Mechanical Property Changes in Metals due to Irradiation

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Sept. 24-Oct. 6, 2007

Outline

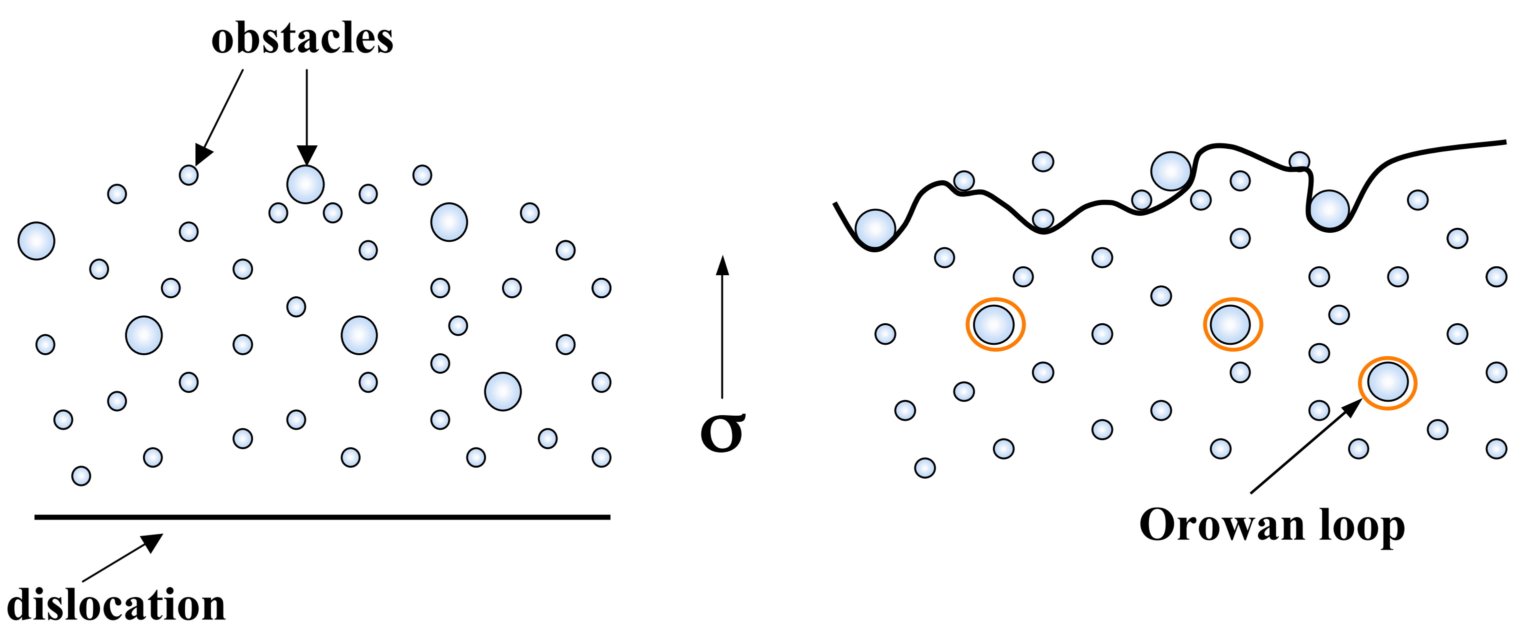
- Effect of low temperature (<0.3 T_M) irradiation on the tensile properties of metals
  - Dose and temperature dependence
  - FCC vs. BCC metal behavior
- Fracture toughness embrittlement in irradiated metals
- High temperature He embrittlement of grain boundaries
- Overview of deformation mechanisms in irradiated metals (restricted to radiation hardening/embrittlement regime)
  - Microscopic flow localization observations (dislocation channeling)
  - Similarities and differences between flow localization phenomena in unirradiated and irradiated metals
    - Practical consequences: e.g., structural design rules for uniform elongation <2%
- Not covered: hardness, fatigue, irradiation creep

Radiation Hardening Mechanisms

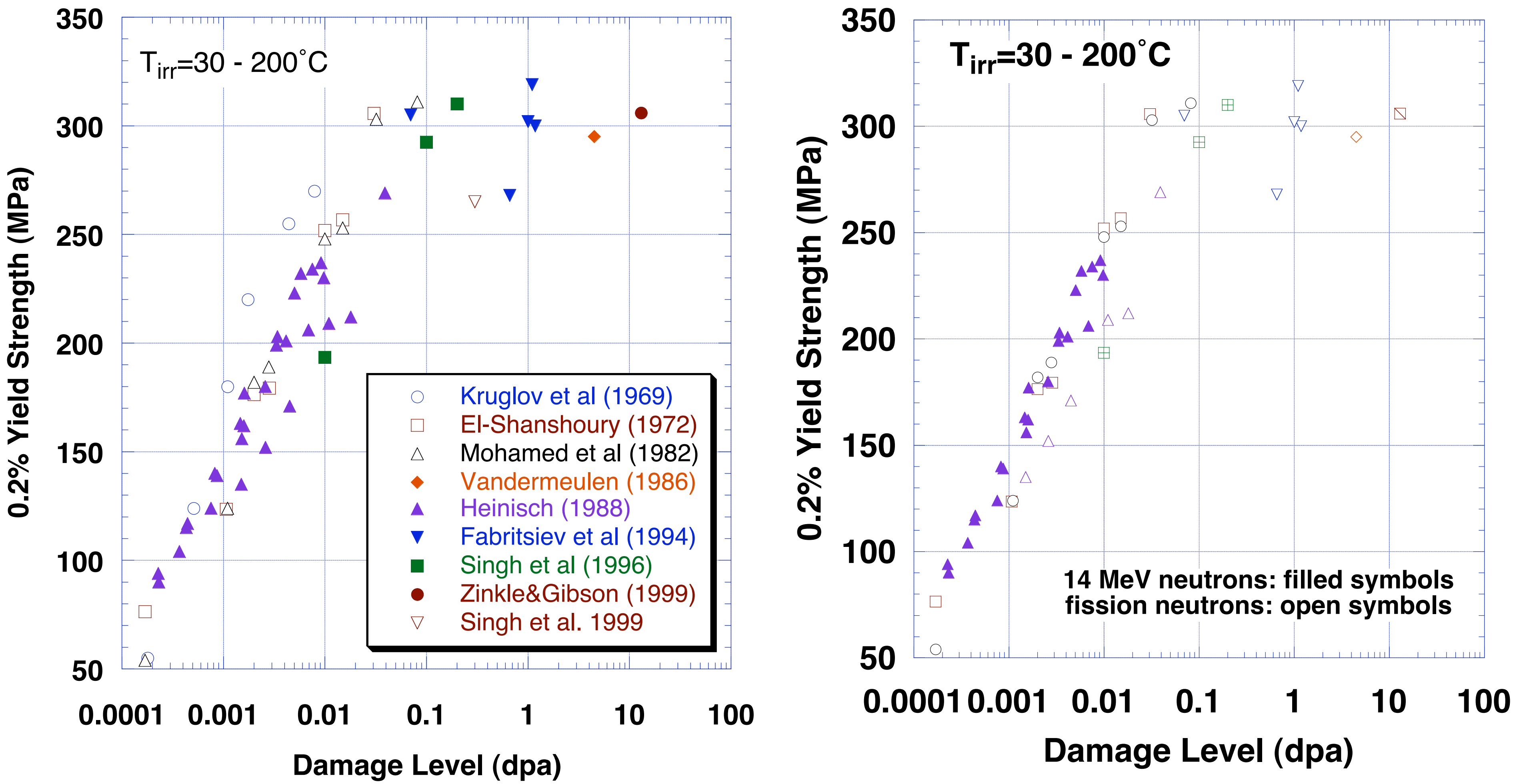
Radiation damage creates obstacles to dislocation motion

