SAND2021-3568C

Tribological and Mechanical Properties of High Entropy Alloys



PRESENTED BY

Morgan Jones

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Our Group + Collaborators

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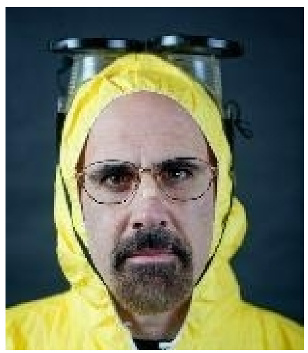


Mike Chandross

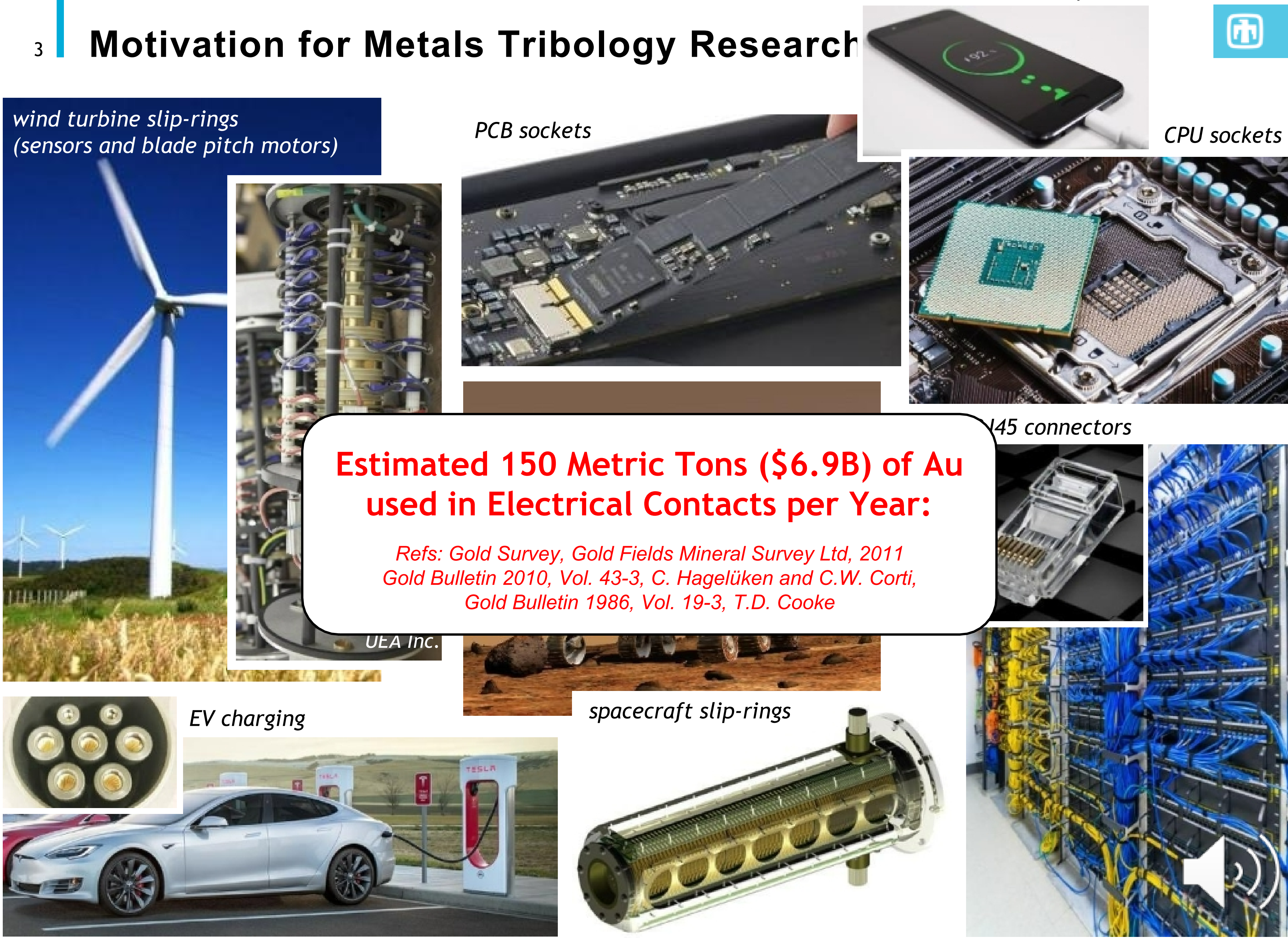
John Curry

Tomas Babuska

Brendan Nation

John Johnson

Motivation for Metals Tribology Research

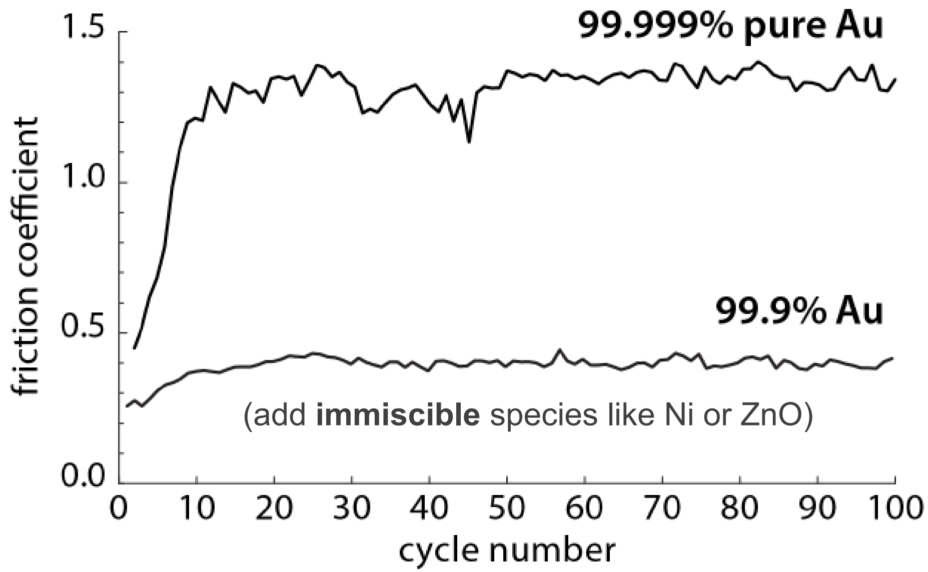


Estimated 150 Metric Tons ($6.9B) of Au used in Electrical Contacts per Year:

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

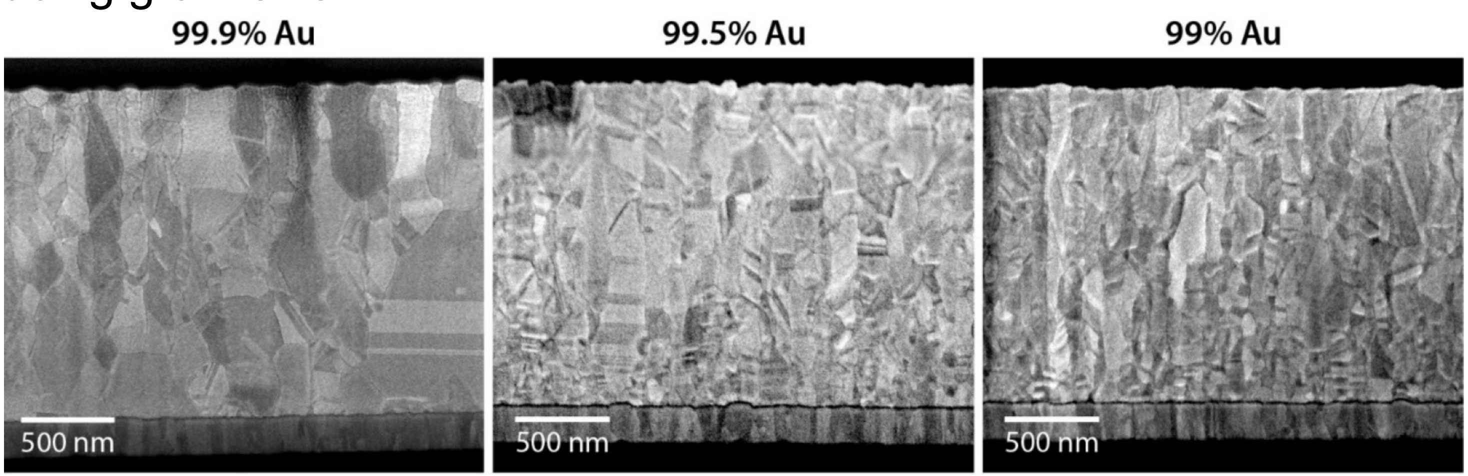
Structure-Dependent Friction of (Bare) Metals

Alloying reduces friction coefficient:



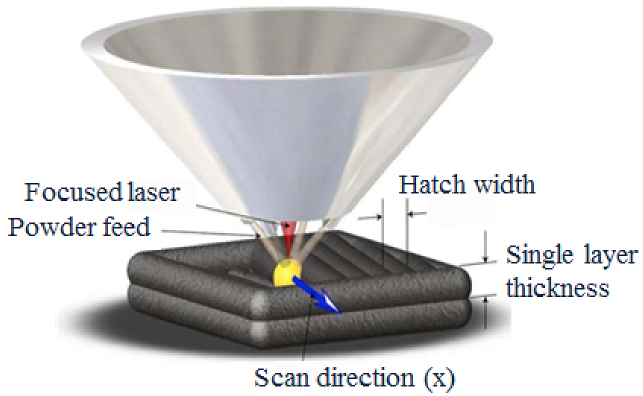
Alloying improves friction & wear performance by reducing and stabilizing grain size

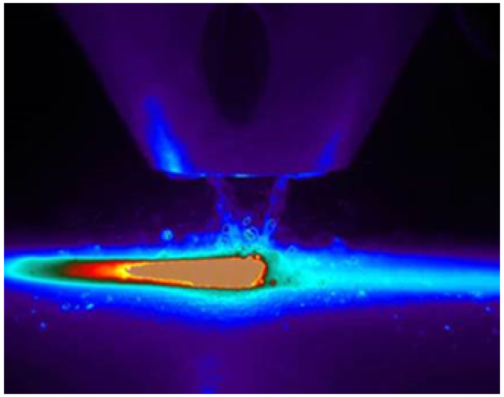
…by reducing grain size:



