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Why *IS* there a correlation between hardness, friction and wear of metal contacts?

Modifying microstructural mechanistic misconceptions

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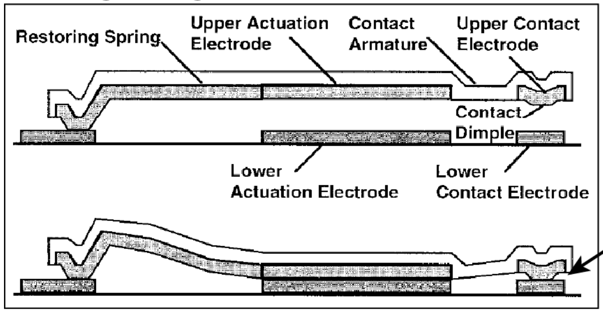
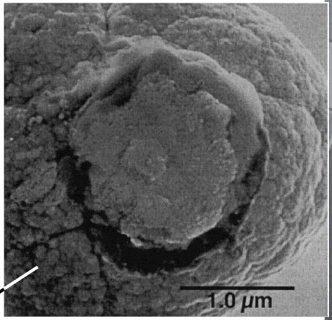
Metals are widely used tribological materials – particularly, electrical contacts

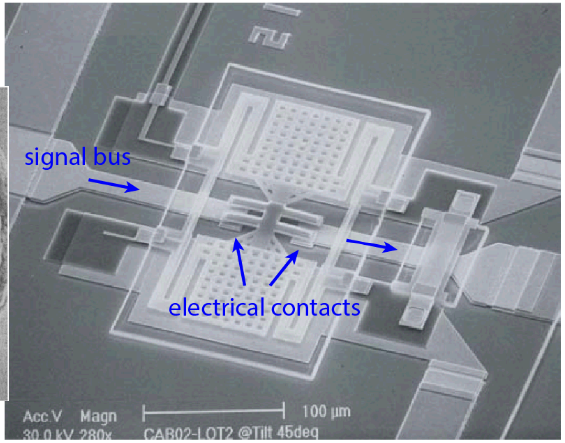
RF Micro Electromechanical Systems (MEMS)

switching GHz signals





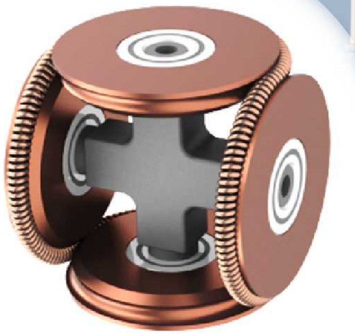
Source: D. Hyman and M. Mehregany, IEEE Trans. & Pack. Tech. 22-3, 1999

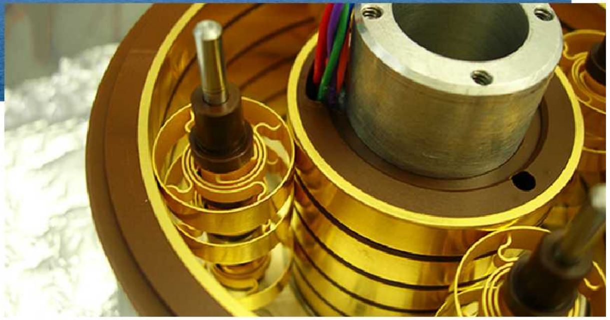


Source: Rockwell Scientific metal-metal switch

Electronics (e.g. PCB blade connectors):
200 - 500 nm thick electroless hard gold

Aerospace and Energy



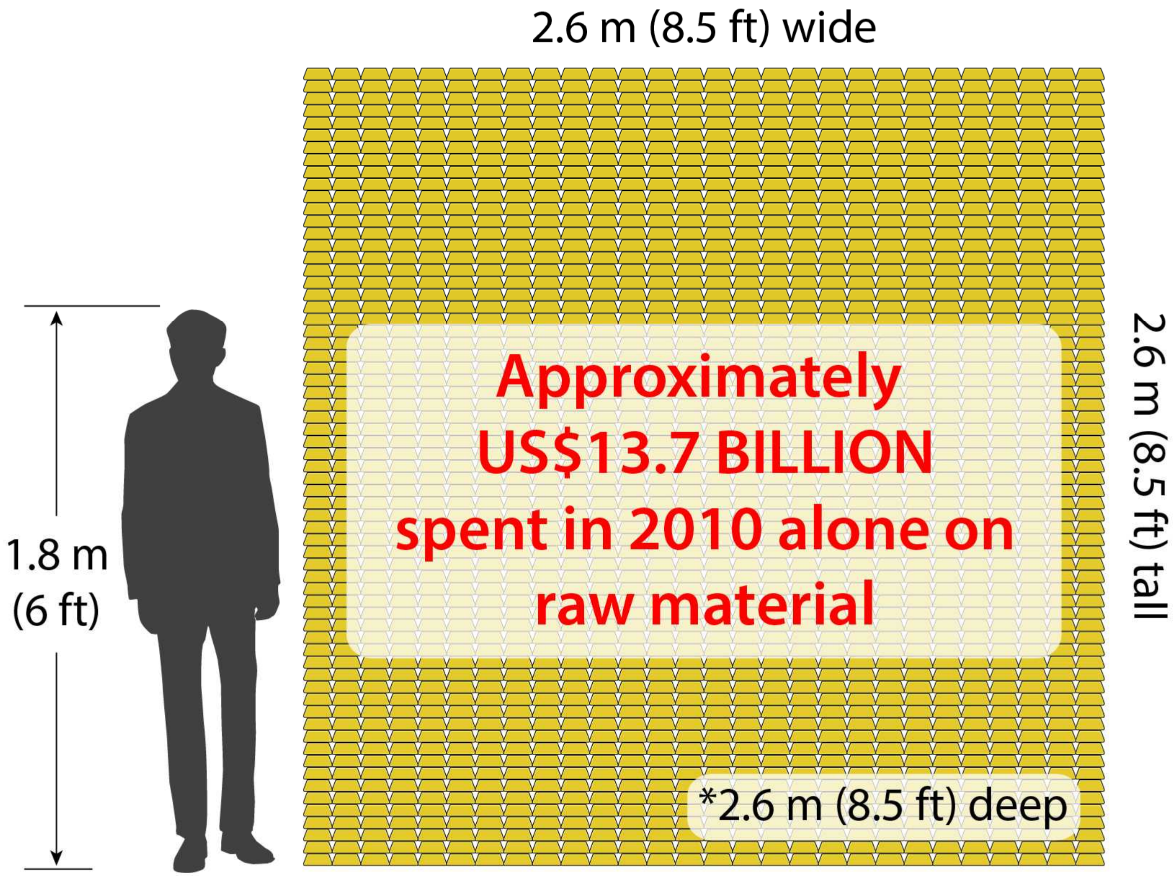


Source: Honeybee Robotics (http://www.honeybeerobotics.com/portfolio/rolling-contact-connector/)

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

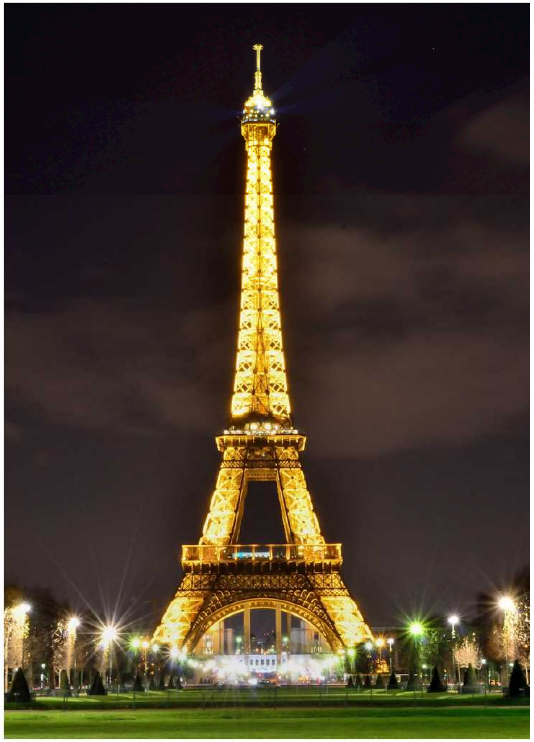
An estimated 300 metric tons/year of gold used in electronics related applications, most of it in electroplated connectors and contacts (11% of yearly amount mined)

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



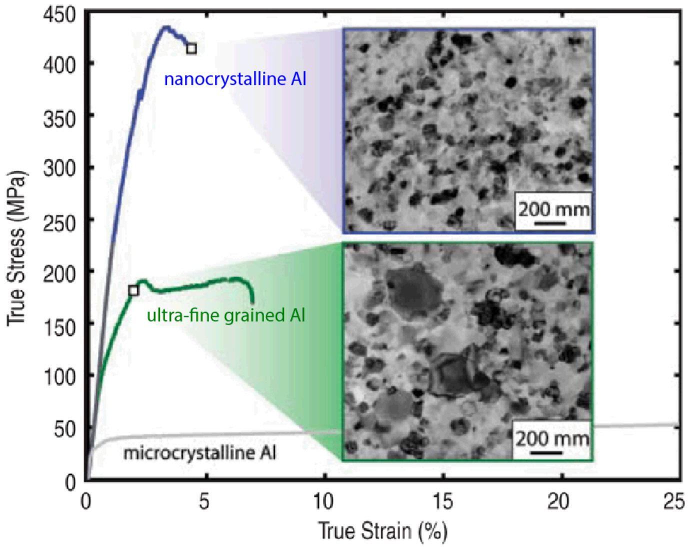
Reference: Gold Survey, Gold Fields Mineral Services Ltd., 2010

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

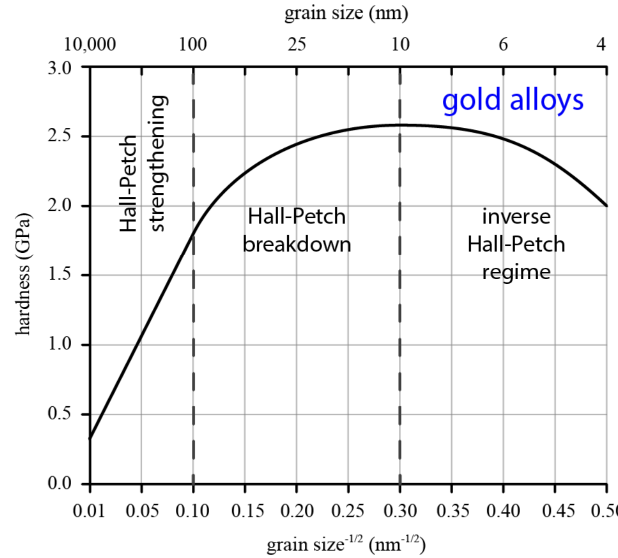


Metal coatings benefit from small grain size and higher hardness (nanocrystallinity)

higher yield strength

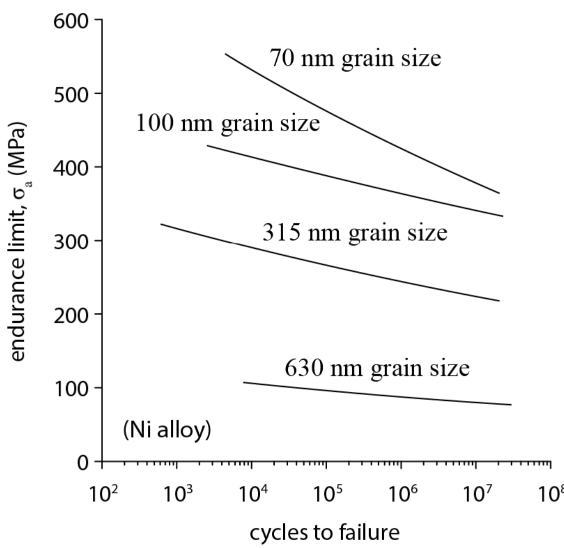


higher hardness

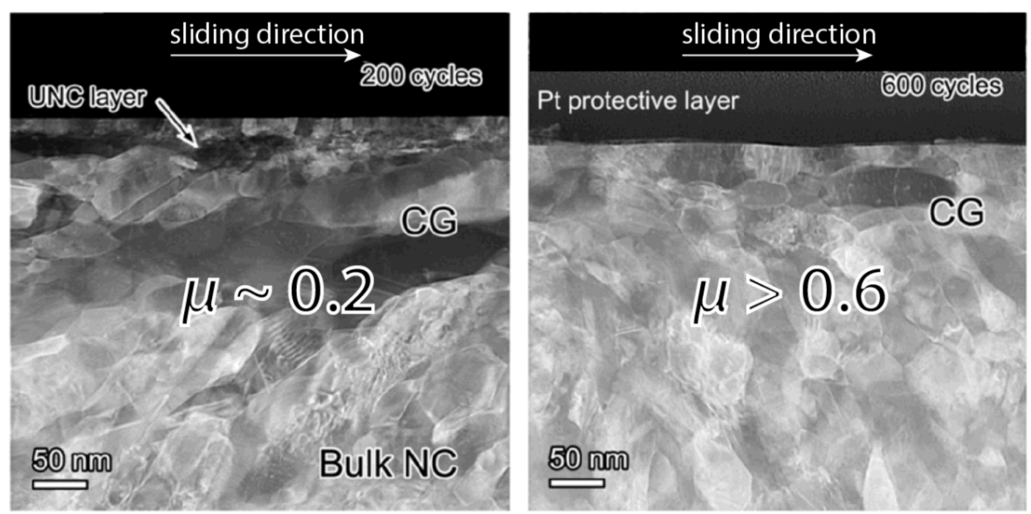


ref: Lo, Augis and Pinnel, JAP (1979)

higher fatigue strength (endurance limit)



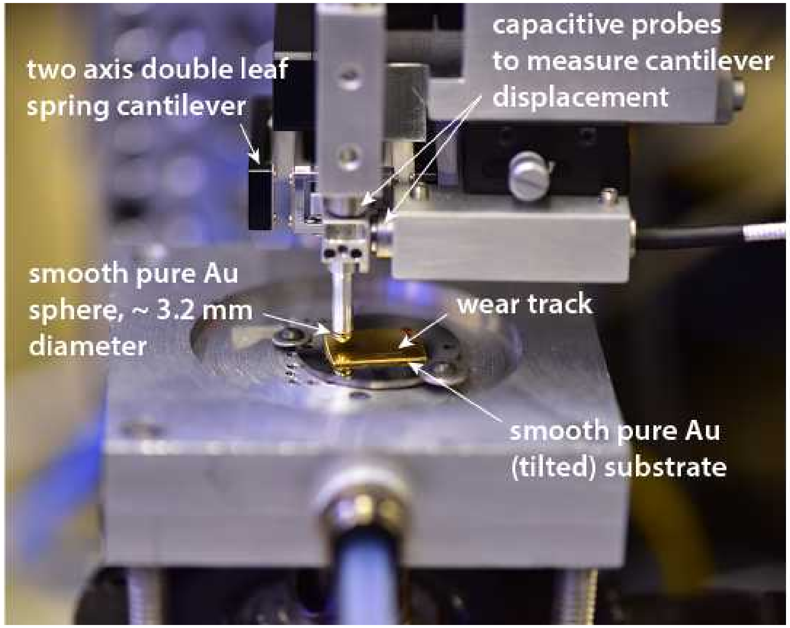
lower friction and wear rates -- *but why?*



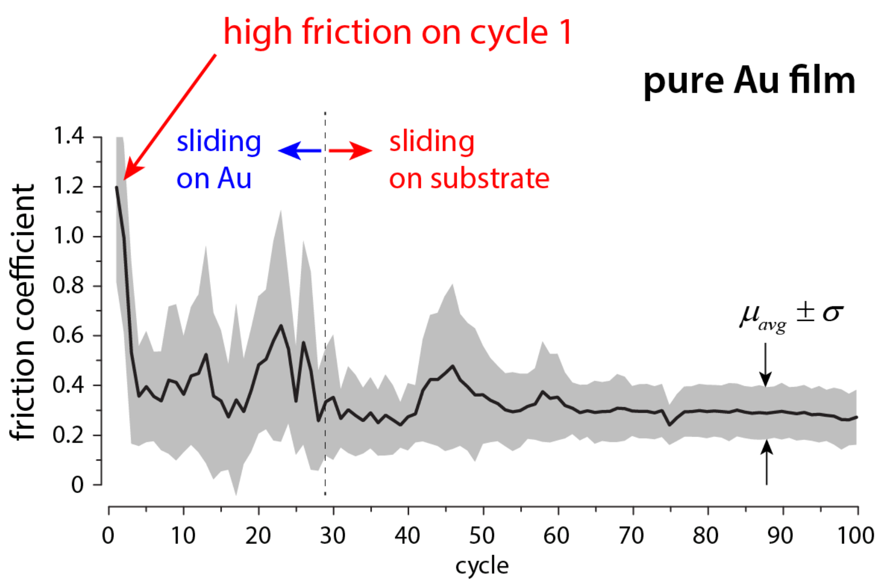
steady-state cross-sections of wear tracks

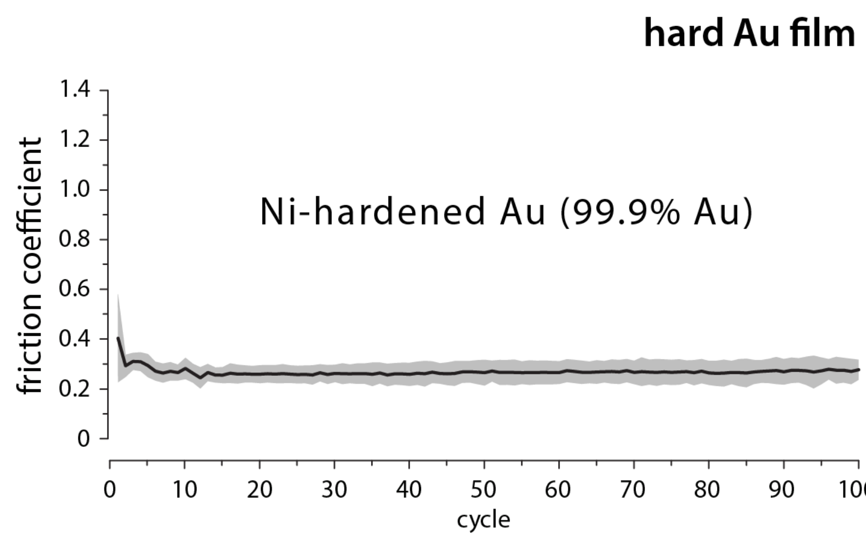
Ref: S.V. Prasad, et al., Scripta Mat. 2011

Examples of typical friction behavior of pure and alloyed (hard) Au



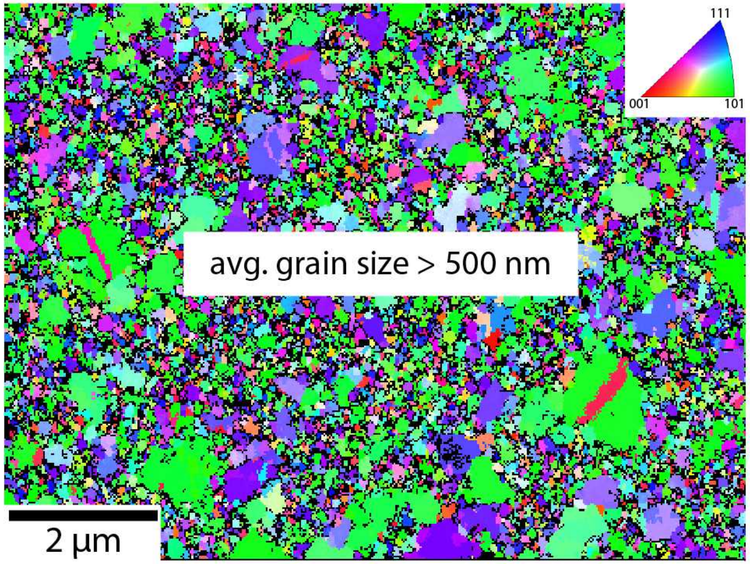
normal force = 100 mN
ball radius = 1.6 mm
speed = 1 mm/s

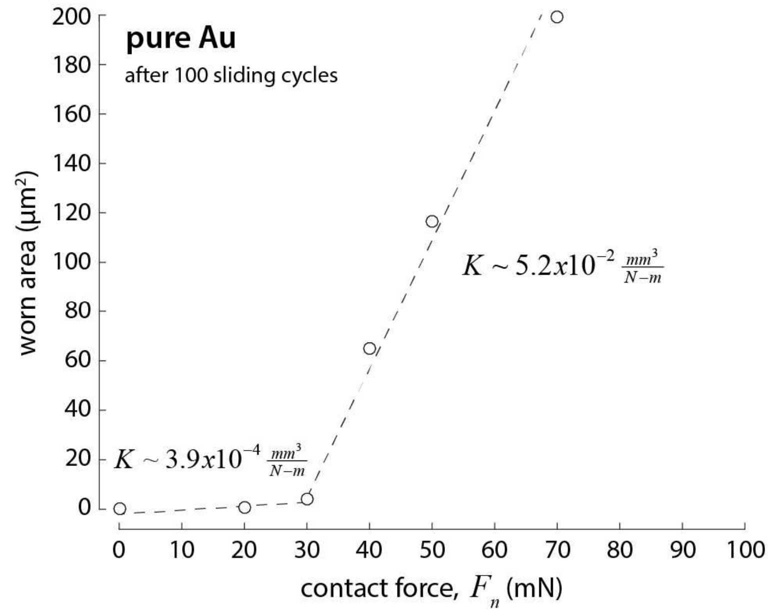




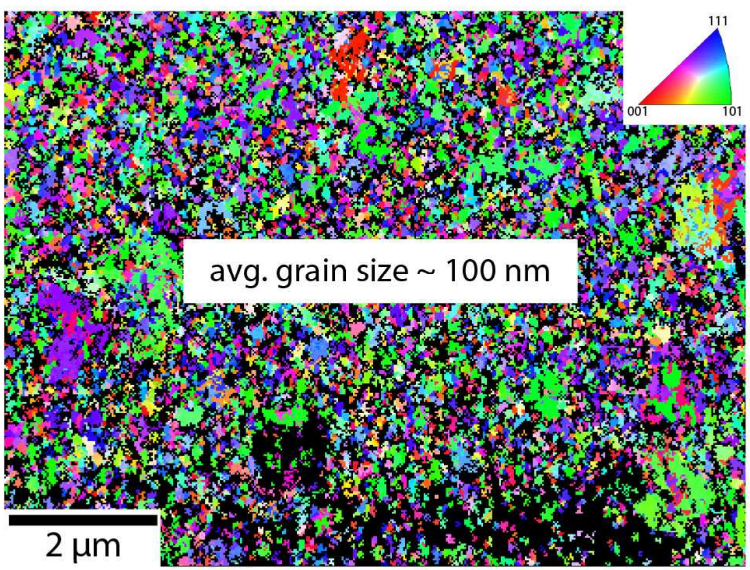
Alloying produces finer grain size by decreasing GB mobility & drastically lowers wear

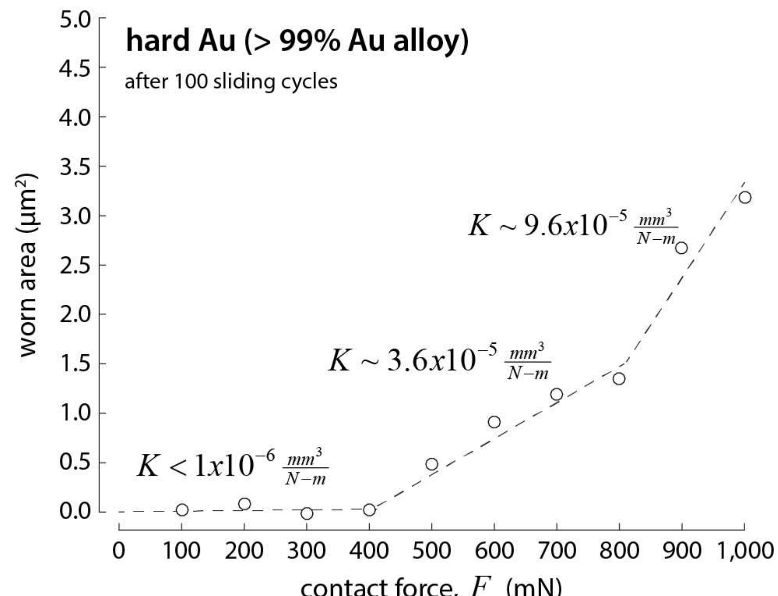
pure Au unworn



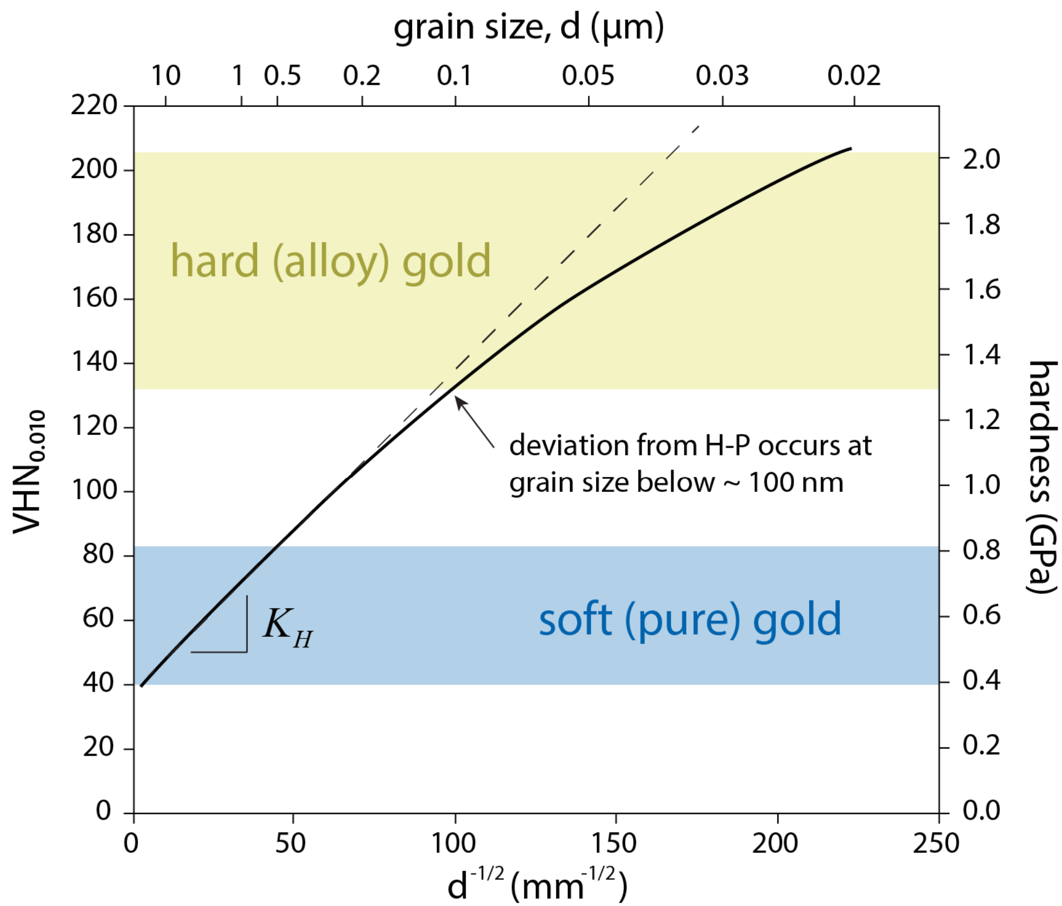


alloy Au (> 99% Au) unworn

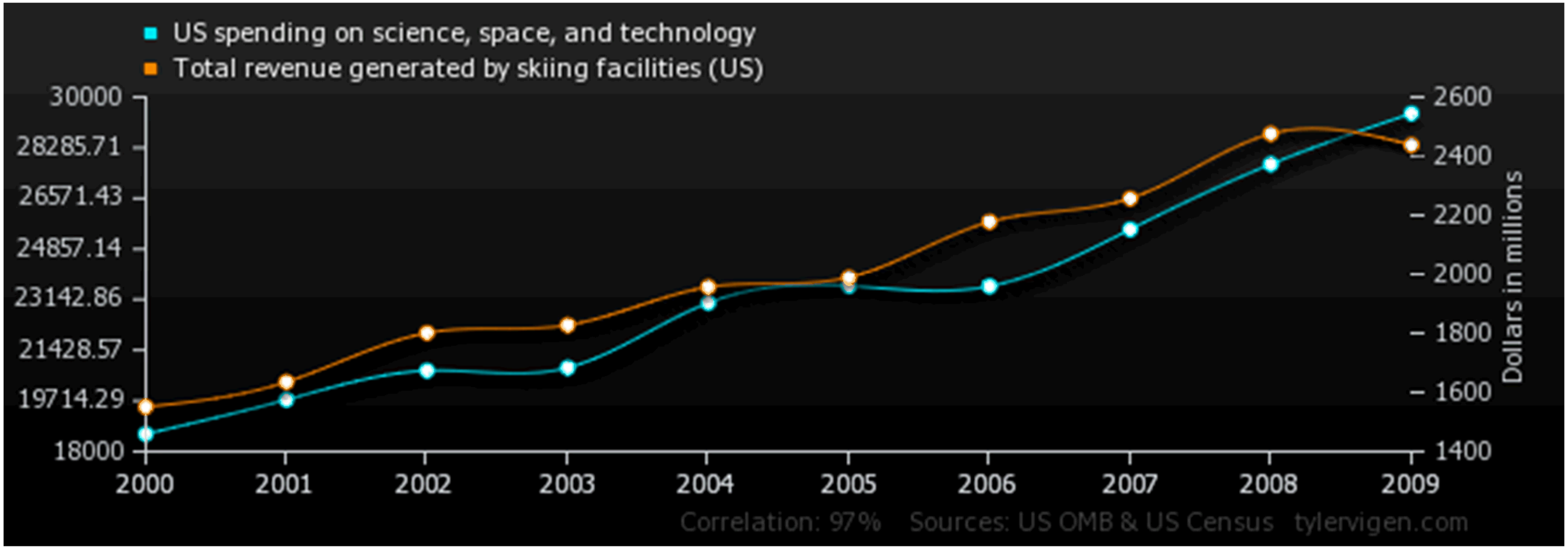




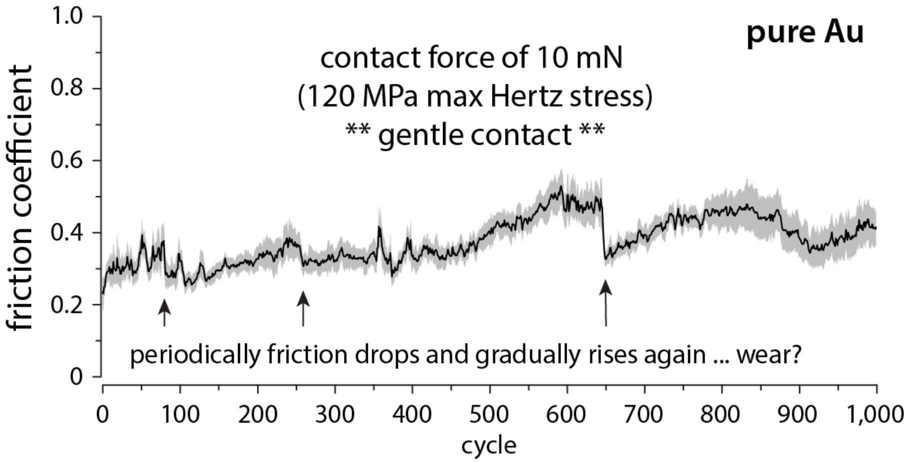
Alloys are harder and have lower friction, so low friction due to high hardness, right?



