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Gradient Microstructures in Single Crystals Induced by Sliding Contact (Invited)

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Frictional contact in metallic materials typically results in plastic deformation beneath the wear surfaces

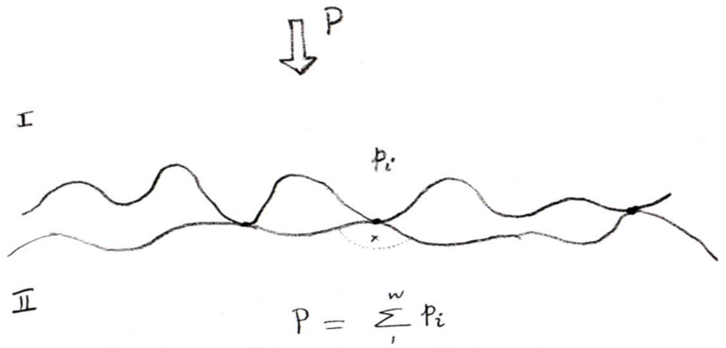
Historical Background

- Sir George Beilby (1900-1921):
  - Top layer of the polished surface *(Glassy)* is different in structure from the underlying metal.
    - Sir George Beilby, *Aggregation and flow of solids; Being the records of an experimental study of the micro-structure and physical properties of solids in various states of aggregation*, Macmillan & co, London, 1921.
  - Controversy on the "Beilby" layer persisted for a few decades, mainly due to limitations with XRD to characterize the near surface layers, until the advent of electron diffraction, G. P. Thompson, *Proc. Roy. Soc*. A128 (1930) 649.

- TEM and ED studied in the late 1930's on Au films revealed diffuse rings, which confirmed the existence of very fine crystal grains in the polished layer.
    - W. Cochrane, *Proc. Roy. Soc*. A160 (1938) 228.

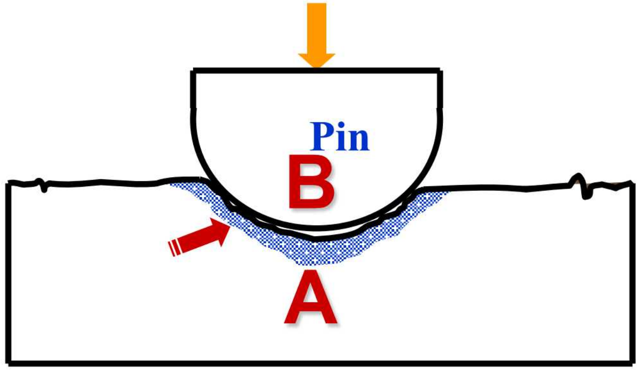
- This concept has found widespread applications, raging from honing in internal combustion engines to metal forming operations, including ECAP.

Engineering surfaces are not flat



Contact will be at asperity level

Archard, J. F. J. Appl. Phys. ***24*** *(1953) 981*
Holm, R. Electrical Contacts (Springer, 1946)

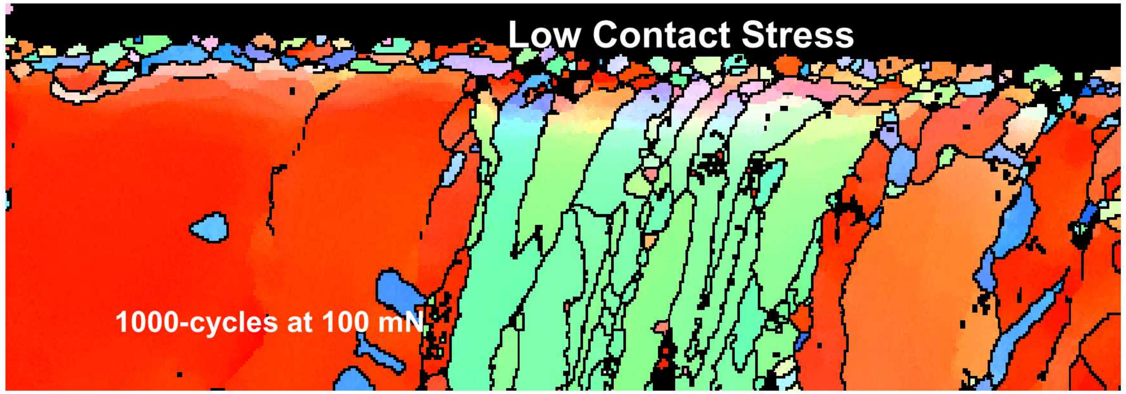


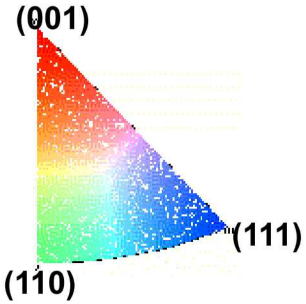
•Plastic deformation
•Diffusion
•Fracture initiation
•Tribochemistry and Environmental Reactions

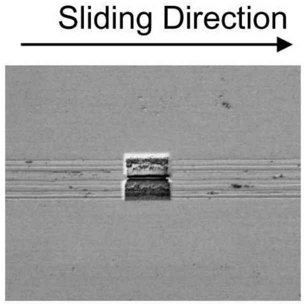
Rigney, D.A., Hirth, J.P. Wear ***53*** *(1979) 345*

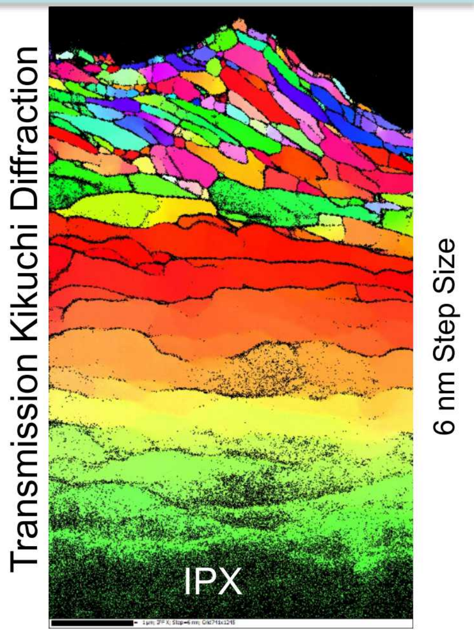
Modern Tools (FIB, Orientation Imaging, TEM) can provide a wealth of Information

Cross-sections of wear surfaces on Eletroformed Nickel

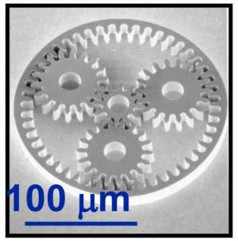


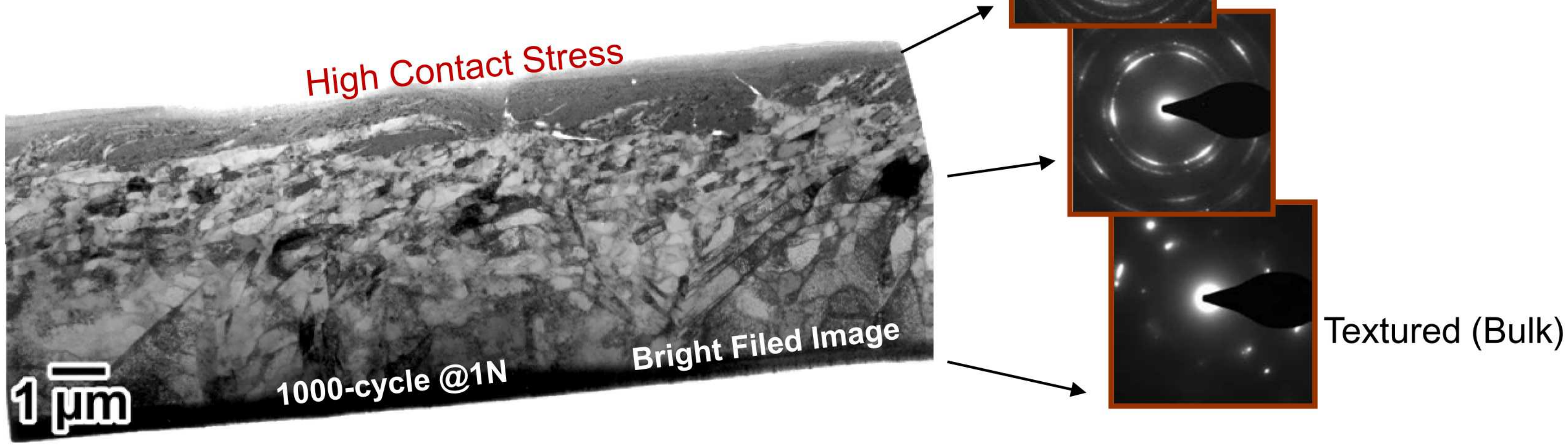


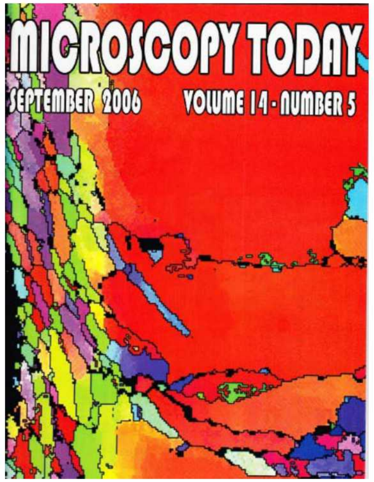




- Bending of columns in the direction of sliding
- More deformation in (110) columns, compared with (001)
- Top surface layer with equiaxed grains (recrystallized)