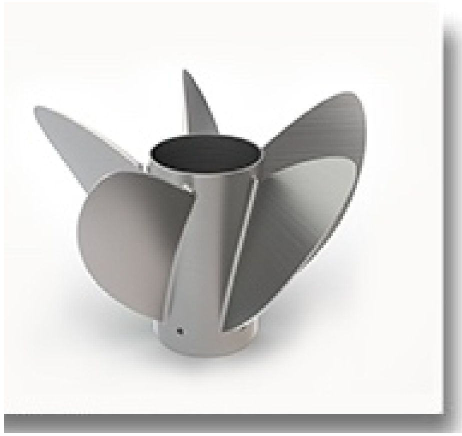
Realizing the Potential of AM

Long-Term Goal: Enable tools like SNL's LENS (Laser Eng. Net Shaping)…





… to make "born qualified" parts (i.e., reliably high strength, ductility, etc):



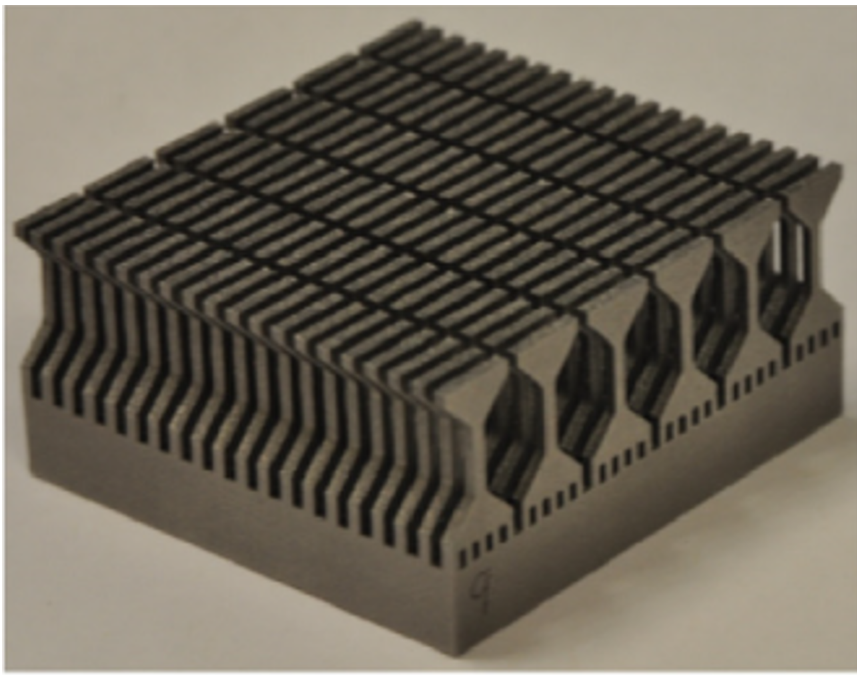
Prototype Airbus A380 bracket

Source: https://www.sciaky.com/additive-manufacturing/contract-additive-manufacturing-services

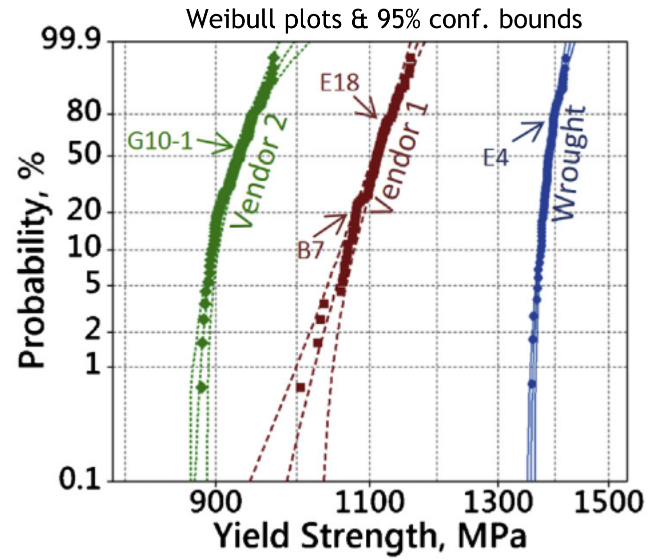
Source: https://www[illegible]metal-am.com/[illegible]duction-to-metal-a[illegible]tive-manufacturing-and-3d-printing/

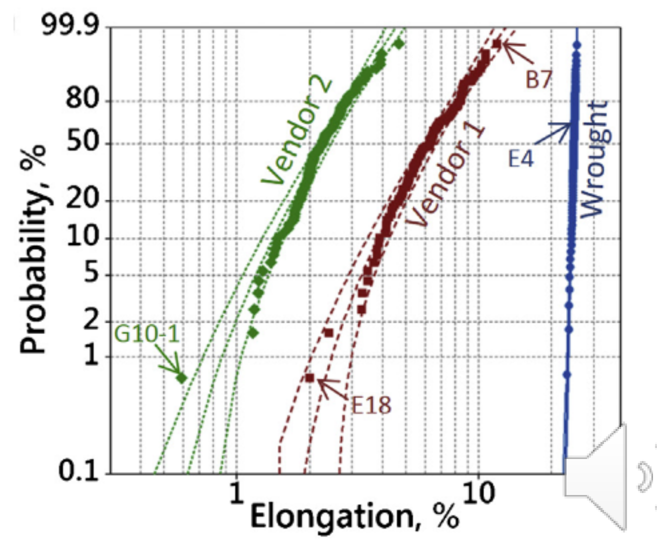
But Conventional Alloys (Steel) Not Optimal For AM

Laser consolidated (powder bed) 17-4 PH Steel:



Conclusion: Reduced strength AND elongation to failure (ductility) attributed to higher surface roughness, porosity, and microstructure (e.g., grain size).





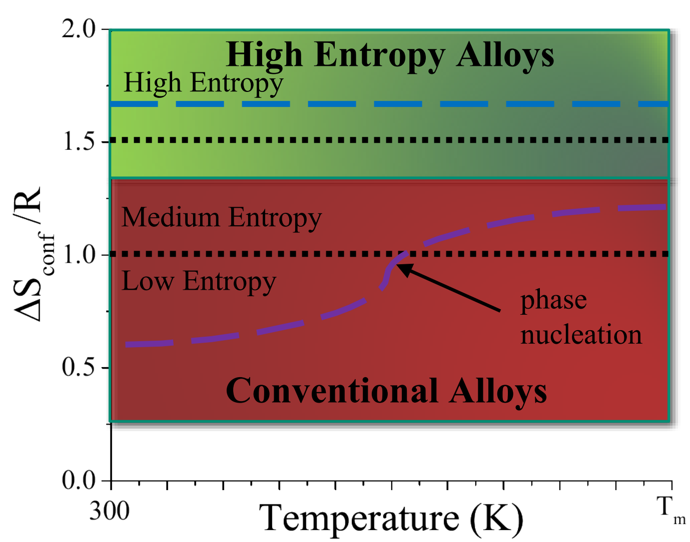
Ref: B. Salzbrenner, et al., **J. Mat. Proc. Tech. 2017**

Why Are We Printing High-Entropy Alloys?

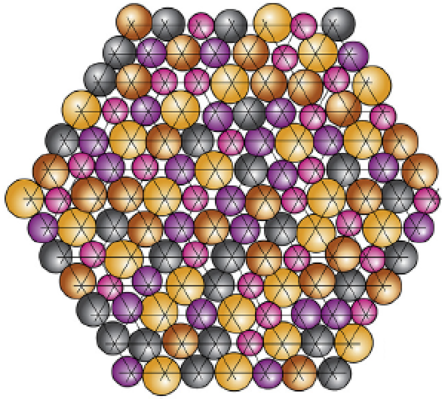
High Entropy Alloys: primarily solid solution alloys that contain 5+ alloying constituents, where microstructures have high configurational entropy (≥ 1.4R).

Competition between Gibbs energy for solid solution and intermetallic formation

$$\Delta G^{SS} < \Delta G^{IM} \quad \rightarrow \quad \Delta S^{SS} > \frac{\Delta H^{IM} - \Delta H^{SS}}{T}$$