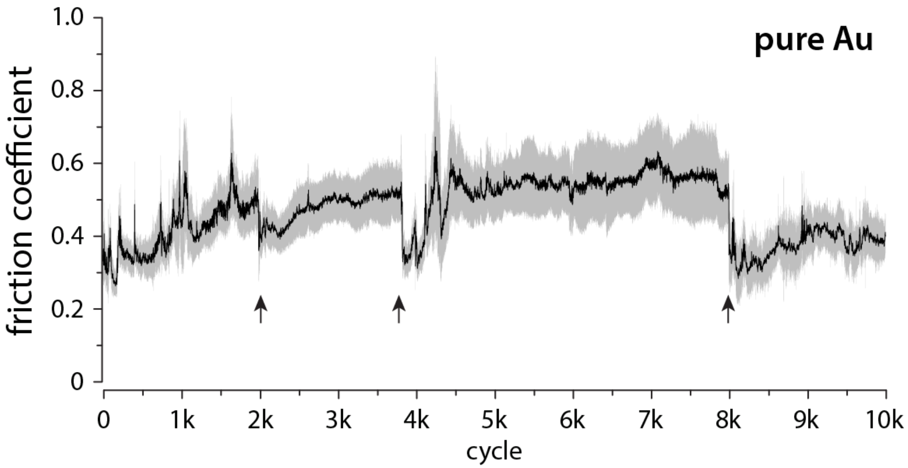
Reference: C. Lo, J. Augis, and M. Pinnel, JAP (1979)


US spending on science, space, and technology
Total revenue generated by skiing facilities (US)
30000
28285.71
26571.43
24857.14
23142.86
21428.57
19714.29
18000
2600
2400
2200
2000
1800
1600
1400
Dollars in millions
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
Correlation: 97%
Sources: US OMB & US Census
tylervigen.com

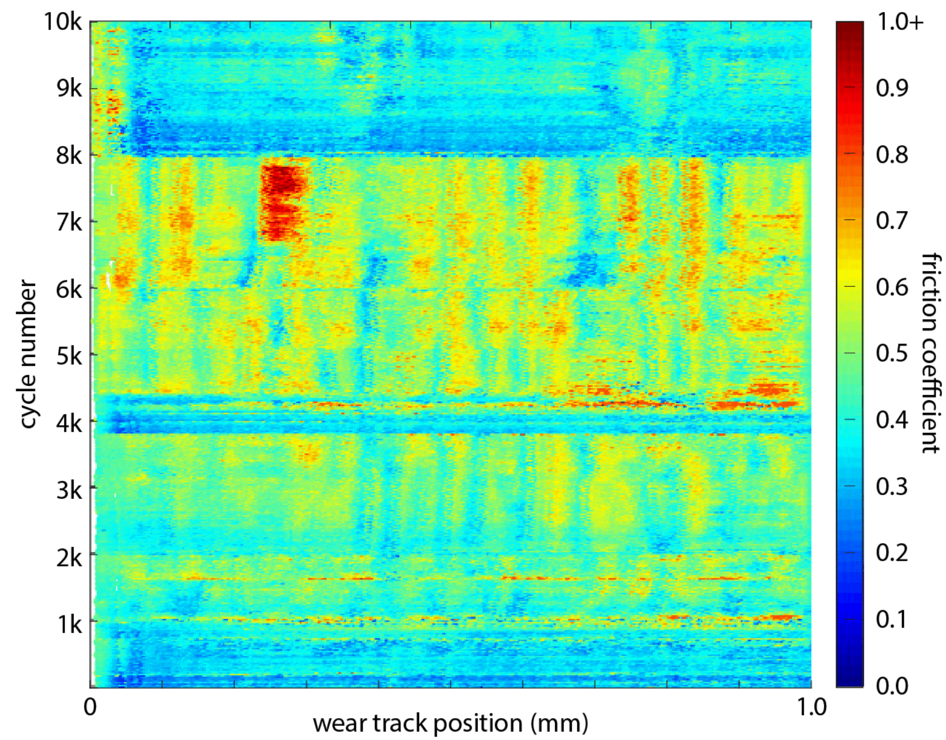
No! Low friction possible even with bulk, coarse grained pure Au



now a longer experiment to 10k cycles:



Friction Mapping Reveals More

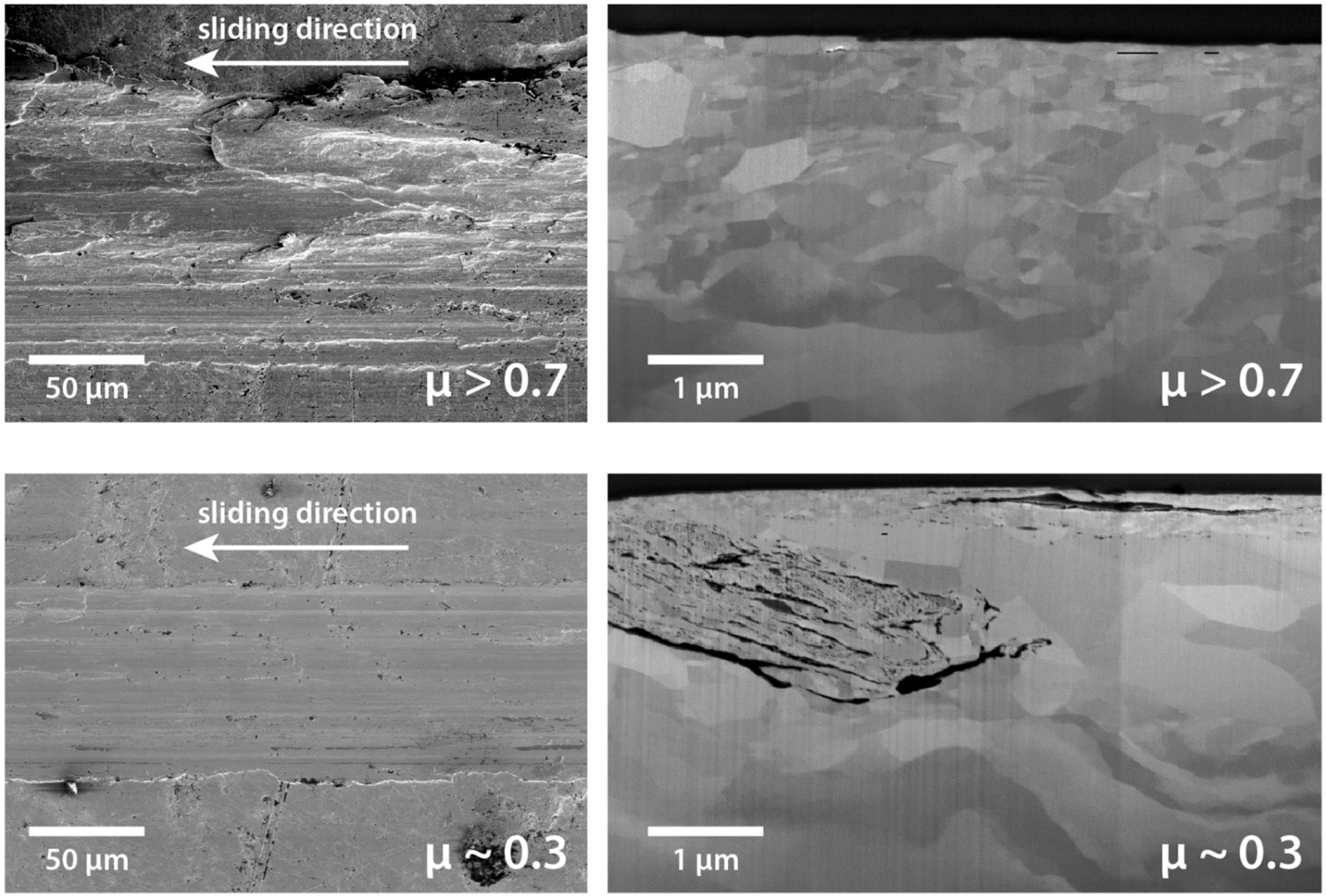


Low friction creates nanocrystalline surface layer

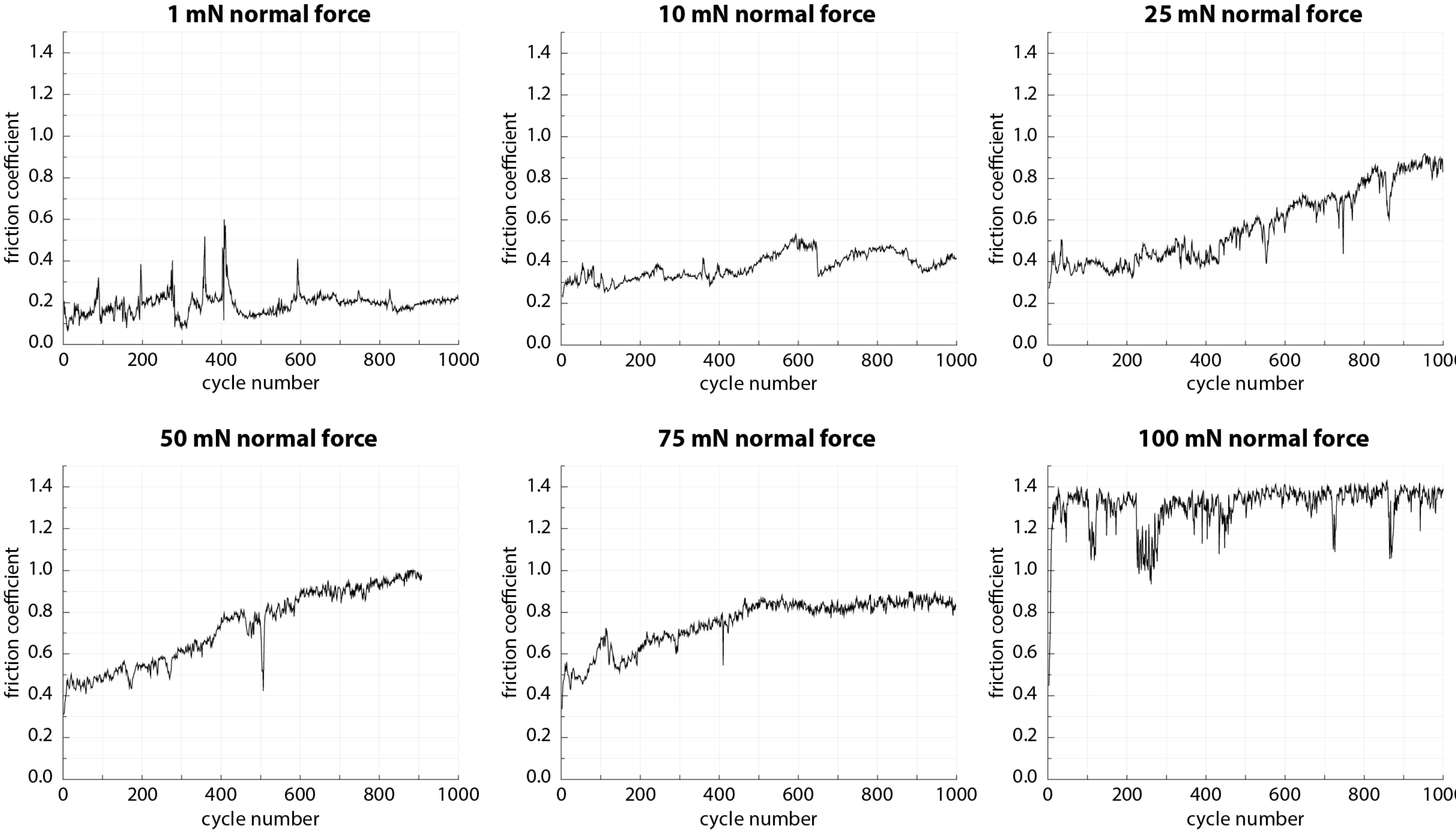
comparing pure Au surfaces and microstructures where low and high friction were measured:

high friction

low friction

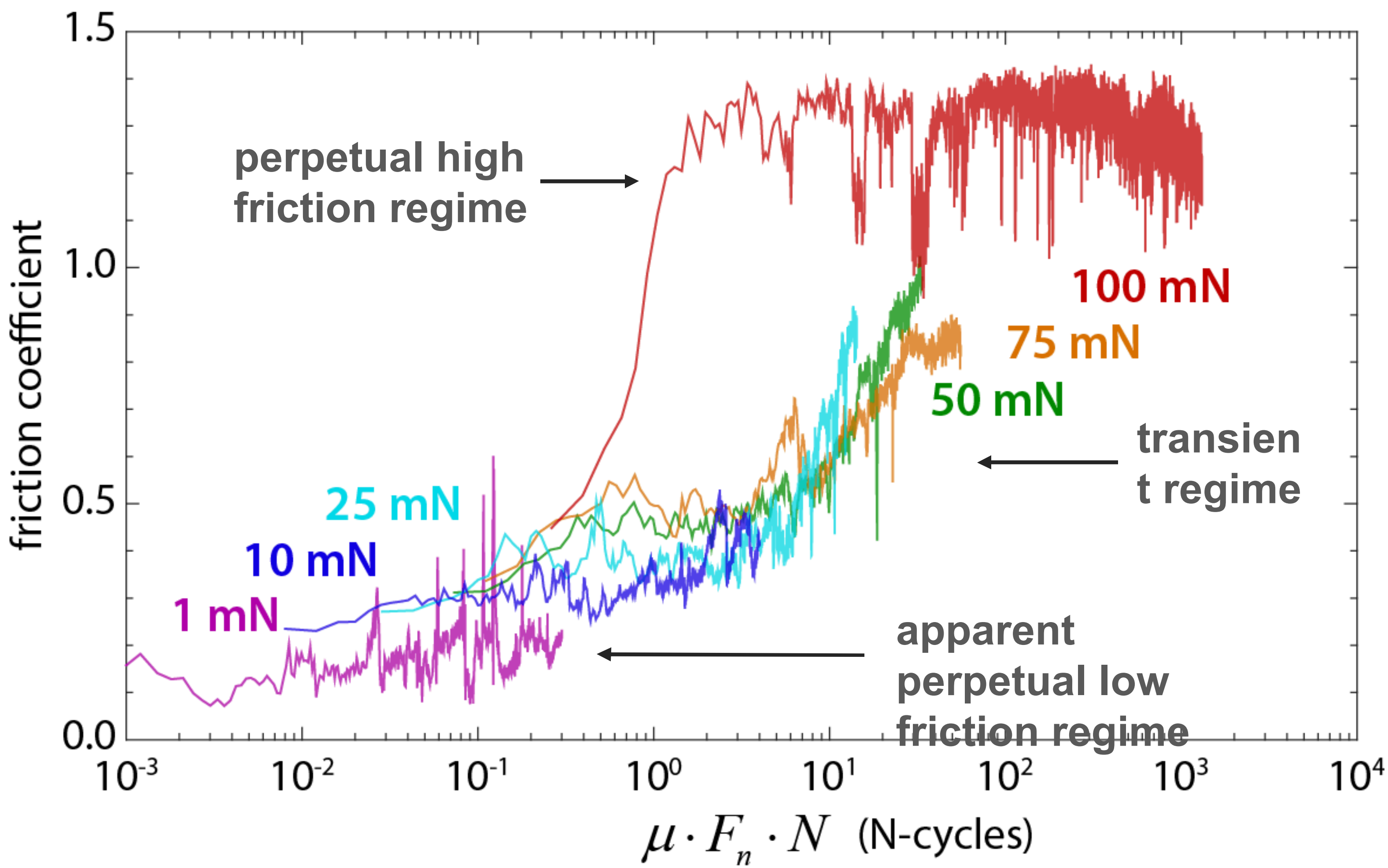


A bit more data: more friction experiments with pure Au revealed friction regimes



hard (alloy) Au pin sliding against bulk pure Au coupon

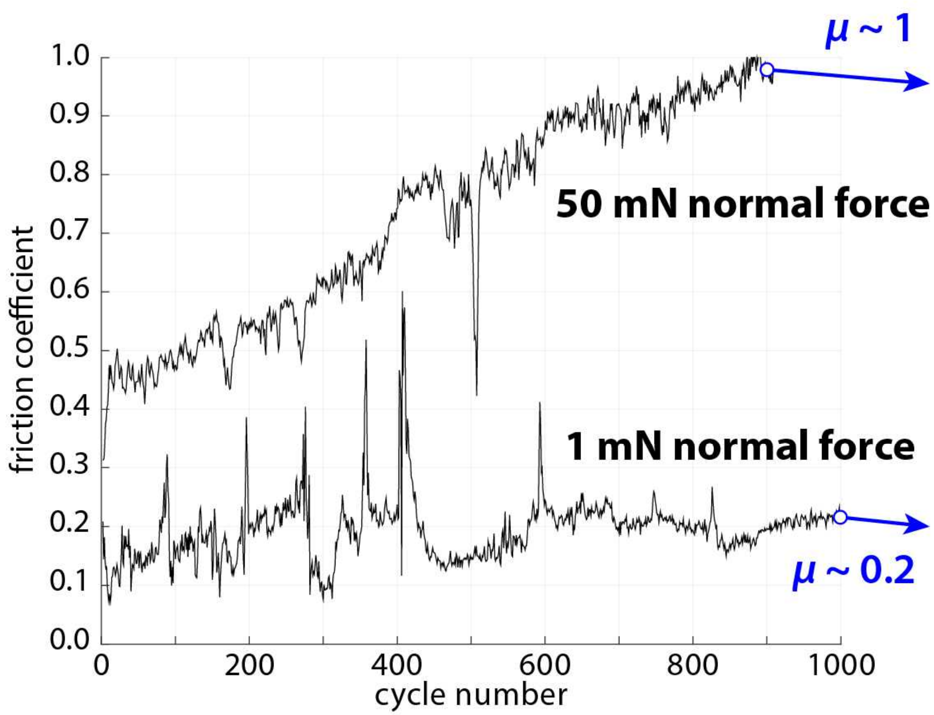
So perhaps this is a function of accumulated plastic strain energy?



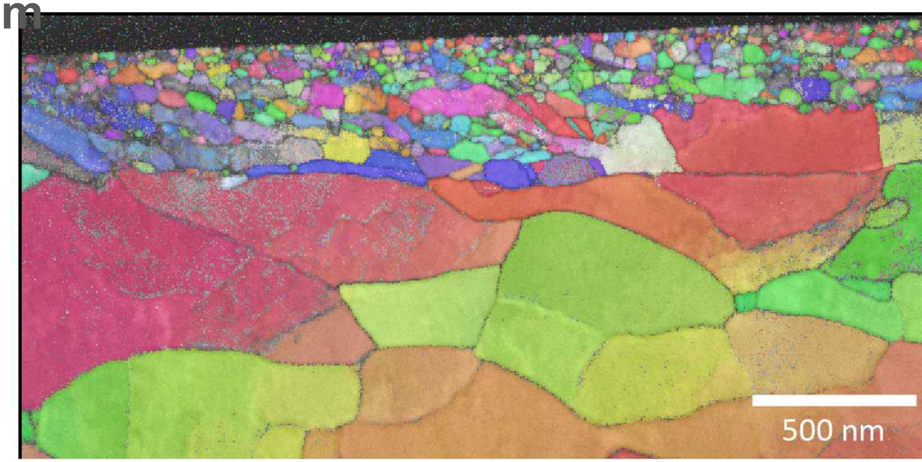
Not that simple, data does not collapse well as a function of “accumulated damage”

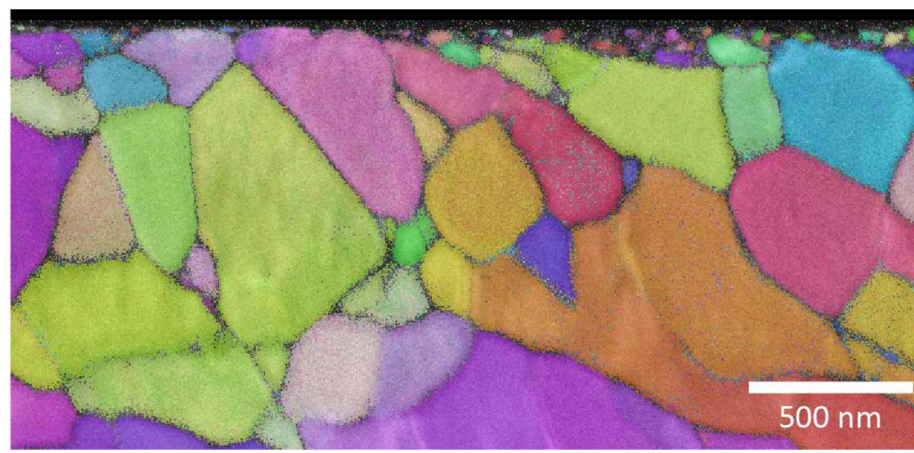
Electron diffraction of high and low friction wear tracks from Au-Au sliding contacts

Electron microscopy of focused ion beam prepared wear track cross-sections



Transmission Kikuchi Diffraction (TKD):
(transmission diffraction performed in an SEM)

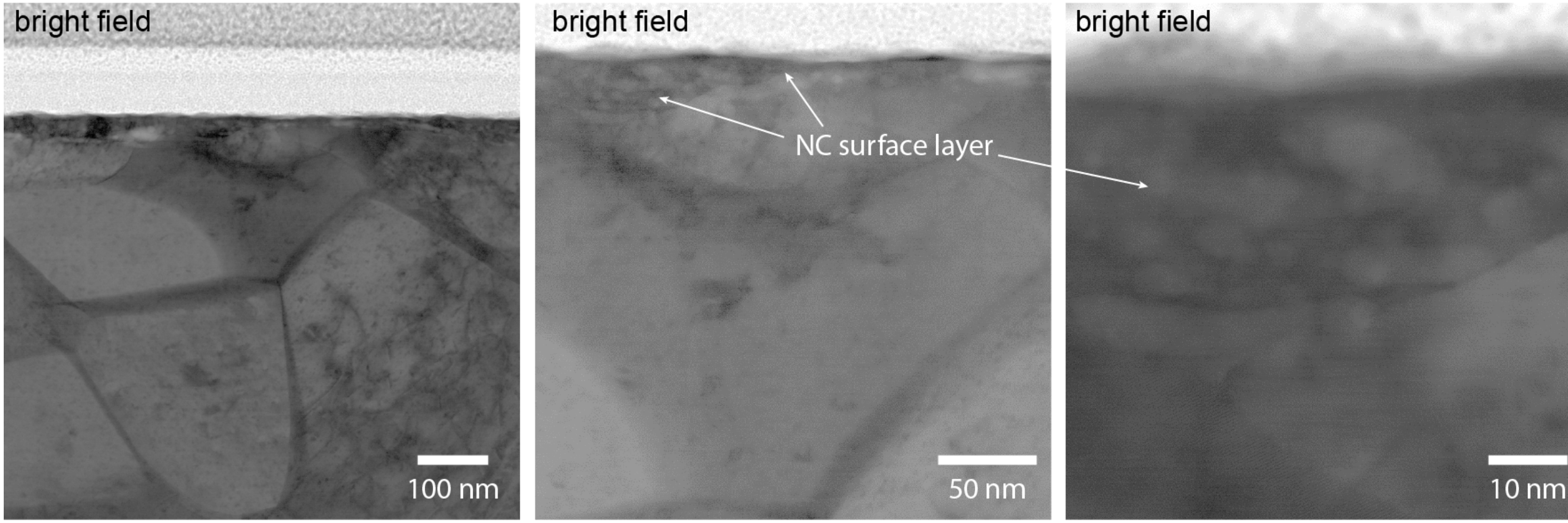




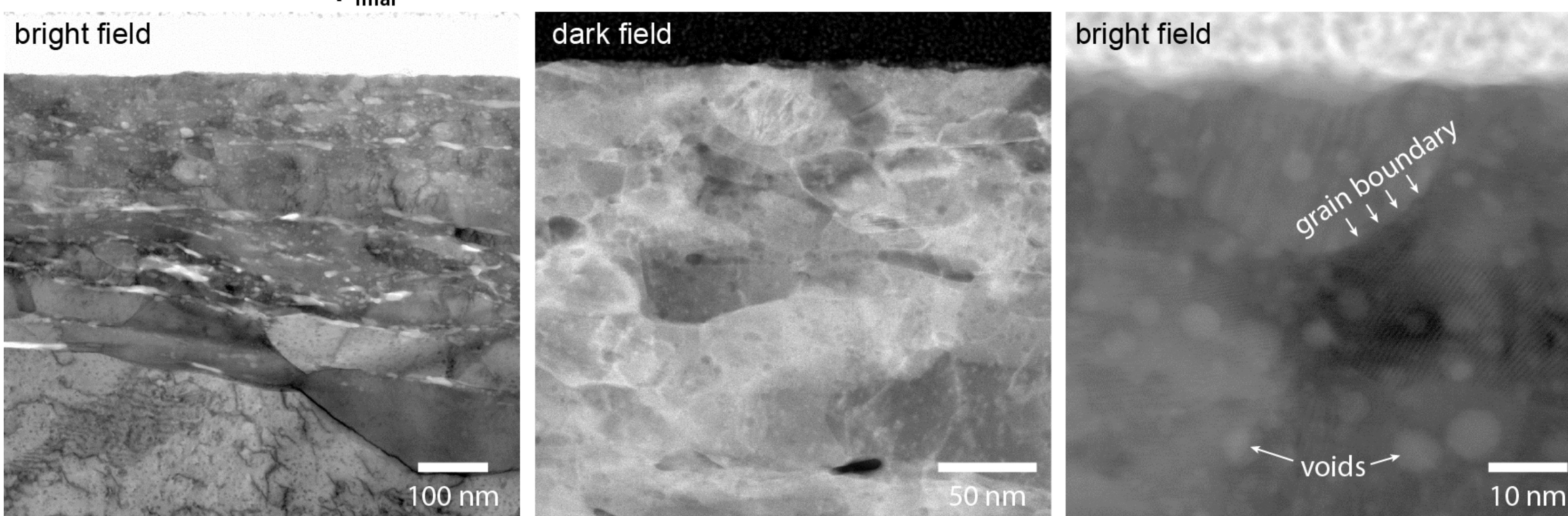
Again we see fine grain size in both cases… but the low friction case seems smaller.