- **point defects (≡ solute strengthening in alloys)**
- **small clusters and precipitates (≡ precipitates in alloys)**
- **impenetrable clusters (≡ Orowan strengthening in alloys)**

- **all give $\Delta\sigma_y$ proportional to $(\text{dose})^{0.3\text{-}0.5}$**



Dose Dependence of Radiation Hardening in Copper



- Fission and fusion neutron radiation hardening behavior are in good agreement
- Hardening "saturation" occurs for doses above ~0.1 dpa (agrees with defect cluster density behavior)

Radiation Hardening in Copper: Seeger vs. Friedel relationships

- Two general models are available to describe radiation hardening ($\Delta\sigma$) in metals:
  - Dispersed barrier model (Seeger, 1958)--valid for strong obstacles

$$\Delta\sigma = M\alpha\mu b\sqrt{Nd}$$

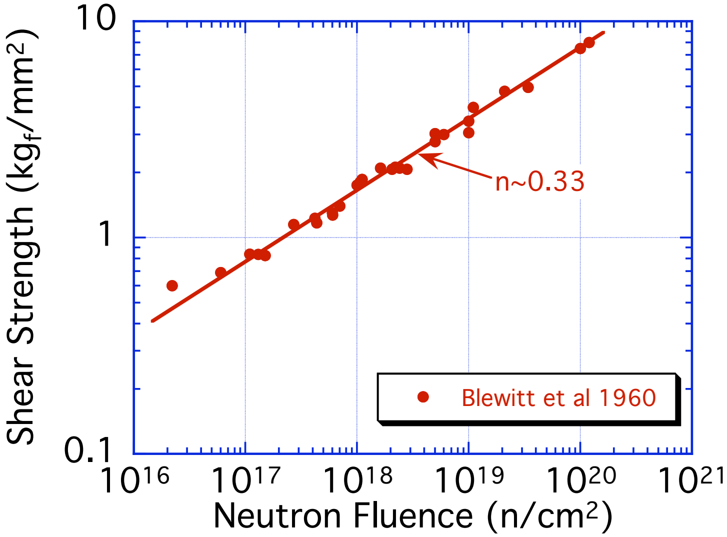
Where
M=Taylor factor
α=defect cluster barrier strength
μ=shear modulus
b=Burgers vector of glide dislocation
N, d=defect cluster density, diameter

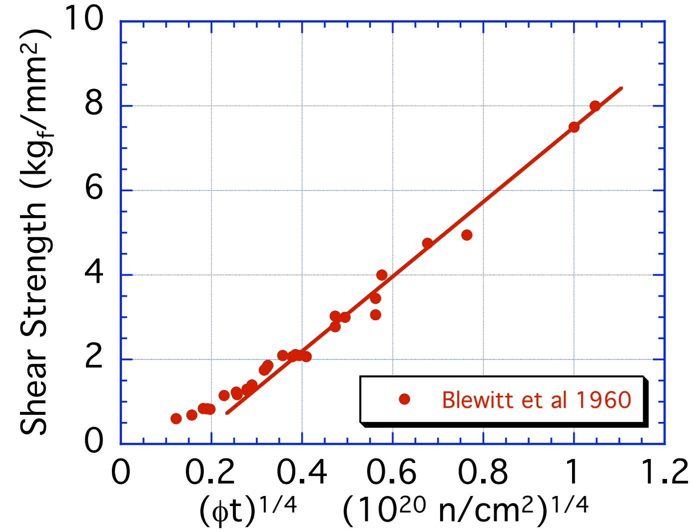
  - Friedel 1963 (also Kroupa and Hirsch 1964) weak barrier model:

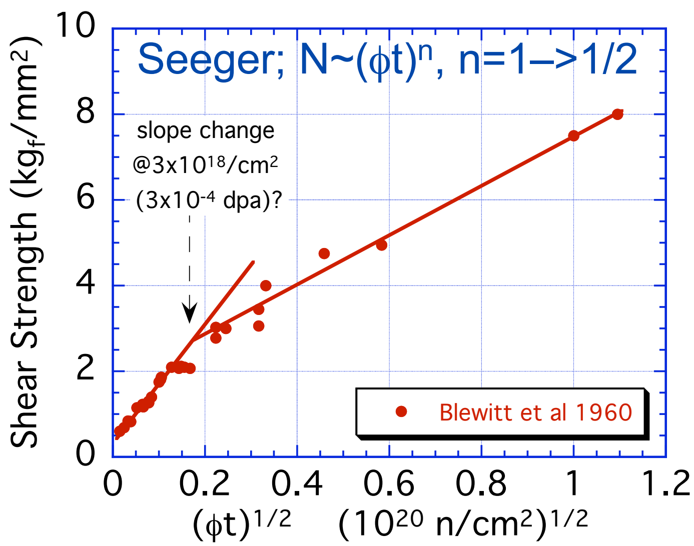
$$\Delta\sigma = \frac{1}{8} M\mu bdN^{2/3}$$

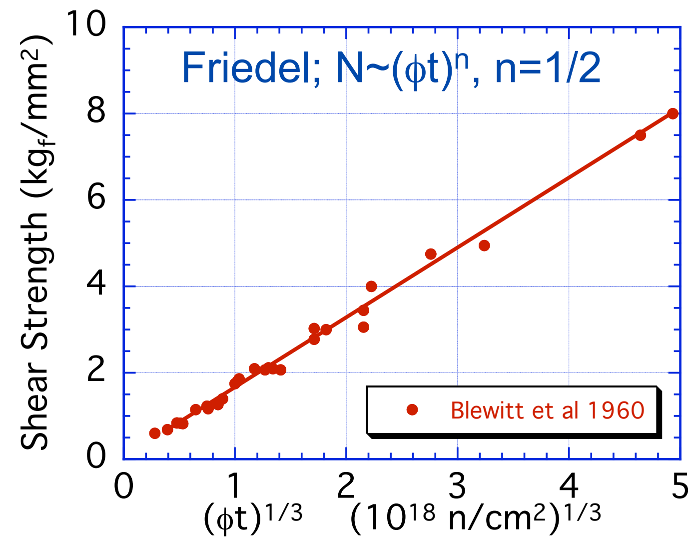
$$\Delta\sigma = M\alpha\mu b\sqrt{Nd} \quad \text{vs.} \quad \Delta\sigma = \frac{1}{8}M\mu b d N^{2/3}$$