D. Miracle et al., Entropy, 2014

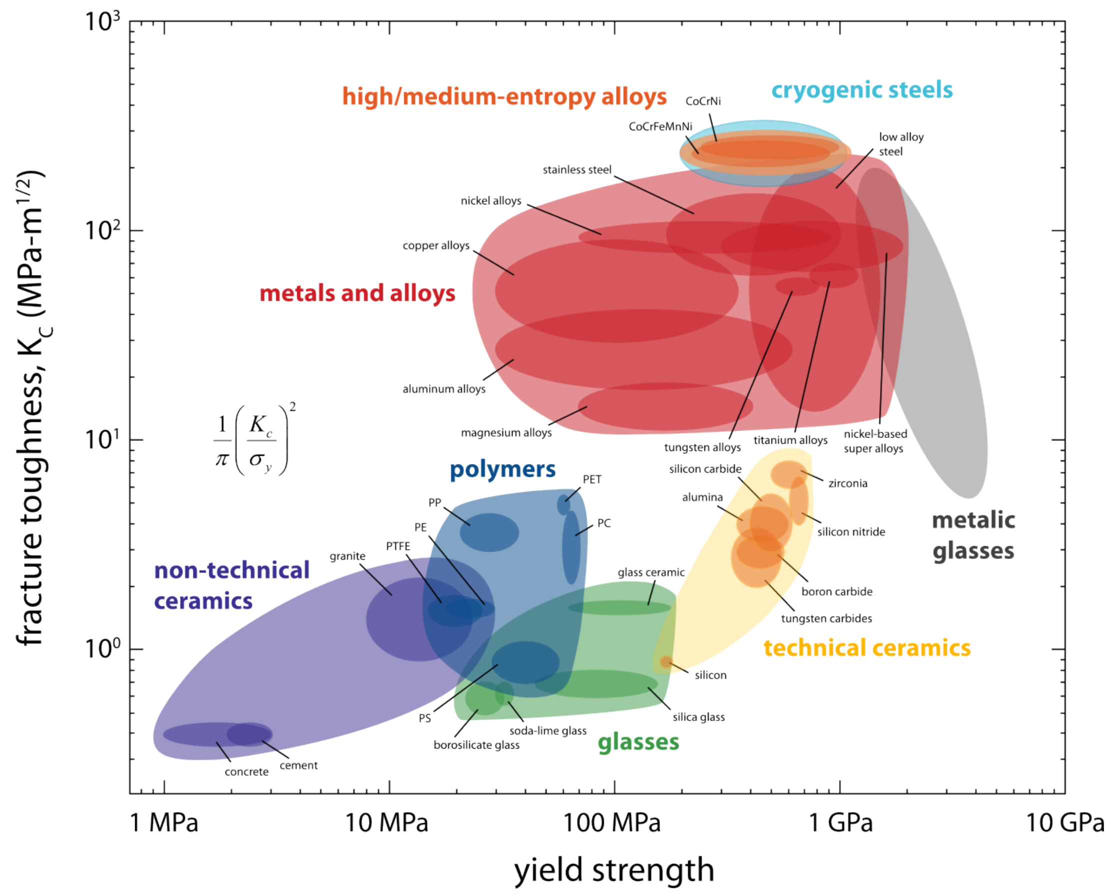


disordered solid solutions

Miracle, et al., Acta Mat., 2017

These alloys derive much of their strength from solution strengthening, and are insensitive to processing conditions (i.e., thermal history).

Why Are We Printing High-Entropy Alloys?

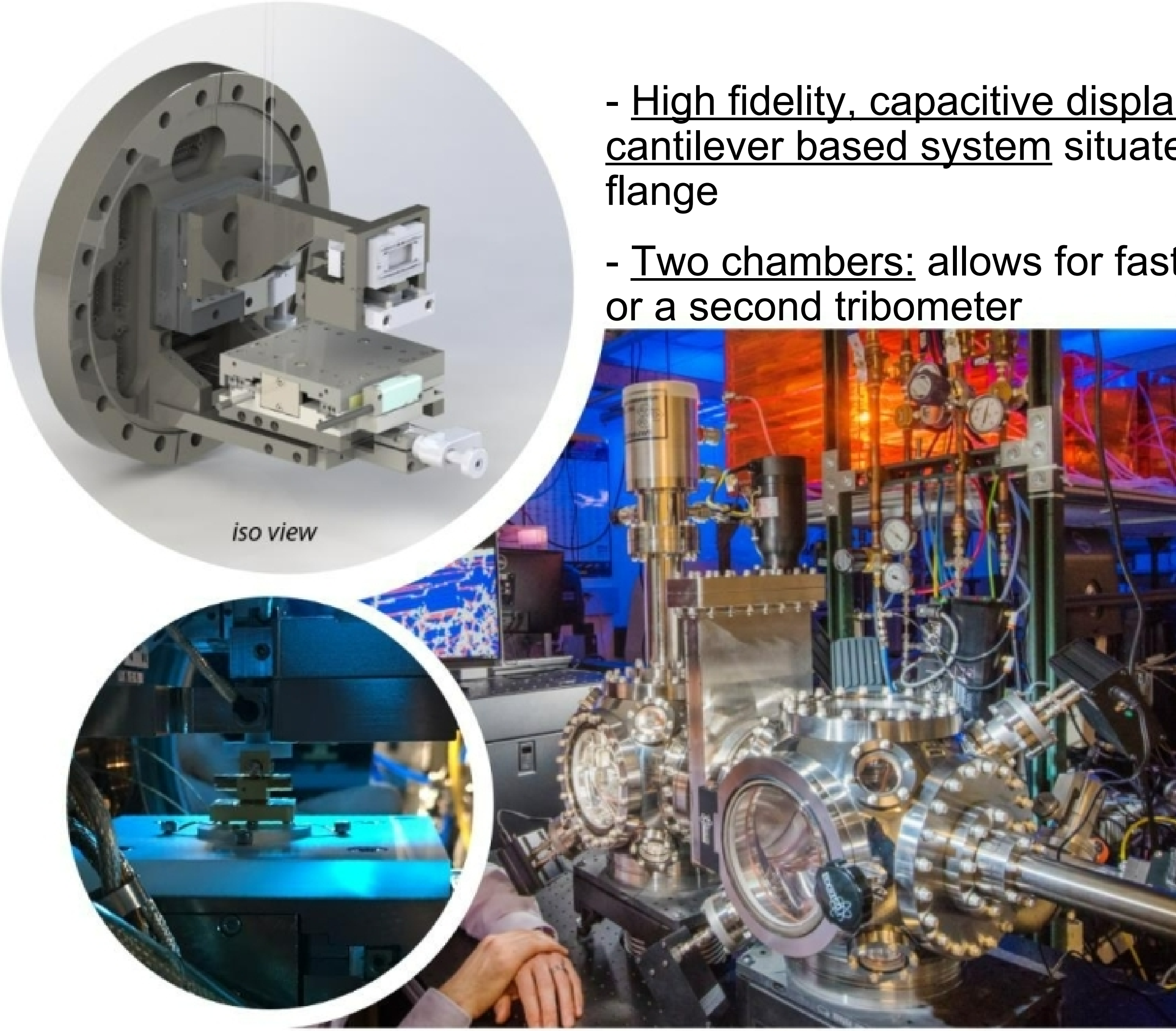


HEAs have properties exceeding most conventional alloys, suggesting improved resistance to failures AM defects.

Goal: demonstrate these alloys as a materials-based solution to ***achieve the promise of metal AM, i.e. insertion into high consequence applications***.

(George, Nature Mat Rev, 2019)

A Starting Point: Use UHV tribometer to Probe (Bare) Metal



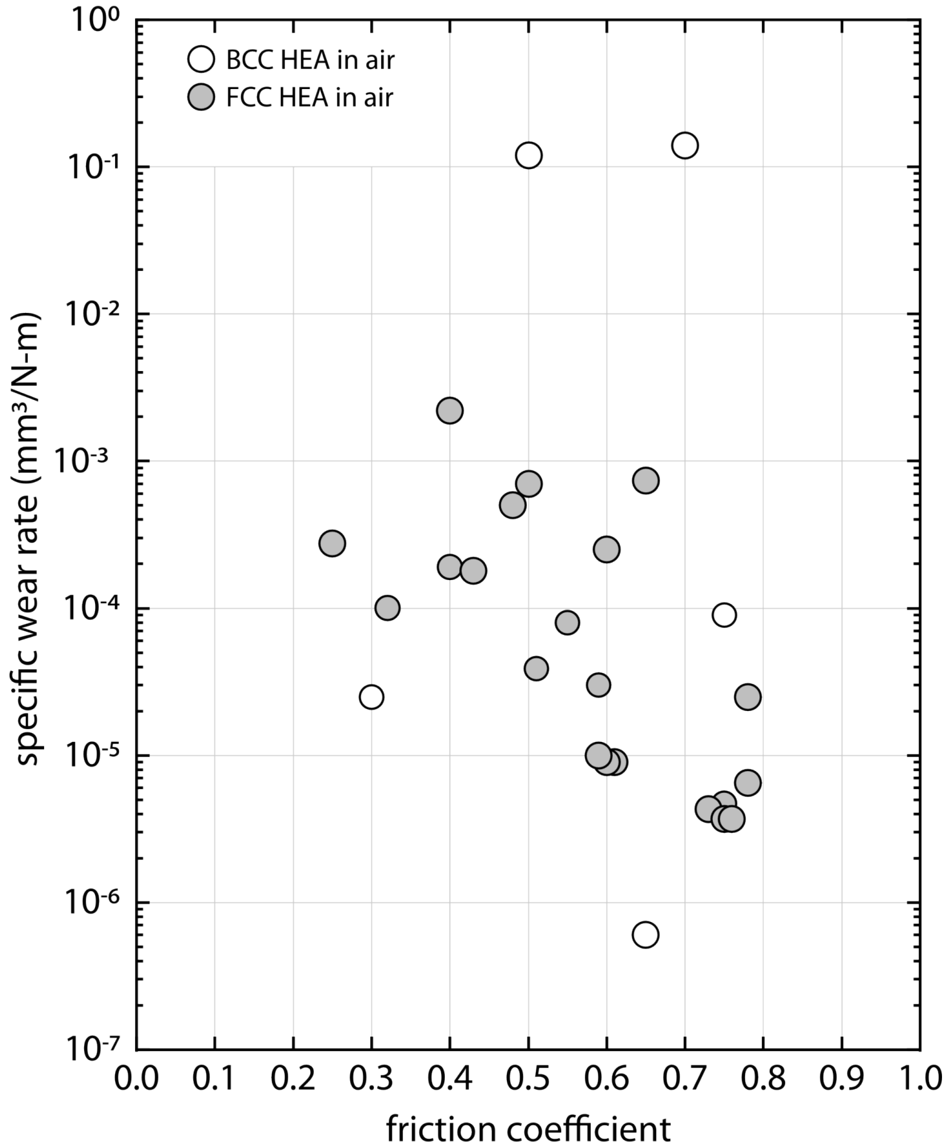
- High fidelity, capacitive displacement & flexural cantilever based system situated on 8” CF vacuum flange

