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Correlating Surface Microstructure Evolution to Regimes of Friction in Metals

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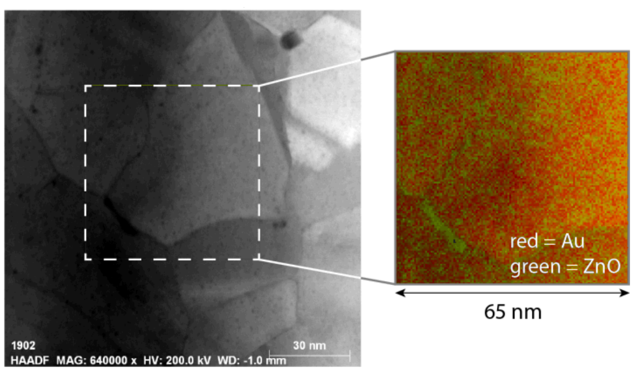

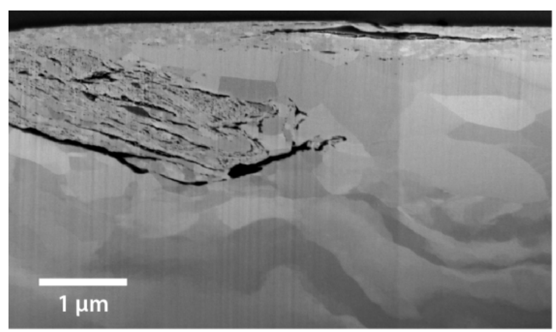

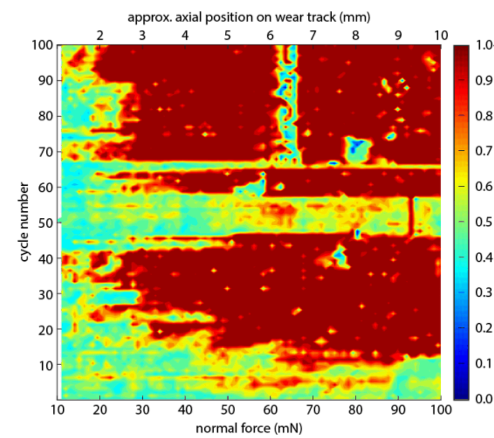

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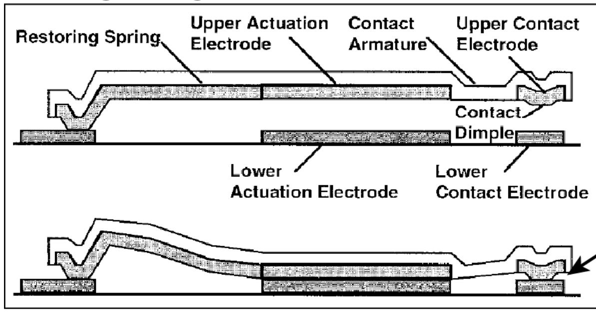
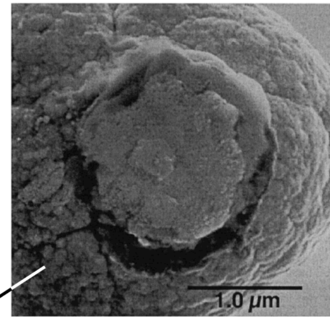
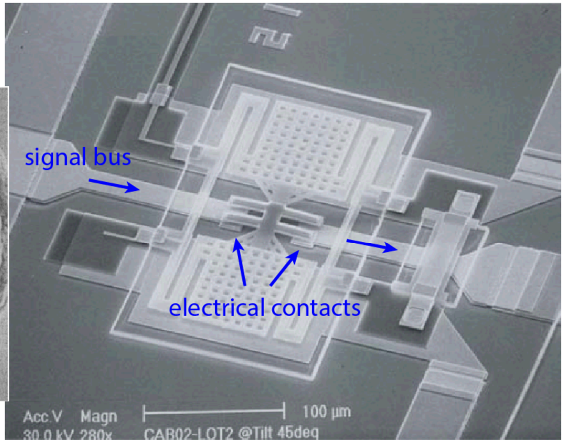
Metals are widely used tribological materials – particularly, electrical contacts

RF Micro Electromechanical Systems (MEMS)

switching GHz signals







Source: D. Hyman and M. Mehregany, IEEE Trans. & Pack. Tech. 22-3, 1999

Source: Rockwell Scientific metal-metal switch

Electronics (e.g. PCB blade connectors):

200 - 500 nm thick electroless hard gold

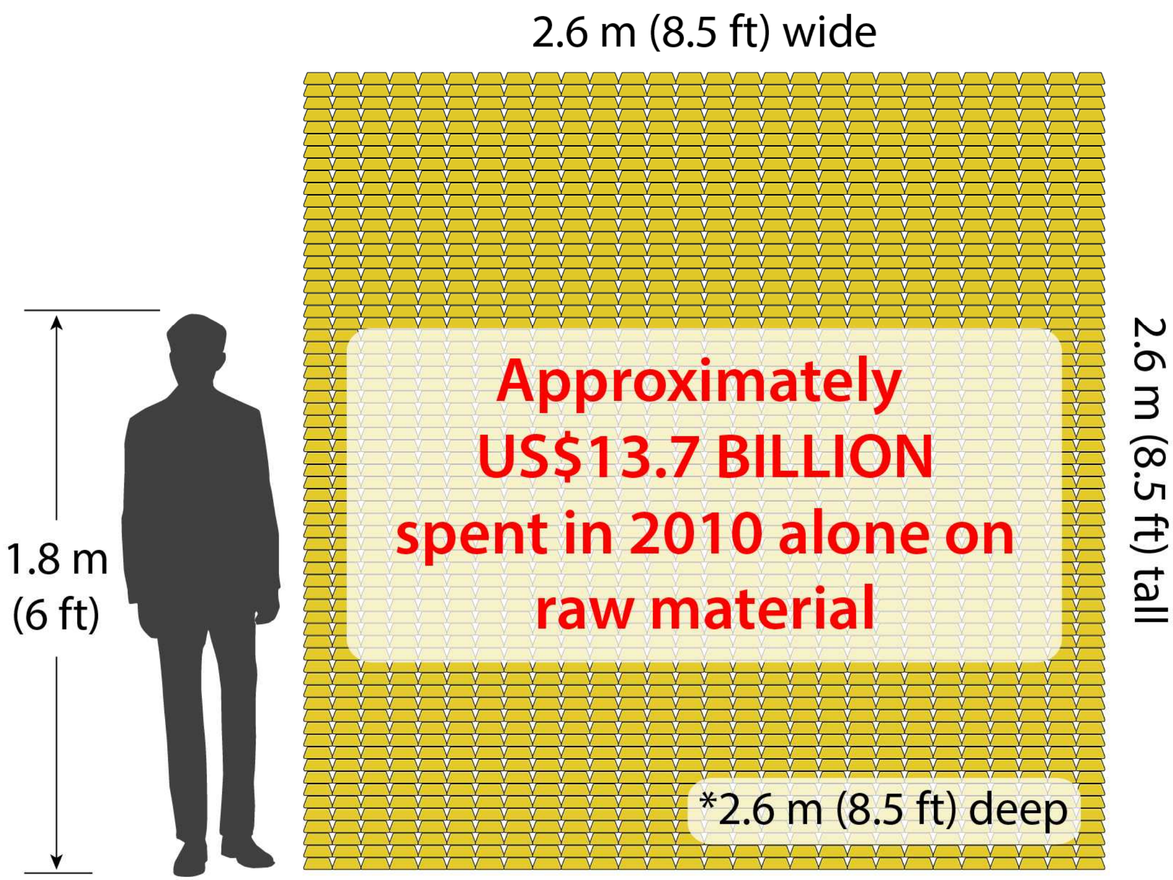
Aerospace and Energy

Source: Honeybee Robotics (http://www.honeybeerobotics.com/portfolio/rolling-contact-connector/)

The Gold Standard… how much gold you may ask?   TONS per year

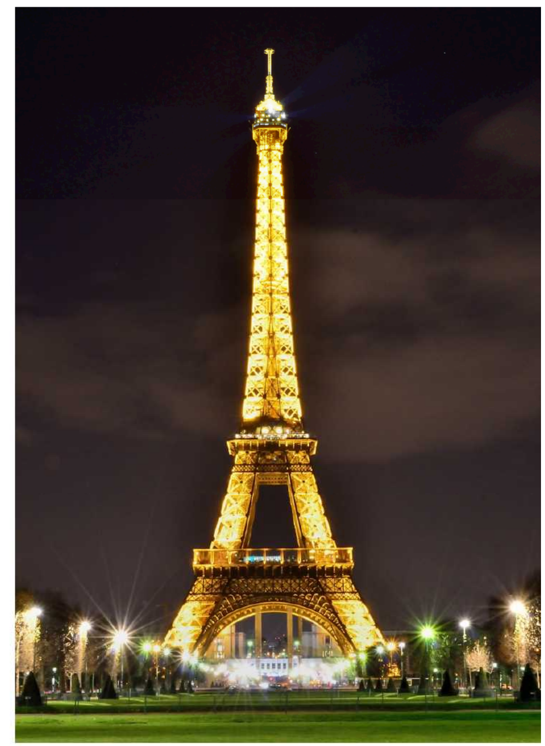
An estimated 300 metric tons/year of gold used in electronics related applications, most of it in electroplated connectors and contacts (11% of yearly amount mined)

Equivalent to a cube comprised of ~25,000 standard gold bars (12 kg/26.4 lb each)…



Reference: Gold Survey, Gold Fields Mineral Services Ltd., 2010

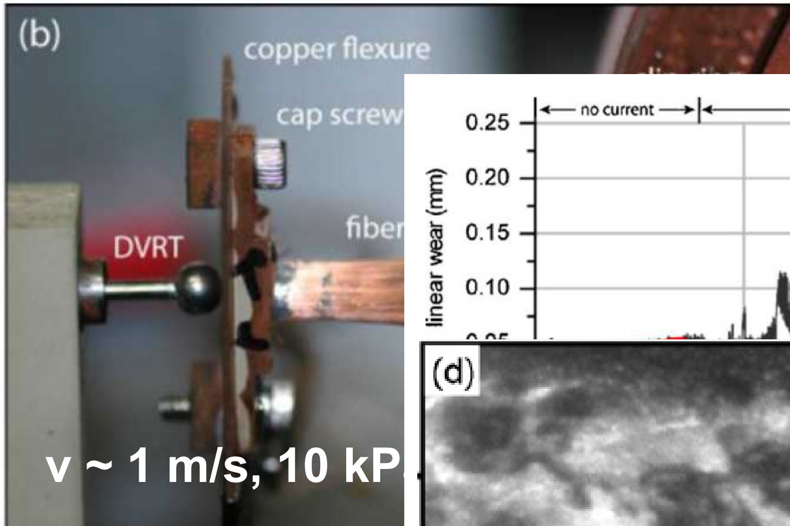
… or enough to clad the surface of the Eiffel Tower with 70 µm of pure gold *every year*

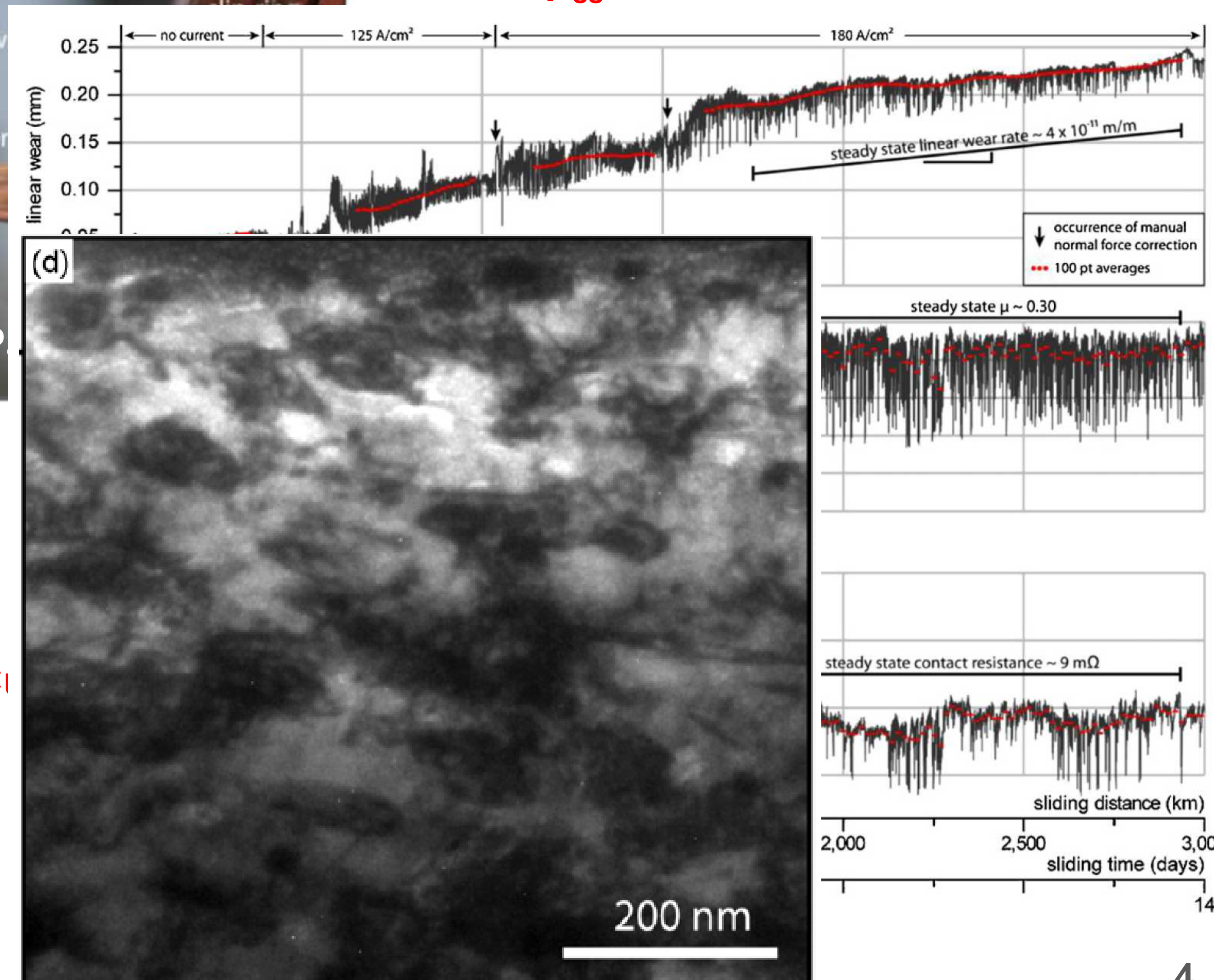


Low friction linked to nanocrystalline surface grain size – even with pure metals

wear rate of ~ 1 nm per kilometer

μ_{ss} ~ 0.3



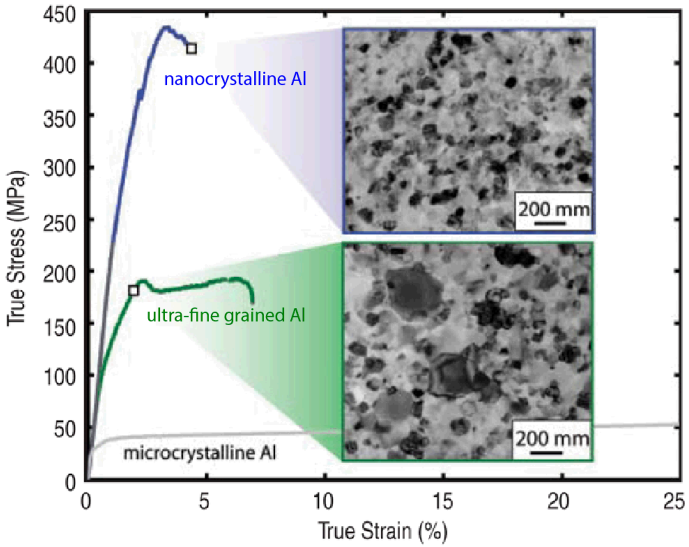


Low friction associated with nanocrystalline surface for a Cu-Cu system

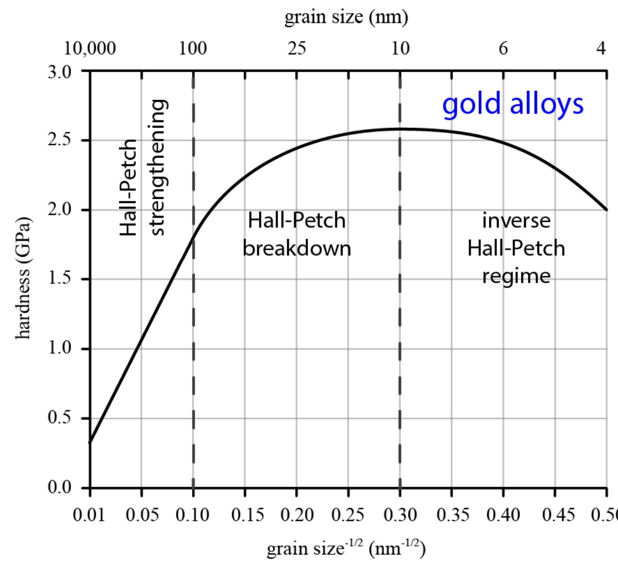
ref: Argibay et al., Wear 2010

Engineering advantages of NC metals, alloys and metal-matrix composites

higher yield strength

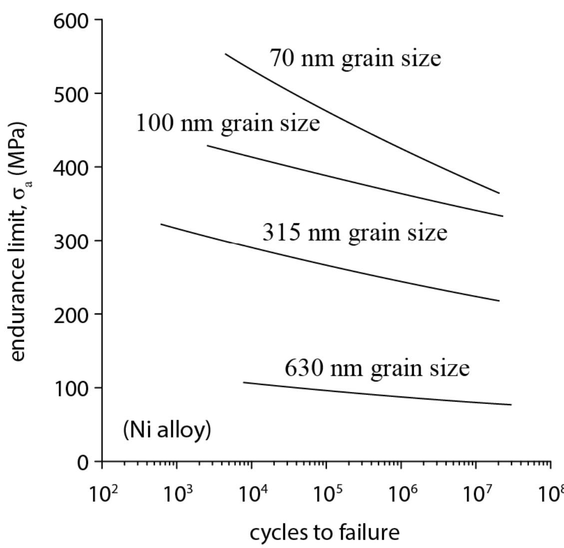


higher hardness

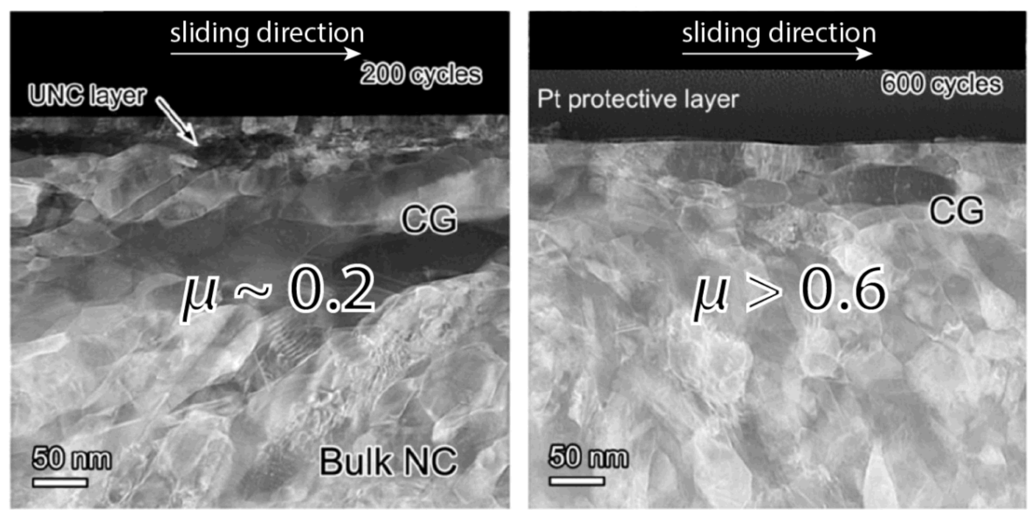


ref: Lo, Augis and Pinnel, JAP (1979)

higher fatigue strength (endurance limit)



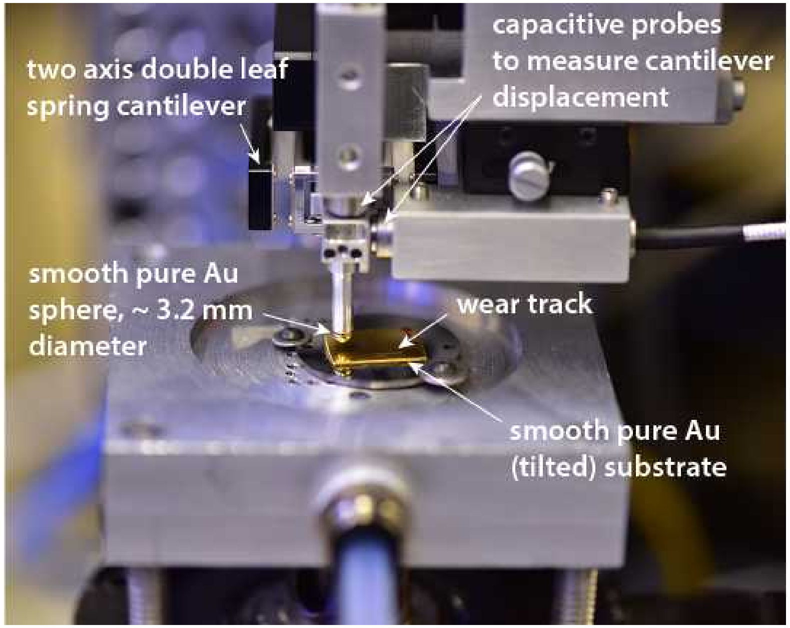
lower friction and wear rates -- *but why?*



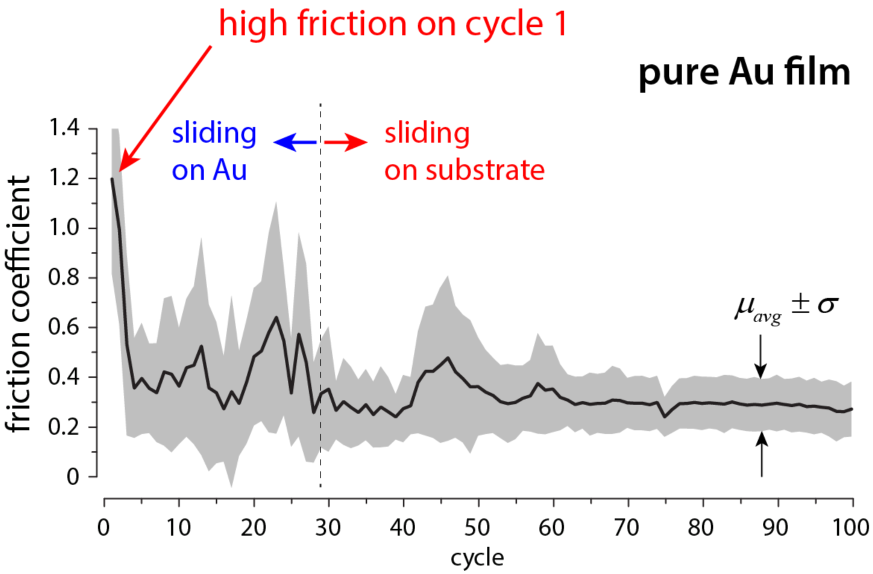
Ref: S.V. Prasad, et al., Scripta Mat. 2011

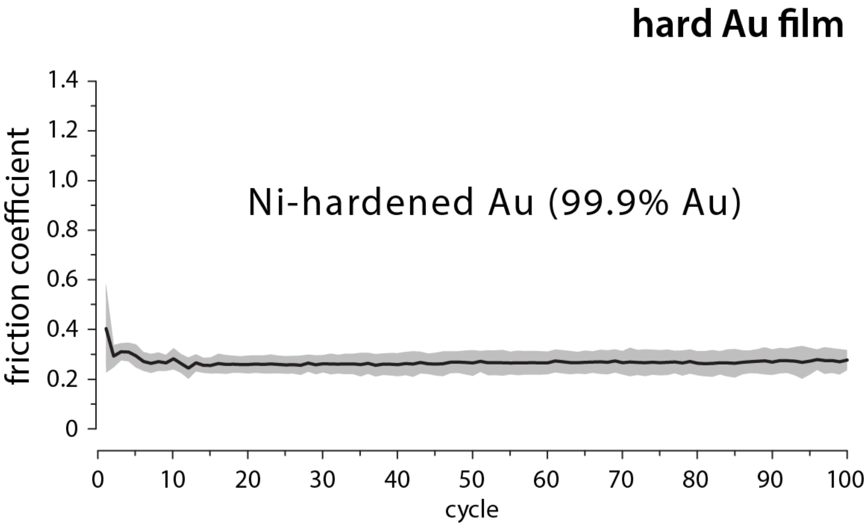
steady-state cross-sections of wear tracks

Example of low friction with unlubricated metal contacts – Hard Au vs Pure Au



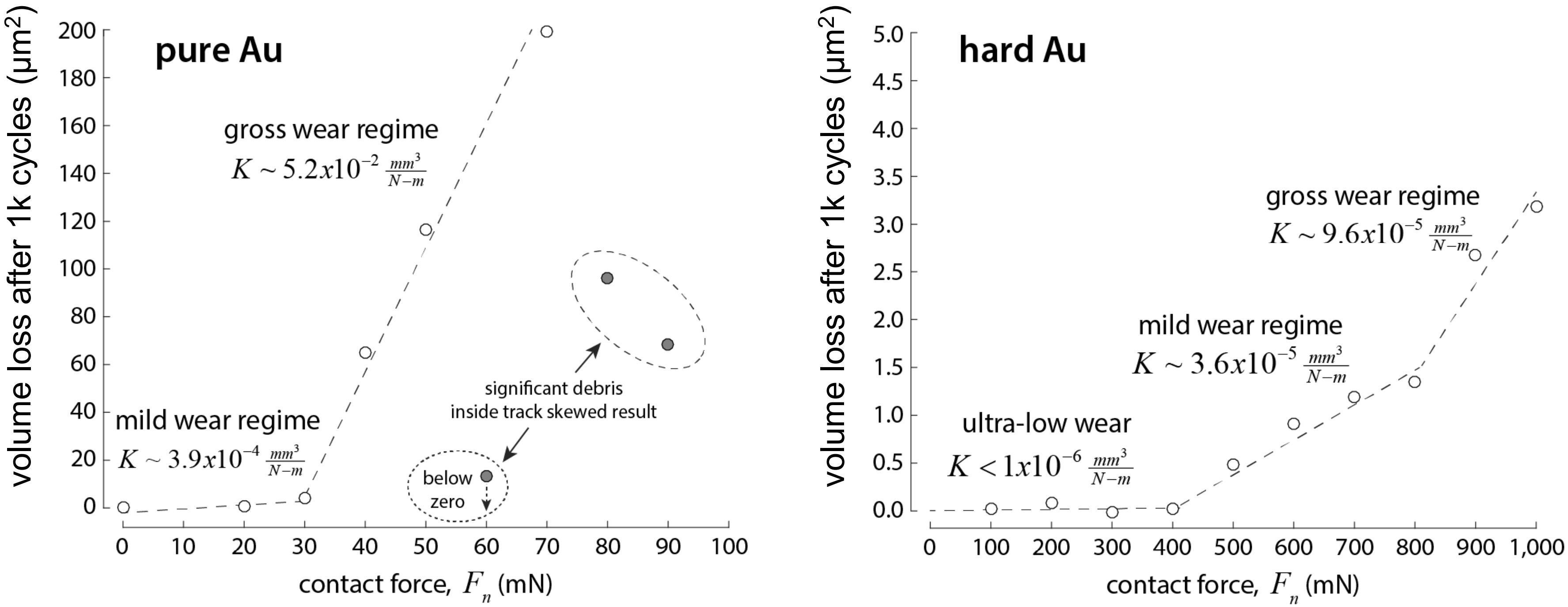
normal force = 100 mN
ball radius = 1.6 mm
speed = 1 mm/s





Example of low wear with unlubricated metal contacts – Hard Au vs Pure Au

Note x- and y-axis scale difference!