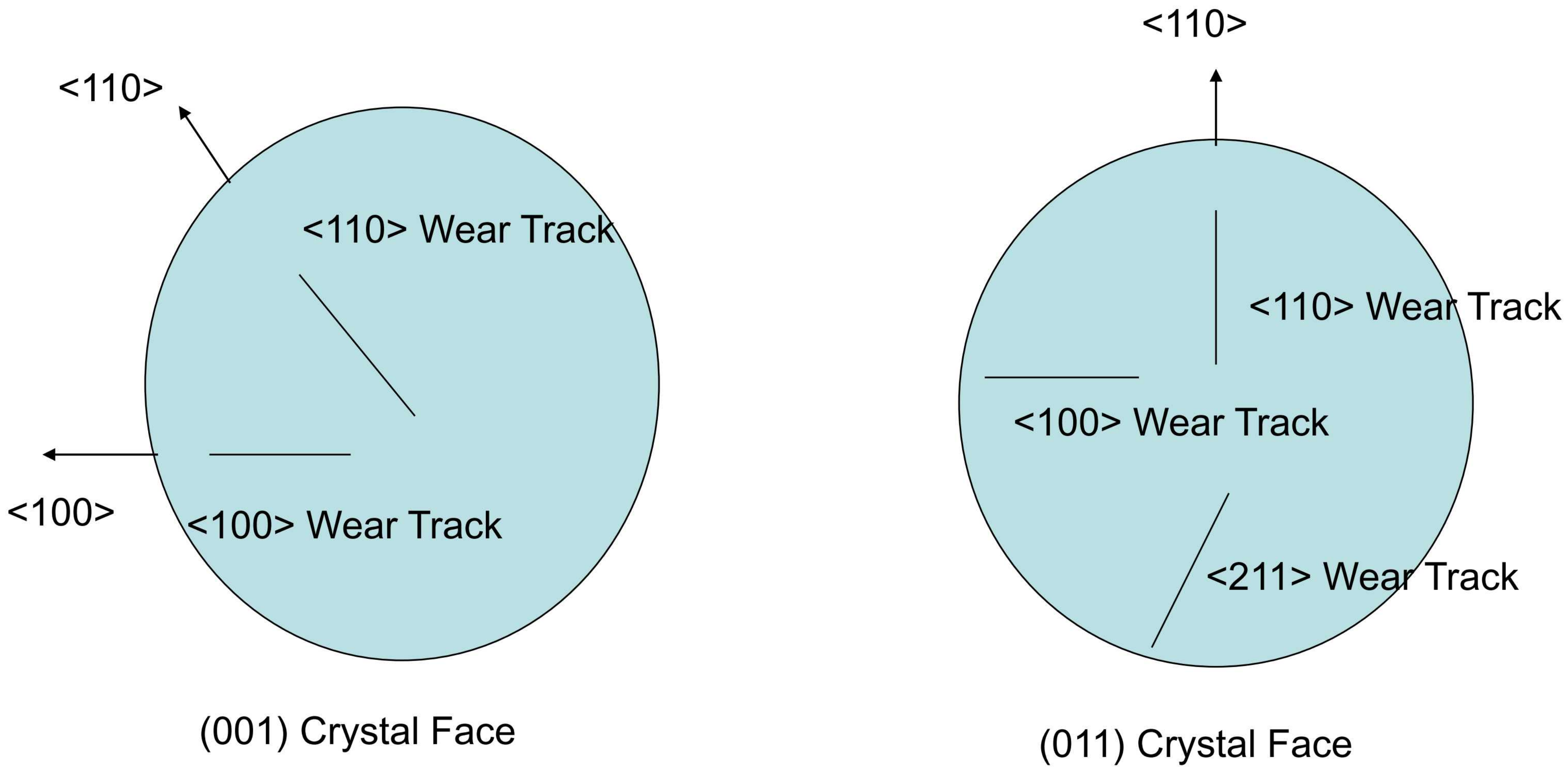




An understanding of the seminal work, dating back to Sir George Beilby and others in England, coupled with our recent work at the turn of this century, led us to investigate friction-induced deformation on single crystals.

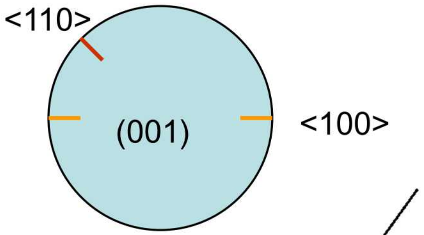
- EBSD and FIB to identify the crystallographic directions (Ni Crystal)
- Rotary friction module to make friction measurements on specific crystal faces along different crystallographic directions
- Analysis of friction induced structures by EBSD and TEM
- Application of this work to the tribology of nanocrystalline thin films

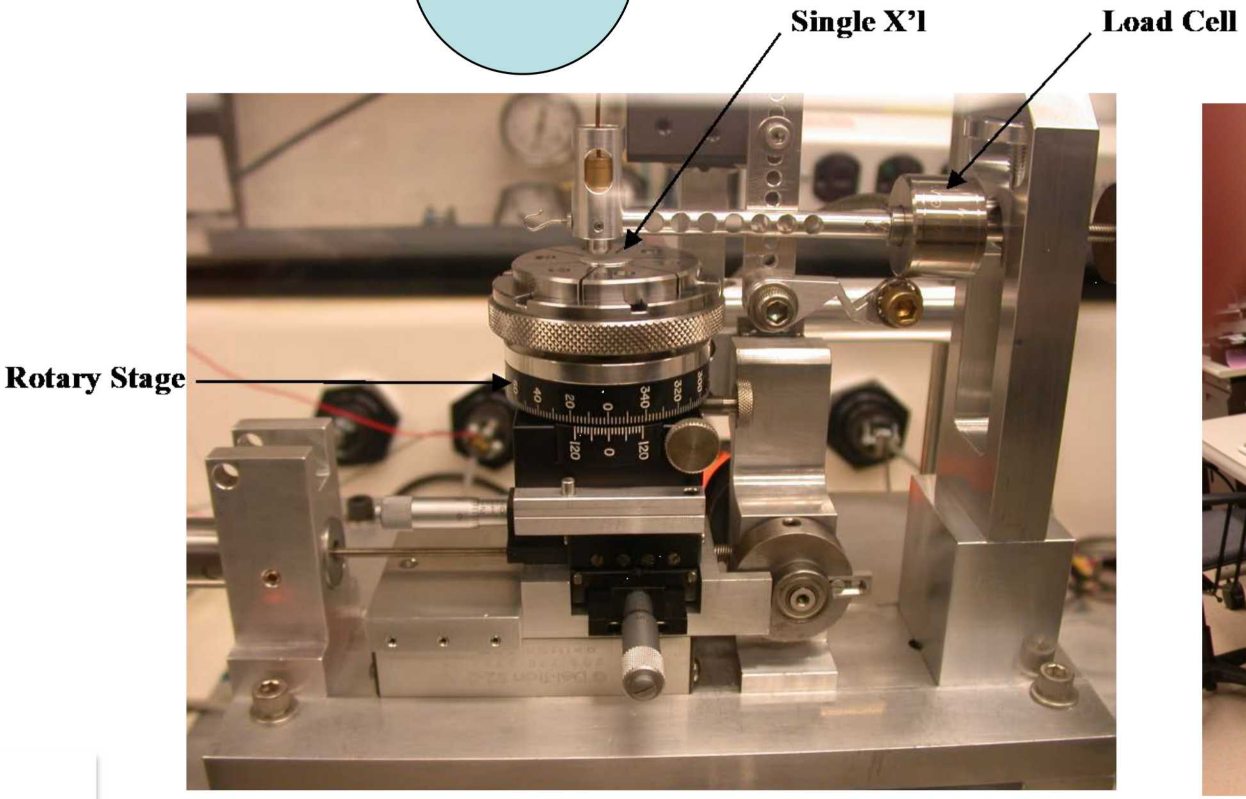
Crystallographic configurations for friction testing on single crystal Ni