- Two chambers: allows for fast entry transfer system or a second tribometer

Specs

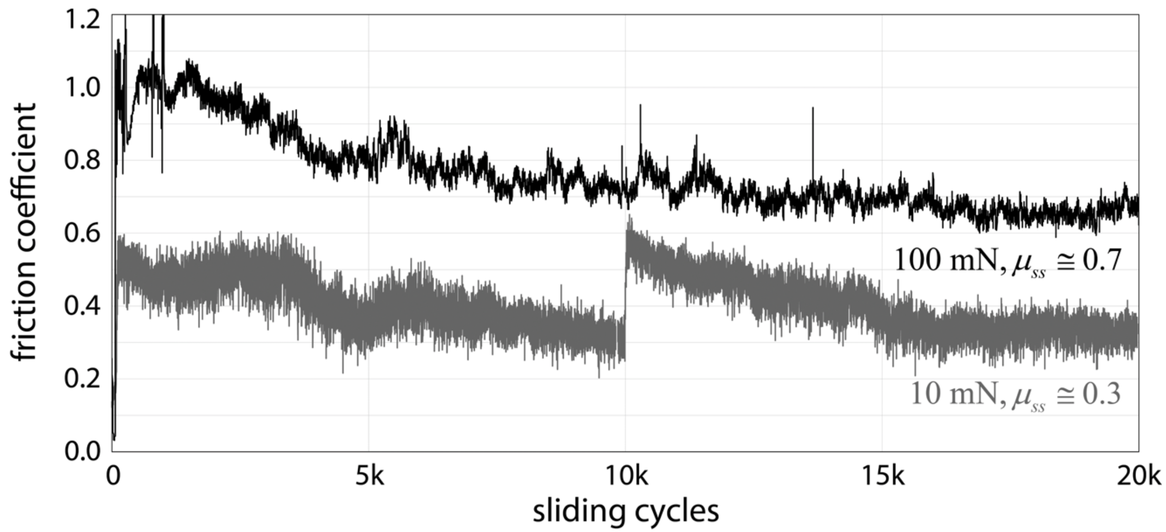
- Linear reciprocating motion
- Load metering (0.1 mN to 1N)
- Cryo stage (4–800K; actual +/-150C)
- 10^0 to 10^{-9} torr
- 100 µm/s – 100 mm/s
- 10 kHz acquisition

Literature Survey ... No Data for Bare Metal Properties

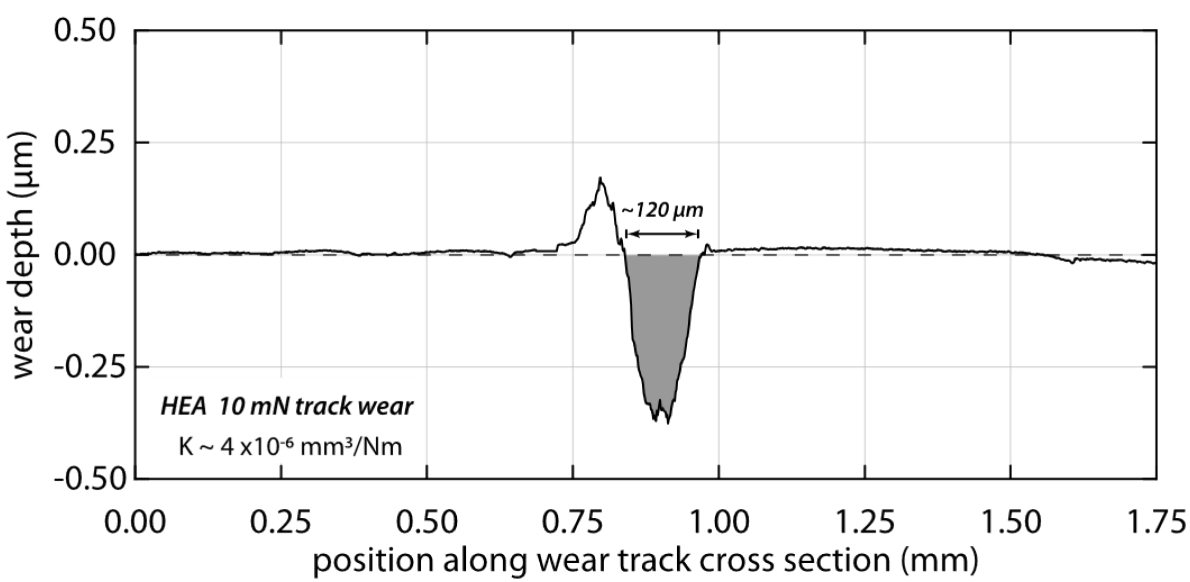


(Jones et al, Sci. Reports 2020)

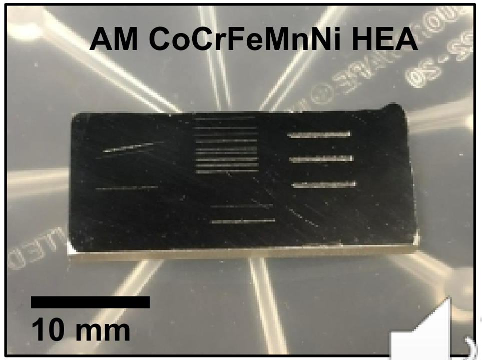
Friction and Wear Testing



UHV testing in the absence of environment allows us to probe fundamental friction behavior of Cantor HEA sliding against a sapphire sphere under different loading conditions.



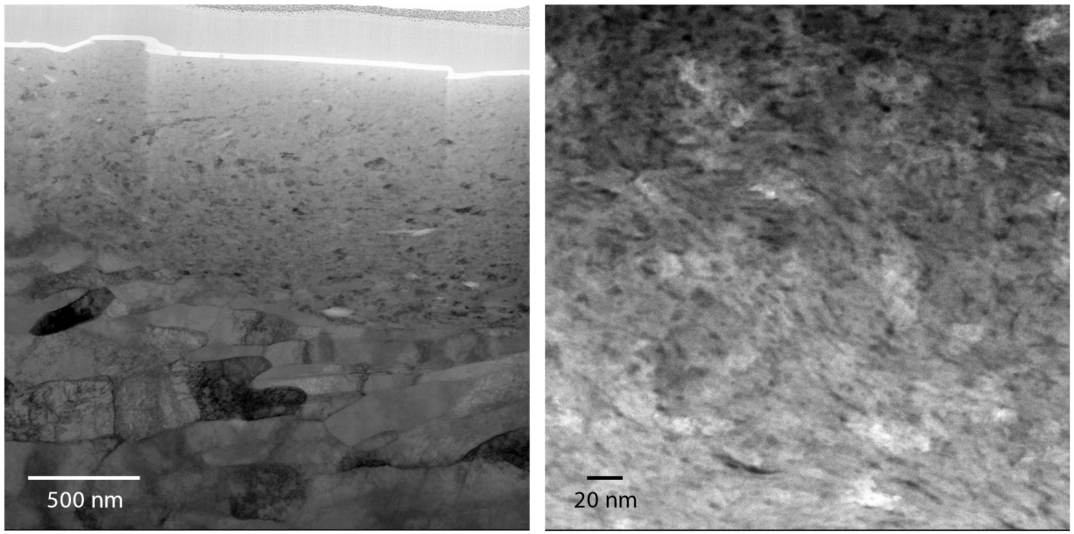
For a relatively soft material, it exhibited high wear resistance.



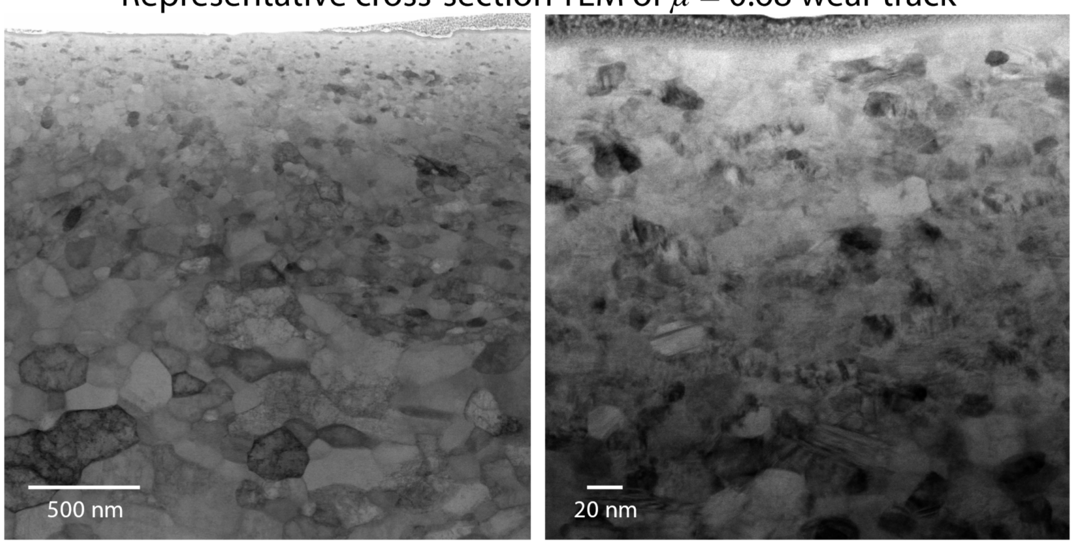
(Jones et al, Sci. Reports 2020)

Different Friction Behavior - TEM of Wear Track Microstructure

Representative cross-section TEM of $\mu = 0.32$ wear track



Representative cross-section TEM of $\mu = 0.68$ wear track



initial grain size 1-10 µm

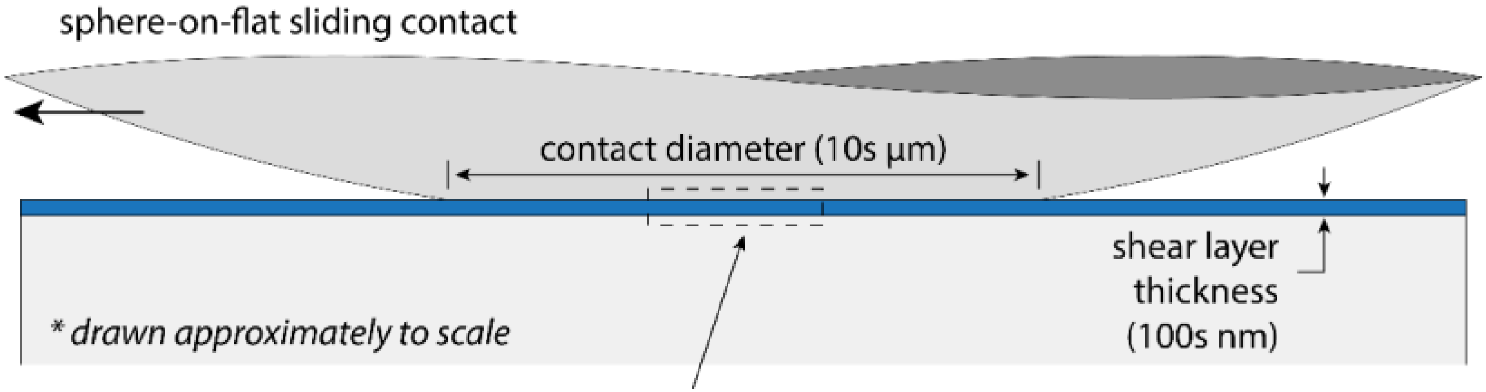
10 mN track showed an average grain size below 10 nm