Shear Strength of Cu Single Crystals Irradiated
and Tested Near Room Temperature









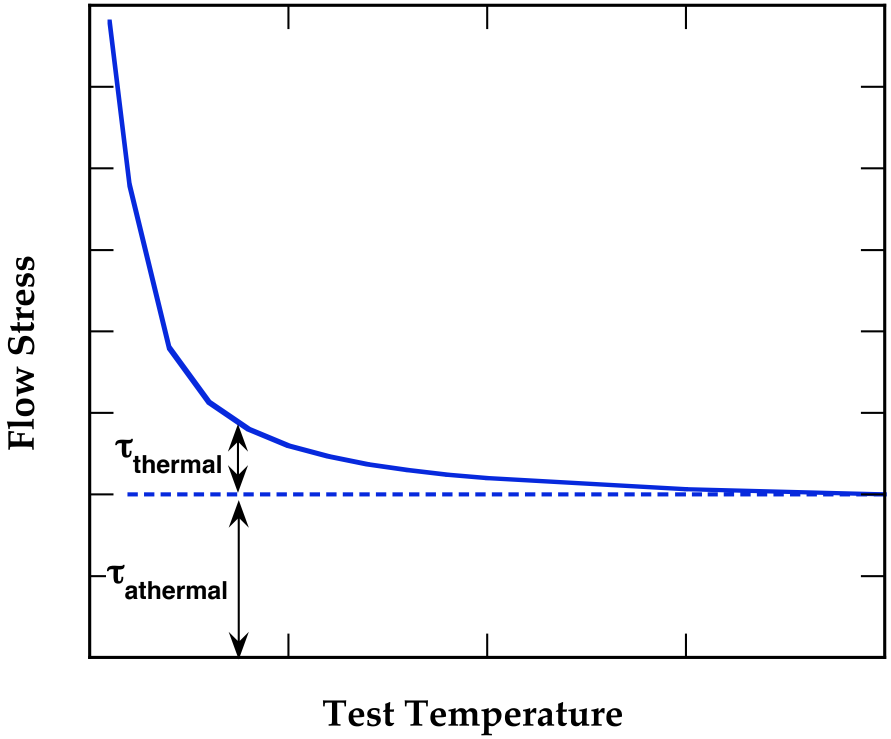
Effect of test temperature on irradiated strength

What is the effect of irradiation on the yield strength test temperature dependence (athermal and thermal components)?

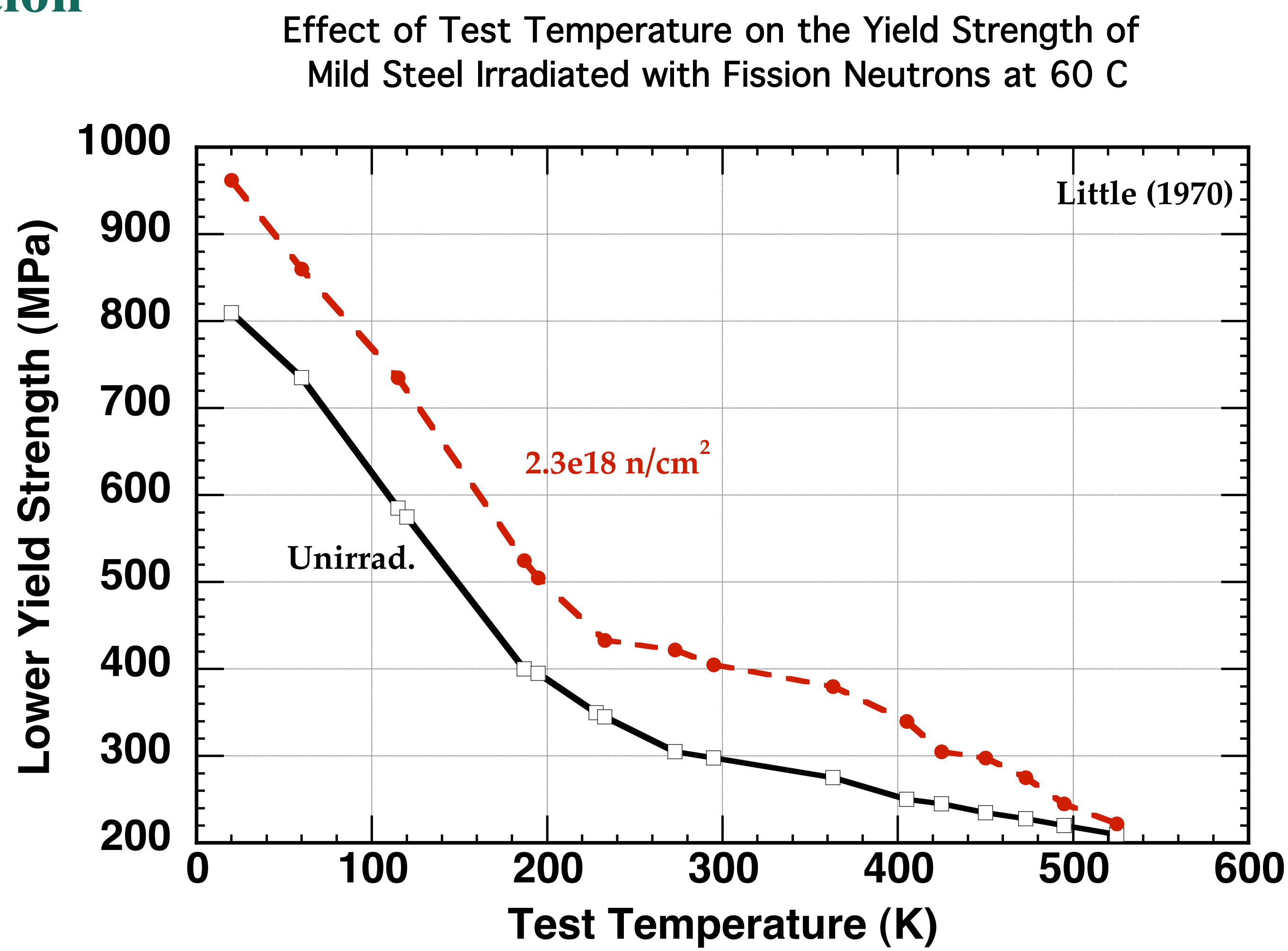
BCC metals: large $\tau_{thermal}$ component