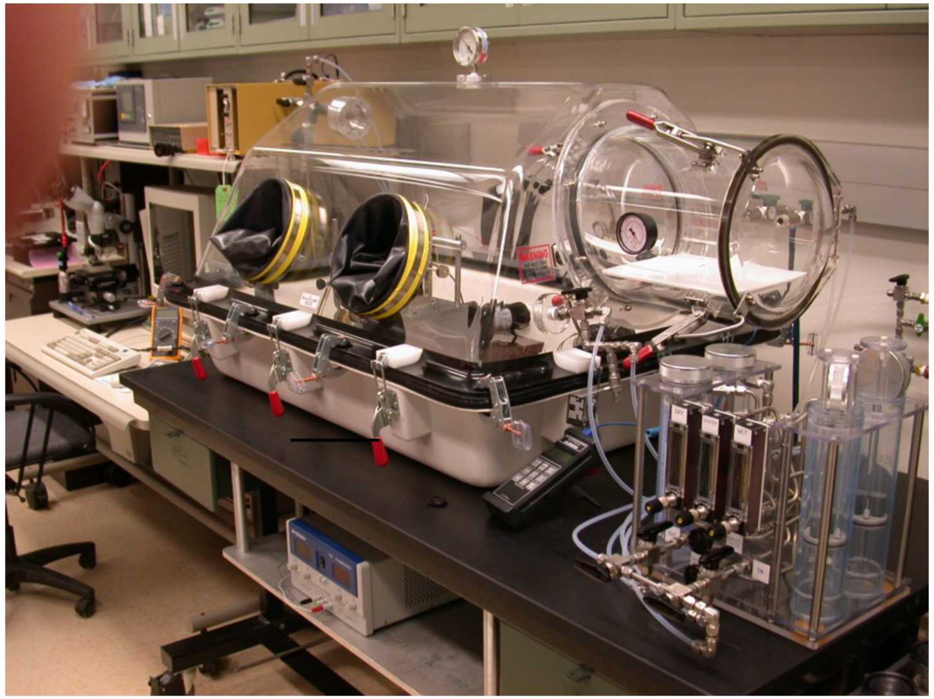


Identified the crystallographic directions with EBSD and marked with FIB

Rotary Friction Test Module Designed and Fabricated



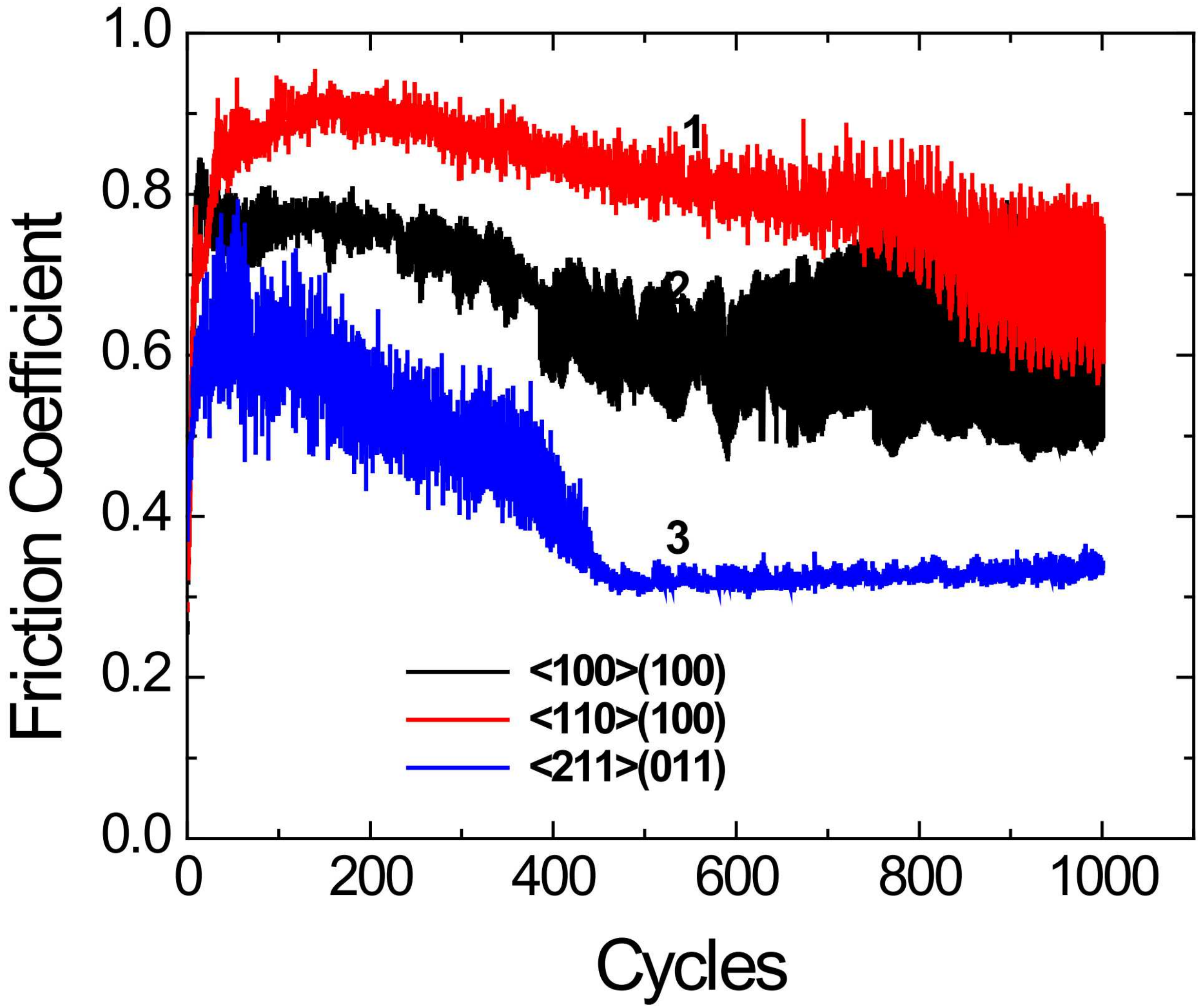




Rotary Stage for Single Crystal Alignment

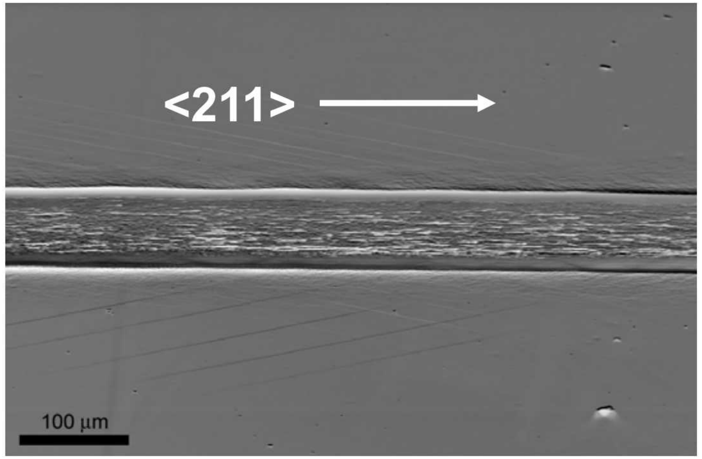
Environmental chamber

Friction behavior is dependent on crystallographic orientations

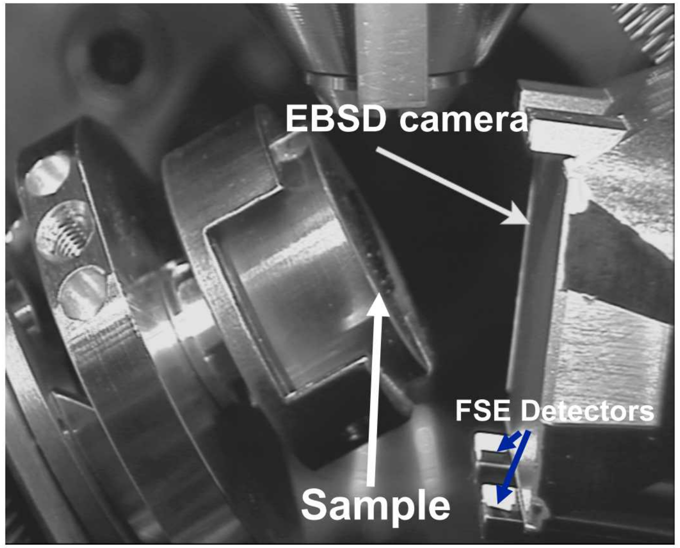


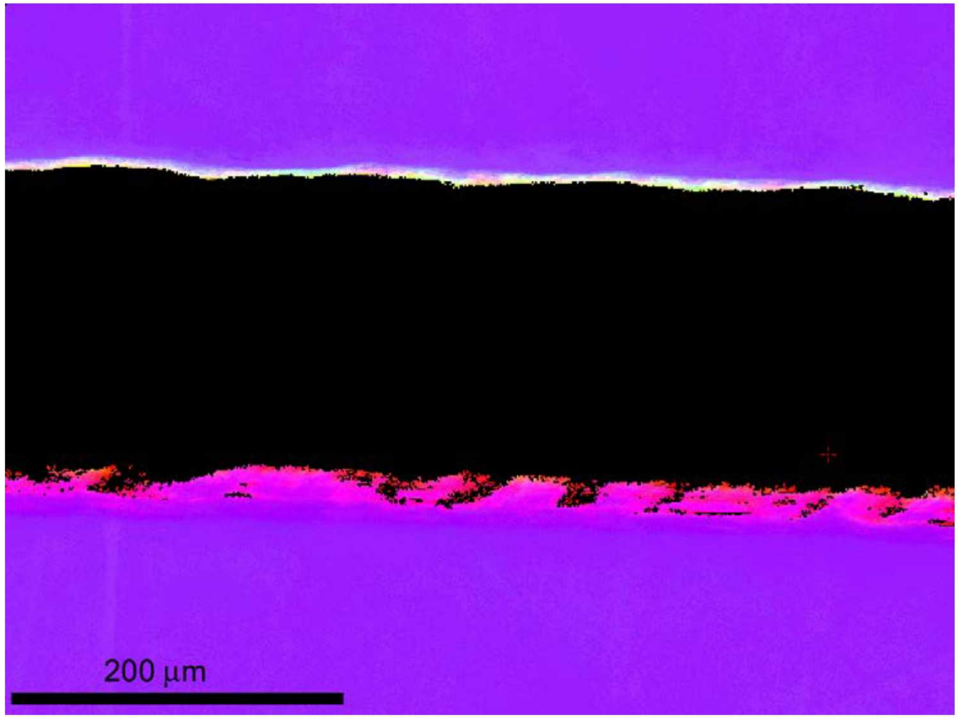
Normal load: 100 mN
Counterface: 1/8” Si_3N_4 Ball

SEM imaging (FSE) and EBSD of wear scars in plan-view provided partial information

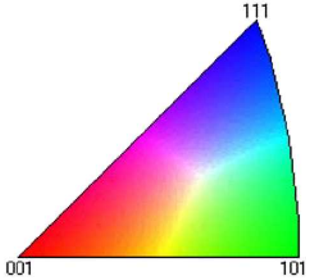


SEM image of forward scattered electrons (FSE). Note visibility of {111} slip traces. (Image not corrected for 70º tilt.)

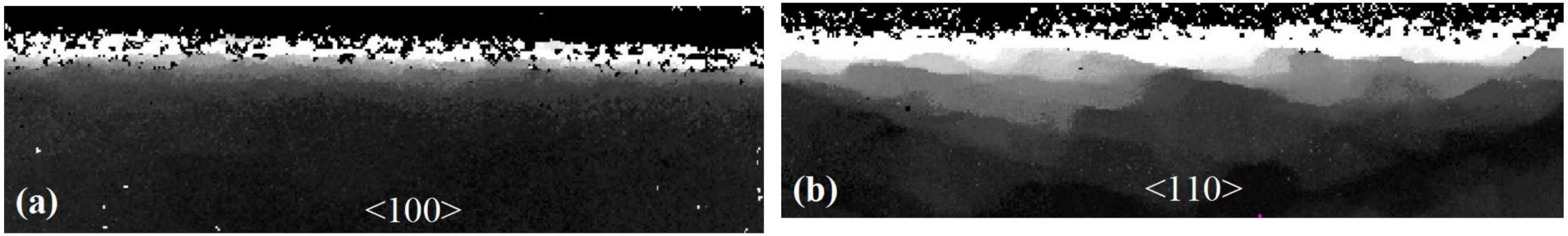




EBSD IPF map with respect to the sliding direction. Note dark region due to high plastic deformation in wear scar

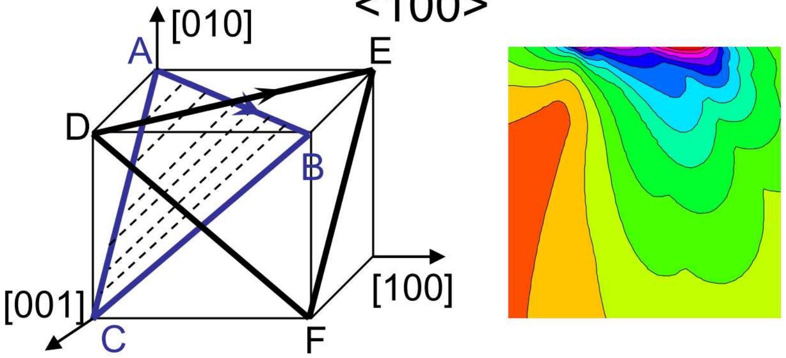


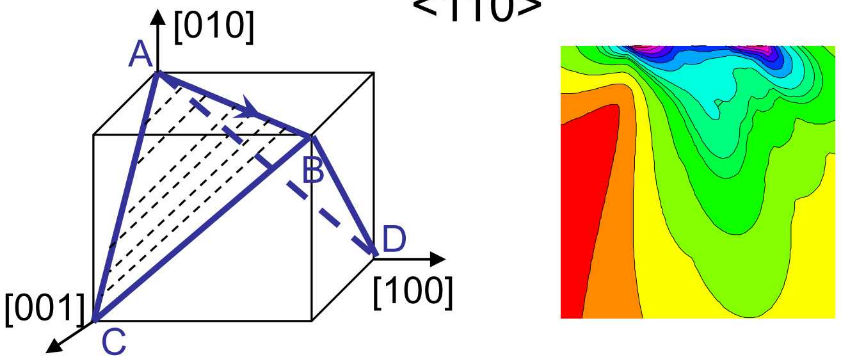
Note the similarities in crystallographic orientation changes and critical resolved stress profiles (bottom)



Maps showing the orientation changes relative to undeformed regions on (100) crystal surface. Brighter color represents larger orientation change. The magnitude of orientation change was about 6º total in for the friction track in the <100> direction and about 13 º for the track in <110> direction.

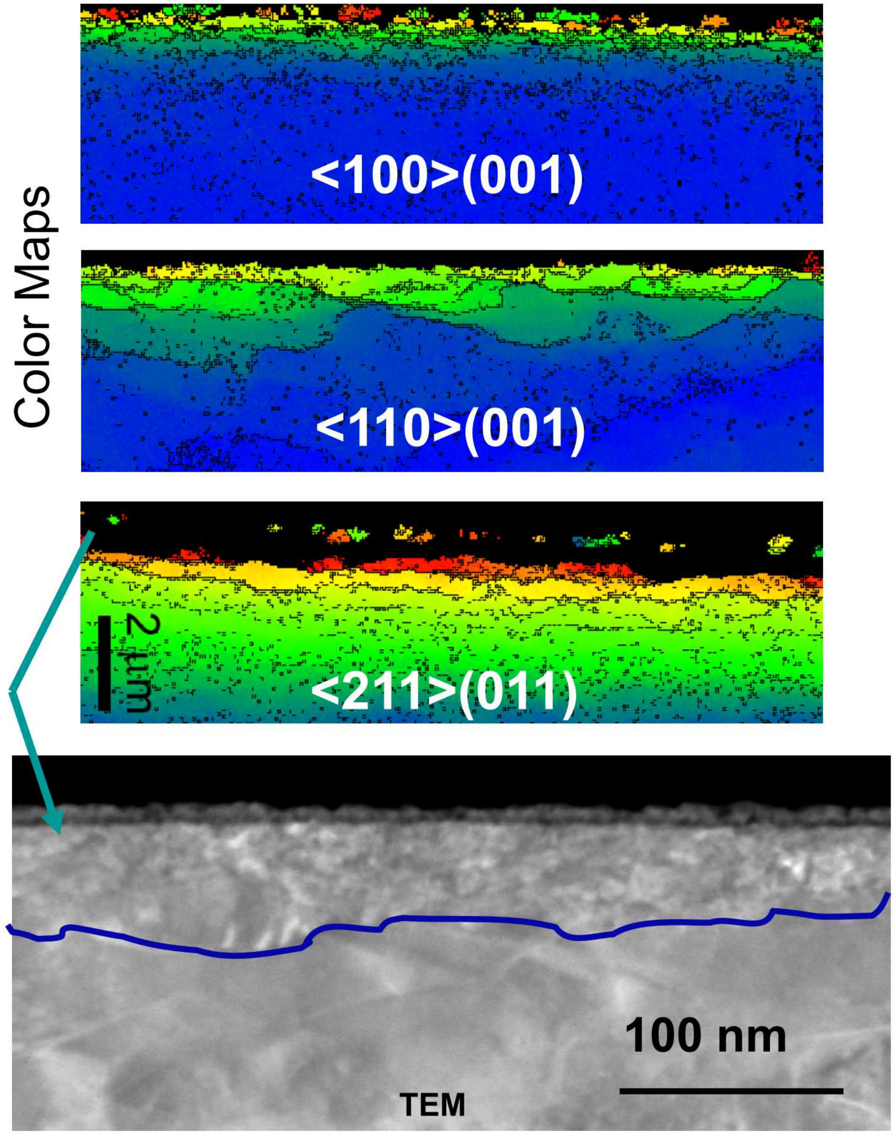
Slip system orientations show intersecting slip systems for <100> wear (ABC plane in AB direction, and DEF in DE), but not for <110> (ABC in AB and ABD in AB), suggesting more hardening for <100>. Color maps of resolved shear stress from analyses of plastic deformation show the strong asymmetry induced by sliding (as opposed to static) contact.