100 mN track showed a slightly larger average grain size of ~ 20 nm

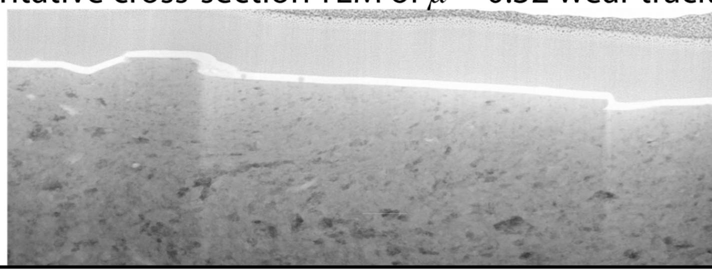
low friction 10 mN wear track surface falls within inverse HP regime

(Jones et al, Sci. Reports 2020)

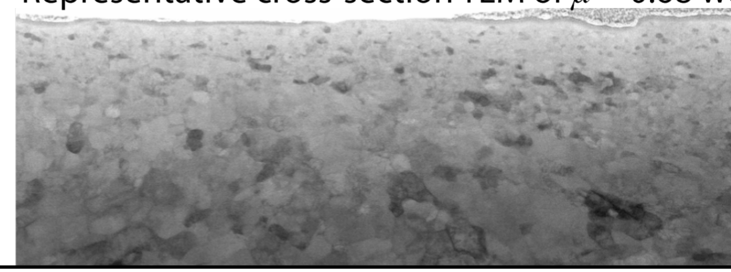
Lower Friction is a Result of Surface Grain Refinement



Representative cross-section TEM of $\mu = 0.32$ wear track



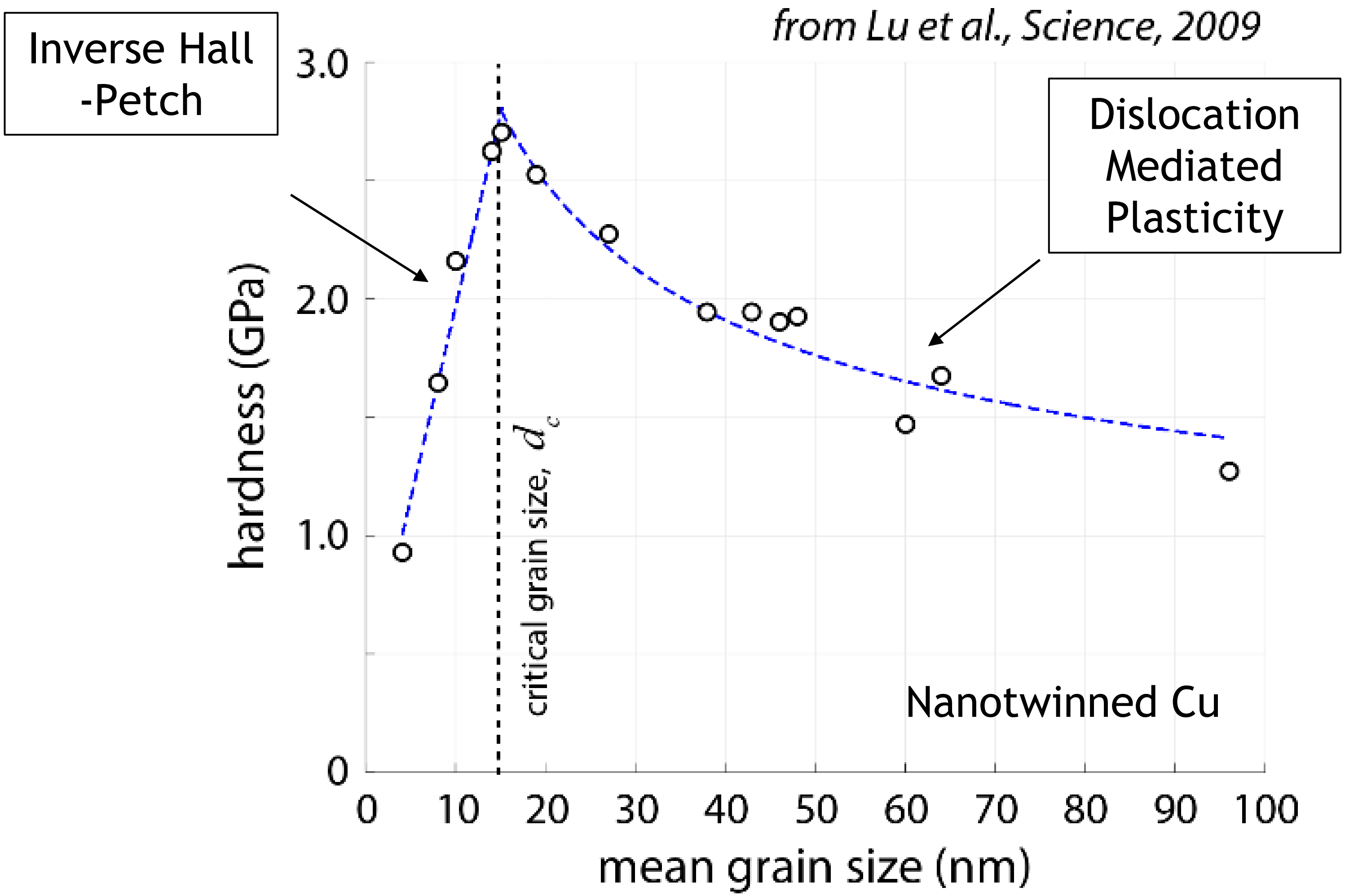
Representative cross-section TEM of $\mu = 0.68$ wear track



It is useful to define the friction coefficient of metals as the ratio of interface shear strength and bulk hardness:

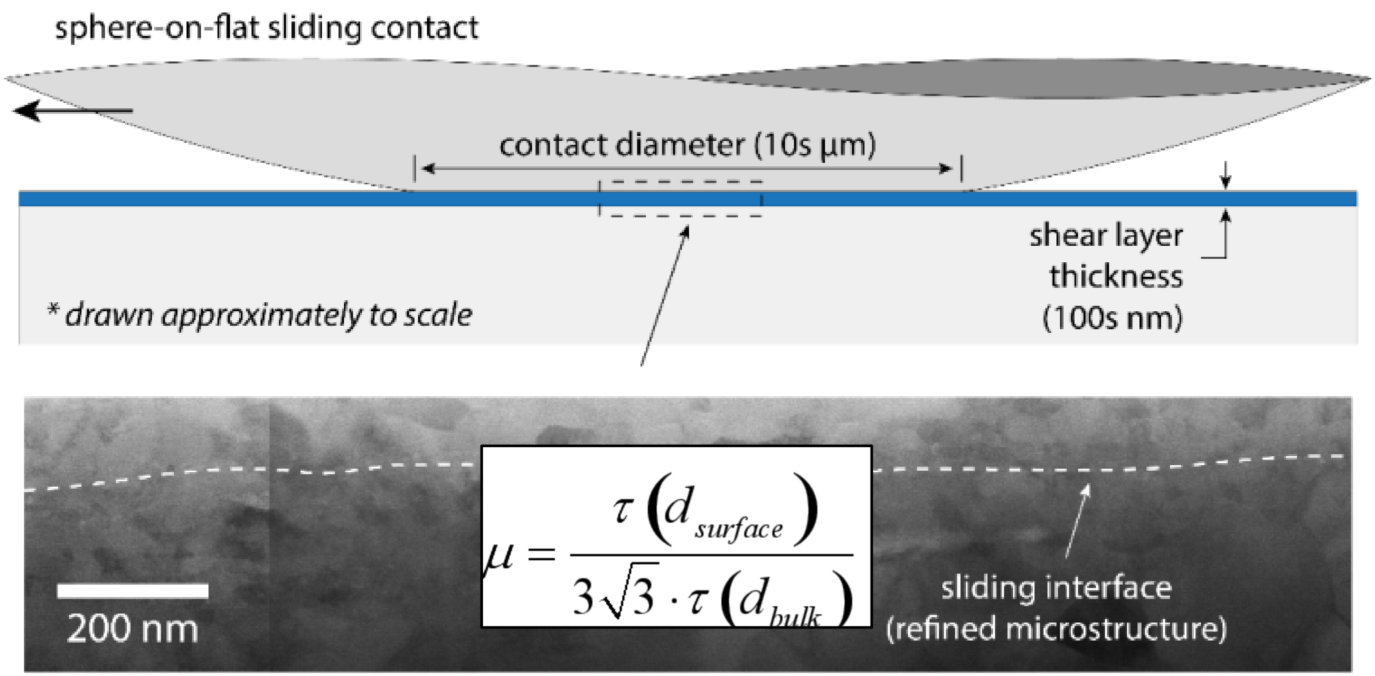
Bowden & Tabor: $\mu = \frac{\tau}{H}$ $\xrightarrow{\text{Tabor}}$ $\mu = \frac{\tau}{3 \cdot \sigma_Y}$ $\xrightarrow{\text{von Mises}}$ $\mu = \frac{\tau\left(d_{surface}\right)}{3\sqrt{3} \cdot \tau\left(d_{bulk}\right)}$