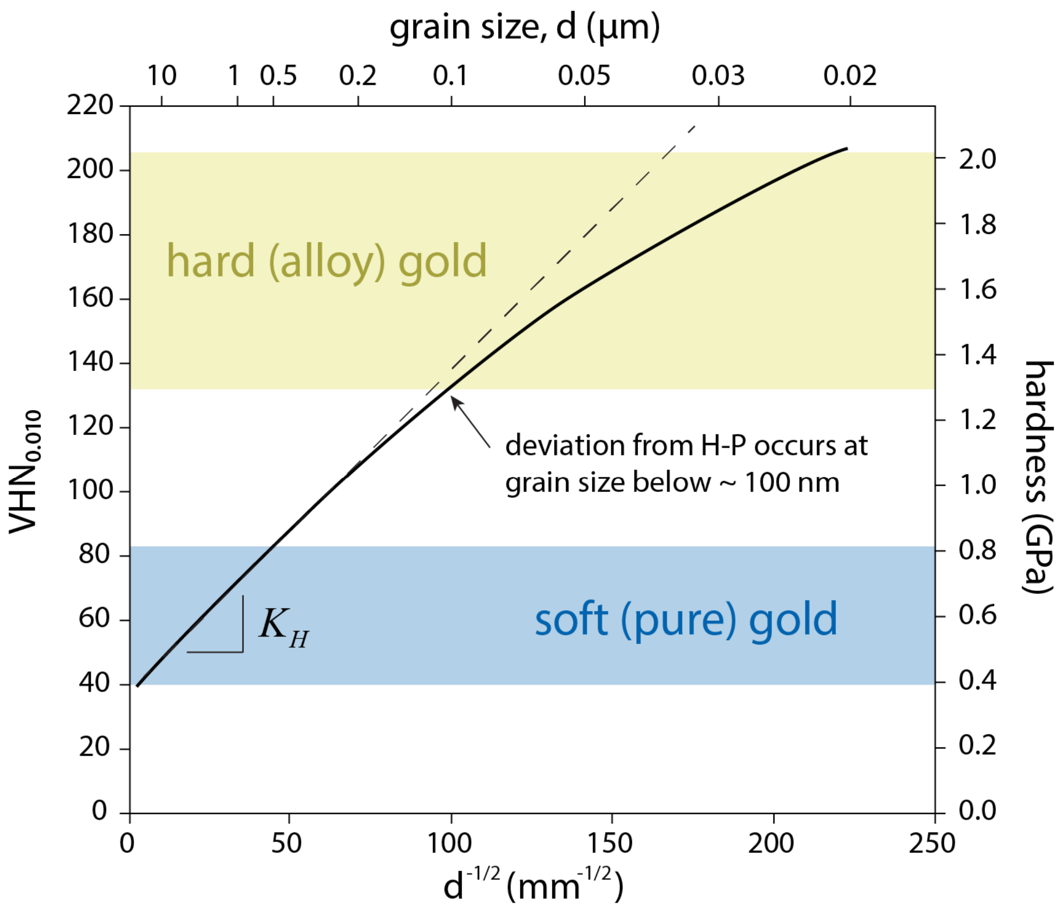


> 10,000x wear rate reduction with addition of 0.1% Ni

Archard wear = rate is linearly dependence to contact force

low wear and friction with pure Au is possible!

Alloying produces stable NC metal in bulk… alloys -> low μ at higher stresses



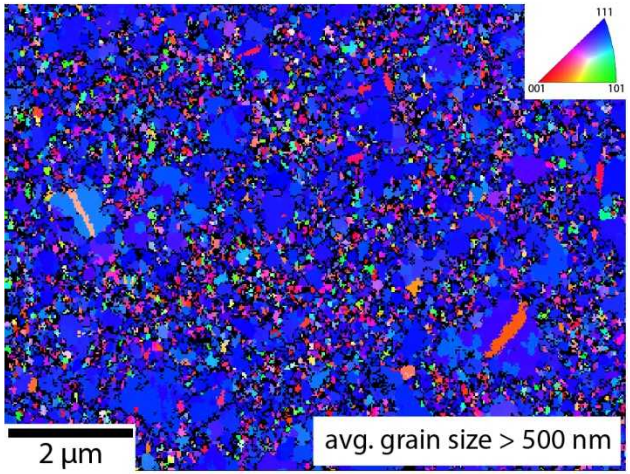
Reference: C. Lo, J. Augis, and M. Pinnel, JAP (1979)

Stable NC grain size can be achieved using non-metals

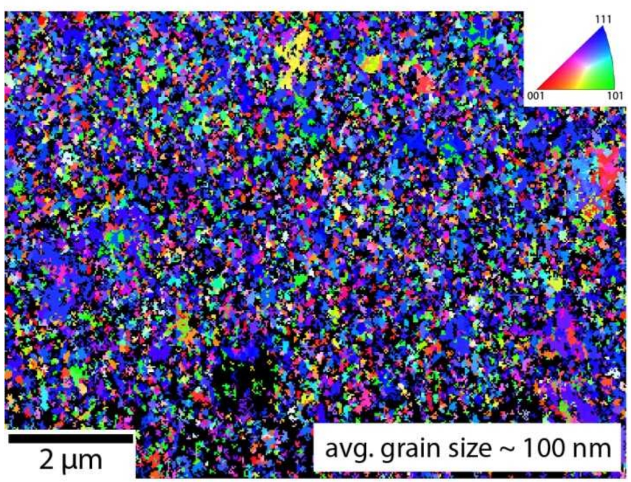
refs: Argibay et al. JAP (2015) and Argibay et al. Wear (2013)

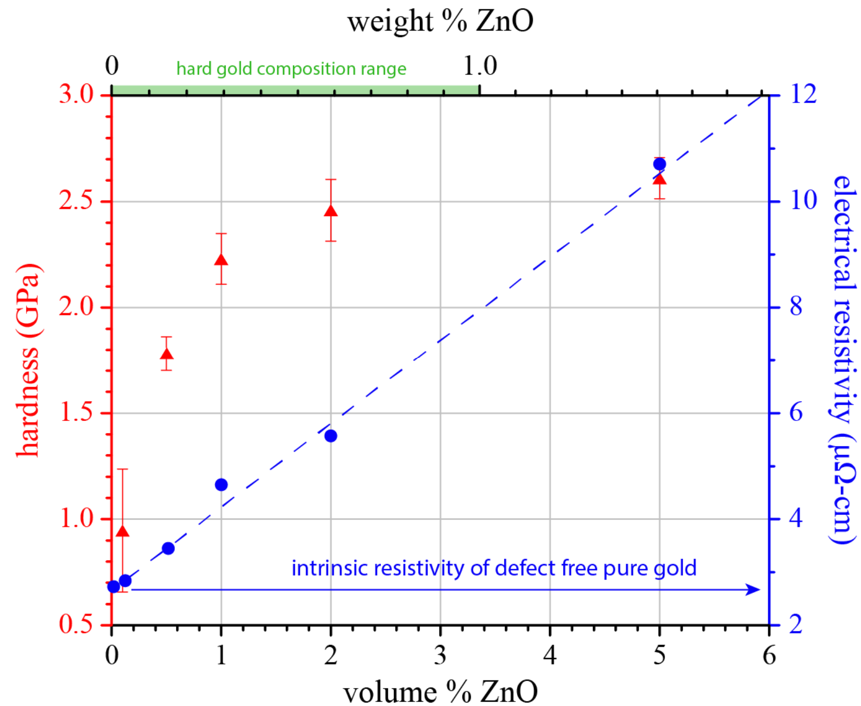
Surface-normal (planar) EBSD maps of e-beam deposited films:

pure Au film

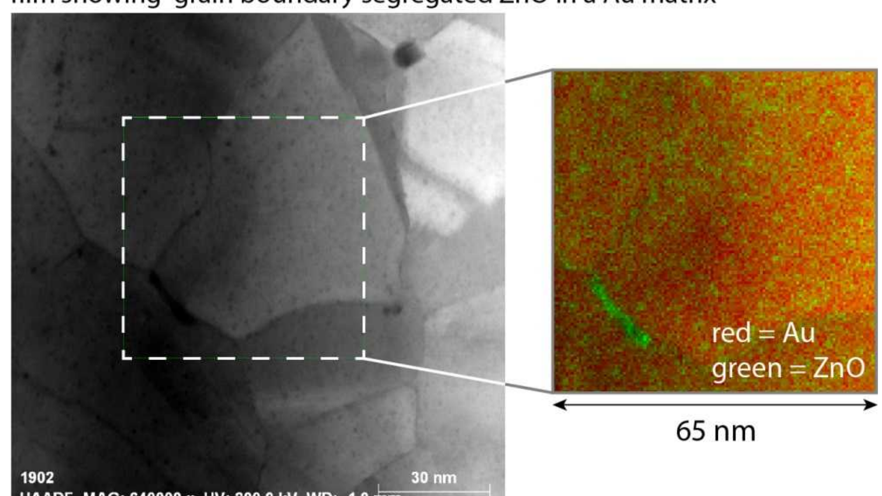


Au film with 0.1 vol. % ZnO

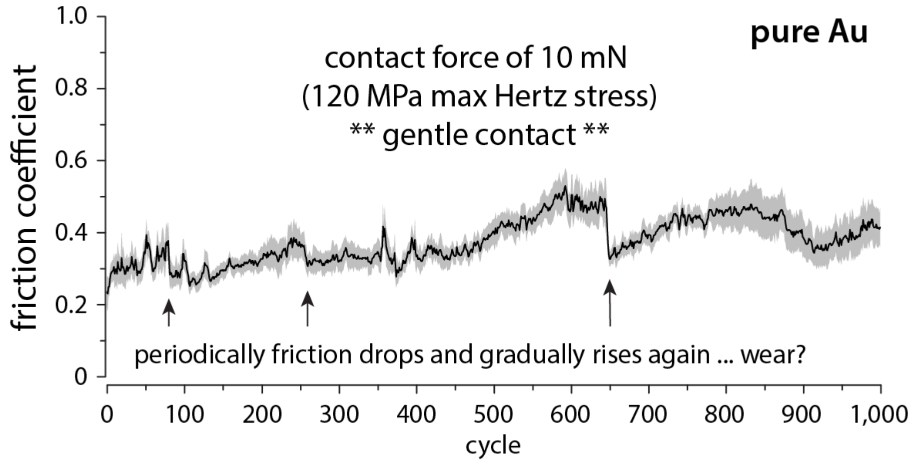




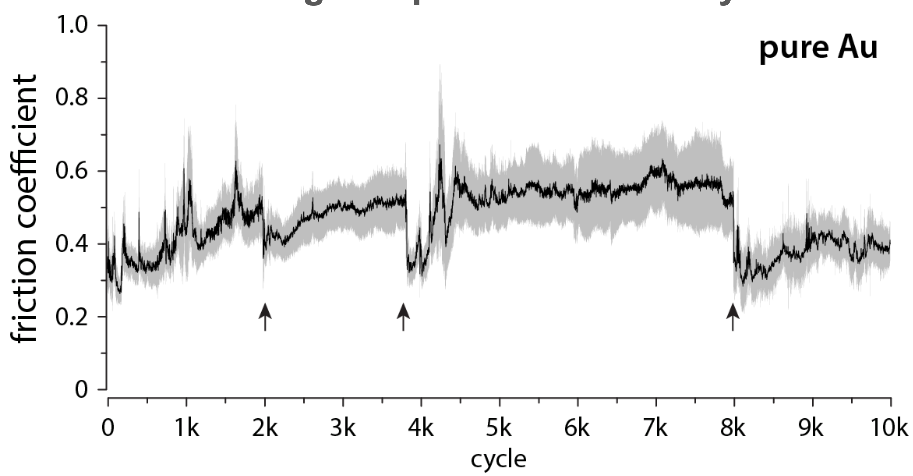
Cross-sectional composition map of a Au- 5 vol. % ZnO film showing grain boundary segregated ZnO in a Au matrix

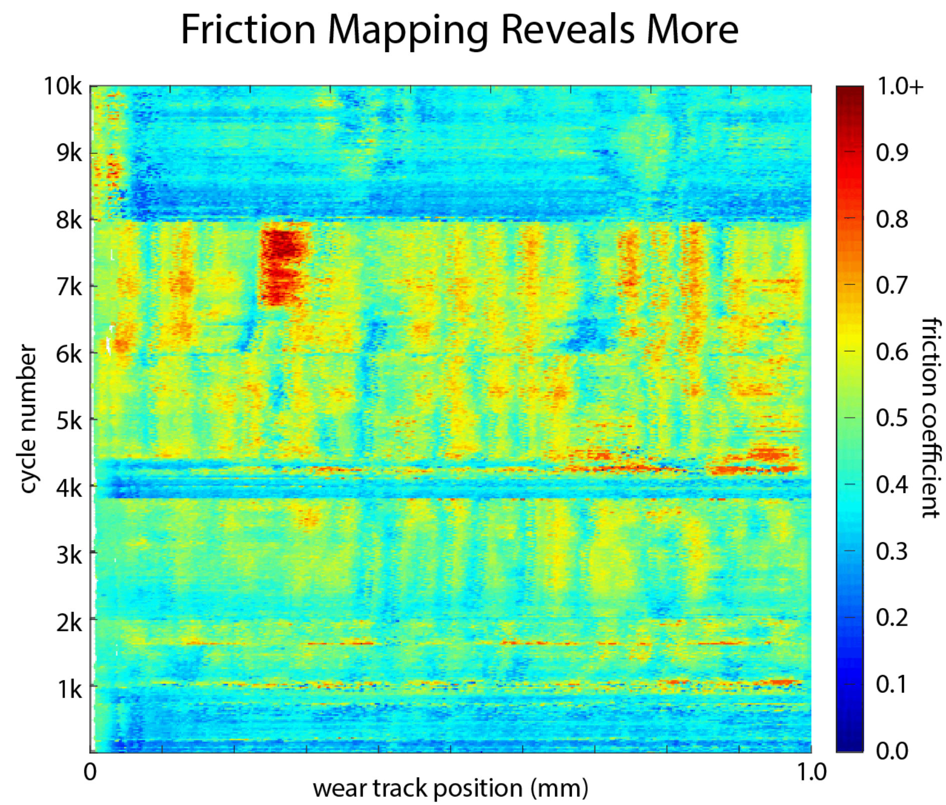


However, low friction possible even with pure Au sliding against hard Au



now a longer experiment to 10k cycles:





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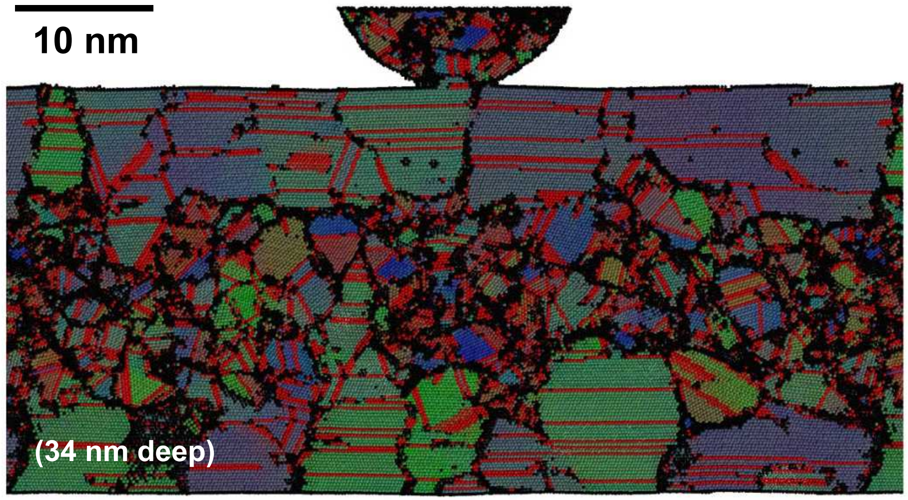
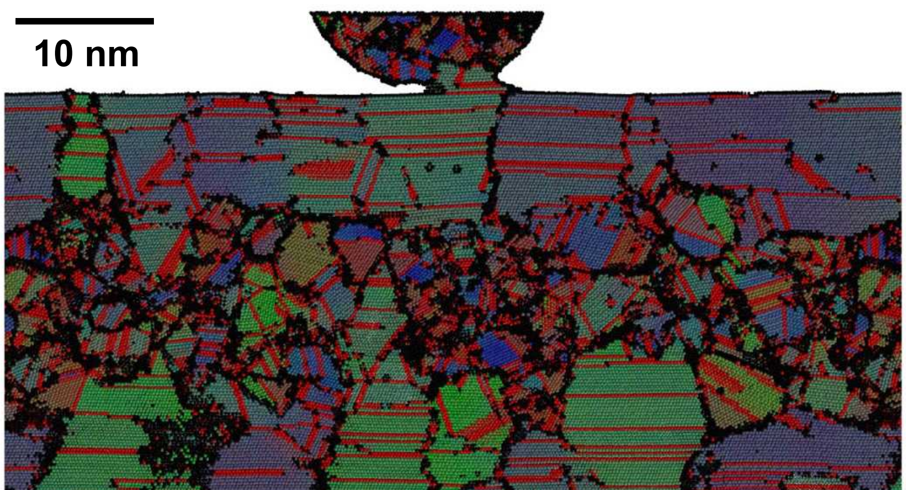
What MD simulations reveal…

initial microstructure of Ag and Ag-Cu alloy (no sliding yet)