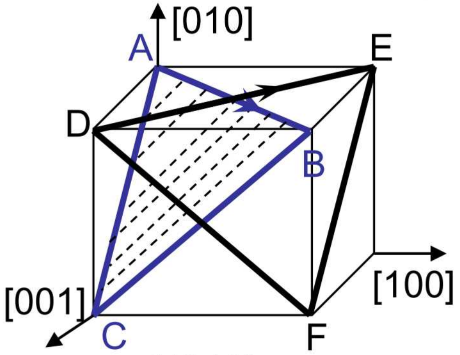




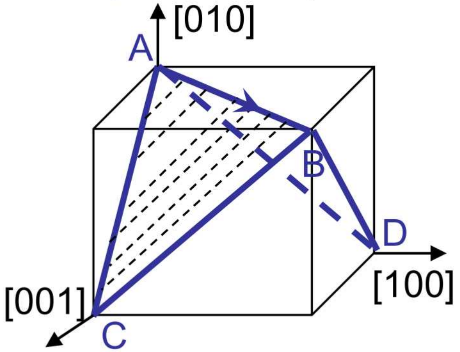
Depth of deformation is related to crystallography: Misorientation wrt undeformed single crysrtal

Blue: Low
Red: High

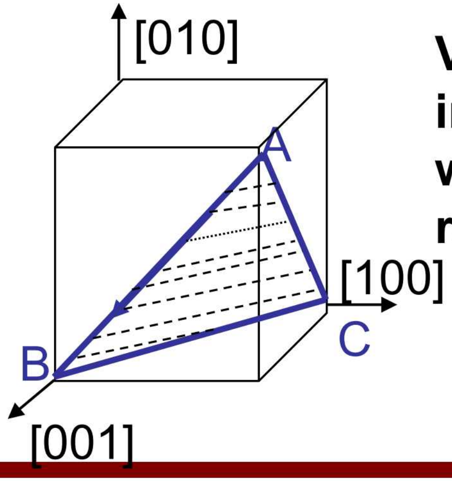




Strong dislocation interactions- high work hardening

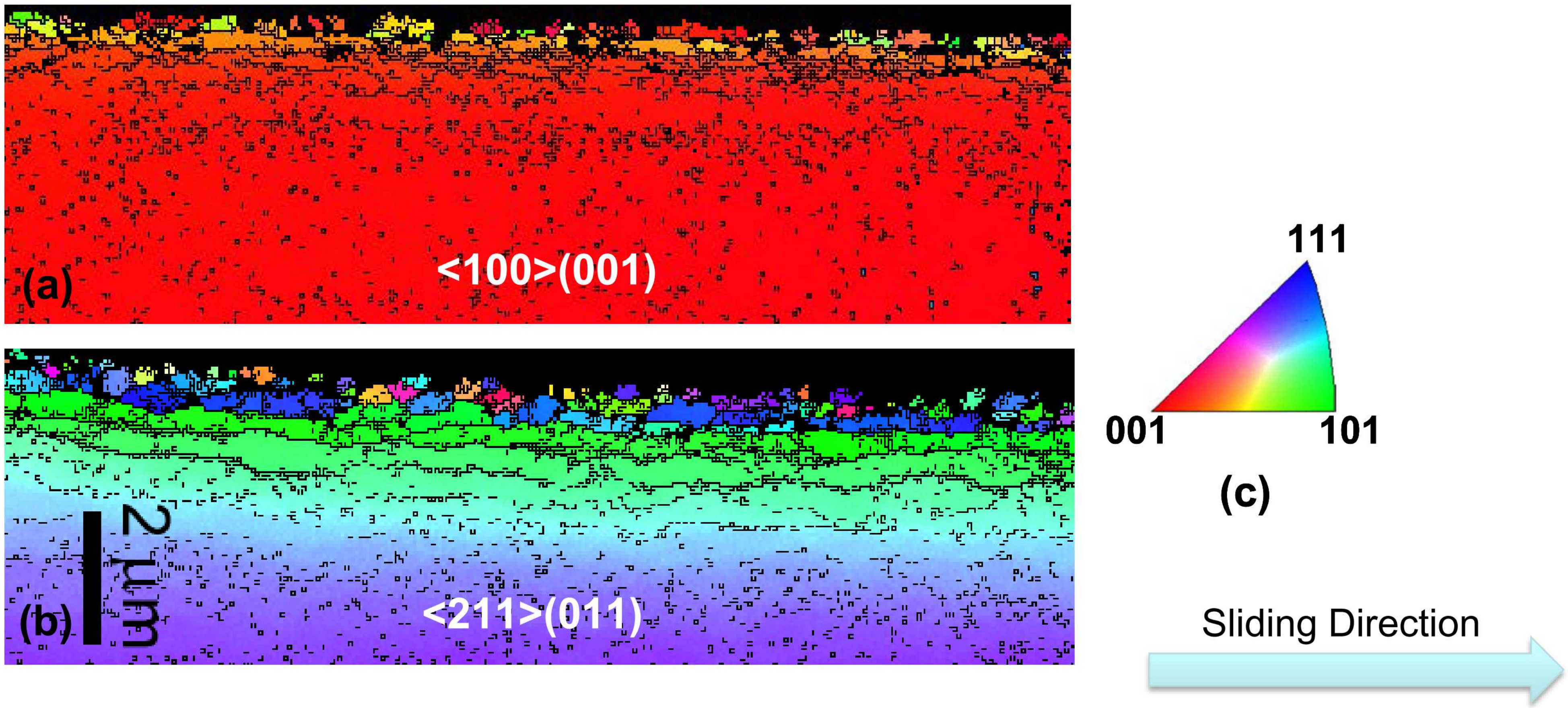


Weak dislocation interactions- low work hardening

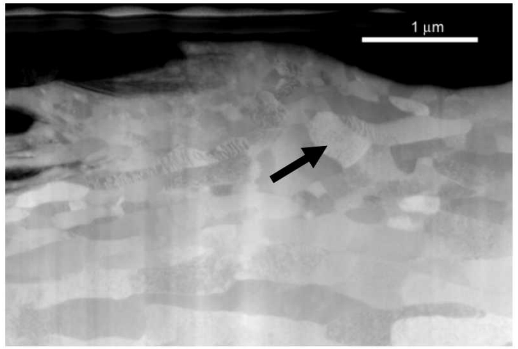


Very weak dislocation interactions- low work hardening – rapid recrystallization

EBSD: Crystallographic maps

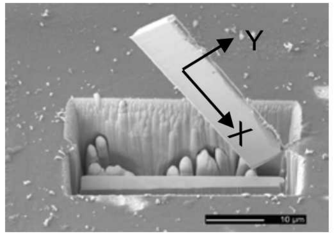


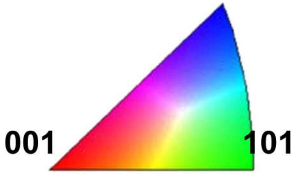
Application of EBSD to monitor the evolution of subsurface microstructures induced by sliding contact (Higher Contact Stresses)

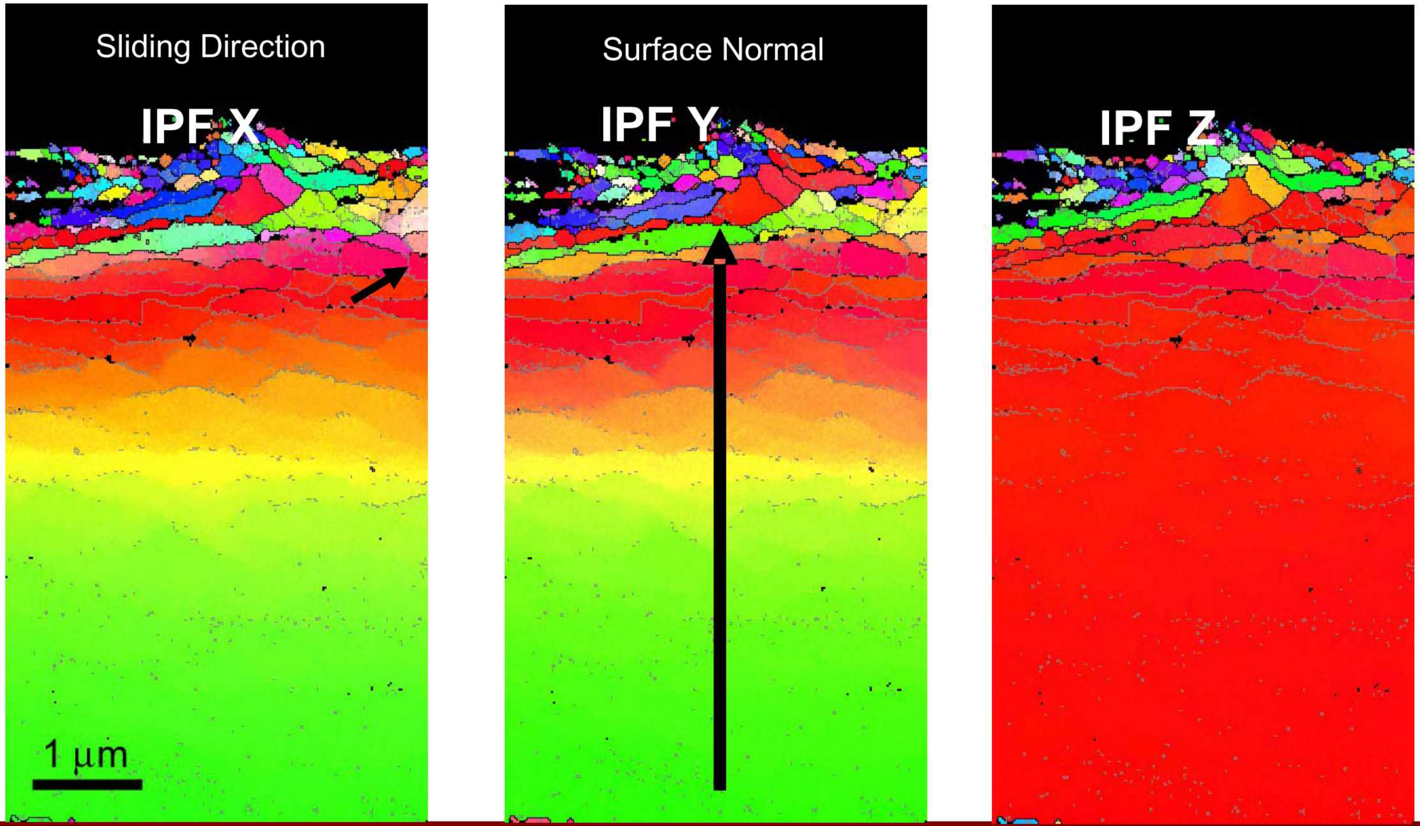


<110> on (011)