FCC metals: small $\tau_{thermal}$ component

Hardening models (Seeger, Fleisher, etc.): Thermal component of flow stress is controlled by radiation-induced hardening centers

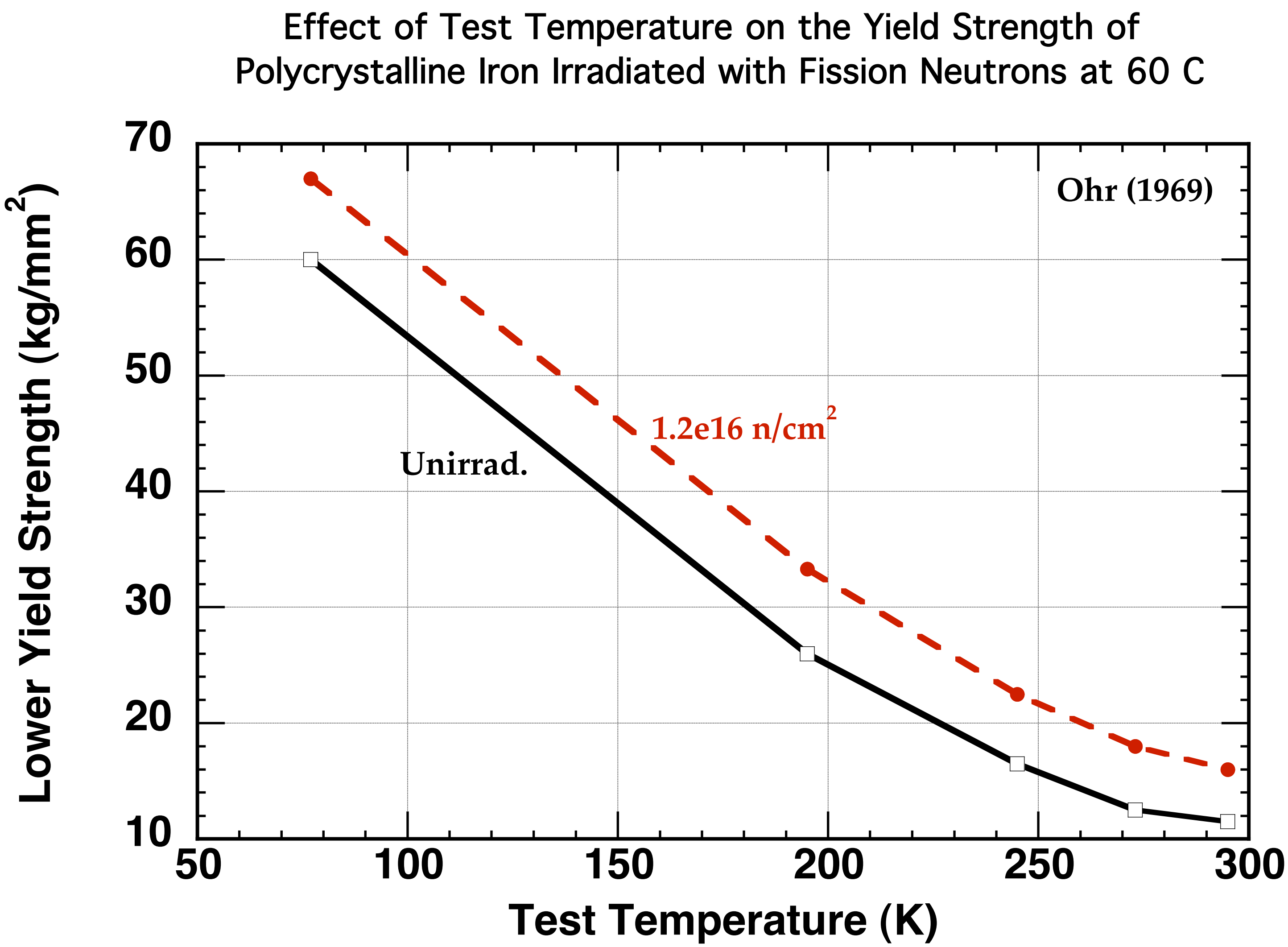


Early Work on BCC Metals such as Fe led to Conclusions that the Test Temperature Dependence was not Affected by Neutron Irradiation