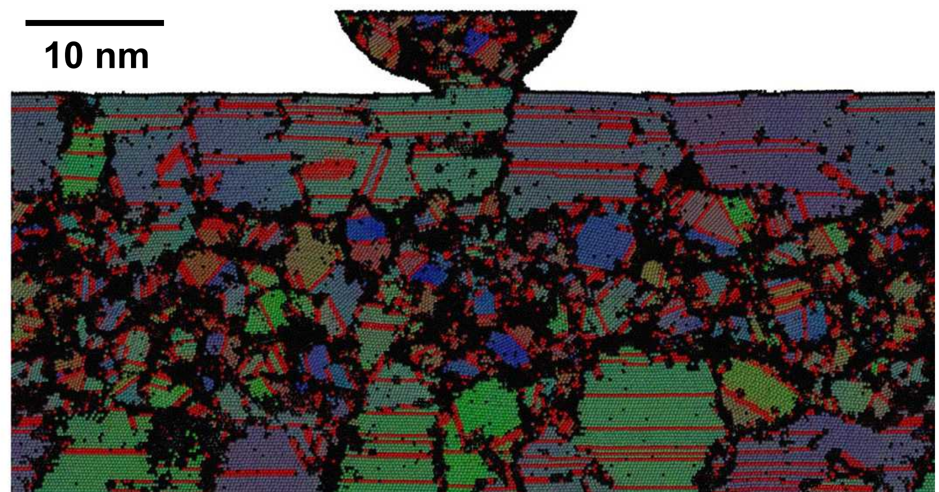


300 MPa contact stress
300 K temperature
2 m/s sliding speed

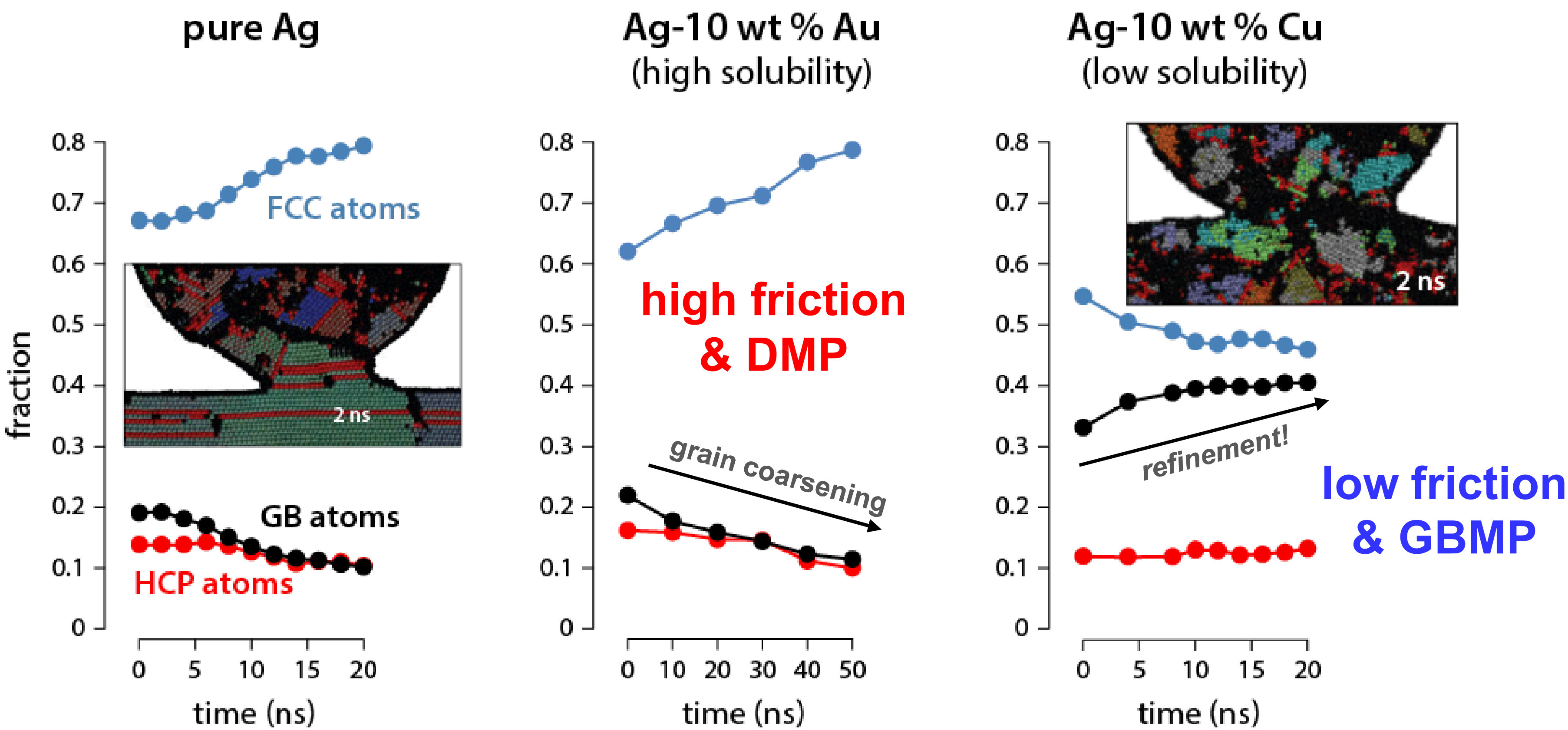
pure Ag after 4 nm of sliding



Ag-10% Cu alloy after 4 nm of sliding

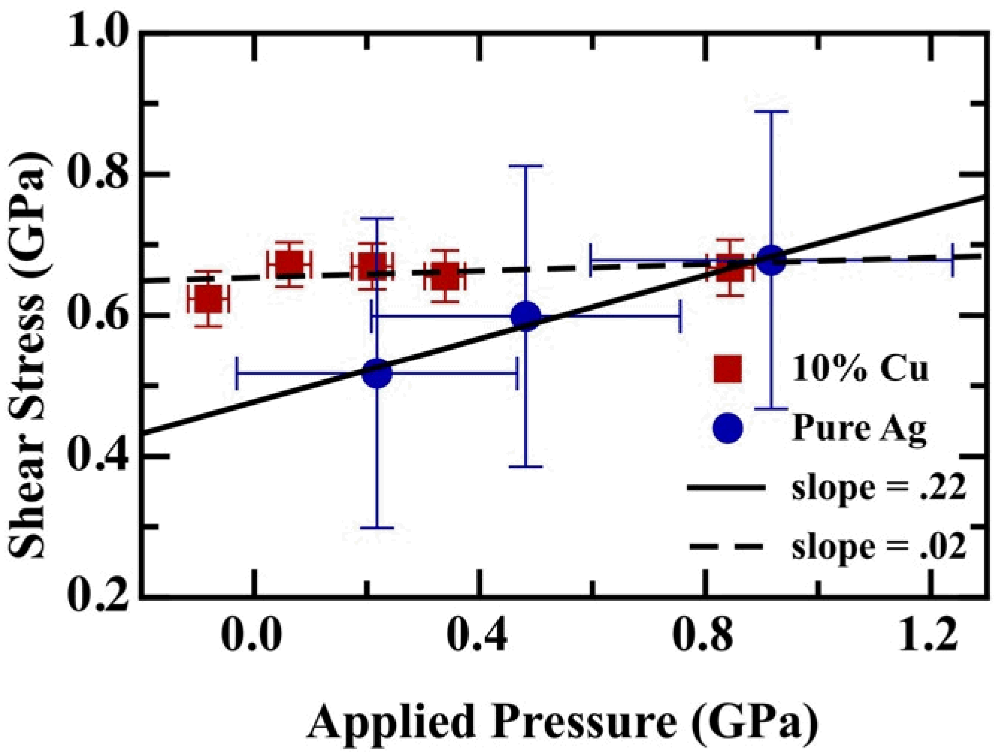


Alloying changed deformation mechanism



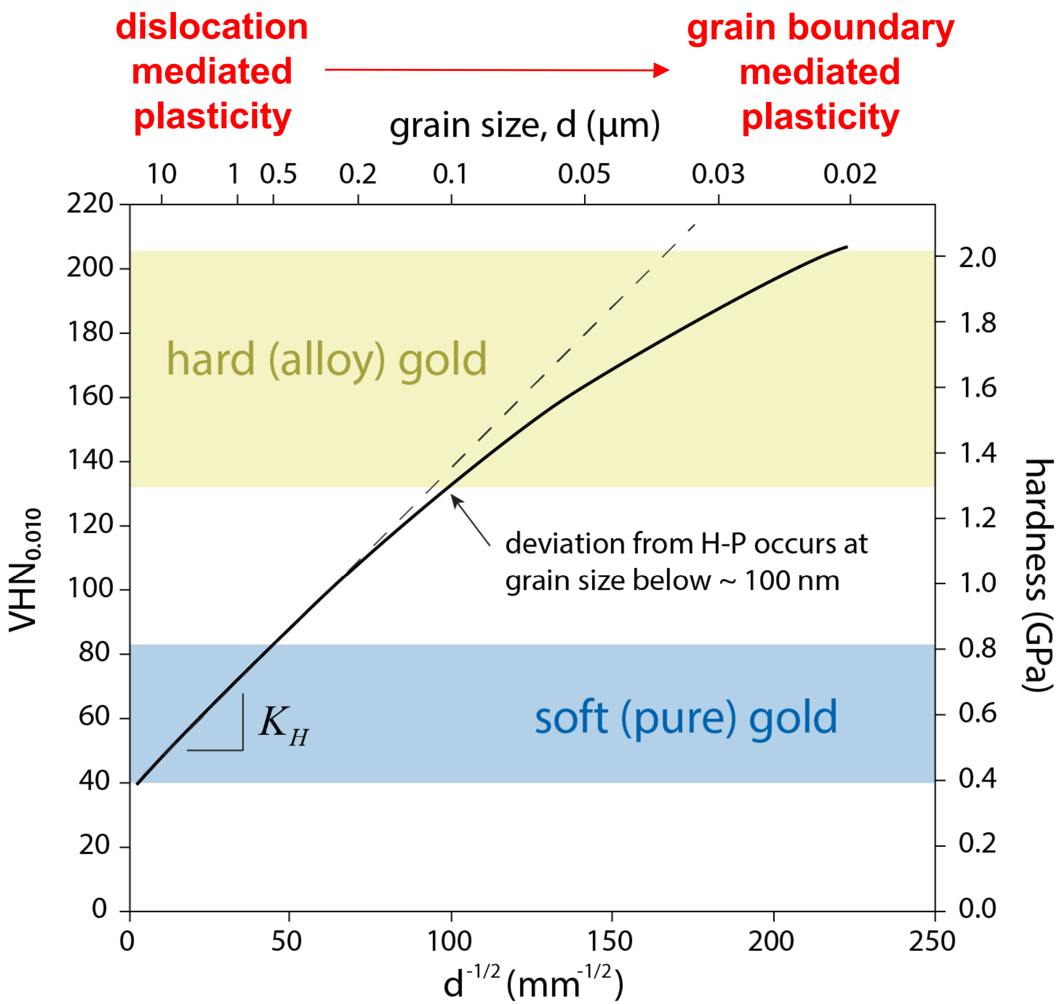
- Experiments: alloying reduces grain size and stabilizes grain boundaries
- Simulations: alloying mitigates stress-driven grain growth at interface and promotes defect (primarily GB) mediated plasticity
- Connection: stable GBs produce low friction at higher stress

MD also showed that low solubility alloys exhibit lower friction at equivalent stress



- AgCu is similar to hard gold (AuNi, AuCo…)
- Friction coefficient is the slope of line
- Change in shear accomodation changes the friction

Why is hard better? Primarily due to grain size reduction & GB stabilization



Reference: C. Lo, J. Augis, and M. Pinnel, JAP (1979)

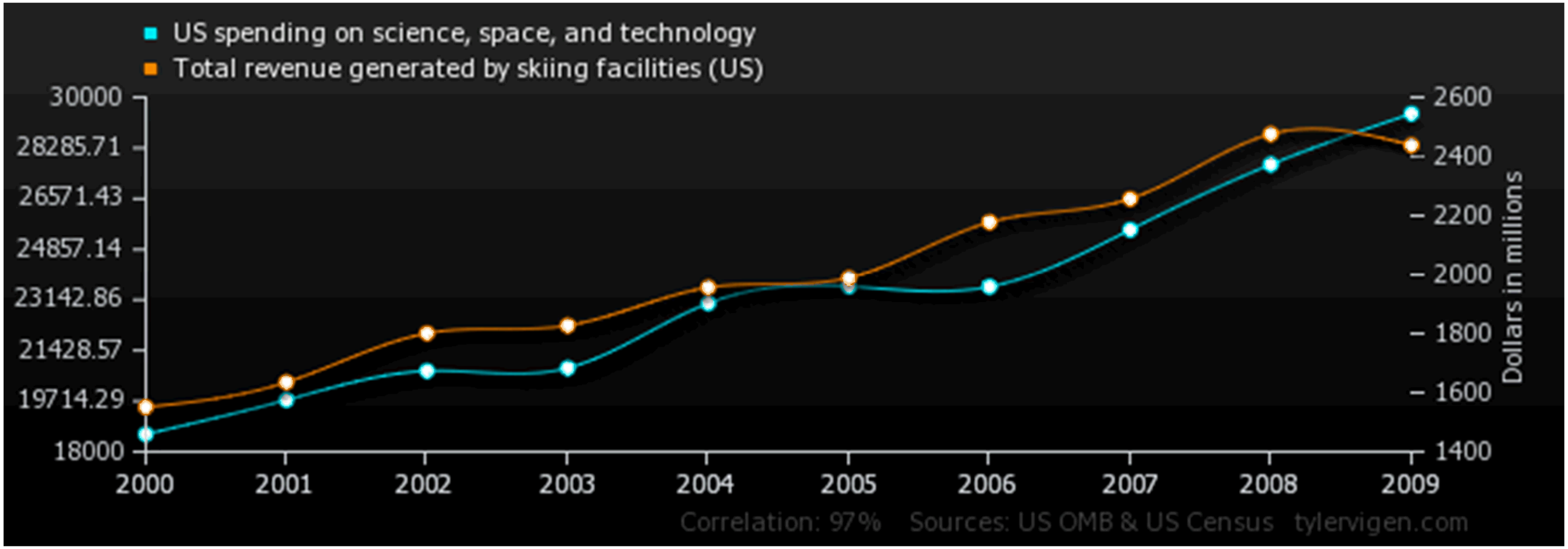
The widely held misconception that hardness increase is the source of low wear and friction is loosely attributed to the notion that real contact area drops with hardness:

$$A_r \cong \frac{F_n}{H}$$

... for metal contacts the real area is a function of hardness and contact force. (Bowden & Tabor, 1939)

Hardness is not the answer

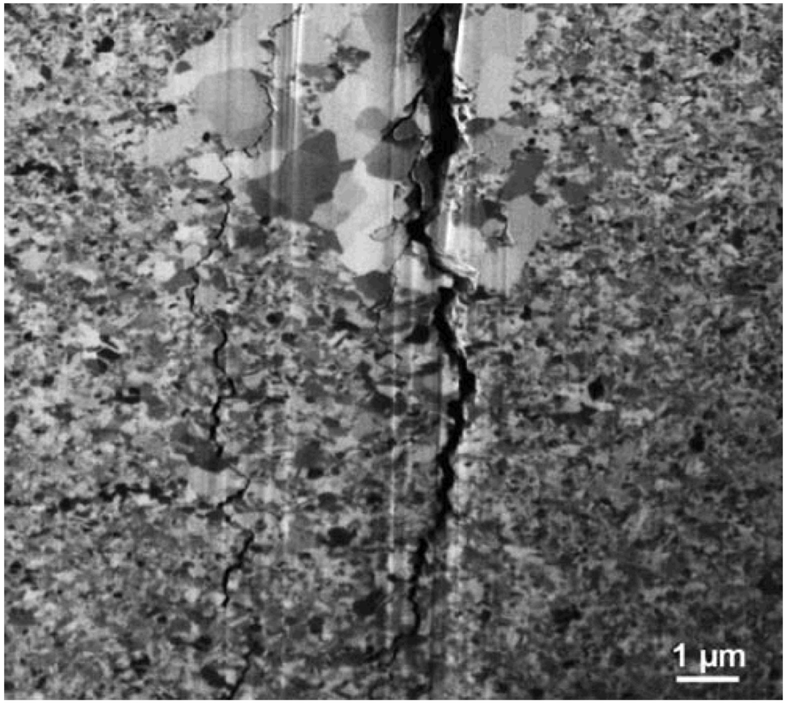
instead, imparting higher stability to GBs makes it easier to achieve GB-mediated plasticity at relatively higher applied stress



Grain size **stability** remains the key challenge to widespread adoption of NC metals

stress-driven grain growth

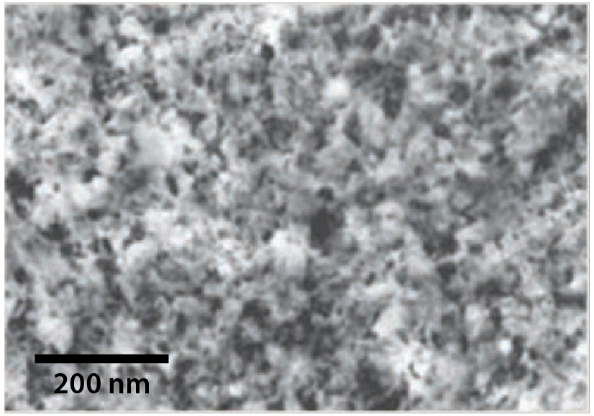
initially nanocrystalline Ni-Mn



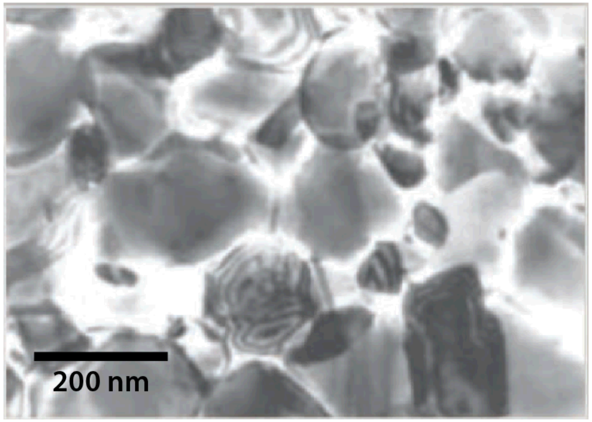
ref: Padilla & Boyce, Exp. Mech. (2010)

thermally-driven grain growth

initially nanocrystalline Ni



after anneal at 300°C for 30 minutes



This implies contact stress can drive coarsening...

... and contact heating can drive coarsening (Blok, Jaeger, Archard, Lim and Ashby)

Two routes to stabilize nanocrystalline metals – kinetic and thermodynamic

ref: Simoes et al., Nanotech. (2010)

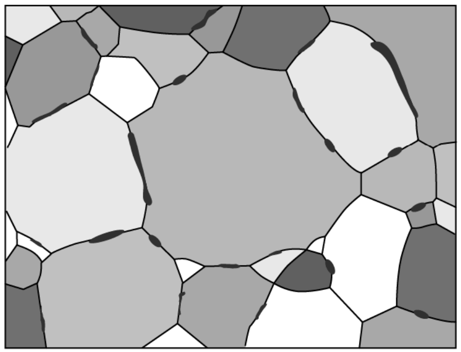
Grain growth is essentialy driven by grain boundary described by speed of grain boundary motion (speed), v

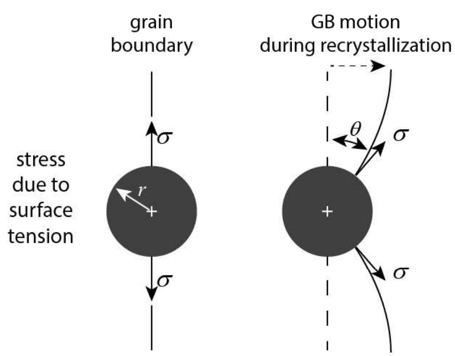
$$v = M \cdot P = M_o \exp\left(-\frac{Q_m}{kT}\right) \cdot \frac{2\gamma_o}{r}$$

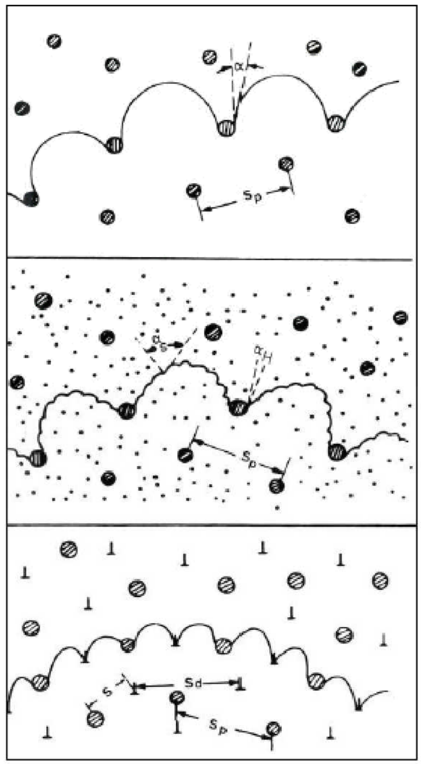
M = grain boundary mobility
P = pressure on grain boundary
γ_o = interfacial energy per unit area
r = mean grain radius

Limit the ***kinetics*** of recrystallization (traditional quasi-stability)

e.g. Zener pinning, solute drag, porosity







drag force: $f_D = 2\pi r\sigma\cos\theta\sin\theta$

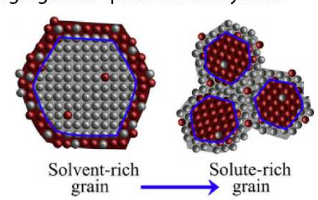
Weissmüller (1993), Kirchheim (2002), and Schuh (2012) have made significant contributions toward understanding and achieving ***thermodynamic*** stability by lowering grain boundary energy through solute segregation

Regular Nanocrystalline Solution (RNS) Model:
ref: Chookajorn et al., Science, 2012

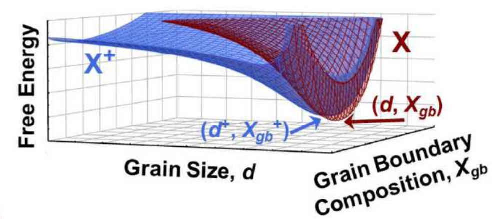
$$\Delta G^{mix} = (1 - f_{gb})\Delta G_c^{mix} + f_{gb}\Delta G_{gb}^{mix} + z\nu f_{gb}(X_{gb} - X_c)\left[(2X_{gb} - 1)\omega_{gb} - \frac{1}{zt}(\Omega^B\gamma^B - \Omega^A\gamma^A)\right]$$

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

Grain structure model:
segregated 2-phase metal system



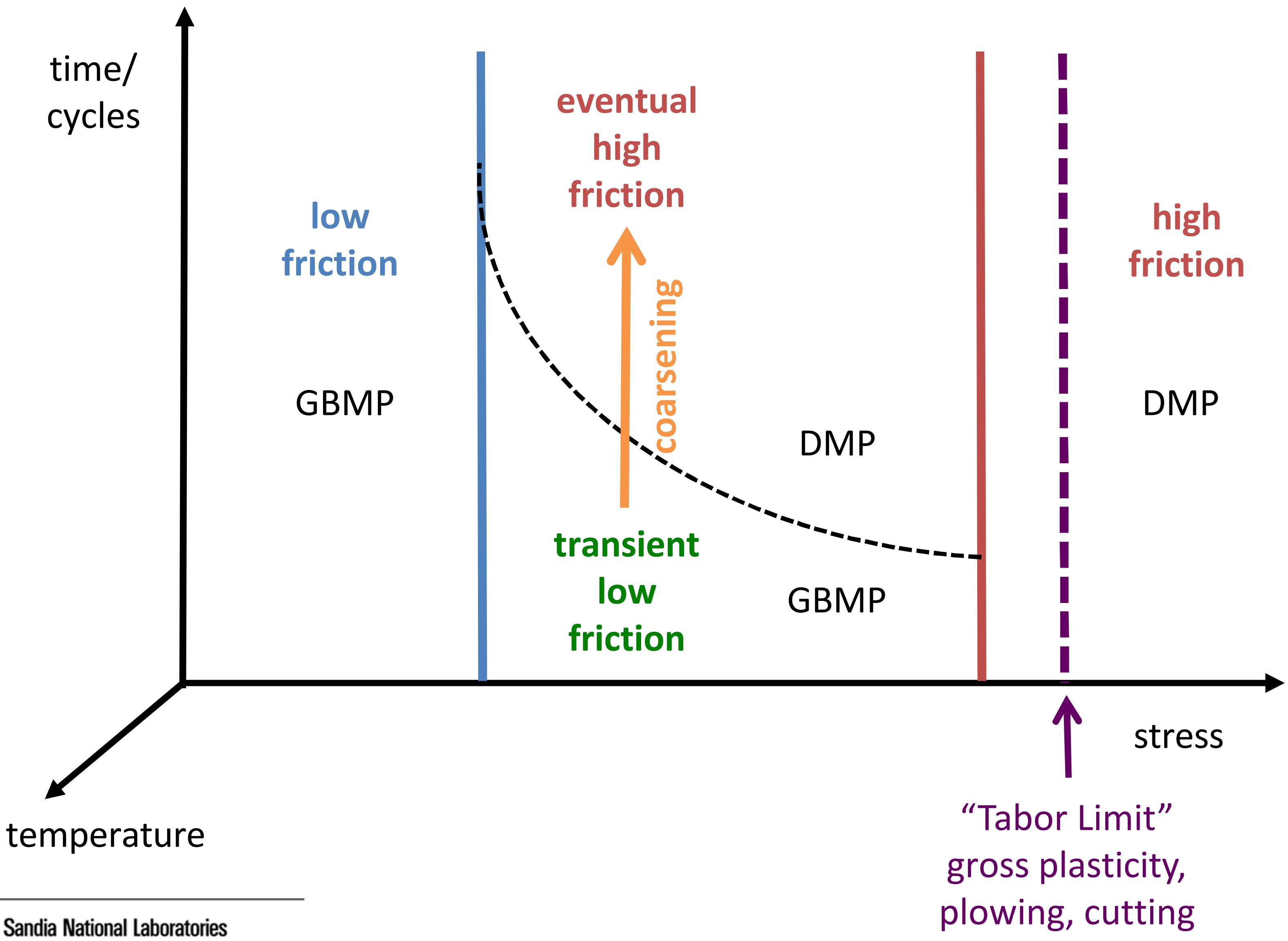
ref: Murdoch et al., Acta Mat. (2013)



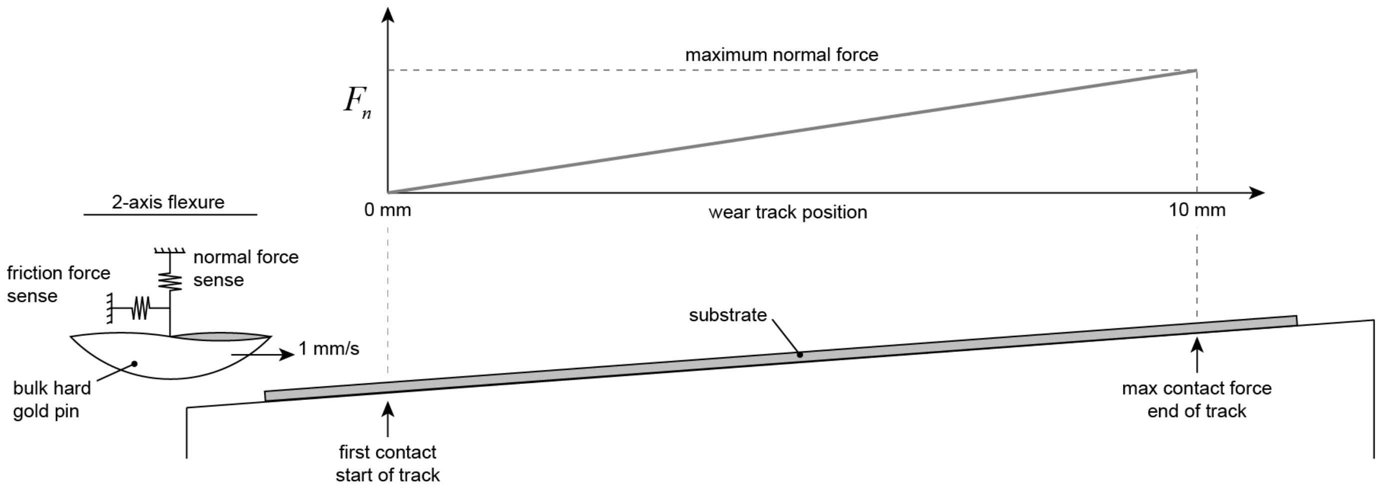
ref: Murdoch et al., Acta Mat. (2013)

Conceptual friction map

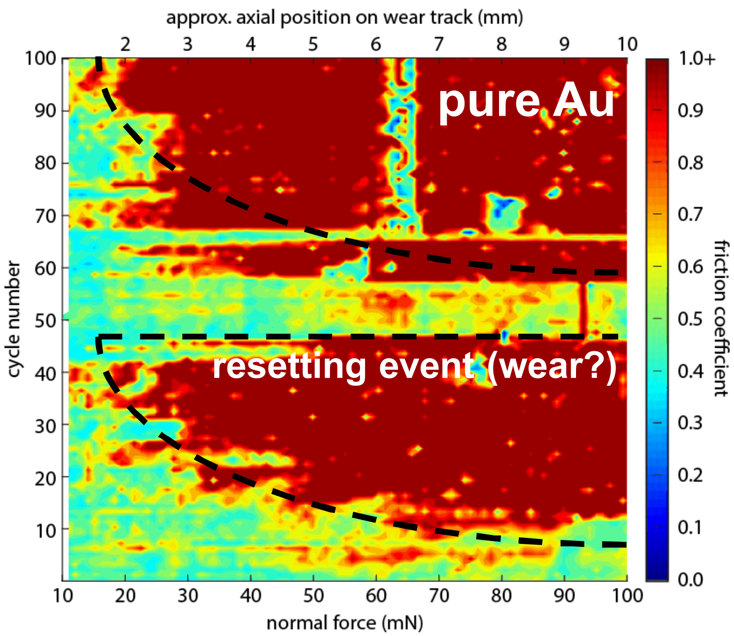
- Friction regimes boundaries based on stress thresholds
- Time evolution only at intermediate stresses

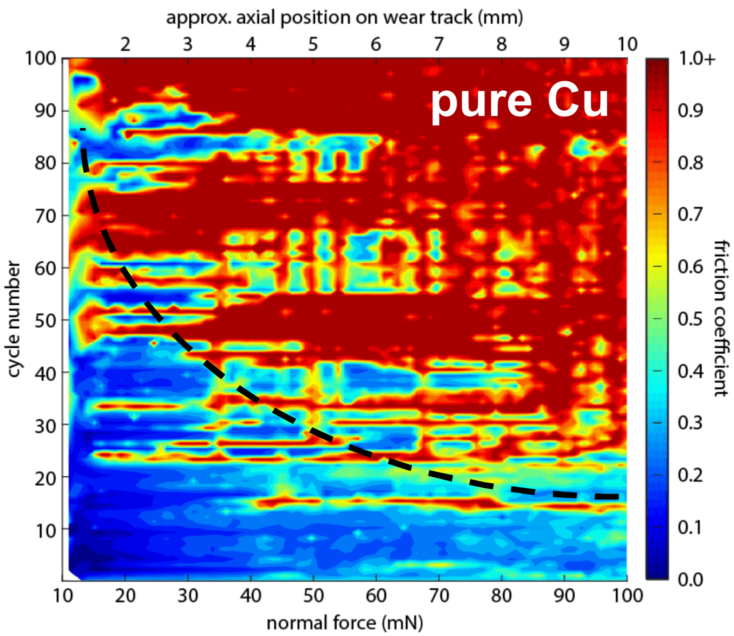


Ramped contact force experiments and friction mapping reveals much!