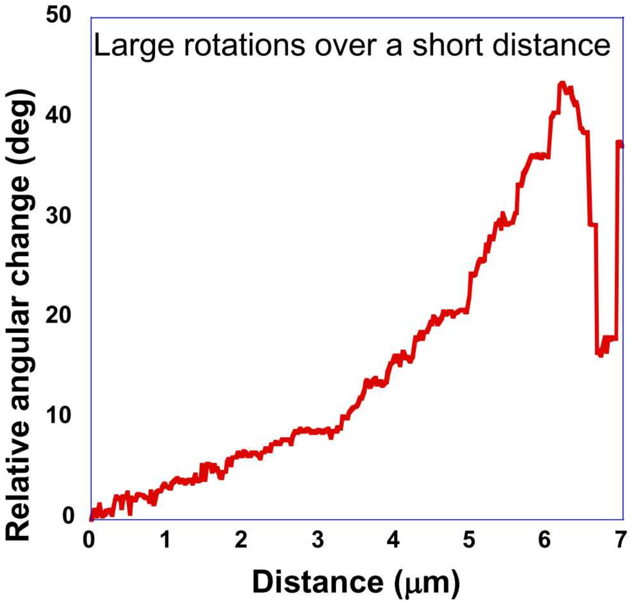
(100 grams for 2000 Cycles)