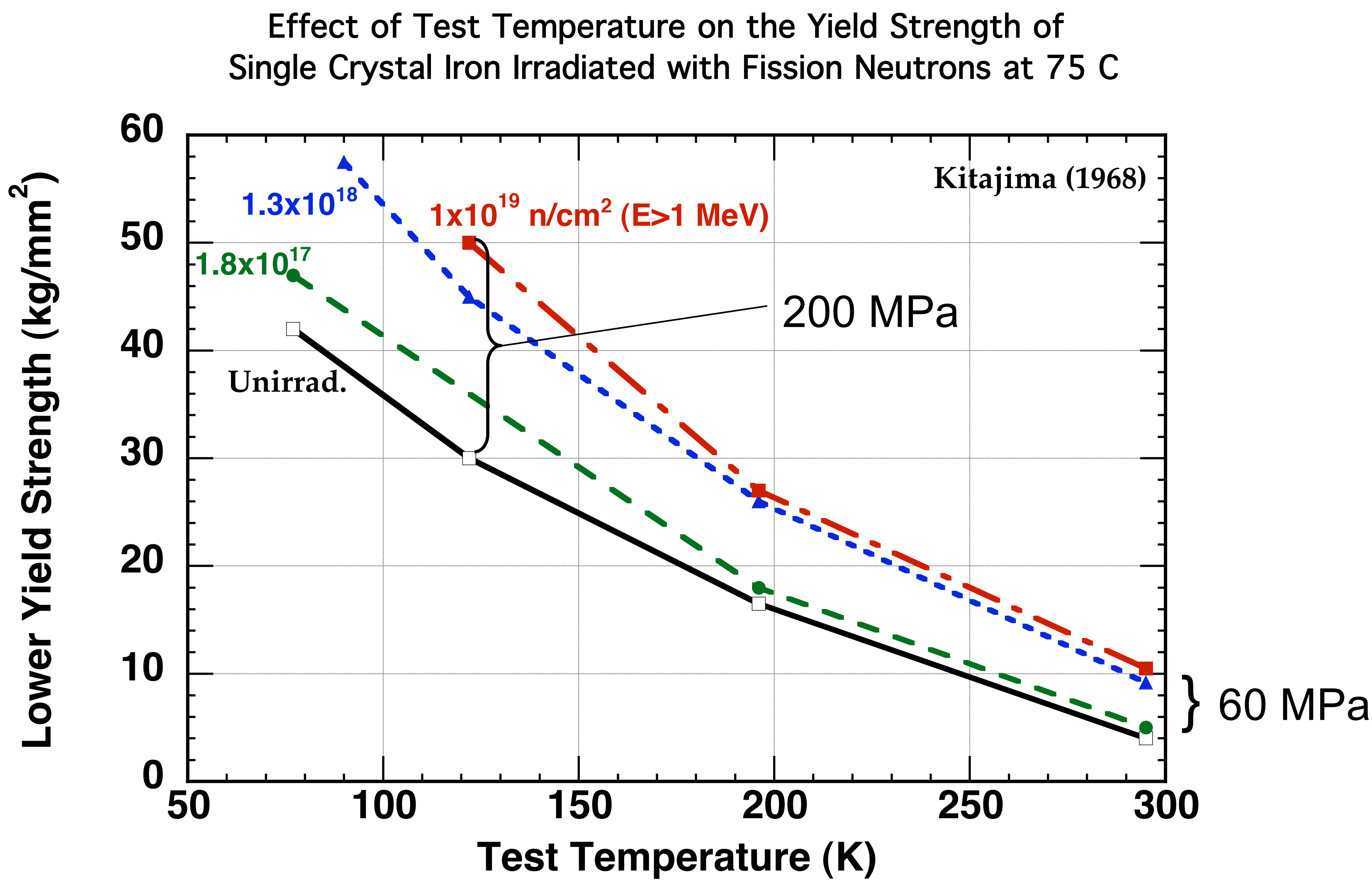


- These early studies were limited to low doses <10^{19} n/cm^2), where the magnitude of radiation hardening (and radiation-induced defect sizes) is relatively small

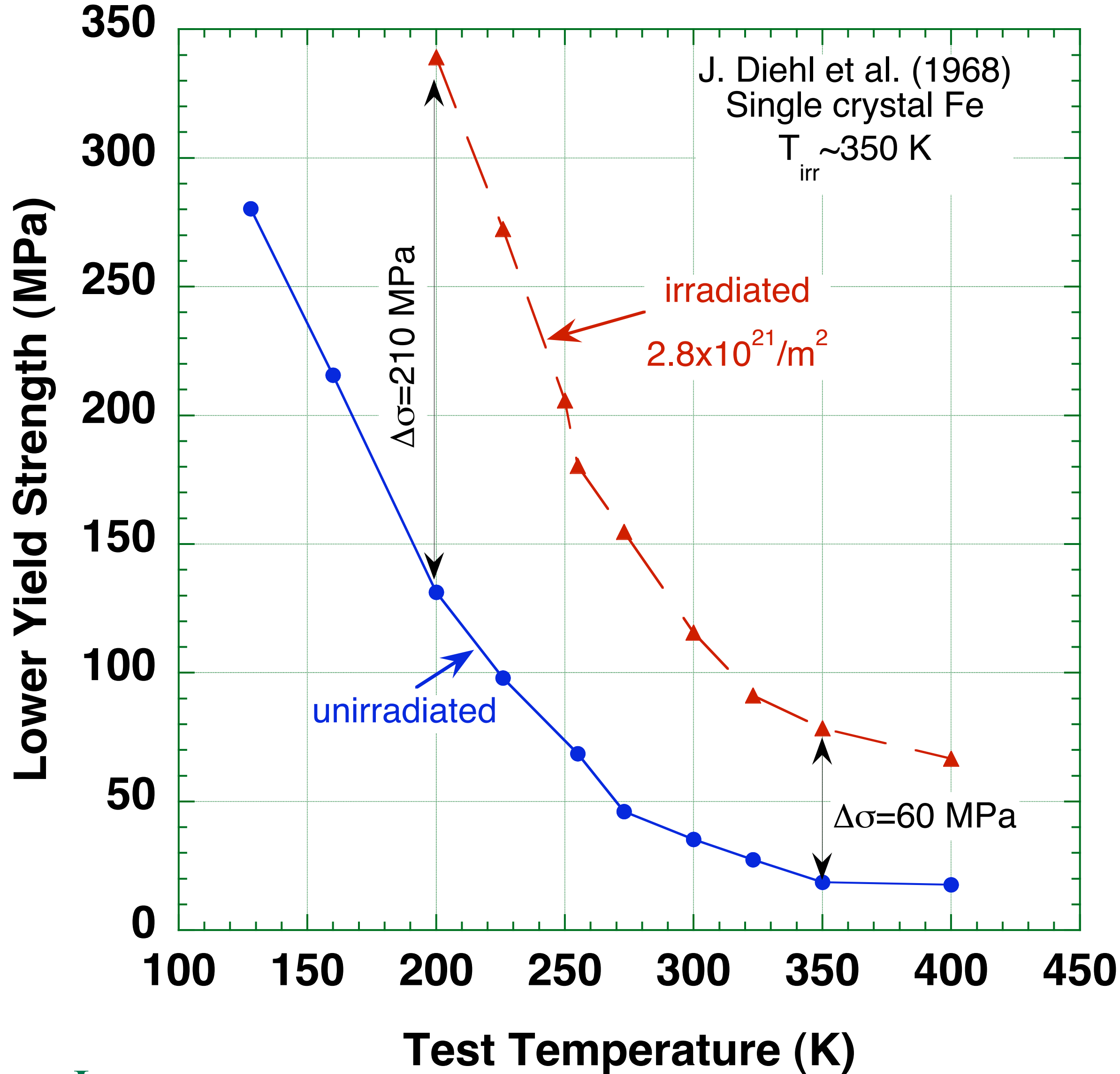
Comparison of the Yield Strength Behavior of Annealed and (low-dose) Irradiated Iron



