Irradiation Creep in Nanostructures Measured Using In-situ TEM

SAND2018-2384C

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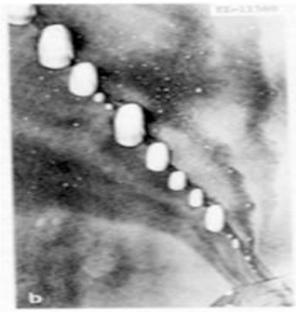
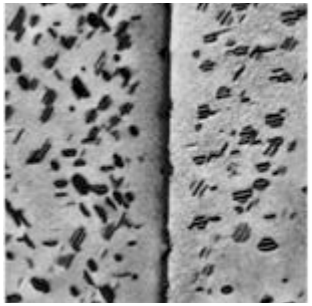
Example Issues in Nuclear Materials

Microscopic

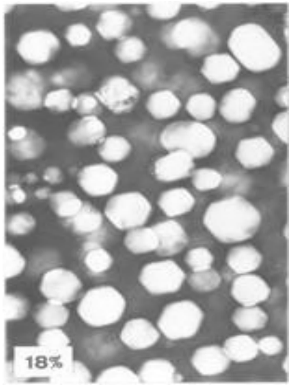
Gas Bubbles



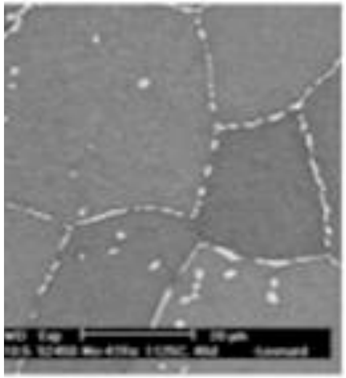
Voids



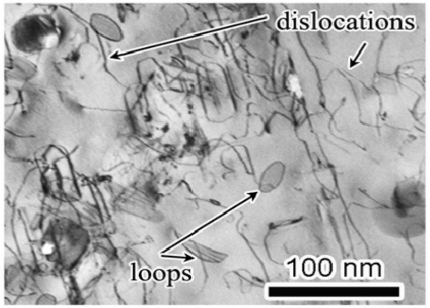
Precipitation



Segregation

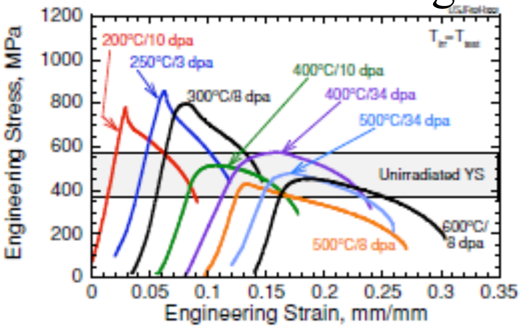


Line Defects



Macroscopic

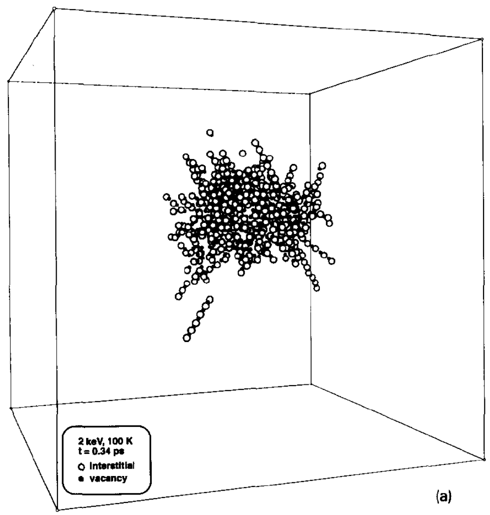
Radiation hardening



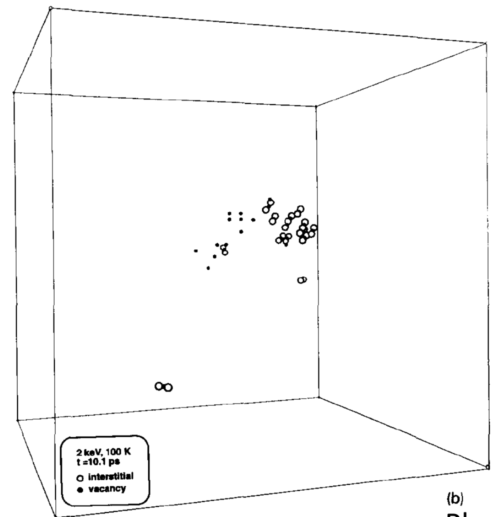
Swelling/Creep

S.J. Zinkle, *Mater Today (2009)*

Point Defect Production and Annihilation



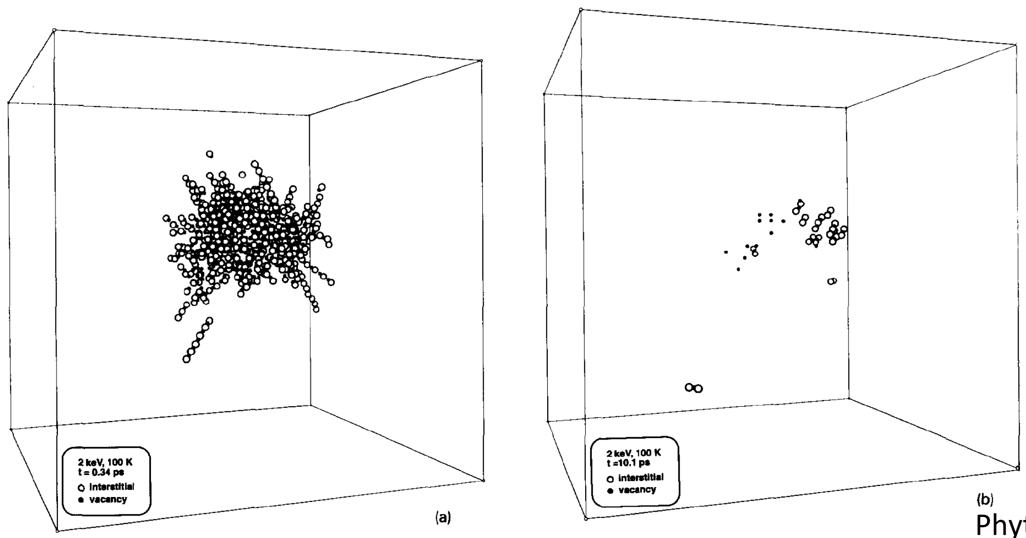
(a)



(b)

Phythian et al. *J. Nuc. Mater.* (1995)

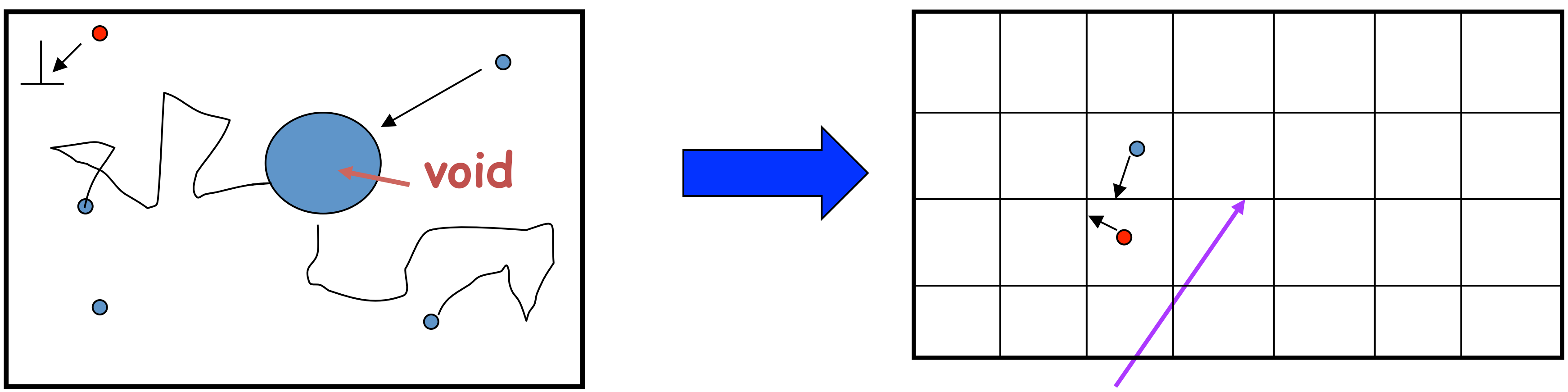
Point Defect Production and Annihilation



Phythian et al. *J. Nuc. Mater.* (1995)

Conventional materials

Nanostructured materials



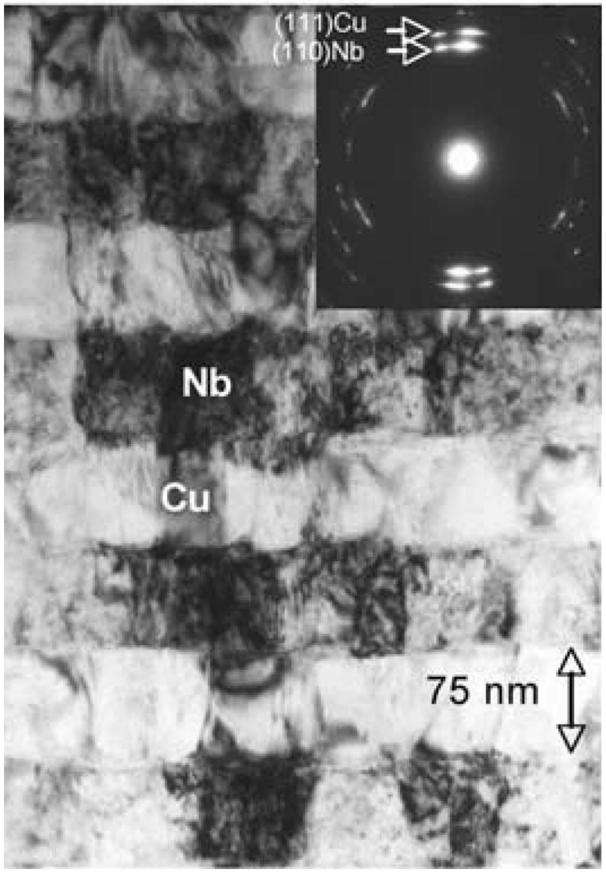
Vacancies, interstitials

Interface & Grain boundaries (defect sinks)

Schematic from Bellon et al.

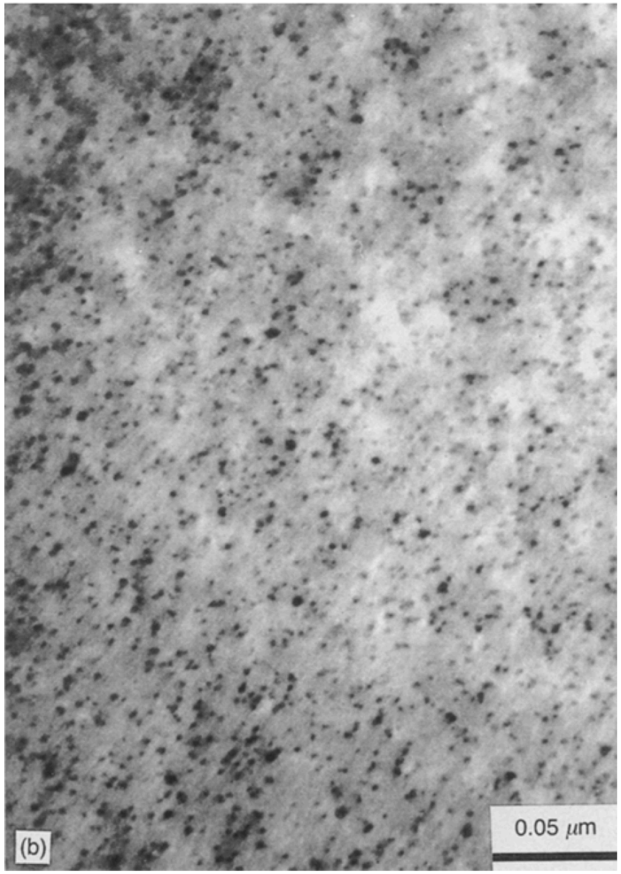
Nanostructured Alloys

Nanolaminates



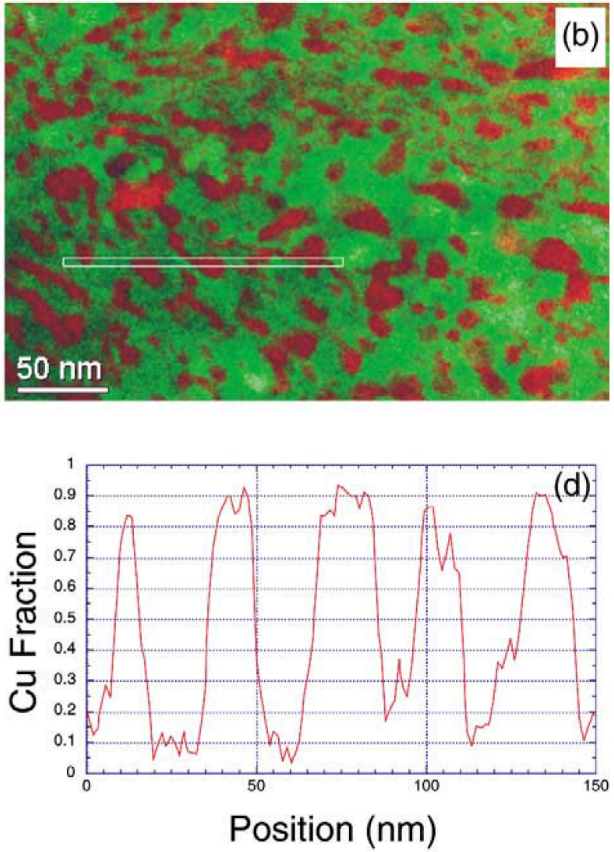
Misra and Hogland, *J. Mater. Sci.* (2007)

