Exploring the Extremes of Mechanical Behavior through In-situ Electron Microscopy

SAND2020-2771C

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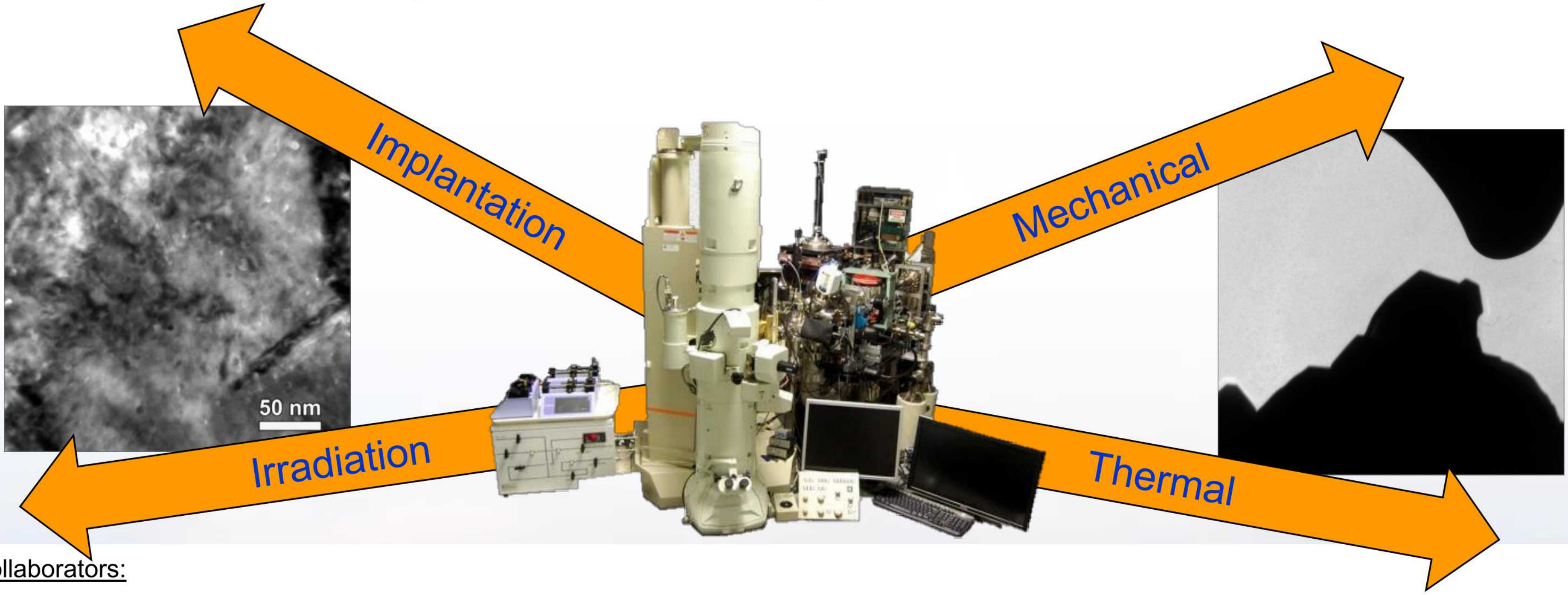
[2]University of Illinois Urbana Champaign, Urbana, IL 61801, USA



Collaborators:

- D.L. Buller, D.C. Bufford, S.H. Pratt, T.J. Boyle, B.A. Hernandez-Sanchez, S.J. Blair, B. Muntifering, C. Chisholm , P. Hosemann, A. Minor, J. A. Hinks, F. Hibberd, A. Ilinov, D. C. Bufford, F. Djurabekova, G. Greaves, A. Kuronen, S. E. Donnelly, K. Nordlund, F. Abdeljawad, S.M. Foiles, J. Qu, C. Taylor, J. Sugar, P. Price, C.M. Barr, D. Adams, M. Abere, L. Treadwell, A. Cook, A. Monterrosa, IDES Inc, J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, W. Mook, Hysitron Inc., G.S. Jawaharram, S. Dillon, R.S. Averback, N. Heckman, J. Carroll, S. Briggs, E. Carnes, J. Brinker, D. Sassaki, T. Nenoff, B.G. Clark, P.J. Cappillino, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, L.R. Parent, I. Arslan, K. Jungjohann, & Protochips, Inc.

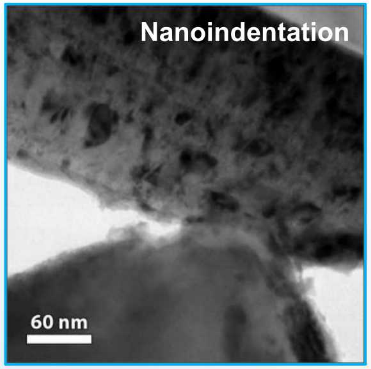
This work was partially funded by Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned sic Energy Sciences, U.S. Department of Energy. This work was subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525. Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

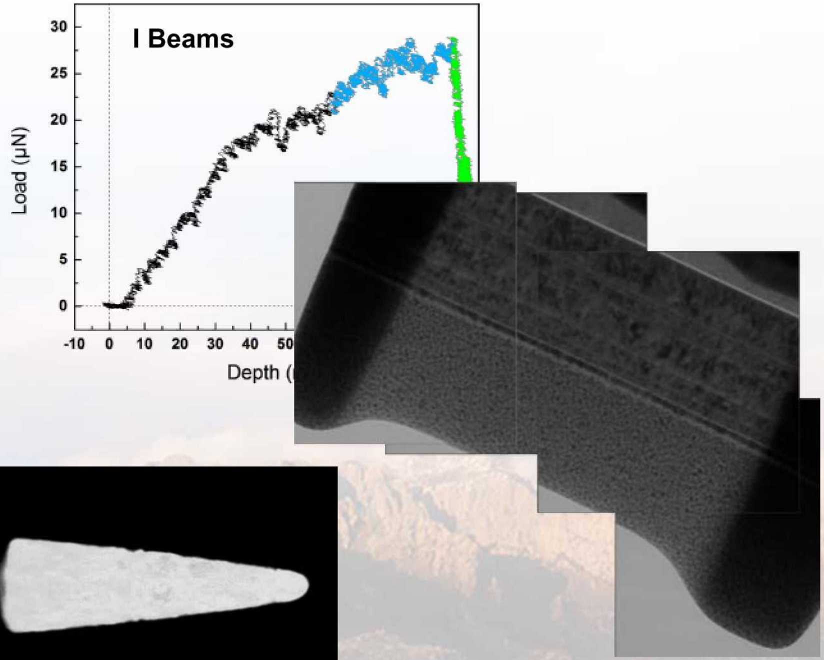
In situ Quantitative Mechanical Testing

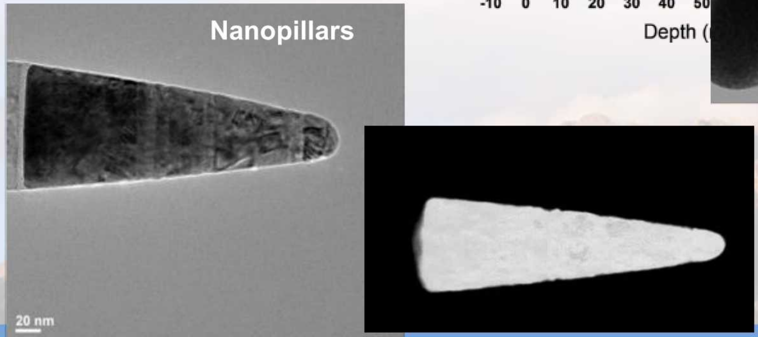
Contributors: J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, P. Hosemann, A.M. Minor, & Hysitron Inc.

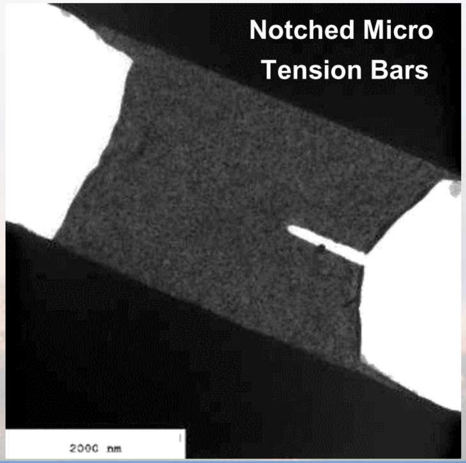
Hysitron PI95 *In Situ* Nanoindentation TEM Holder

- Sub nanometer displacement resolution
- Quantitative force information with μN resolution
- **Concurrent real-time imaging by TEM**