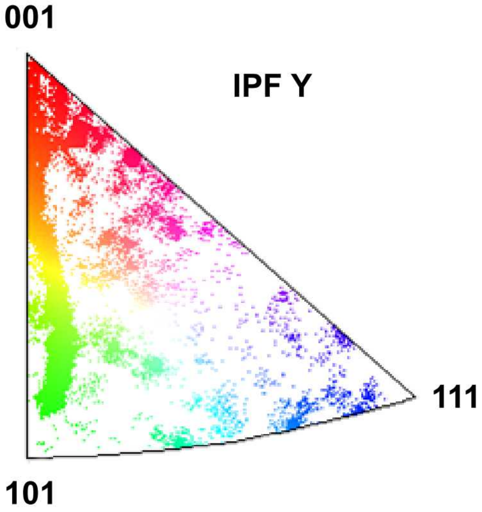




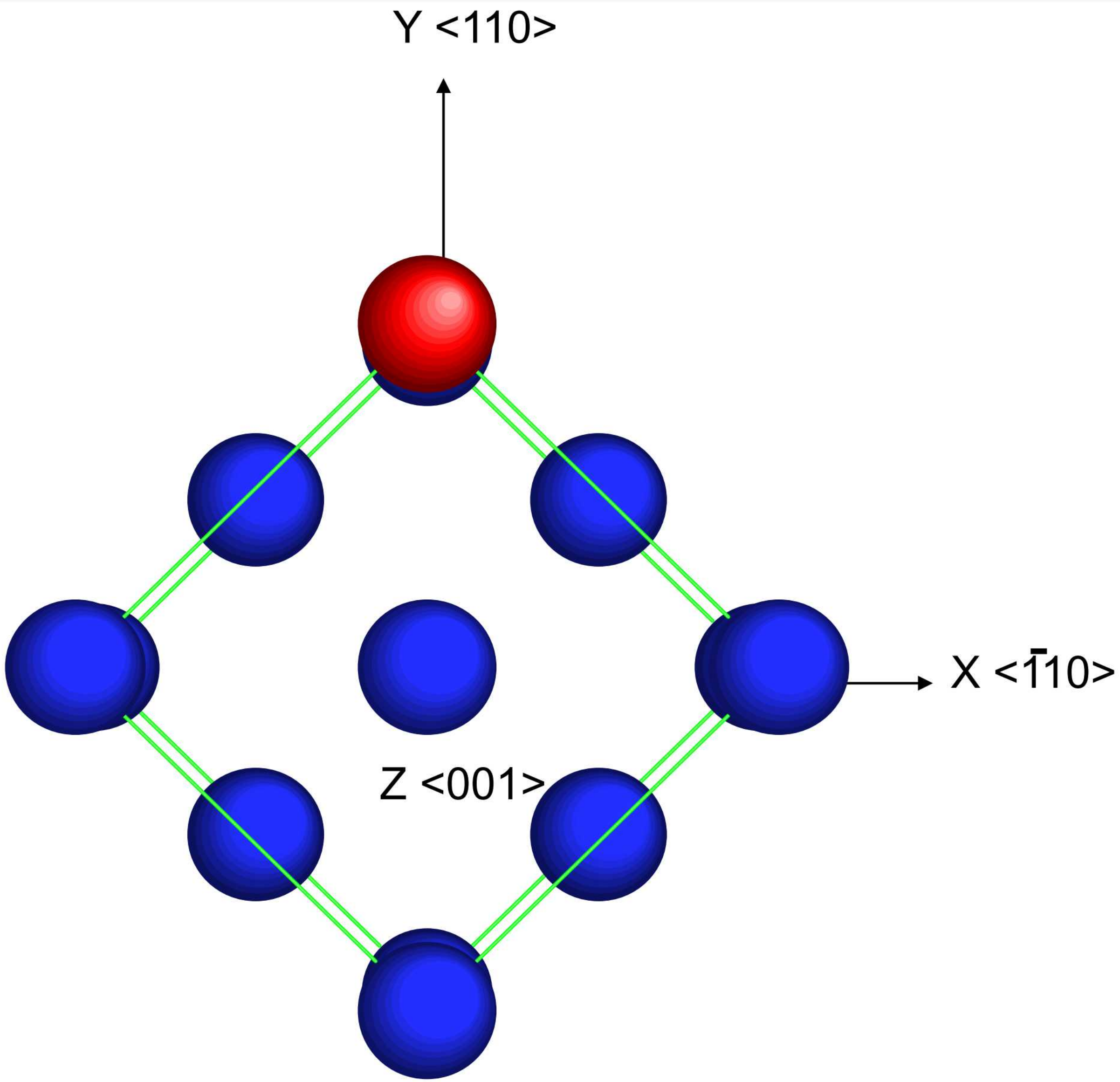


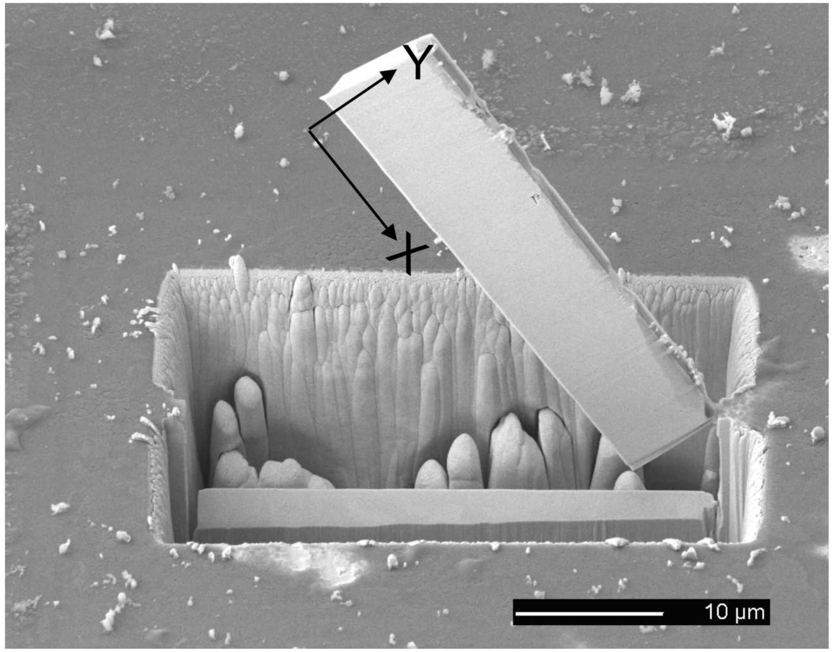
200 x 385 x 25 nm steps



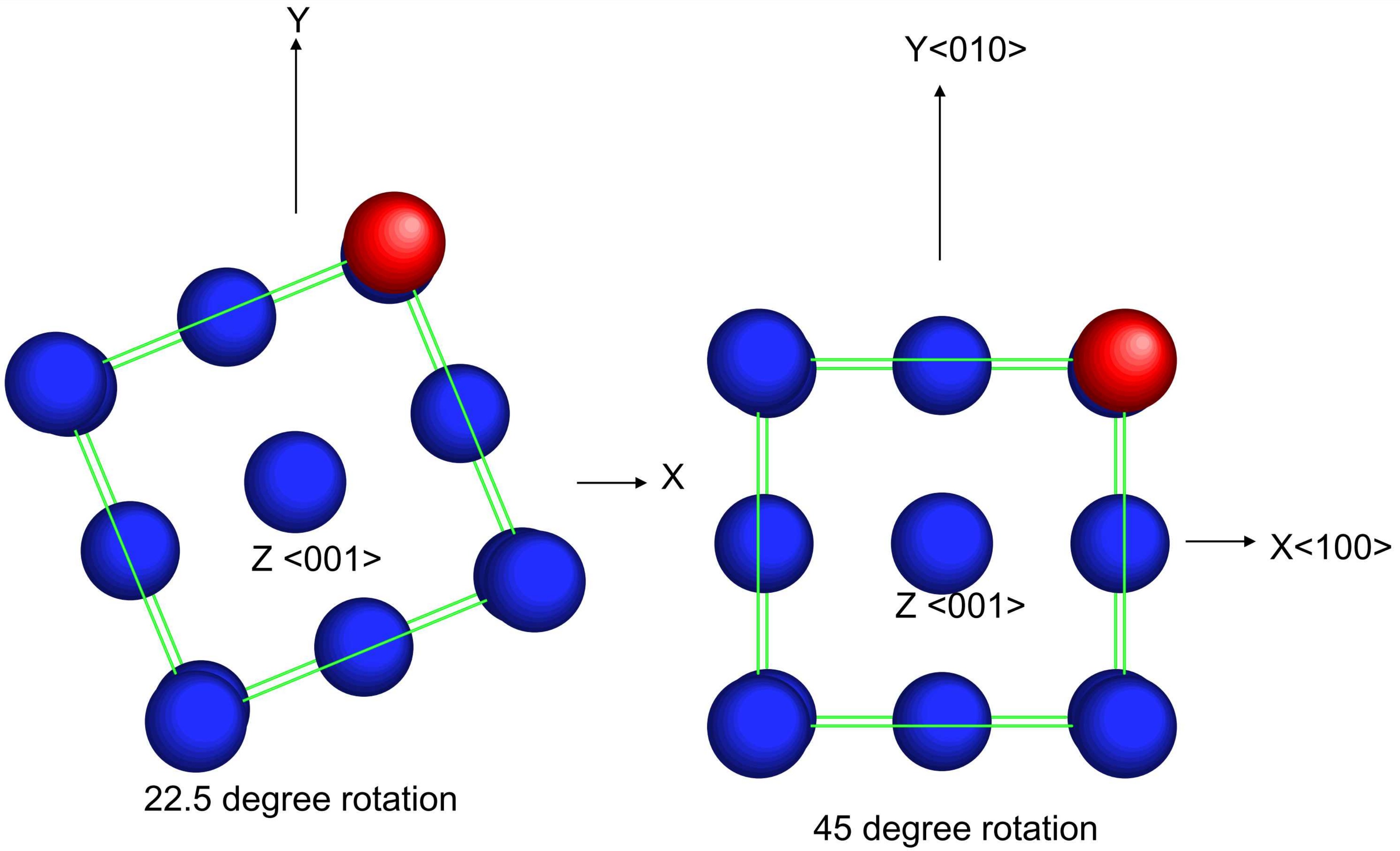


Schematic illustration of grain rotation. 1



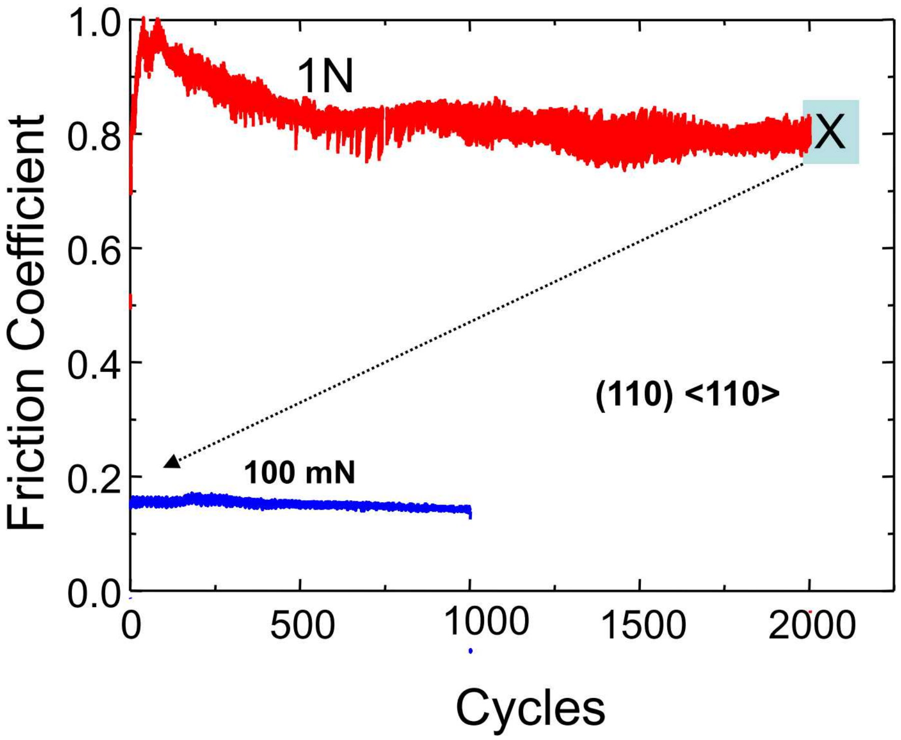


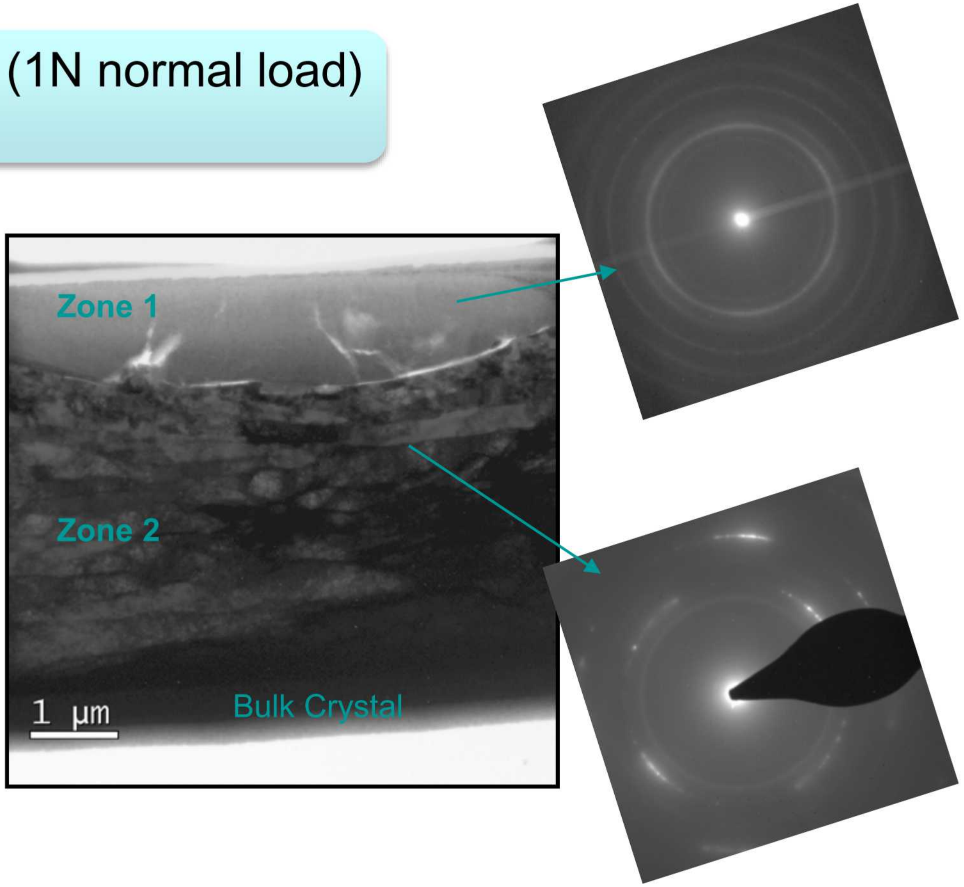
Schematic illustration of grain rotation. 2



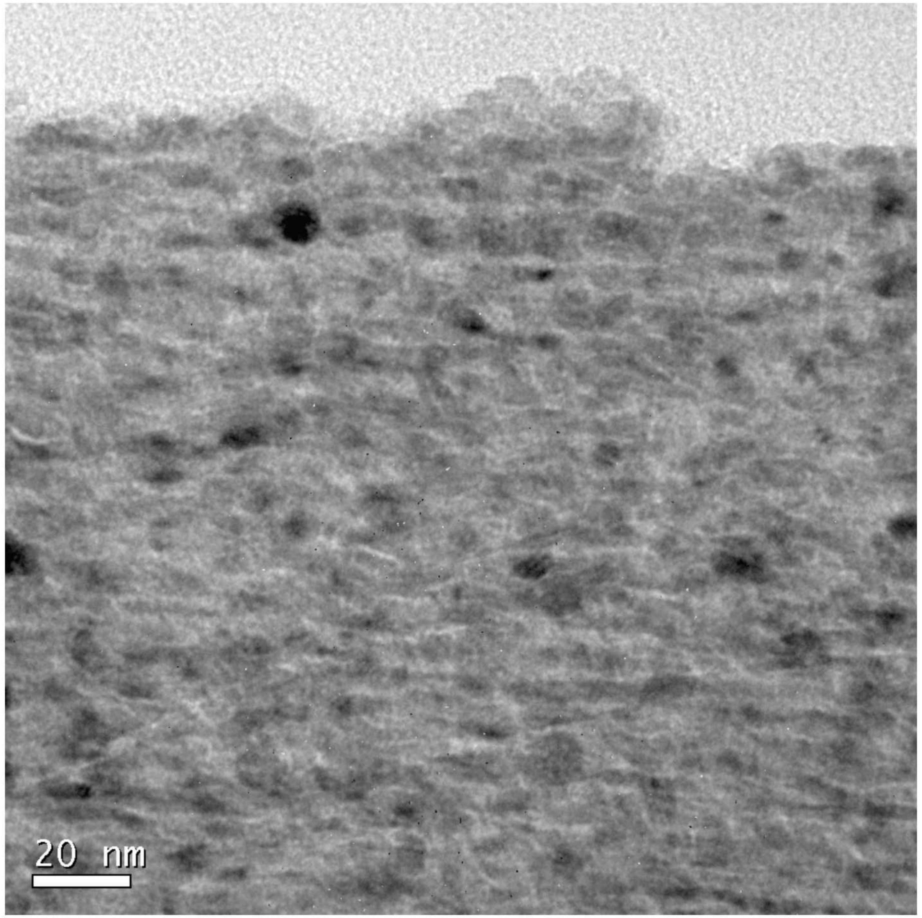
Higher normal loads (1N) produced unique substructures with interesting friction behavior

Create the unique structures at higher contact stress (1N normal load) and make the friction measurement at 100 mN load