A closer look at the surface in TEM…

1 mN normal force, μ_{ss} ~ 0.2

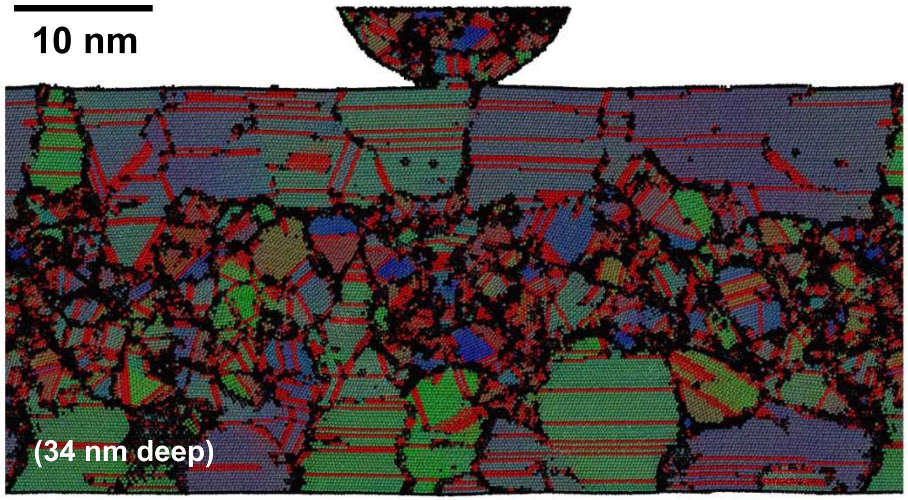


50 mN normal force, μ_{final} ~ 1.0



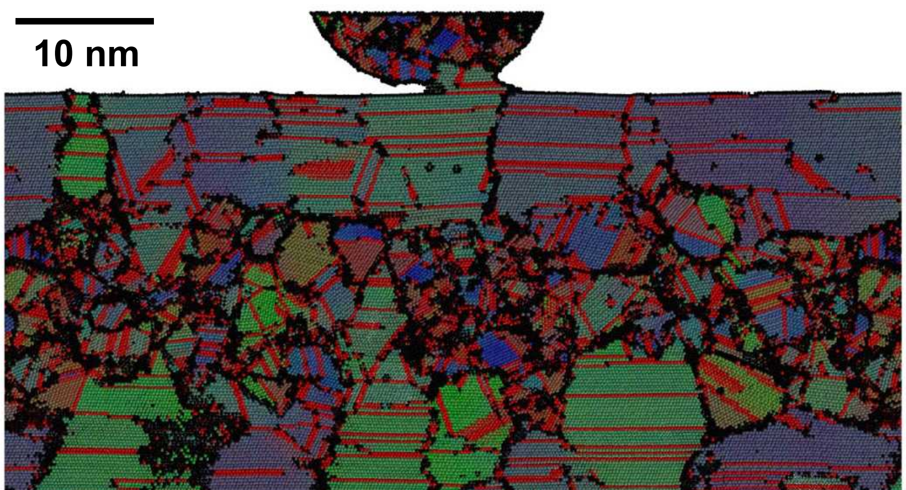
What MD simulations reveal…

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

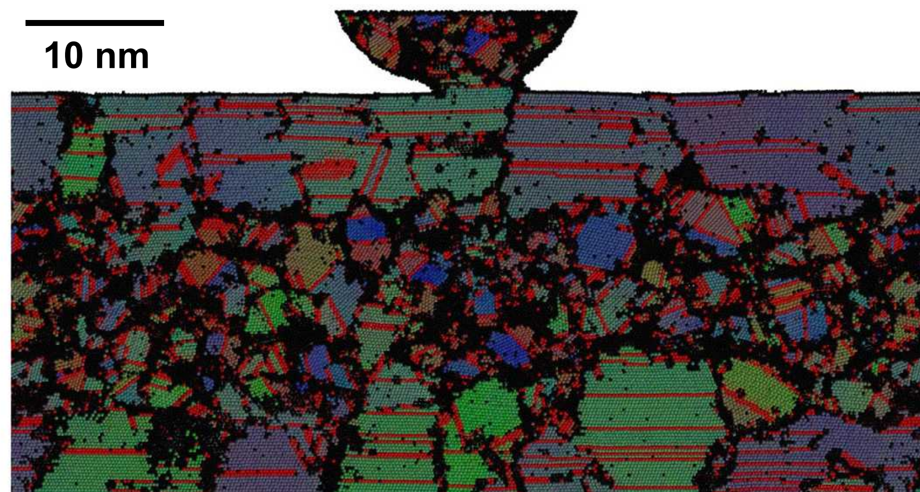


300 MPa contact stress
300 K temperature
2 m/s sliding speed

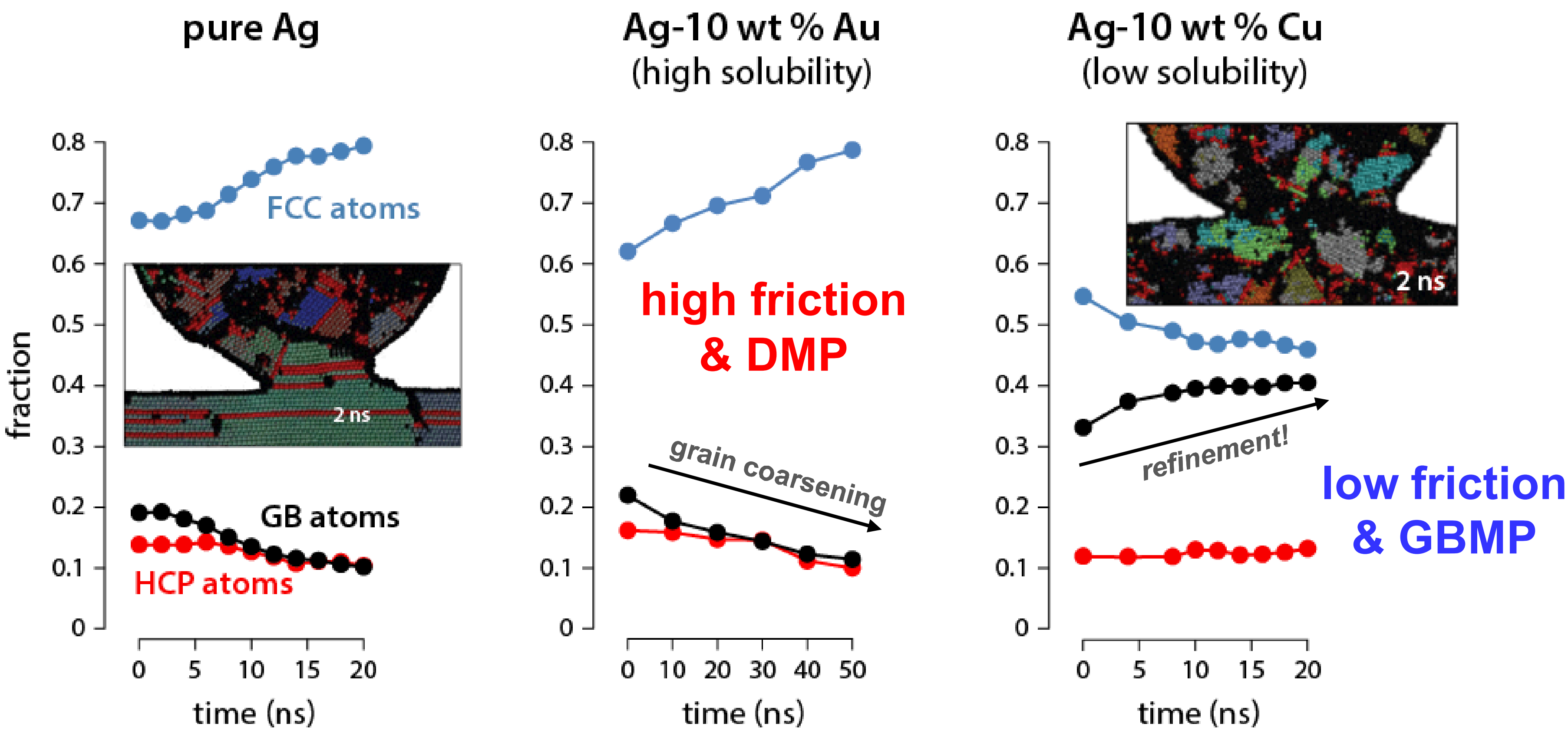
pure Ag after 4 nm of sliding



Ag-10% Cu alloy after 4 nm of sliding

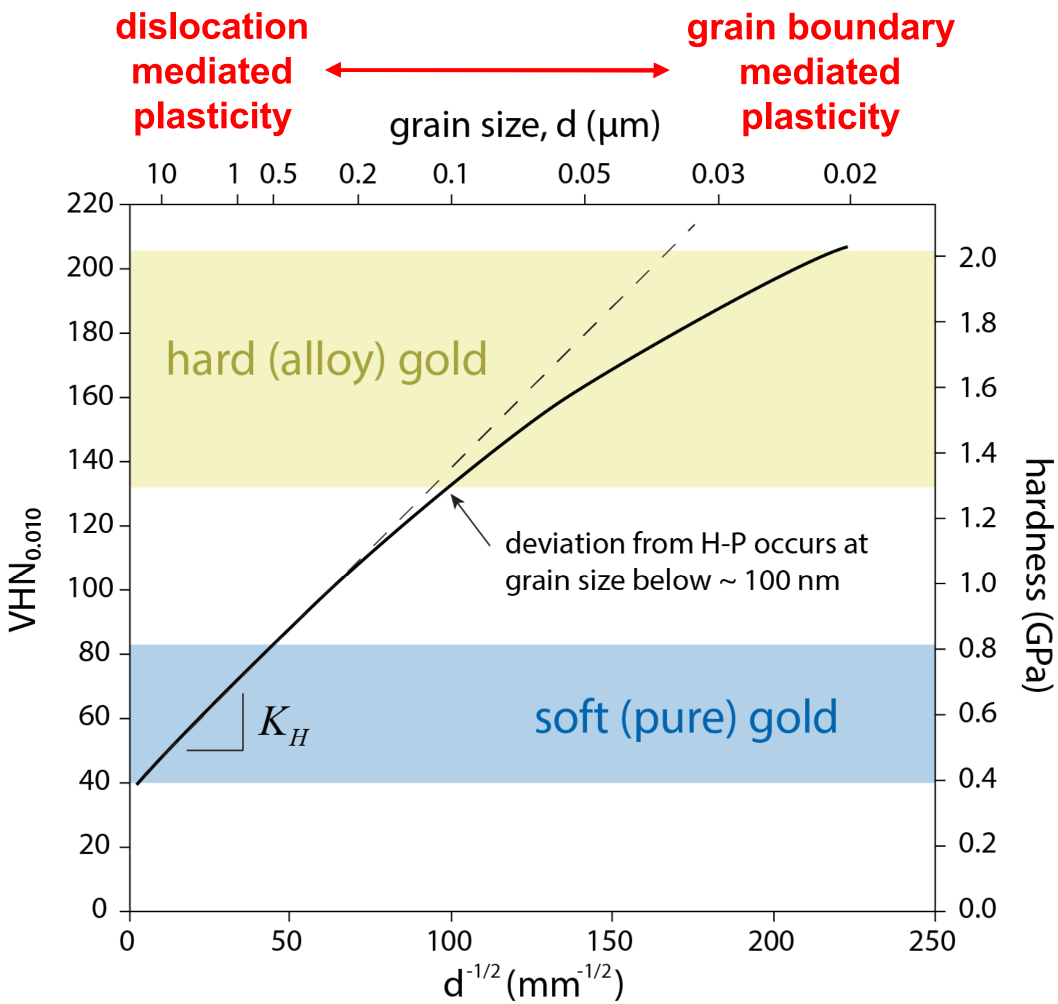


… alloying (stabilized GBs) changed **dominant deformation mechanism**



- Experiments: alloying reduces grain size and stabilizes grain boundaries
- Simulations: alloying mitigates stress-driven grain growth at interface and promotes grain boundary mediated plasticity
- Connection: higher stability, smaller grains produce low friction at higher stress

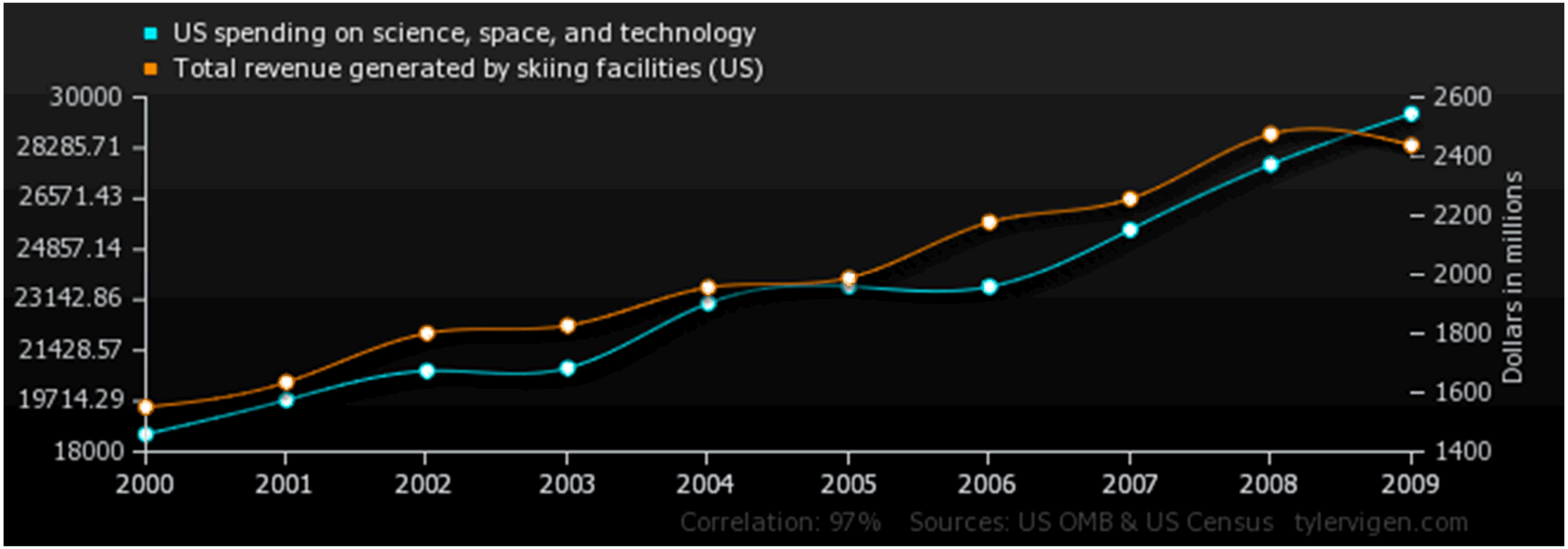
So why IS harder better?



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

Hypothesis: the source of low friction between pure, unlubricated metals is due to a <u>change in the dominant mechanism of plasticity</u>

Correlation, not causation…



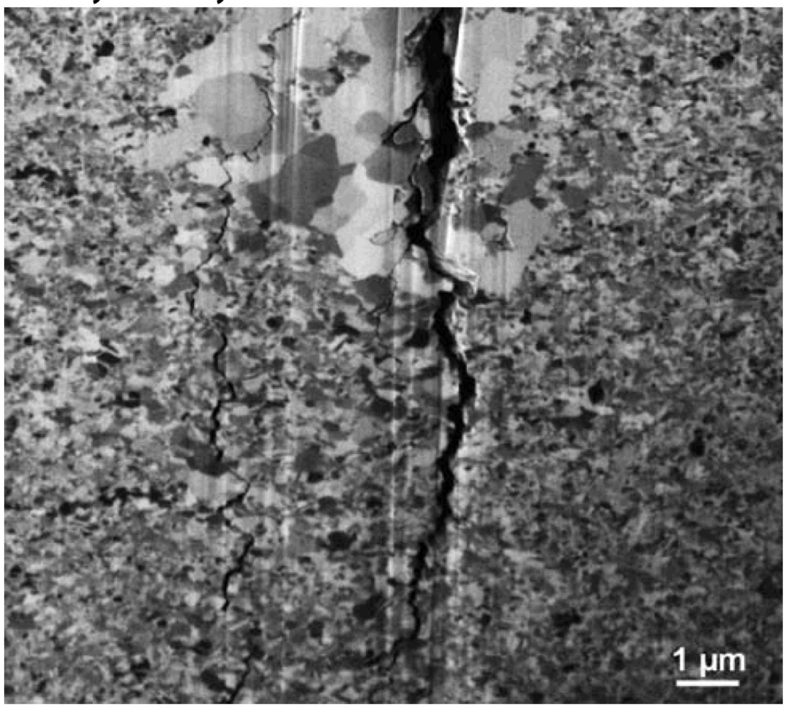
High hardness is not the source of low friction

instead, imparting higher stability to GBs slows surface grain growth and allows grain refinement to dominate at increasingly higher stress

Stress and temperature determine rate of grain coarsening

stress-driven grain growth

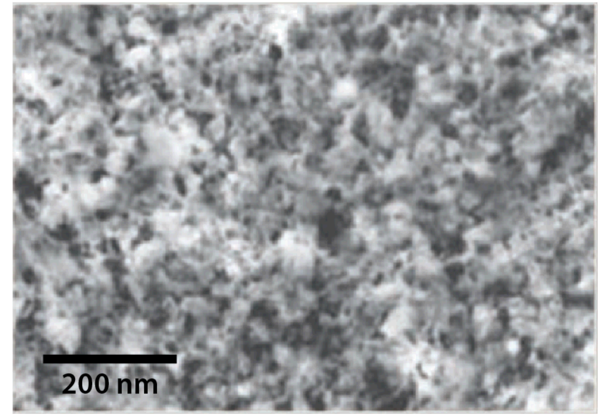
initially nanocrystalline Ni-Mn



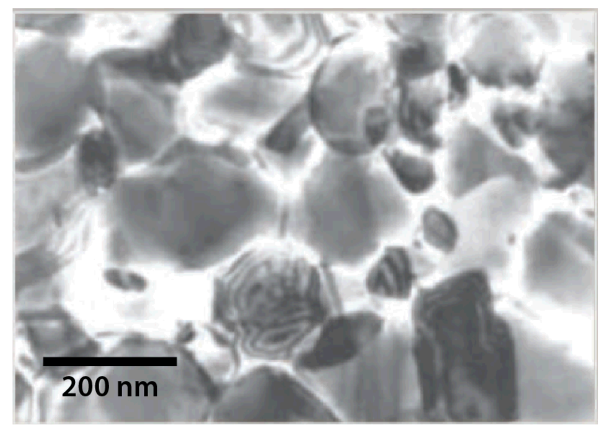
ref: Padilla & Boyce, Exp. Mech. (2010)

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

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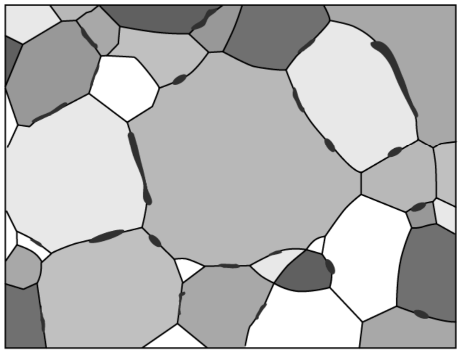
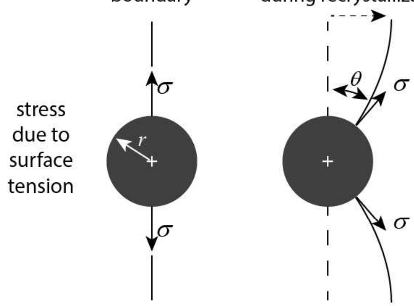
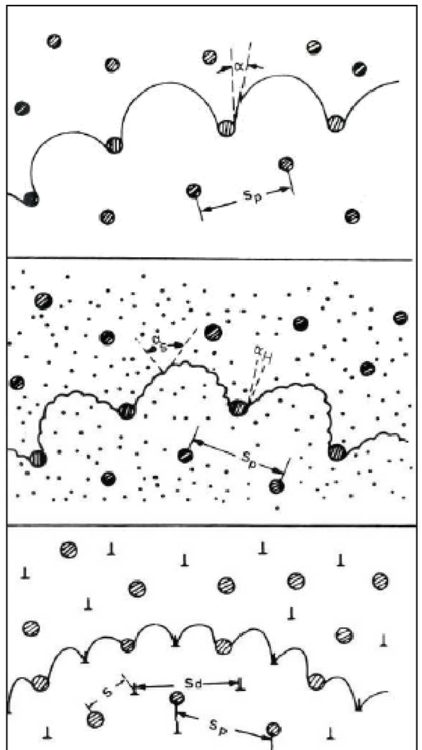
Limit the ***kinetics*** of recrystallization (traditional quasi-stability)

e.g. Zener pinning, solute drag, porosity







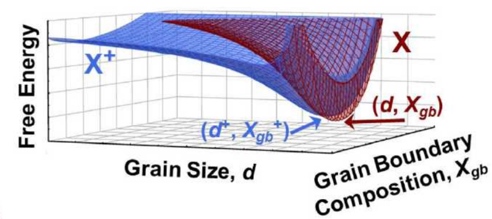
drag force: $f_D = 2\pi r\sigma \cos\theta \sin\theta$

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

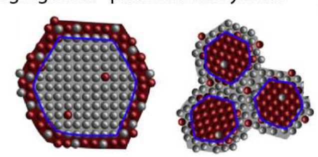
$$\Delta G^{mix} = (1 - f_{gb})\Delta G_c^{mix} + f_{gb}\Delta G_{gb}^{mix} + z\nu f_{gb}(X_{gb} - X_c)\left[(2X_{gb} - 1)\omega_{gb} - \frac{1}{zt}(\Omega^B\gamma^B - \Omega^A\gamma^A)\right]$$

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



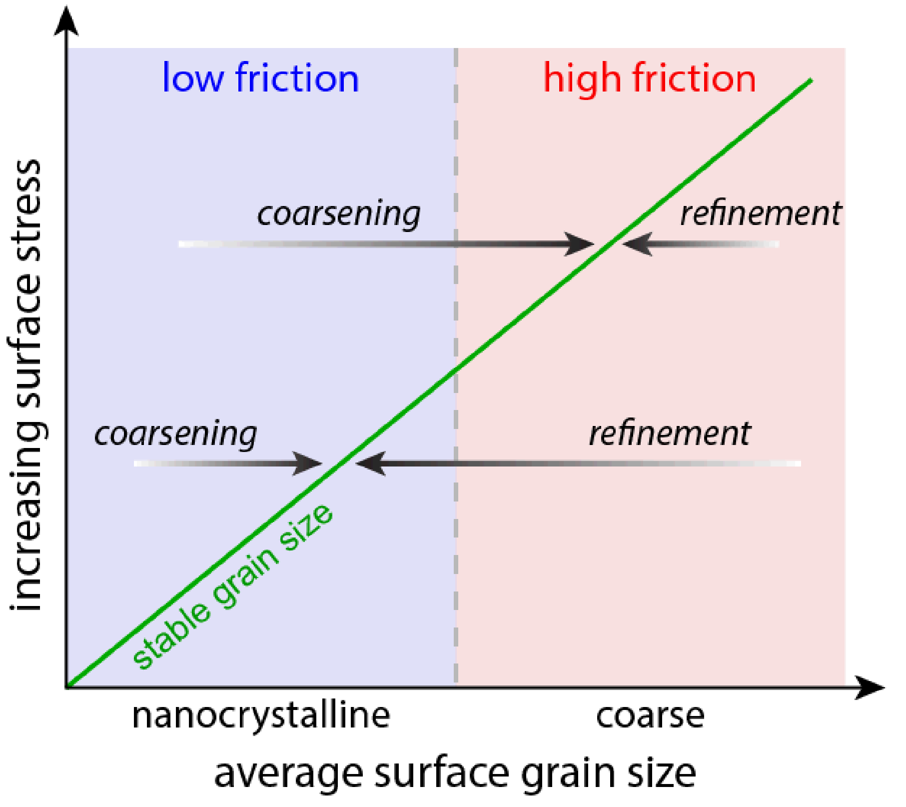
ref: Murdoch et al., Acta Mat. (2013)

Grain structure model:
segregated 2-phase metal system



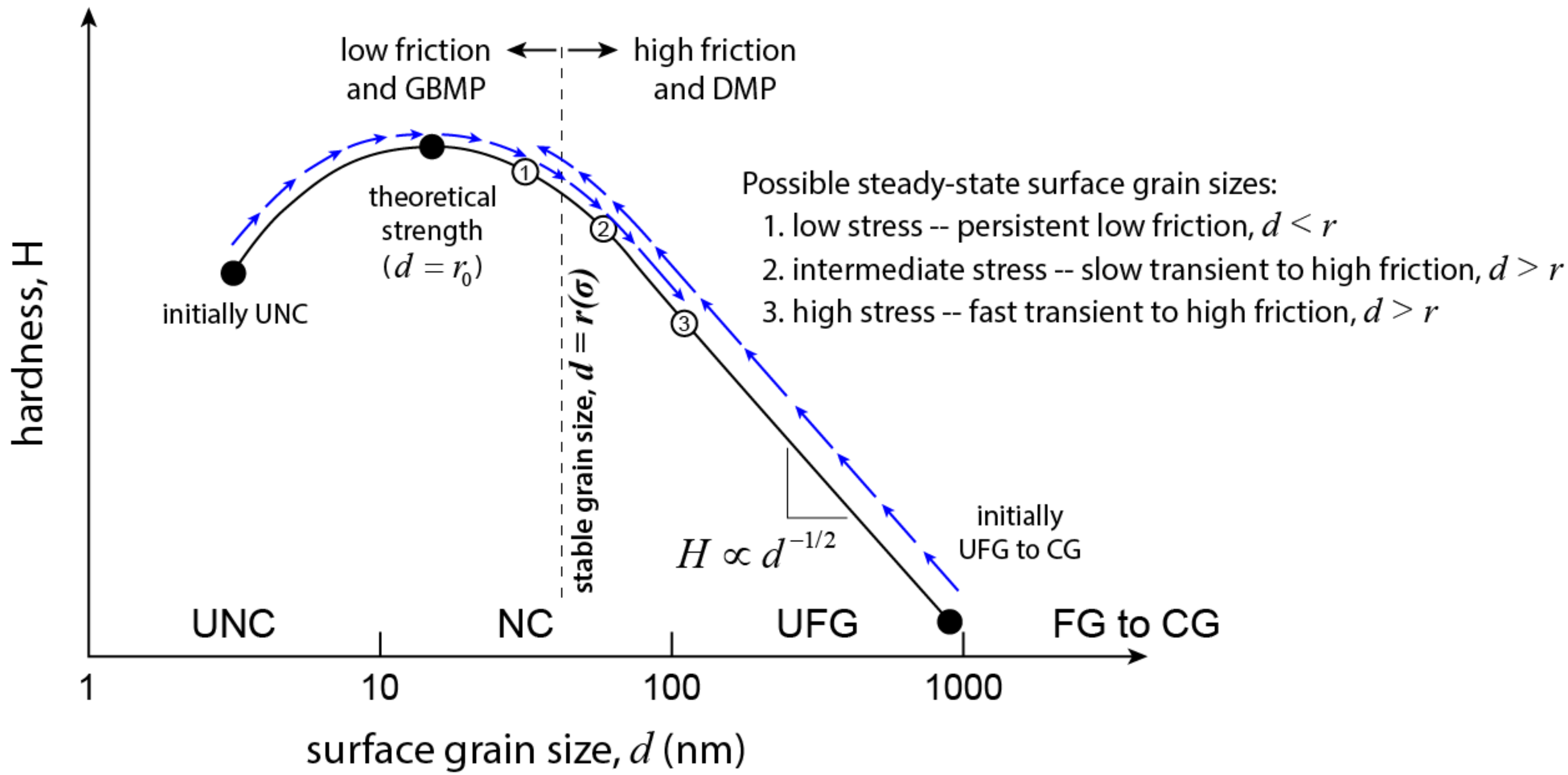
ref: Murdoch et al., Acta Mat. (2013)

We propose that there exists a stress-dependent steady-state (asymptotic) grain size



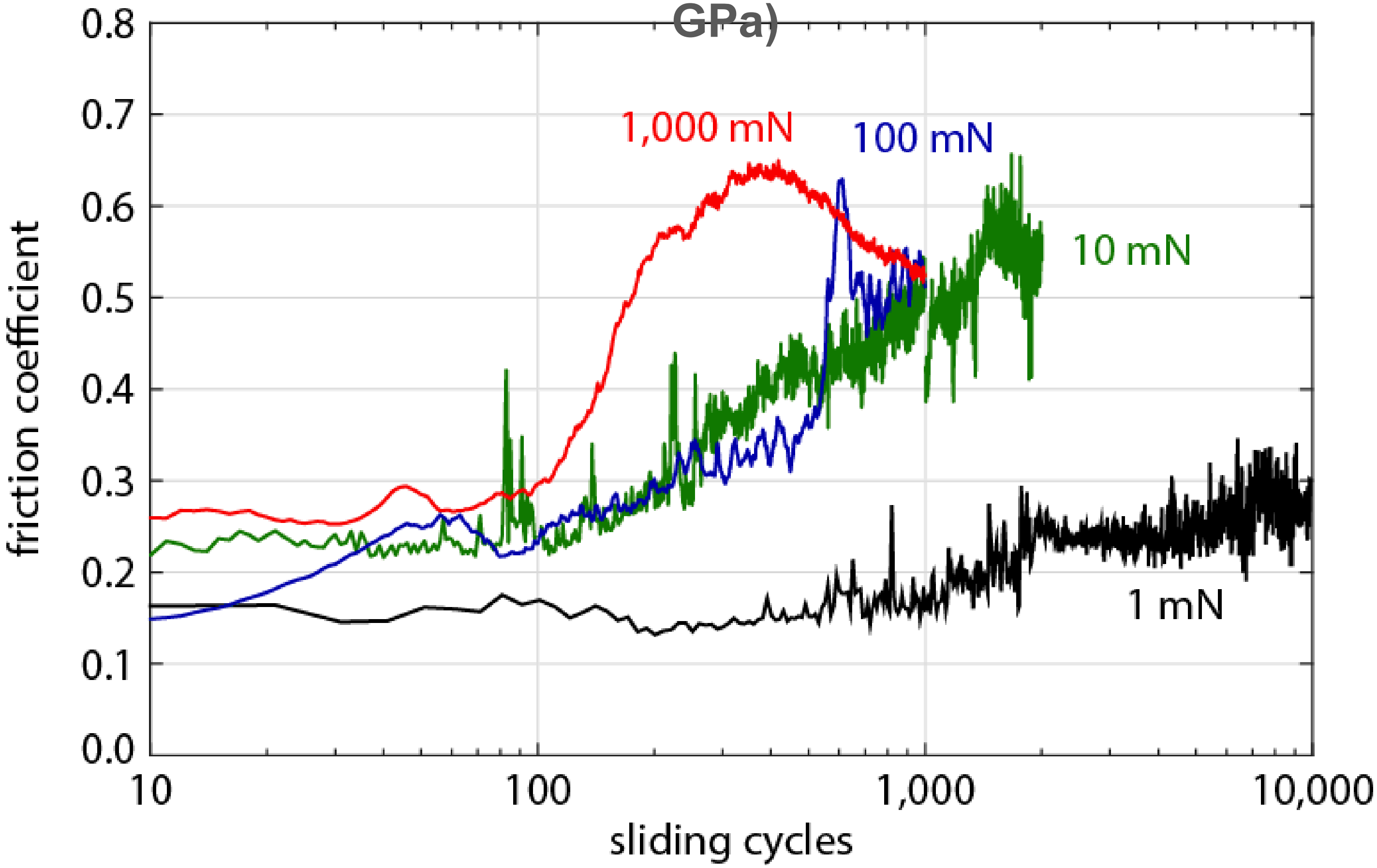
… that is stress dependent

Hardness (i.e. *grain size*) evolution toward stress-dependent steady-state value