Oxide Dispersion Strengthened



Okuda and Fujiwara, *J. Mater. Sci. Lett.* (1995)

Self-Organizing Alloys

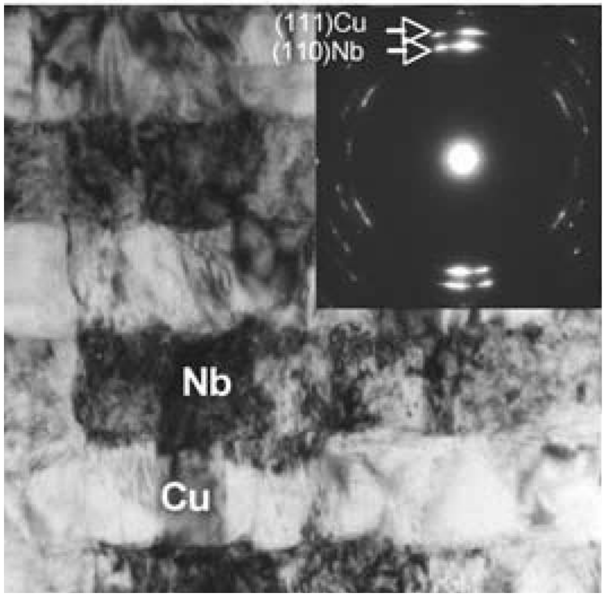


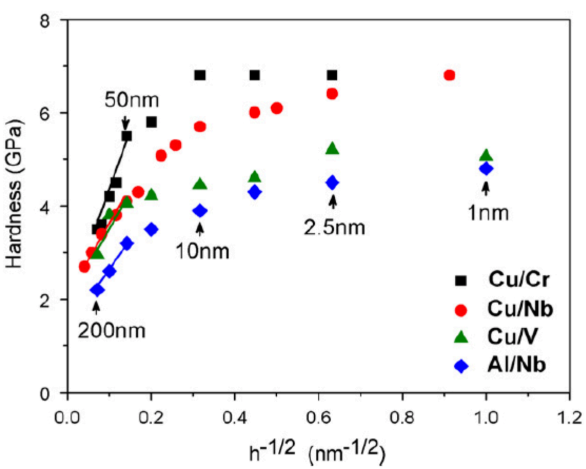
Zghal et al., *Acta Mater.*. (2002)

1. Relatively thermally stable
2. High strength
3. High density of interfaces for point defect recombination

Nanostructured Alloys

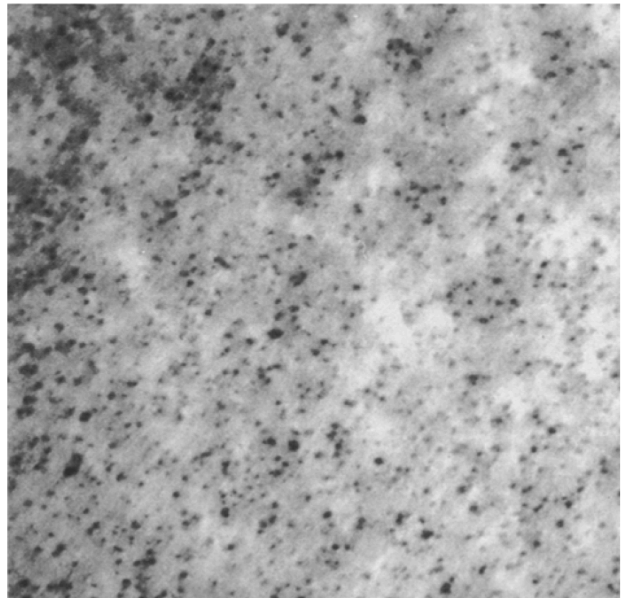
Nanolaminates

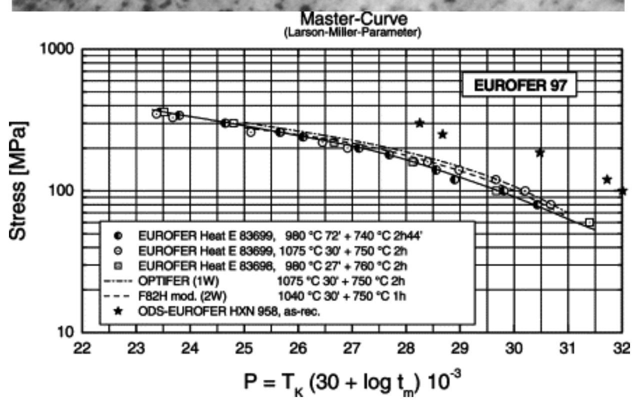




Misra and Hogland, *J. Mater. Sci.* (2007)
Fu et al., *Mater. Sci. A* (2008)

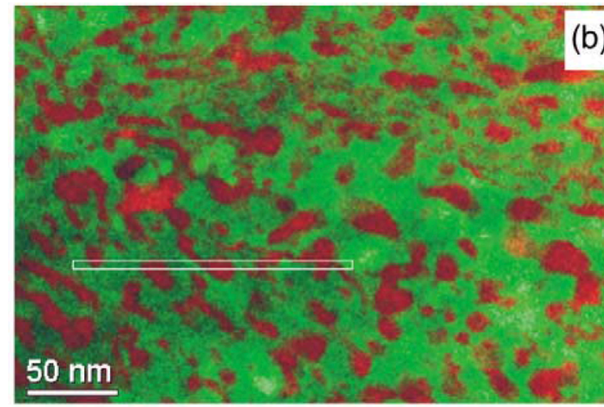
Oxide Dispersion Strengthened

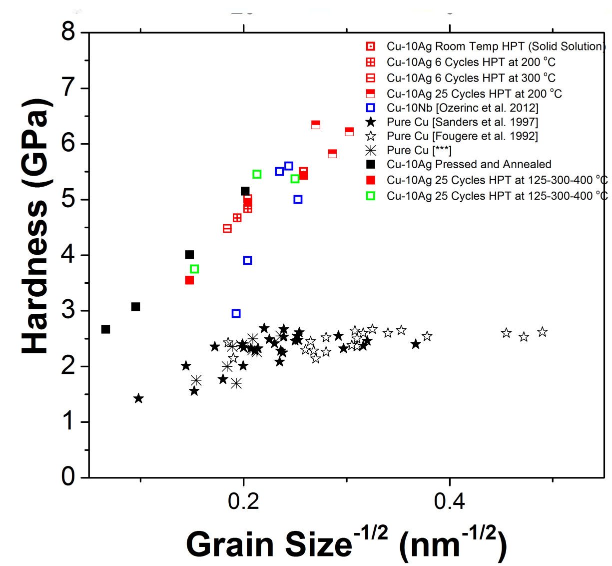




Okuda and Fujiwara, *J. Mater. Sci. Lett.* (1995)
Lindau et al., *J. Nuc. Mater.* (2002)

Self-Organizing Alloys

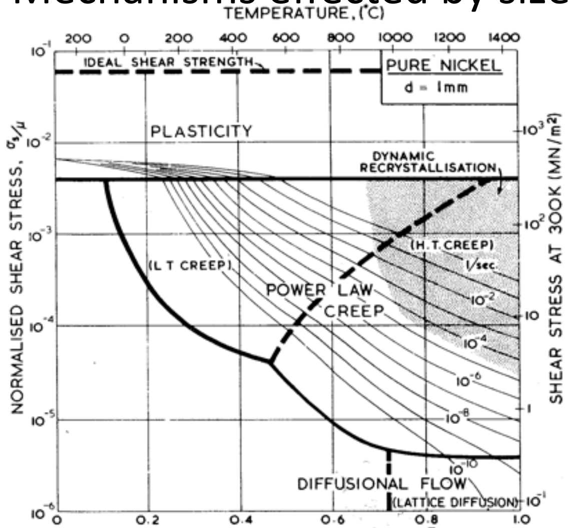


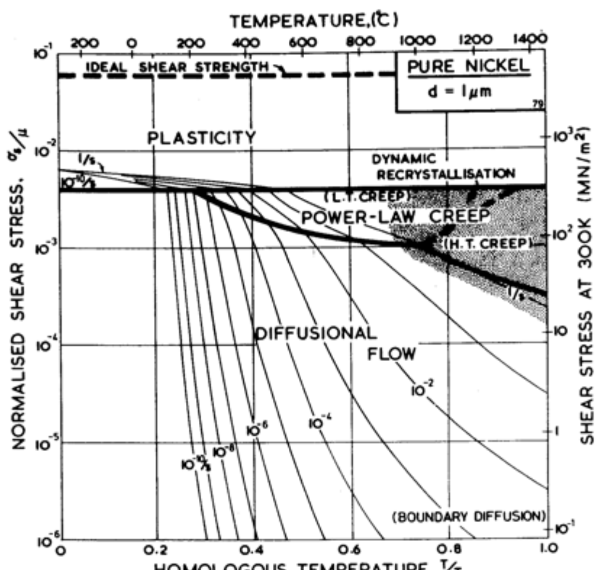


Zghal et al., *Acta Mater..* (2002)
Arshad, Thesis (2014)

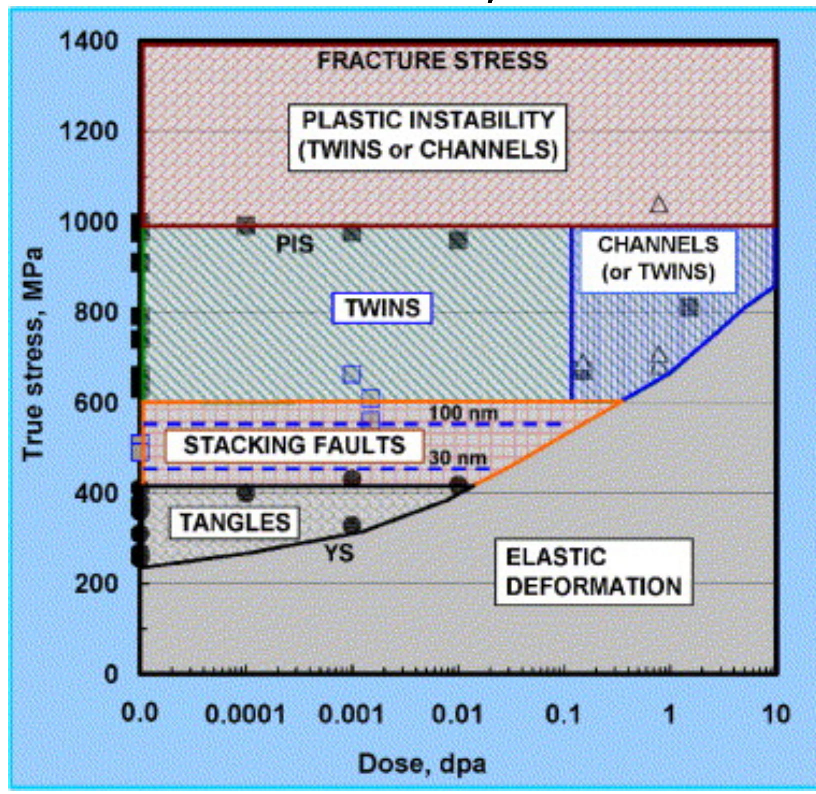
Size Effects (Nanograin) and Irradiation Induced Creep (IIC)?