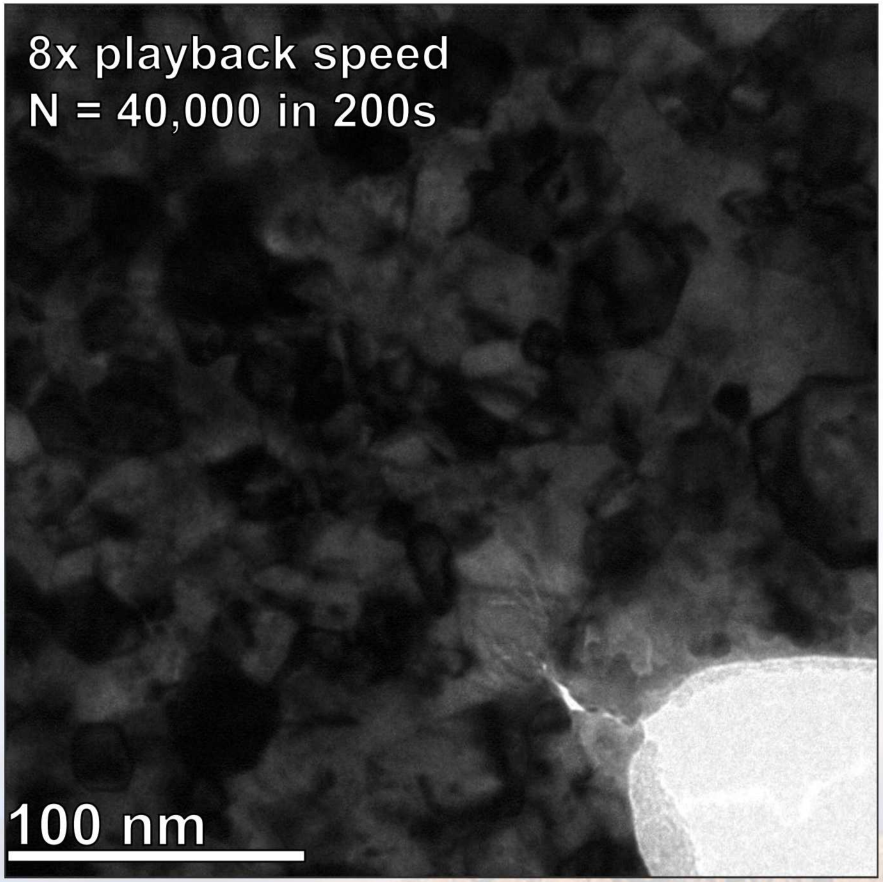




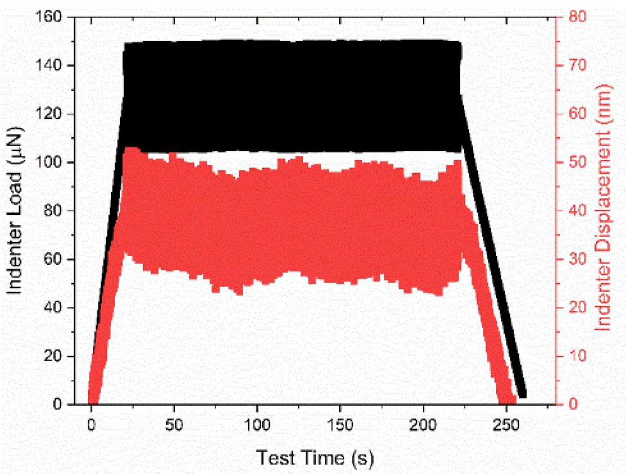
Fatigue Failure in Real Time?

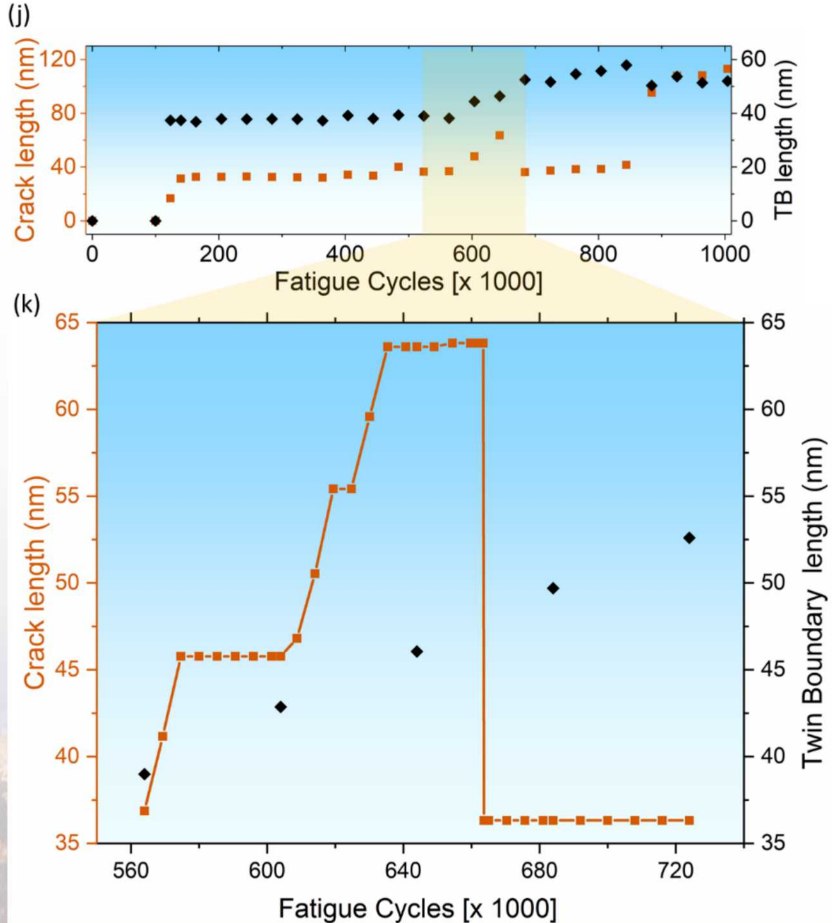
Collaborators: C. Barr, B. Boyce, & W. Mook

- Mean load: 135 uN; Amplitude load: 35 uN
- 200 Hz, 200s test (15 fps 1k x 1k camera)



~ 2 pm/cycle

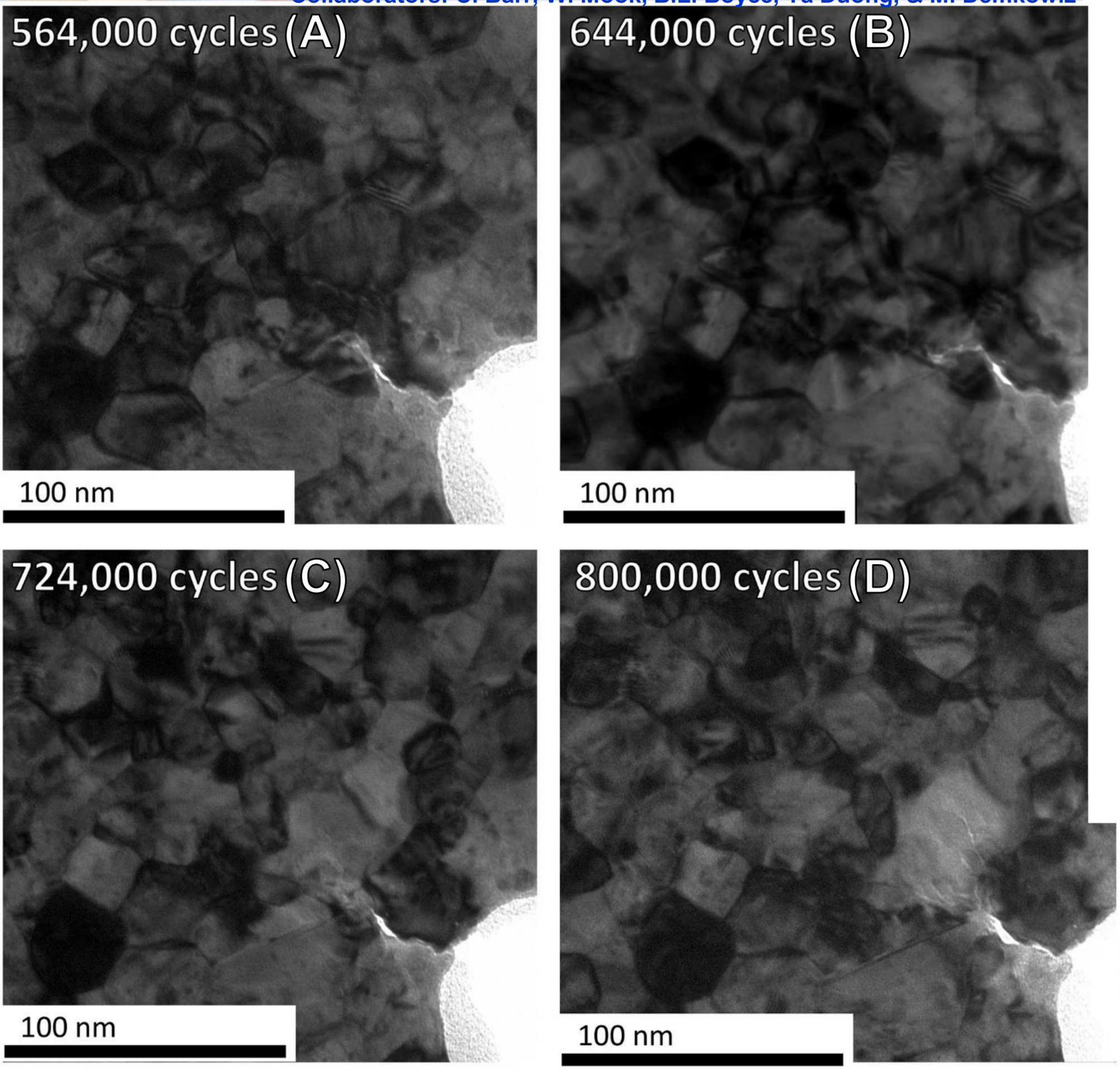


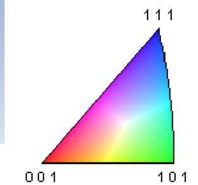


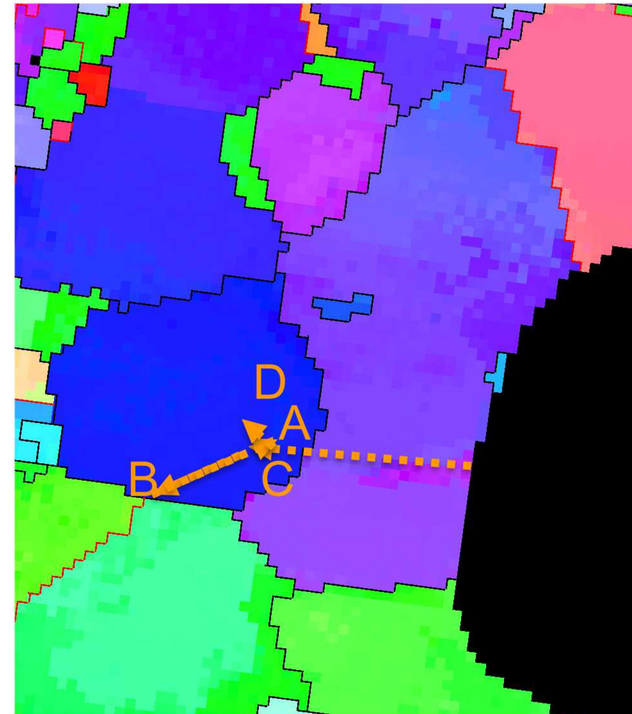
- $da/dN = 1.7 \times 10^{12}$ m/cycle
- Non-linear crack extension rate
- Crack propagation path changes "direction"