Messy (tribology…), but there is stress-time envelope!



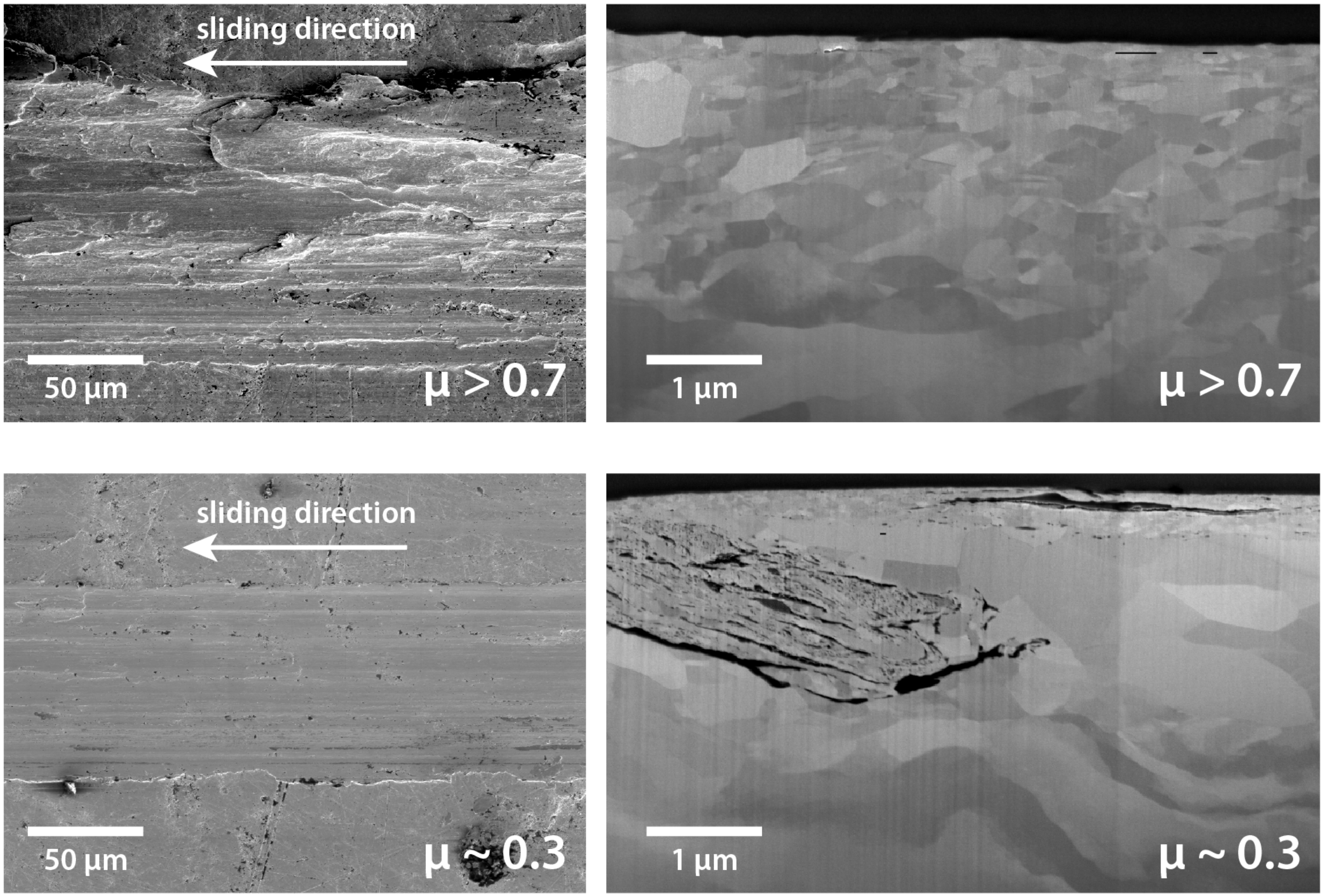


Again, low friction associated with nanocrystalline surface.. see shear banding too

comparing pure Au surfaces and microstructures where low and high friction were measured:

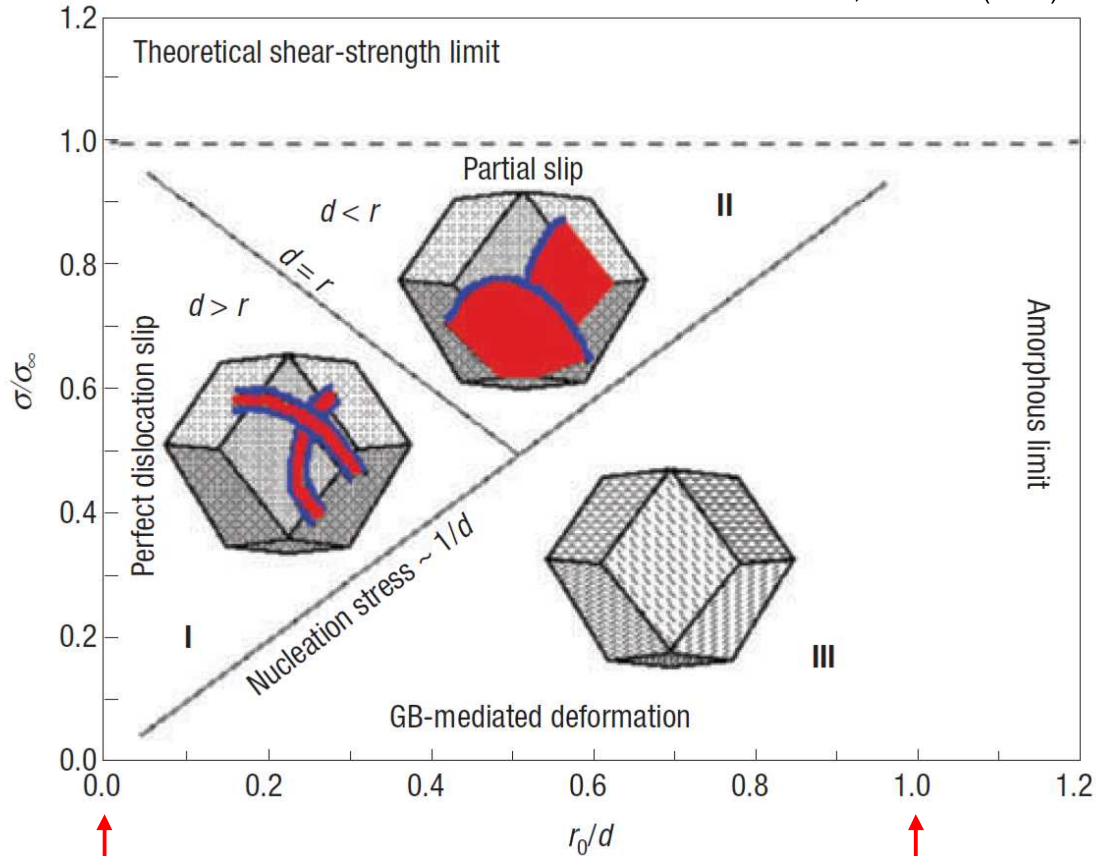
high friction

low friction



What parameter can we use to make **predictions** about stress boundaries?

ref: Yamakov et al., Nat. Mat. (2004)



grain size goes to single crystal

increasing grain size

minimum attainable grain size (peak H-P)

Equilibrium (zero stress) dislocation splitting distance:

$$r_0 = \frac{(2+\nu)Gb^2}{4\pi(1-\nu)\gamma_{sf}}$$

Stress-dependent splitting distance:

$$r_e = \frac{r_0}{1-\sigma_a/\sigma_\infty}$$

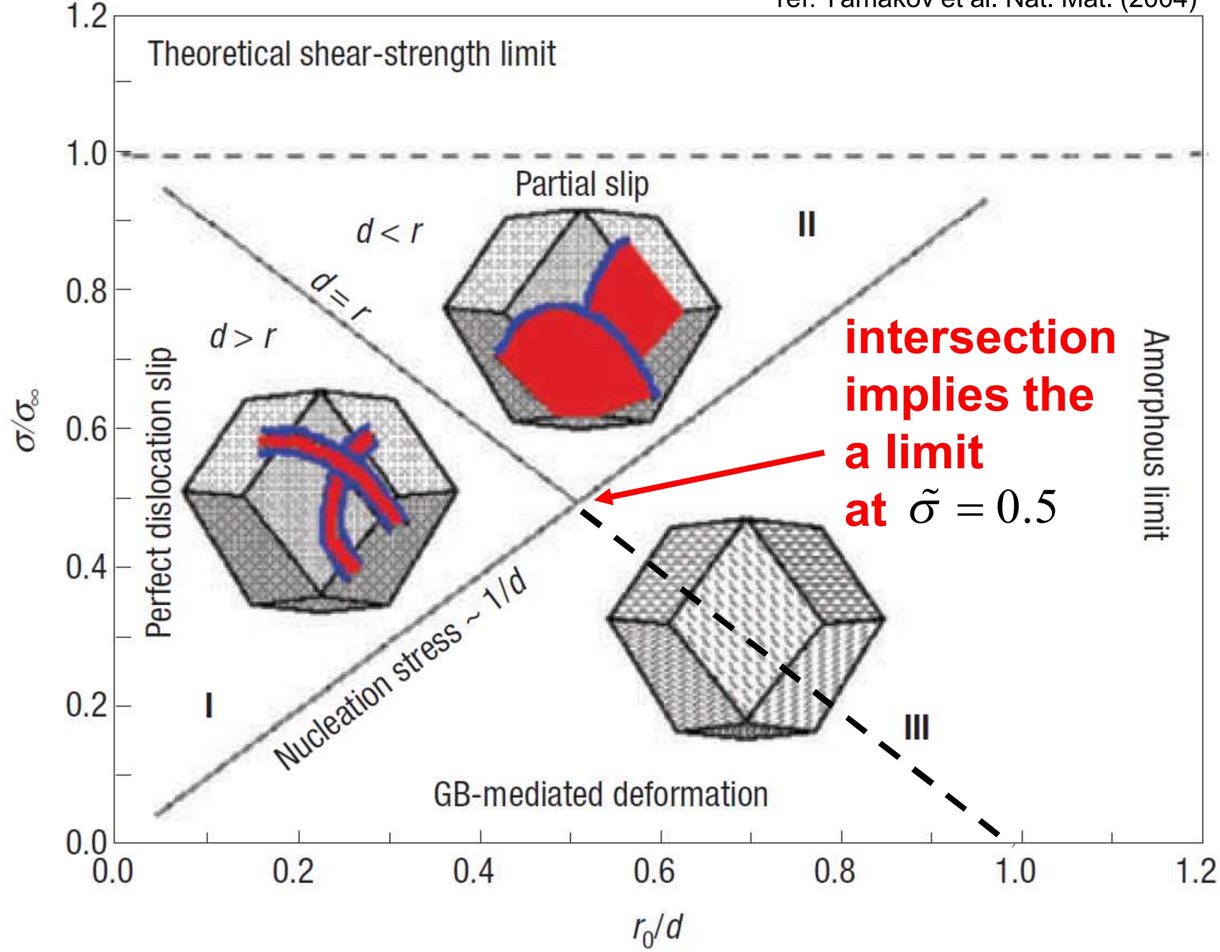
Theoretical strength, grain size where Hall-Petch reaches max:

$$\sigma_\infty = \frac{2\gamma_{sf}}{b}$$

Ref: Froseth et al., Acta Mat. (2004)

Defining the Beilby limit: applied stress below which GBMP always dominates

ref: Yamakov et al. Nat. Mat. (2004)

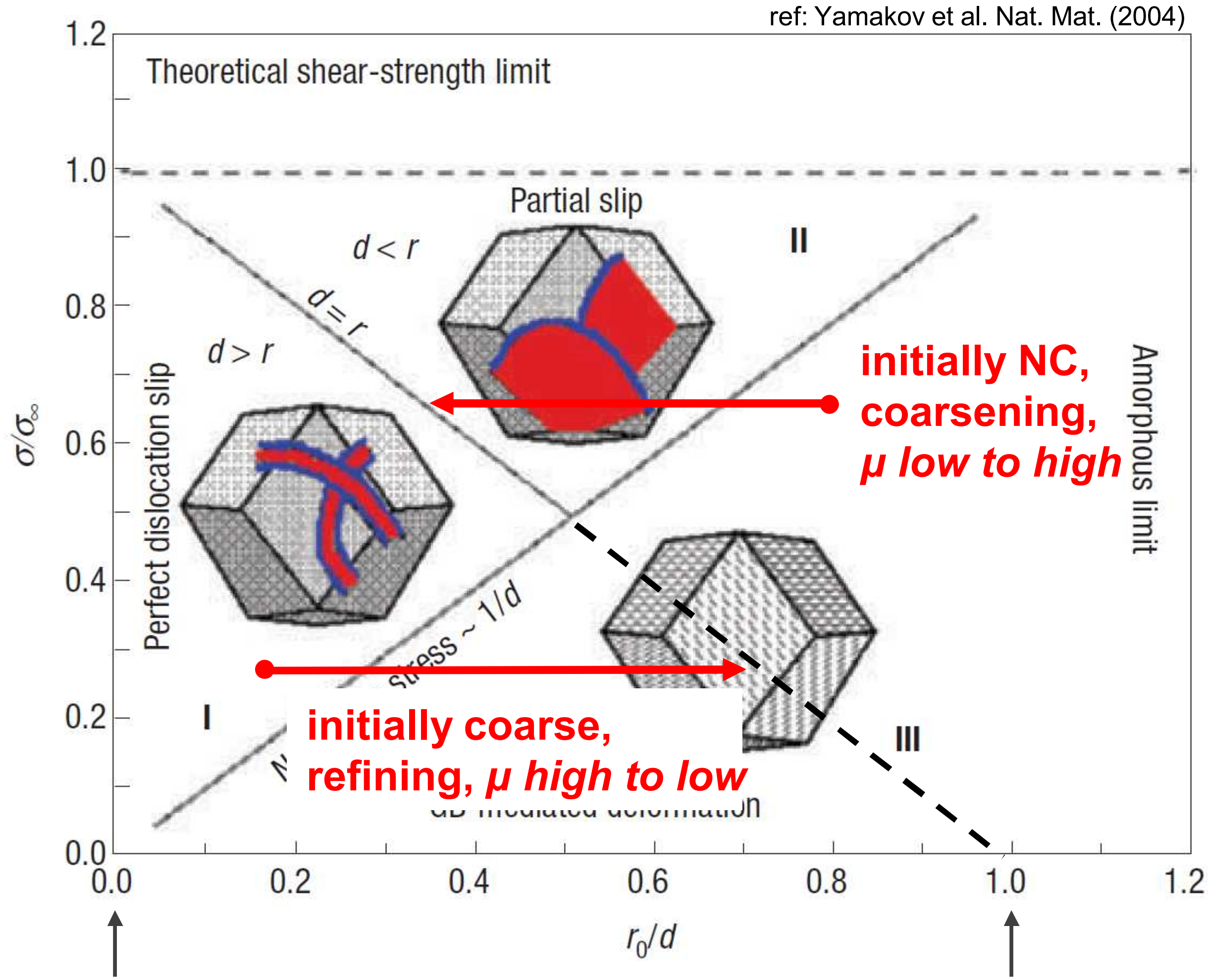


Assumptions:

1. grain size goes to splitting distance, $\rightarrow d$

2. nucleation stress goes as inverse grain size, $\tilde{\sigma} \propto \frac{1}{d}$

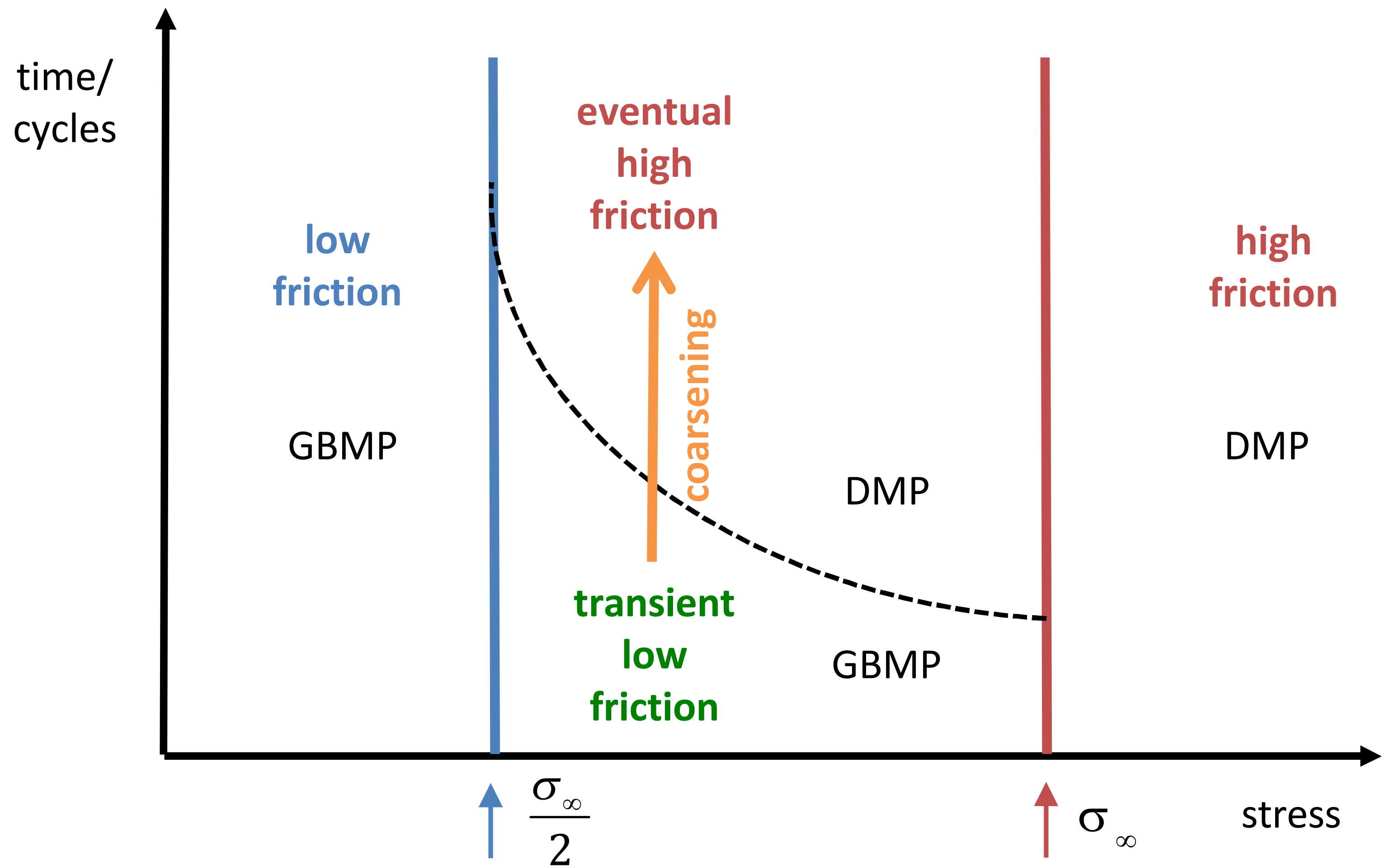
What about evolution? … coarse grained surface can be driven to NC



large grain size

minimum grain size, H-P rollover

Two limits defined



stress limit below which GBMP will always occur

"Bielby limit"

stress limit above which DMP will always occur

"Hall-Petch limit"

Defined by materials parameters only!

What about grain size evolution in the transient regime?

$$v_{gb} = \frac{2\gamma_{GB}}{d} M_0 e^{(-Q/kT)}$$

γ_{GB} = grain boundary energy

d = grain diameter

M_0 = grain boundary mobility

Q = activation energy

- Classical grain growth equation

Defined by materials parameters only!

What about grain size evolution?

$$v_{gb} = \frac{2\gamma_{GB}}{d} M_0 e^{(-Q/kT)} e^{[(\sigma - \sigma_{\infty}/2)V^{*}/kT]}$$

γ_{GB} = grain boundary energy

d = grain diameter

M_0 = grain boundary mobility

Q = activation energy

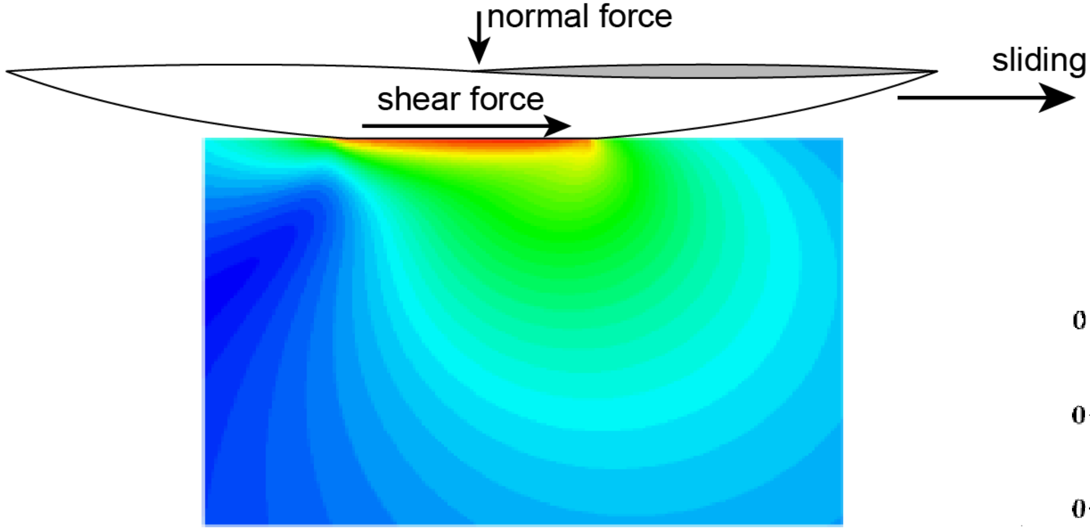
V^{*} = activation volume $\simeq 10b^3$

- Classical grain growth equation
- Extra term depends on applied stress
- Assume initial cycle heavily refines surface to r_0
- Use this to see how long it takes to evolve grains to $2r_o$

Defined by materials parameters only!