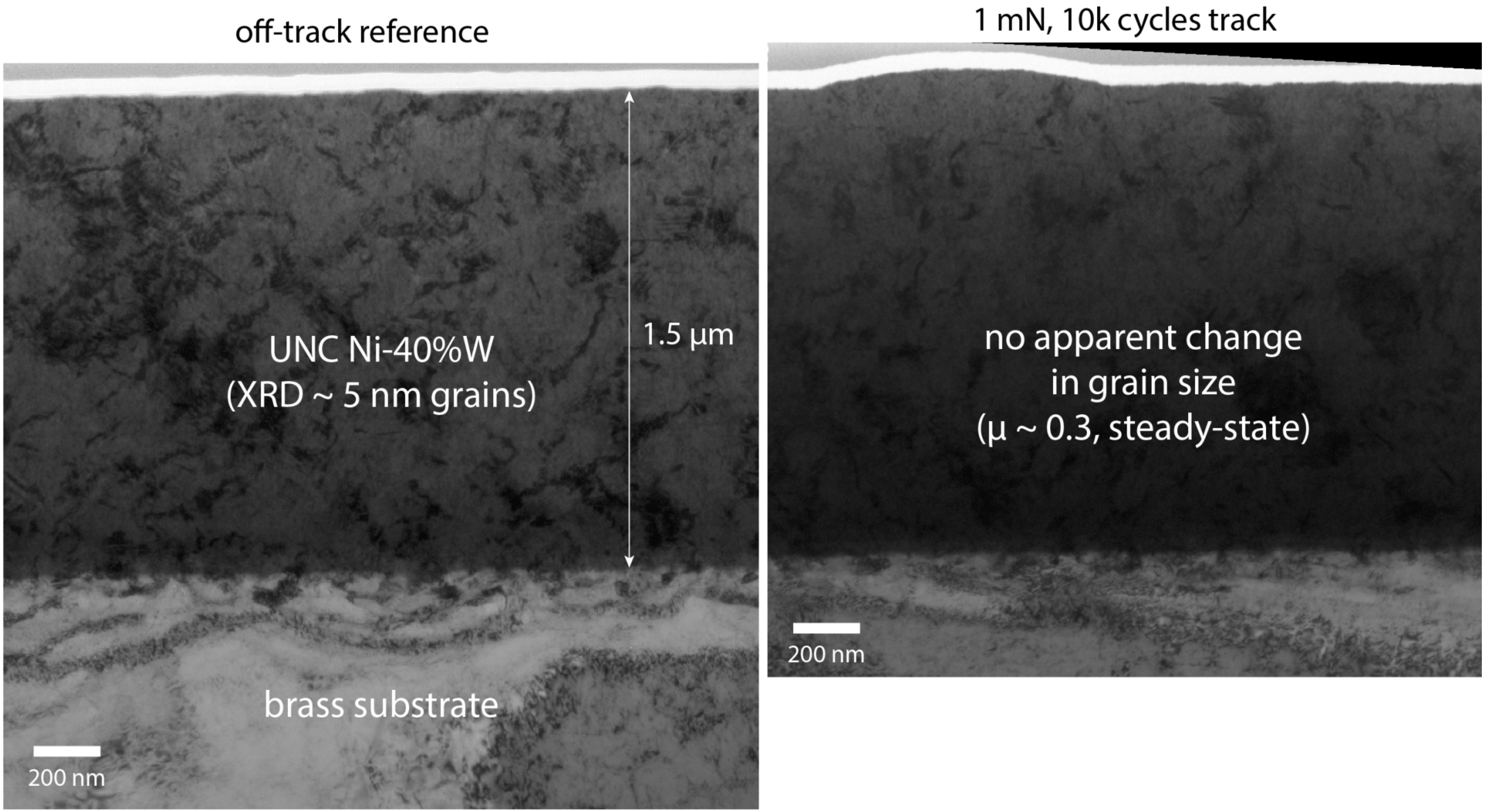


Example of grain size evolution in an initially UNC material (Ni - 40wt% W)

this is VERY hard metal (H ~ 8-9 GPa)



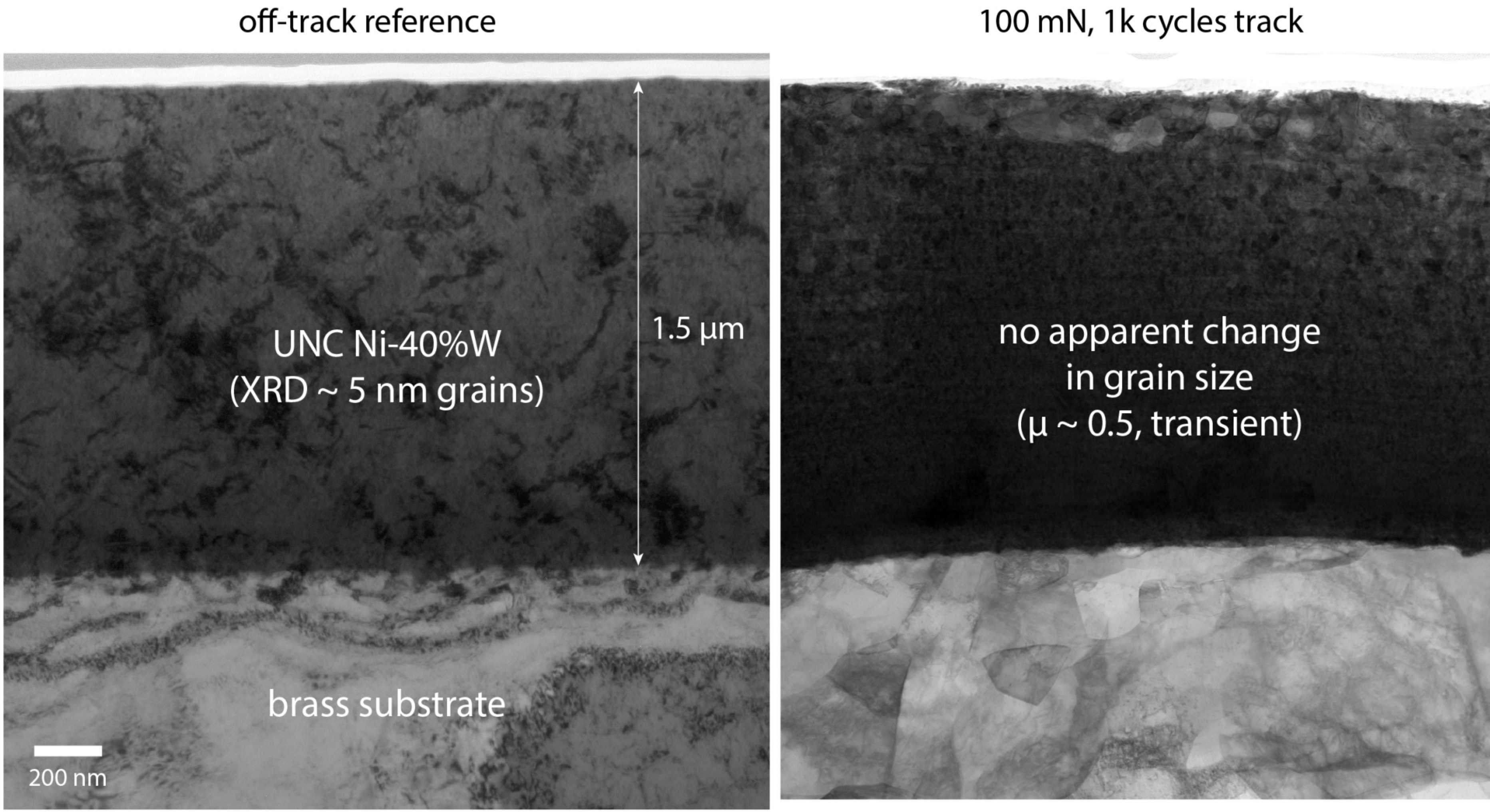
FIB-TEM wear track cross-section of 1 mN normal force / 10k cycle test



see low friction and no change in grain size… right?

(INCREASE in surface hardness by 11%)

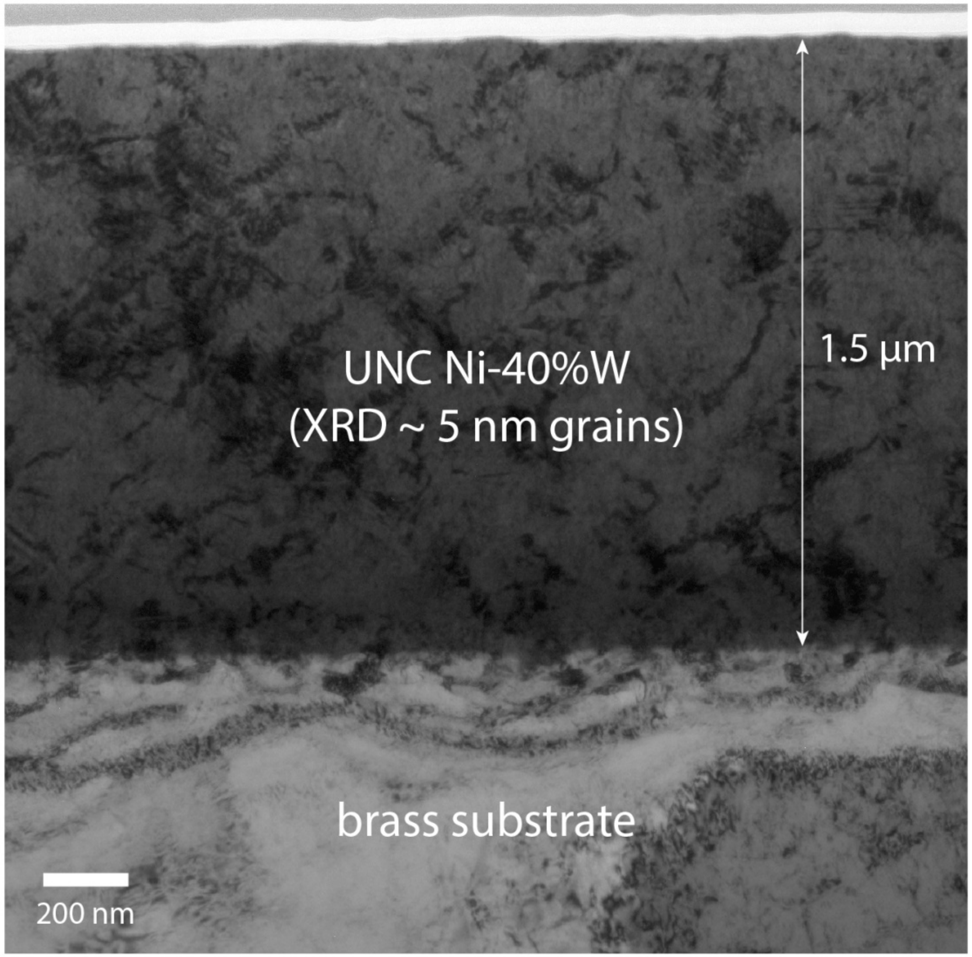
FIB-TEM wear track cross-section of 100 mN normal force / 1k cycle test



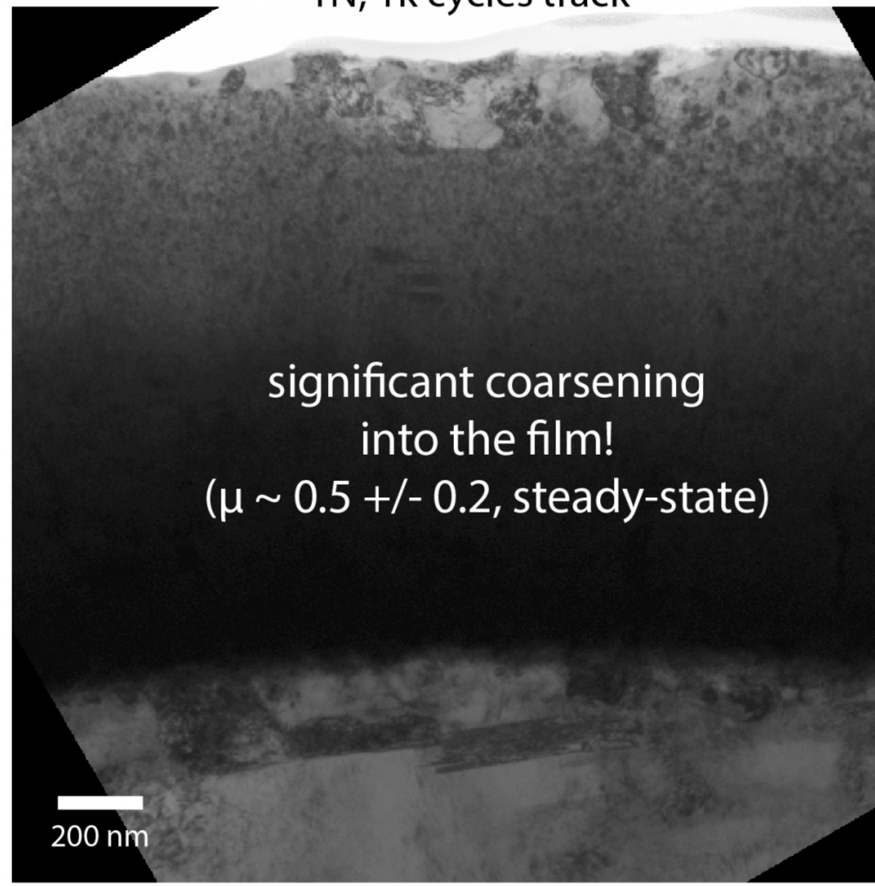
significant grain growth, higher friction

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

off-track reference

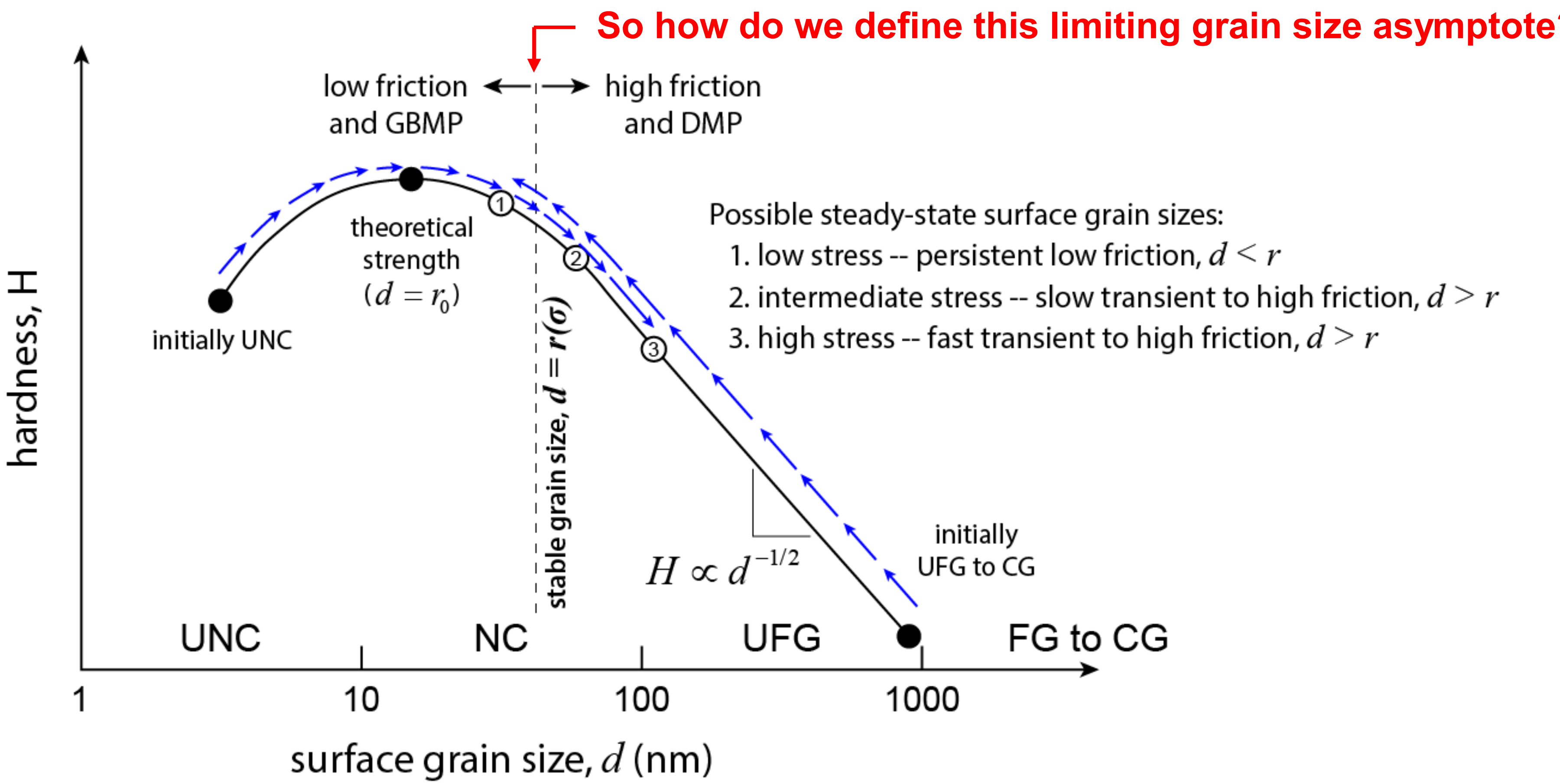


1N, 1k cycles track



again see significant grain growth, higher friction

Example of grain size evolution for an initially UNC metal (Ni - 40wt% W)

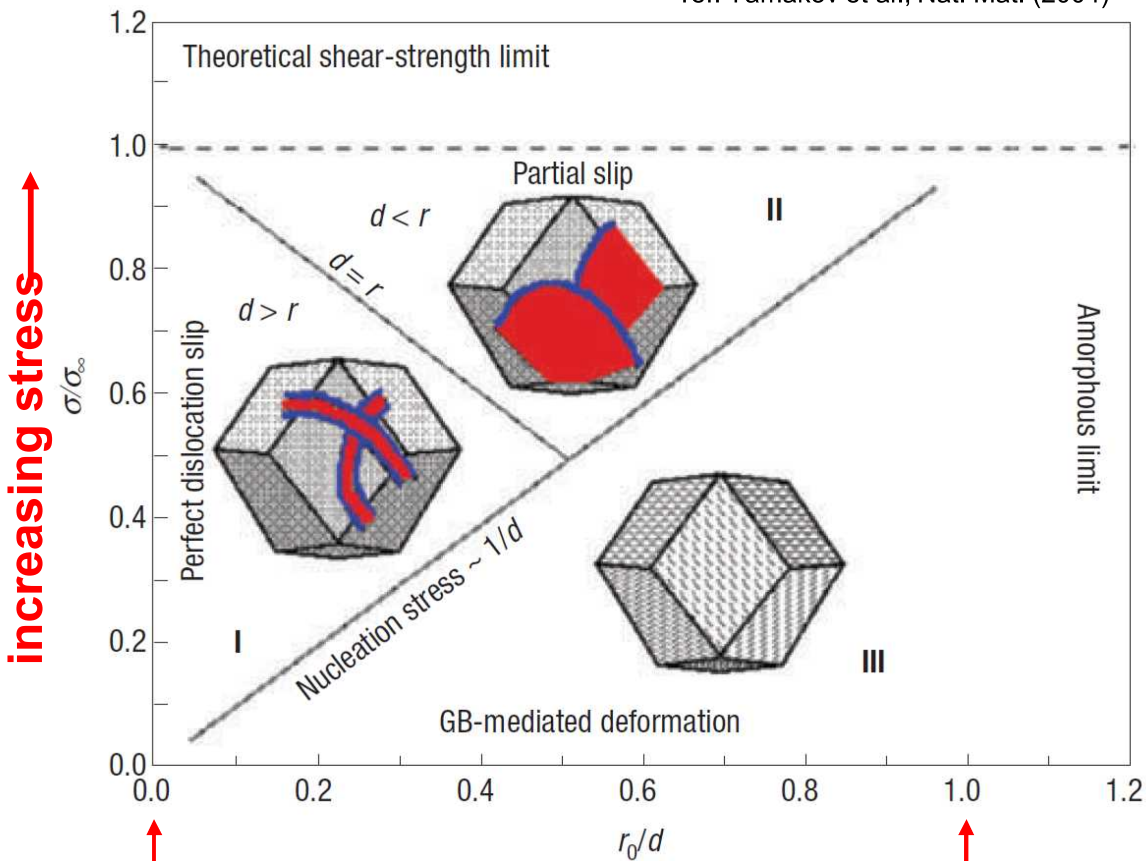


We find that only the **LOW FRICTION** track **HARDENED**

This is similar to a result from Rupert and Schuh, Acta Mat. (2011) where they find that grain growth of UNC Ni-W via annealing can lead to hardening

Yamakov et al. (Nat. Mat. 2004) provide a useful parameter

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



grain size goes to single crystal

increasing grain size

minimum grain size (peak H-P) $d = r_0$

Equilibrium (zero stress) dislocation splitting distance:

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

Stress-dependent splitting distance:

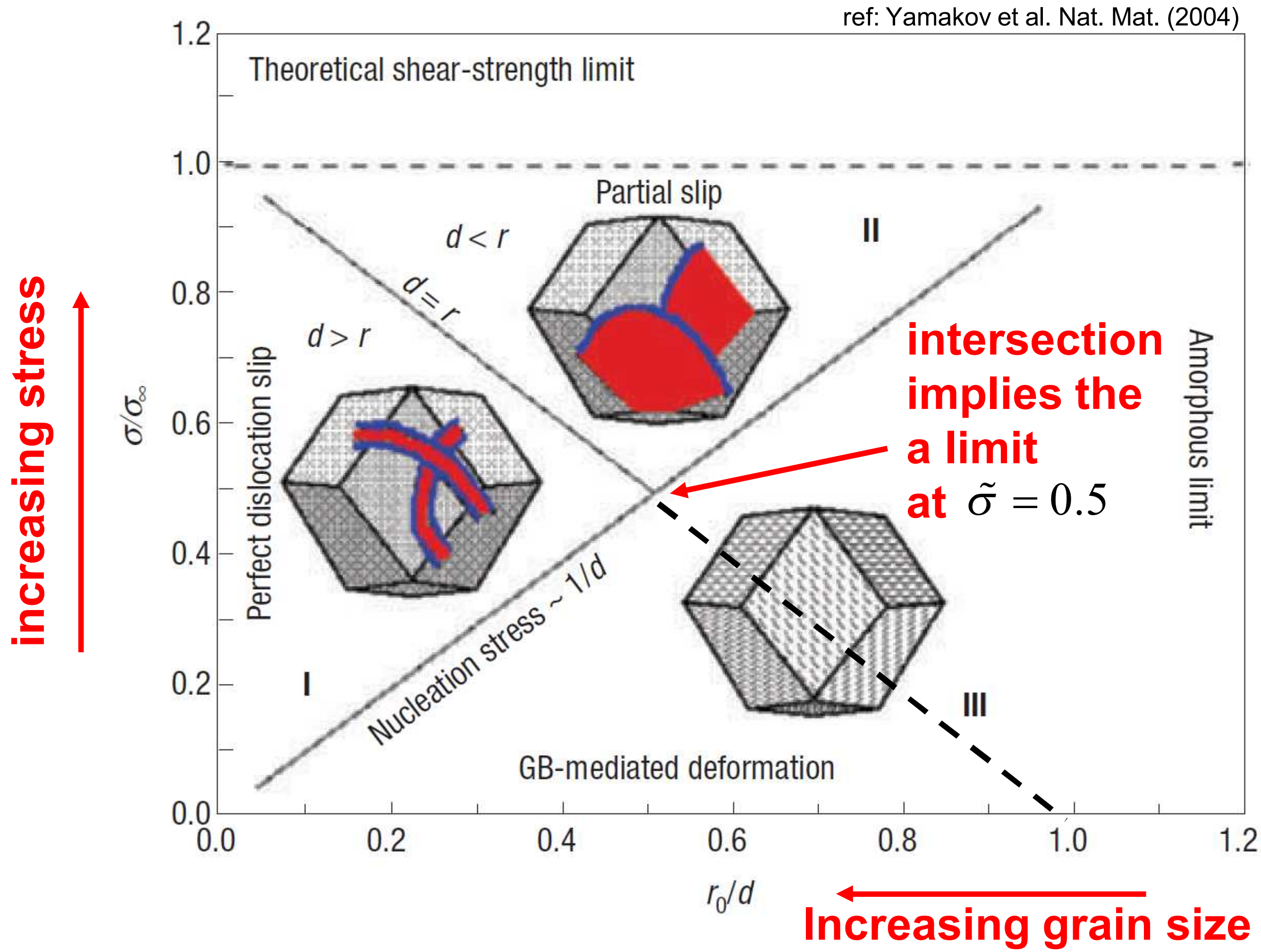
$$r = \frac{r_0}{1-\sigma_a/\sigma_\infty}$$

Theoretical strength - grain siz where Hall-Petch reaches max

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

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

Boundary of applied stress below which GBMP always dominates



Assumptions:

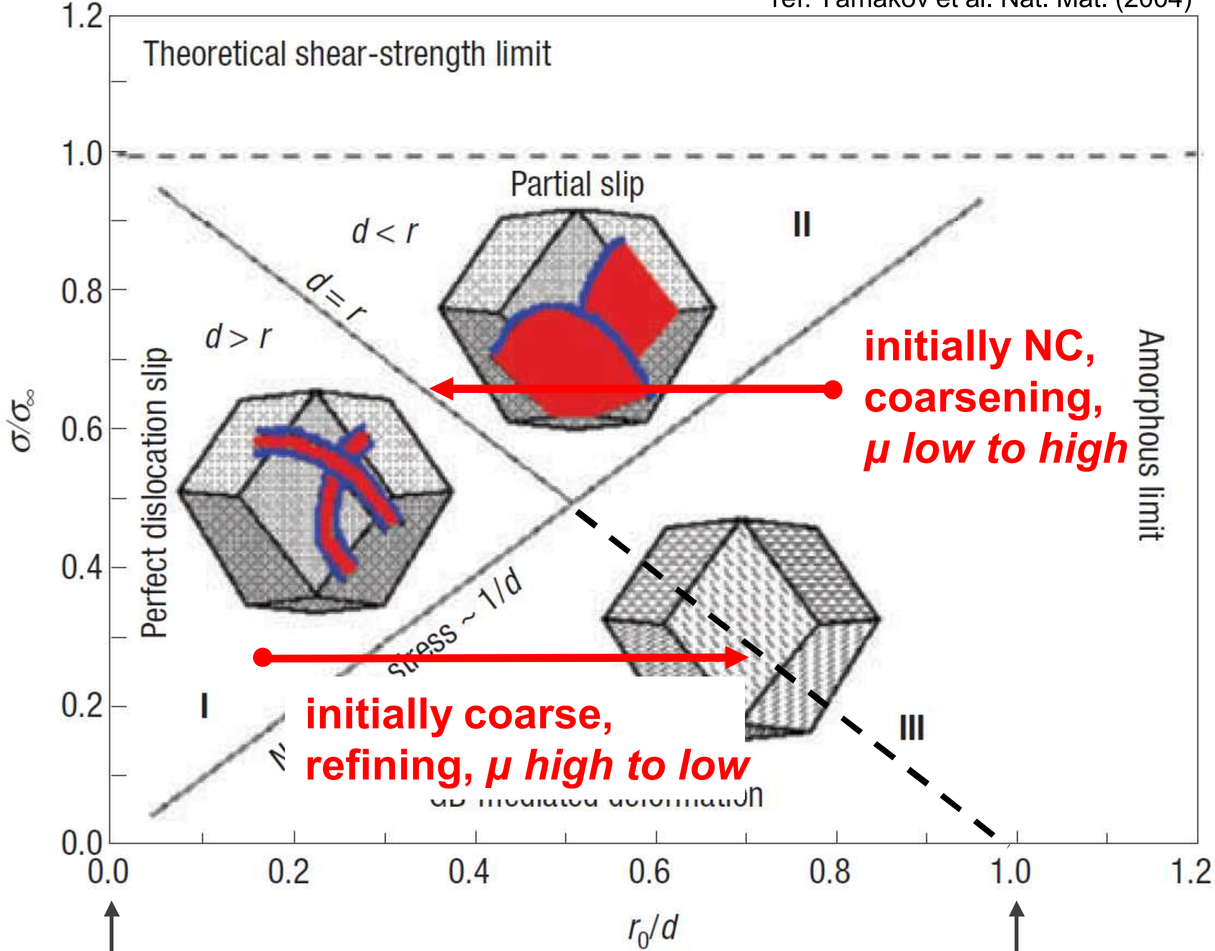
1. (new) grain size goes to splitting distance, $\to d$ $\quad r = f(\sigma)$