Mechanisms effected by size





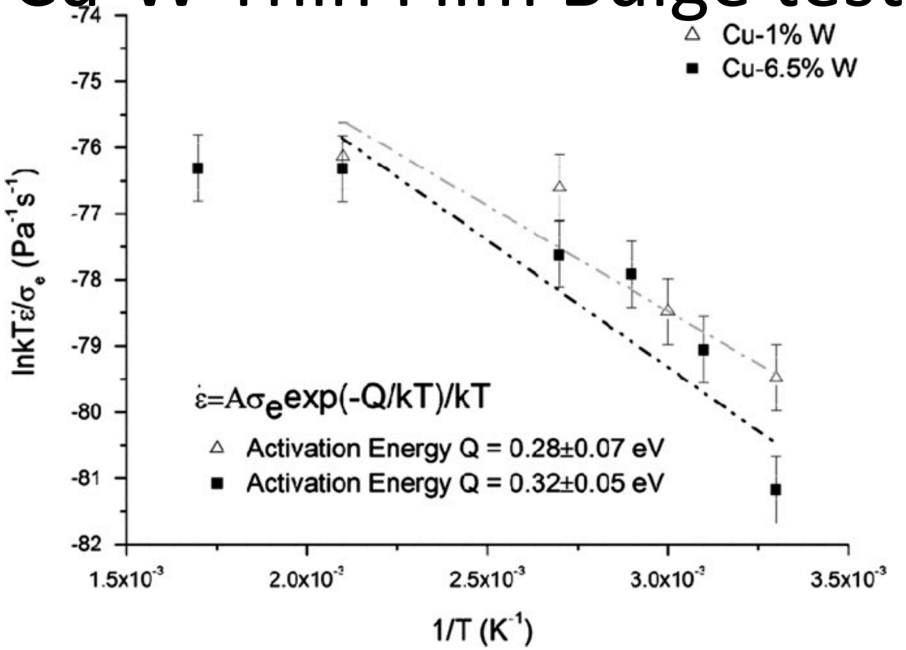
Mechanisms effected by irradiation

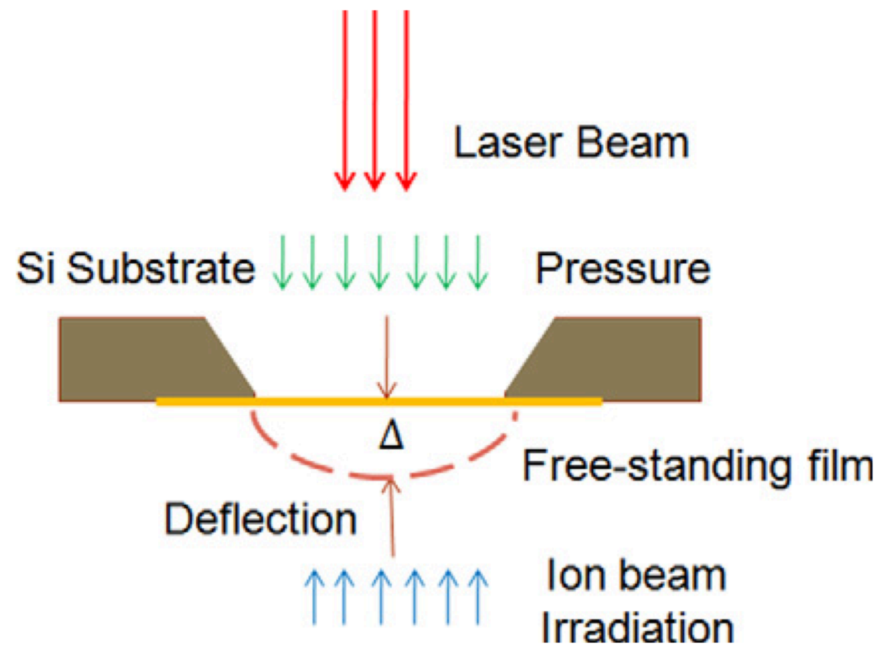


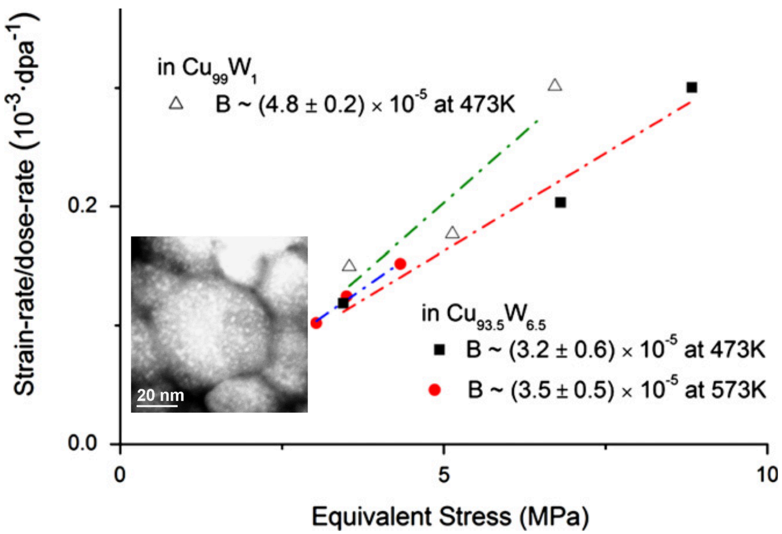
Frost and Ashby, Deformation-Mechanism Maps

Byun et al. JNM (2006)

Nanocrystalline Irradiation Creep Mechanisms
Cu-W Thin Film Bulge test

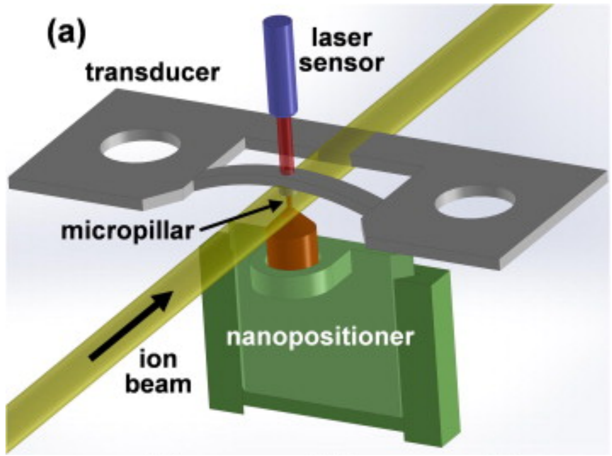


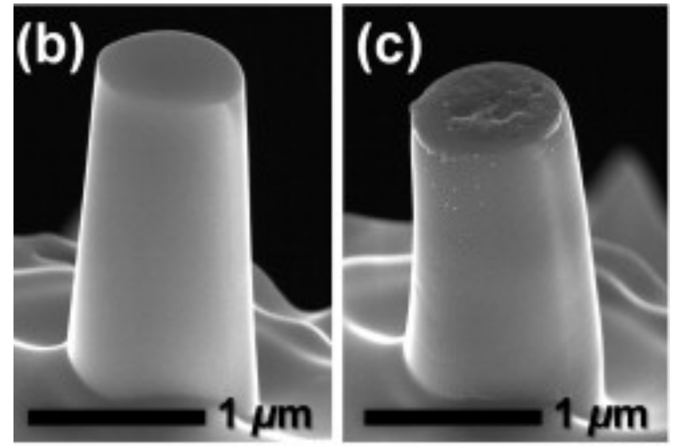


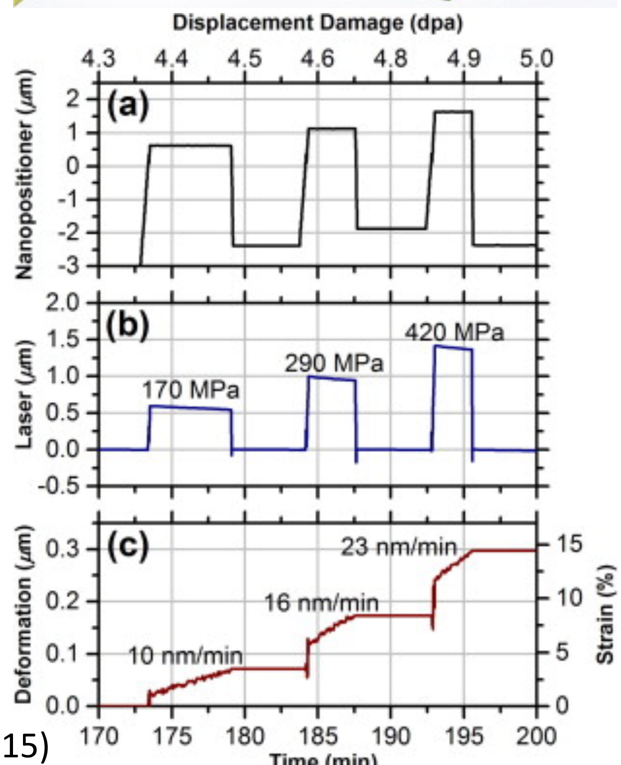


Tai et al. J. Nuclear Mater. (2012)

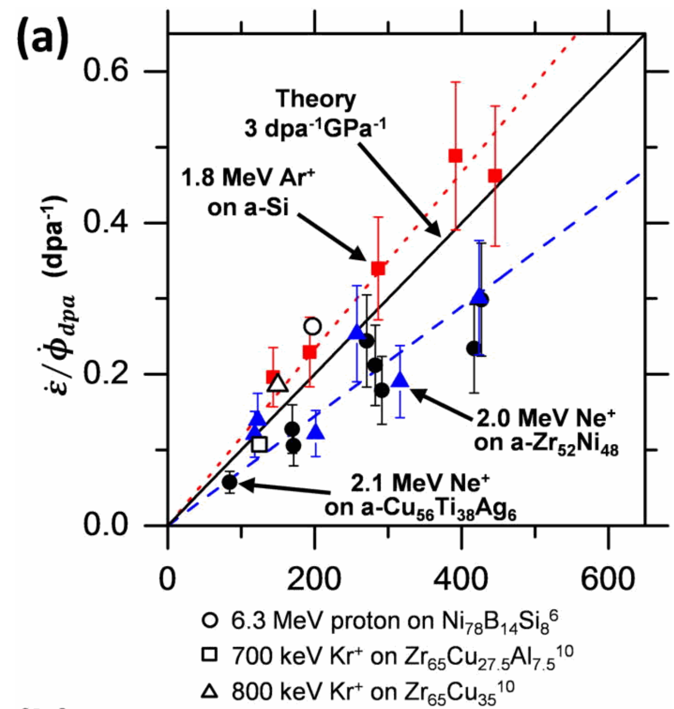
Nanopillar Experiments





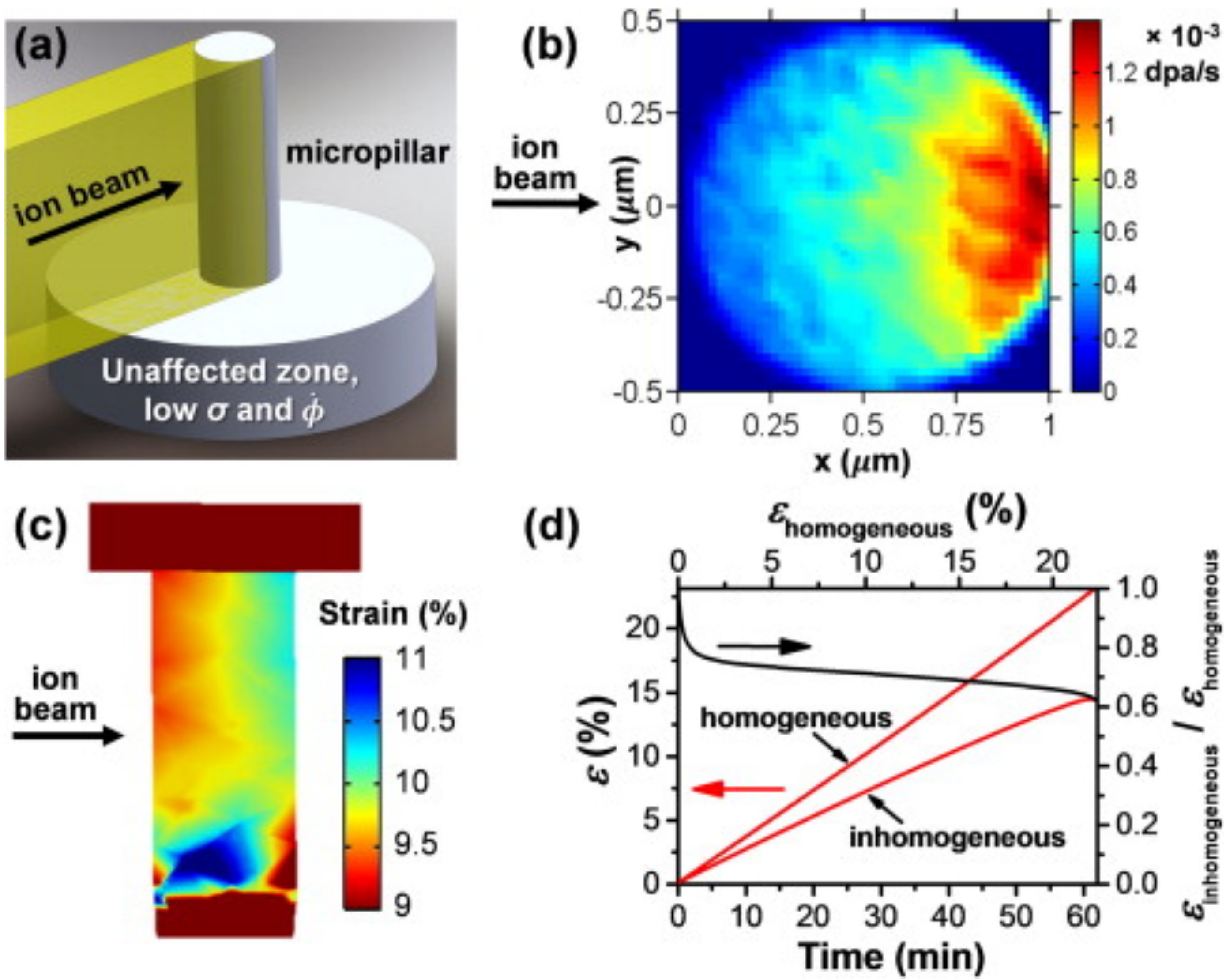


Ozerinc et al. JNM (2015)



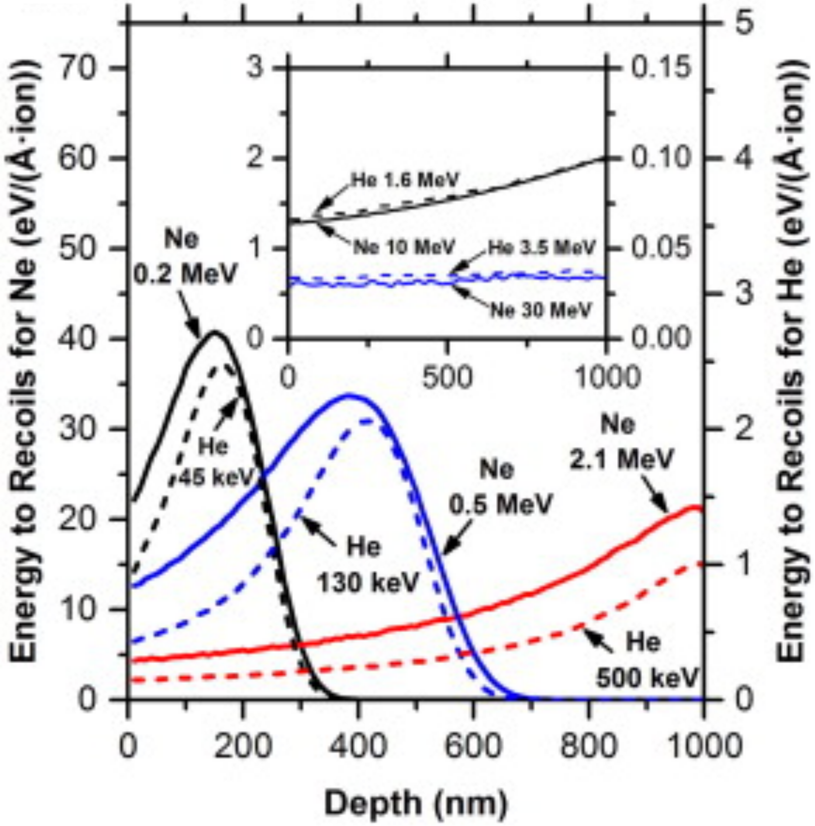
Ozerinc et al. JAP (2015)