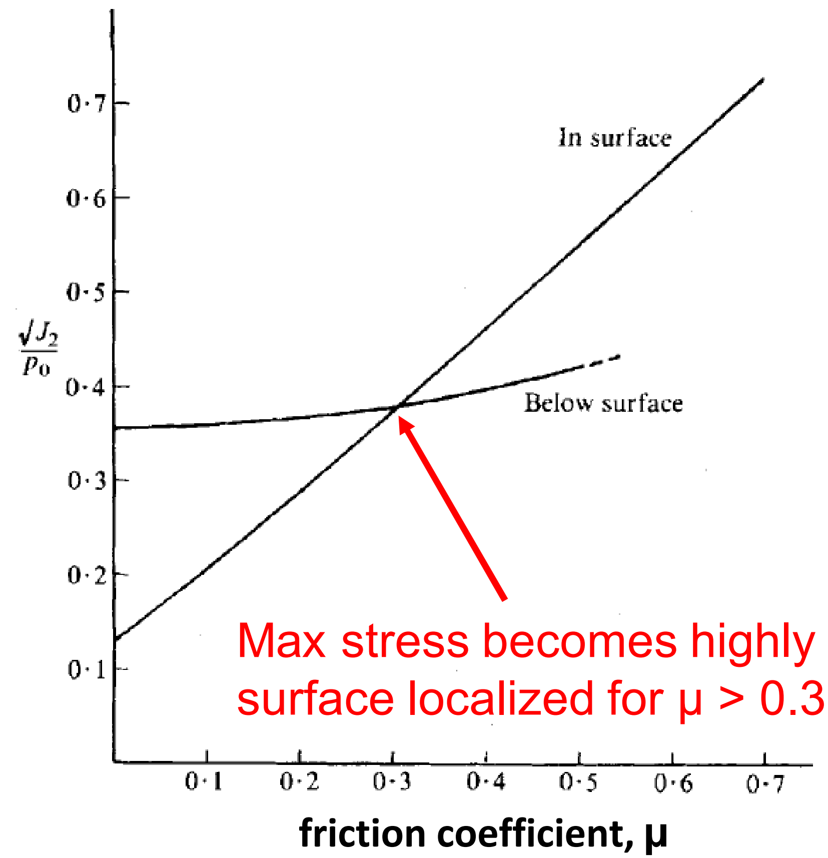
Finally, applied stress? Hamilton model -> max surface von Mises stress

von Mises stress contour lines:



$$\sigma_{surf,\max} = \frac{3F_n}{2\pi a^2}\left[\frac{1-2\nu}{3} + \frac{(4+\nu)}{8}\pi\mu\right]$$

- *G. Hamilton, Proc. Inst. of Mech. Eng. C, 1983*
- Like Hertz, but with friction
- Uses Hertz solution for contact radius



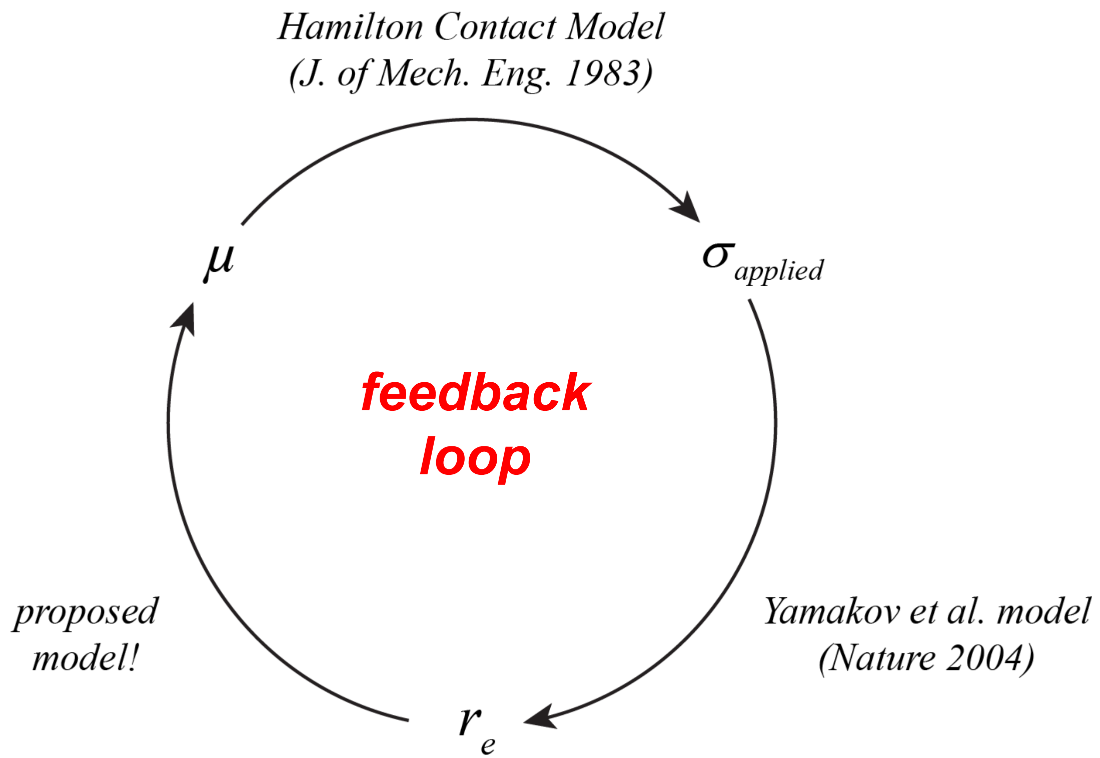
Now we make it dimensionless

reduced stress: $$\tilde{\sigma} = \frac{\sigma_{surf,\max}}{\sigma_{\infty}}$$

reduced time: $$\tilde{\tau} = \log_{10}\left[\left(\frac{2\lambda_a}{v_s}\right)\left(\frac{4\gamma_{gb}M_0}{r_0^2}\right)\right]$$

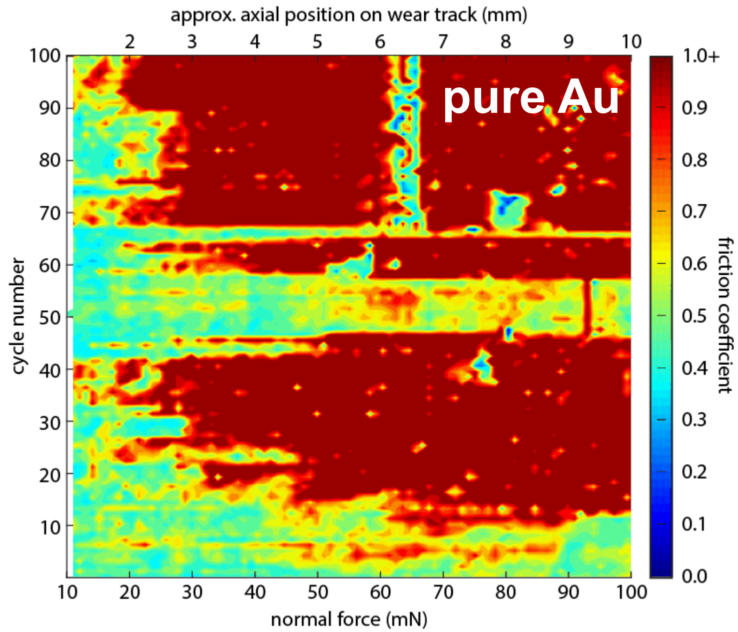
- Normalize stress by a fundamental stress
- Normalize time by the fundamental “grain boundary time”
- Plot semilog

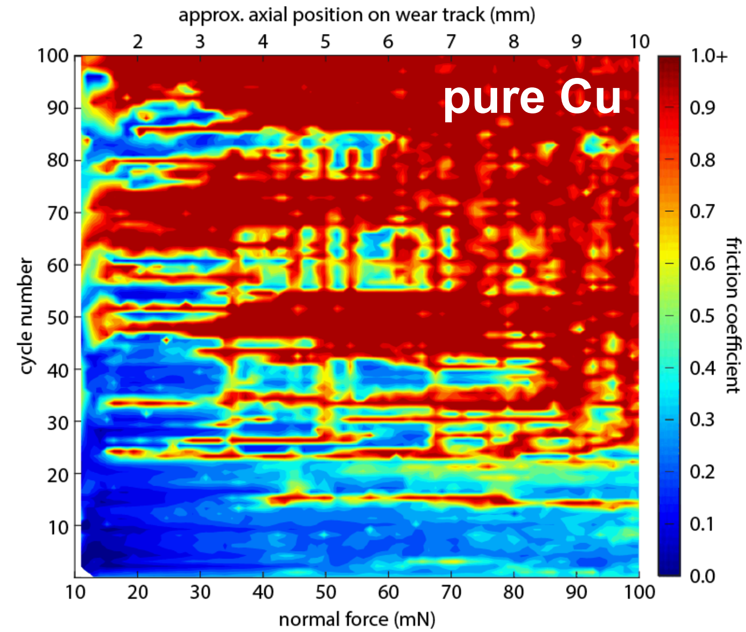
Can Now Complete the Circle

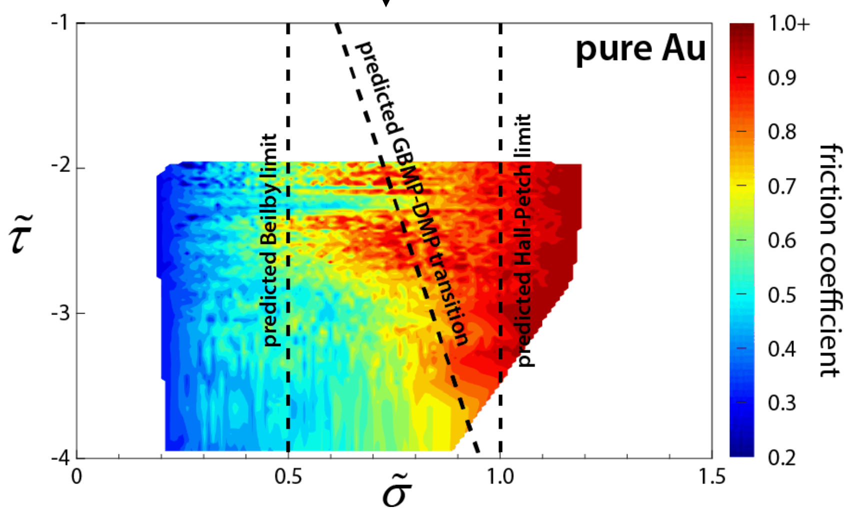


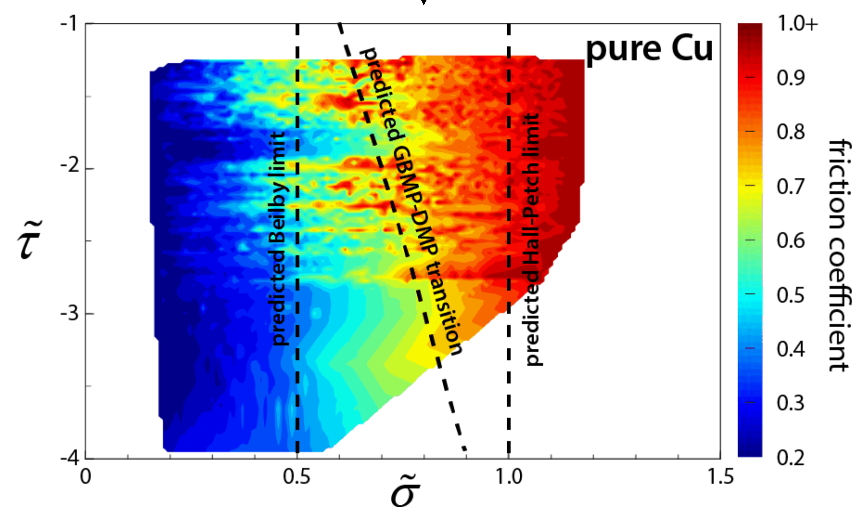
- Numerical correlation between applied stress, grain size and friction coefficient.
- All based on materials parameters.

Apply reduction to ramped friction data…

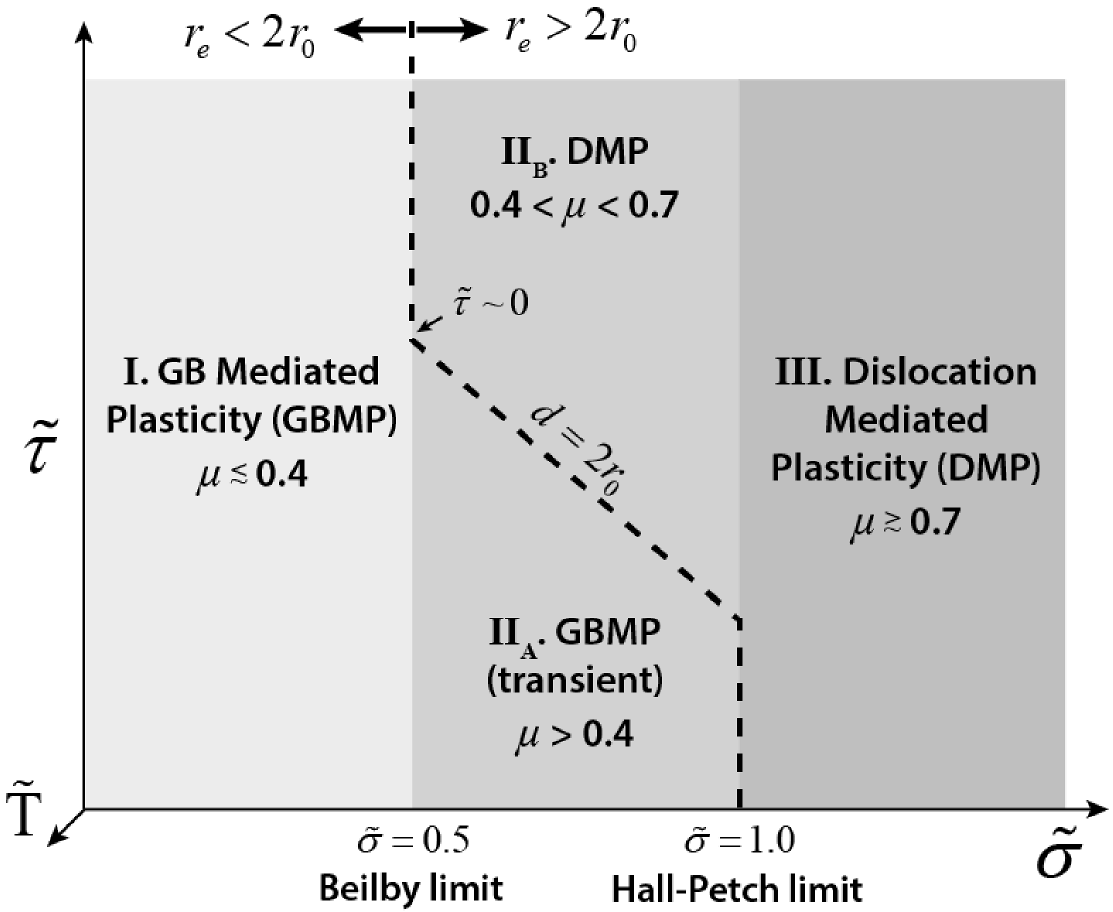






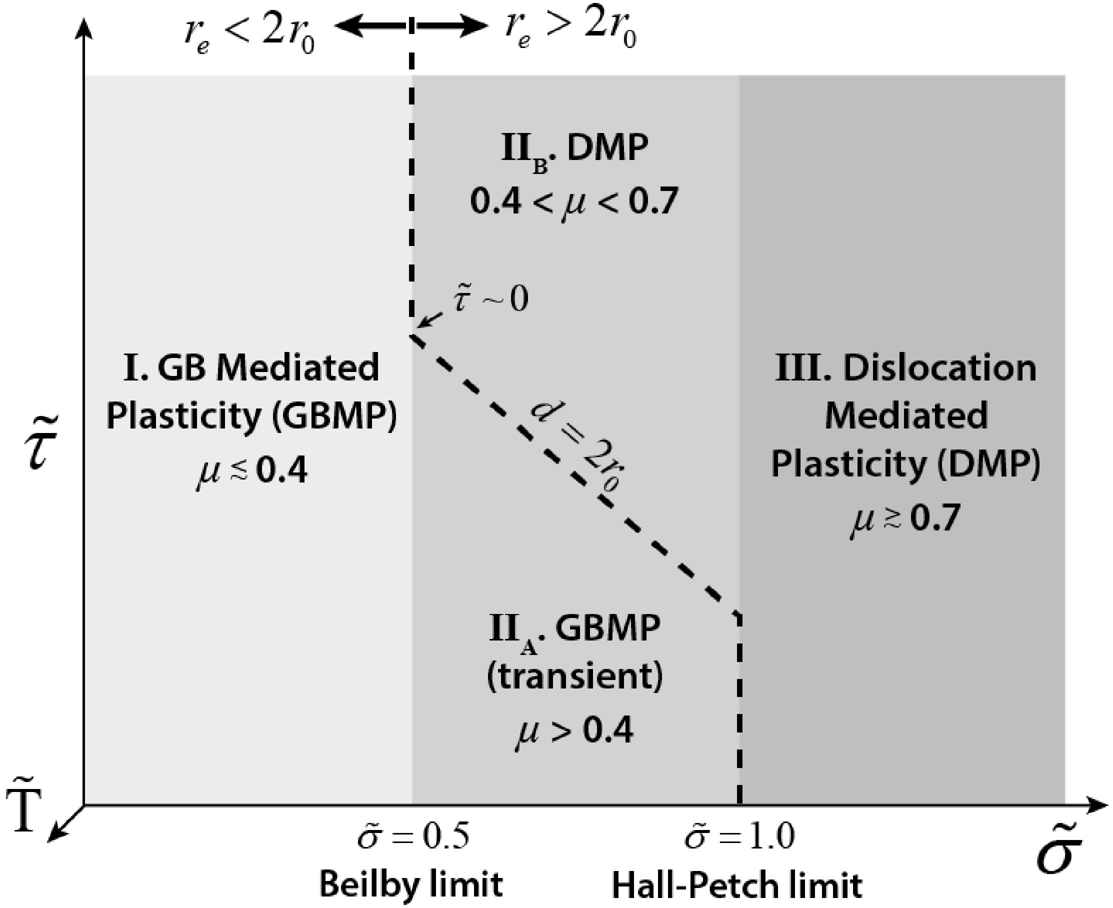


Returning to the microstructure-based friction regimes model…



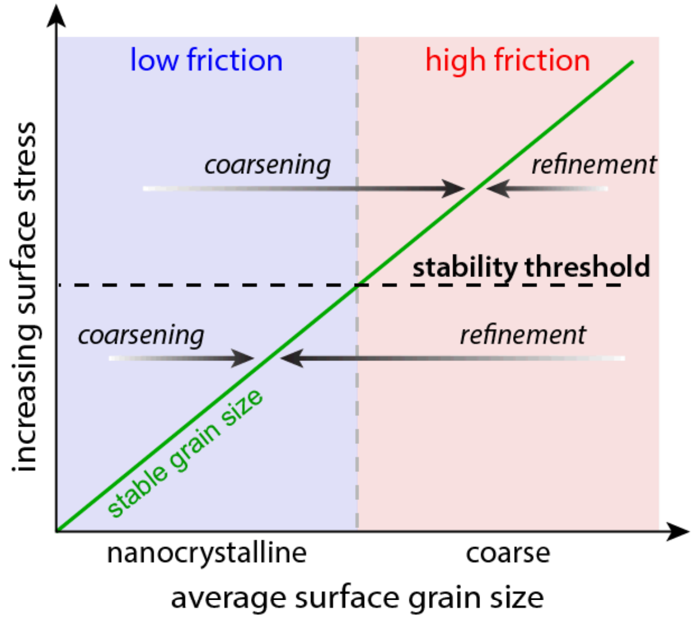
We assume that wear events reset the surface relatively fast, where in the right conditions even coarse grained material is first rapidly refined then gradually coarsened via cyclic stress

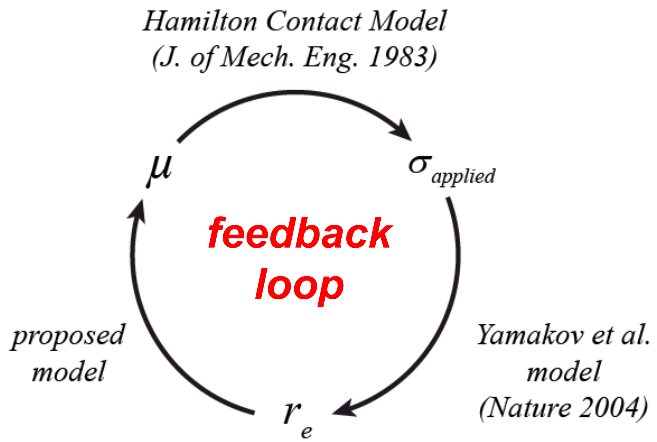
What about boundary lubrication of metal contacts (e.g. graphite, DLC, MoS_2)?

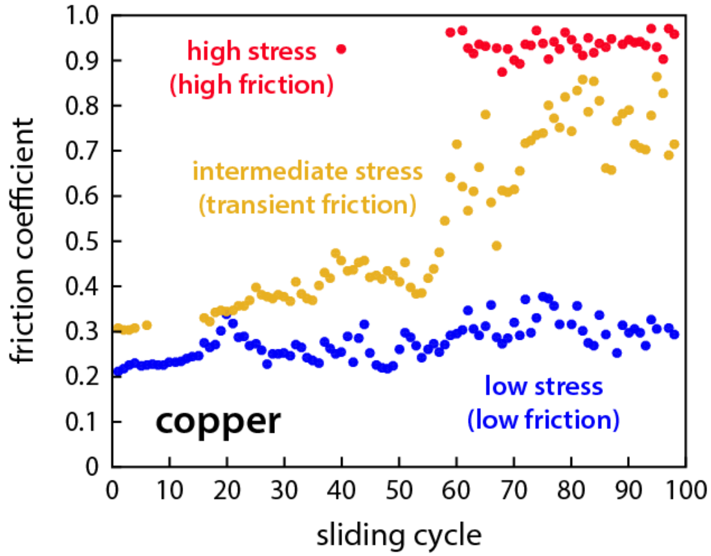


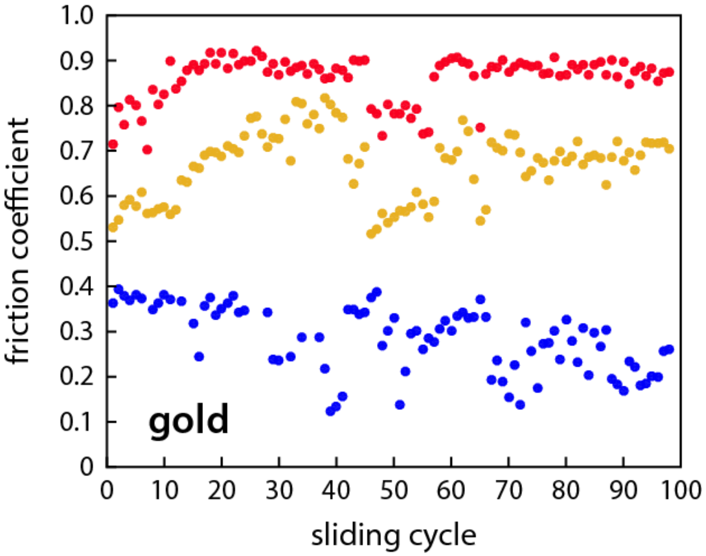
Boundary lubrication (e.g. graphite, MoS_2, engine oil) mitigates commensurate contact –
thus it is possible to achieve low friction at higher normal force

Ok, that was a lot of information. Big picture is…



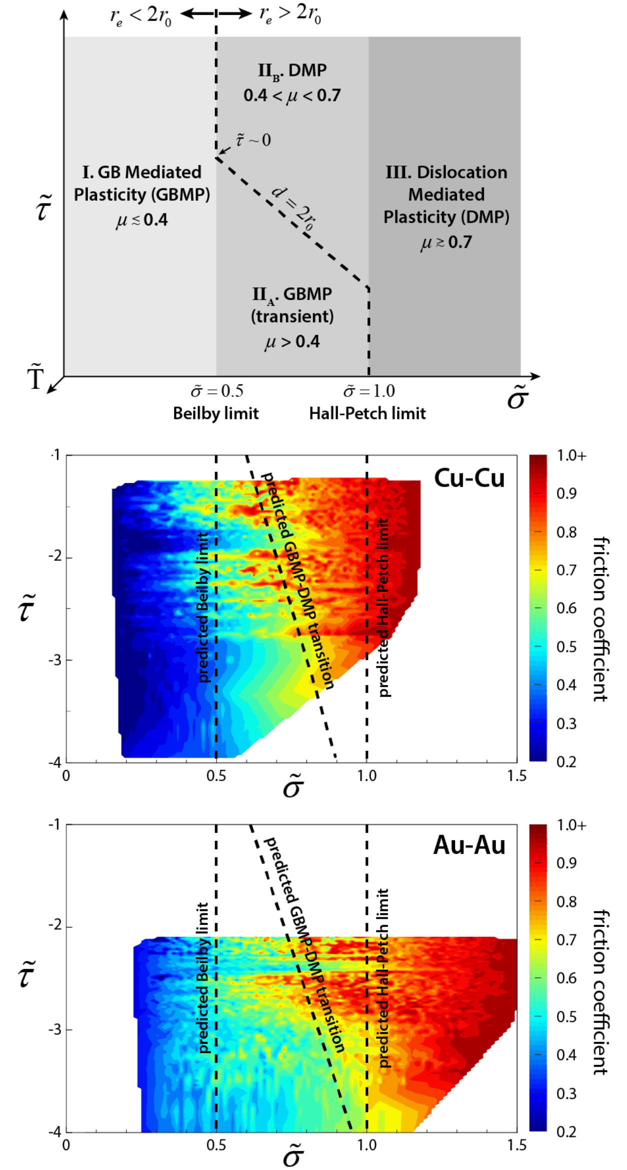






Only the beginning, much left to do…

- So far only applied to FCC metals. Apply to BCC metals, ionic solids -- ductility observed in nanoparticles of alumina
- Now exploring the temperature axis: optimizing high current density electrical sliding and rolling contacts
- Clearly there are other regimes and boundaries that have not been identified…
- Low friction regime is result of a competition between wear and stress-driven grain growth
- Can we ***determine*** stacking fault energy or grain boundary mobility for alloys?
- Can we model competing wear? …difficult, but maybe



Appendix Slides

Classical attempts to define wear & friction regimes were empirical/phenomenological

Scripta METALLURGICA et MATERIALIA Vol. 24, pp. 805-810, 1990 Printed in the U.S.A.

