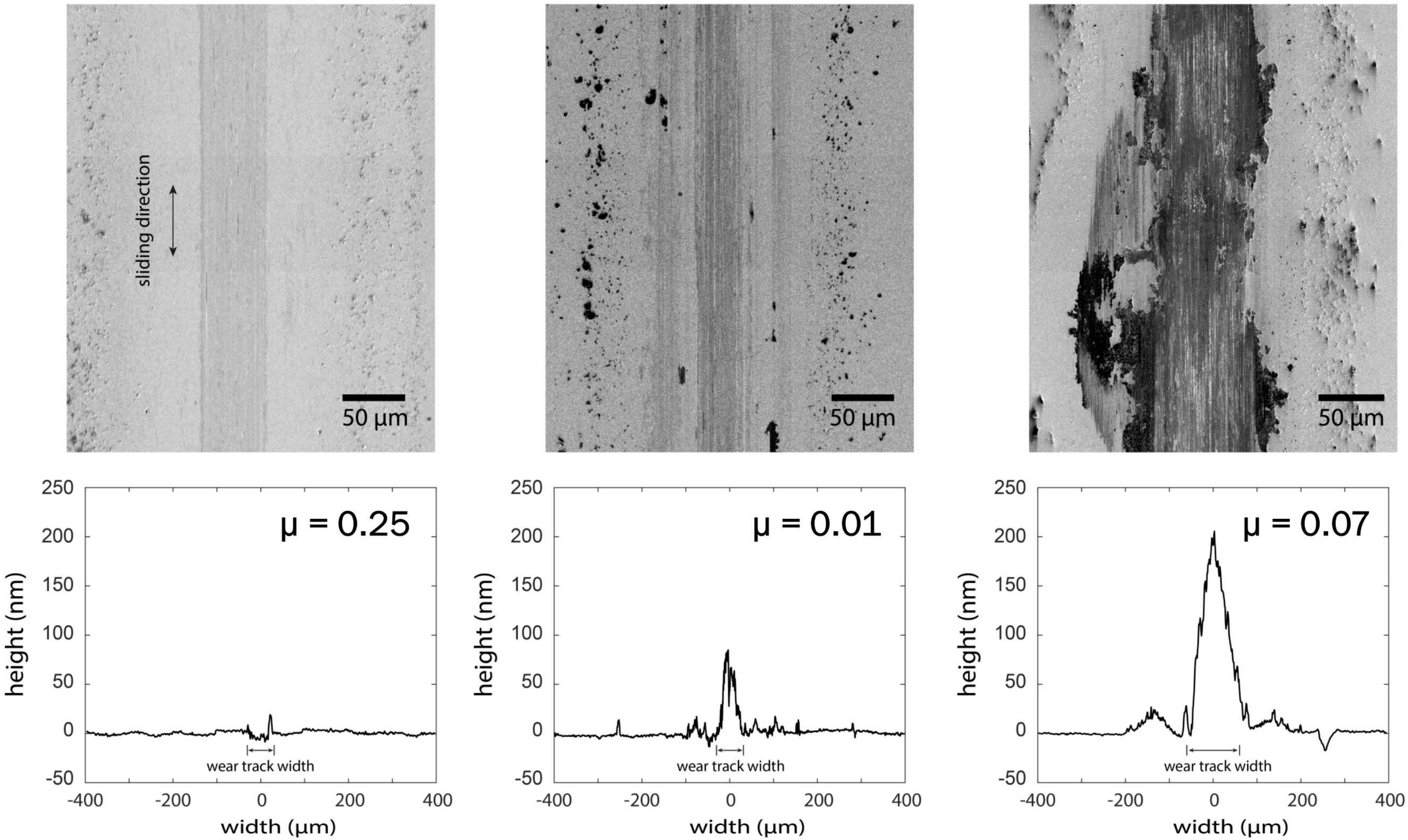
*N. Argibay et al., **Carbon (2018)***

Hydrocarbon concentration is important (competing rates)