Inverse Hall-Petch Regime (Softening) is Key to Low Friction



Fundamental mechanism of softening during sliding remained poorly understood…

New Model Developed Based on Dynamic Amorphization



Energy barrier (or stress) for the creation of a dynamic amorphous interface, which is analogous to generating a continuous high angle grain boundary…

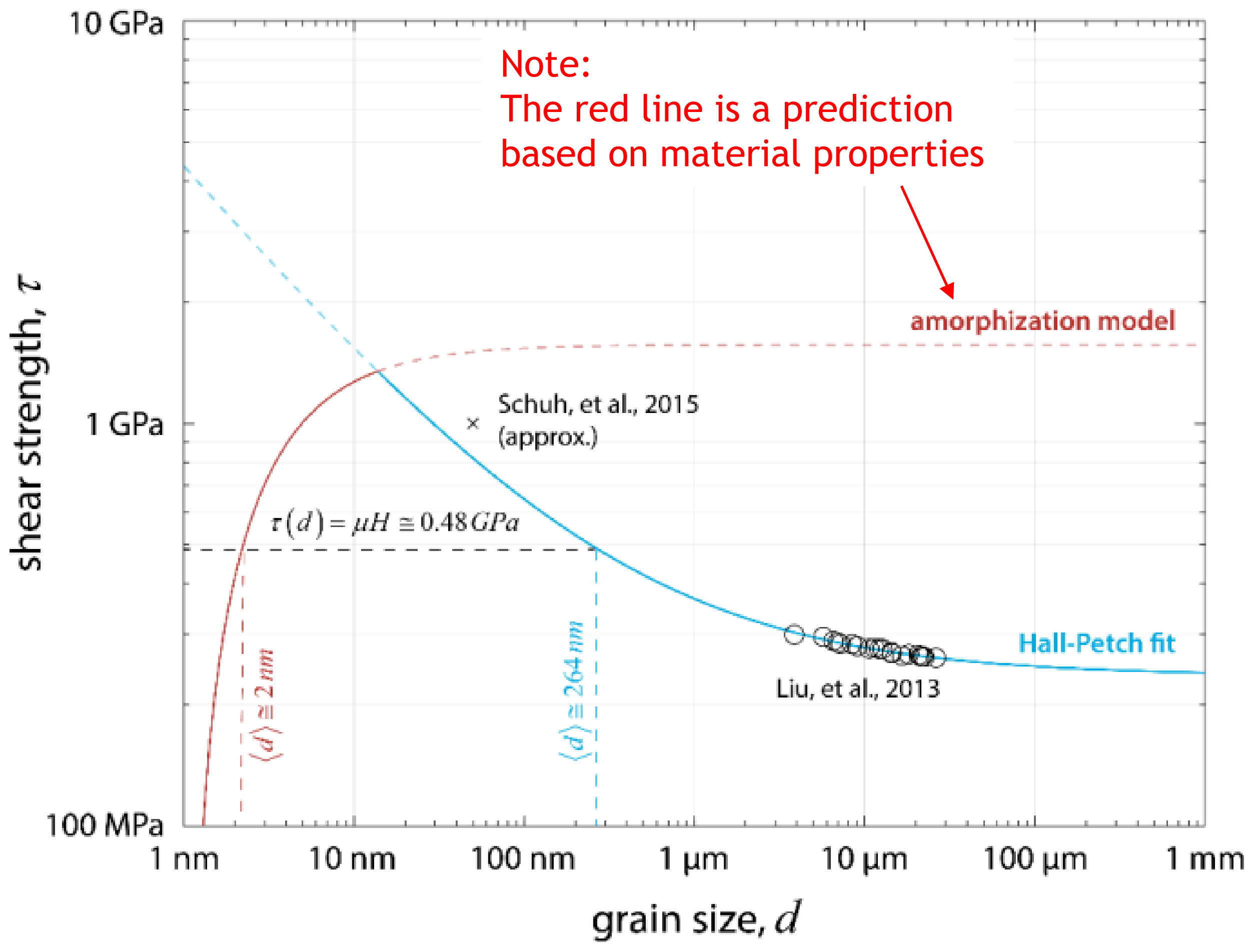
Amorphization model: $$\tau(d) = \left(L\frac{\rho_L}{M}\right)\left(1-\frac{T}{T_m}\right)\left(\frac{d-\delta}{d}\right)^3 + \left(\frac{\dot{\varepsilon}_{GBS}}{\dot{\varepsilon}_{tot}}-1\right)\frac{kT}{b^3}$$

atomic volume of amorphous metal (ρ_L); *volume fraction of GB to crystal* ($\left(\frac{d-\delta}{d}\right)^3$); *thermal energy* ($kT$); *heat of fusion* ($L$); *homologous temperature* (T/T_m); *strain rate (0 to 1)* ($\dot{\varepsilon}_{tot}$); *per atomic diameter^3* (b^3)

No fitting parameters!

(Argibay & Chandross, PRL, 2020)

Model Predictions?



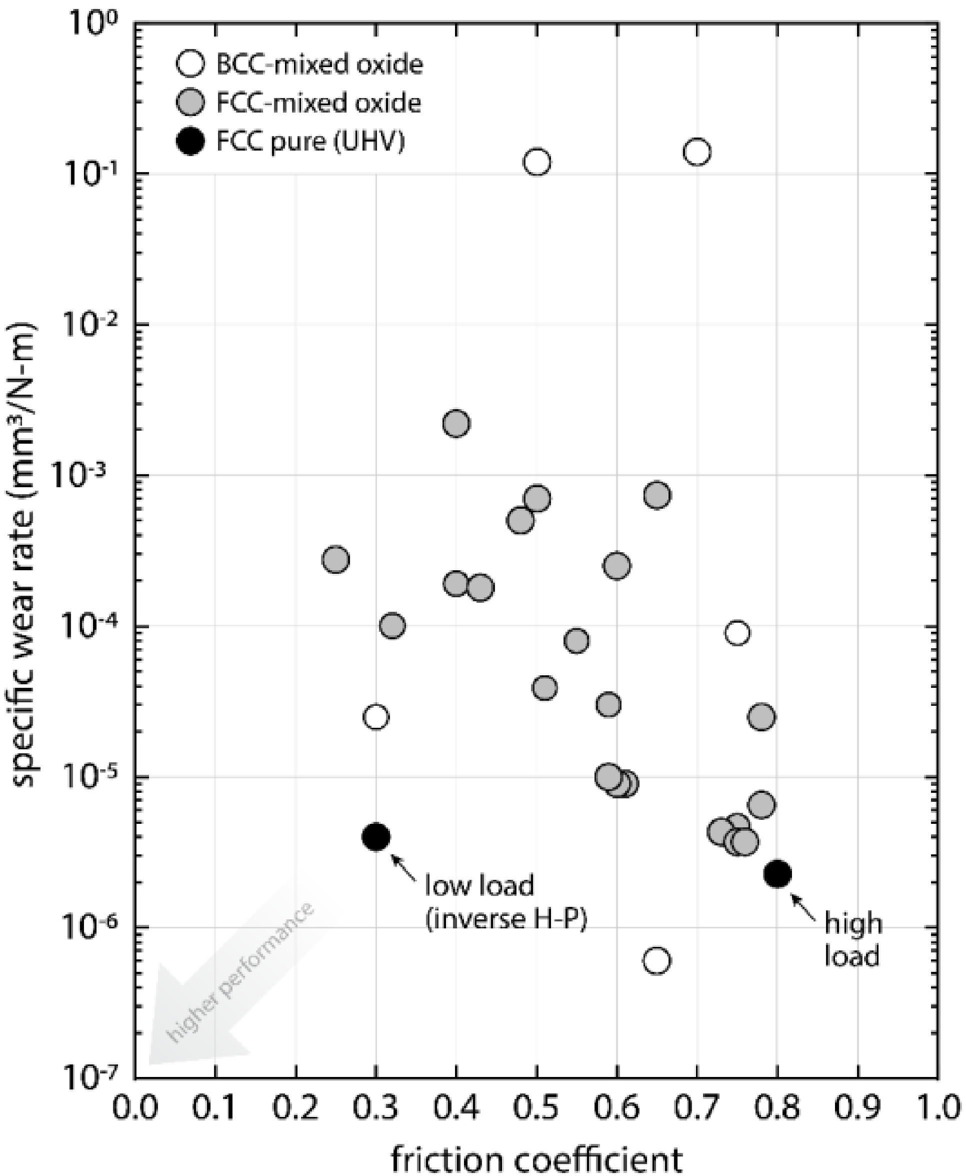
Bulk hardness = 1.6 GPa, so for:

$$\mu = 0.3 \rightarrow \tau\left(d_{surface}\right) = \mu H \cong 0.48 GPa$$

$$\mu = 0.7 \rightarrow \tau\left(d_{surface}\right) = \mu H \cong 1.12 GPa$$

(Jones et al, Sci. Reports, 2020)

Literature Survey Revisited

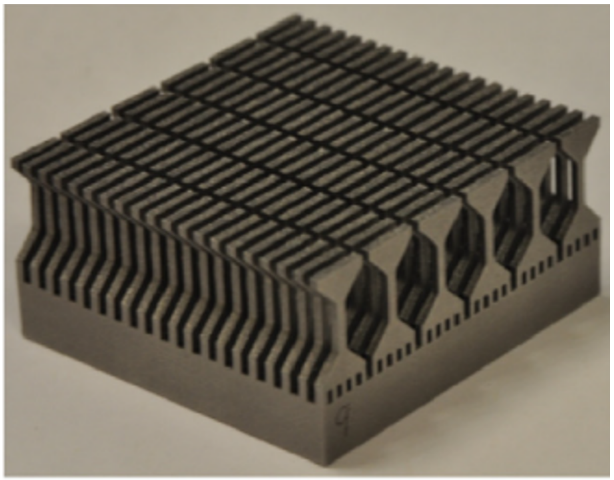


mixed metal-oxide HEAs, as do pure metals, exhibit very different properties than the metal without oxidation