Crack Propagation, Closure, and Re-Direction

Collaborators: C. Barr, W. Mook, B.L. Boyce, Ta Duong, & M. Demkowiz

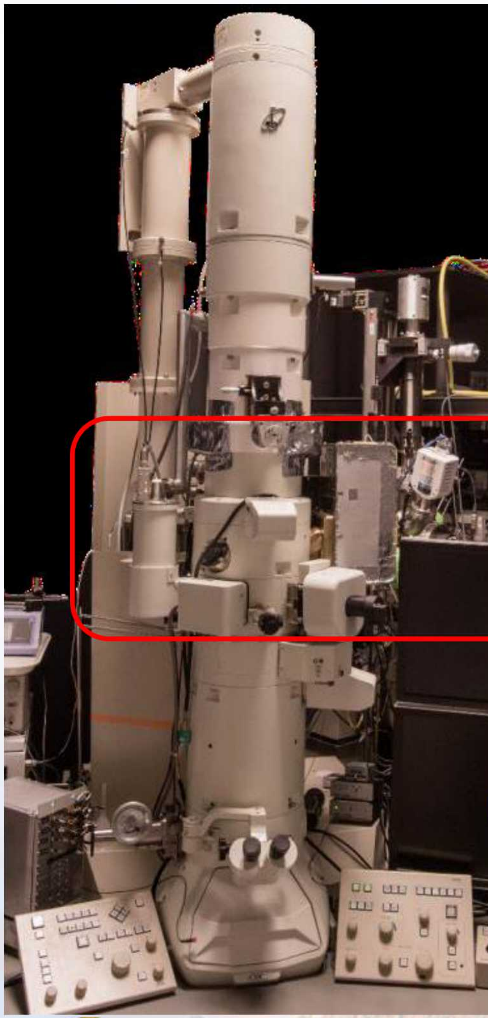


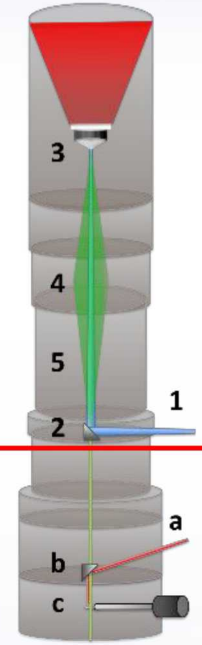




In-situ Specimen Drive Laser System

Collaborator: P. Price, A. Monterrosa, D. Adams, M. Abere, & IDES Inc.





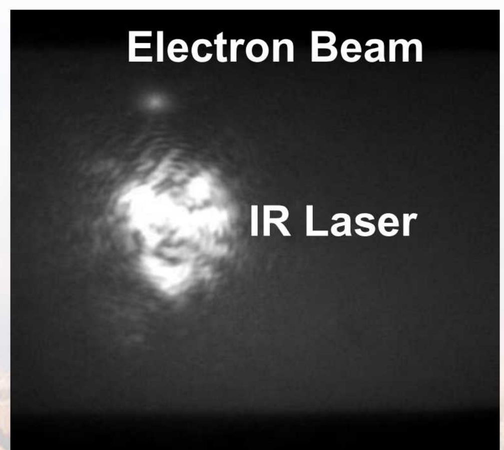
<u>**Specimen Drive Laser**</u>

a. **Adjustable power 1064 nm infrared specimen (IR) drive laser**

b. **IR laser is reflected directly onto the specimen with metal mirror**

c. **Heat specimens in *in situ* holders, which otherwise would not be possible**

- **Laser capabilities:**
  - **2-20 Watts**
  - **Pulsed or continuous operation**
  - **50 μm diameter spot size**
  - **Positioning mirror, which can be used during laser operation**



<u>**Laser Alignment TEM Holder**</u>

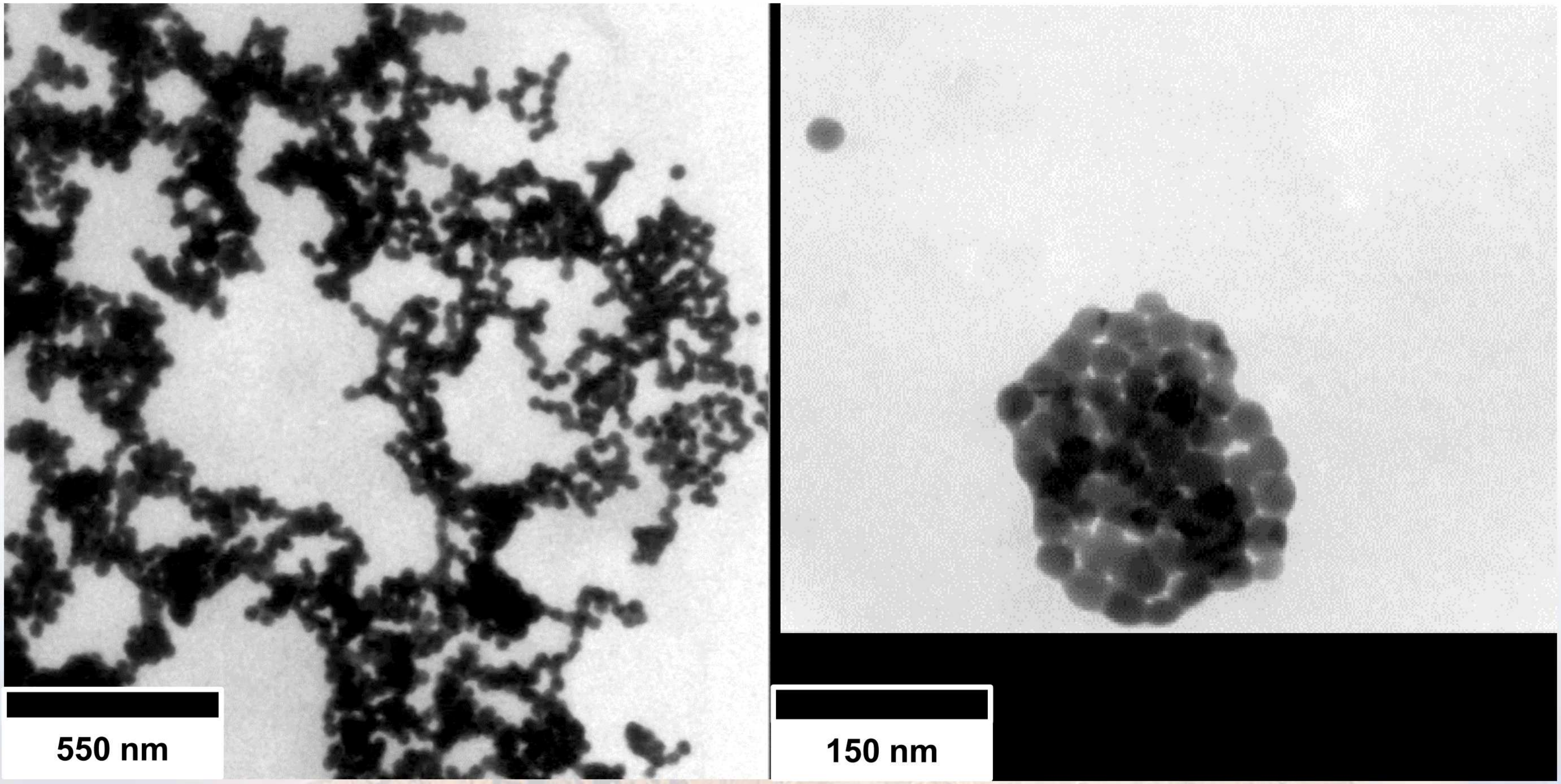
- **Phosphor screen**
- **Borescope**
- **CCD camera**
- **Precise alignment of the laser to the electron beam**

IDES INTEGRATED DYNAMIC ELECTRON SOLUTIONS

Sandia National Laboratories

Complex Interaction Au NPs Exposed to Laser Irradiation

Contributors: P. Price, L. Treadwell, A. Cook, & IDES Inc.