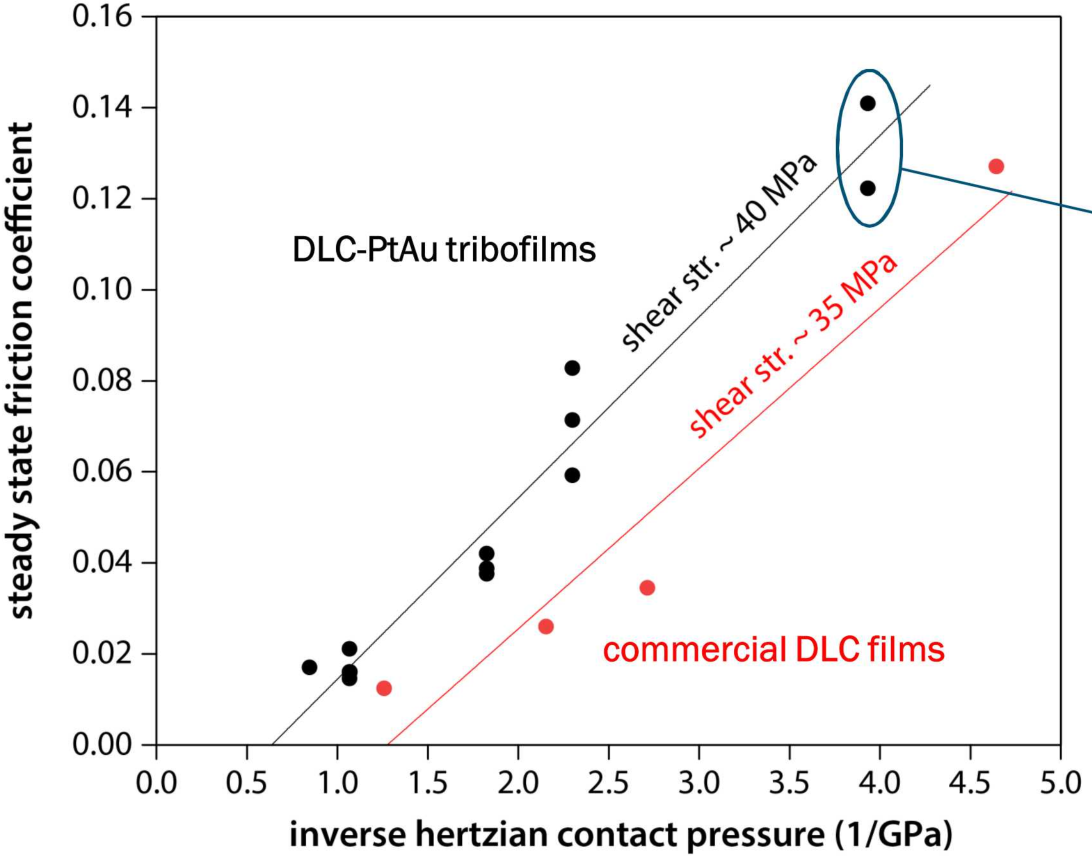


Hydrocarbon concentration is important (competing rates)

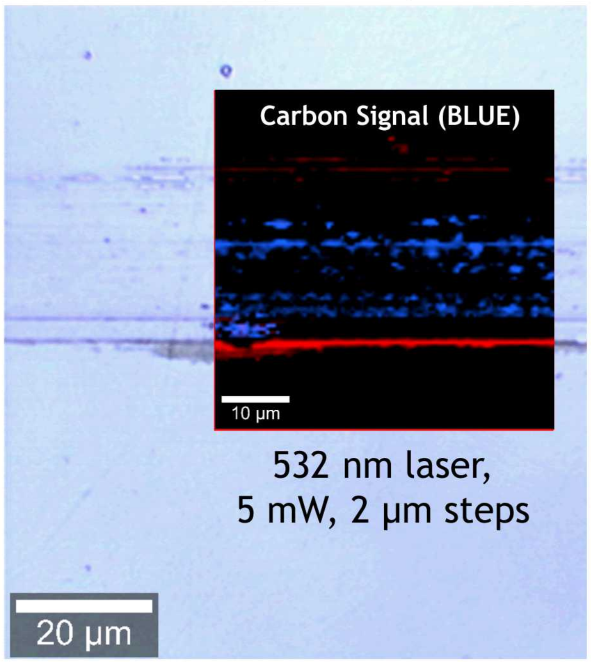
lab air | **N_2 and low concentration of hydrocarbons** | **N_2 and high concentration of hydrocarbons**