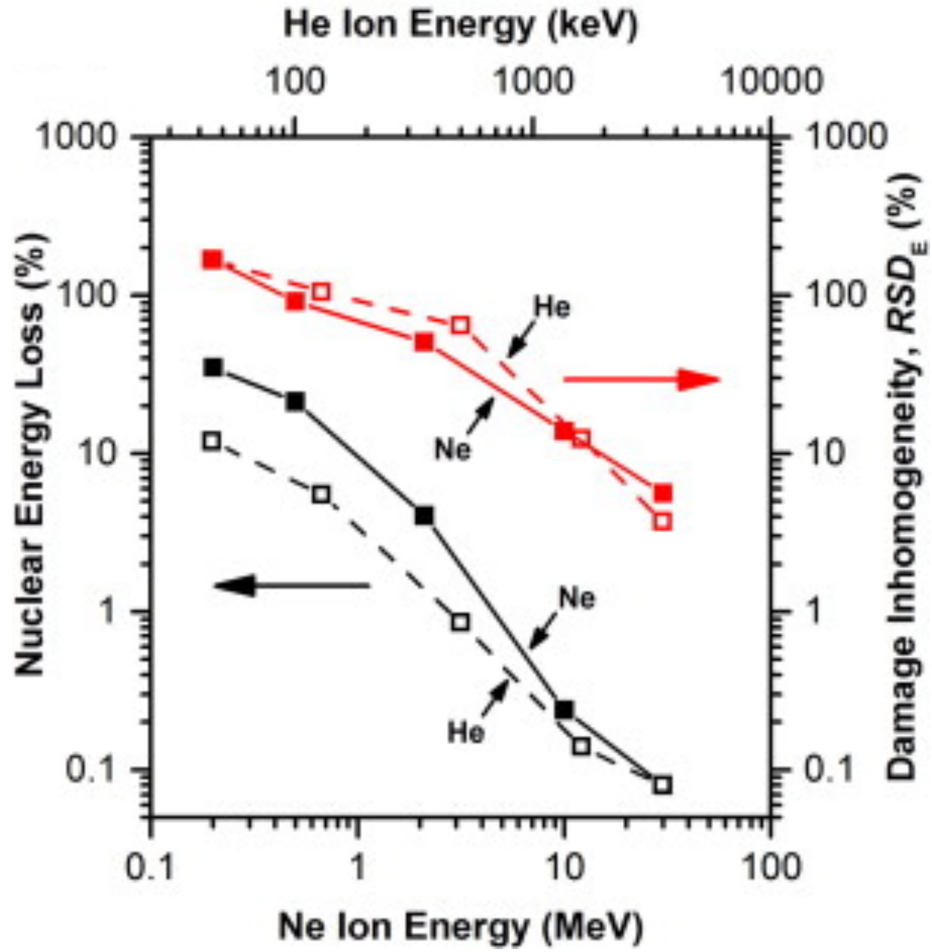
Experimental Challenges



Ozerinc et al. JNM (2015)

Experimental Challenges

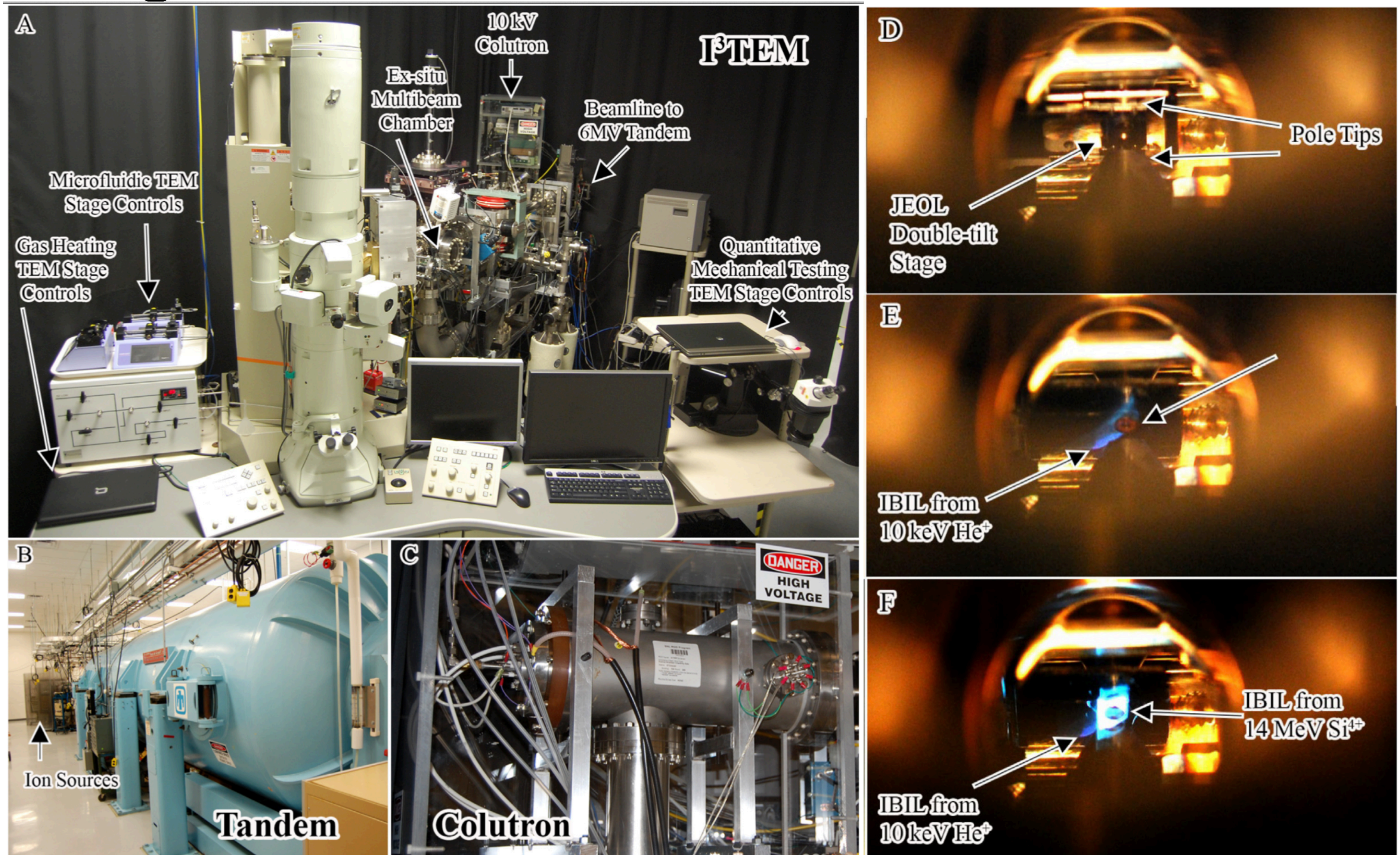




1. Selection of particle for irradiation to high dose
2. Need for small specimens for homogeneous ion damage
3. Testing of bulk materials (not thin films)

Ozerinc et al. JNM (2015)

Measuring Irradiation Creep In-situ Using Sandia National Lab. IBL I^3TEM



Hattar et al. Nuclear Instruments and Methods in Physics Research B (2014)

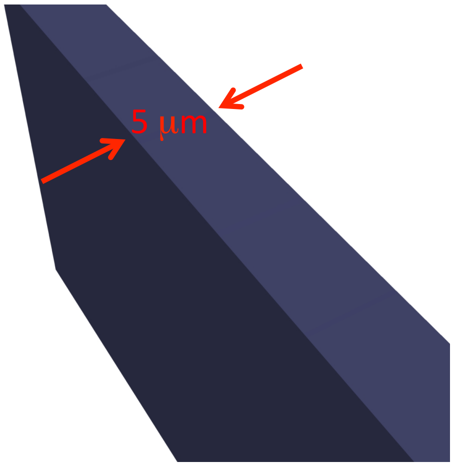
Goals and Experiments

- Can we measure IIC in the TEM (at high T)?
- Mechanical response of nanograin and nanolaminate materials under irradiation
- Pillar size effect at high T in the sink limited regime (Ag)