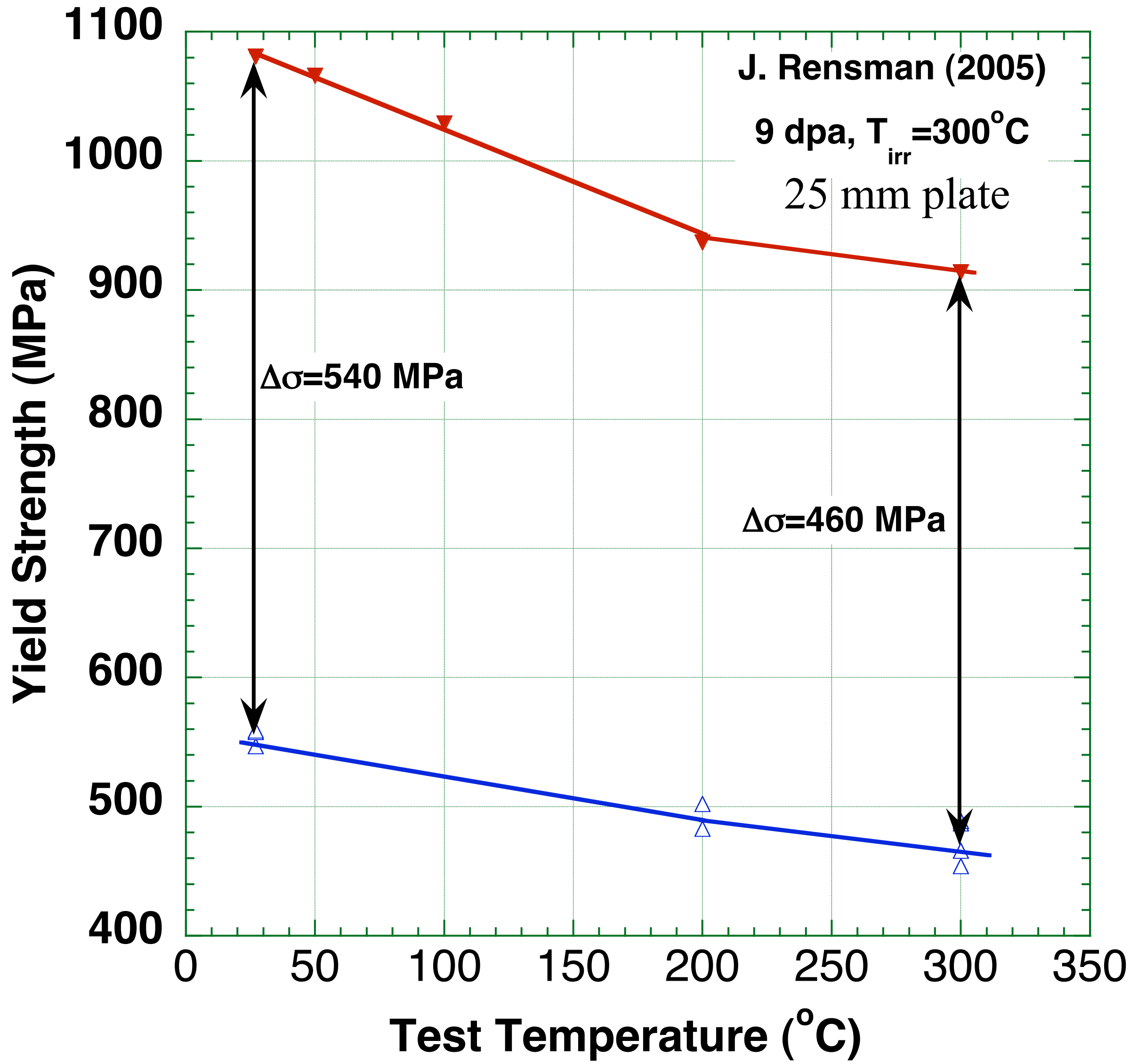
Comparison of the Yield Strength Behavior of Annealed and Irradiated Iron at Higher Doses



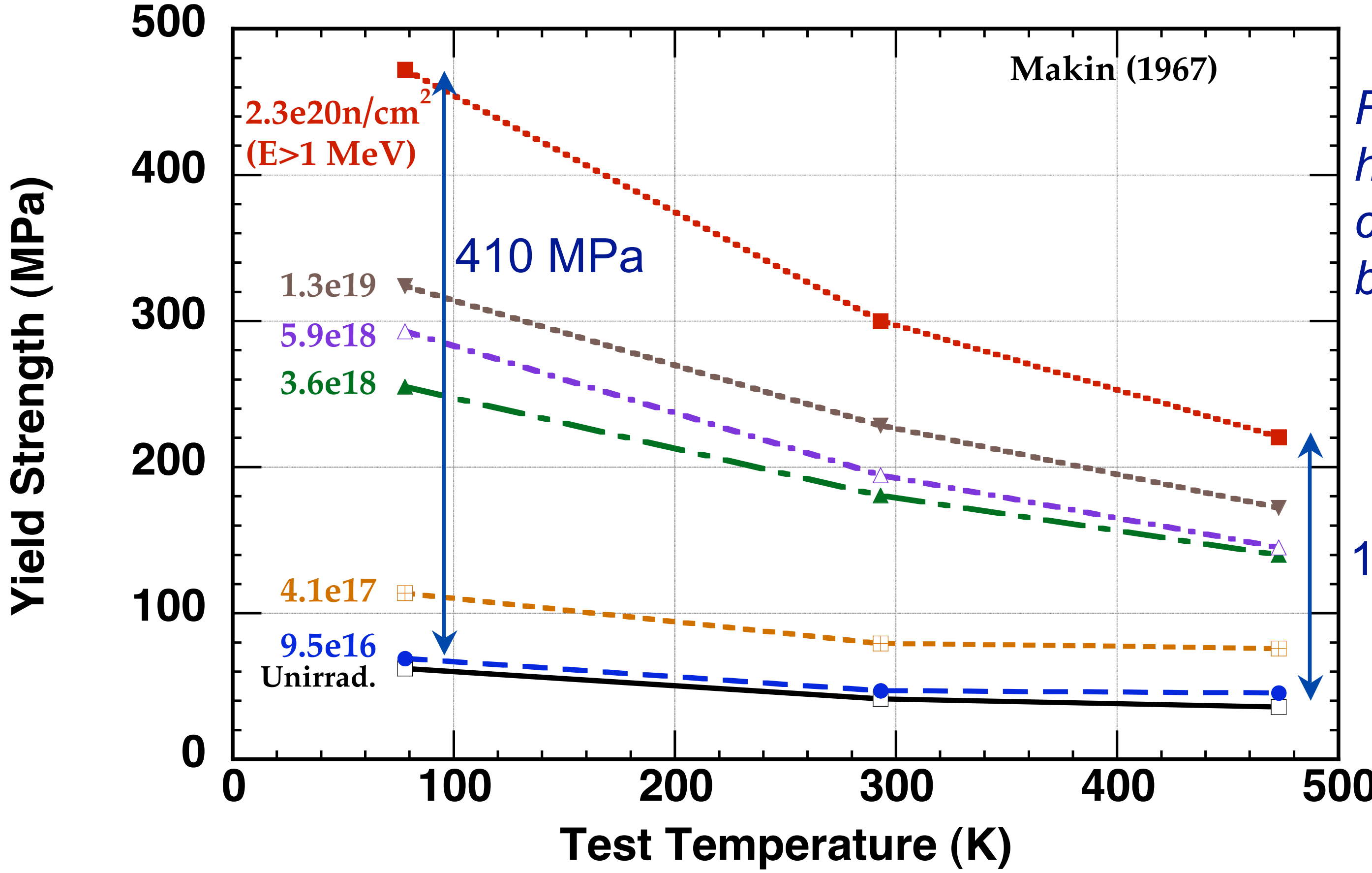
Comparison of the Yield Strength Behavior of Annealed and Irradiated Iron at Higher Doses