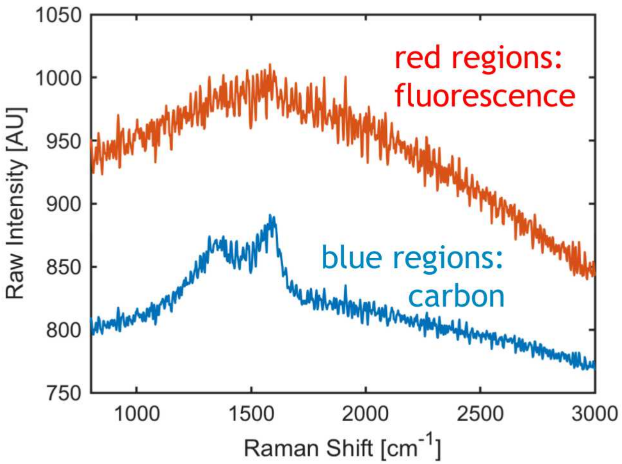


Load Dependent Friction Behavior of DLC-PtAu Tribofilm



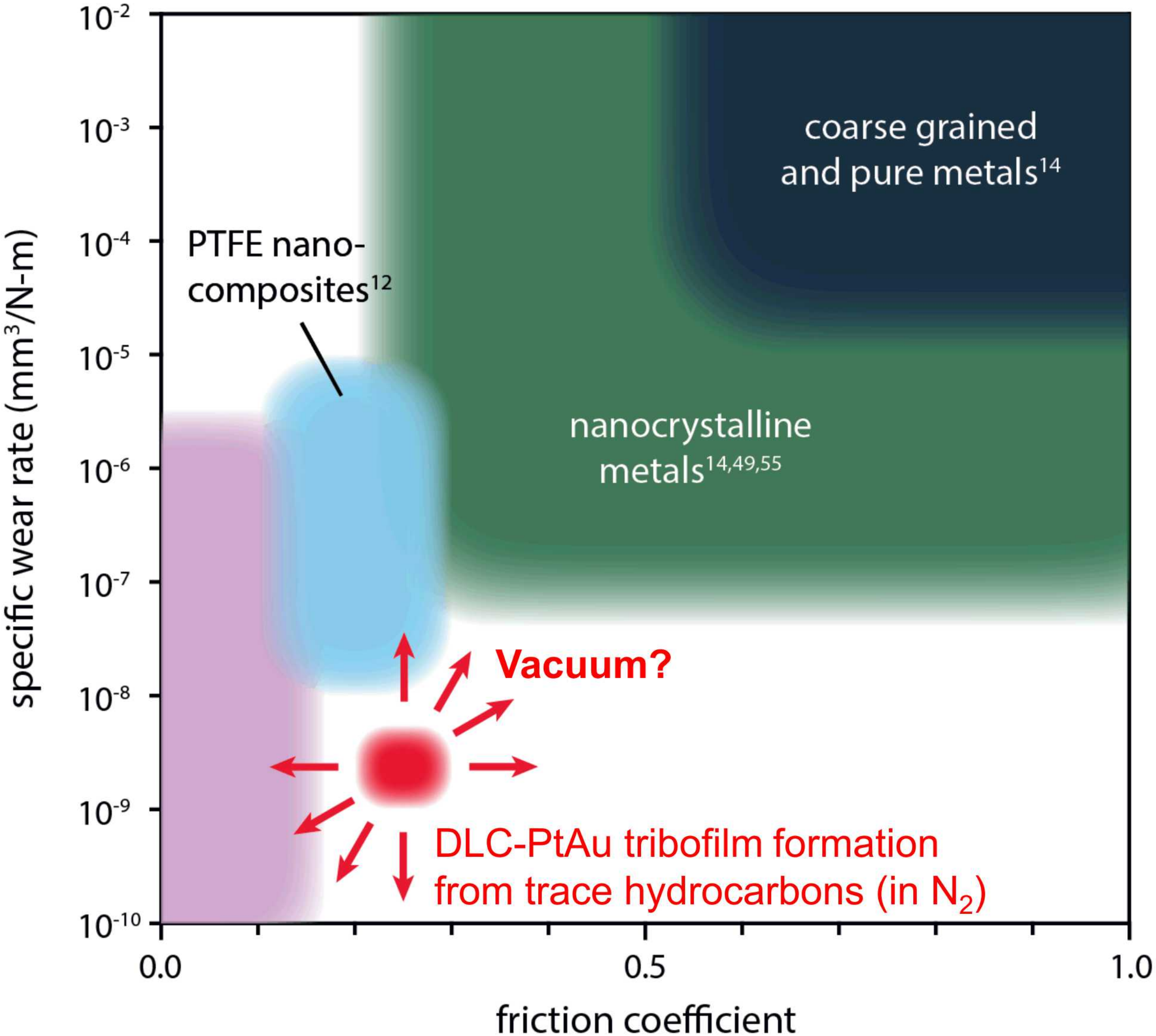
low load (10 mN) track





- Shear strengths are commensurate with commercial DLC films