VIEWPOINT SET No. 14

WEAR-MECHANISM MAPS

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(Received August 15, 1989)
(Revised October 16, 1989)

WEAR-MECHANISM MAPPING: THE APPROACH

Wear is the loss or transfer of material when contacting surfaces slide. In general, the wear rate W (defined here as the volume loss per unit area of surface per unit distance slid) depends on the bearing pressure F/A_n (where F is the load carried by the contact and A_n is its nominal area), on the sliding velocity, v, and on the material properties and geometry of the surface (Figure 1):

$$W = f(F/A_n,\ v,\ \text{Mat. Props., Geometry}) \qquad (1)$$

But one such equation is not enough. There are many mechanisms of wear, each dependent in a different way on the variables. The dominant mechanism, at any given F and v, is the one leading to the fastest rate of wear. Table 1 lists some of the mechanisms encountered in wear studies of metals and of ceramics; it includes wear by melting, by chemical change induced by frictional heating, by low-temperature plasticity and by brittle fracture.

TABLE 1: MECHANISMS OF WEAR

METALS	CERAMICS
SEIZURE	SEIZURE (?)
MELT WEAR	MELT WEAR
SEVERE-OXIDATIONAL WEAR	THERMALLY-INDUCED STRUCTURE CHANGE
MILD-OXIDATIONAL WEAR	THERMAL CRACKING AND SPALLING
PLASTICITY-DOMINATED WEAR	BRITTLE SPALLING; INDENTION CRACKING
ULTRA MILD WEAR	

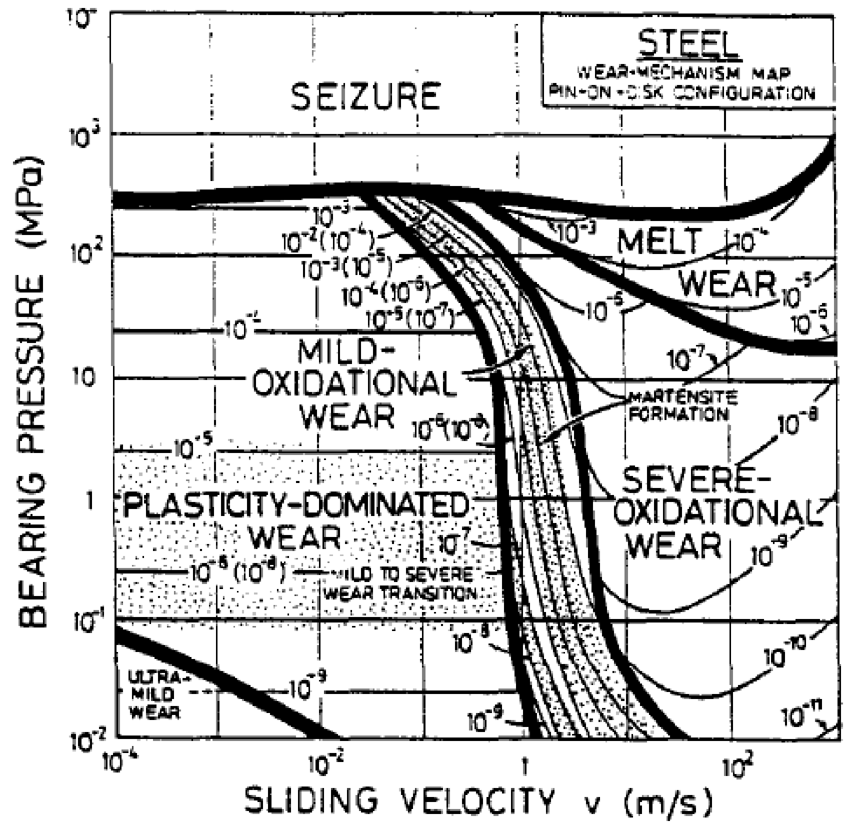
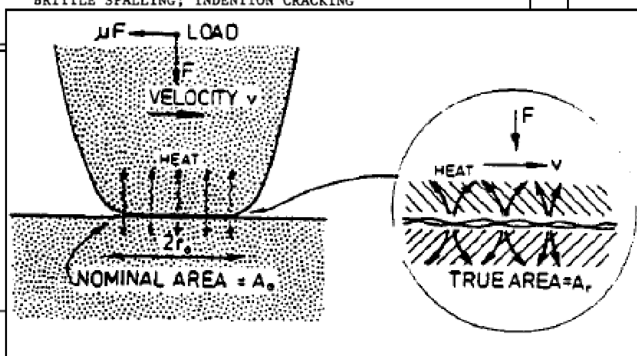
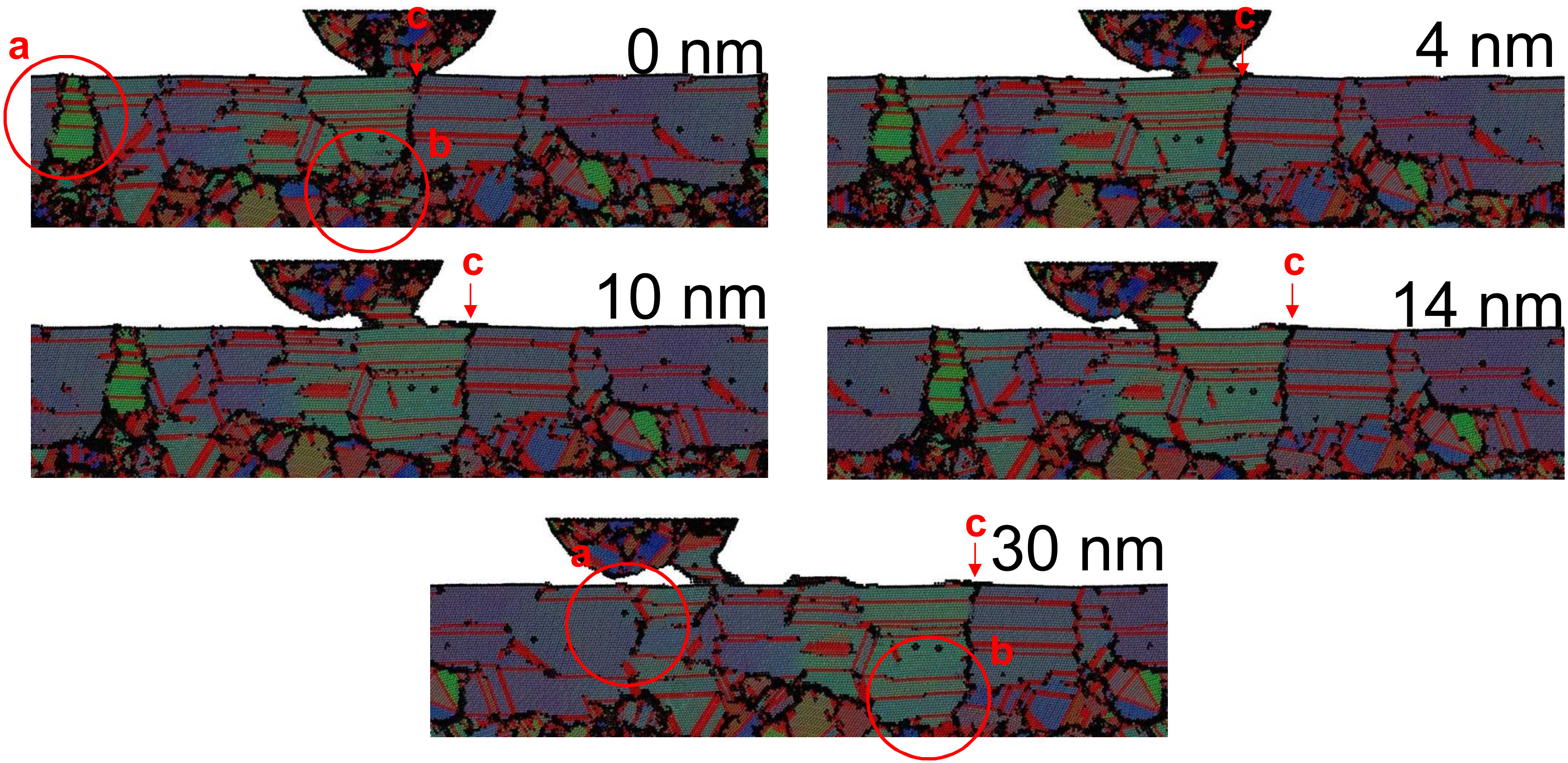


Figure 3. A wear-mechanism map for low-carbon steel based on physical modelling calibrated to experiments. The shaded regions show transitions.



Another look, now at pure Au tip/slab contact evolution over a longer sliding time

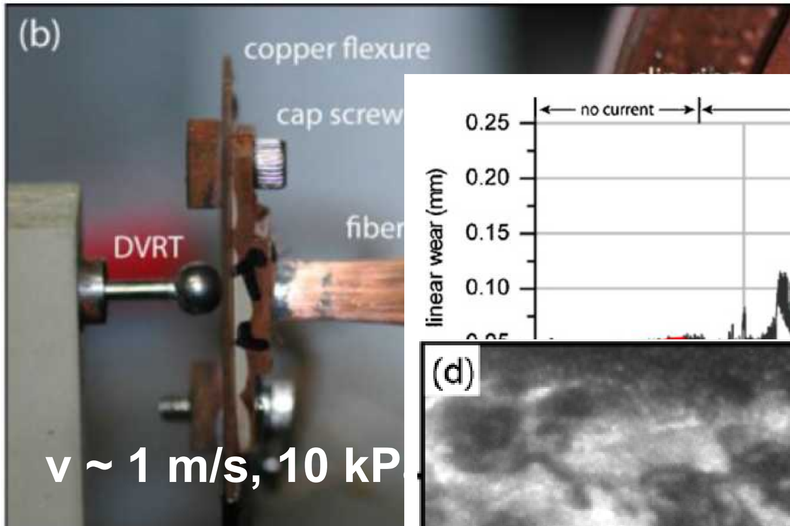


- Initially distinct grains
- After shear (adhesive load), coalescence – now a mode II crack
- Single grain forms across interface – stress induced grain growth

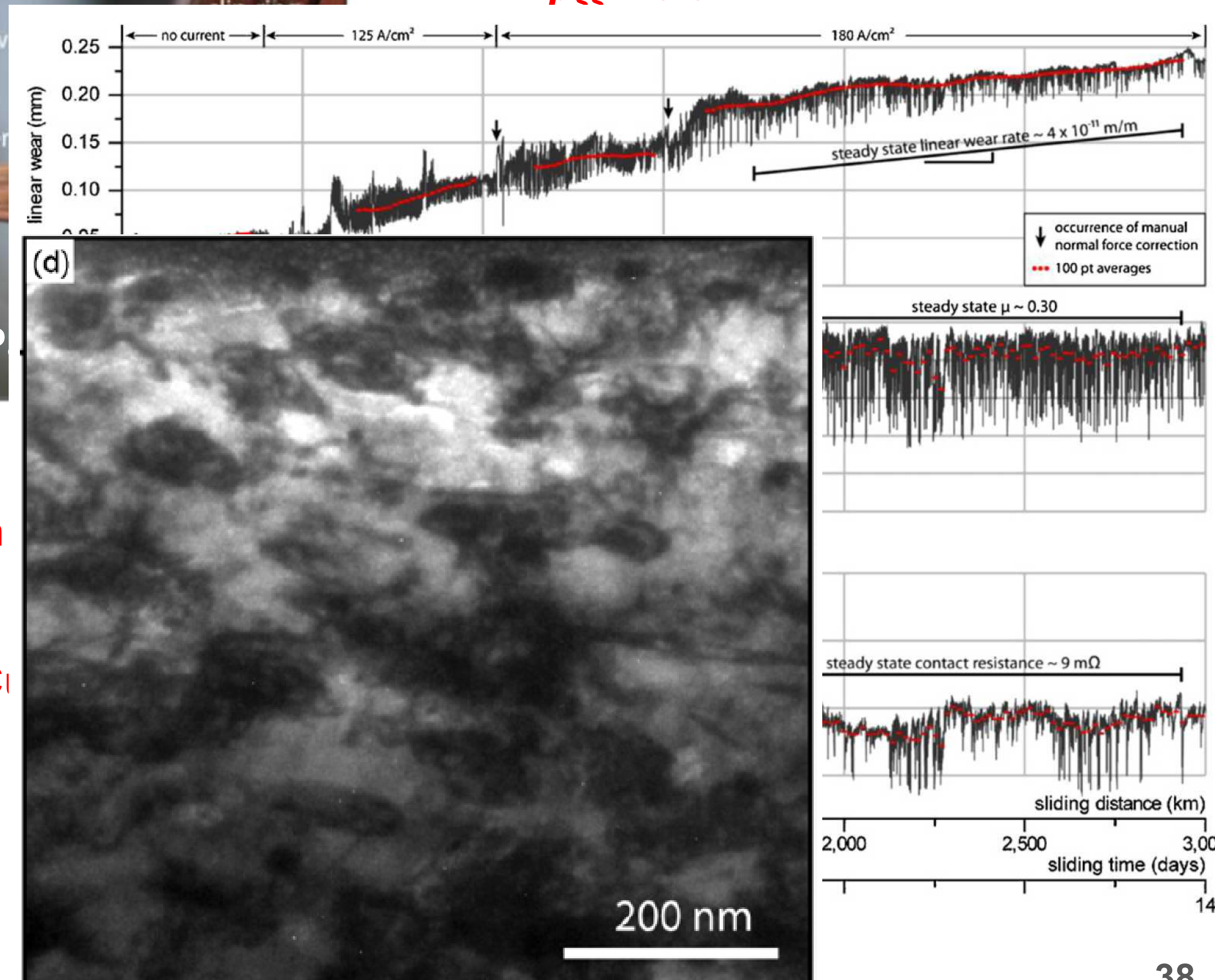
Low friction linked to nanocrystalline surface grain size – even with pure metals

wear rate of ~ 1 nm per kilometer

μ_{ss} ~ 0.3



v ~ 1 m/s, 10 kP



Again, low friction associated with nanocrystalline surface for a Cu-C system

Classical attempts to define wear & friction regimes were empirical/phenomenological

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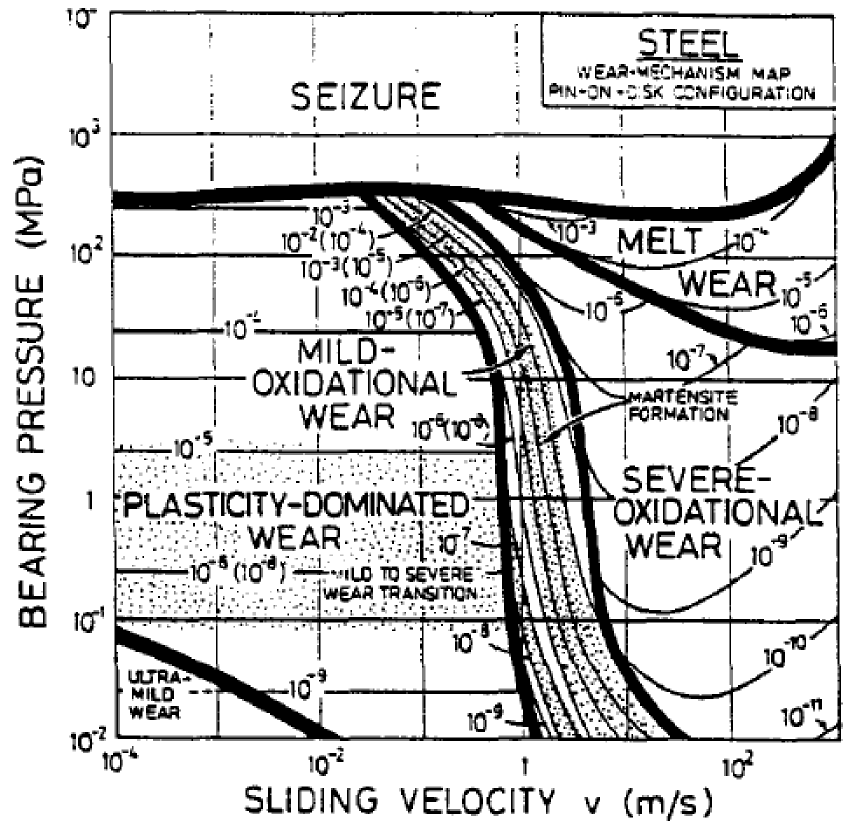

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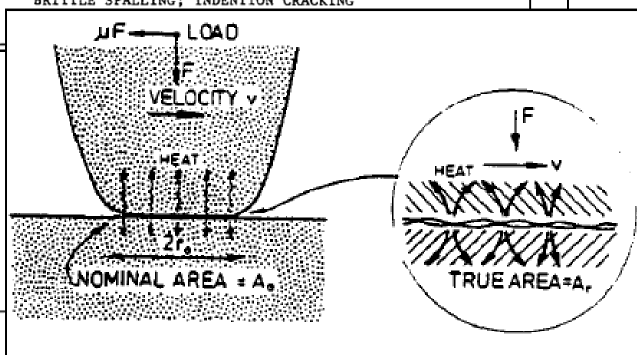
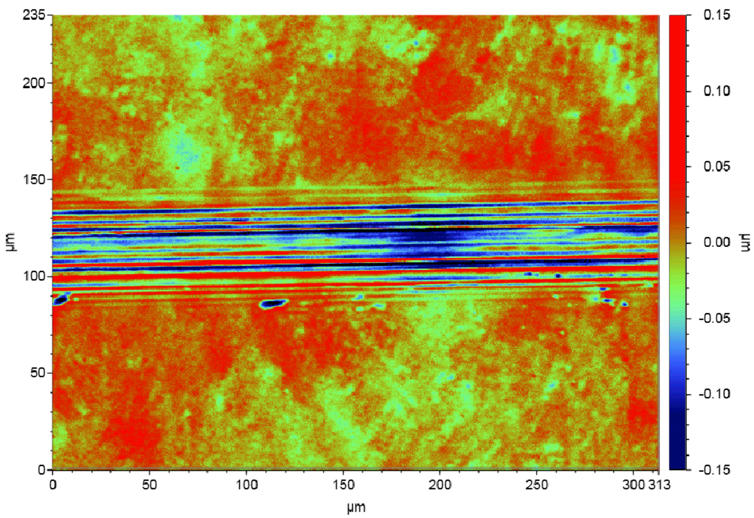


Wear analysis of pure and alloy gold surfaces along wear track for ramped force test

Wear tracks analyzed using a scanning white light interferometer, sample image shown below:



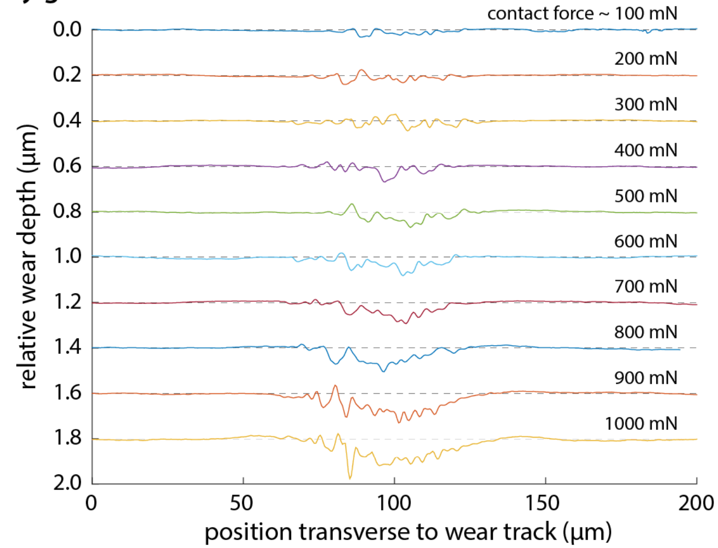
Images taken at 1 mm intervals along 10 mm long wear tracks

Each image then collapsed into a single line plot showing the average wear track cross-section (right images)

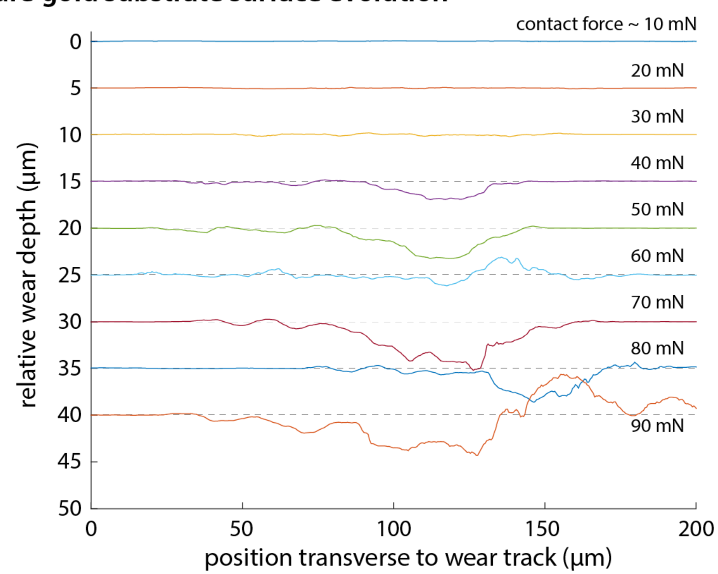
Wear at each interval calculated based on contact force average in this part of the track, number of cycles, and volume loss