Radiation Hardening in Eurofer97 Steel irradiated at 300°C



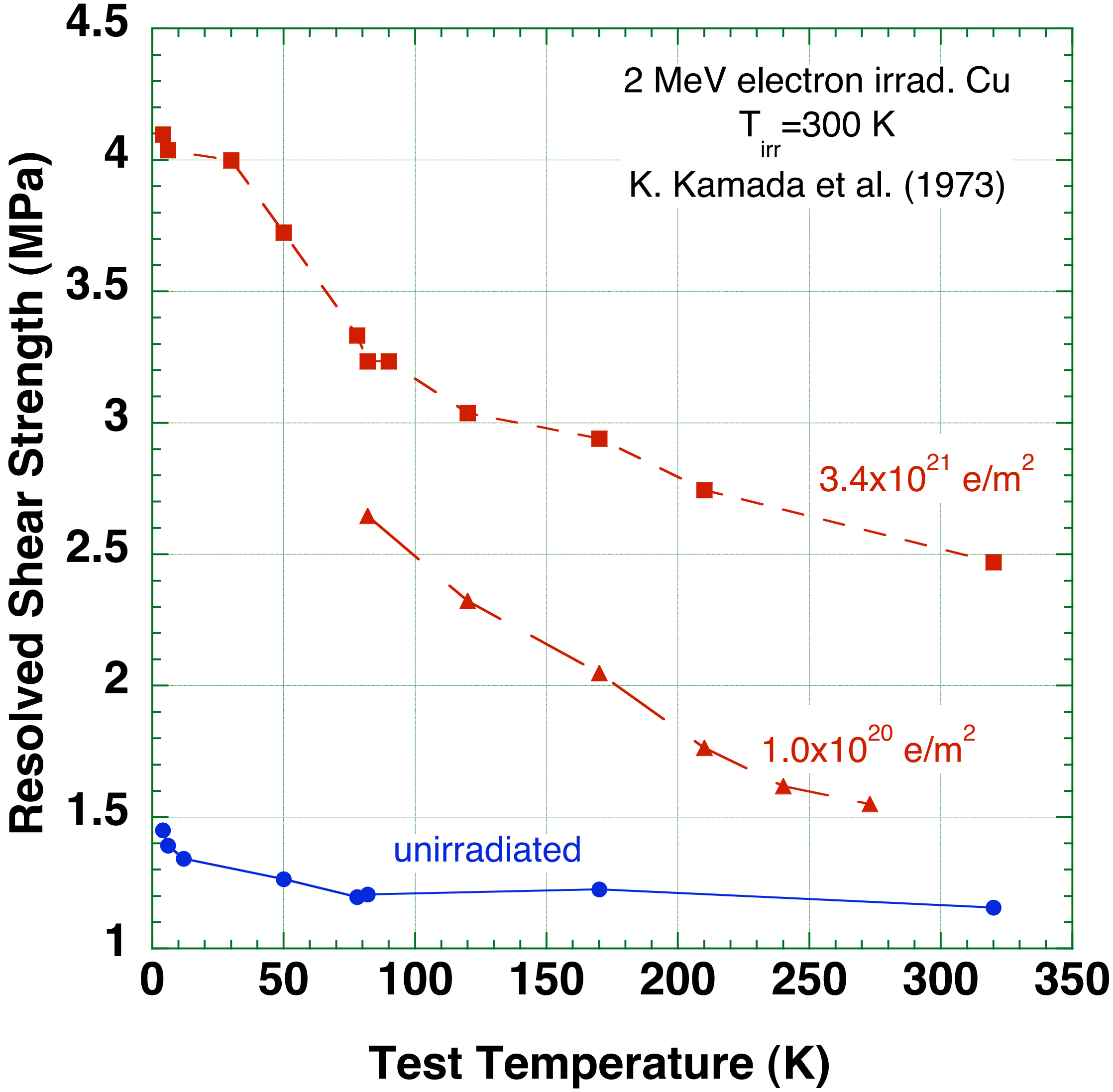
Effect of Test Temperature on the Yield Strength of Polycrystalline Copper, Neutron Irradiated at 60°C



Radiation hardening controlled primarily by SFTs

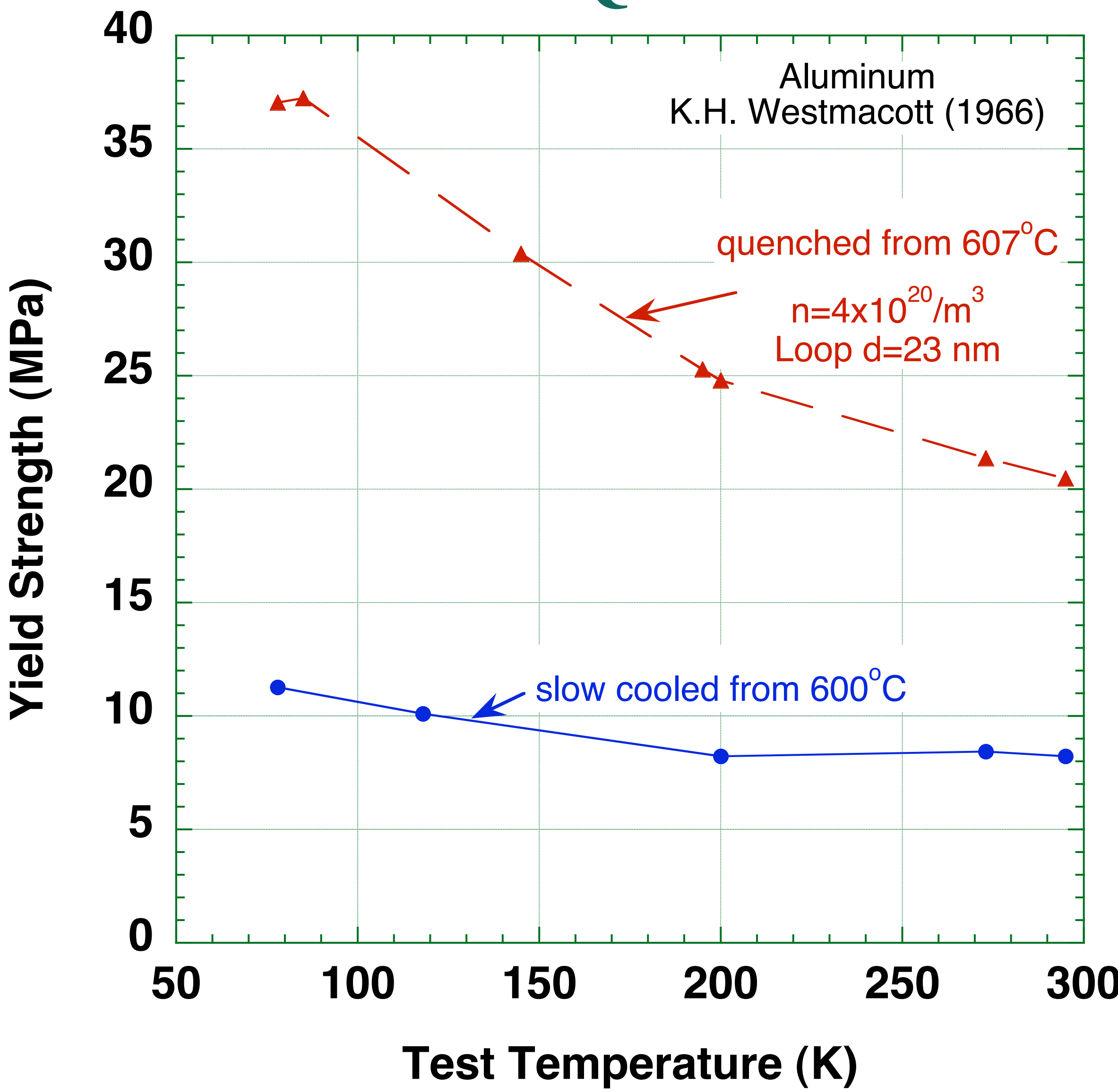
- Change in test temperature dependence from unirradiated behavior occurs for fluences above ~0.5 to 1x10^{18} n/cm^2, E>1 MeV (Makin 1967, Koppenaal 1965)
- Similar range of test temperature dependence occurs in as-irradiated vs. postirradiation annealed Cu (Rühle, Makin, Howe, Koppenaal, etc.)