- Even at low loads, we see DLC formation, though it is fractional

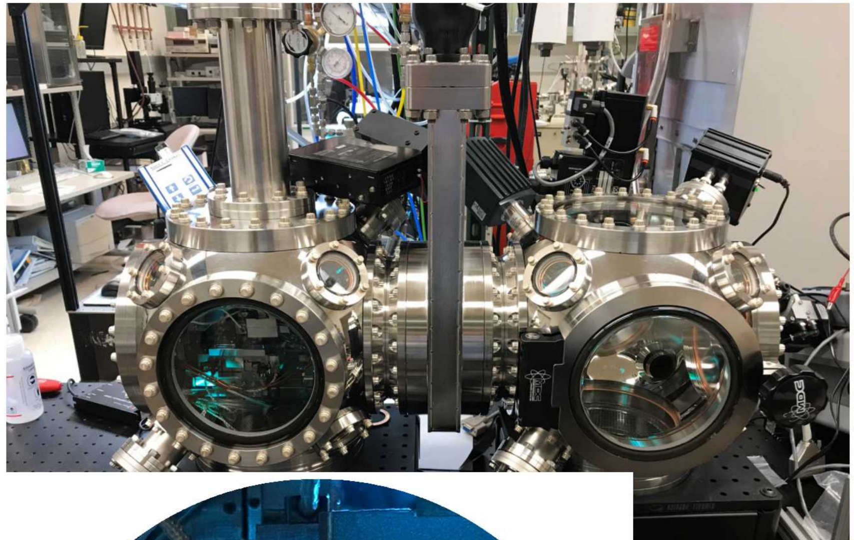
But wait! Are adsorbates the reason for low wear with PtAu in air?



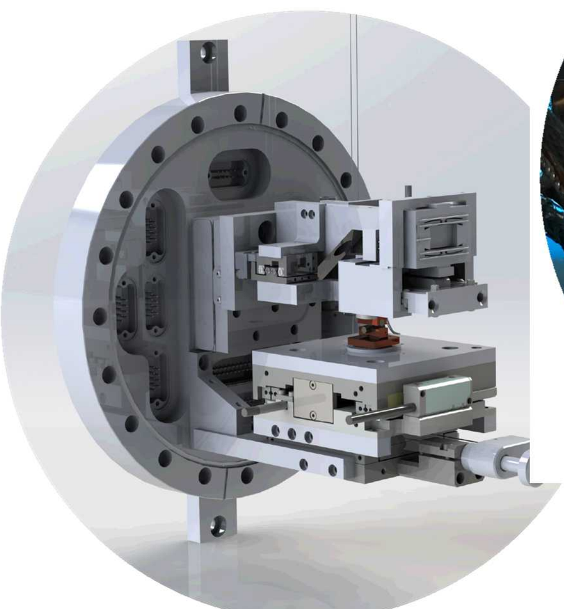
J. F. Curry, et al., ***Advanced Materials (2018)***