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

So we are adding a layer of evolving (i.e. time-dependent) grain size

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

increasing stress



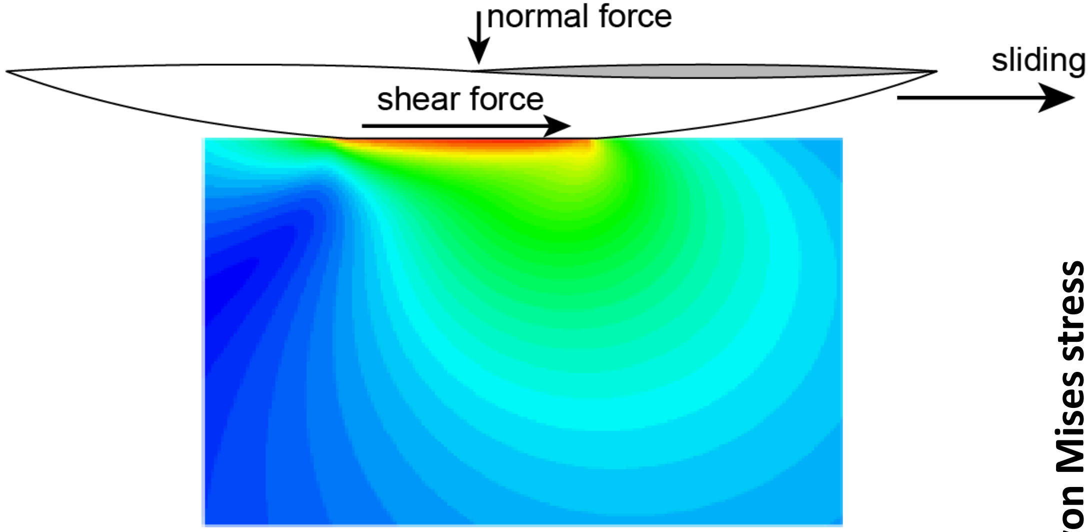
large grain size

Increasing grain size

minimum grain size, H-P rollover

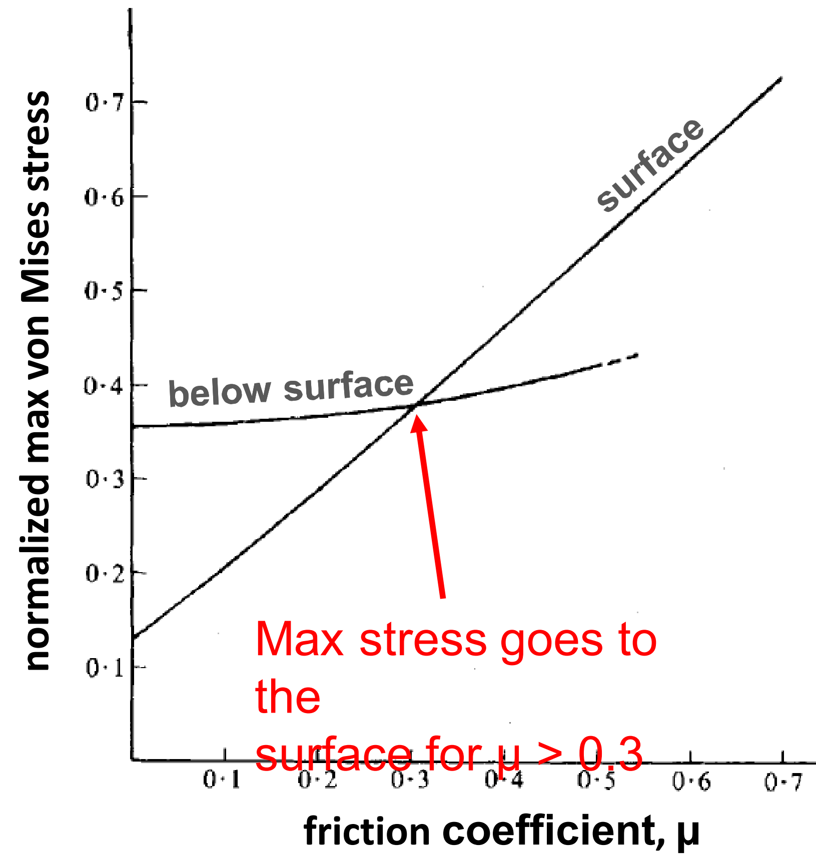
What stress? Hamilton model gives the maximum von Mises stress

von Mises stress contour lines:

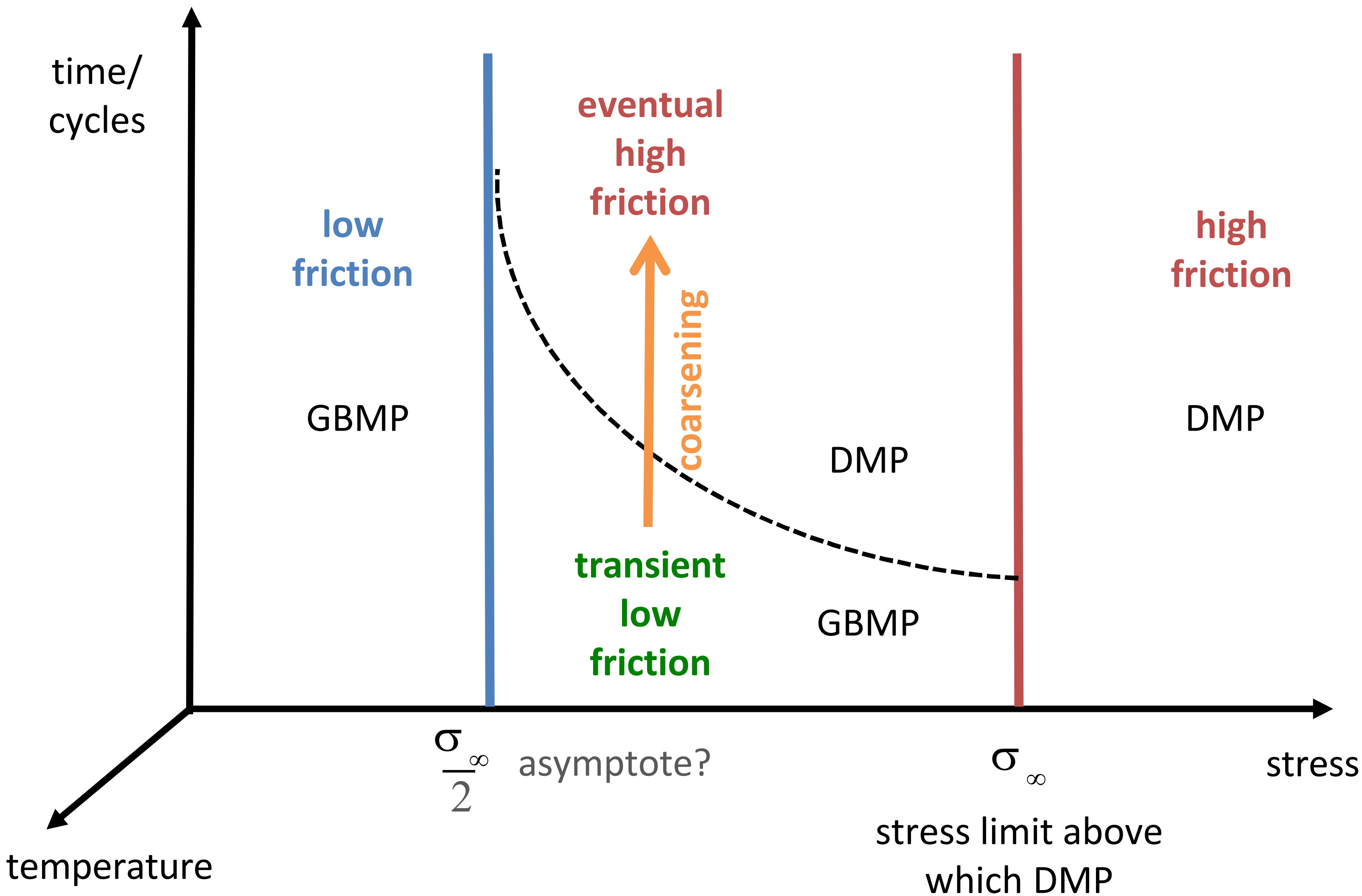


$$\sigma_{surf,\max} = \frac{3F_n}{2\pi a^2}\left[\frac{1-2\nu}{3} + \frac{(4+\nu)}{8}\pi\mu\right]$$

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



We can now define a generalized friction regimes map for metals



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 only by materials parameters!

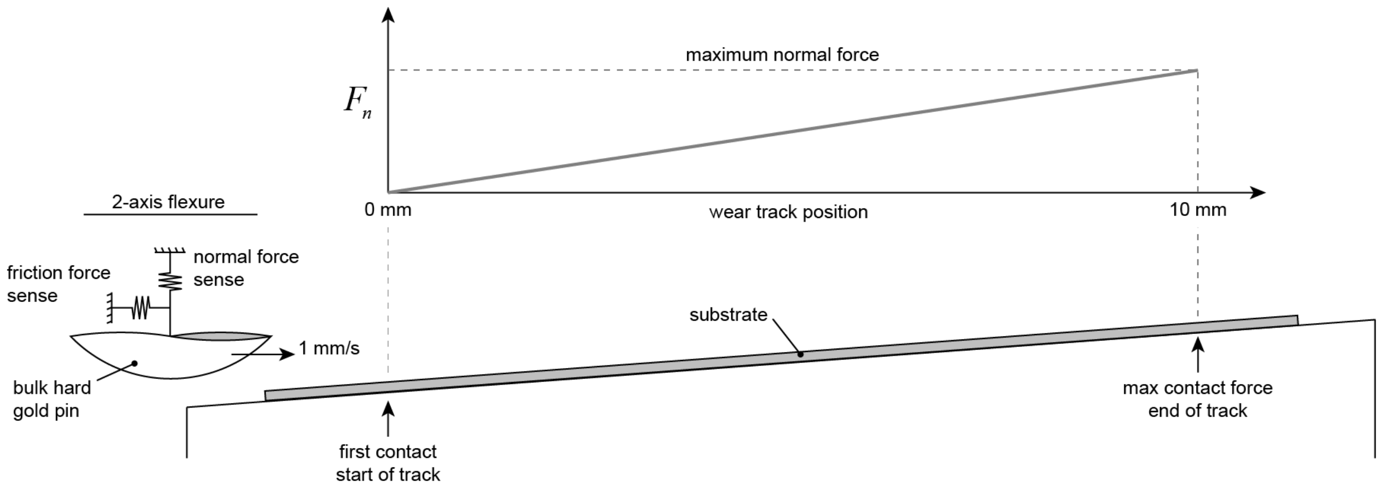
reduced stress: $$\tilde{\sigma} = \frac{\sigma_{surf,\max}}{\sigma_{\infty}}$$

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

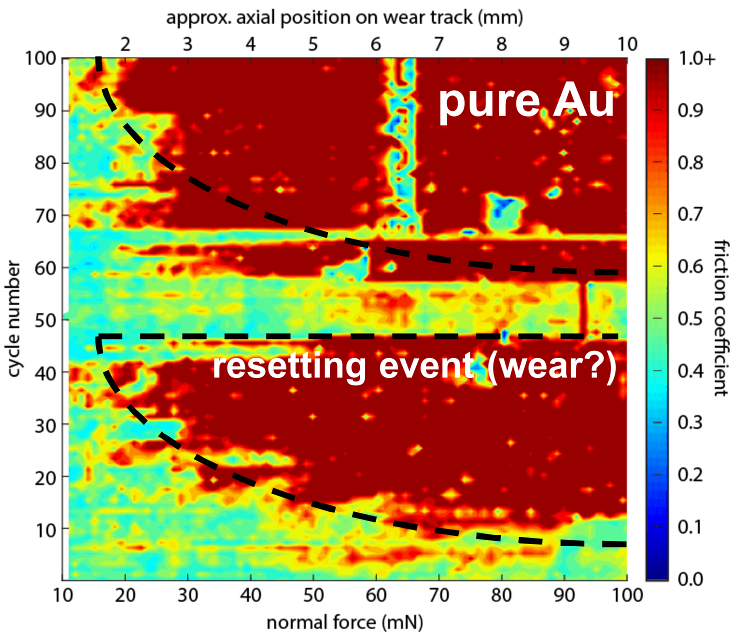
- Normalize applied stress theoretical strength
- Normalize time by the fundamental “grain boundary time”
- Plot semilog

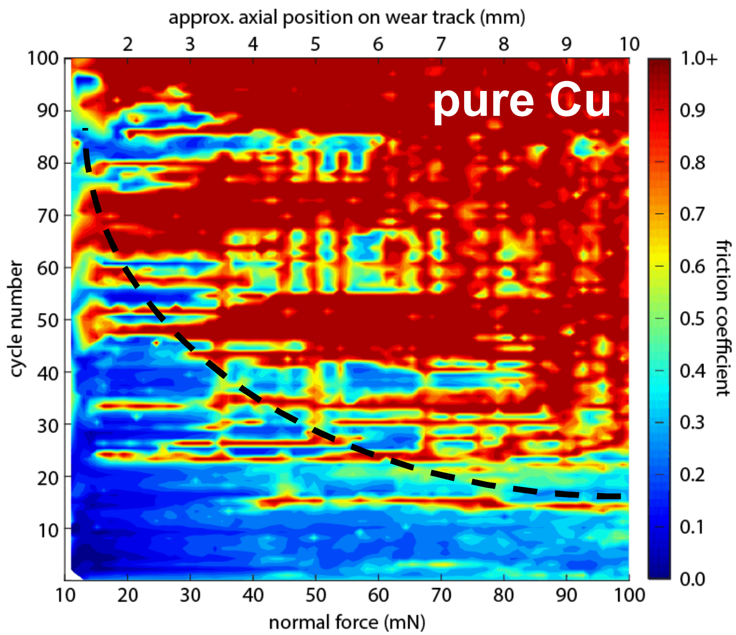
Defined only by materials parameters!

Ramped contact force experiments and friction mapping reveals much more!

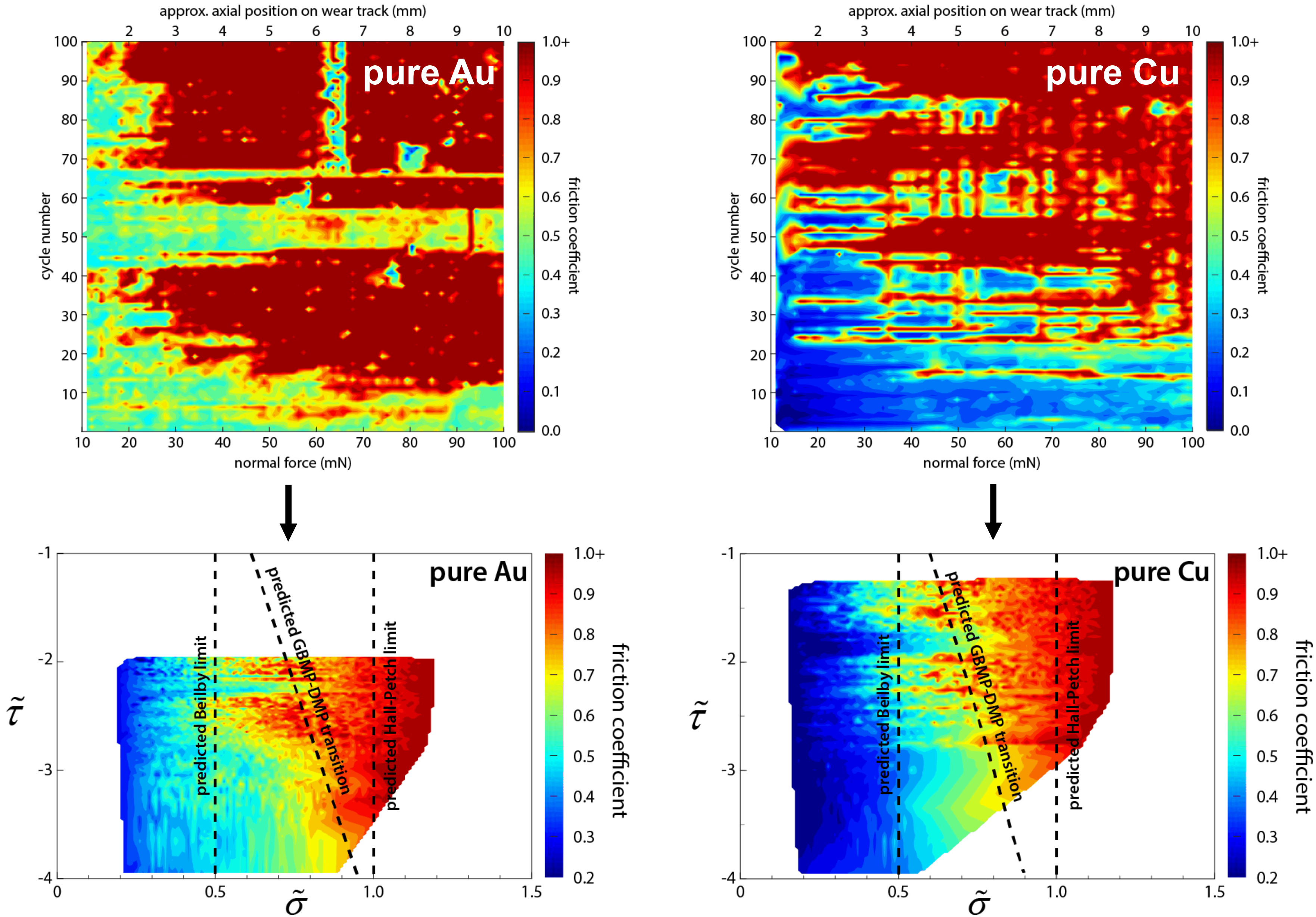


Messy (tribology…), but there is stress-time envelope!

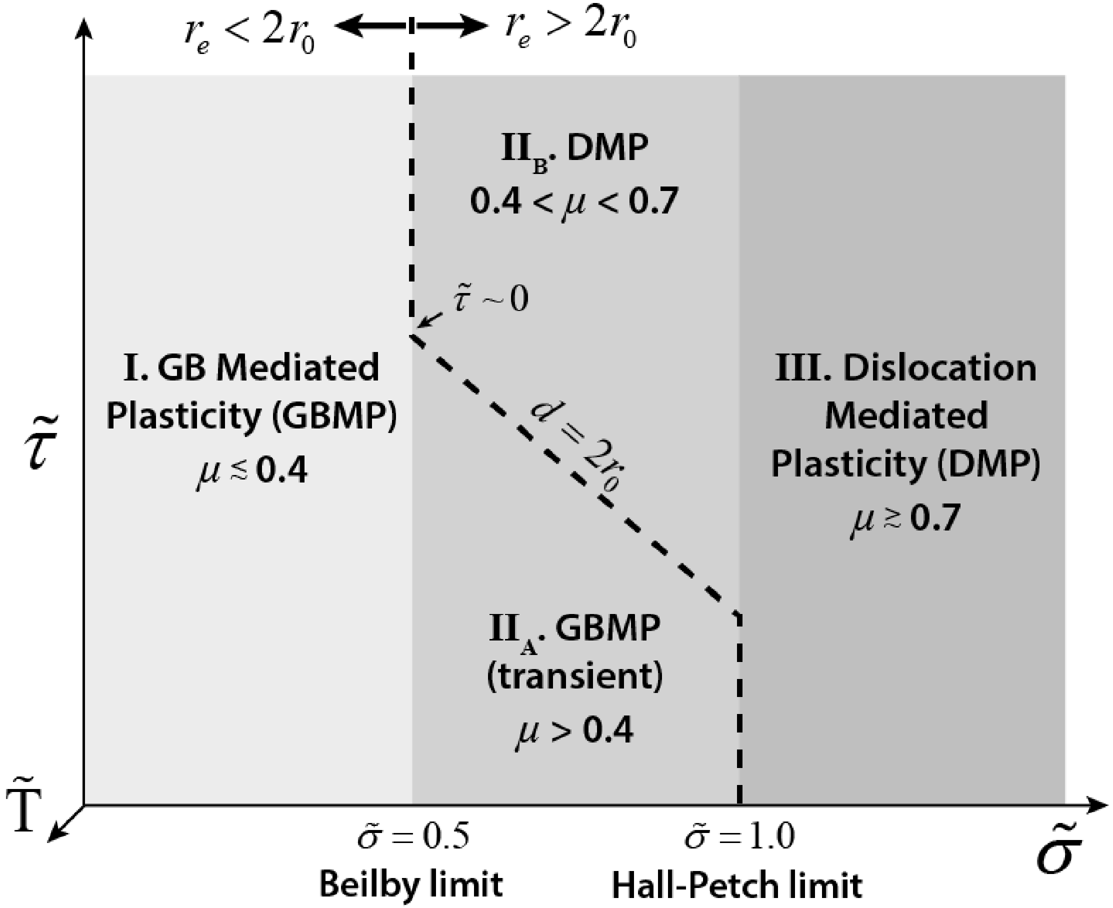




Apply reduction to ramped friction data…



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

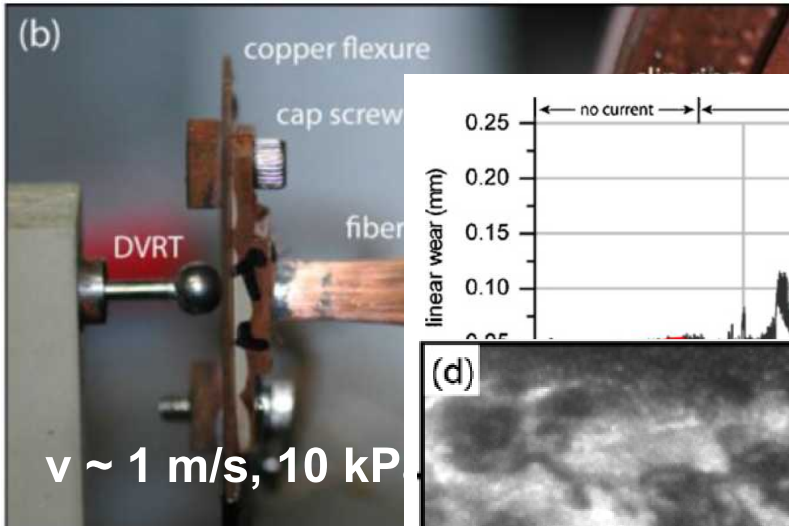


Friction modifiers (e.g. graphite, MoS_2, hydrocarbons) provide boundary lubrication and mitigate commensurate contact –
this allows low friction at higher normal force

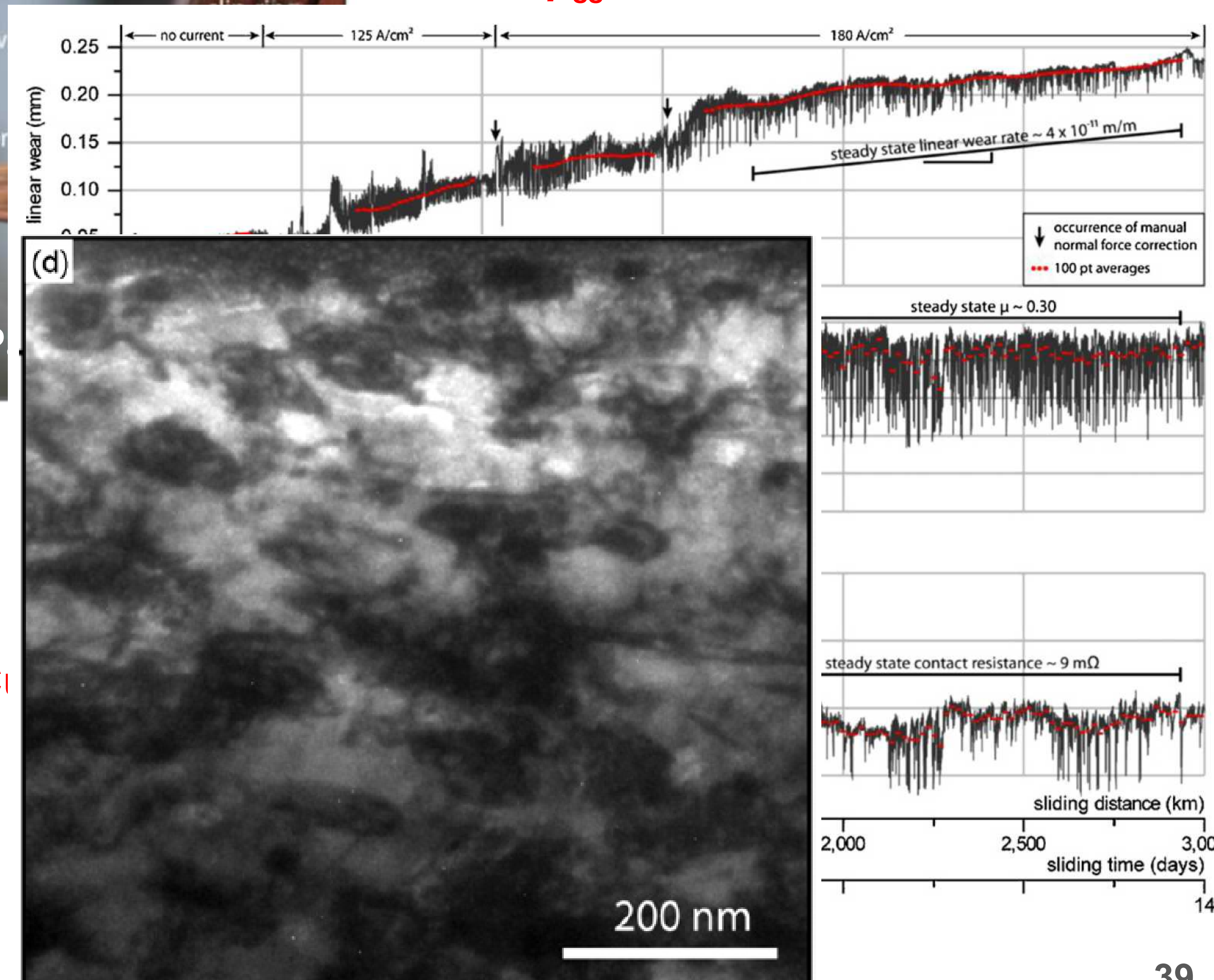
Copper alloy brush sliding against pure Cu disk in humid CO_2 (i.e. boundary lubricated)

wear rate of ~ 1 nm per kilometer

μ_{ss} ~ 0.3



v ~ 1 m/s, 10 kP

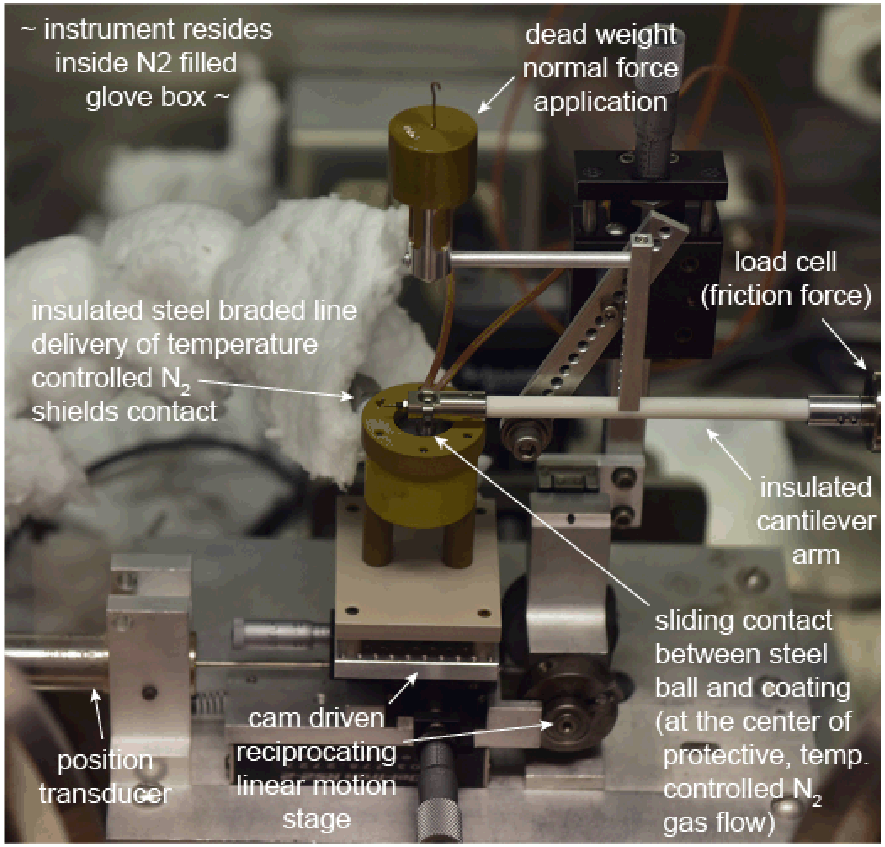


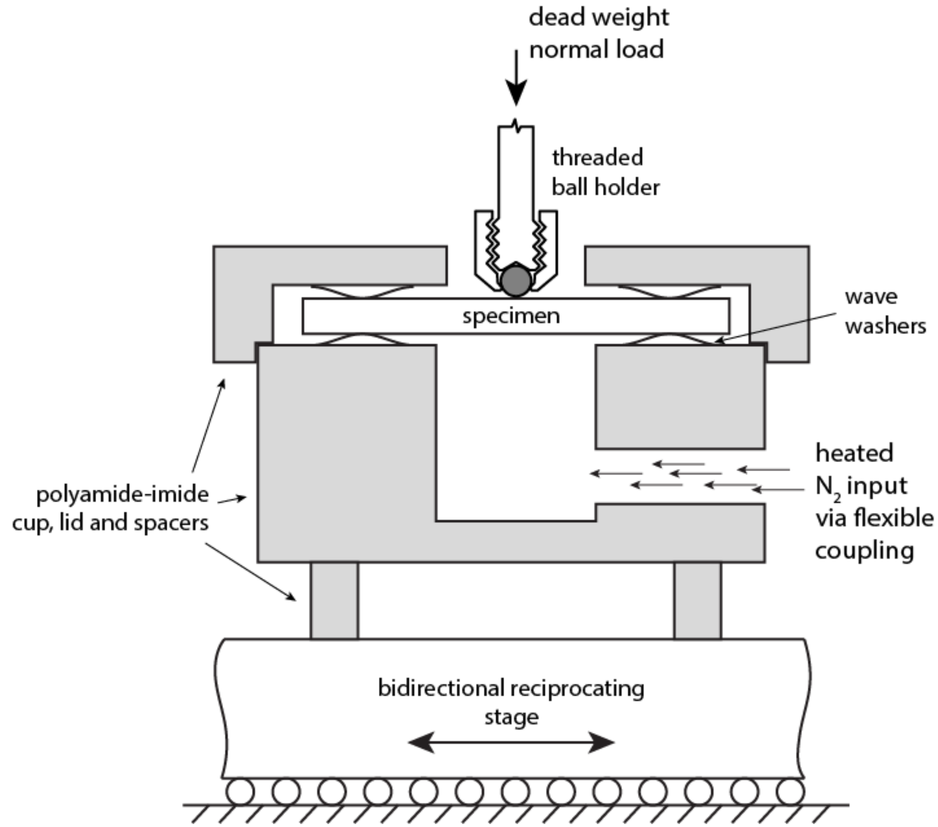
Low friction associated with nanocrystalline surface for a Cu-Cu system

ref: Argibay et al., Wear 2010

A preview of future work… impact of temperature on friction regime bounds

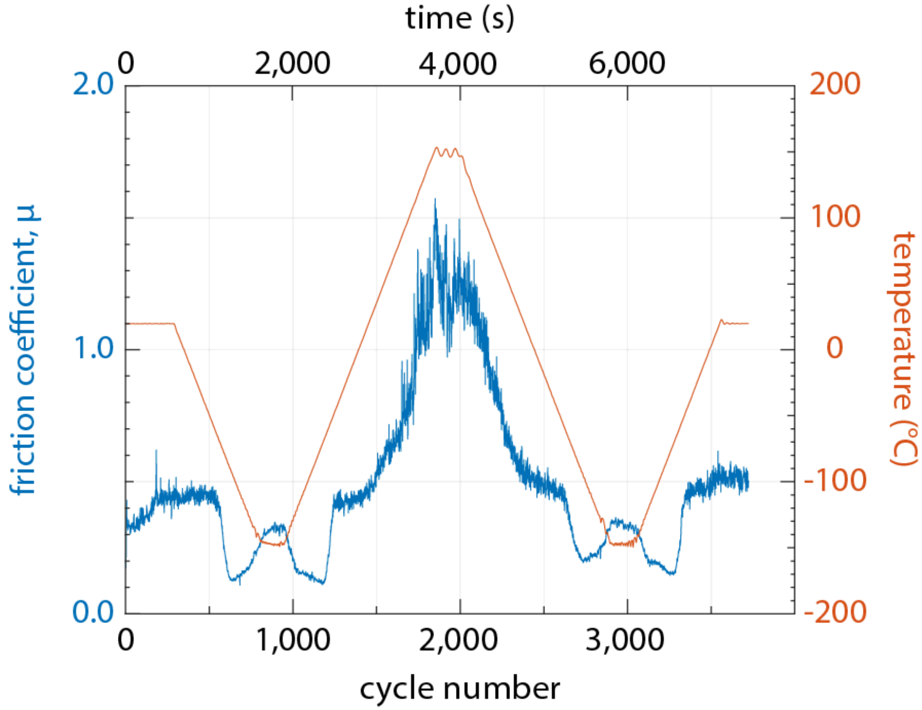
variable temperature tribometer (-190°C to +250°C) in inert gas environment (liq. N_2 input)