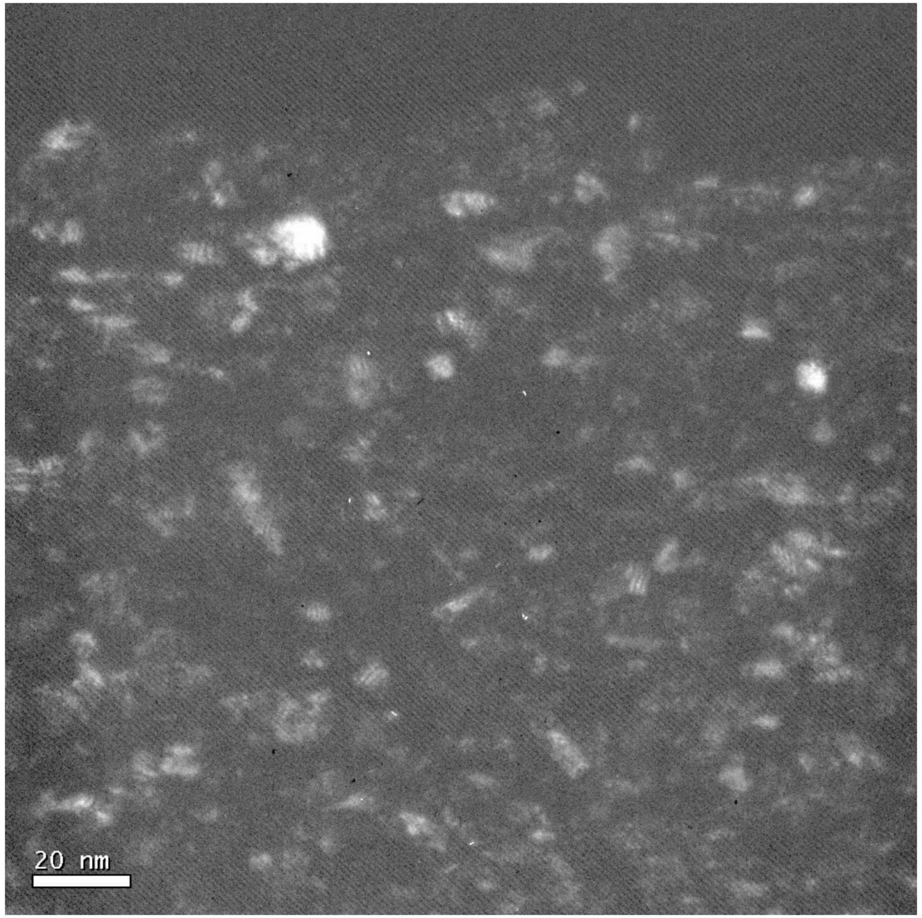




High resolution images of Zone 1

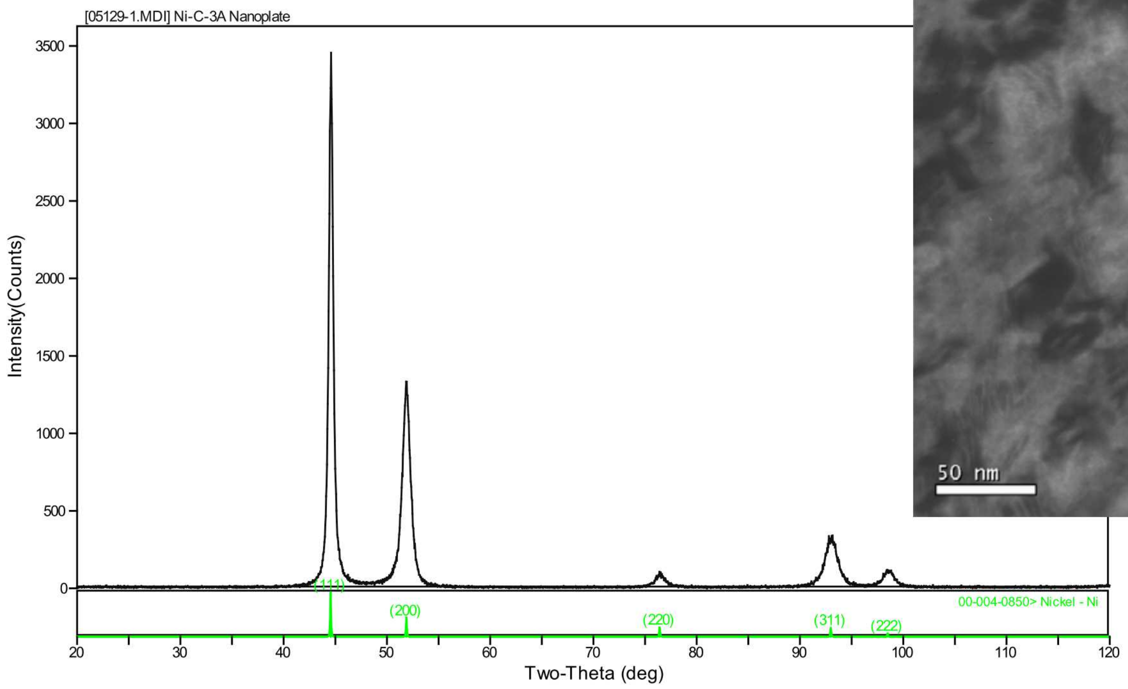


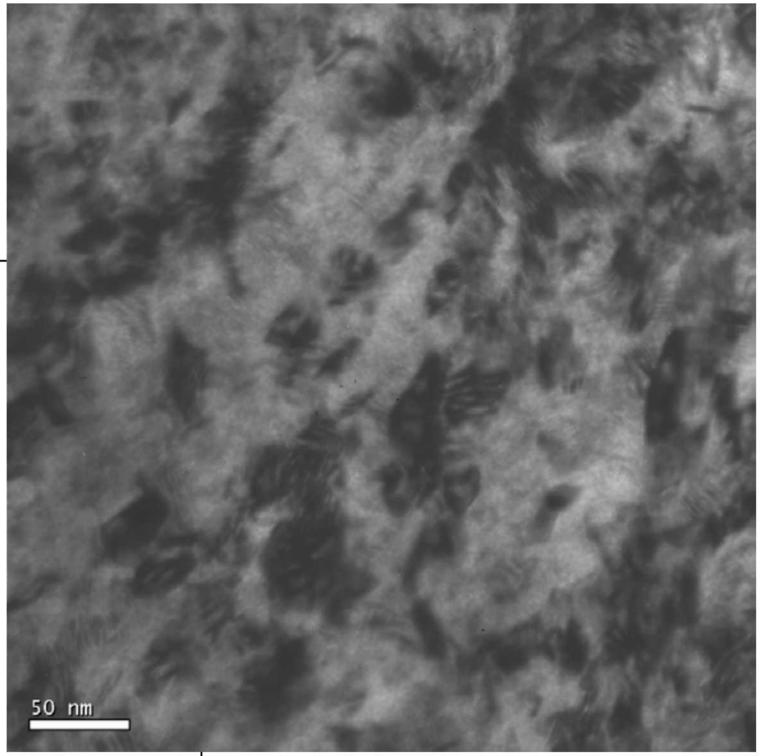
Bright-field TEM image



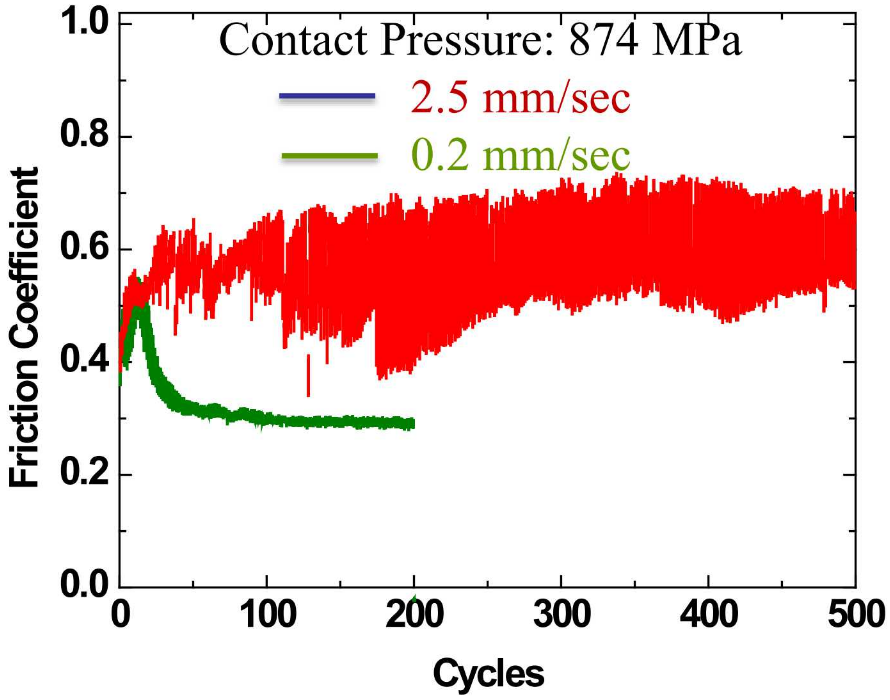
Dark-field TEM image

Application to Nanocrystalline Thin Films

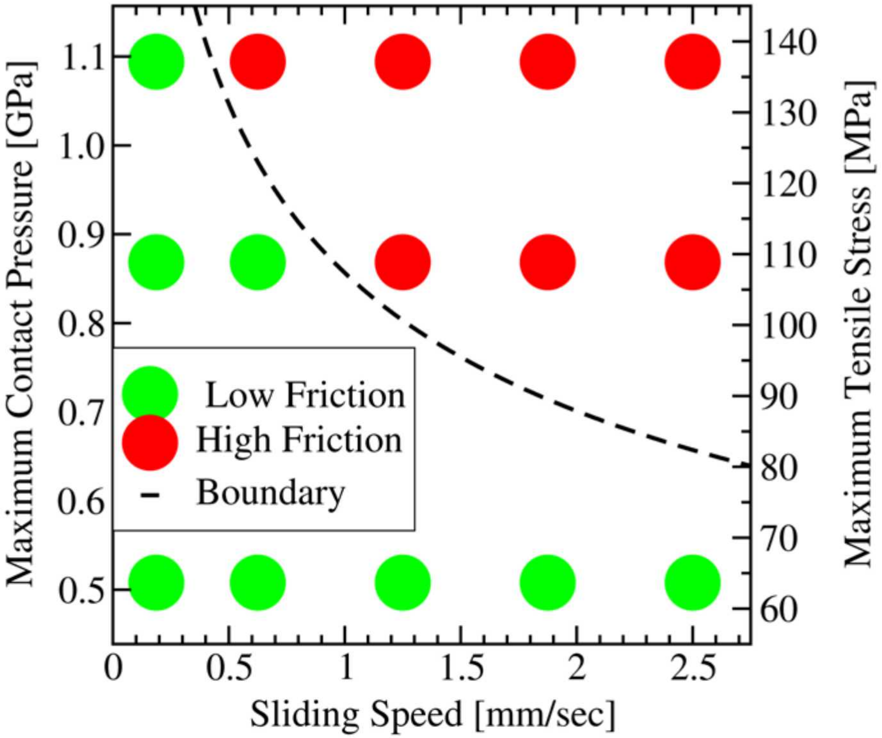




Nanocrystalline Ni films exhibited two different friction behaviors depending on the sliding speed and contact stress

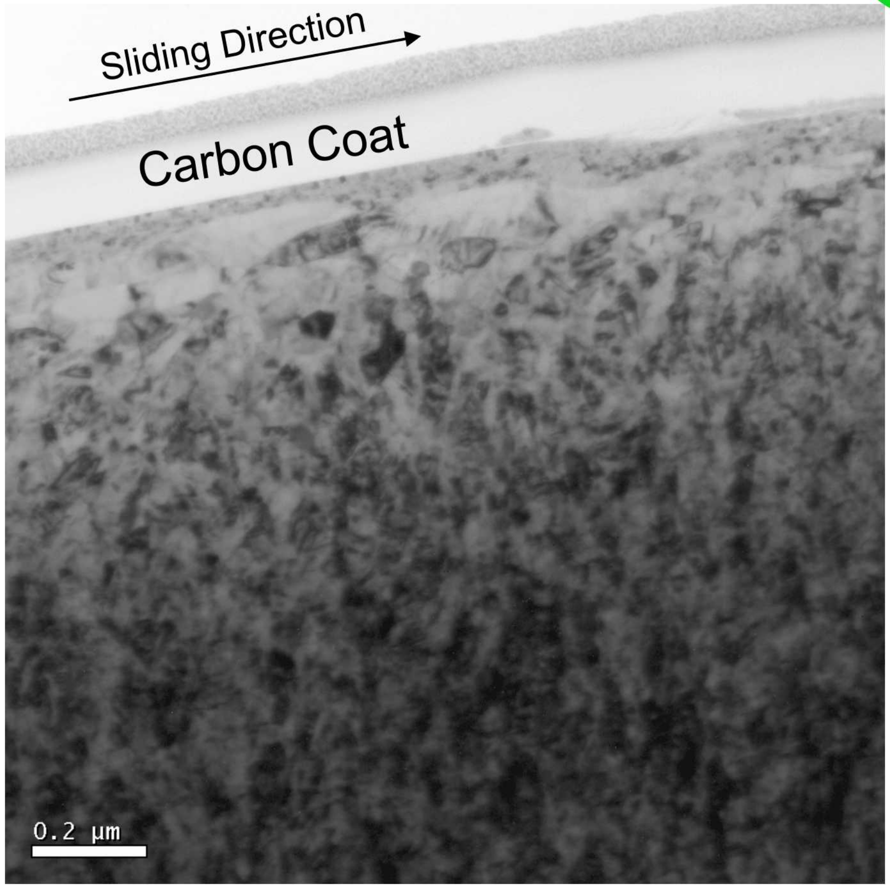


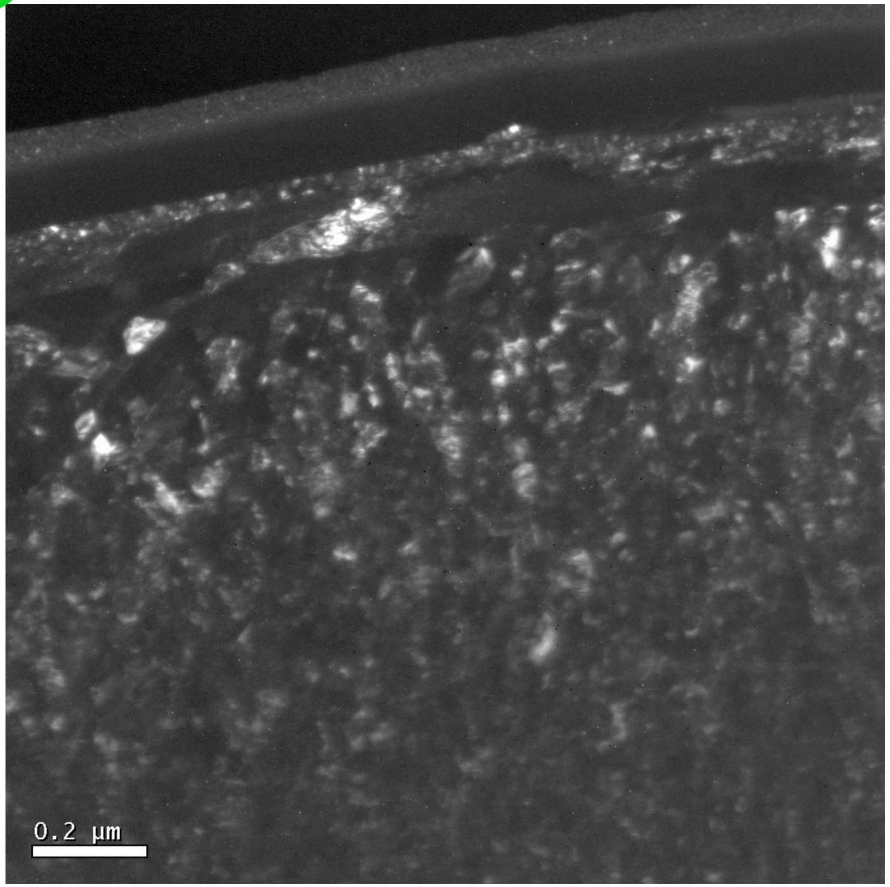
Friction Transitions show a clear dependence on stress and sliding speed



Prasad, S.V., C.C. Battaile, and P.G. Kotula, Scripta Mater, (64) 2011, 729-732.