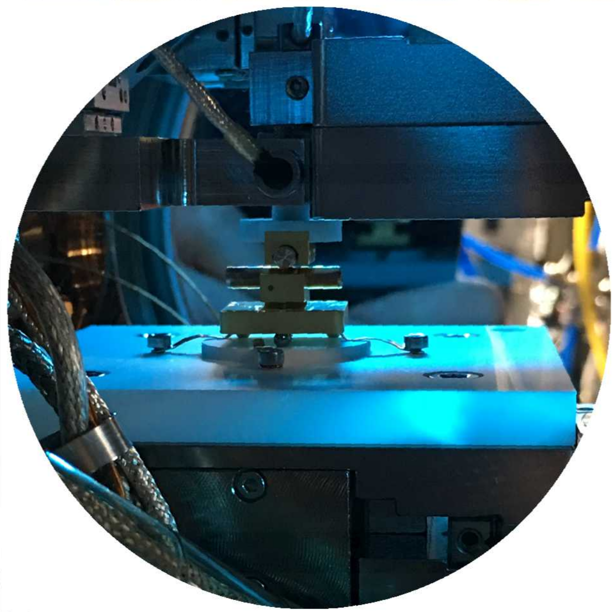
What about adsorbates? Wear of PtAu in UHV

Left Module:
- Linear Reciprocator
- Load metering
- Cryo stage (4–800K)
- 10^0 to 10^{-9} torr
- 0.1 mN to 1 N
- 100 μm/s – 100 mm/s
- 10 kHz acquisition
- capacitive displacement sensors & flexural cantilevers



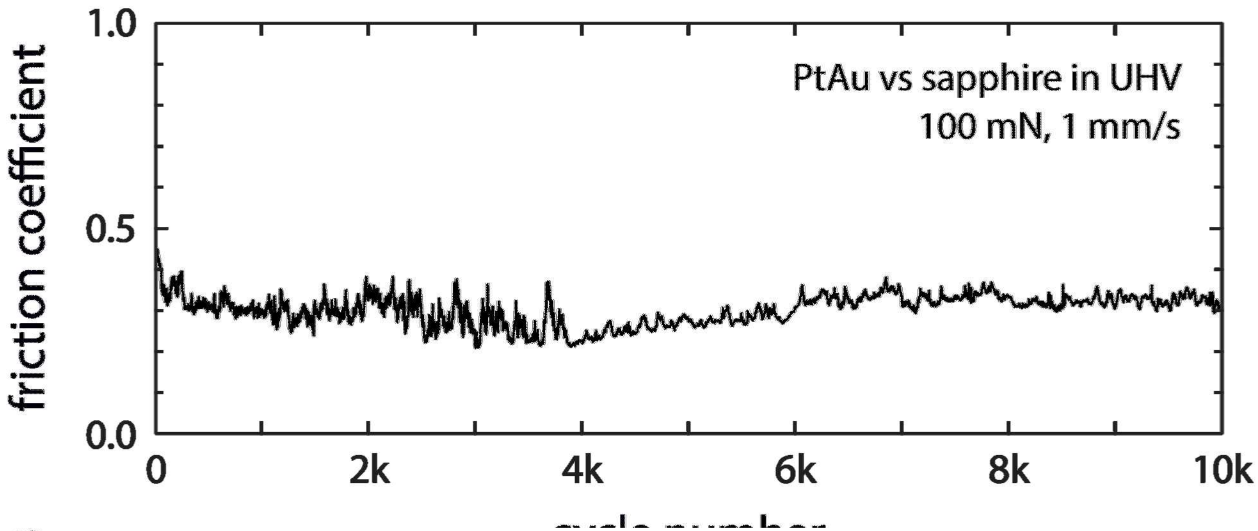
Right Module:
- Rotary Module
- Dead weight
- 5 mN to 10 N
- 100 Hz acquisition
- 10^0 to 10^{-9} torr
- Strain gage sensor