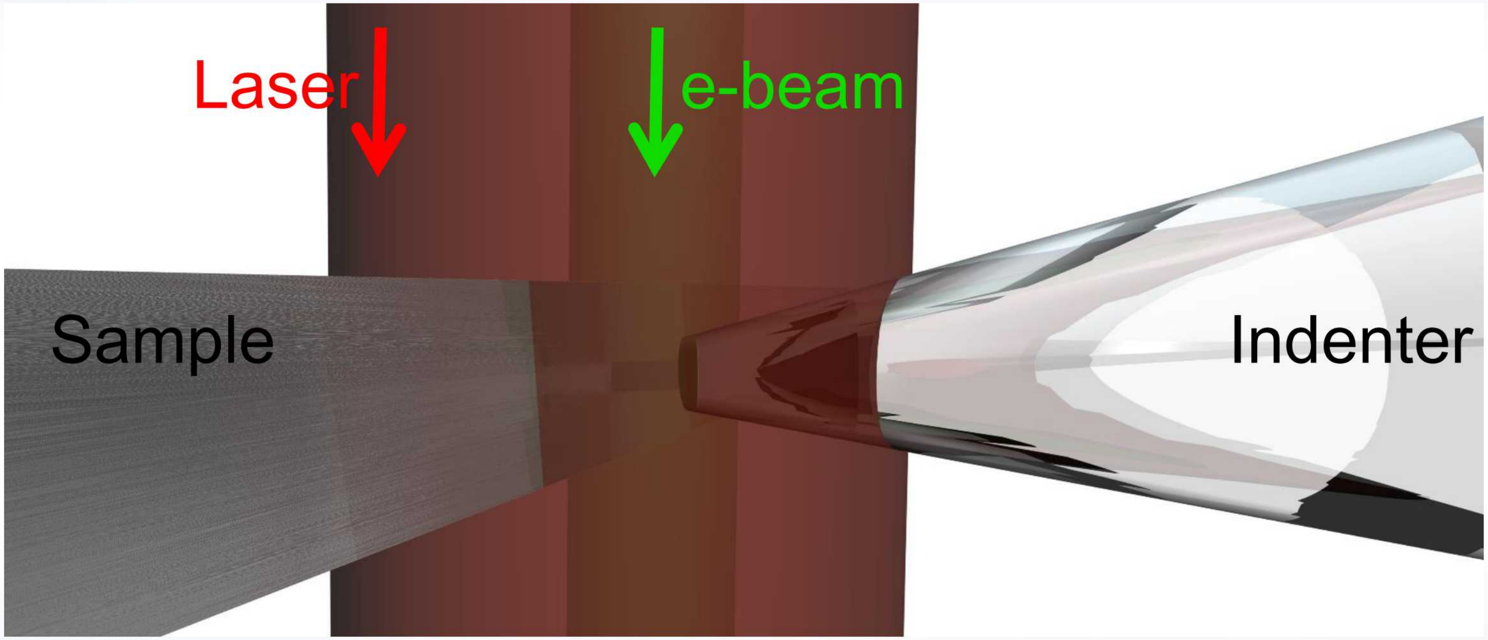


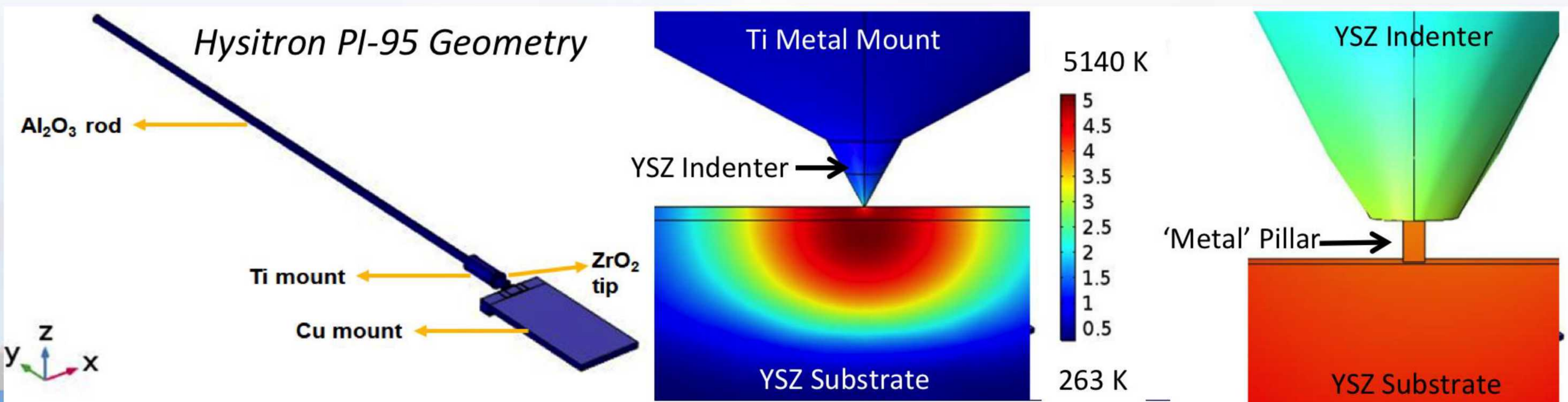
Speed = 2.5x

A Complex Combination of Sintering, Reactions, and Ablation Occurs

Can we Combine Laser Heating with Mechanical Testing?

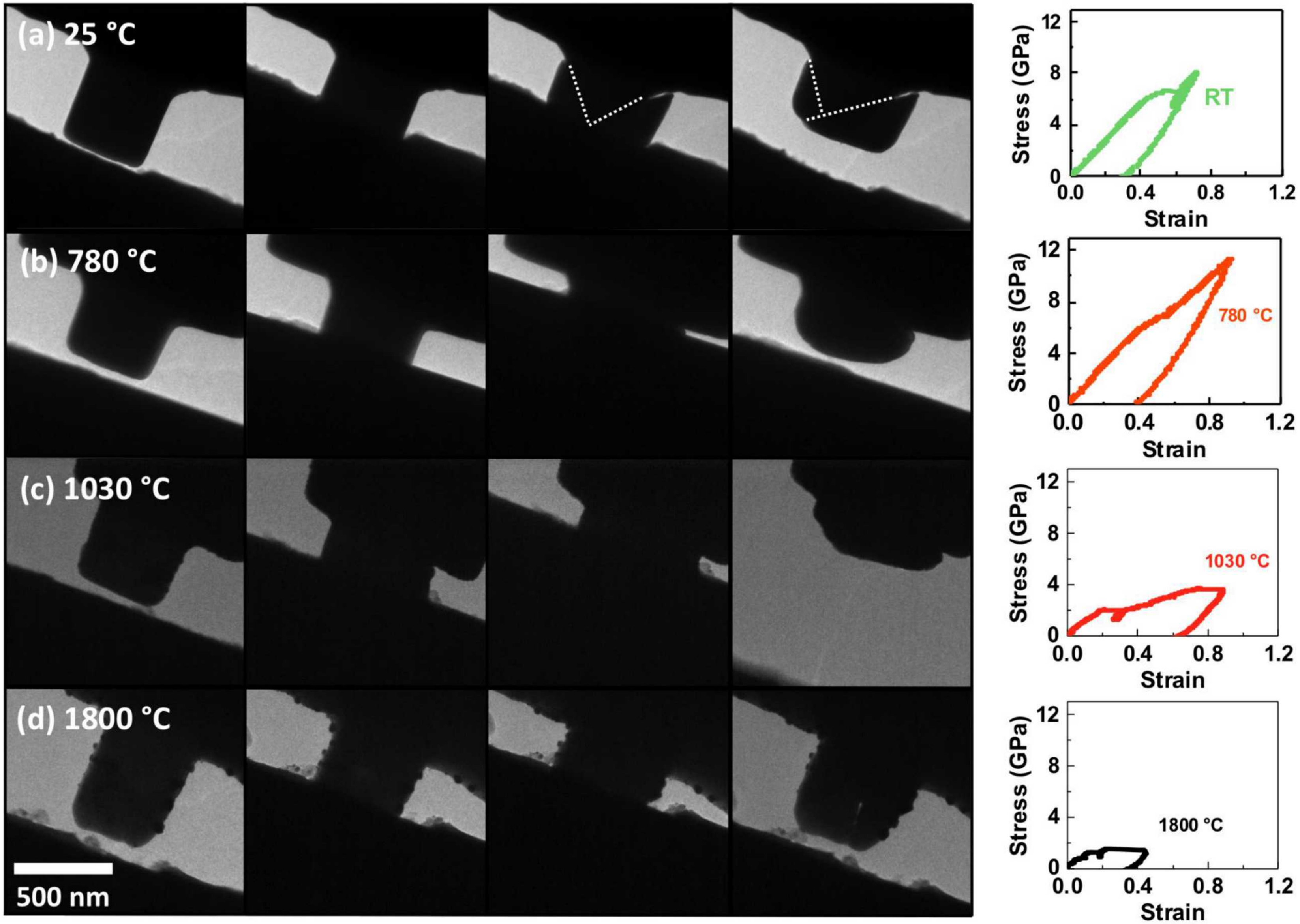
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon