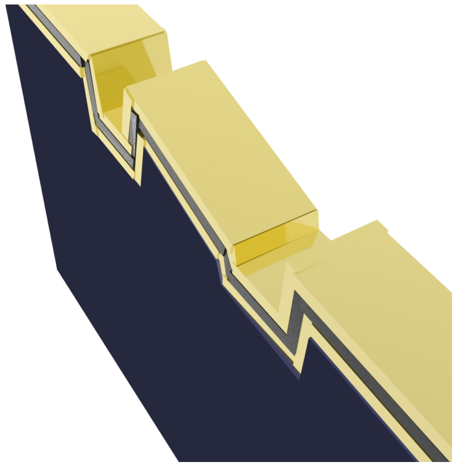
Sample Preparation and Testing

Multilayer Samples

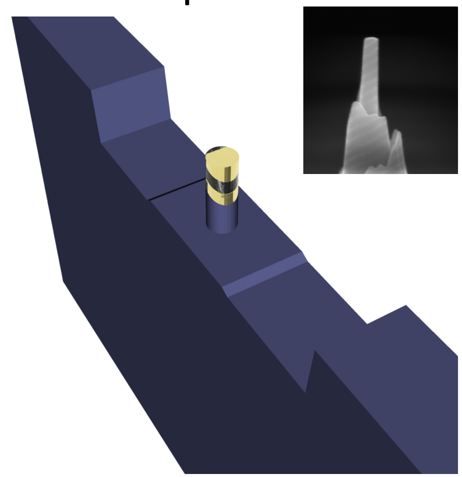
Substrate



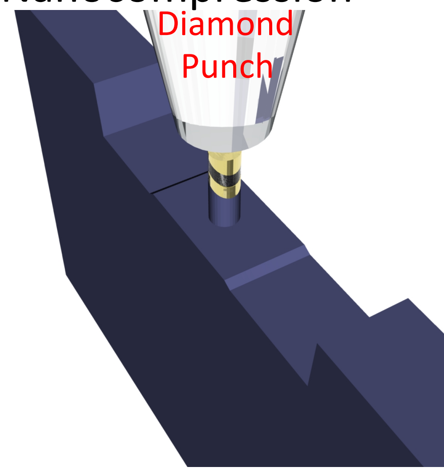
Pre-cut and Grow Films



FIB Sample



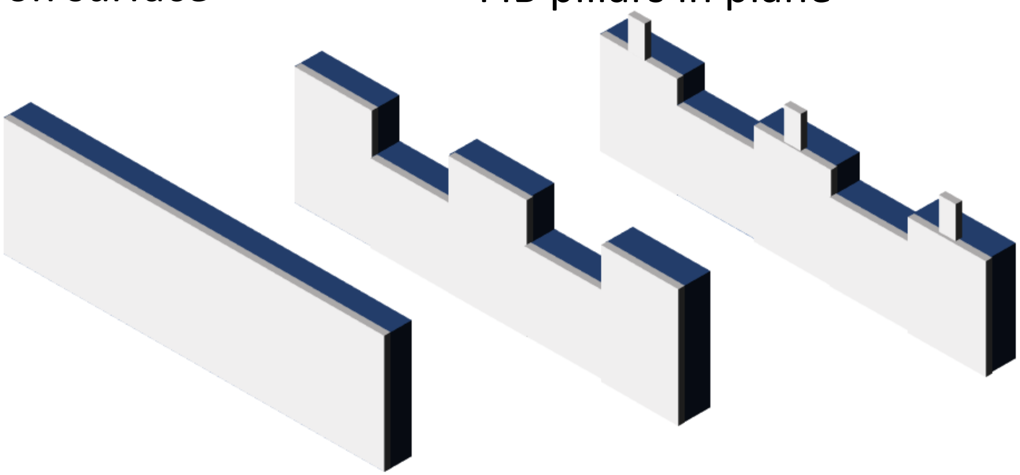
Nanocompression

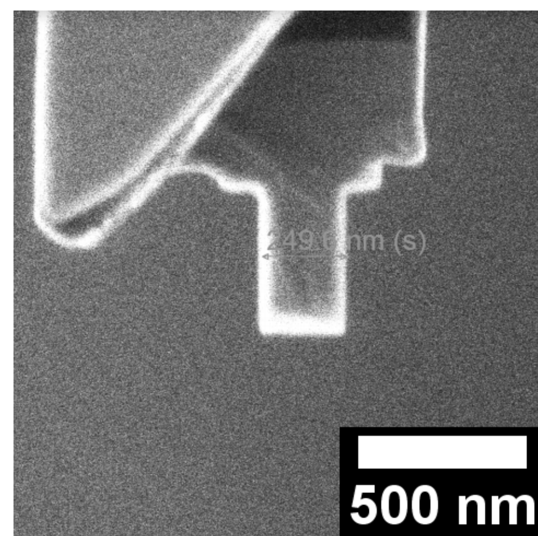


Ag Samples

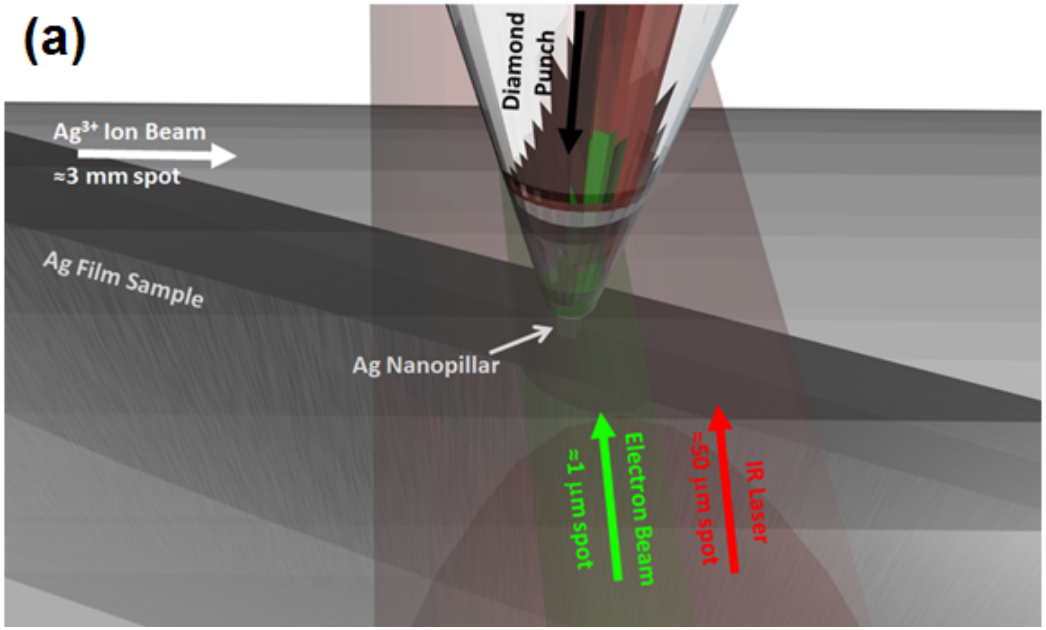
Film on surface

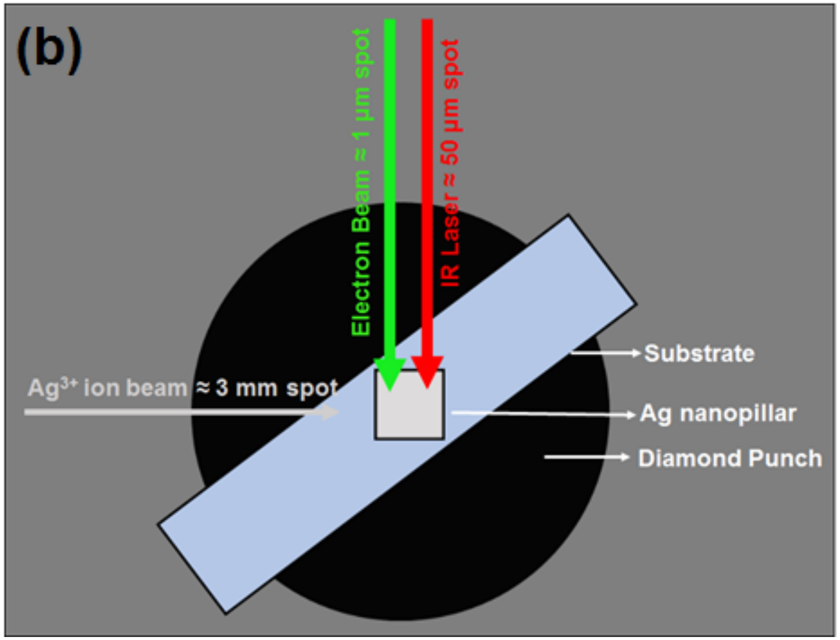
FIB pillars in plane



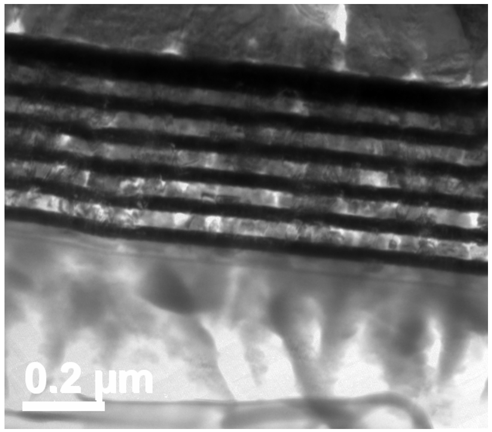


Loading Geometry

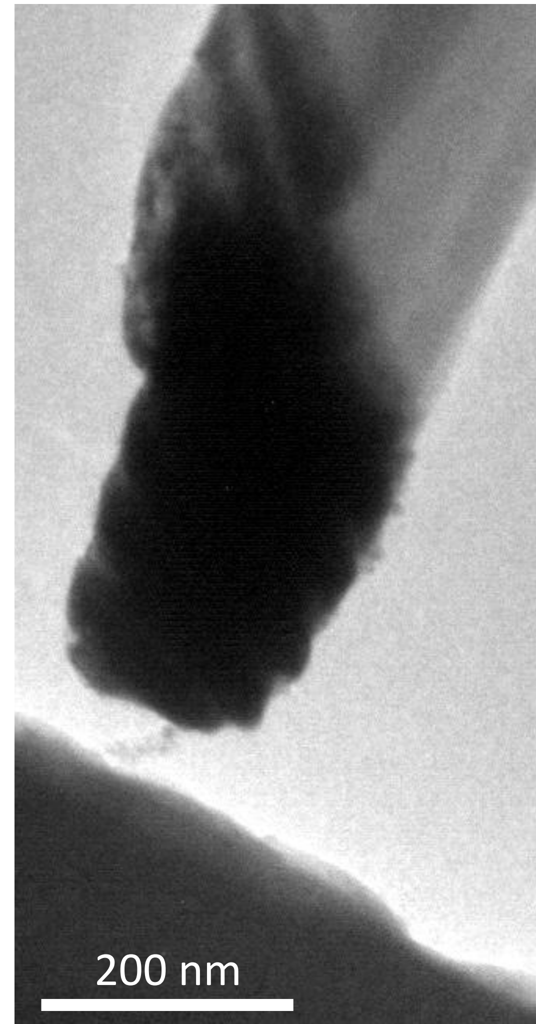




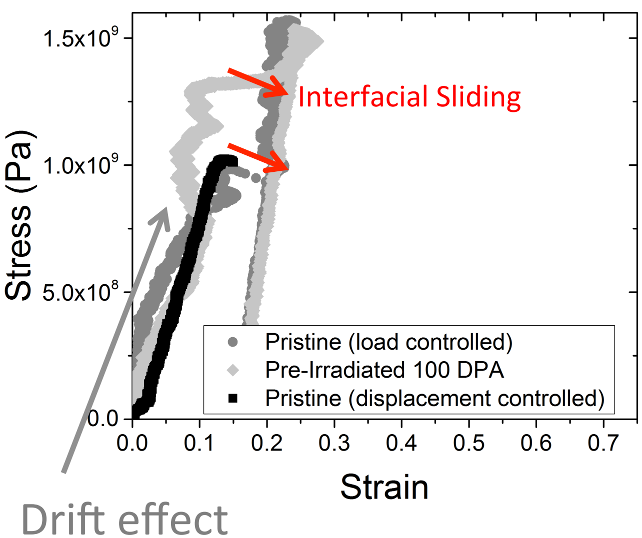
Irradiation Creep (4 MeV Cu^{3+} 10^{-2} DPA/s)



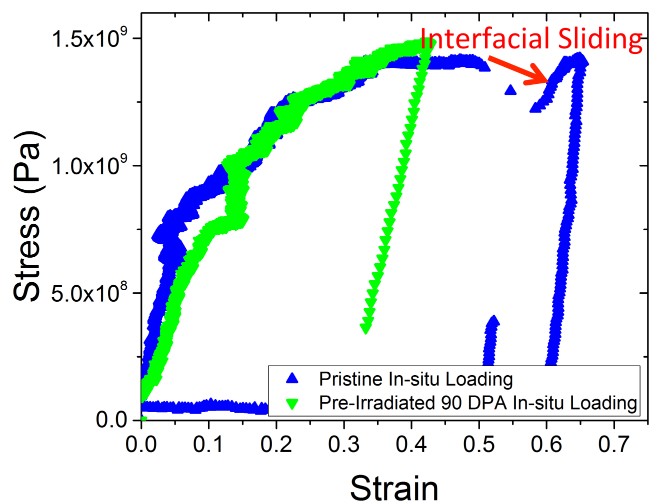
50 nm Cu-W multilayer
20 Min



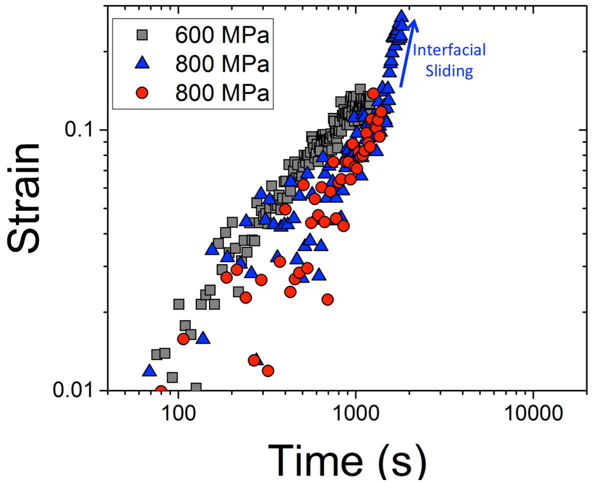
No Irradiation
(Loading rate 0.6 Mpa s^{-1})



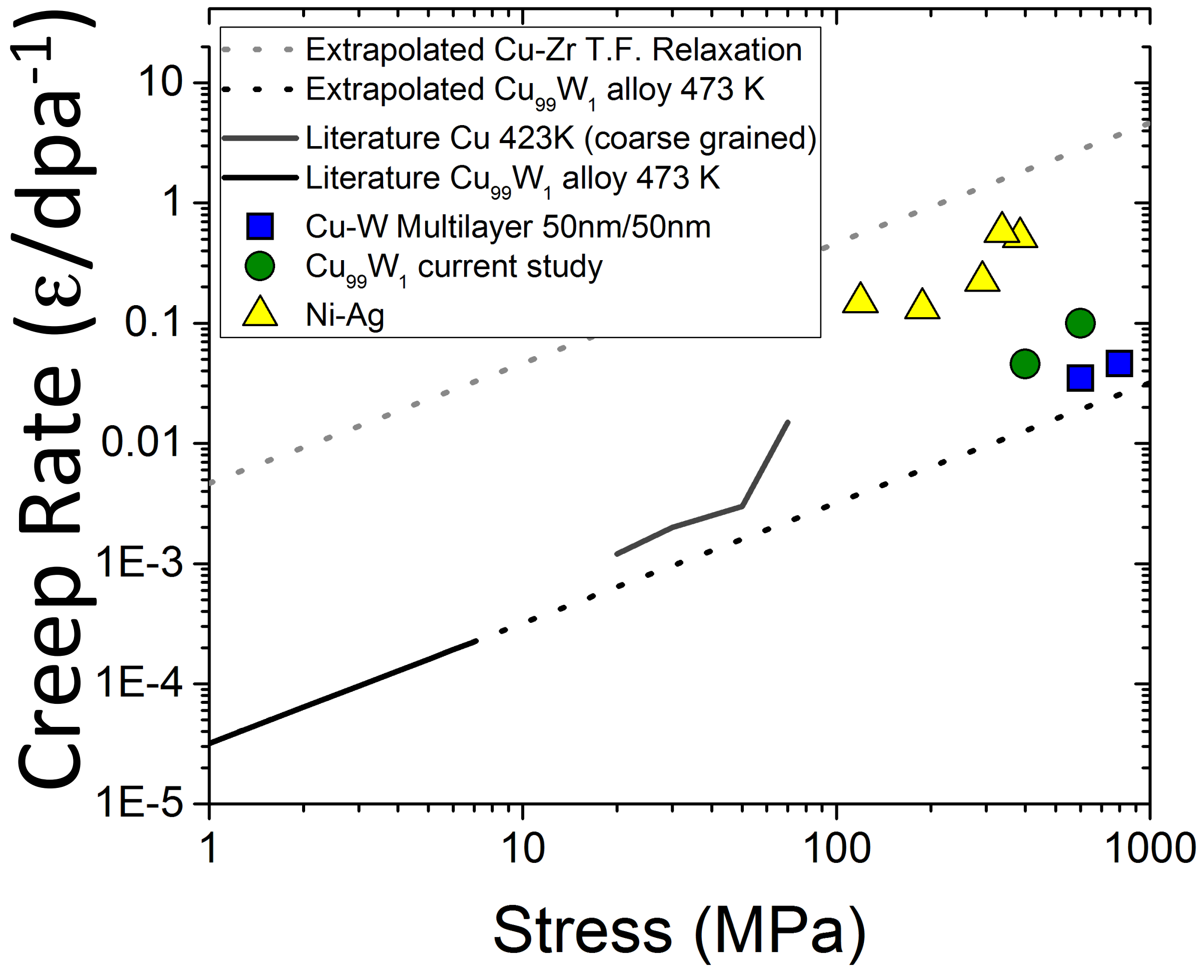
Irradiation Creep
(Loading rate 0.6 Mpa s^{-1})