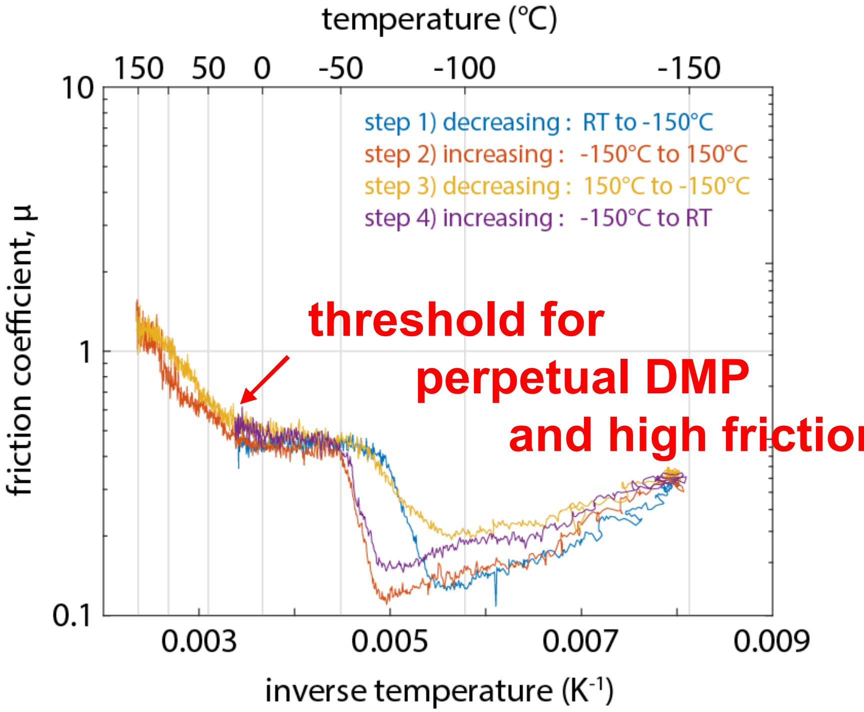




A preview of the impact of temperature change on self-mated pure Cu

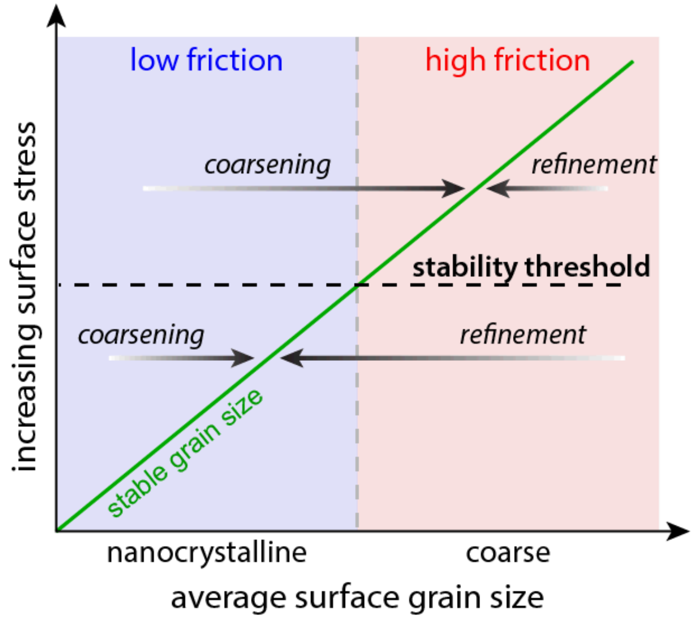
normal force 100 mN:

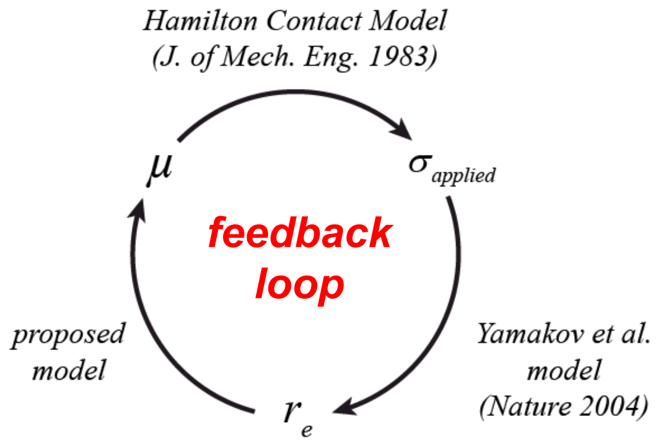


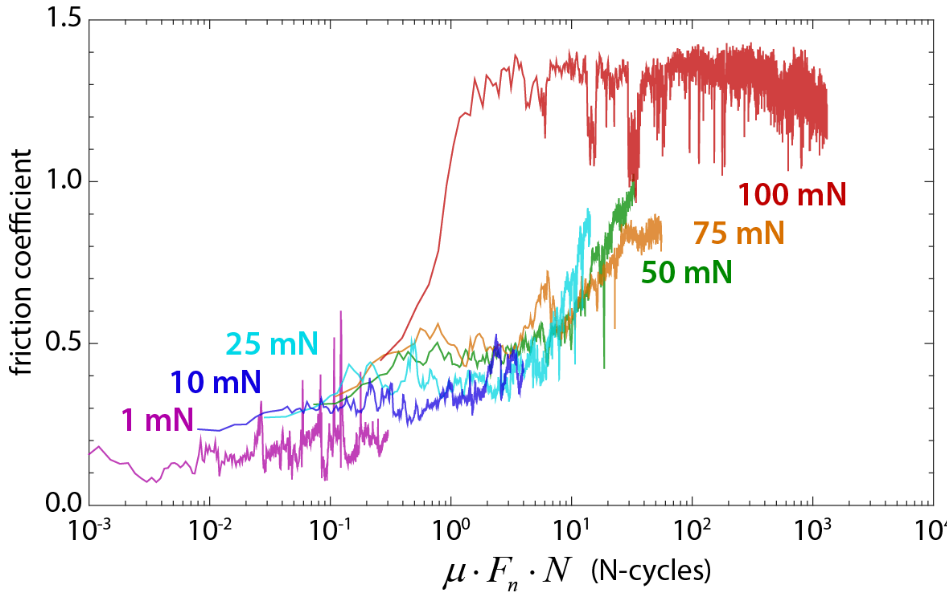


More experiments and microscopy needed, but two transitions appear to exist at about 30°C and -75°C

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



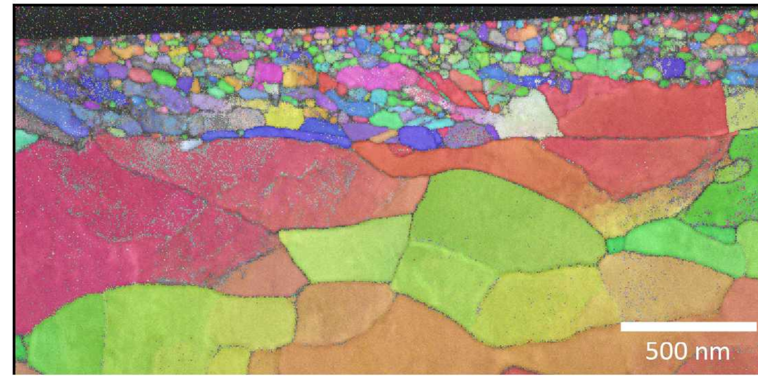




Only the beginning, much left to do…

- 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?
  - Preliminary result with Ni-W says **<u>yes</u>!**
- Can we model competing wear? …difficult, but maybe

Transmission Kikuchi Diffraction (TKD):
(transmission diffraction performed in an SEM)



Appendix Slides

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

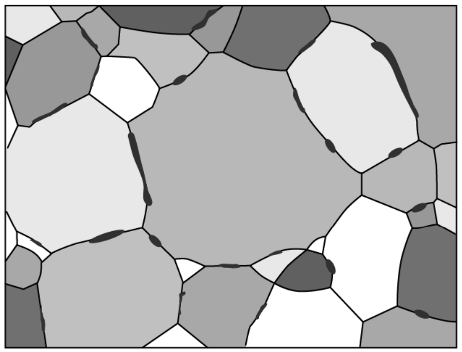
P = pressure on grain boundary

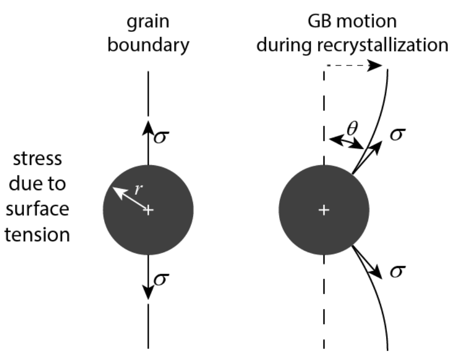
γ_o = interfacial energy per unit area

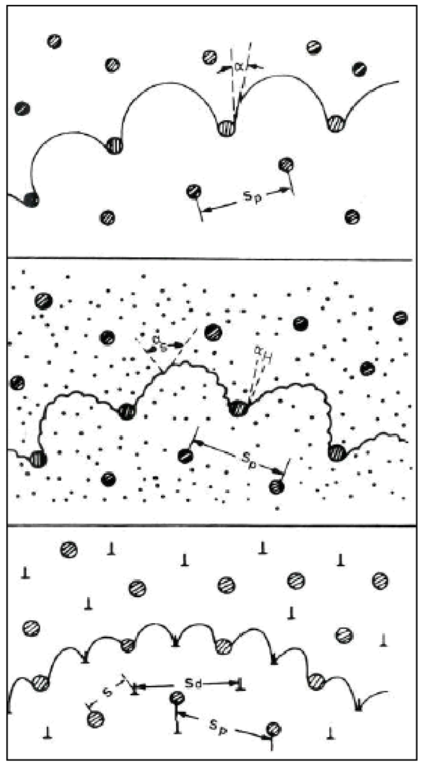
r = mean grain radius

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

e.g. Zener pinning, solute drag, porosity







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

Two routes to stabilize nanocrystalline metals – kinetic and thermodynamic

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

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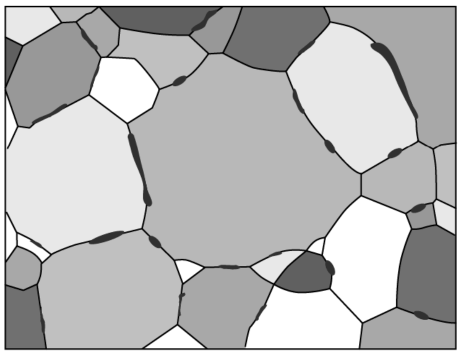
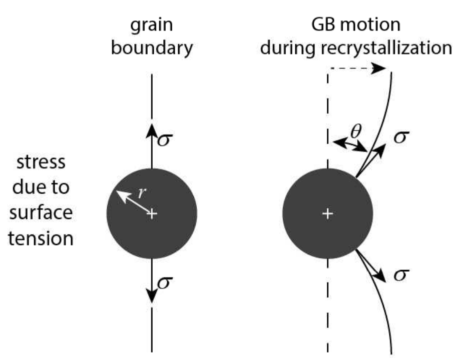
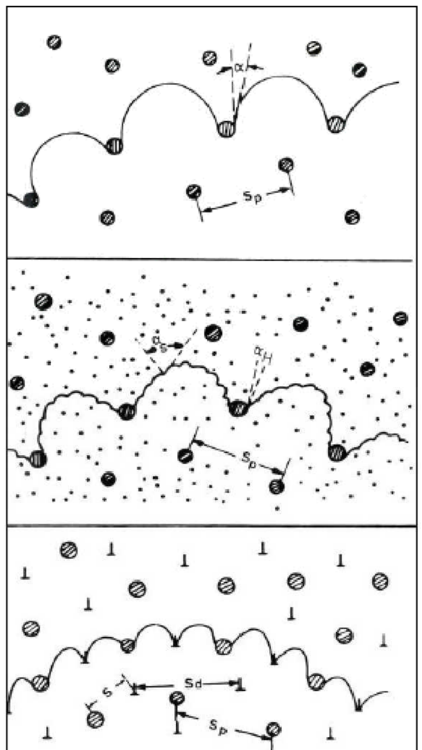




drag force: $f_D = 2\pi r \sigma \cos\theta \sin\theta$



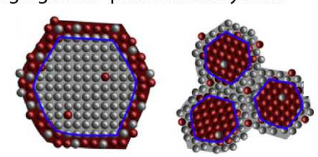
Weissmüller (1993), Kirchheim (2002), and Schuh (2012) have made significant contributions toward understanding and achieving ***thermodynamic*** stability by lowering grain boundary energy through solute segregation

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

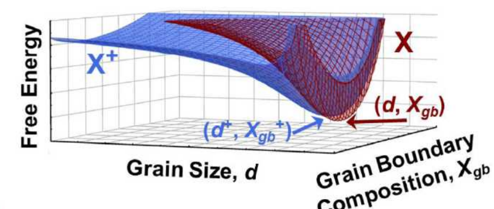
$$\Delta G^{\text{mix}} = (1 - f_{\text{gb}})\Delta G_{\text{c}}^{\text{mix}} + f_{\text{gb}}\Delta G_{\text{gb}}^{\text{mix}} + z\nu f_{\text{gb}}(X_{\text{gb}} - X_{\text{c}})\left[(2X_{\text{gb}} - 1)\omega_{\text{gb}} - \frac{1}{zt}(\Omega^{\text{B}}\gamma^{\text{B}} - \Omega^{\text{A}}\gamma^{\text{A}})\right]$$

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

Grain structure model:
segregated 2-phase metal system

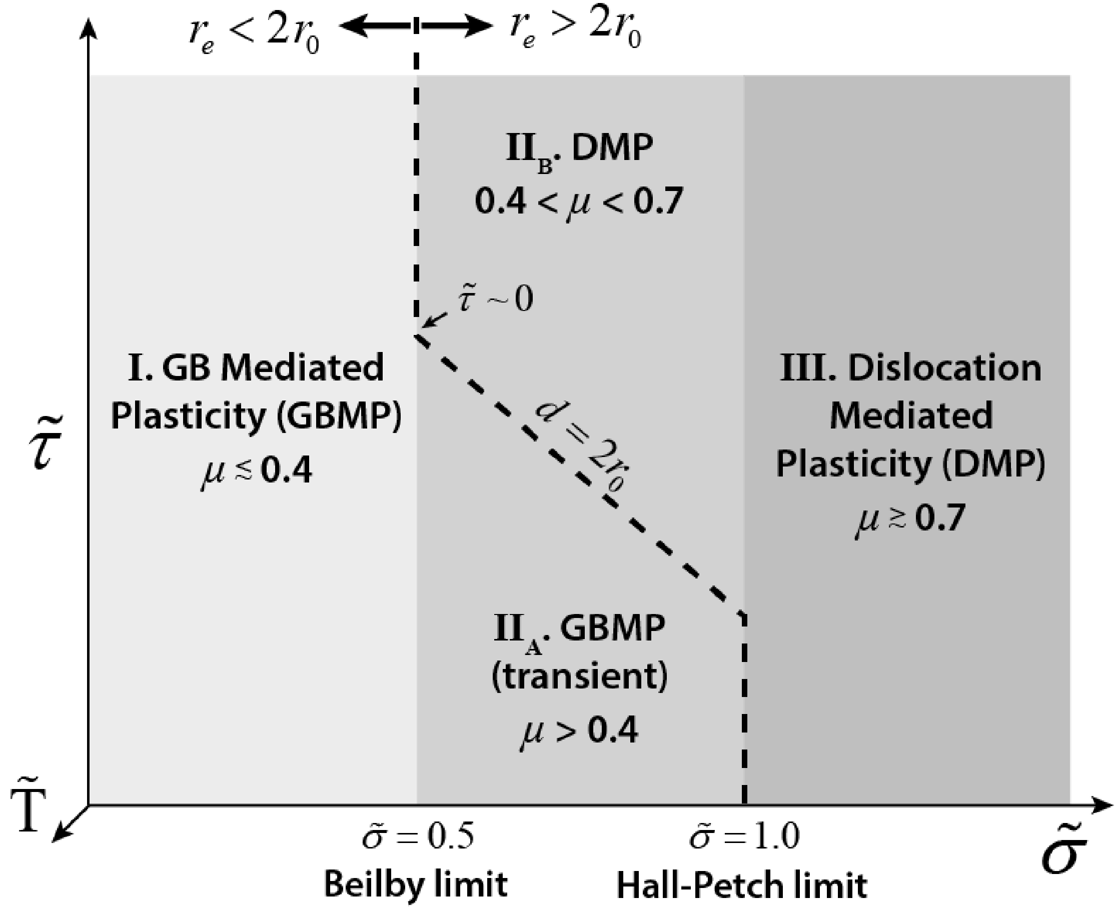


ref: Murdoch et al., Acta Mat. (2013)



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

Returning to the microstructure-based friction regimes model…



We assume:

1) that wear events reset the surface,
2) a competition between refinement and coarsening that drives *d*-> r_e

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	M_0	= grain boundary mobility
d	= grain diameter	Q	= activation energy

- Classical grain growth equation

Defined only by materials parameters!

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

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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):

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

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	

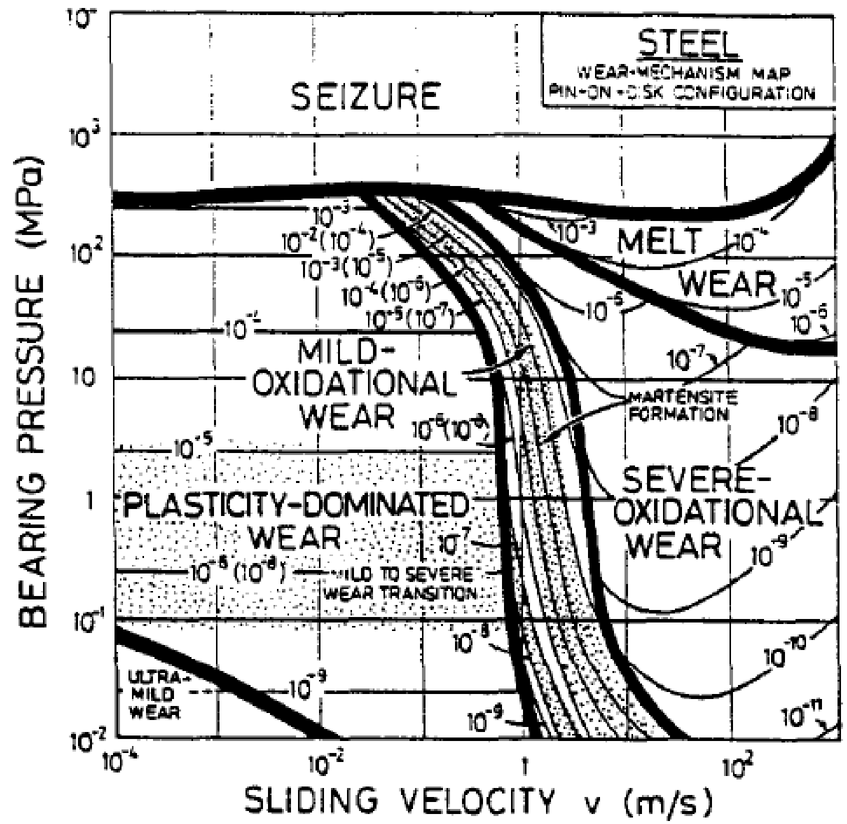
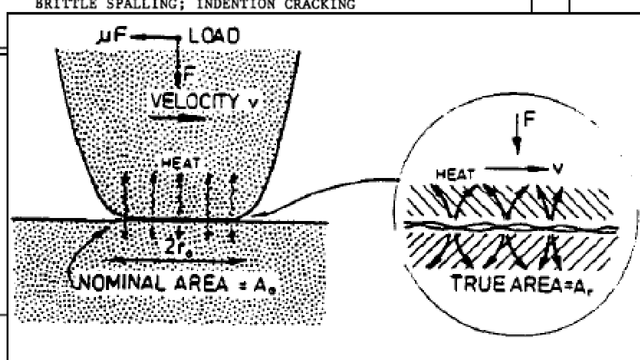
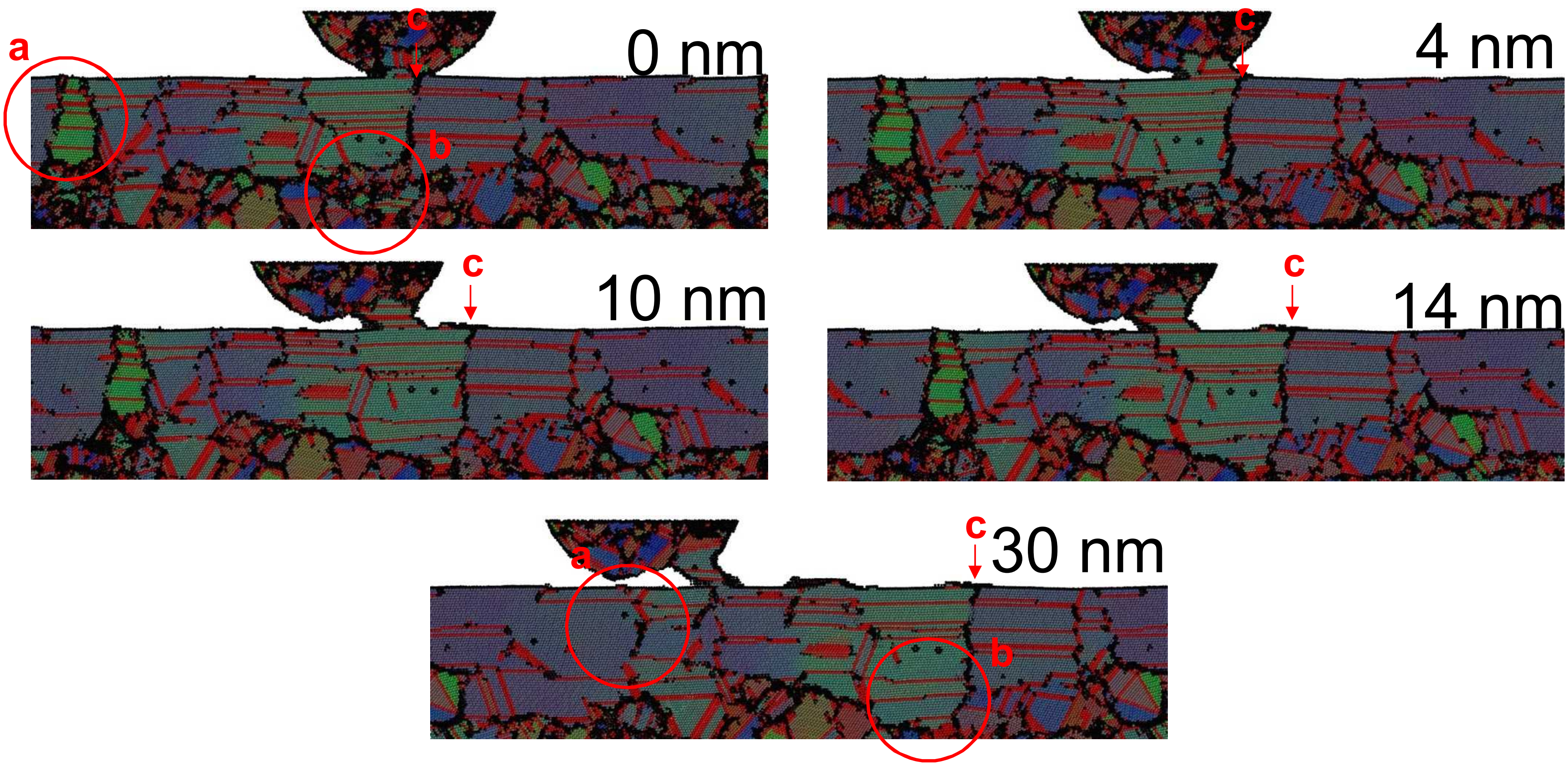


Figure 3. A wear-mechanism map for low-carbon steel based on physical modelling calibrated to experiments. The shaded regions show transitions.

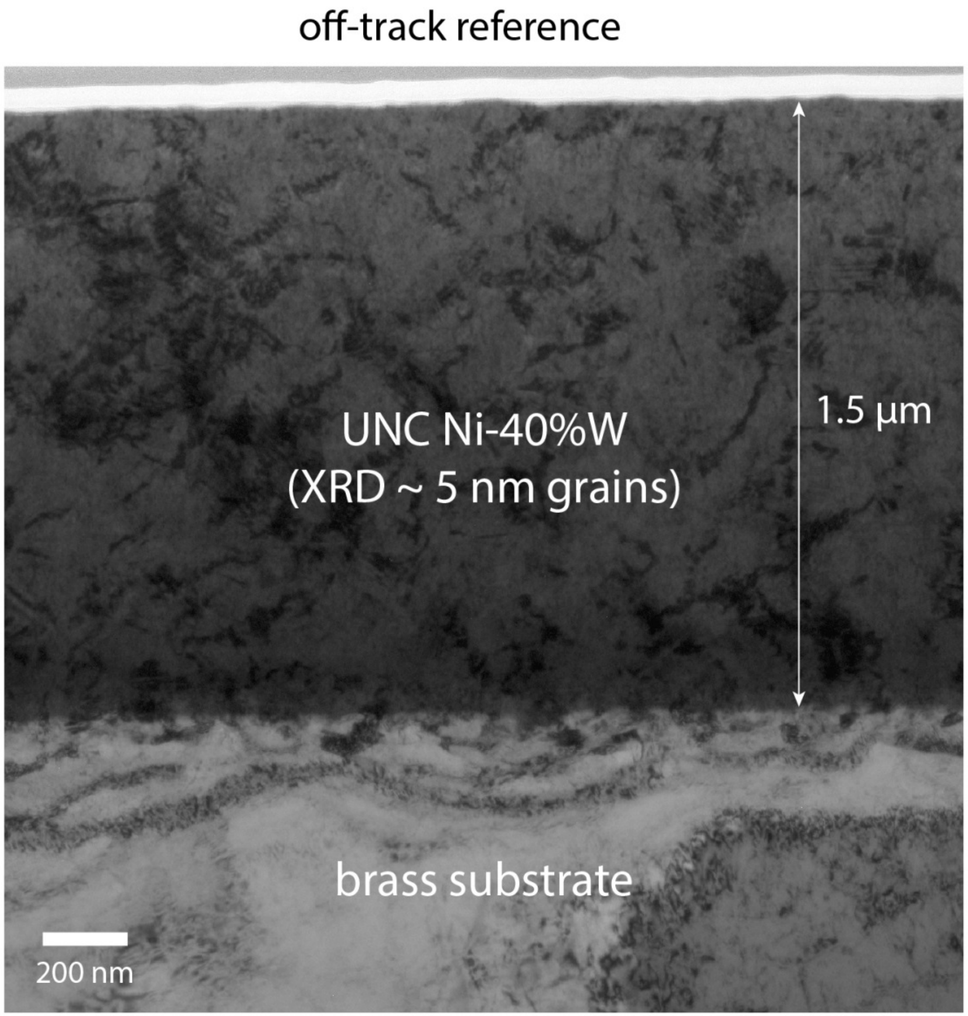


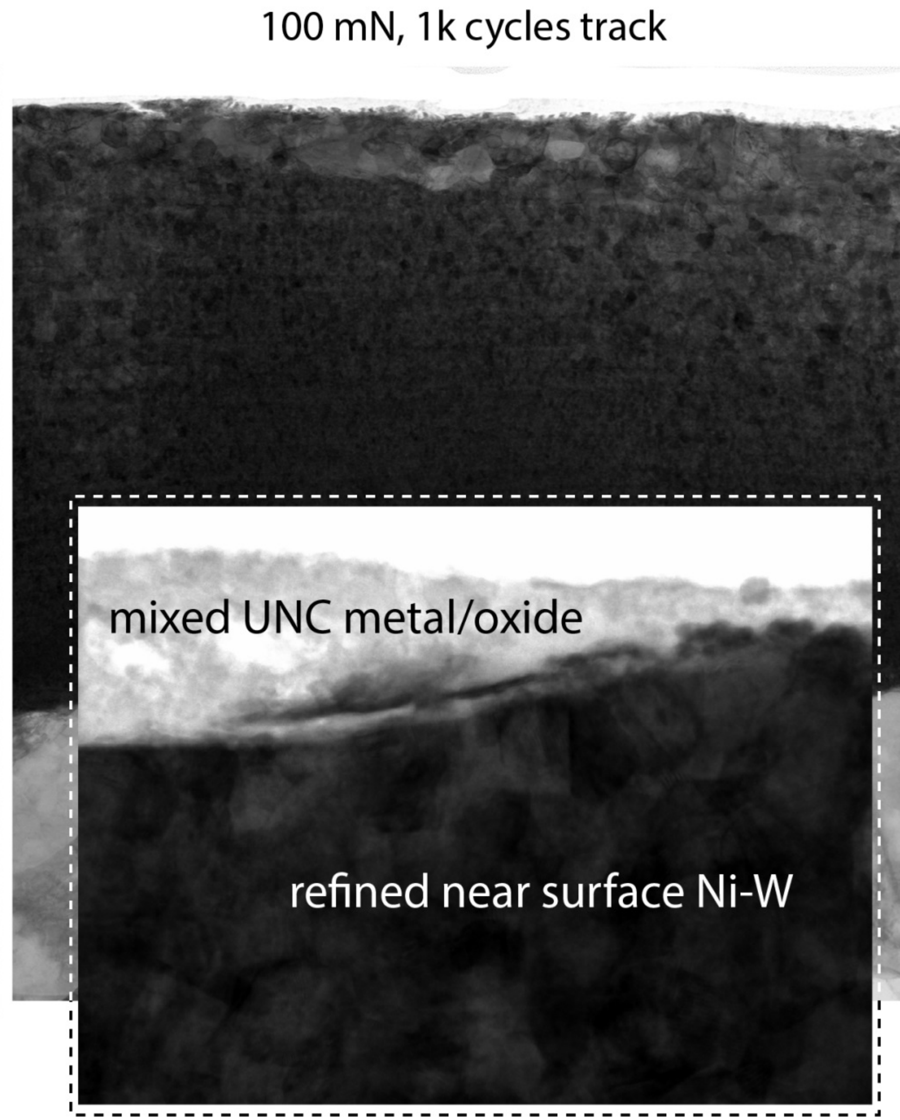
Another look, now at pure Au tip/slab contact evolution over a longer sliding time