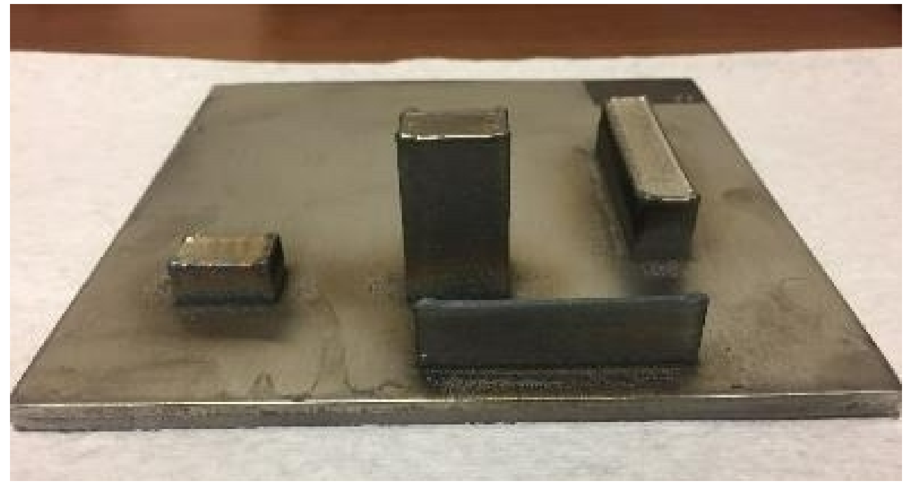
under both a 10 mN and 100 mN normal load, the AM Cantor HEA exhibited high wear resistance

(Jones et al, Sci. Reports 2020)

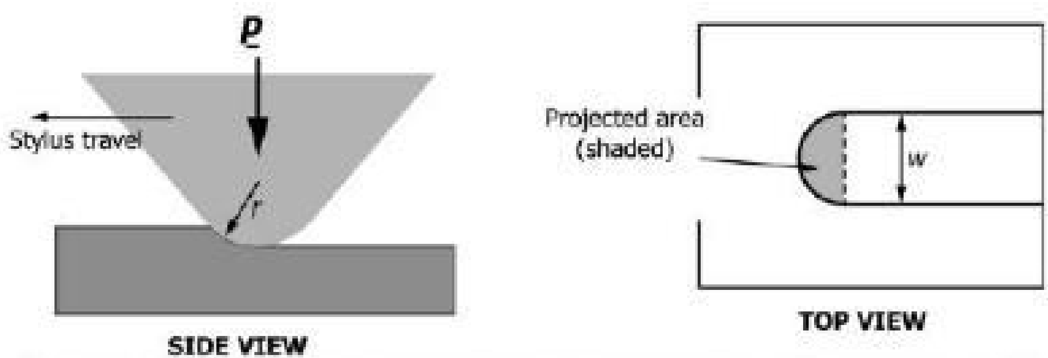
AM+ Tribology – Rapid Materials Discovery (Synthesis and Characterization)



Challenging to Make
(Inconsistent because of defects)



Easy to Make
(Ideal for Tribological Testing)



NOTE 1—The contact of the stylus is assumed to produce a semi-circular projected area when viewed from the top.
FIG. 2 Final Scratch Width

AM+ Tribology – Rapid Materials Discovery (Synthesis and Characterization)

Enhanced solid solution effects on the strength of nanocrystalline alloys

Timothy J. Rupert, Jonathan C. Trenkle, Christopher A. Schuh *

STRAIN HARDENING OF SINGLE ALUMINUM CRYSTALS DURING POLYSLIP

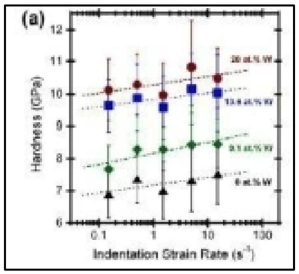
A. K. Mukherjee,[1] J. D. Mote[2] and J. E. Dorn[3]

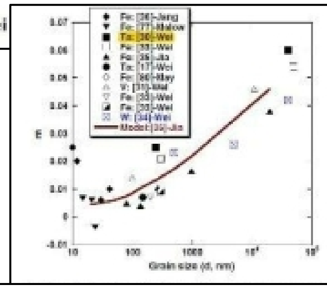
Strain rate effects in the ultrafine grain and nanocrystalline regimes—influence on some constitutive responses

Q. Wei

The temperature and strain rate dependence of the flow stress of tantalum

K. G. HOGE
Energy Research and Development Administration, Washington, D.C., USA
A. K. MUKHERJEE
Department of Mechanical Engineering and Materials and Devices Research Group, University of California, Davis, California, USA





A MICRO-INDENTATION STUDY OF SUPERPLASTICITY IN Pb, Sn, AND Sn–38 wt% Pb

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Department of Materials Science and Engineering, Stanford University, Stanford, CA 94305, U.S.A.

(*Received* 7 *December* 1987)

Characterization of Strain-Rate Sensitivity and Grain Boundary Structure in Nanocrystalline Gold-Copper Alloys

LUKE O. NYAKITI and ALAN F. JANKOWSKI

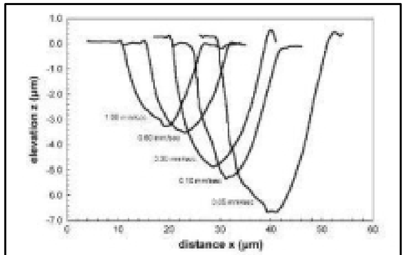


Fig. 1—Profilometer traces across the microscratches made on a 7-nm grain gold-copper alloy are shown to provide a measure of scratch width (w) as made with a 98 mN load and scratch velocities (v) of 0.05 to 1.0 mm s^{-1}.

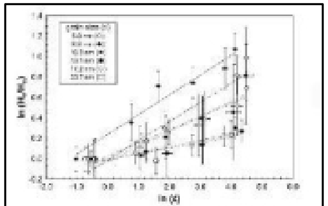


Fig. 2—Log-scale variation of microscratch hardness with strain rate is plotted for nanocrystalline gold-copper specimens with grain sizes of 6 to 34 nm.

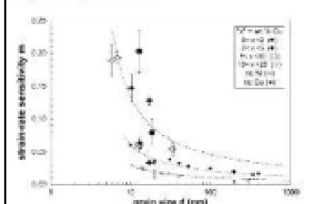


Fig. 3—Variation of strain-rate-sensitivity exponent (m) as a function of log-scale grain size (d) is plotted for nanocrystalline gold-copper specimens as measured by microscratch testing.

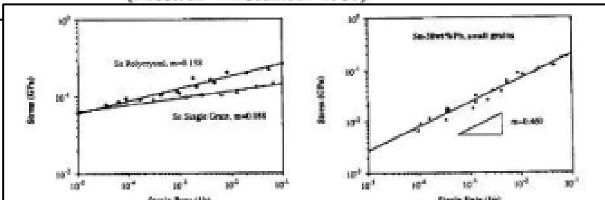


Fig. 5. Enhancement of strain rate sensitivity due to the presence of grain boundaries is shown in these CRL test data of polycrystalline vs single grain pure Sn.

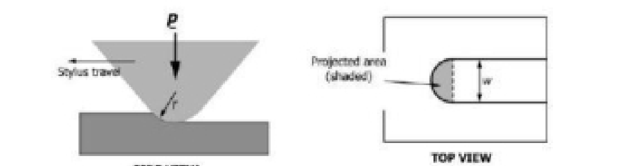
Fig. 6. CRL test data showing the high strain rate sensitivity of the Sn-38 wt% Pb alloy. The mean linear intercept grain size of this alloy is 1.3 μm.

Measurement of hardness and elastic modulus by instrumented indentation: Advances in understanding and refinements to methodology

W.C. Oliver
G.M. Pharr

Standard Test Method for Scratch Hardness of Materials Using a Diamond Stylus[1]

This standard is issued under the fixed designation G171; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.



NOTE 1—The contact of the stylus is assumed to produce a semi-circular projected area when viewed from the top.

FIG. 2 Final Scratch Width

High-Throughput Scratch Testing for Rapid Material Characterization

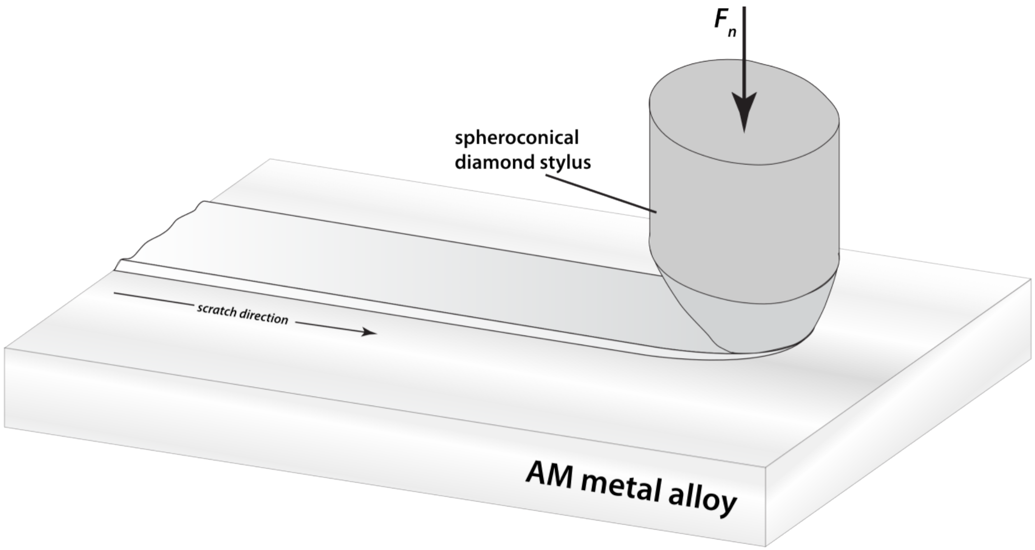
strain rate
(1/s)