Comparison of Steady-State Creep Data

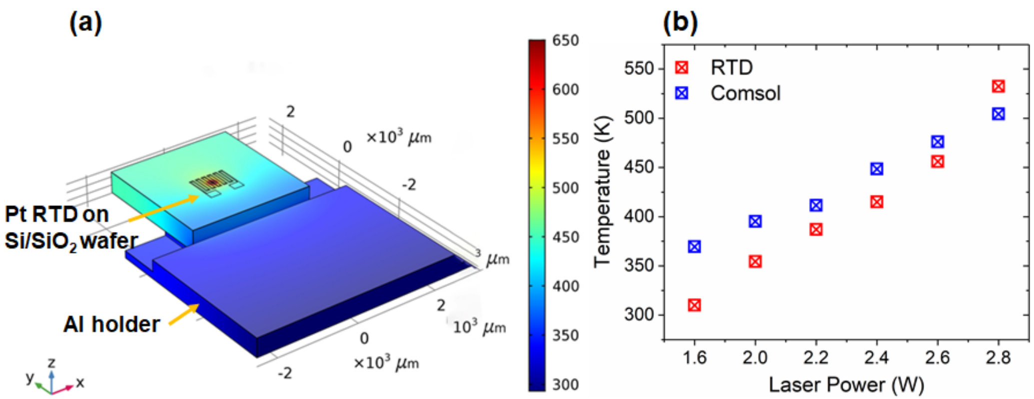


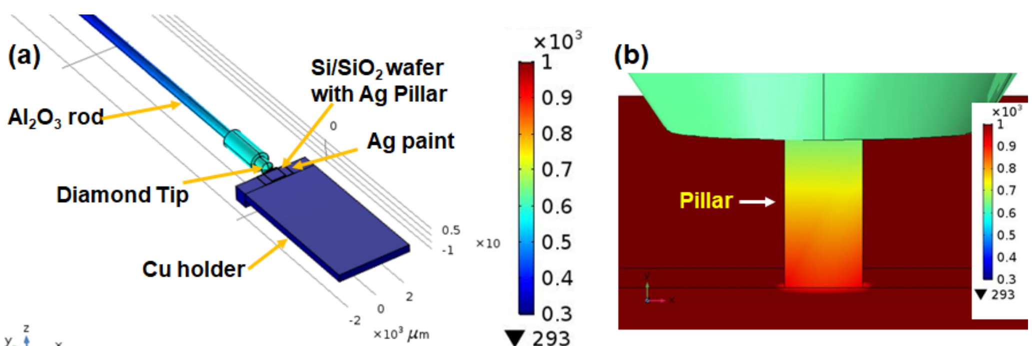
- R.T. IIC rate in nanoliminates significant at <10% σ_Y
- IIC rates in Ni-Ag approaching theoretical maximum
- Mechanism for Cu-W in high stress regime likely different than prior low stress measurements

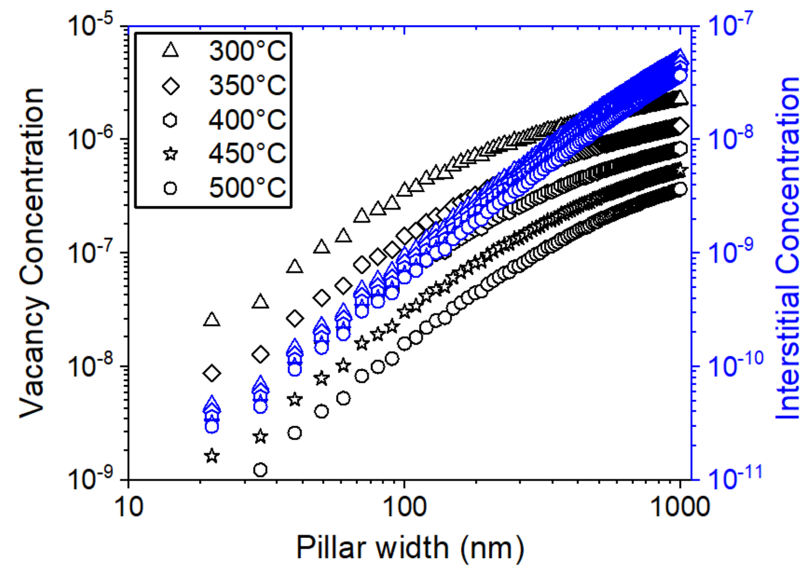


Dillon et al. J. Nuc. Mater. (2017)

High Temperature Experiments on Ag: Approximating Temperature Regime







Prior IIC on Ag

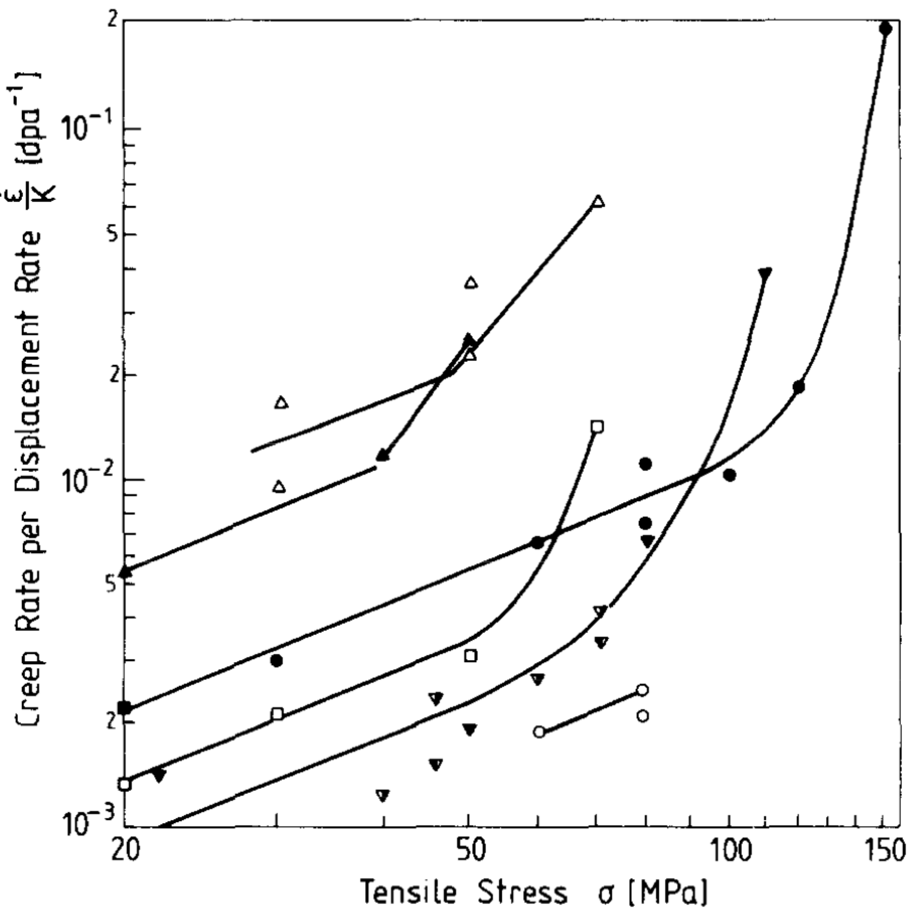
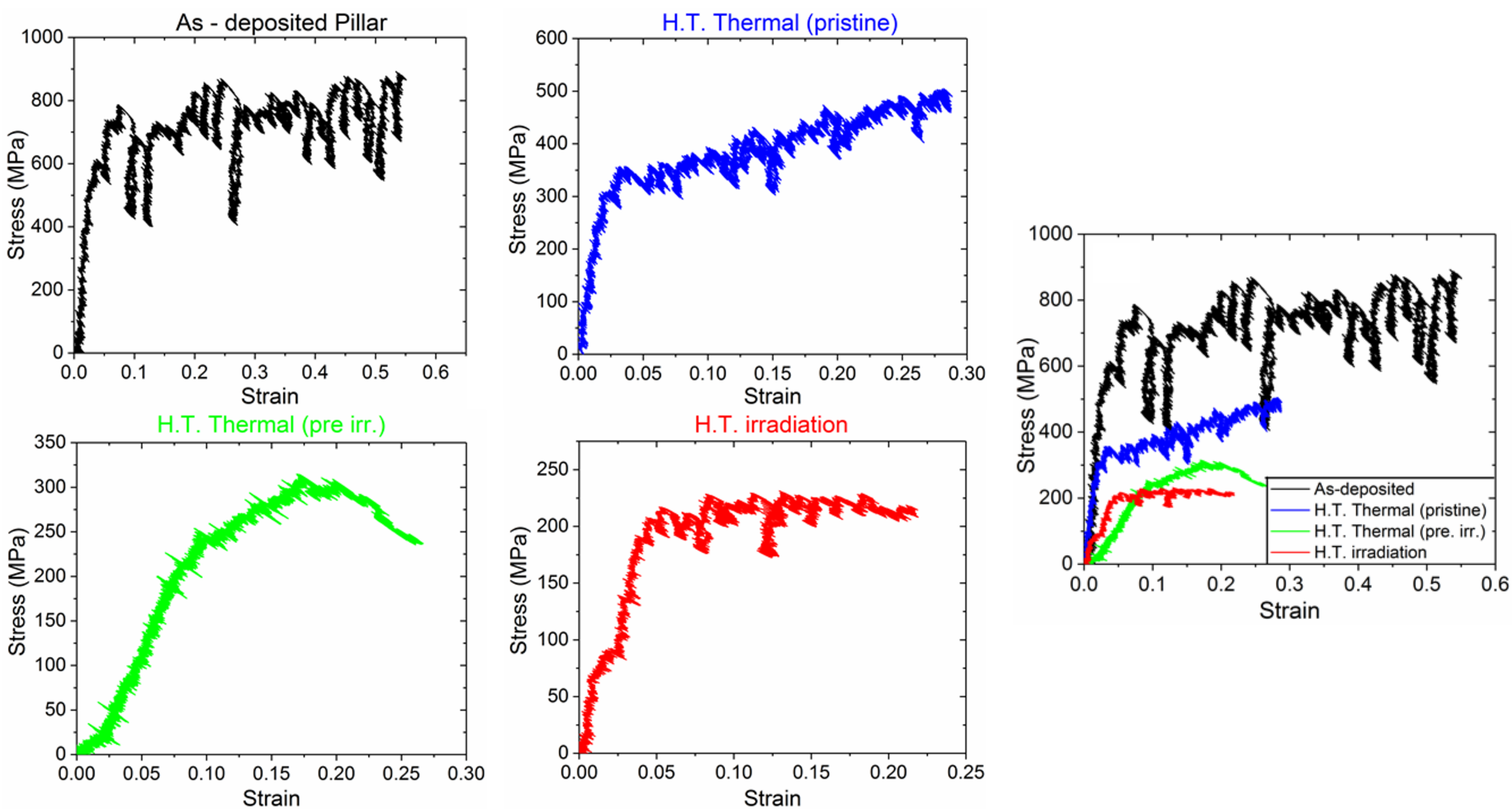


Fig. 5. Irradiation creep rate per displacement rate as a function of tensile stress of 50 μm foils of 20% c.w. high purity metals at various temperatures. Nickel: 200°C (○), 300°C (●); copper: 150°C (□), 200°C (■); silver: 97°C (△), 150°C (▲); platinum: 220°C (▽), 240°C (▽), 300°C (▼).

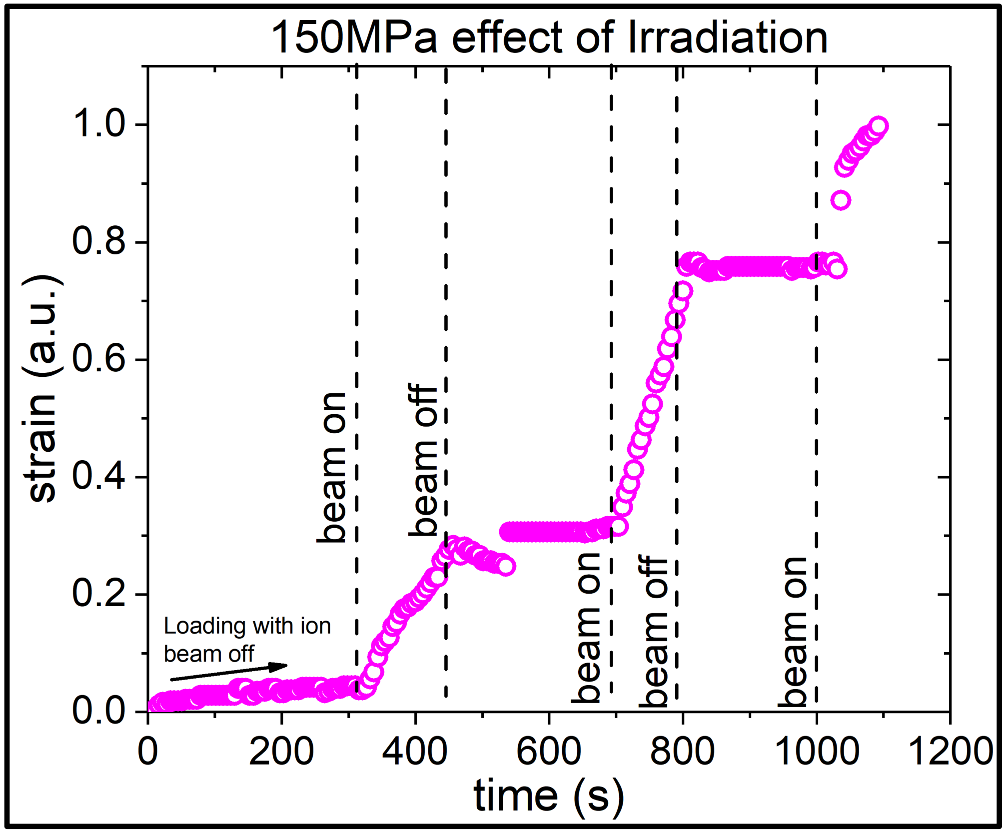
Sink limited regime
activation energy: ≈0.002 eV

Jung and Ansari, JNM (1986)