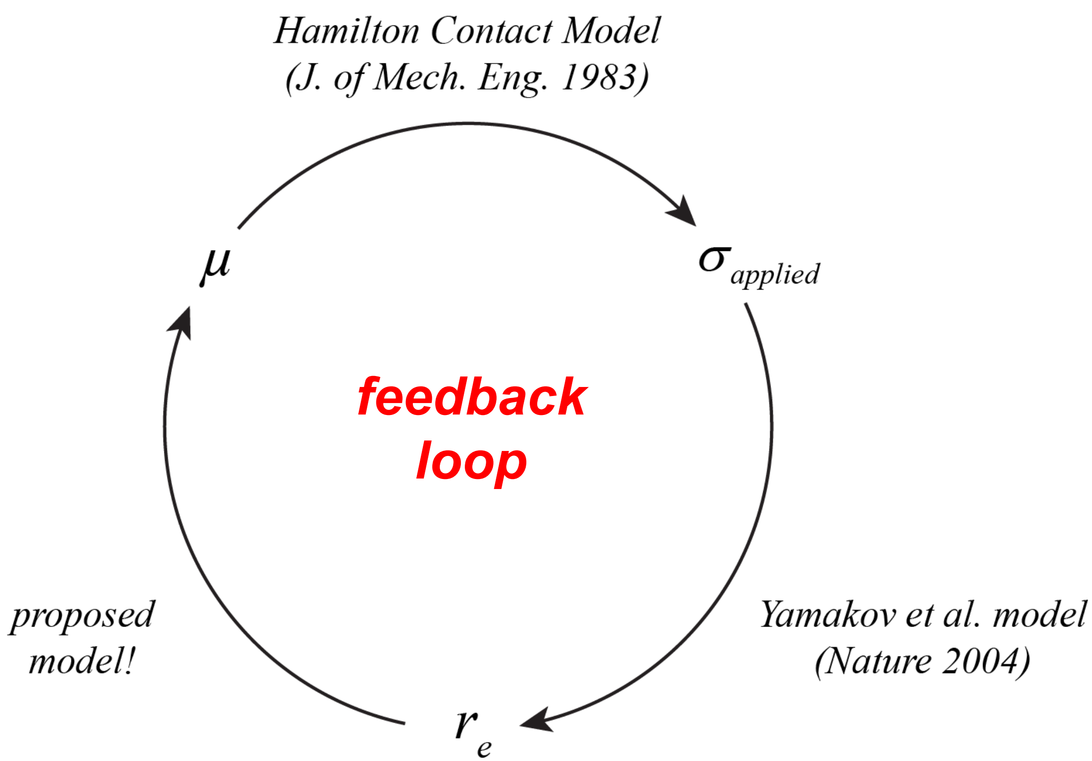
- Initially distinct grains
- After shear (adhesive load), coalescence – now a mode II crack
- Single grain forms across interface – stress induced grain growth

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





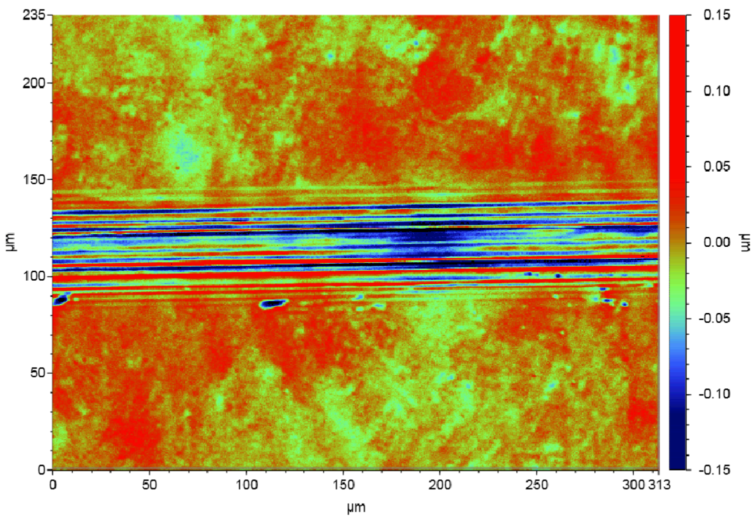
Can Now Complete the Circle



- Numerical correlation between applied stress, steady-state surface grain size and friction coefficient.
- Stable grain size determination based exclusively on materials parameters.

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:



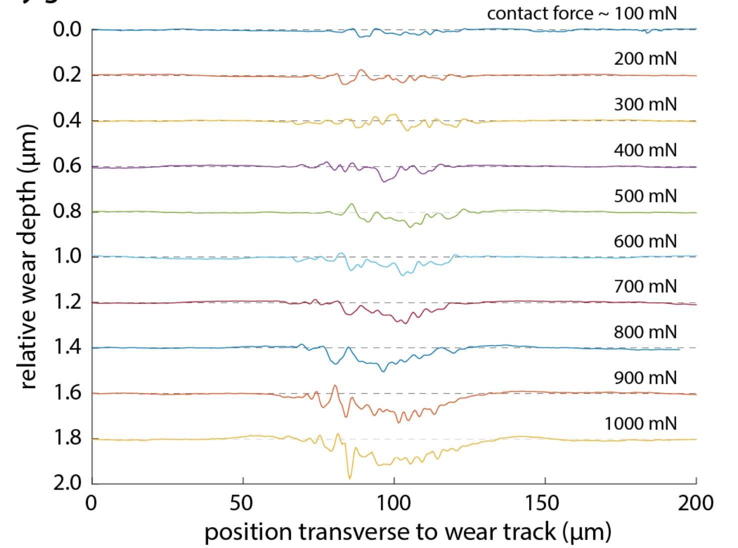
Images taken at 1 mm intervals along 10 mm long wear tracks

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

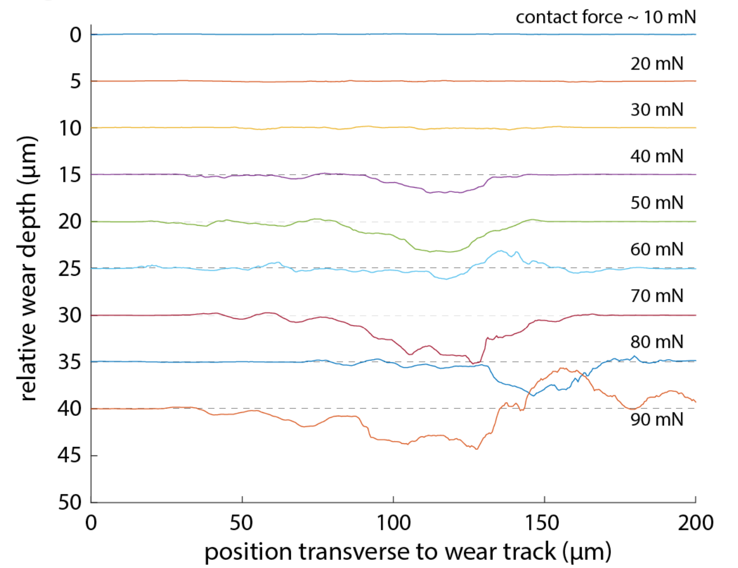
Wear at each interval calculated based on contact force average in this part of the track, number of cycles, and volume loss

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

alloy gold film surface evolution

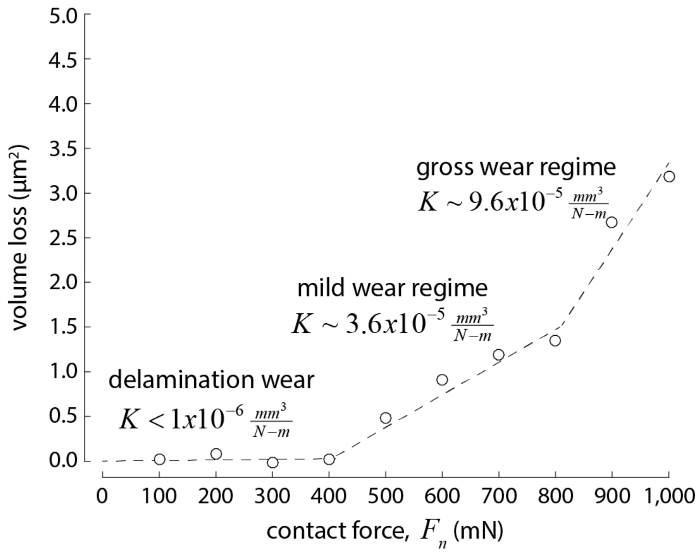


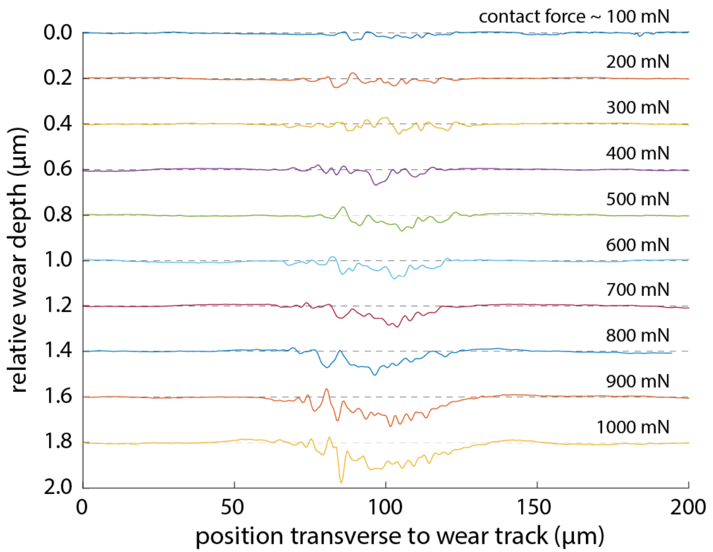
pure gold substrate surface evolution



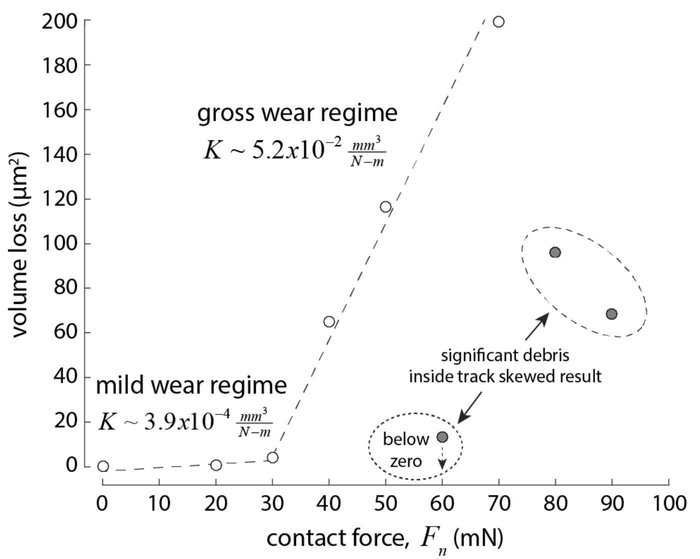
Observed three wear regimes

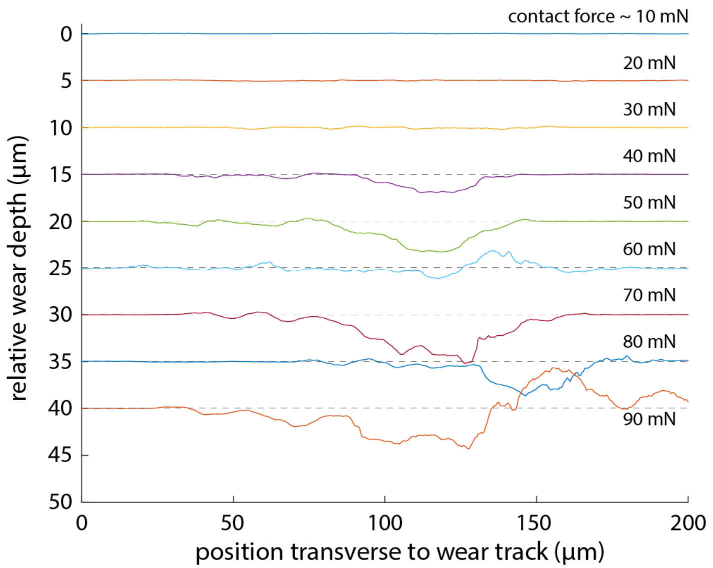
alloy gold film surface evolution





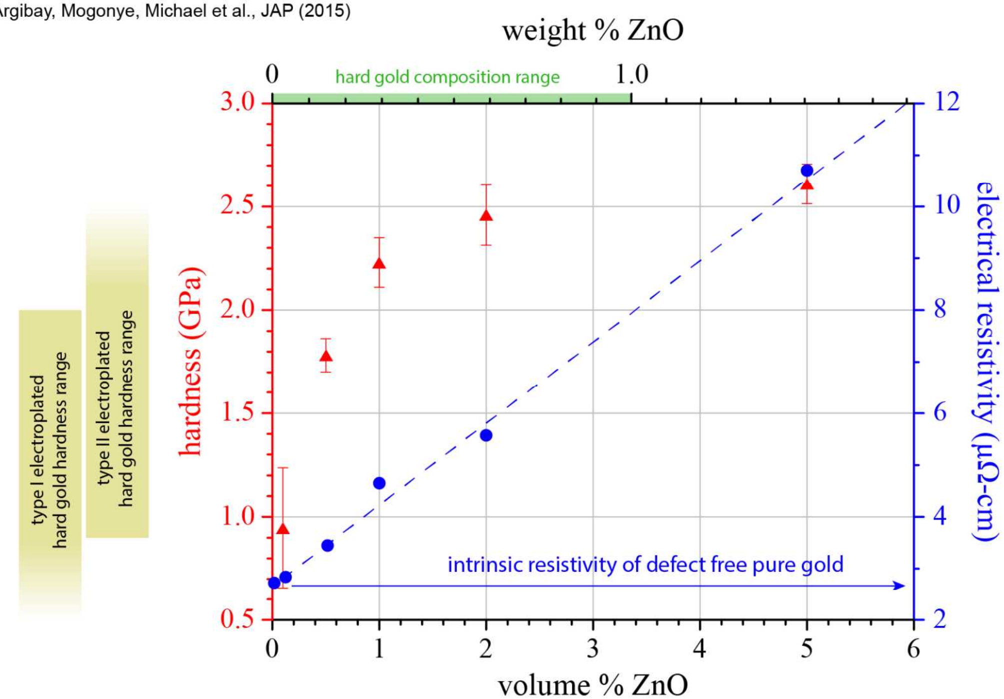
pure gold substrate surface evolution





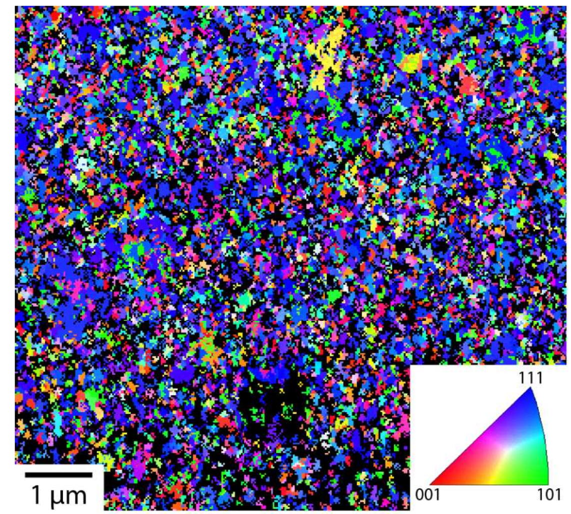
Recently published work showed oxide nanoparticles work just as well as Ni or Co

ref 1: Argibay, Prasad, Dugger, et al., Wear (2013)
ref 2: Argibay, Mogonye, Michael et al., JAP (2015)



Film surface-normal EBSD mapping:

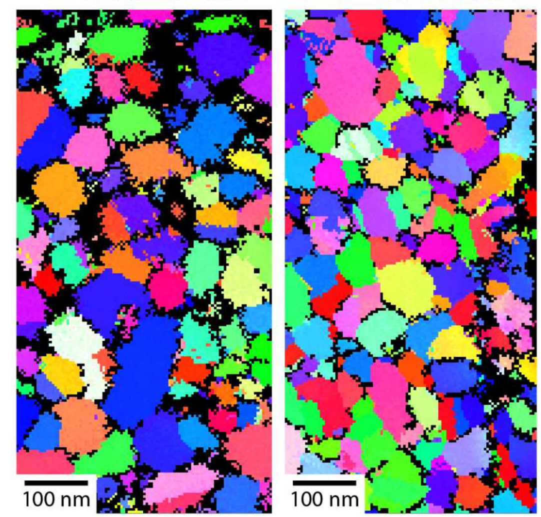
0.1 vol. % ZnO film



Transmission Kikuchi diffraction:

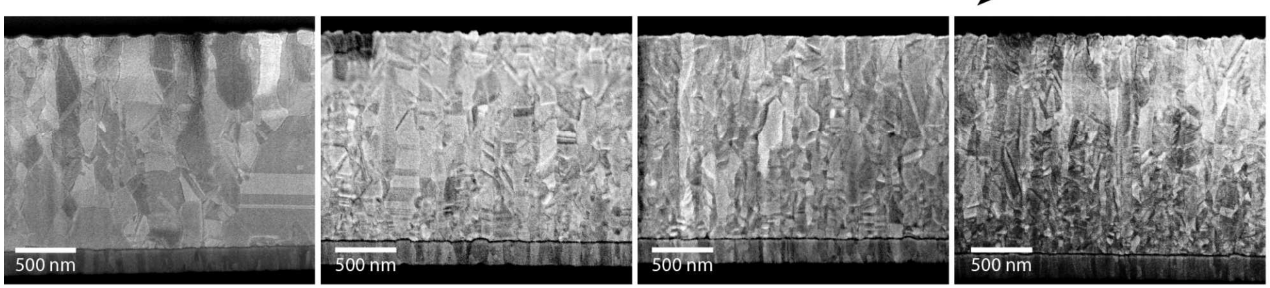
1.0 vol. % ZnO film

2.0 vol. % ZnO film



SEM of FIB milled and etched cross-sectional views:

Increasing ZnO concentration



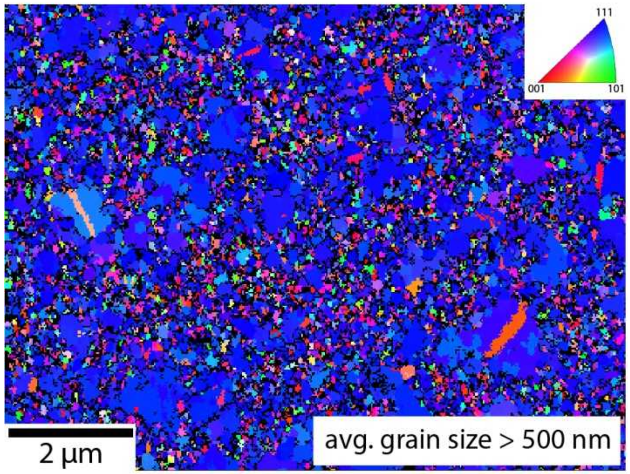
0.1 vol. % ZnO film | 0.5 vol. % ZnO film | 1.0 vol. % ZnO film | 2.0 vol. % ZnO film

Stable NC grain size can be achieved using non-metals

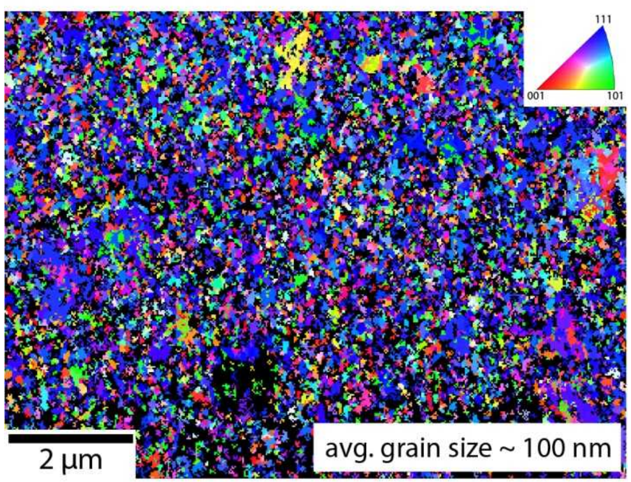
refs: Argibay et al. JAP (2015) and Argibay et al. Wear (2013)

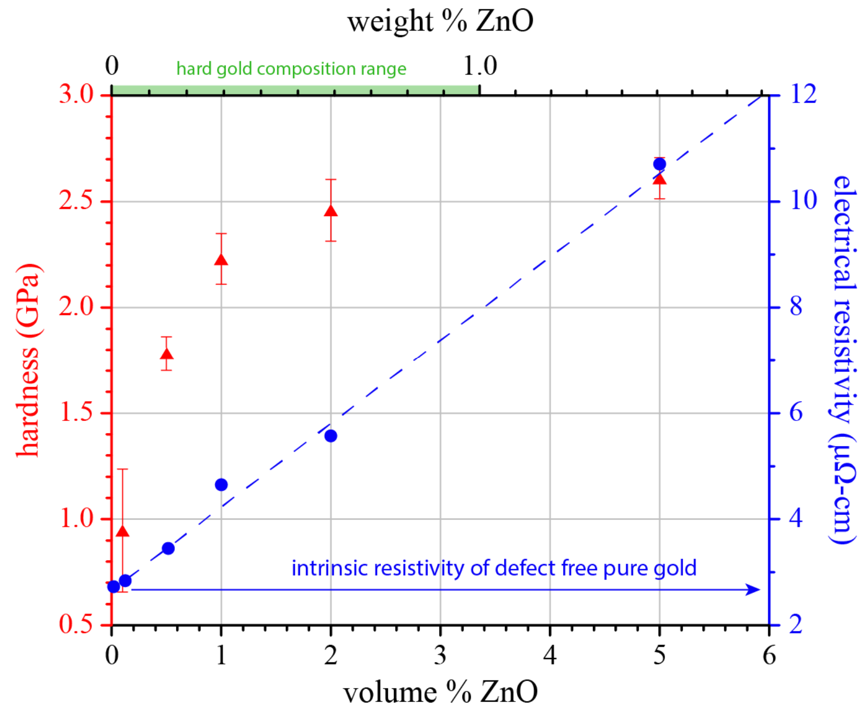
Surface-normal (planar) EBSD maps of e-beam deposited films:

pure Au film

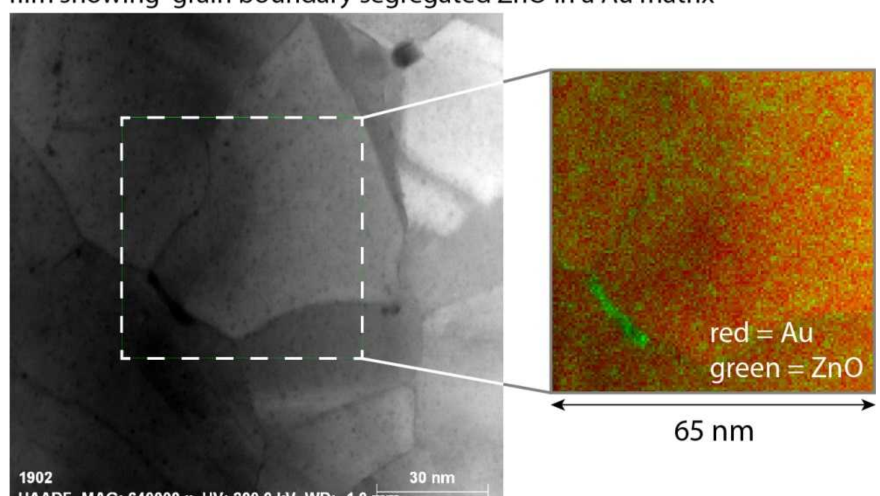


Au film with 0.1 vol. % ZnO

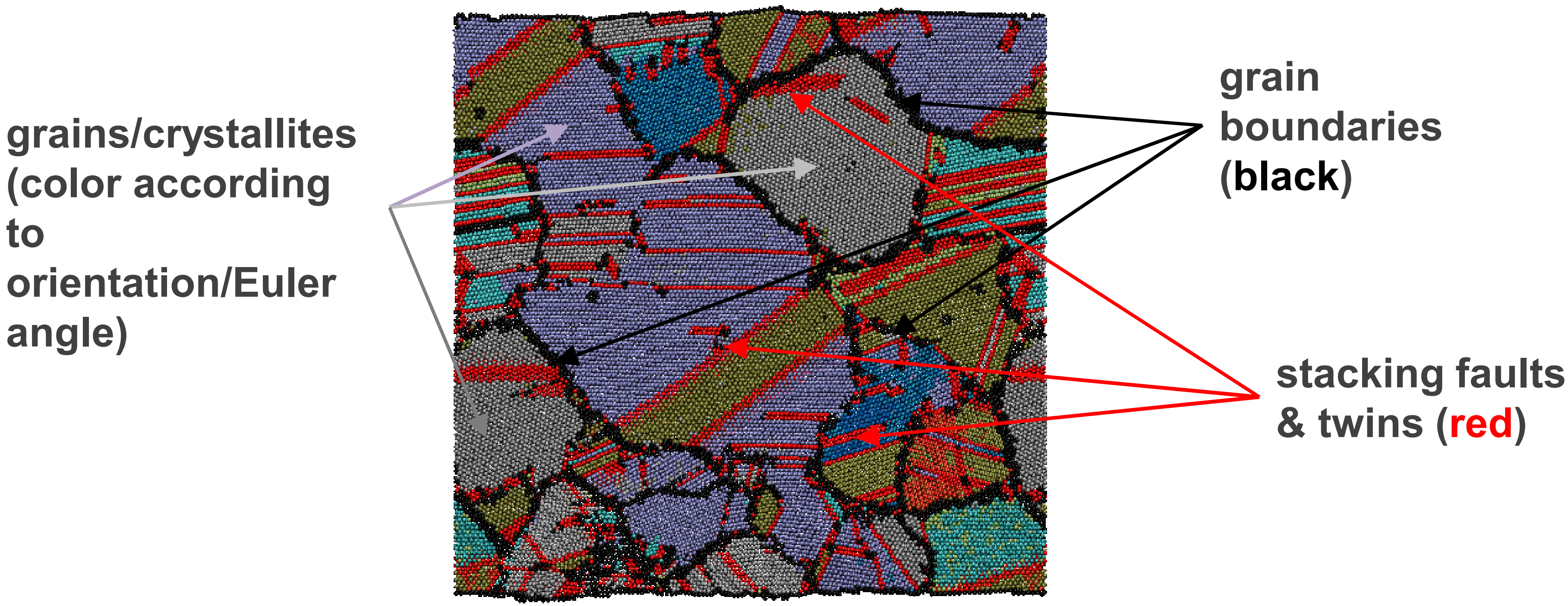




Cross-sectional composition map of a Au- 5 vol. % ZnO film showing grain boundary segregated ZnO in a Au matrix