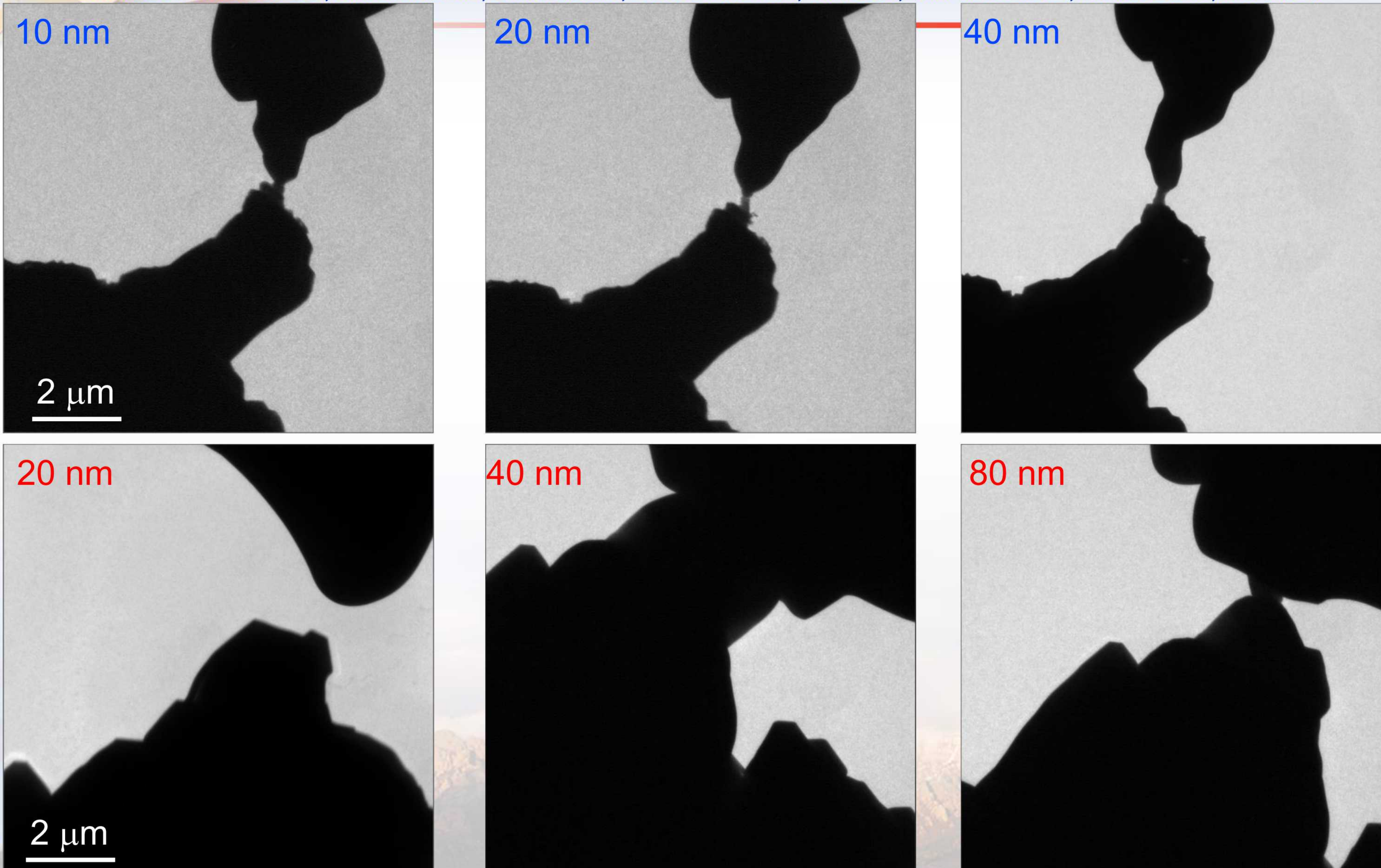
High Temperature Stress-Strain

Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon



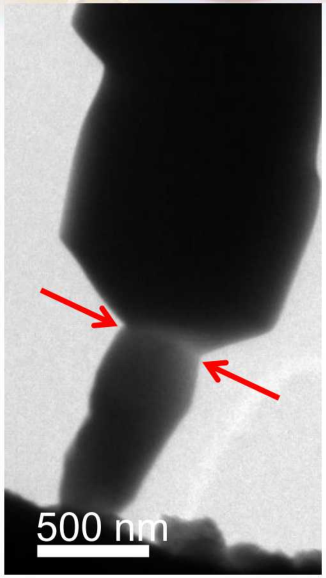
Pushing the Laser Limit - 1604 °C and 2056 °C ScSZ-ScSZ

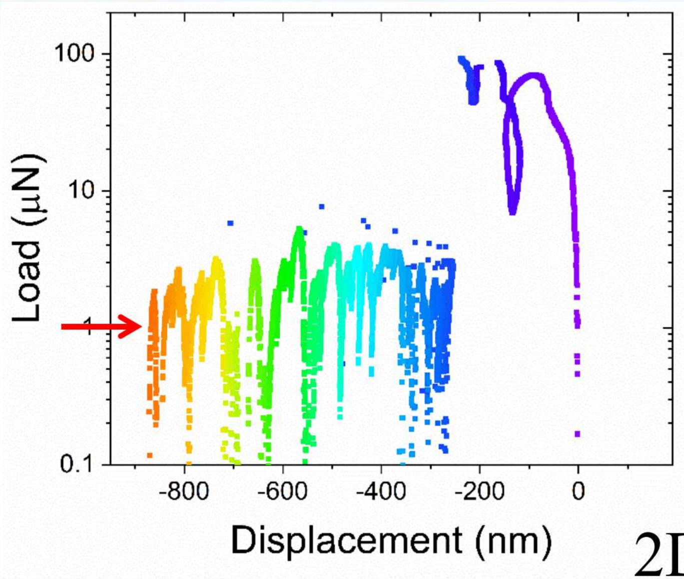
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon

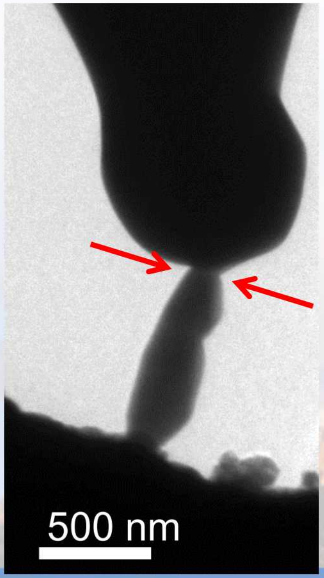


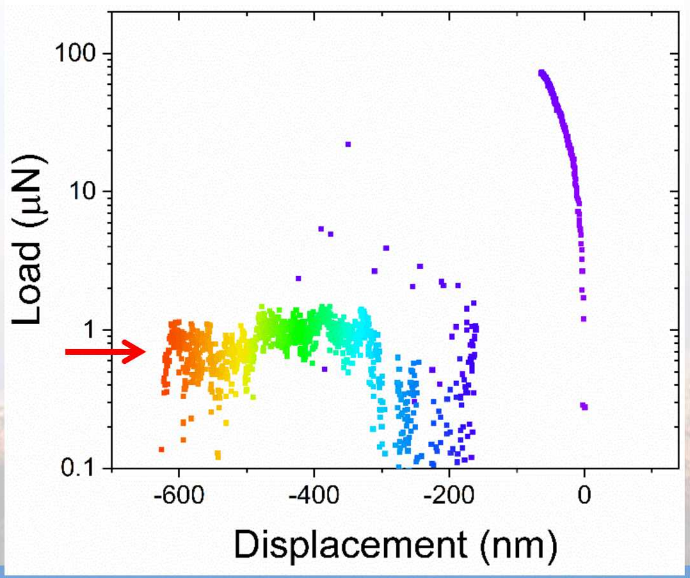
Mechanism for Fiber Growth

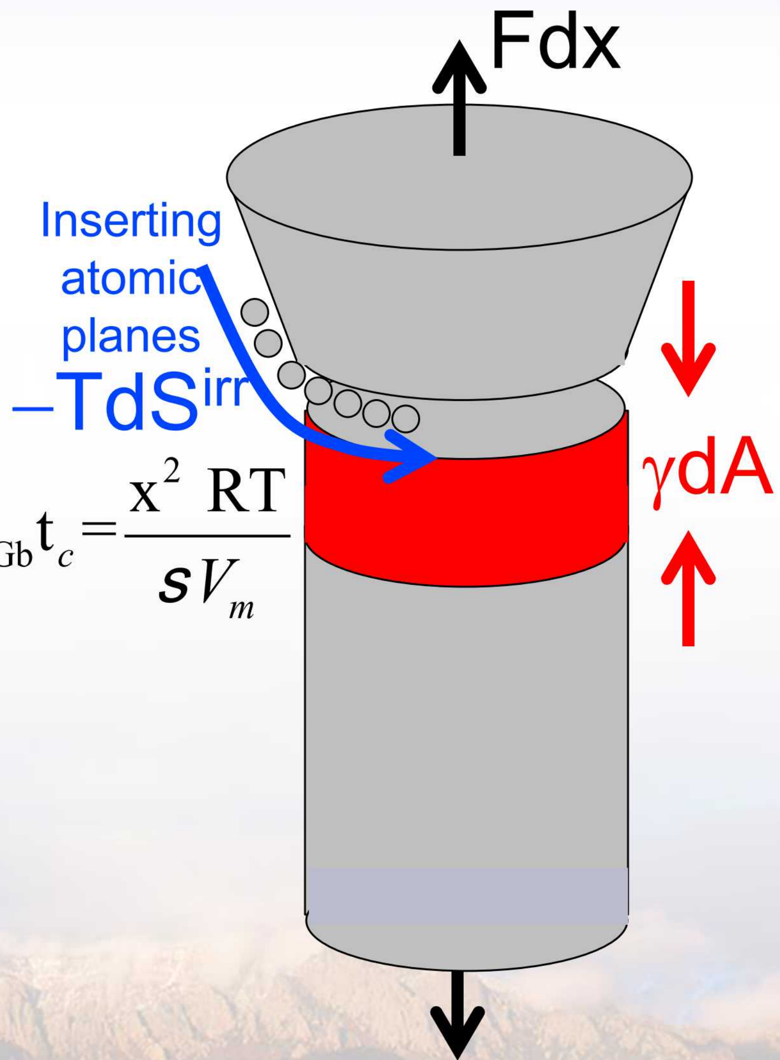
Contributors: R.L. Grosso, E.N.S. Muccillo, D.N.F. Muche, G.S. Jawaharram, C.M. Barr, A.M. Monterrosa, R.H.R. Castro, S.J. Dillon