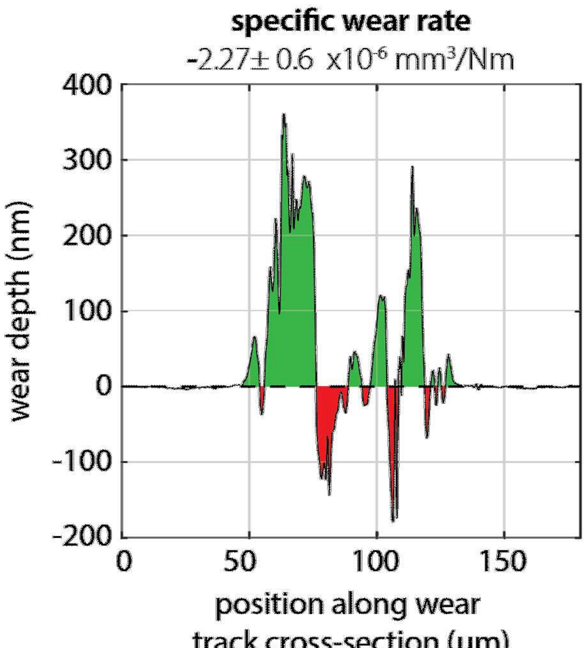


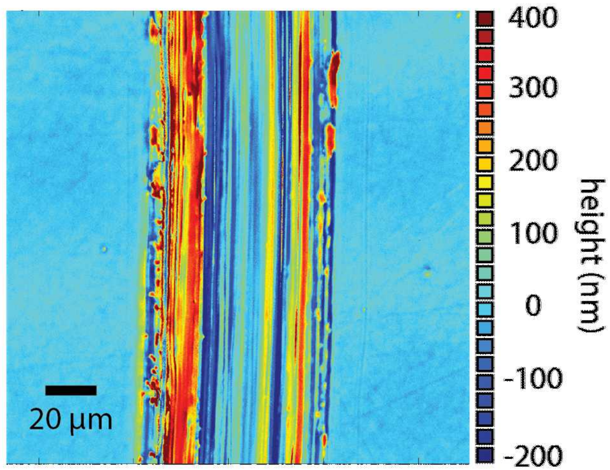


crossed-cylinders and sphere-on-flat configurations

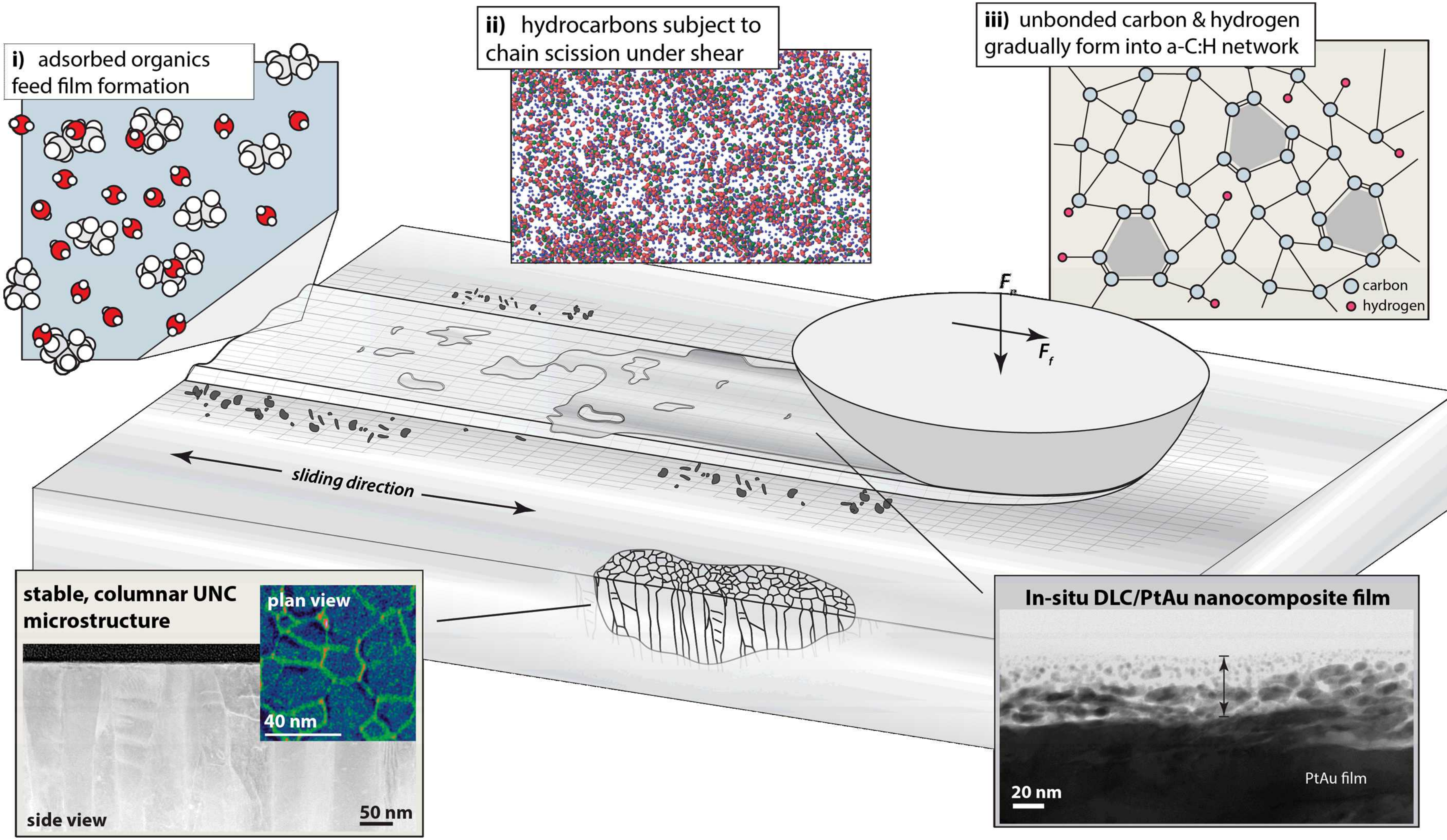
PtAu films sliding against sapphire in UHV retain low friction/wear







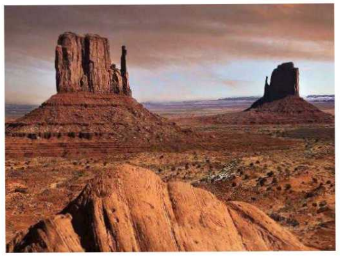
<u>Negative</u> wear rate (i.e., film growth) after 10k sliding cycles against sapphire in UHV…


i) adsorbed organics feed film formation