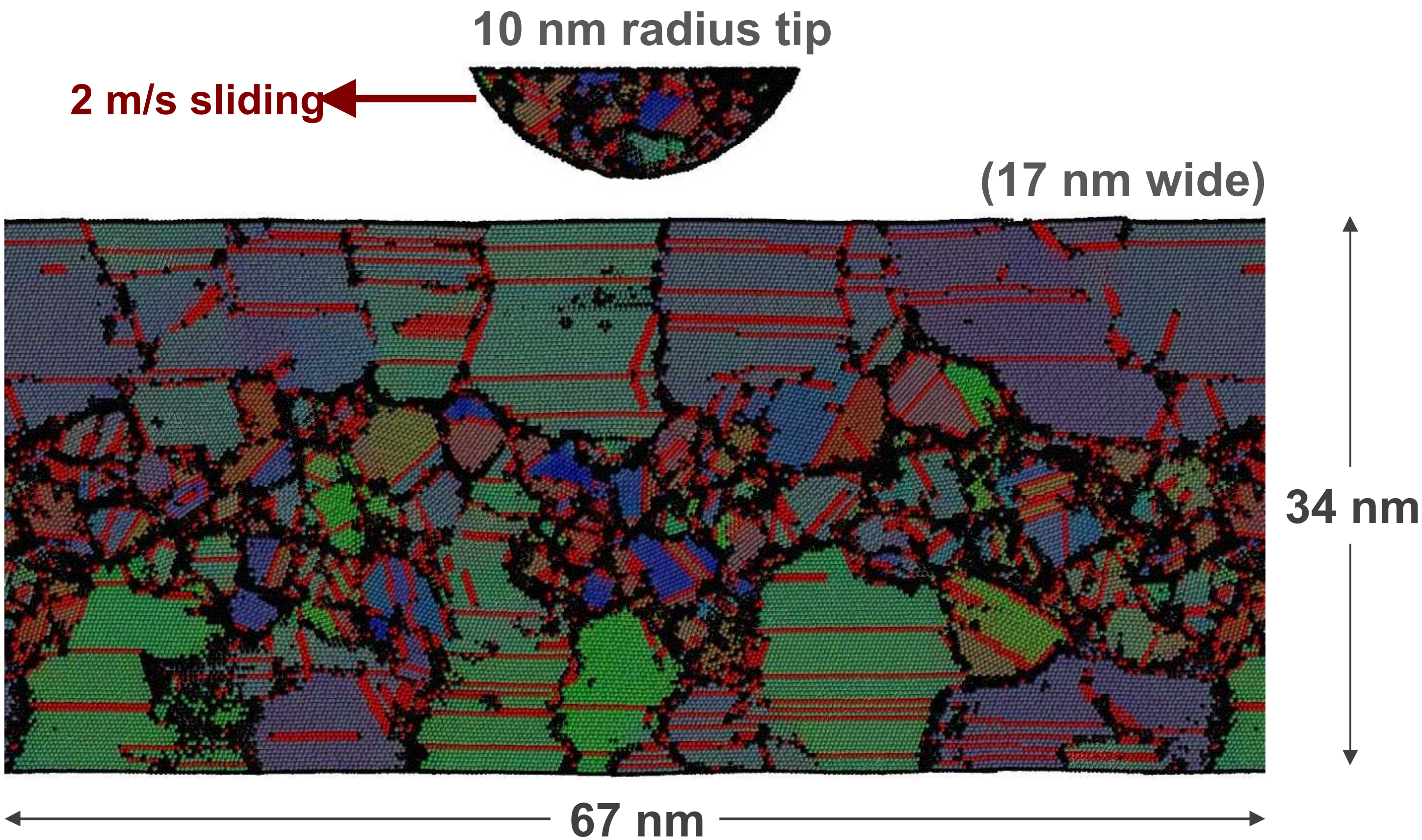


Cross-sectional slices of a 3D space filled with atoms



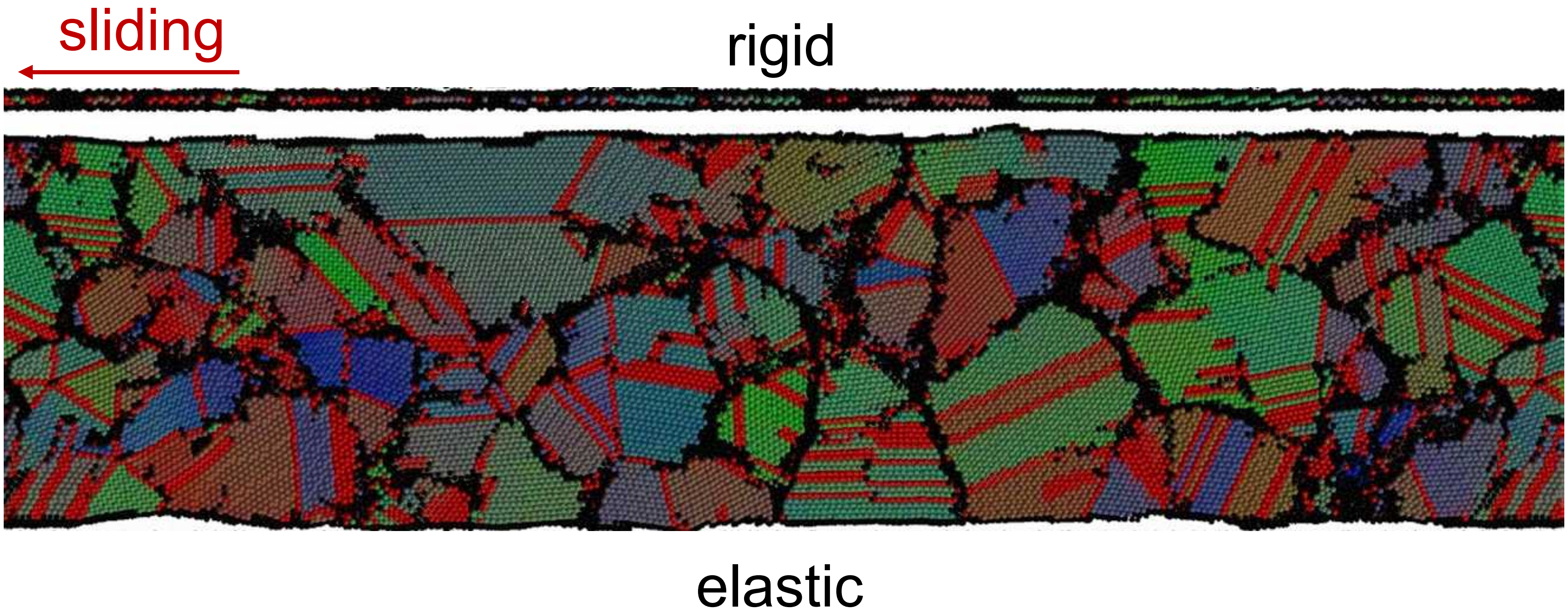
- Locally FCC atoms colored according to Euler angle
- Locally HCP atoms colored red – twins & stacking faults
- Otherwise colored black – grain boundaries

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



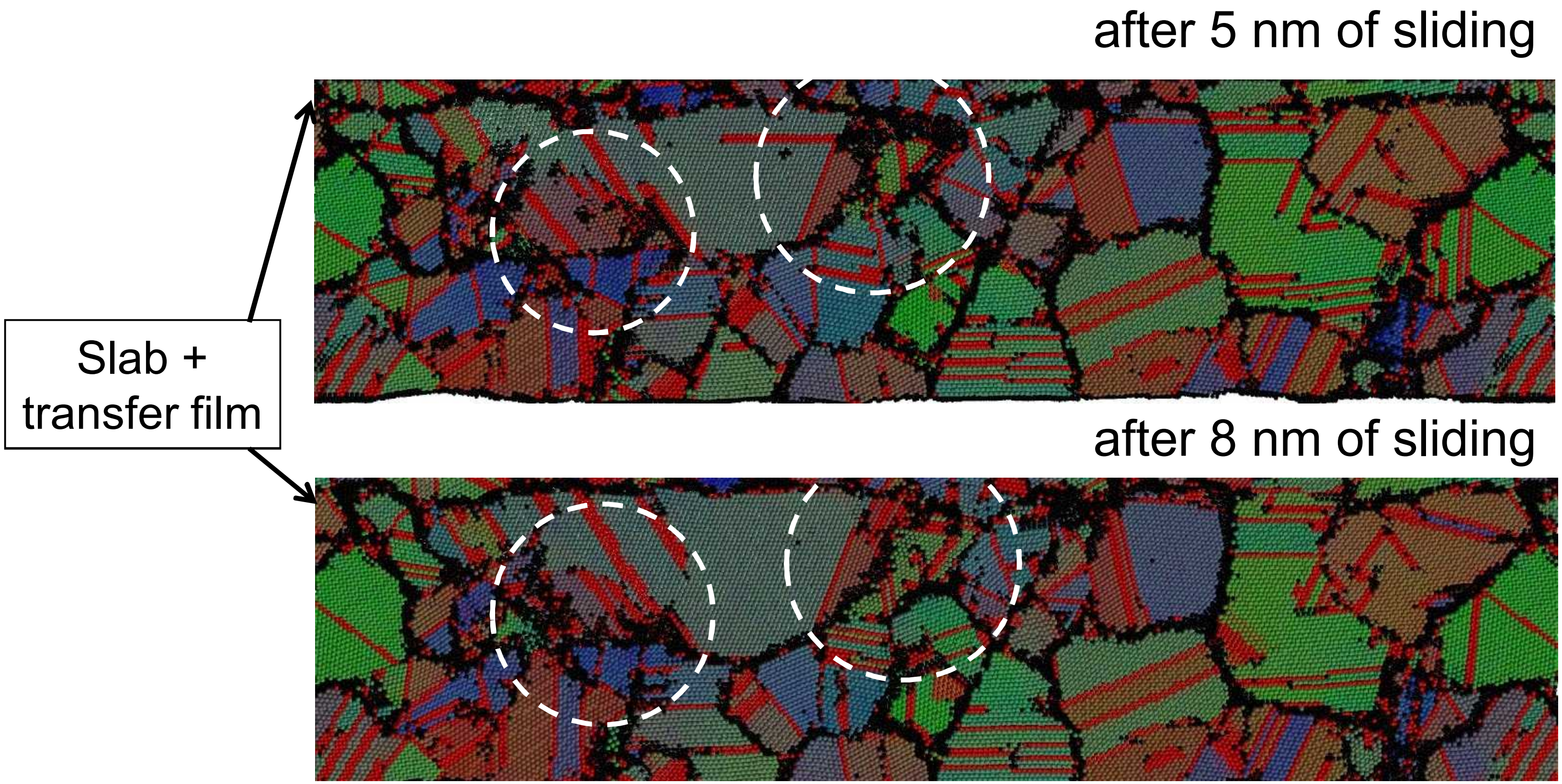
Substrate: nanocrystalline Ag
Constraint 1: constant velocity
Constraint 2: constant separation ***or*** normal force

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



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

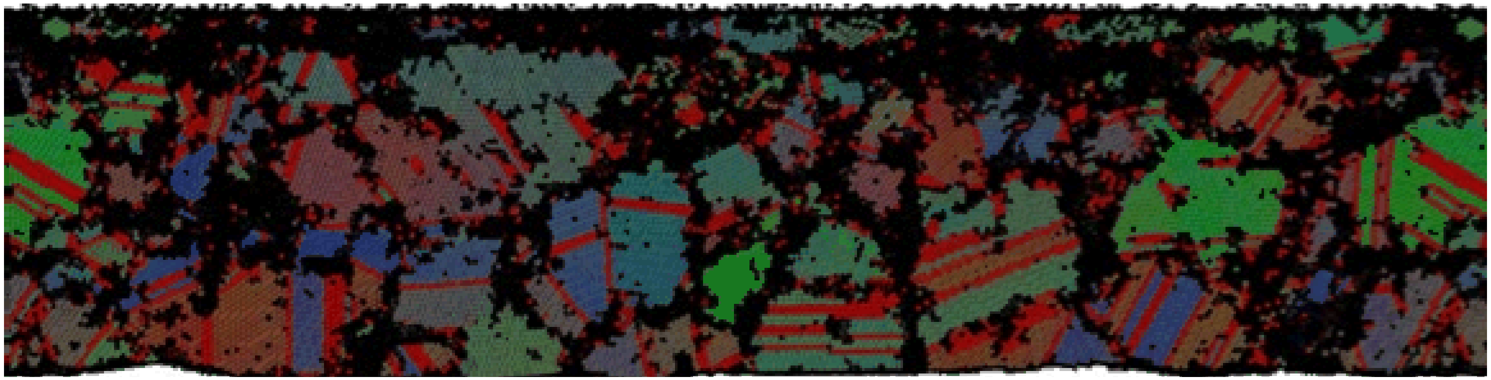
Sliding of pure Ag slabs



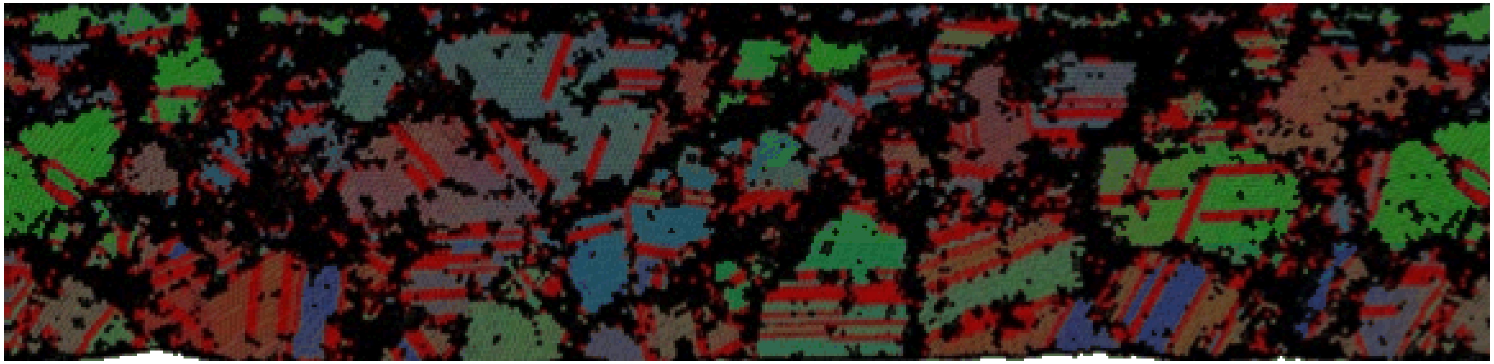
- Slight grain growth, forms transfer film
- Slides along transfer film grain boundaries or nearby stacking faults depending on availability

Sliding of Ag alloy (10% Cu) contact

after 6 nm of sliding



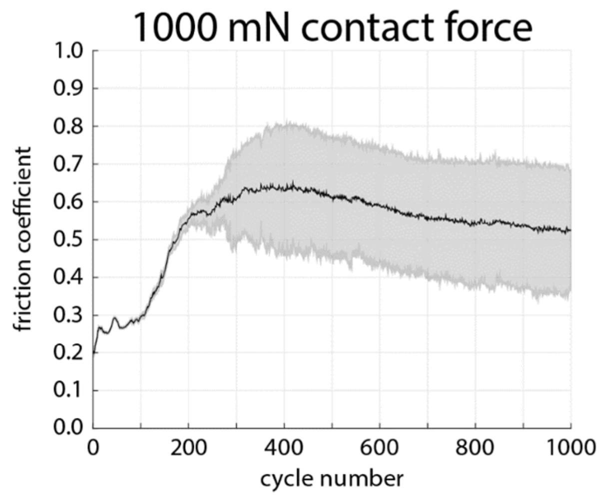
after 16 nm of sliding

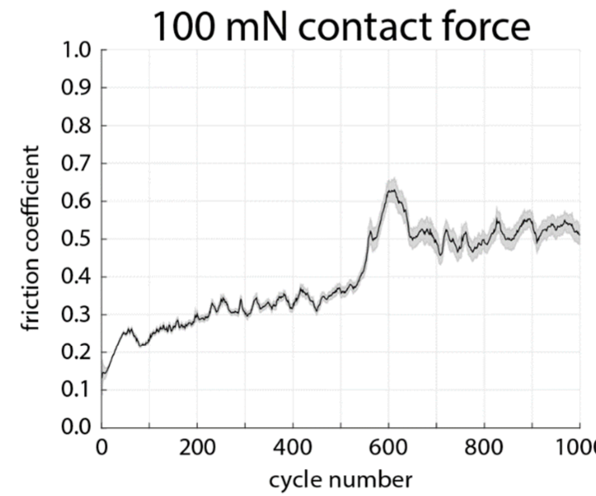


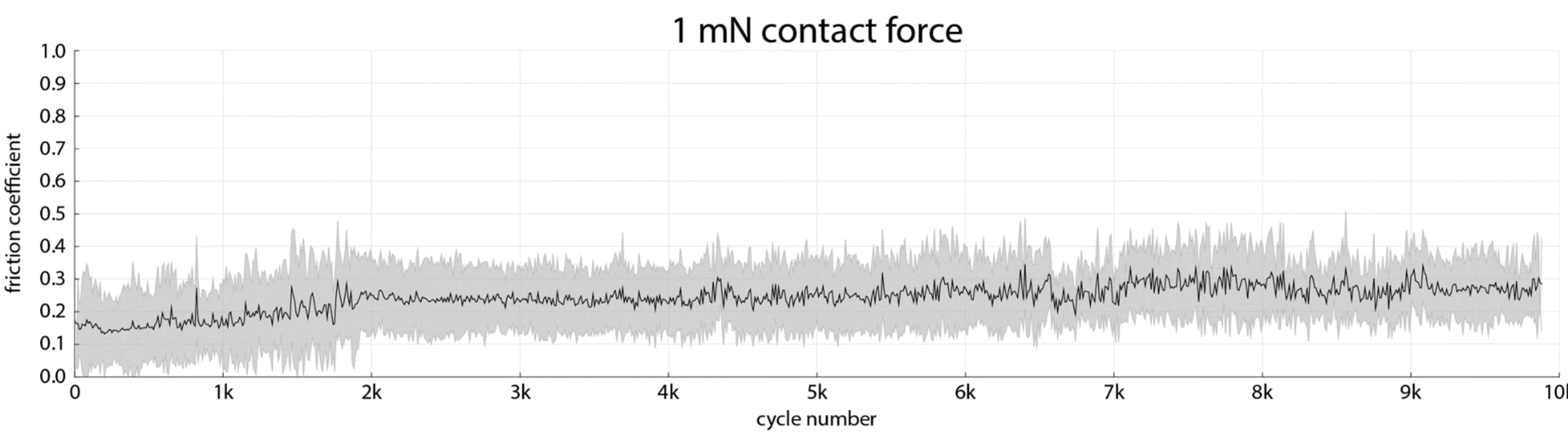
- Alloy slides at transfer film boundary, but also throughout substrate
- The pure Ag slabs on previous slide started with the exact same microstructure (lots of coarsening on the pure Ag slabs simulation!)

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

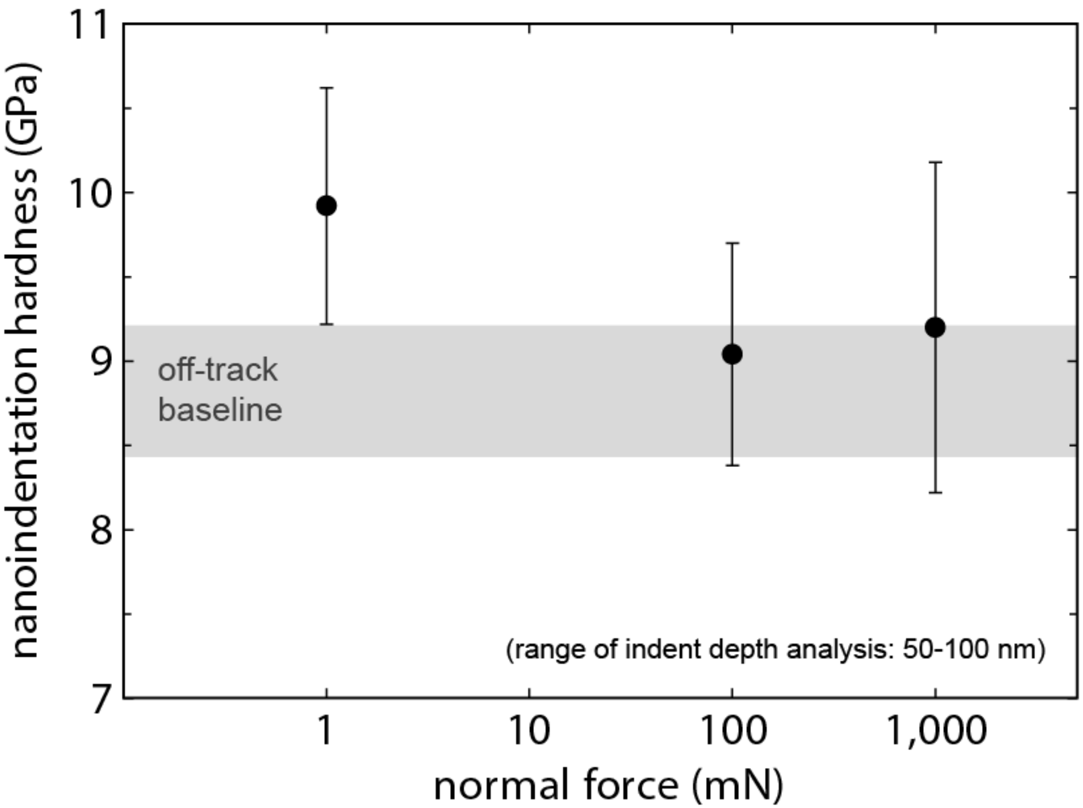
1 mm/s sliding speed
three contact forces used
bidirectional sliding
2mm long track
sapphire ball 1.6 mm diameter
sliding in ***lab air***







Ni-40 wt. % W hardness data



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

Regular Nanocrystalline Solution (RNS) model

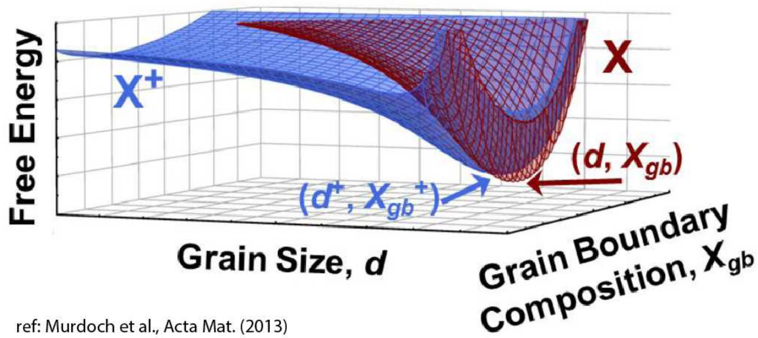
ref: Chookajorn et al., Science, 2012

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

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

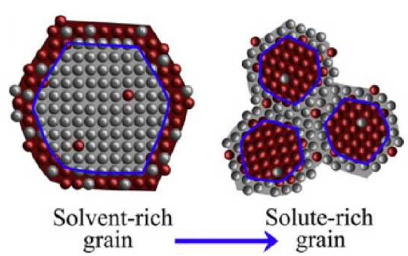
Implications:
Will not drive toward fine grain size, but will remain there

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:



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

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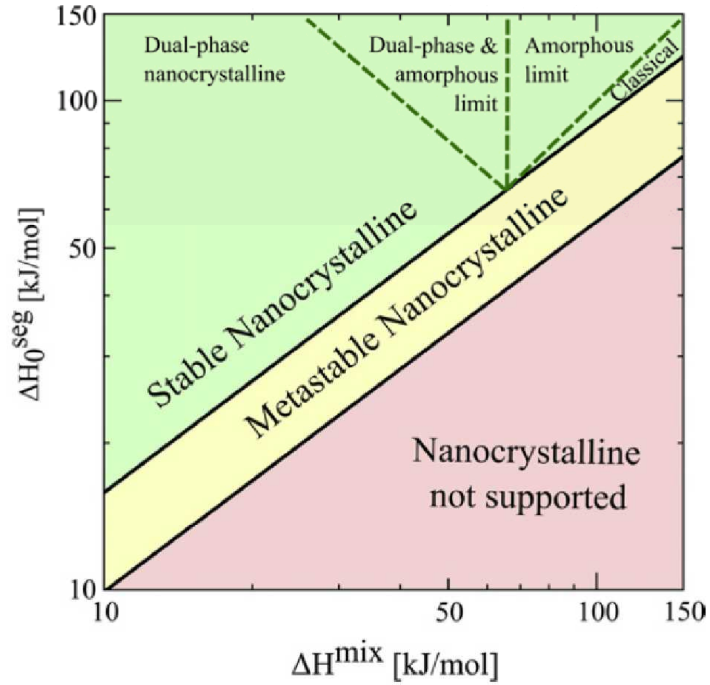
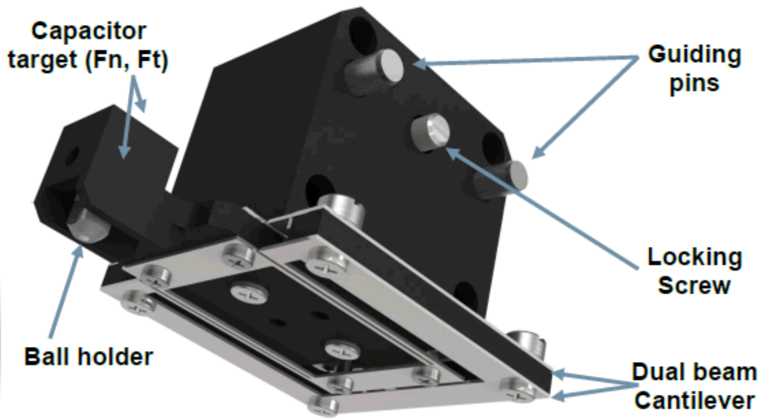


$$\Delta H_{o}^{seg} = z\left(\omega_{c} - \frac{\omega_{gb}}{2}\right) \qquad \Delta H^{mix} = z\omega_{c}X(1-X)$$

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

Modified CSM Nanotribometer – friction and wear testing platform

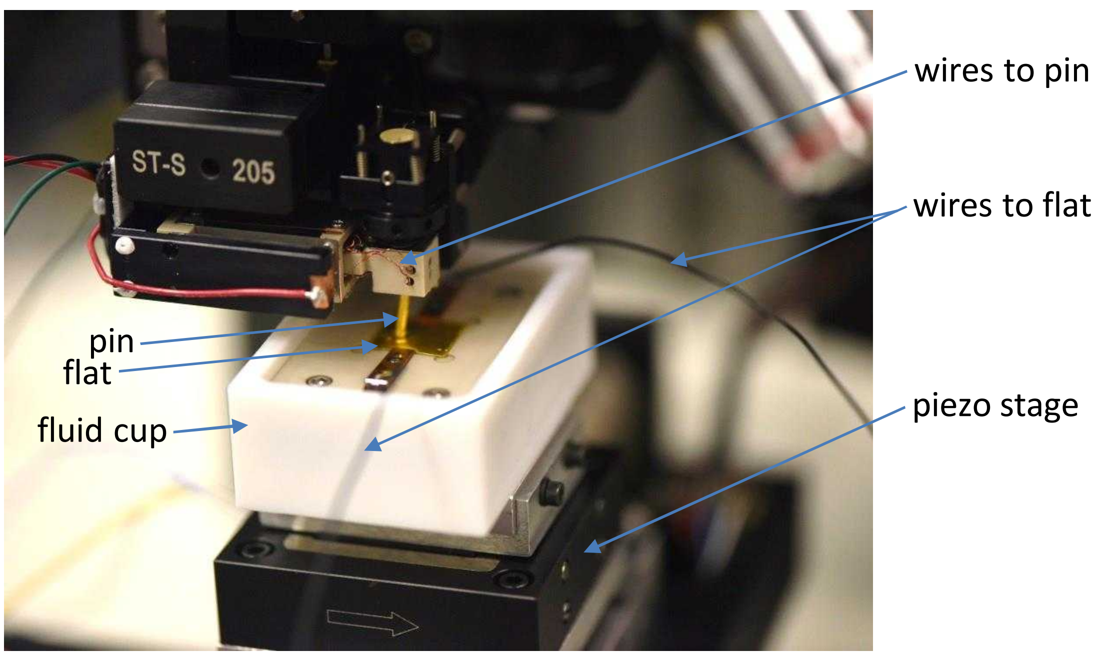


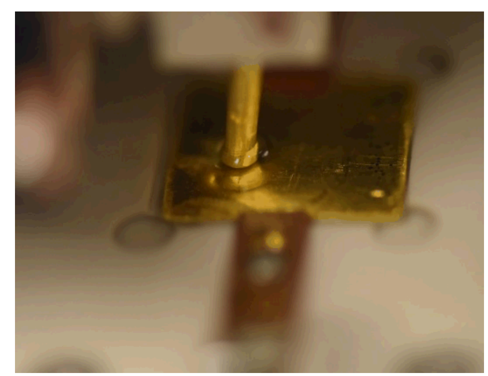
CSM nanotribometer modified for 4-wire ECR measurement

- DC power supply
- nano-ohm meter

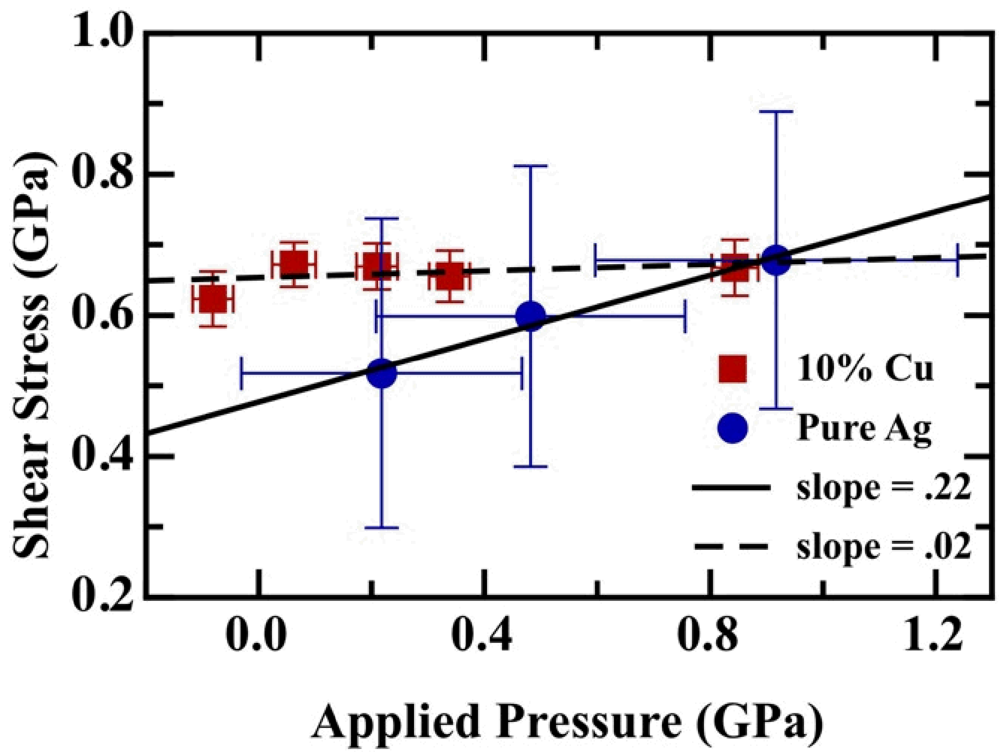
Test parameters:

- 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





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