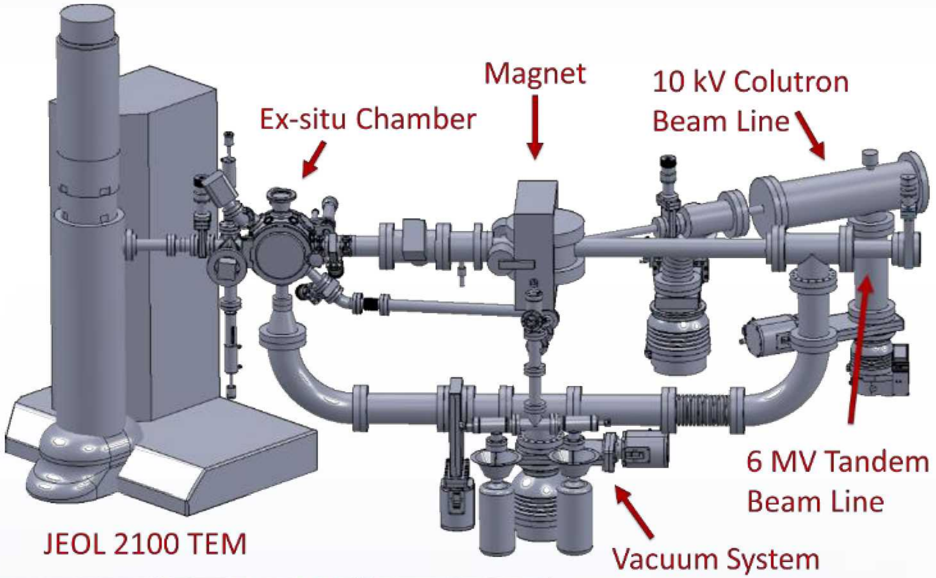


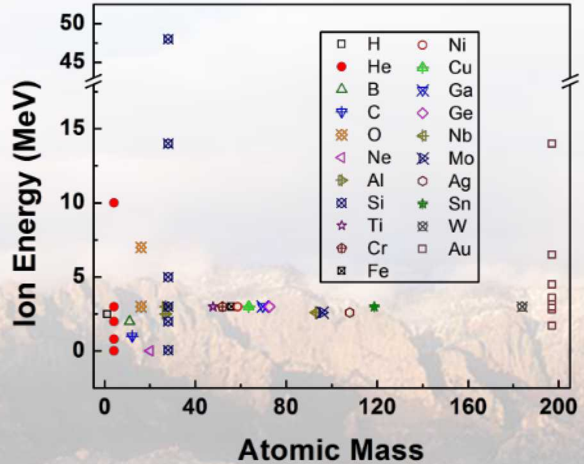
$$2D_{Gb}t_c = \frac{x^2\ RT}{s V_m}$$

Sandia's Concurrent *In situ* Ion Irradiation TEM Facility

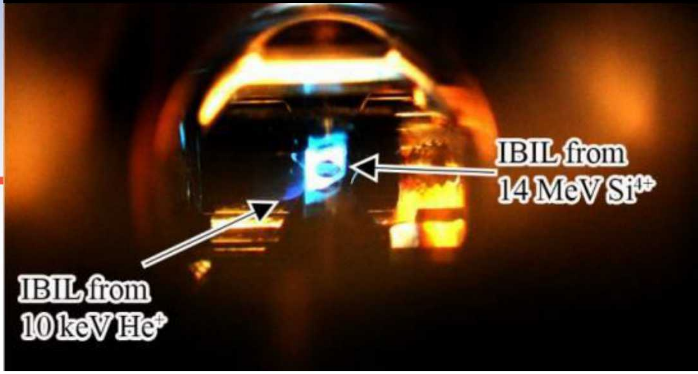
Collaborator: D.L. Buller

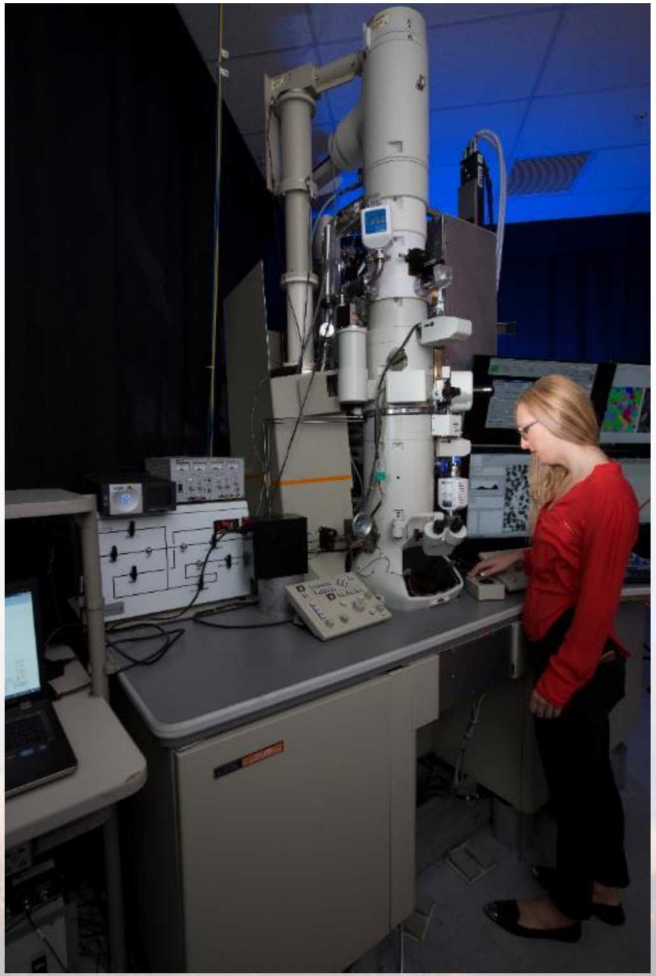
10 kV Colutron - 200 kV TEM - 6 MV Tandem





IBIL from a quartz stage inside the TEM



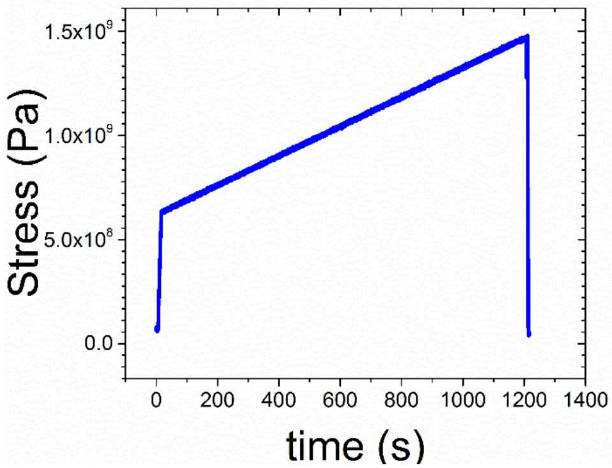


In situ TEM Ion Irradiation + Mechanical Testing = *In situ* TEM Irradiation Creep

Contributors: G.S. Jawaharram, S. Dillon & R.S. Averback

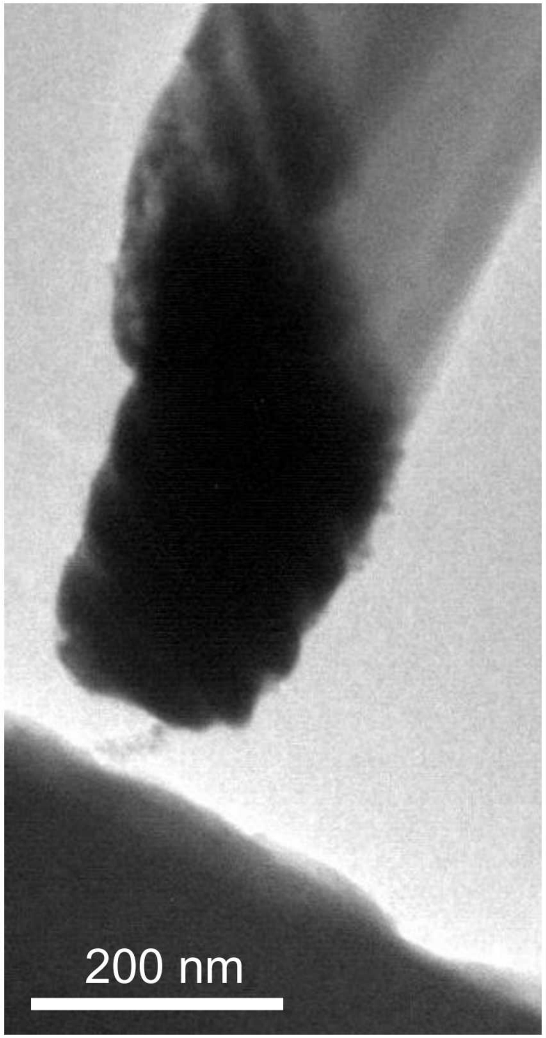
Controlled Loading Rate Experiments

4 MeV Cu^{3+}
10^{-2} DPA/s

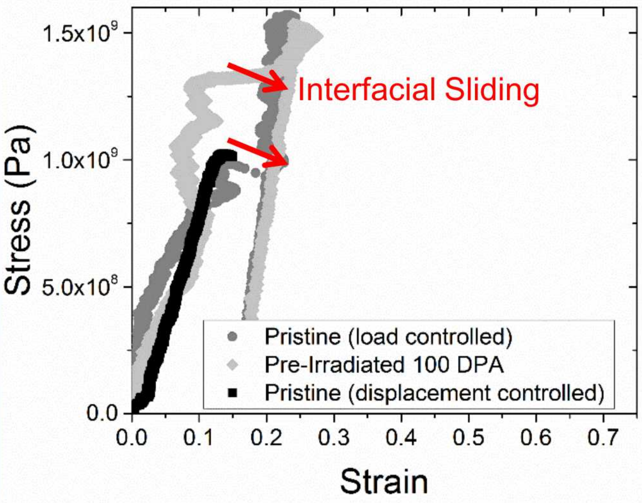


In-situ TEM radiation creep is feasible!

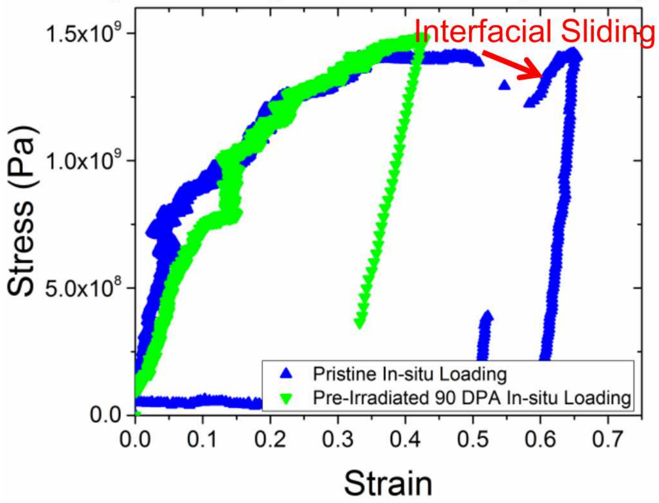
50 nm Cu-W multilayer
20 Min



No Irradiation
(Loading rate 0.6 Mpa s^{-1})