Transmission Electron Microscopy of Subsurfaces: Low Friction Case





BF-TEM

DF-TEM

Sample preparation: FIB microscopy with low KeV cleaning

Low magnification micrographs

Ni-3C-A1 #1 051202D Track 19, 10g, 20rpm, 600cycles

XSTEM image showing three distinct regions:

(Ultrananocrystalline (1), recrystallized zone (2) and the bulk

Ni-3C-A1 #1 051202D Track 19, 10g, 20rpm, 600cycles

Zone 1+

Zone 1

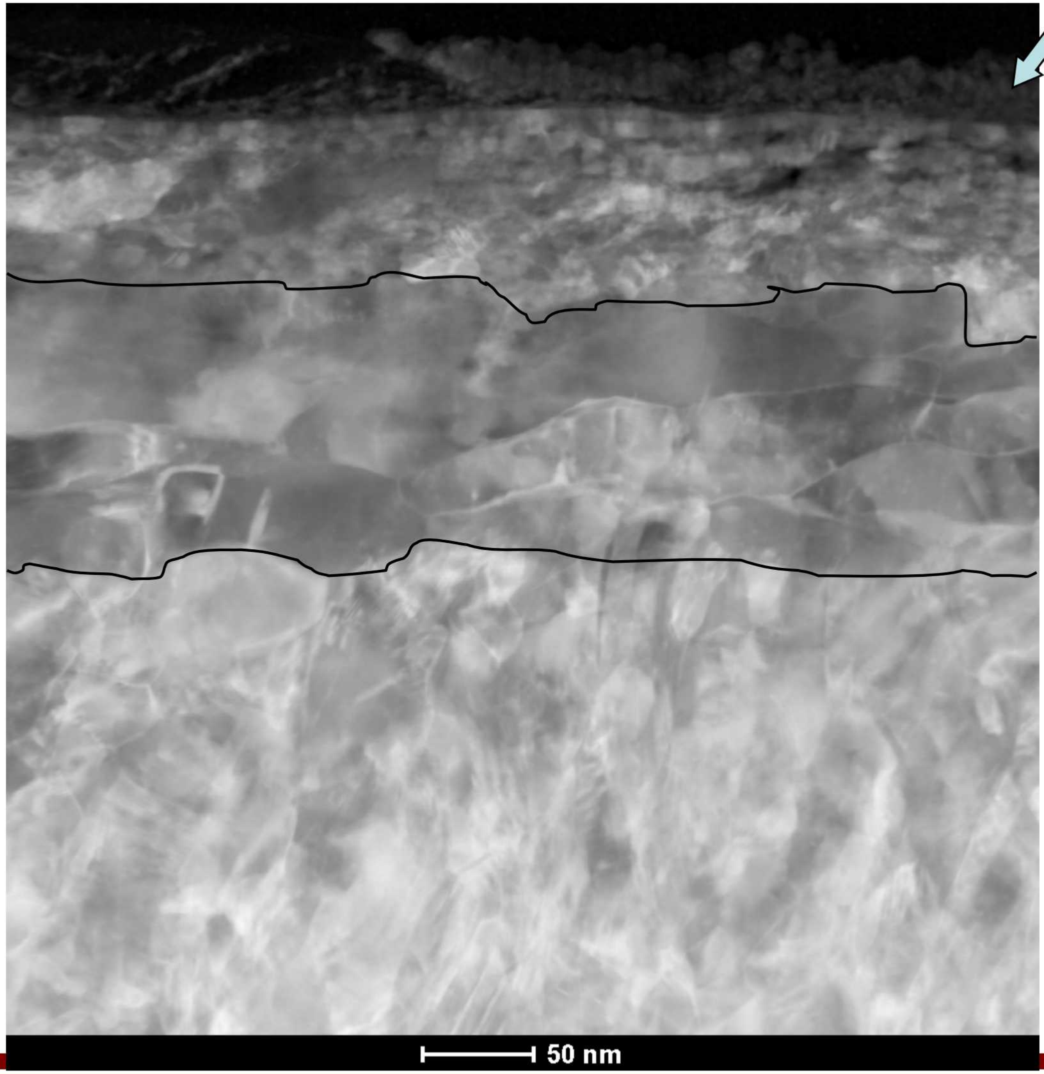
Ultra Nanocrystalline

Zone 2

Grain Growth + Texture

Zone 3

Bulk

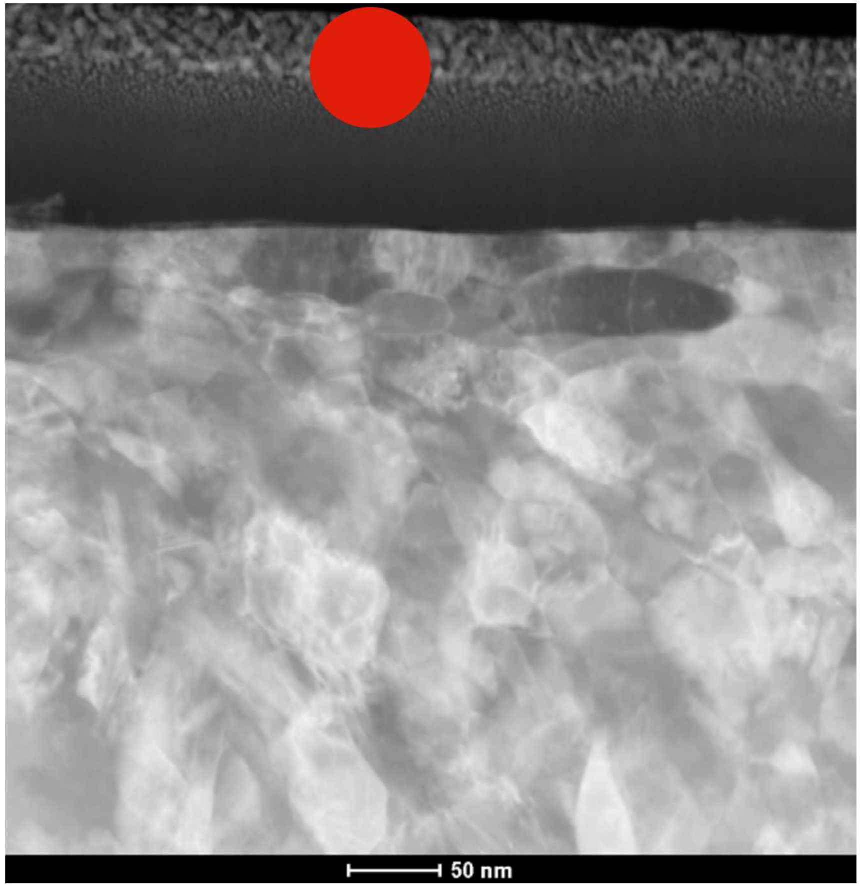


Annular DF Image

Annular DF STEM Image

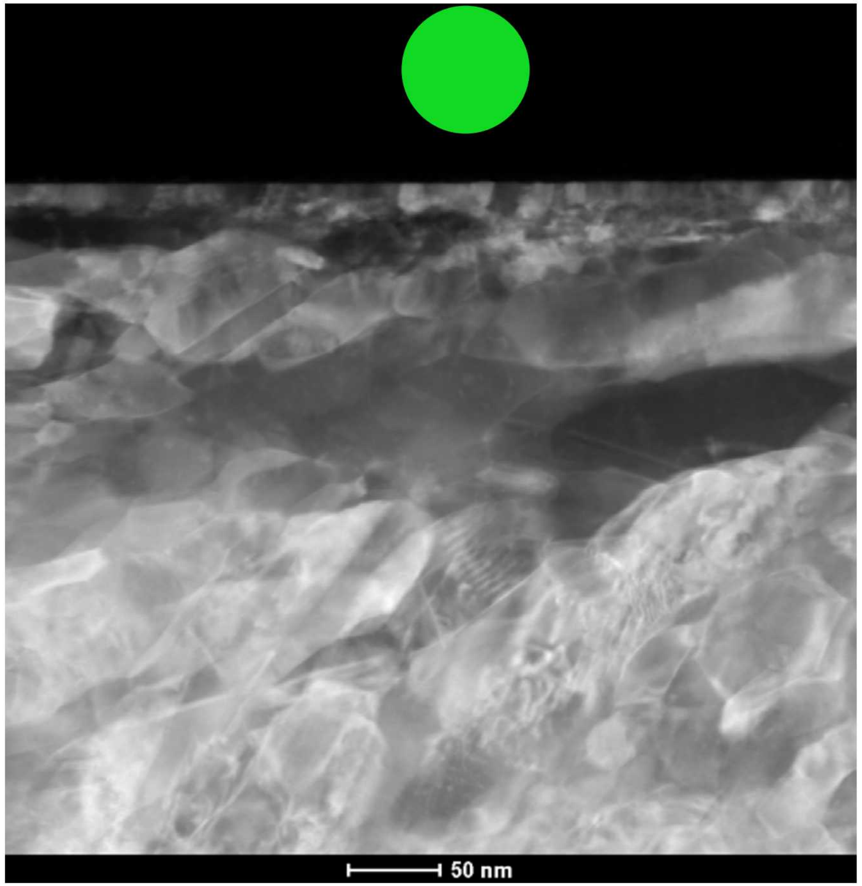
Comparison of Subsurfaces: High Friction (Red) and Low friction (Green)

Ni-C-3A #1 051201G Track 14, 100g, **20rpm**, 600cycles



No Zone 1

Ni-C-3A #1 051129B Track 3, 100g, **3rpm**, 200cycles



Zone 1 Present

Annular DF STEM Images

Concluding Remarks

- Friction-induced deformation is related to crystallography.
  - Advanced microscopy techniques are key towards understanding the friction-induced microstructures.
- Grain boundary sliding appears to be a viable deformation accommodating mechanism, when ultrafine nanocrystalline layers with 2-10 nm size were present. This is a viable route to reduce the COF and mitigate stick-slip behavior.
- However, friction behavior of nanocrystalline materials appears to sensitive to contact stress and sliding speed.

Acknowledgements

Rotary friction module was designed and fabricated by Rand Garfield

FIB samples were prepared by Michael Rye

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