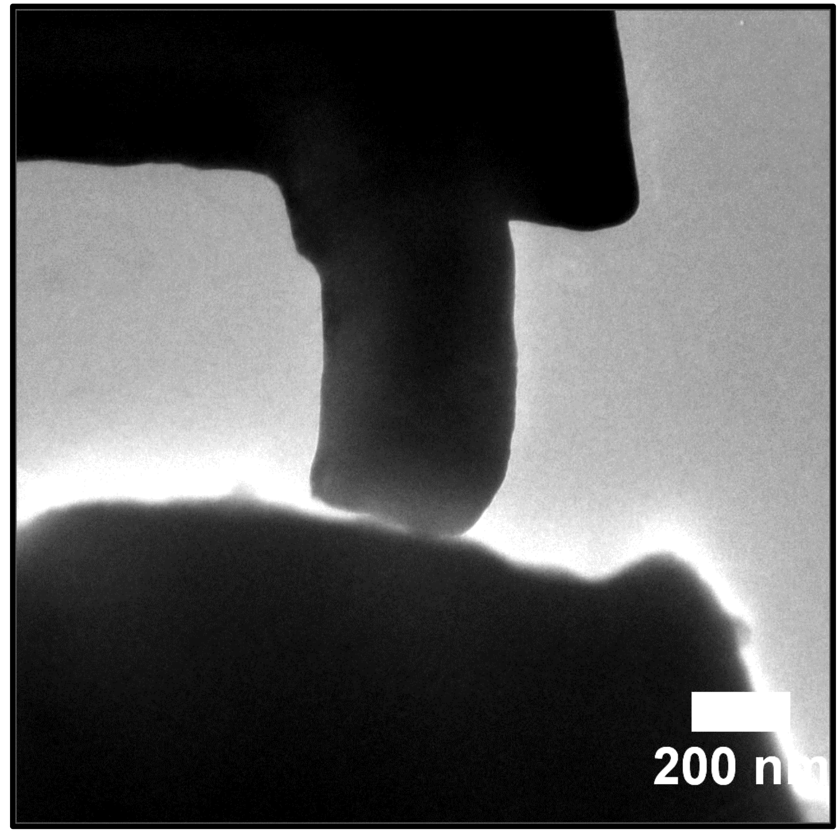
Stress-Strain: Effect of Irradiation and Temperature



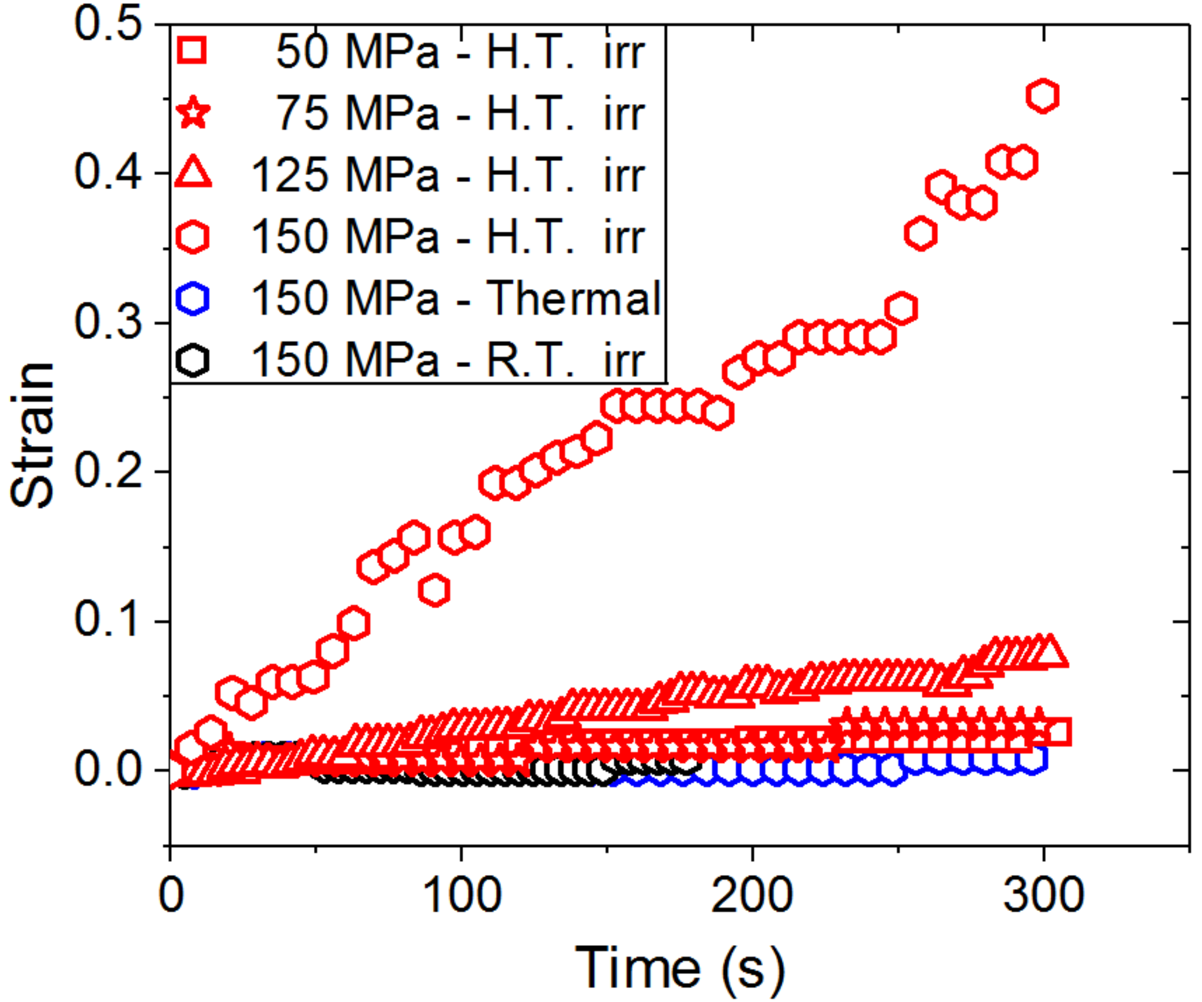
IIC in Sample with Non-ideal Geometry/ Deformation

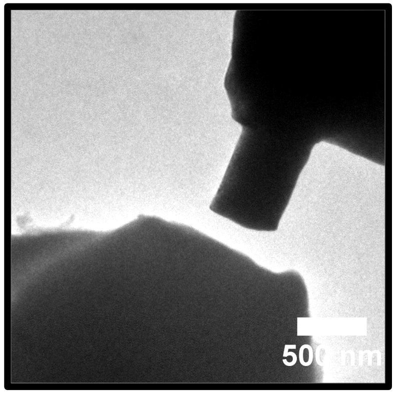


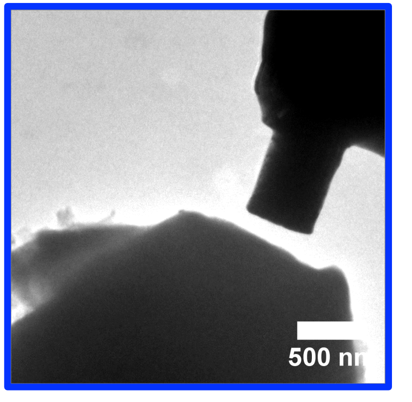
Speed ≈75x

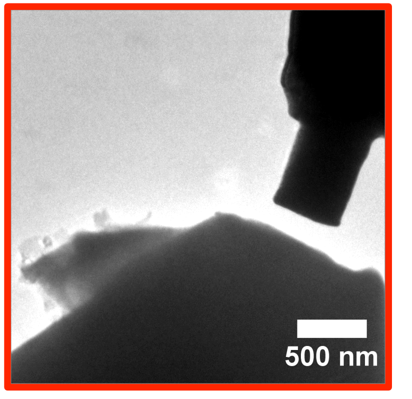


Steady-State Creep Rates in Ag



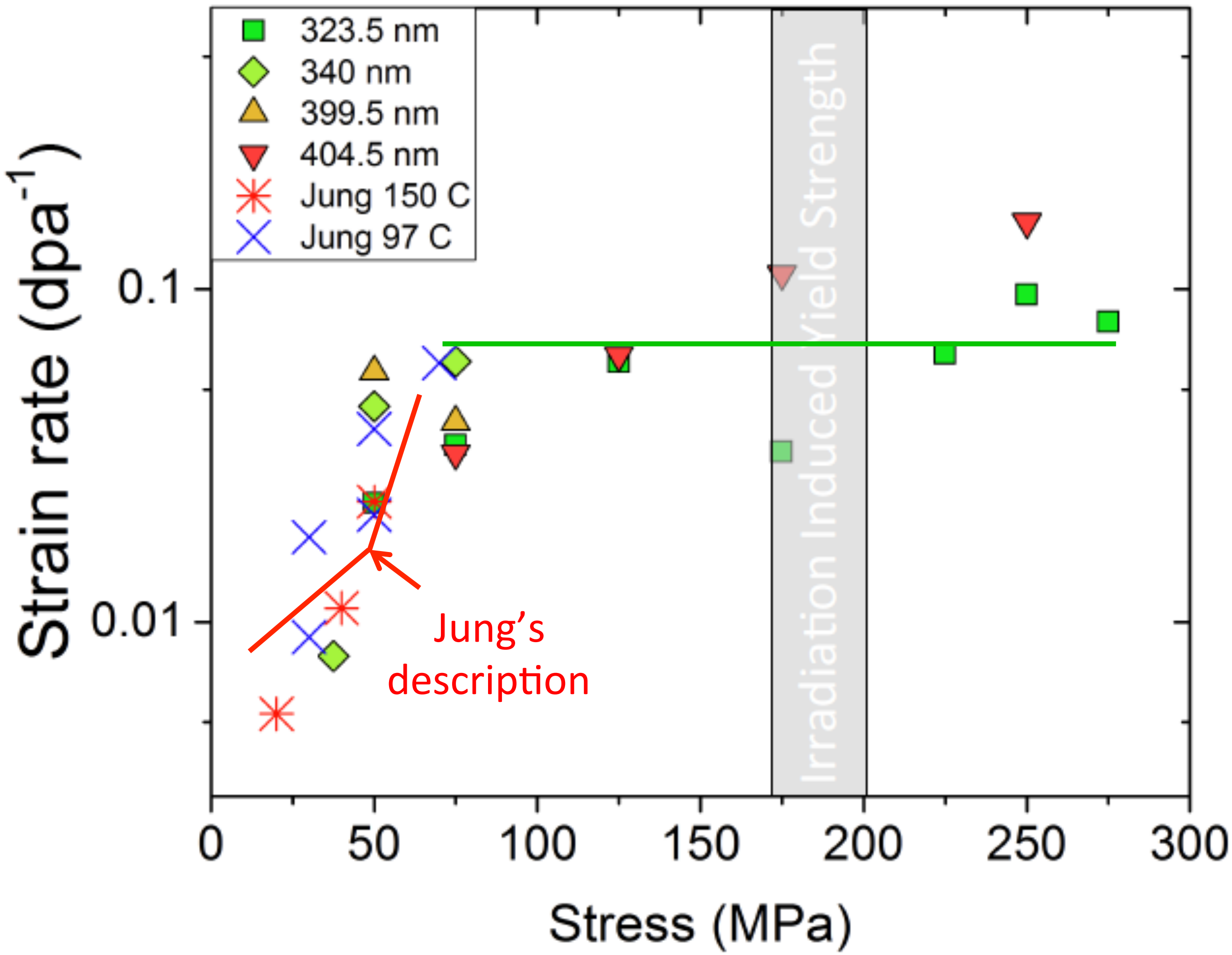






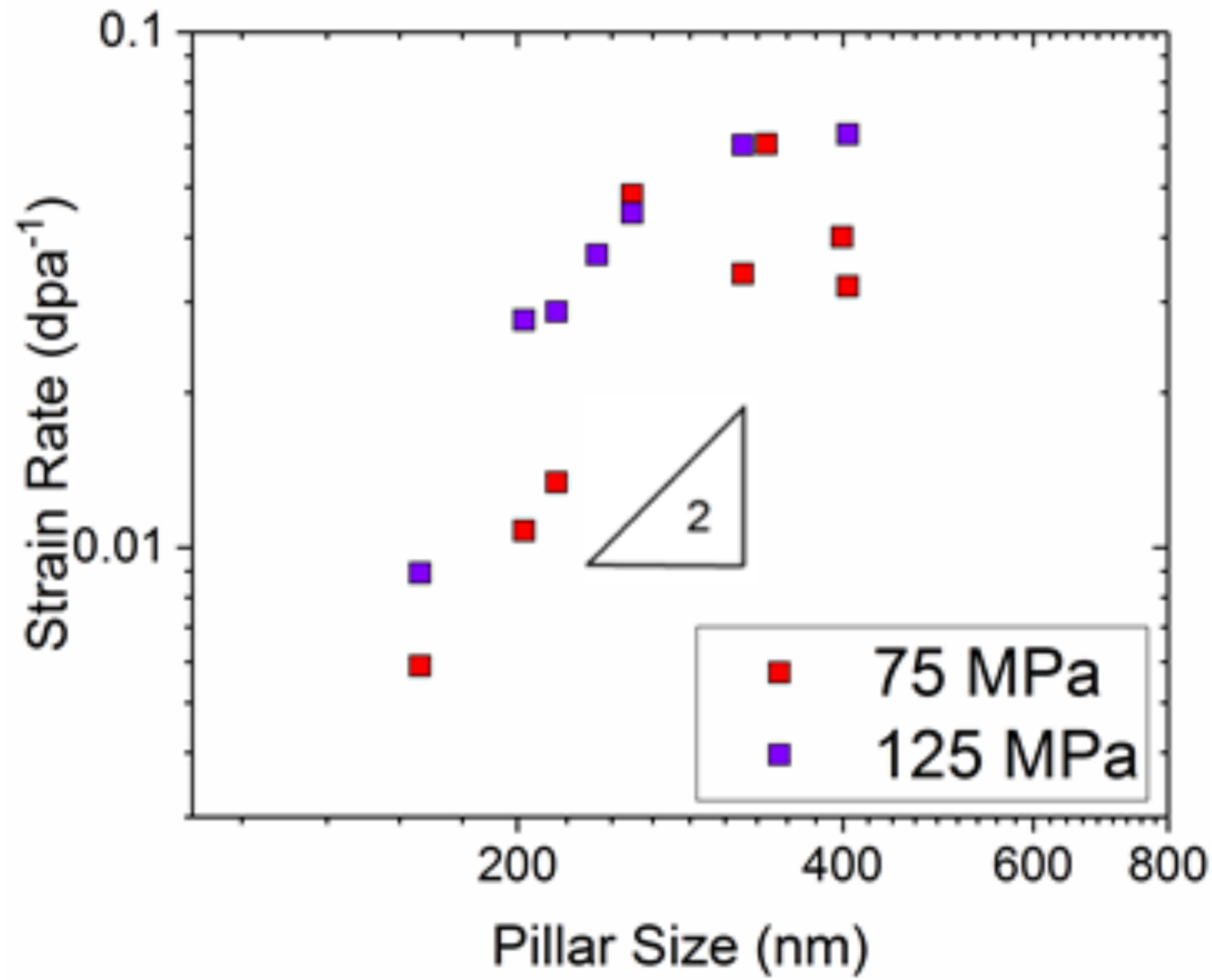
Jawaharram et al. Scripta Mater. (2017)