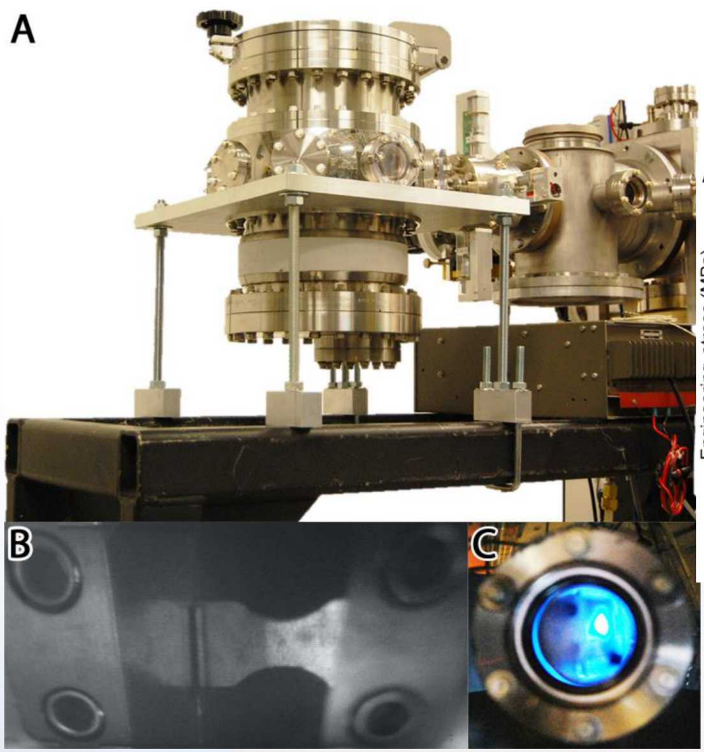
Irradiation Creep
(Loading rate 0.6 Mpa s^{-1})

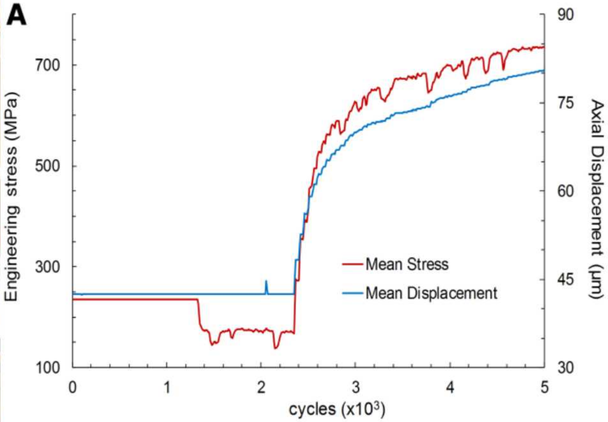


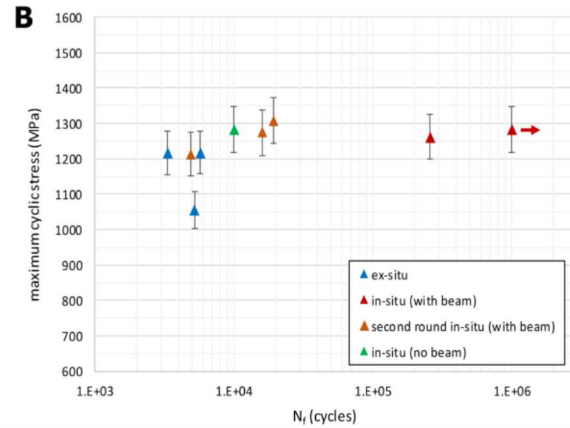
Ex situ Mechanical Testing End Station

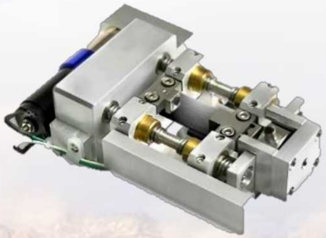
Collaborators: D. Buller, B. Boyce, J. Carroll, P. Price, C. Taylor, B. Muntifering, S. Briggs, N. Heckman, J.A. Scott

- Combined three individual mechanical testing in tandem beamline end station
- Limited (optical, IR only) imaging capabilities
- Have successfully collected preliminary data using this system



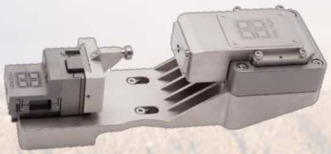


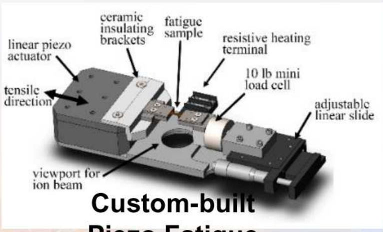




MTI Fullam Straining Heating

Hysitron PI85 Nanoindenter



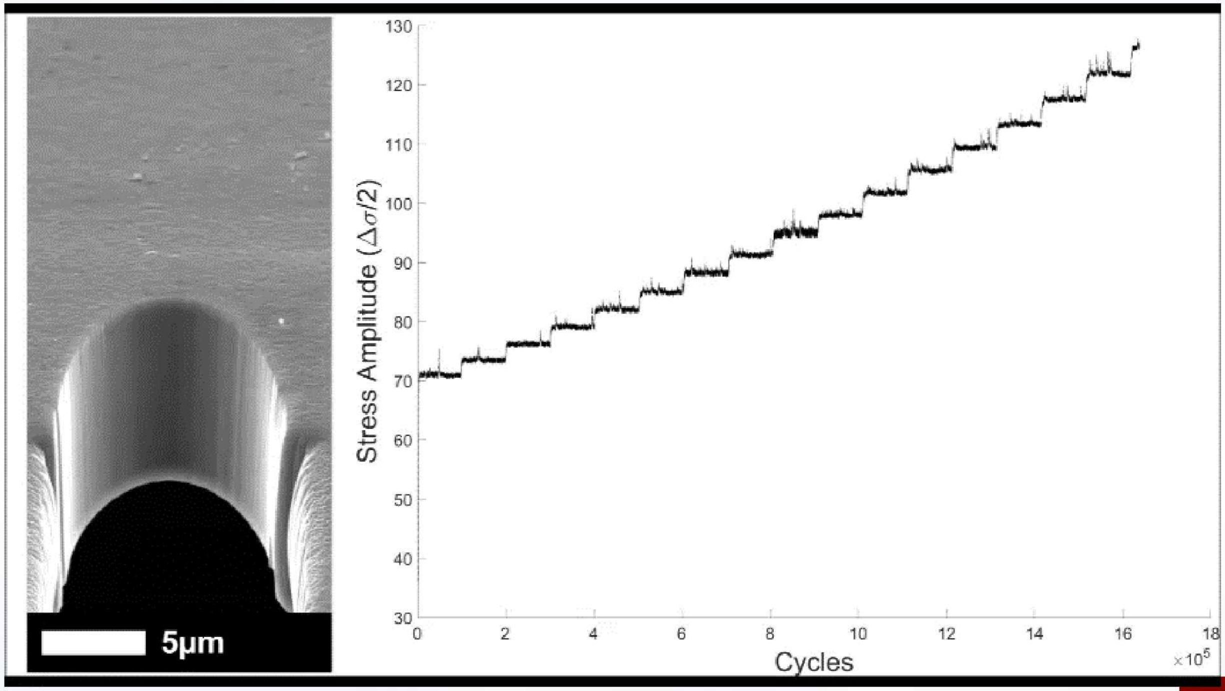


Custom-built Piezo Fatigue tester

Gatan Cryostage

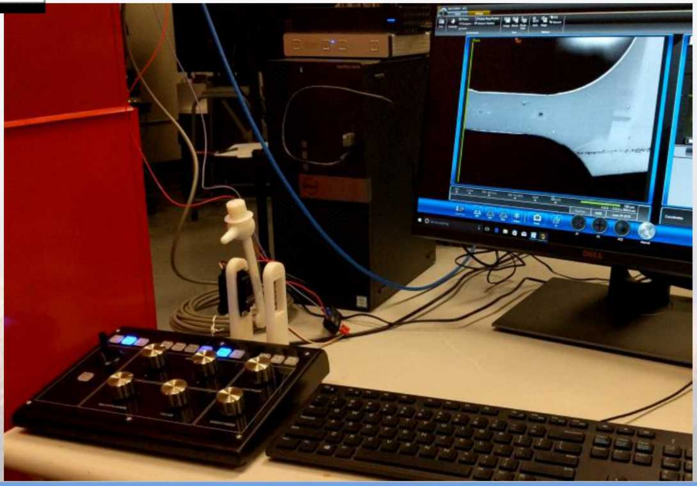
In situ High-cycle Fatigue

Collaborators: .N. Heckman, B.L. Boyce,



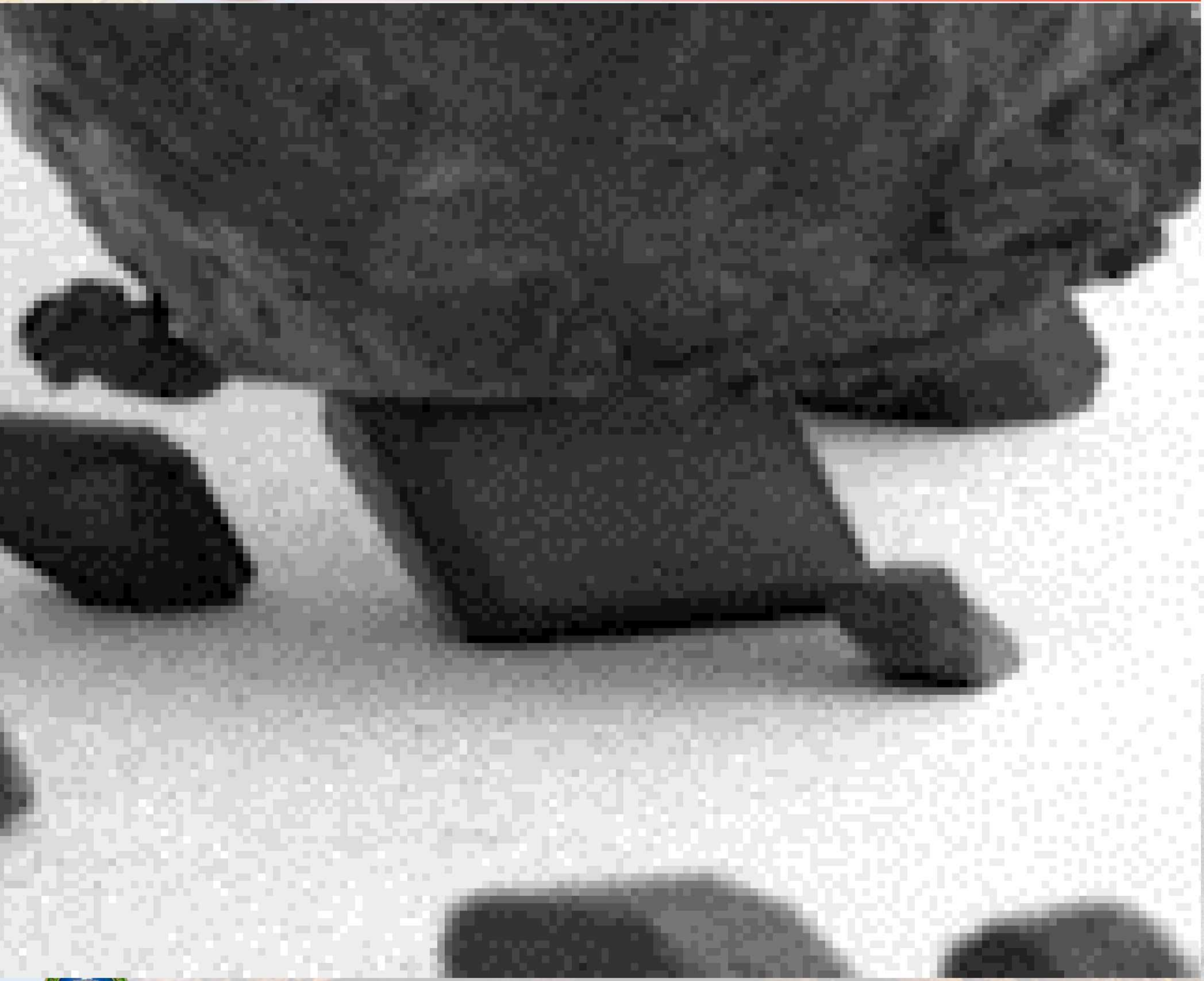
- Nanocrystalline Ni-40Fe, 10-60 nm grain size, 10 μm notch, imaged at 60˚
- Cycled at 30 Hz, 4000 cycles between images