Change in contact force along length of image (313 µm) was about +/- 3% of max load

alloy gold film surface evolution

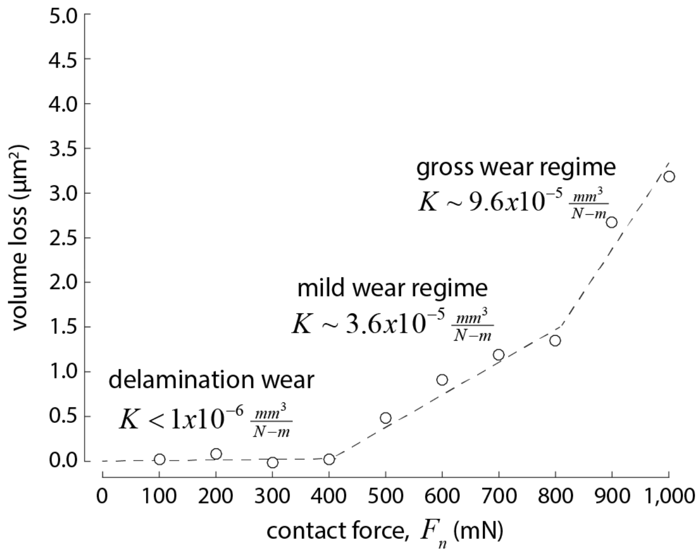


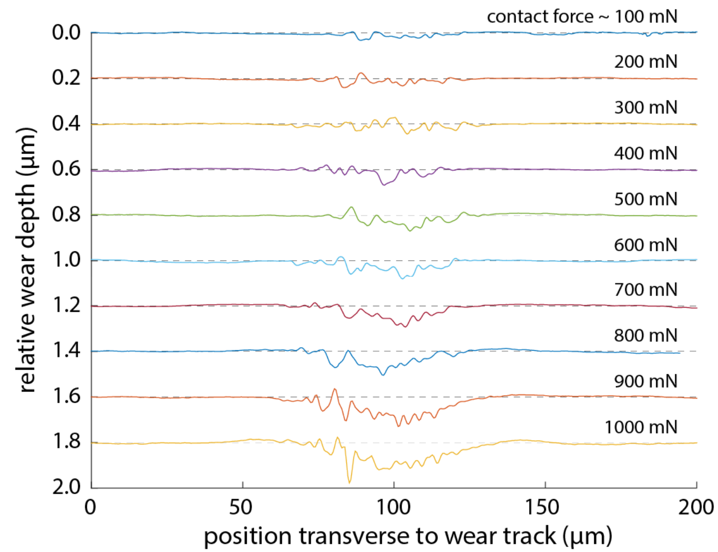
pure gold substrate surface evolution



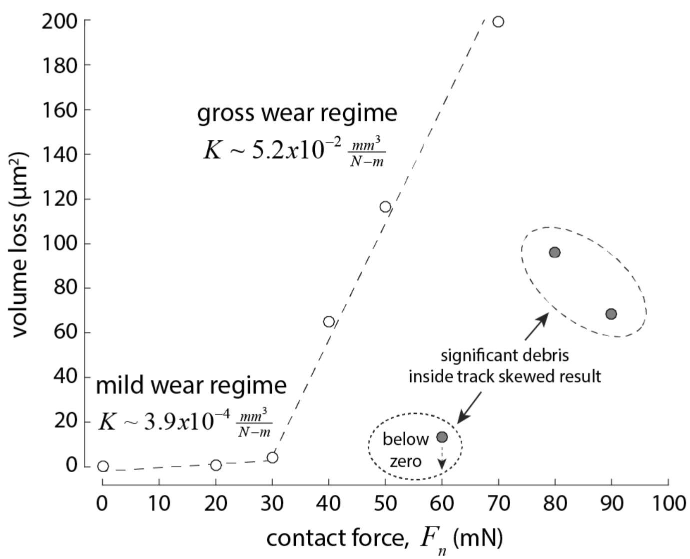
Observed three wear regimes

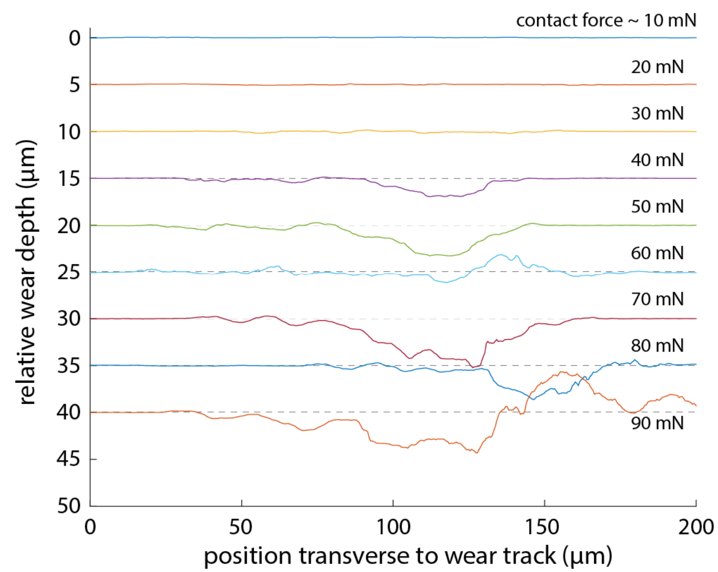
alloy gold film surface evolution





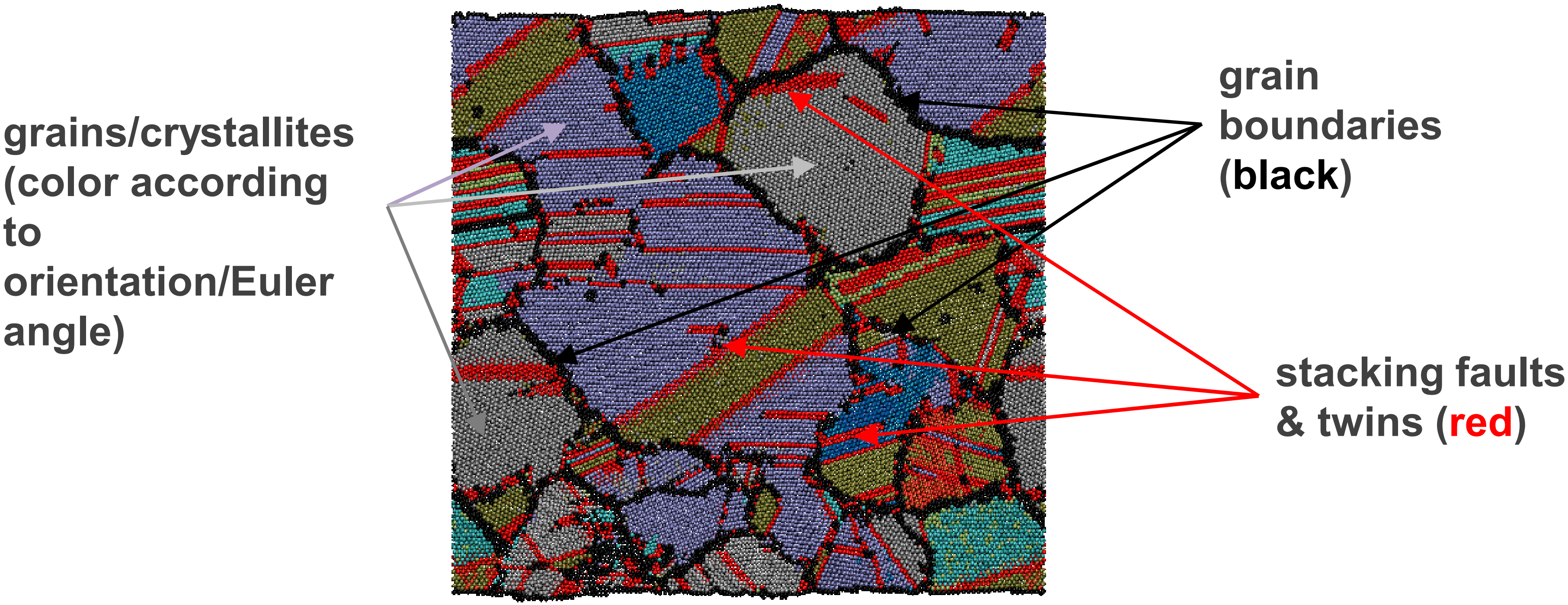
pure gold substrate surface evolution





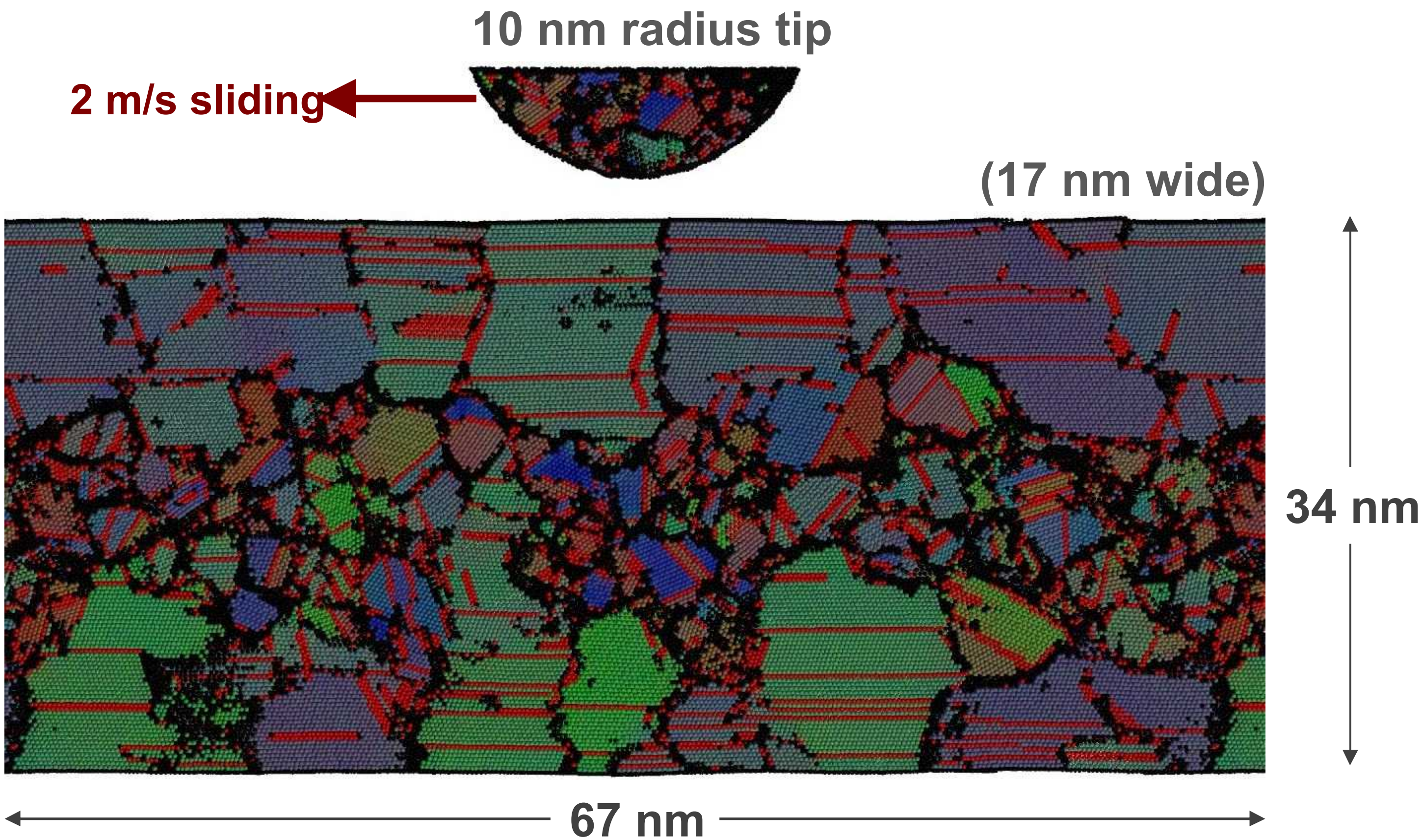
MD Simulations: how to interpret the following images…

Cross-sectional slices of a 3D space filled with atoms



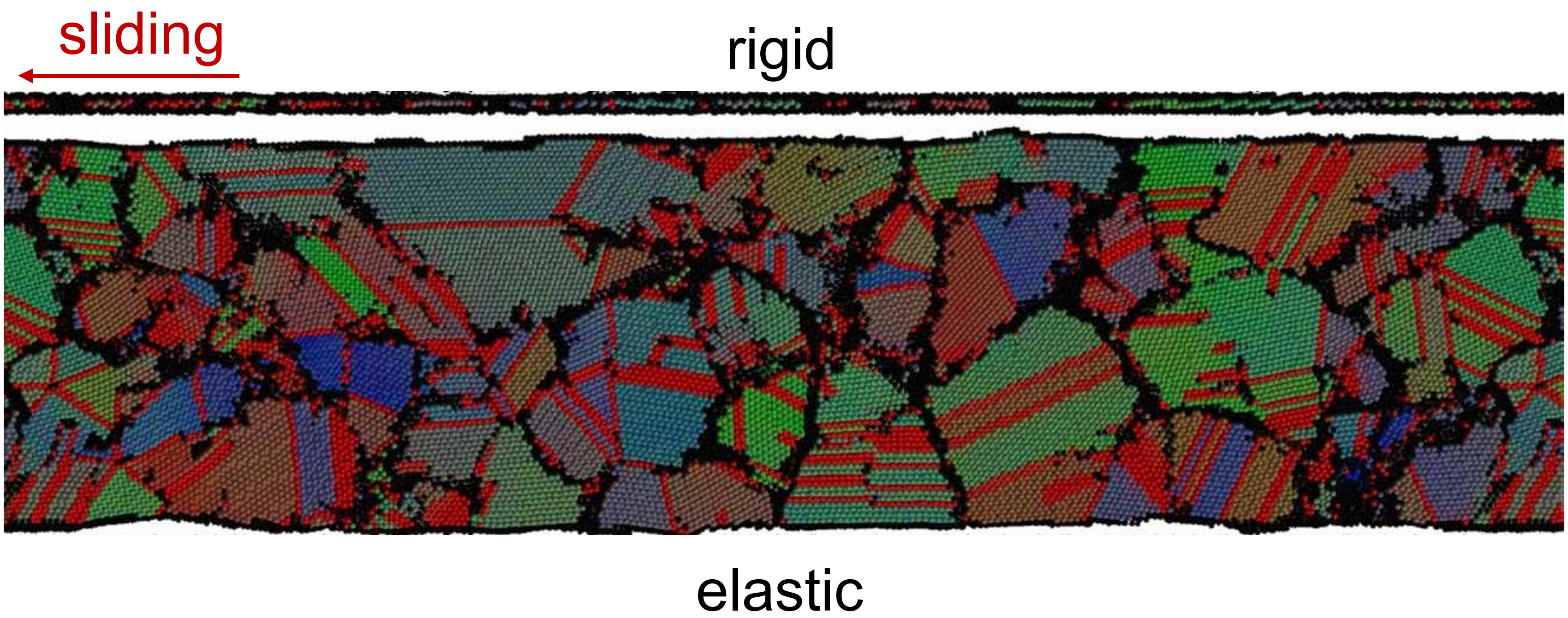
- Locally FCC atoms colored according to Euler angle
- Locally HCP atoms colored red – twins & stacking faults
- Otherwise colored black – grain boundaries

Tip based friction simulations : this is what the initial condition looks like



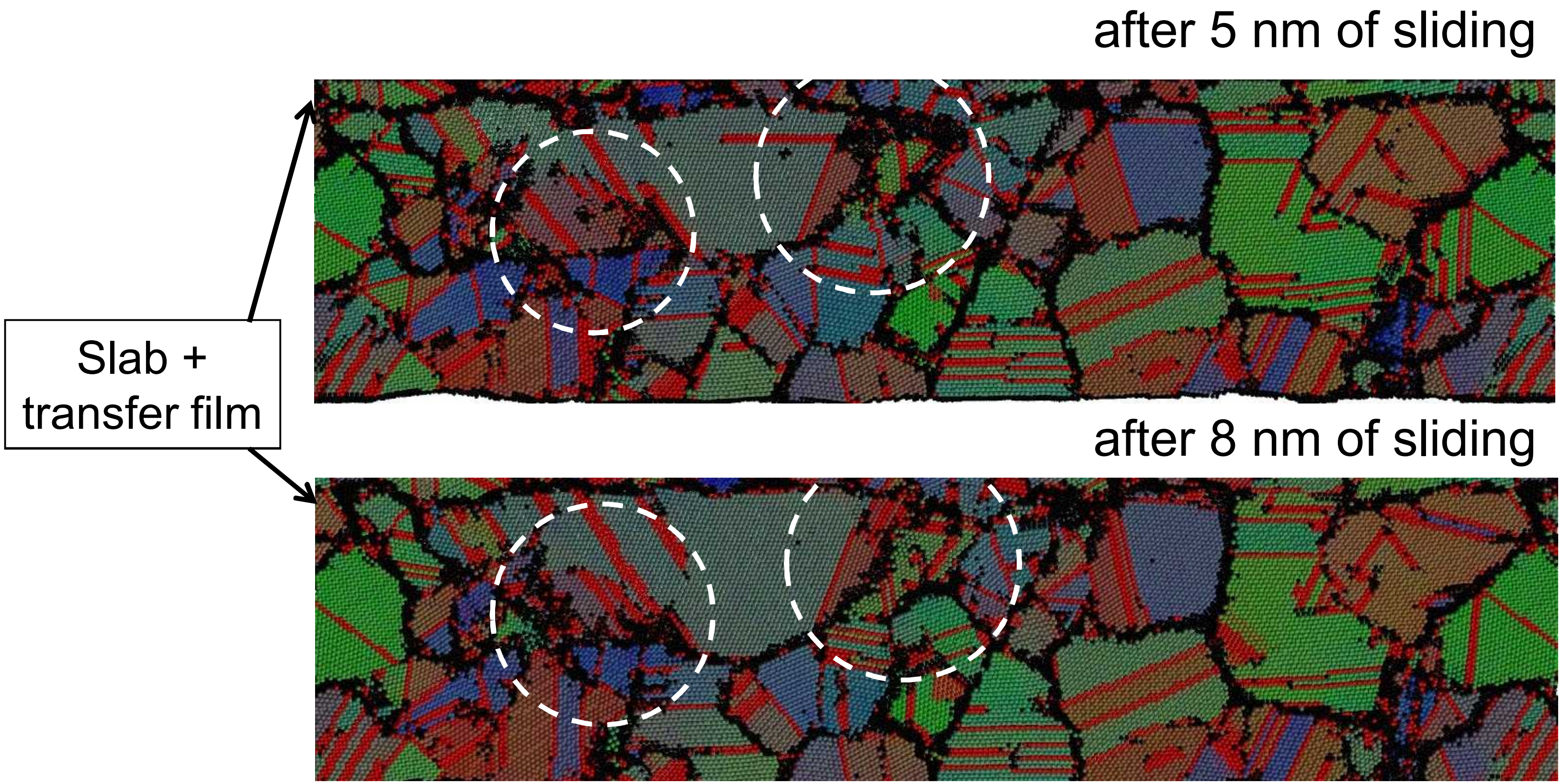
Substrate: nanocrystalline Ag
Constraint 1: constant velocity
Constraint 2: constant separation ***or*** normal force

Slab-on-slab sliding contact simulations remove wear, enable friction quantification



- Rigid slabs suppress grain growth
- No plowing is possible/reduced contact stress

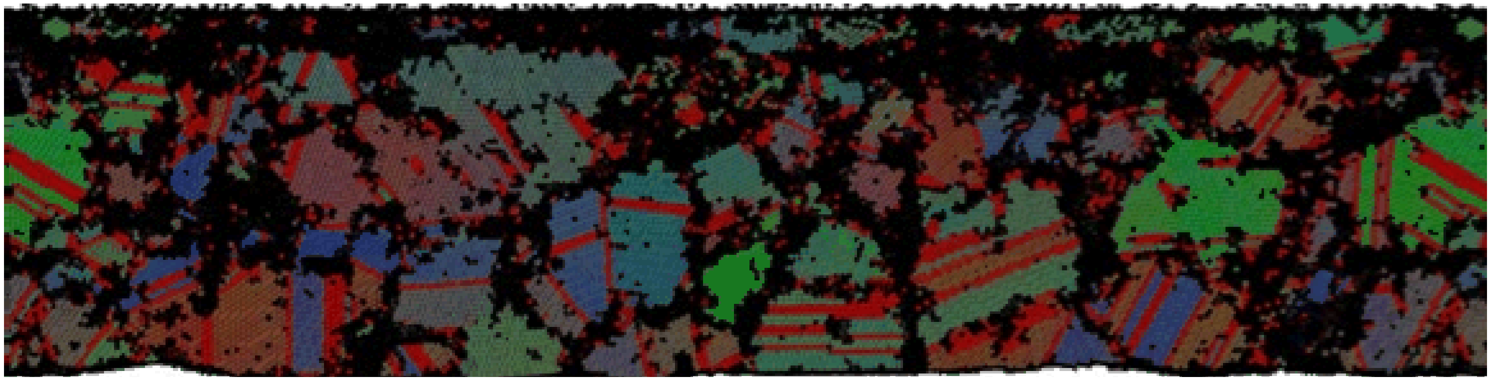
Sliding of pure Ag slabs



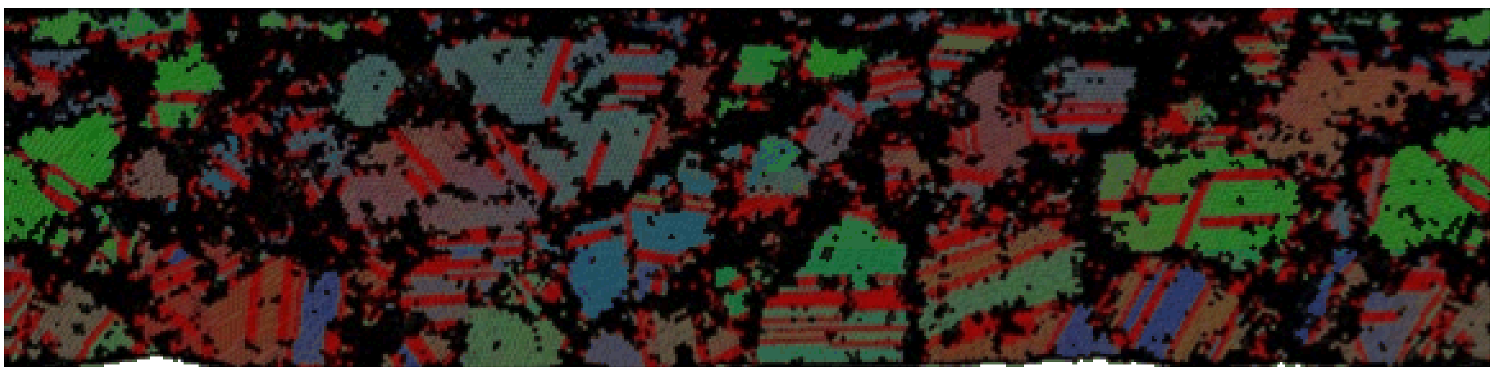
- Slight grain growth, forms transfer film
- Slides along transfer film grain boundaries or nearby stacking faults depending on availability

Sliding of Ag alloy (10% Cu) contact

after 6 nm of sliding



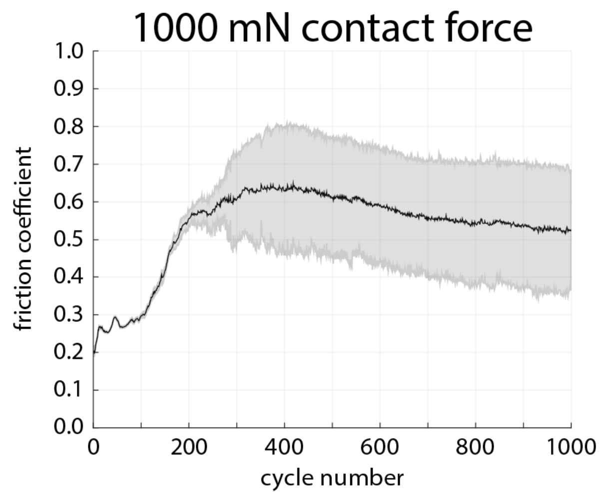
after 16 nm of sliding

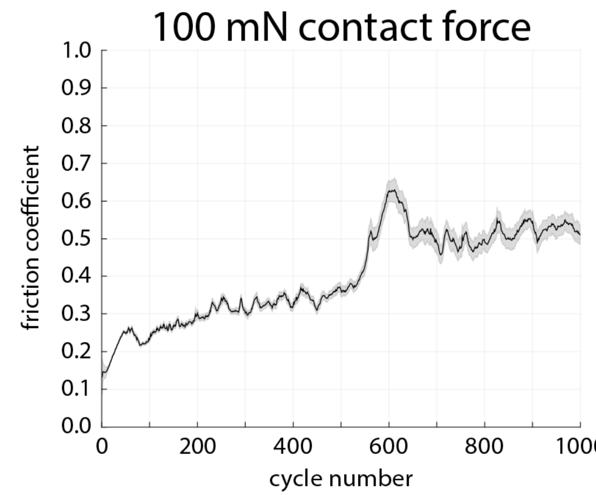


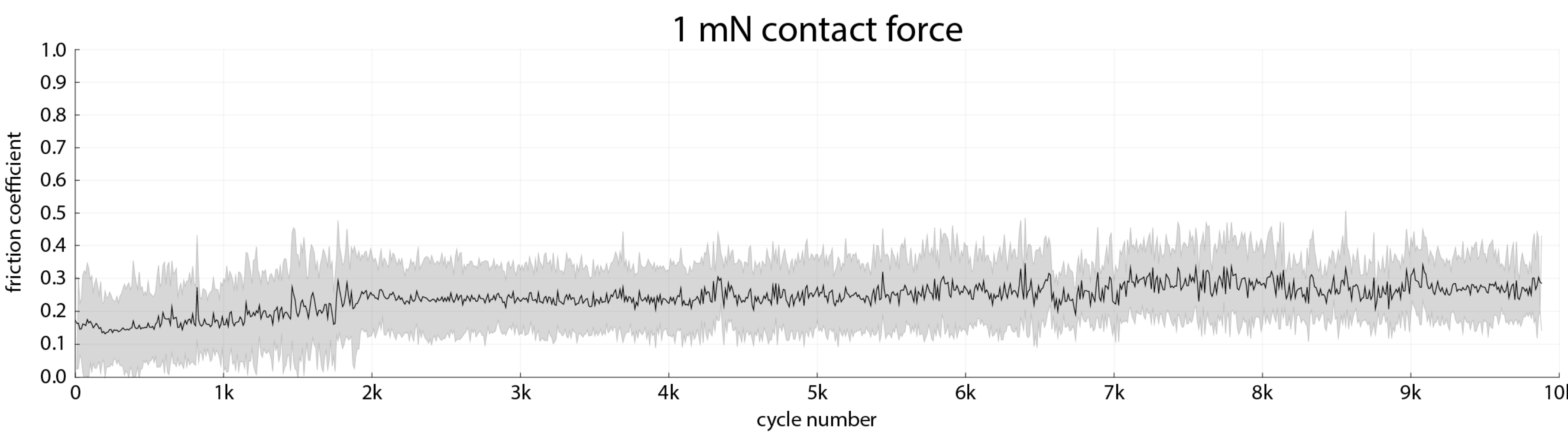
- Alloy slides at transfer film boundary, but also throughout substrate
- The pure Ag slabs on previous slide started with the exact same microstructure (lots of coarsening on the pure Ag slabs simulation!)