Effects of Stress on IIC



Jawaharram et al. Scripta Mater. (2017)

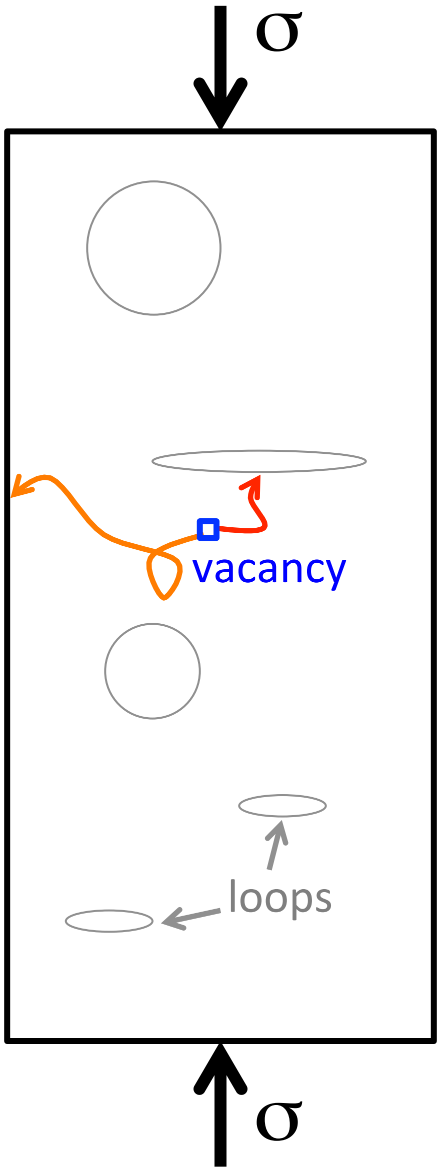
Effects of Pillar Size on IIC



Jawaharram et al. Scripta Mater. (2017)

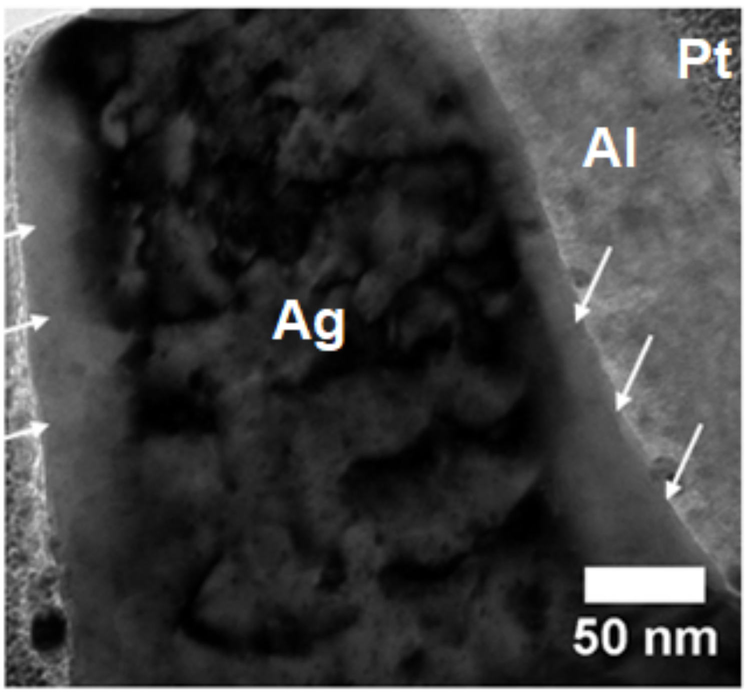
Size Effect in Sink Limited Regime

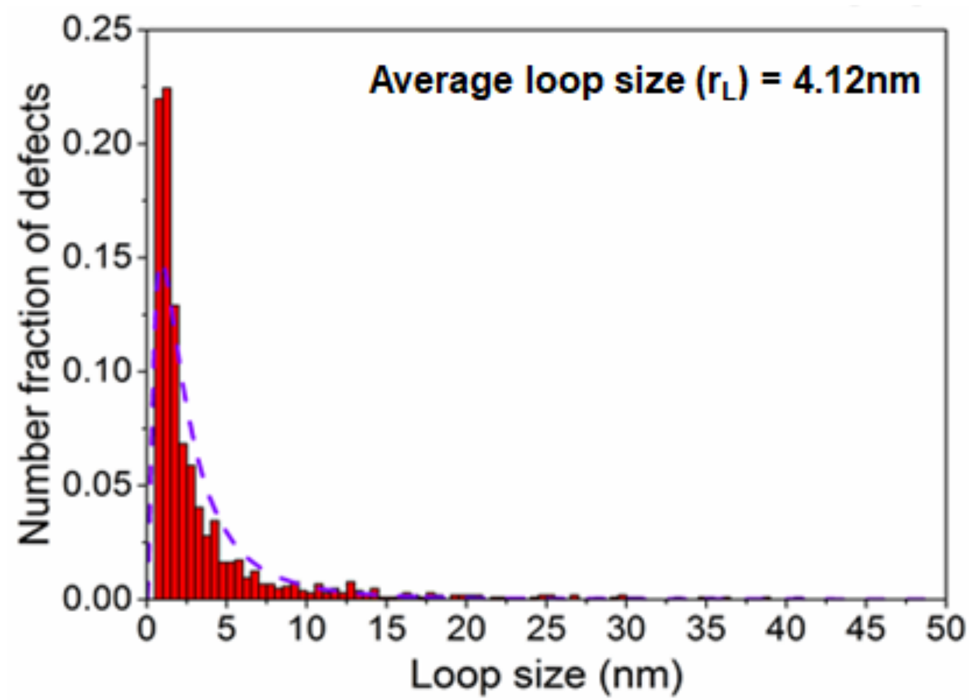
Flux to the surface does not induce creep



Stress induced preferential adsorption to loops induces creep

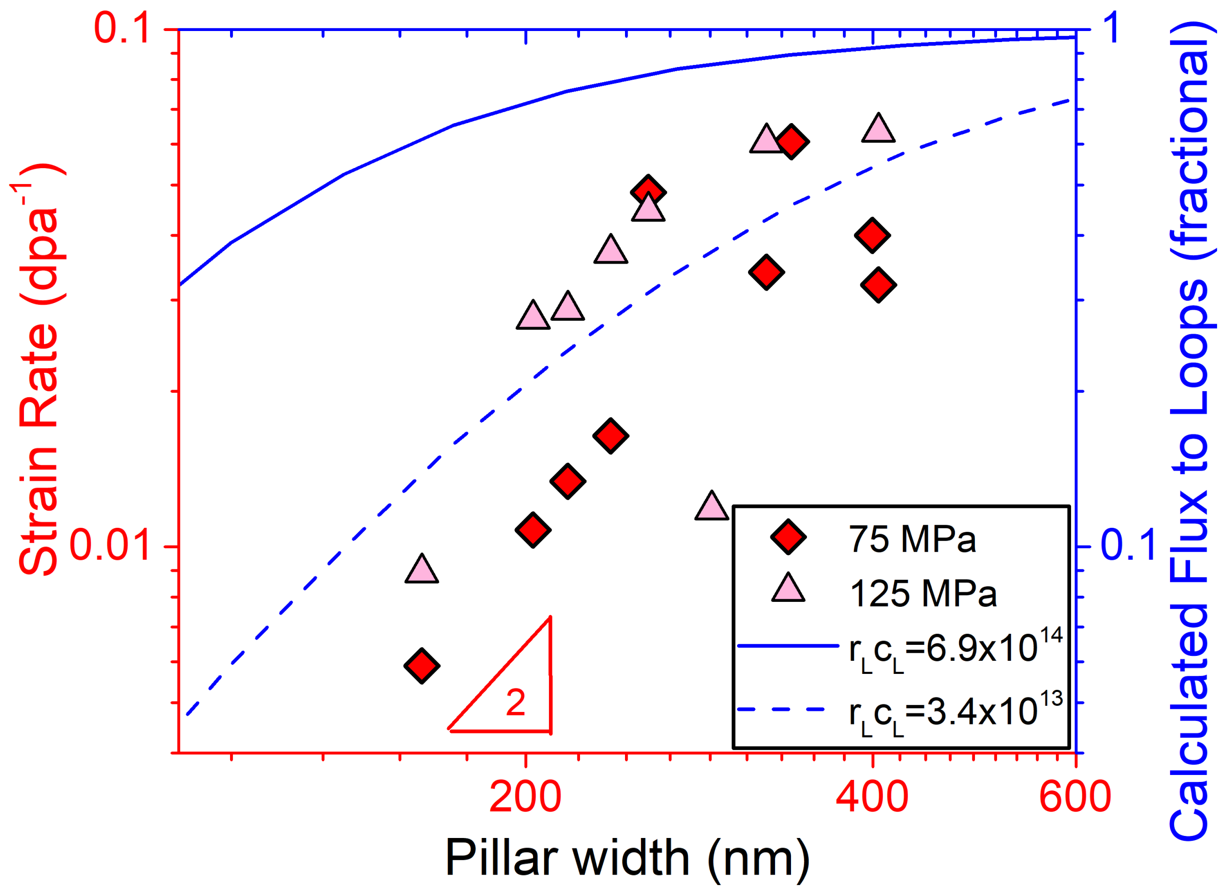
Competition between Dislocations and Interfaces





Fit Predicted from S.S. Rate Equation

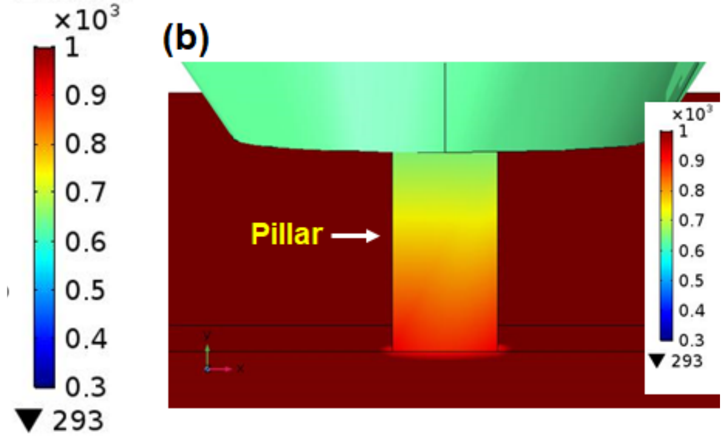
$$\frac{\partial c_{i(v)}}{\partial t} = 0 = \xi_{FM} K_o - \frac{4\pi r_{iv}}{\Omega}(D_i + D_v) c_{i(v)} c_{v(i)} - \frac{4\pi r_L}{\mathrm{Ln}\left({}^{8r_L}/_{r_c}\right)} D_{i(v)} c_{i(v)} c_L - \frac{2\pi^2}{L^2} D_{i(v)} c_{i(v)}$$



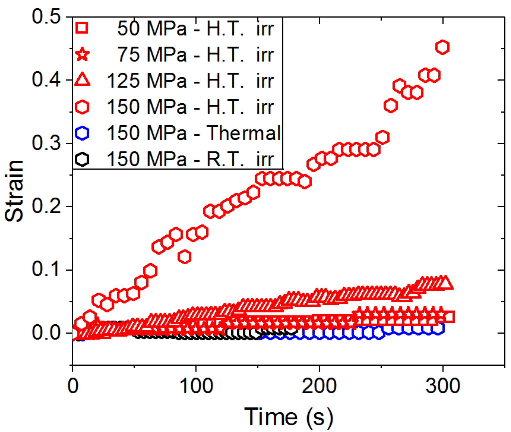
Jawaharram et al. Scripta Mater. (2017)

Remaining Challenges

- Determining temperature and limit the temperature gradient



- Amplifying strain such that is is directly measureable during long (e.g. 1 hour) steady-state creep experiments



Conclusions

- In situ TEM promising for small scale IIC testing
- IIC in ‘large’ Ag samples comparable to bulk measurements
- Competition between interfaces and loops as point defect sinks quantified through pillar size effects
- R.T. IIC rates may be high in high strength nanostructured materials at a fraction of their yield strengths