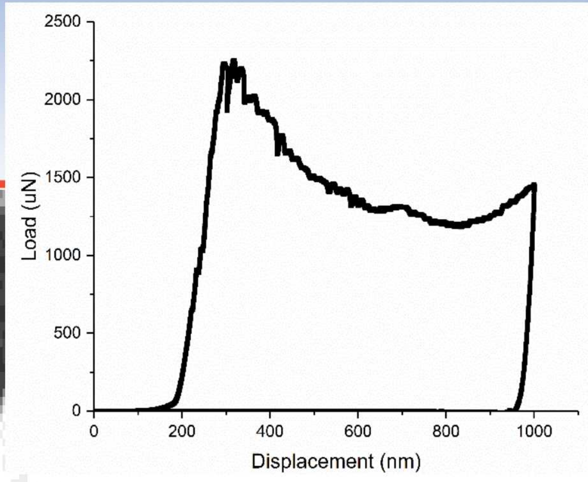
Direct insight into crack propagation and failure during cyclic loading

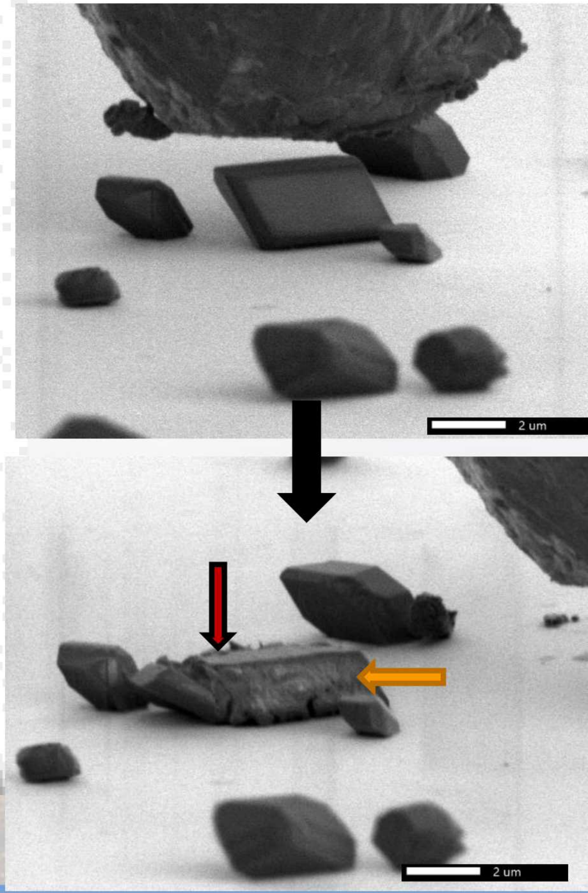


In situ Compression: Molecular Crystals

Collaborators: C.M. Barr, M. Cooper, D.C. Bufford, and J. Lechman



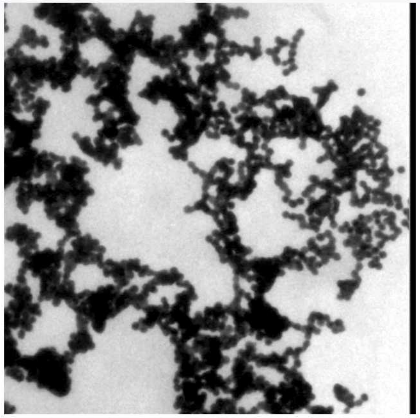




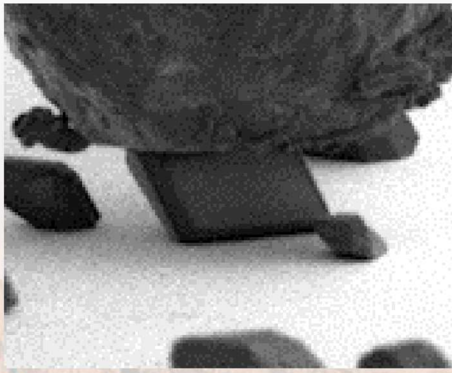
Displacement controlled fracture of molecular crystal

Unconventional *In situ* Microscopy Creates a Wealth of Possibilities

- Plethora of extreme environments that have not been fully explored.
- Utilizing the TEM as an experimental chamber provides a range of nanoscale extreme environments.
- Combining extreme conditions opens up the ability more complex real world applications.
- ACOM and other analytical techniques coupled with in situ observations provides a nice bridge to MD and mesoscale modeling.
- If you would like to hear about the I^3SEM let me know



The future is bright and fastly approaching for coupled *in situ* TEM



<u>Collaborators:</u>

D.L. Buller, D.C. Bufford, S.H. Pratt, T.J. Boyle, B.A. Hernandez-Sanchez, S.J. Blair, B. Muntifering, C. Chisholm , P. Hosemann, A. Minor, J. A. Hinks, F. Hibberd, A. Ilinov, D. C. Bufford, F. Djurabekova, G. Greaves, A. Kuronen, S. E. Donnelly, K. Nordlund, F. Abdeljawad, S.M. Foiles, J. Qu, C. Taylor, J. Sugar, P. Price, C.M. Barr, D. Adams, M. Abere, L. Treadwell, A. Cook, A. Monterrosa, IDES Inc, J. Sharon, B. L. Boyce, C. Chisholm, H. Bei, E.P. George, W. Mook, Hysitron Inc., G.S. Jawaharram, S. Dillon, R.S. Averback, N. Heckman, J. Carroll, S. Briggs, E. Carnes, J. Brinker, D. Sassaki, T. Nenoff, B.G. Clark, P.J. Cappillino, B.W. Jacobs, M.A. Hekmaty, D.B. Robinson, L.R. Parent, I. Arslan, K. Jungjohann & Protochips

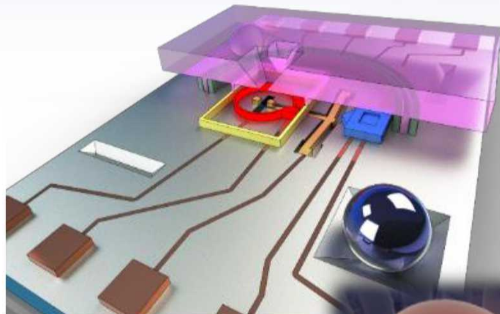
This work was partially funded by the Division of Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. This work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

Nuclear Science User Facilities

Sandia National Laboratories

Sandia's User and Position <u>Oppurtunities</u>

D. Hanson, W. Martin, M. Wasiolek

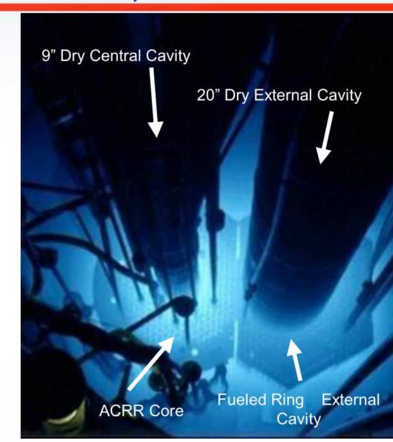


www.cint.lanl.gov

- Spring and Fall proposals for 18 months
- Rapid Access proposal anytime for 3 months

www.nsuf.inl.gov

- Three proposal a year for 9 months



Core Facility - SNL

Gateway Facility - LANL

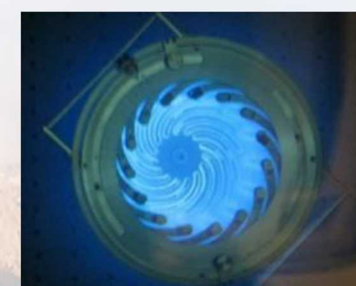
Position Oppurtunities at:

https://www.sandia.gov/careers/

Post-doc = 671121

Grad Student = 670865

Undergrad Student = 670864



This work was partially funded by the Division of Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Materials Science and Engineering, Office of Basic Energy Sciences, U.S. Department of EnergyThis work was performed, in part, at the Center for Integrated Nanotechnologies, an Office of Science User Facility operated for the U.S. Department of Energy (DOE) Office of Science. Sandia National Laboratories is a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. DOE's National Nuclear Security Administration under contract DE-NA-0003525. The views expressed in the article do not necessarily represent the views of the U.S. DOE or the United States Government.

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