ii) hydrocarbons subject to chain scission under shear
iii) unbonded carbon & hydrogen gradually form into a-C:H network
carbon
hydrogen
F_n
F_f
sliding direction
stable, columnar UNC microstructure
plan view
40 nm
side view
50 nm
In-situ DLC/PtAu nanocomposite film
PtAu film
20 nm

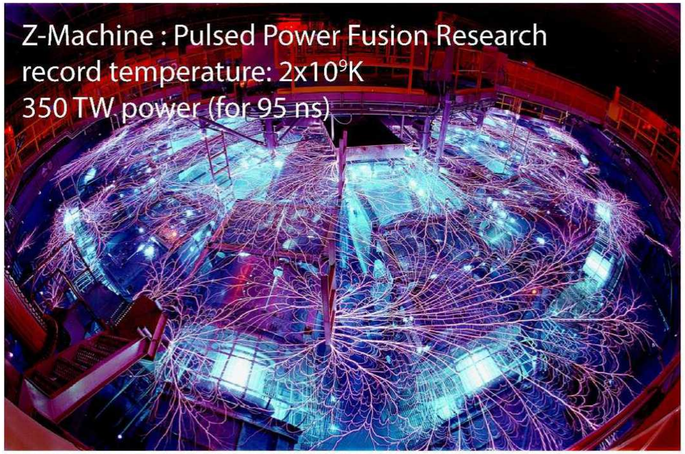
Questions?

Supplemental Slides

Albuquerque, NM:



Sandia National Laboratories – Some Highlights



Contact stress dependent friction of DLCs and DLC-PtAu