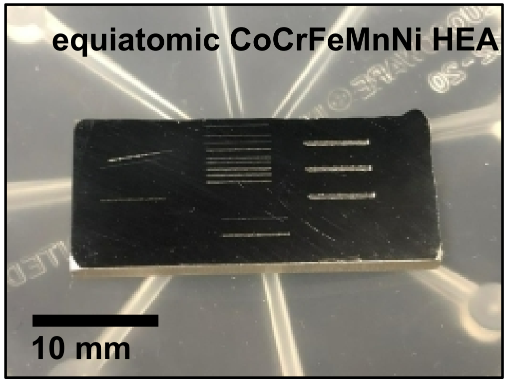
hardness
(GPa)

strain rate sensitivity exponent

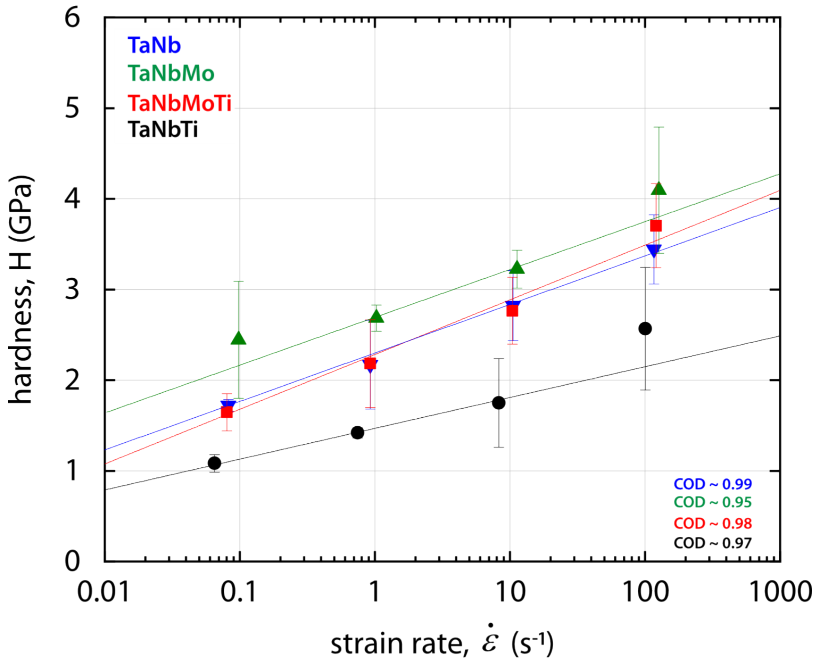
activation volume

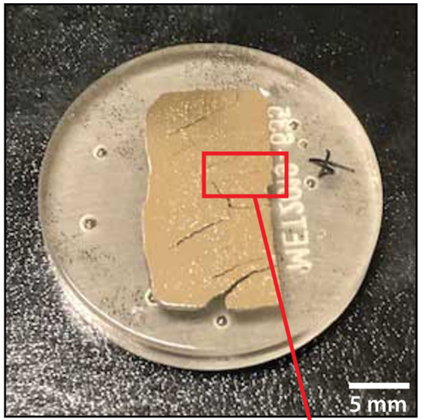
characteristic length

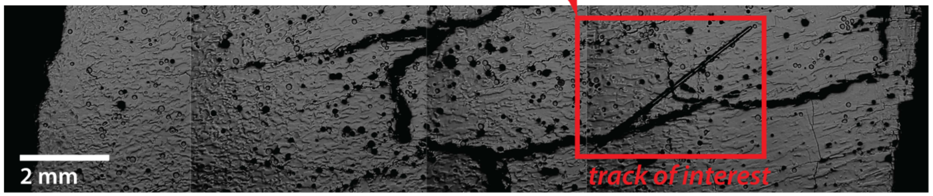


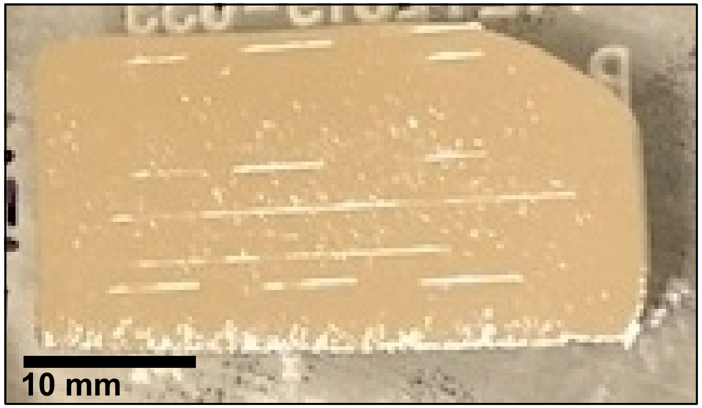


Characterization Possible Even with 'Bad' AM Specimens



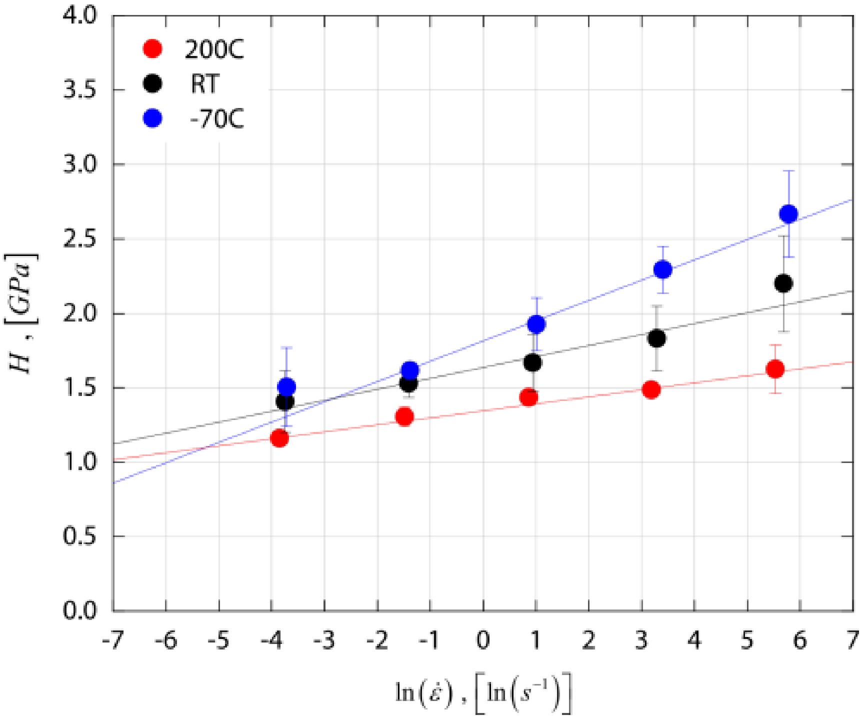


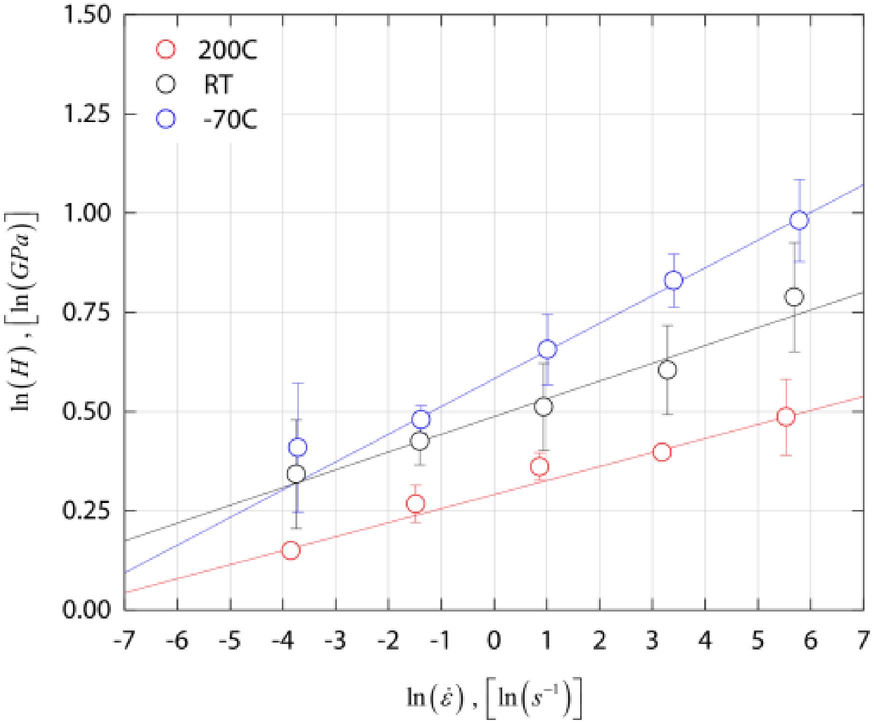




Voids, dimples, cracks would make these specimens unusable for tensile testing, but all we need is a polished surface.

AM Cantor HEA Revisited – Temperature and Strain Rate Dependent Hardness





	m	***σ(m)***	***V*** **(nm^3)**	***V*** $^{1/3}$ **(nm)**	***σ(V)*** **(nm^3)**
CoCrFeMnNi -70C	0.070	0.004	0.158	0.541	0.013
CoCrFeMnNi 25C	0.045	0.005	0.293	0.664	0.035
CoCrFeMnNi 200C	0.035	0.003	0.458	0.771	0.025

Summary

- Low friction and wear of metal sliding contacts can be achieved by mitigating thermomechanically-driven microstructural evolution (e.g., grain growth).

- Fundamental investigations of metal contacts led to the development of a simple model that can be used to guide alloy design – prediction of ultimate strength based on materials properties like heat of fusion.

- Evidence that high entropy alloys (HEAs) may be an ideal alloy system for additive manufacturing of tribological and structural components.

- Able to rapidly elucidate hardness, strain rate dependence, fracture toughness, etc. from scratch testing AM specimens.

Questions?