Three regimes observed for 60Ni-40W at.% vs sapphire in oxidizing environment

1 mm/s sliding speed
three contact forces used
bidirectional sliding
2mm long track
sapphire ball 1.6 mm diameter
sliding in ***lab air***

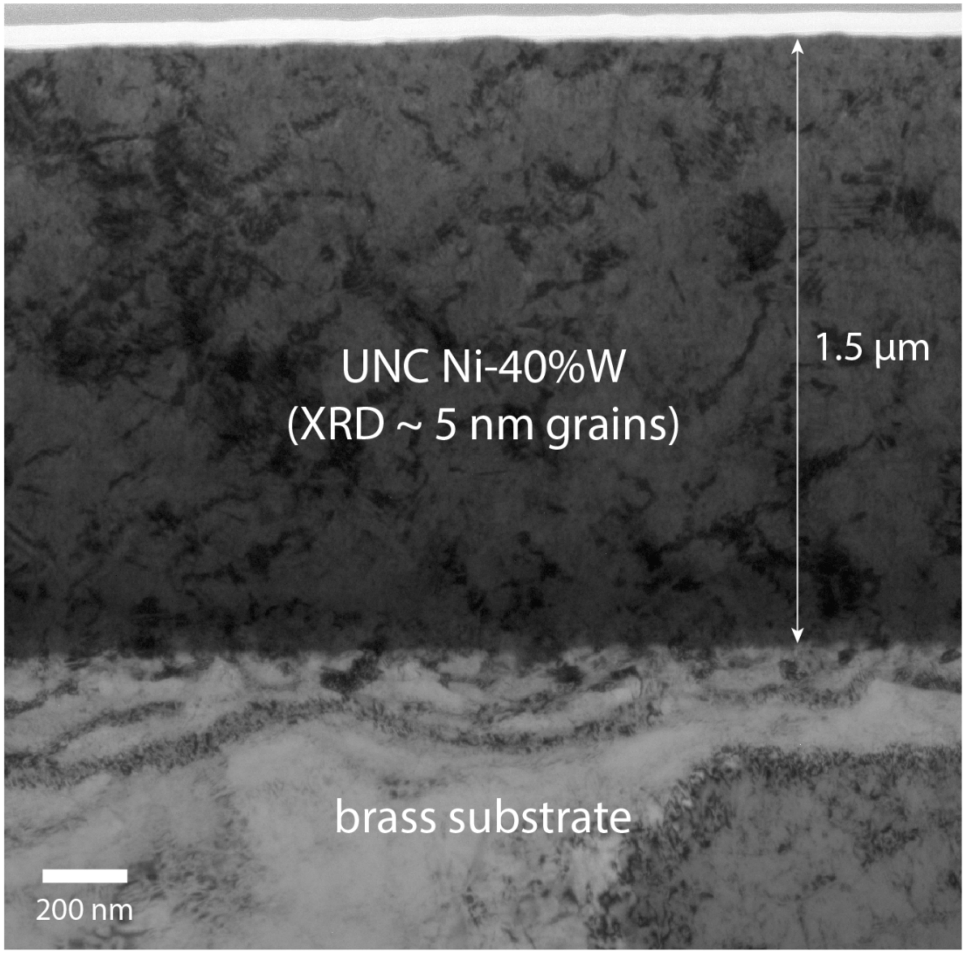






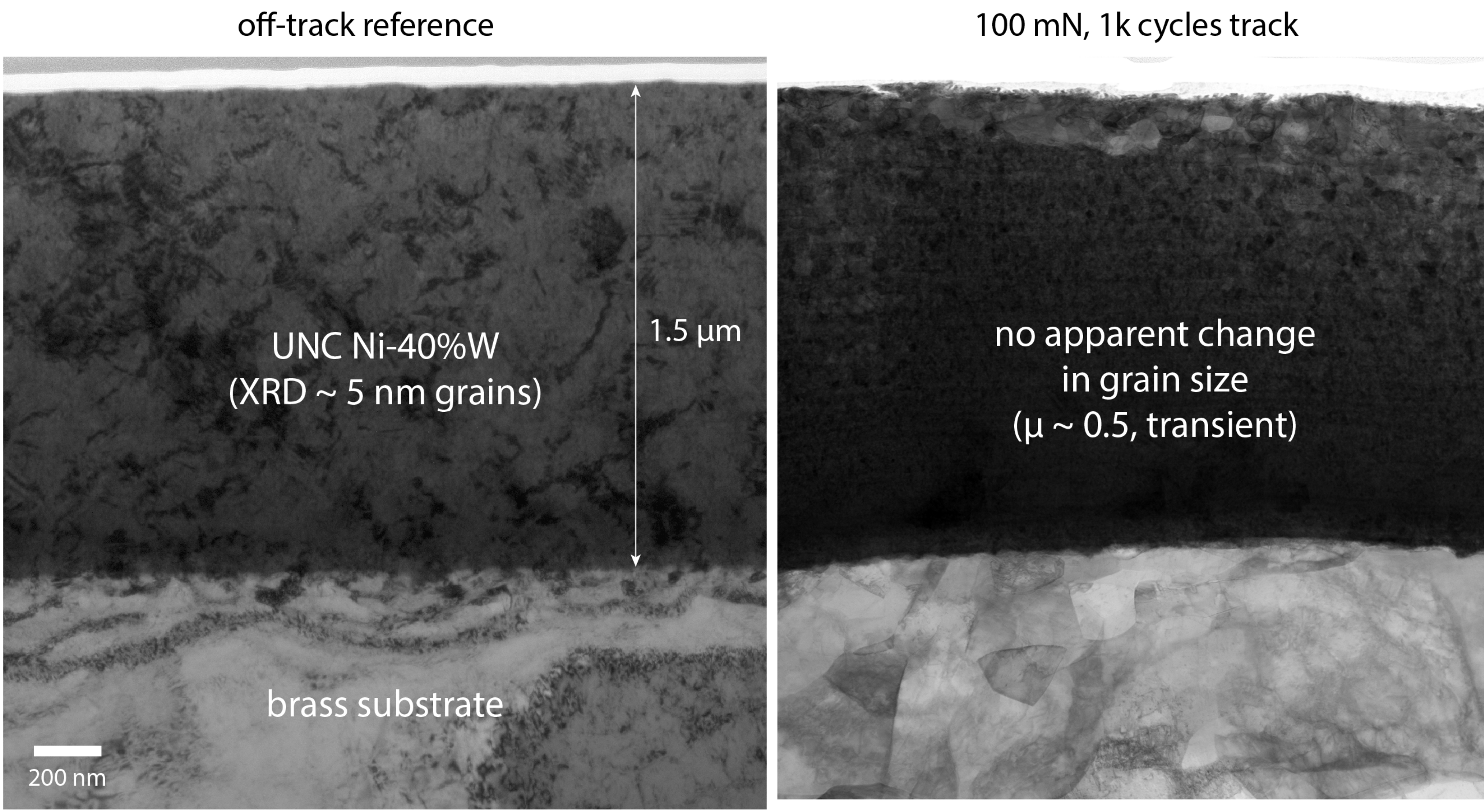
FIB-TEM wear track cross-section of 1 mN normal force / 10k cycle test

off-track reference

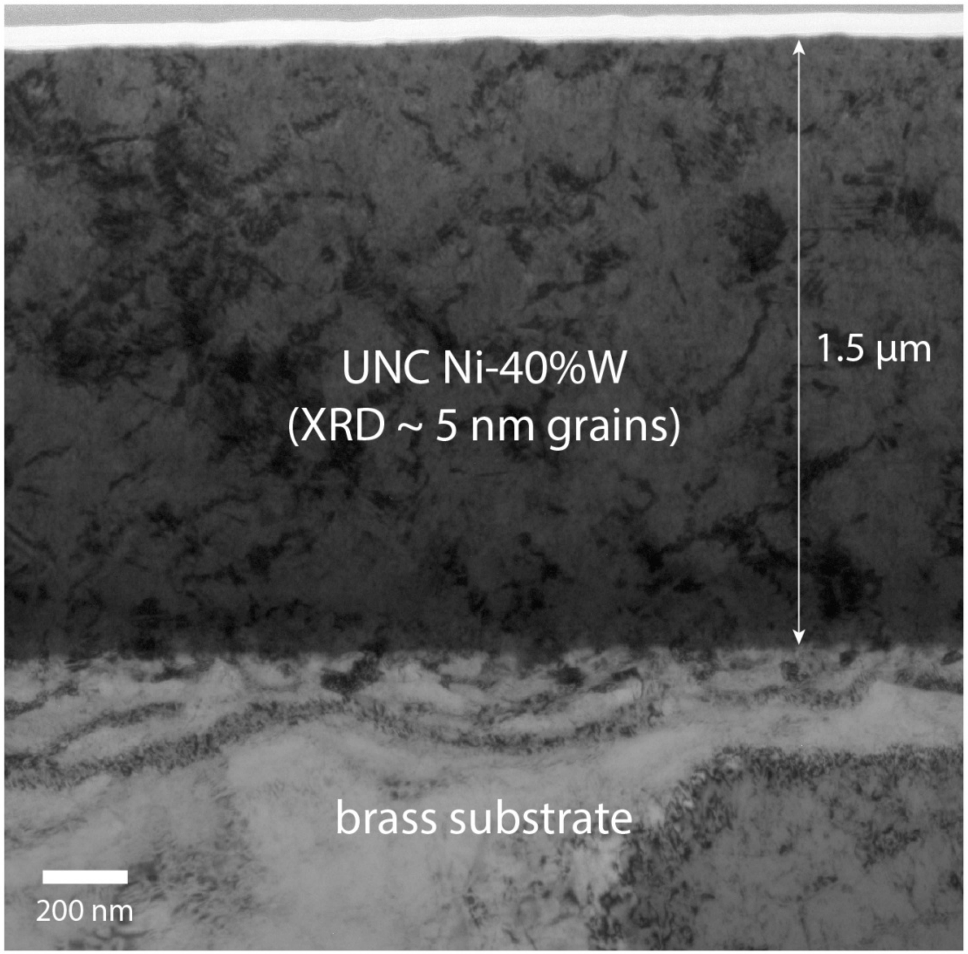


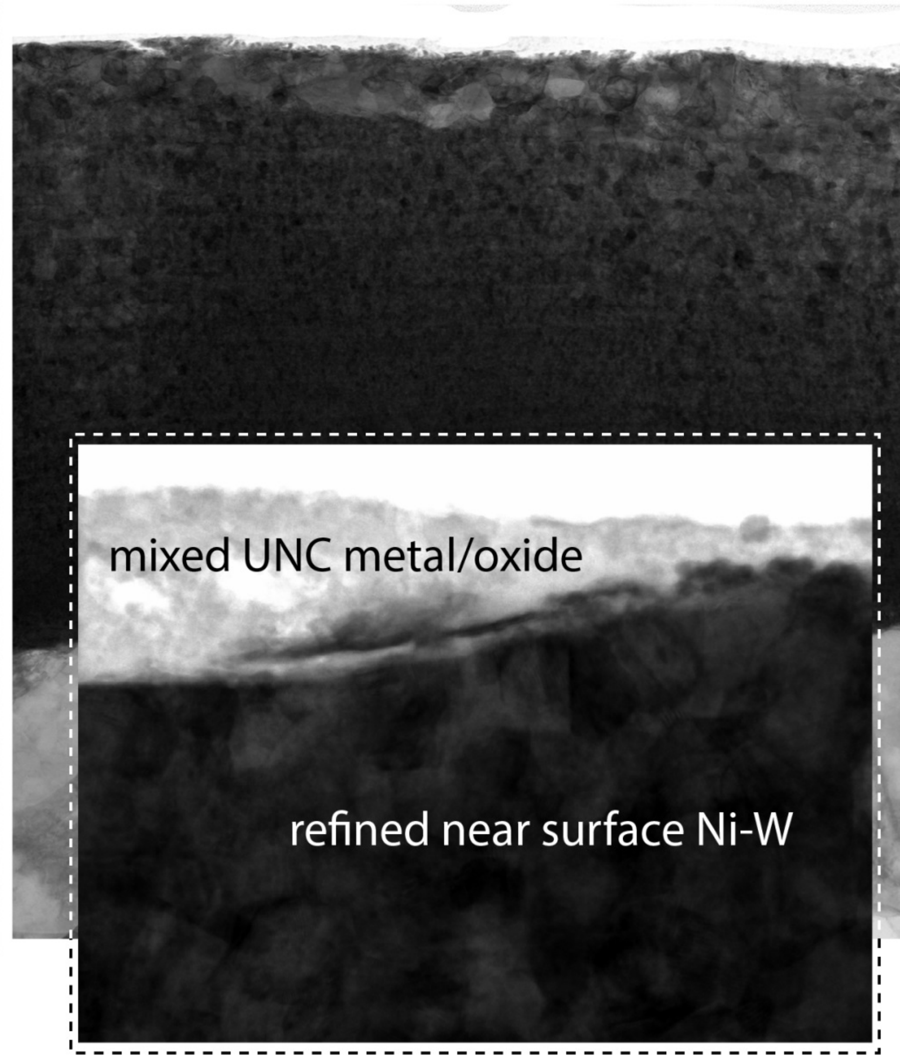
1 mN, 10k cycles track

FIB-TEM wear track cross-section of 100 mN normal force / 1k cycle test



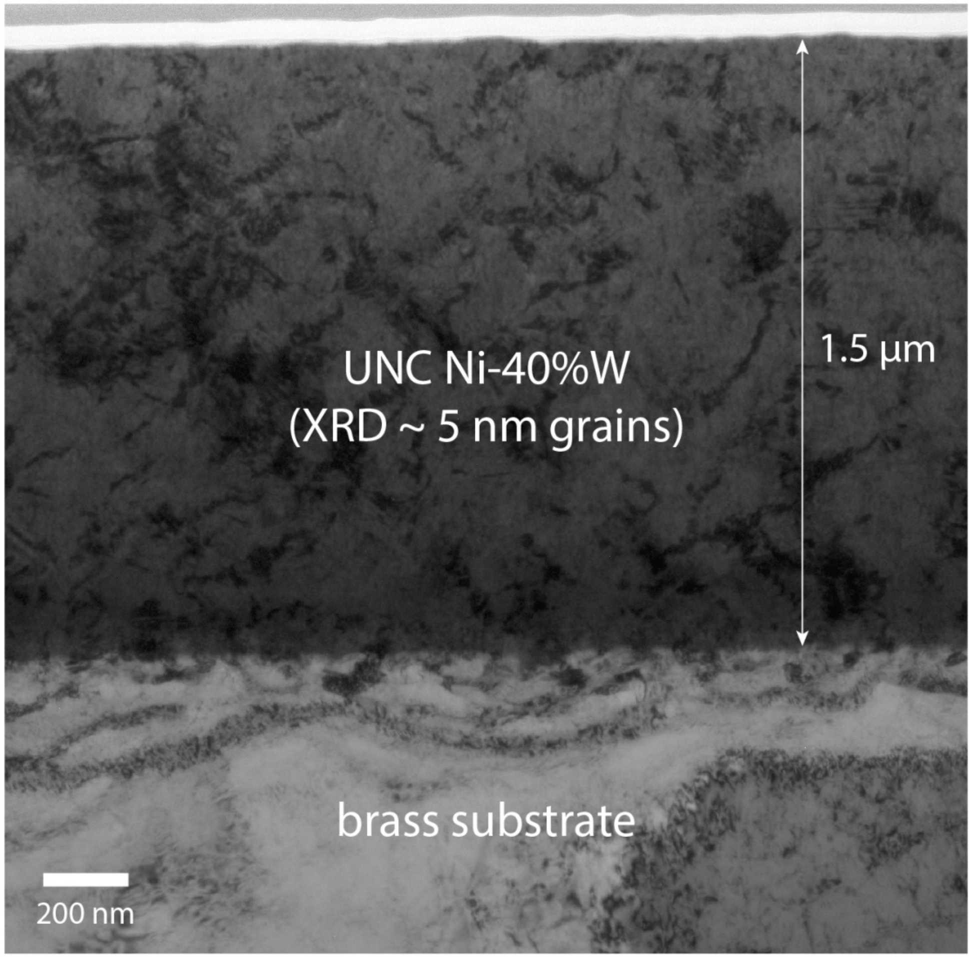
FIB-TEM wear track cross-section of 100 mN normal force / 1k cycle test



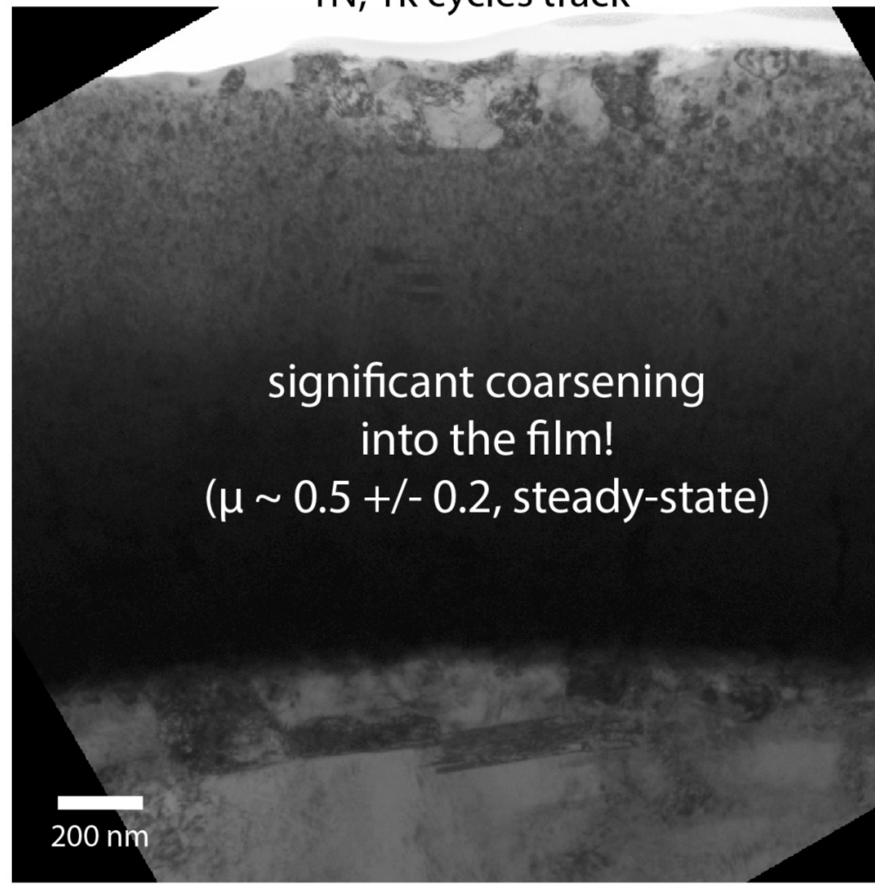


FIB-TEM wear track cross-section of 1000 mN normal force / 1k cycle test

off-track reference



1N, 1k cycles track



Disruptive breakthrough in 2012: *intrinsic thermal stability* possible with NC alloys!

Regular Nanocrystalline Solution (RNS) model

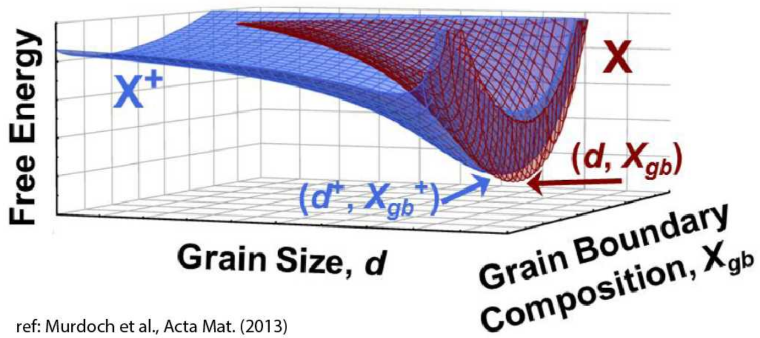
ref: Chookajorn et al., Science, 2012

$$\Delta G^{mix} = (1 - f_{gb})\Delta G_c^{mix} + f_{gb}\Delta G_{gb}^{mix} + z\nu f_{gb}(X_{gb} - X_c)\left[(2X_{gb} - 1)\omega_{gb} - \frac{1}{zt}(\Omega^B\gamma^B - \Omega^A\gamma^A)\right]$$

change in Gibbs free energy is positive, but ***local minimas exist***!

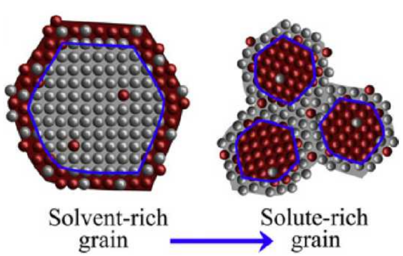
Implications:
Will not drive toward fine grain size, but will remain there

Two examples of predicted nanocrystalline intrinsic stability for global solute concentrations (X and X+) for a W-based binary alloy:



ref: Murdoch et al., Acta Mat. (2013)

Grain structure model: segregated 2-phase metal system:



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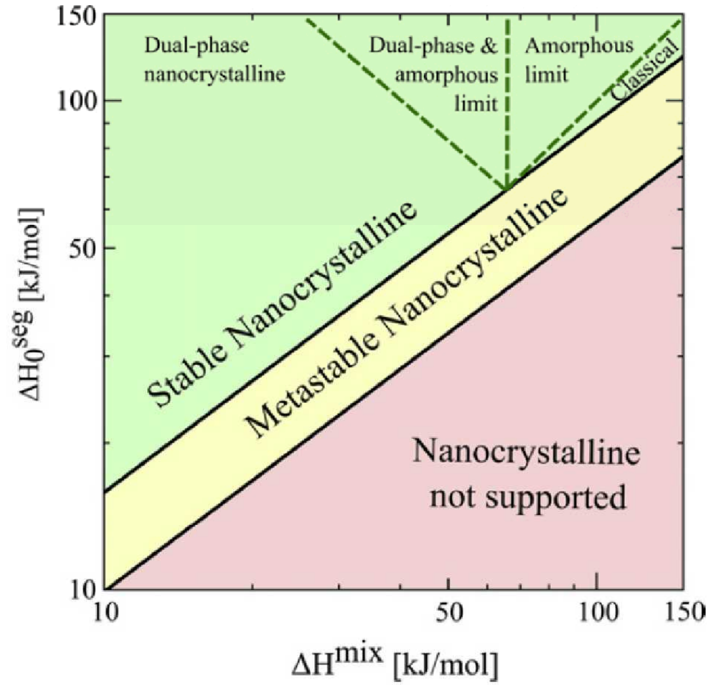
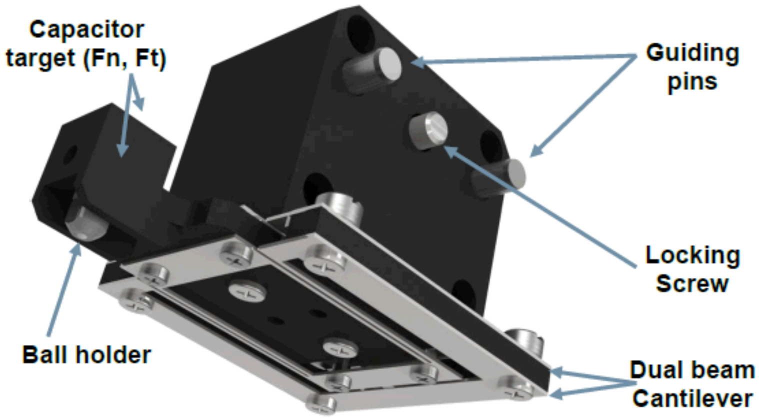


$$\Delta H_o^{seg} = z\left(\omega_c - \frac{\omega_{gb}}{2}\right) \qquad \Delta H^{mix} = z\omega_c X(1 - X)$$

General condition for stability: $\Delta H_o^{seg} > \Delta H^{mix}$

Modified CSM Nanotribometer – friction and wear testing platform



CSM nanotribometer modified for 4-wire ECR measurement

- DC power supply
- nano-ohm meter

Test parameters:

- Fn = 100 µN to 1000 mN
- pin radius = 1.6 mm
- track length = 0.1 to 10 mm
- v = 0.01 to 10 mm/s