Effect of Electron Irradiation on the Yield Strength Behavior of Single Crystal Copper



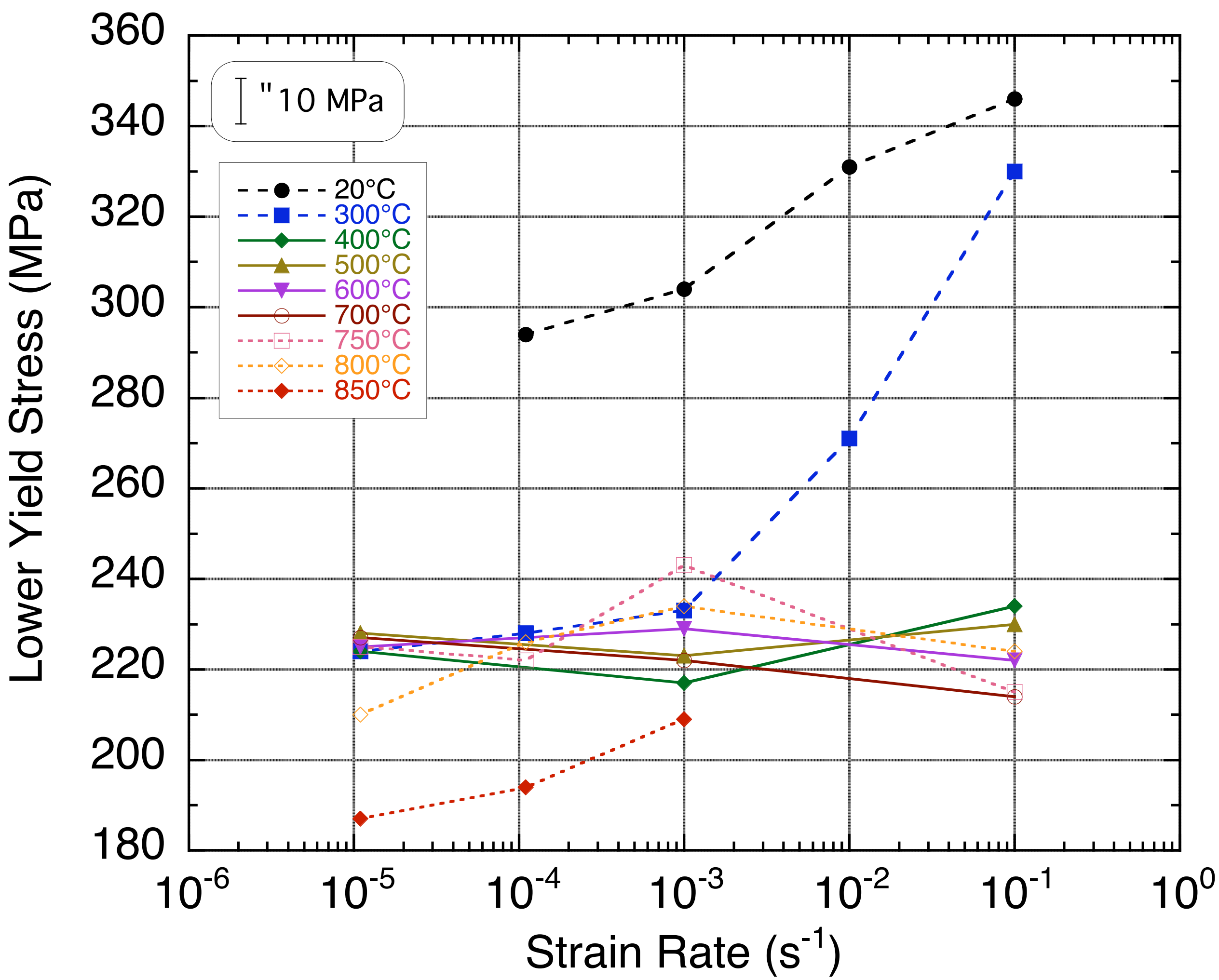
Radiation hardening controlled primarily by dislocation loops

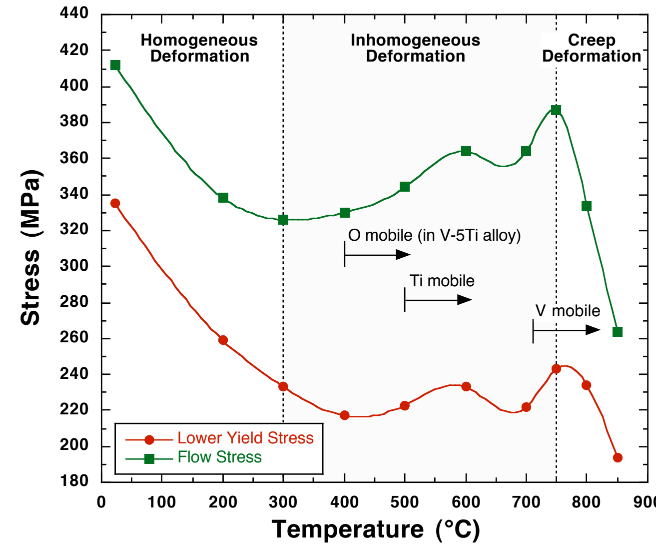
Comparison of the Yield Strength Behavior of Annealed and Quenched Aluminum

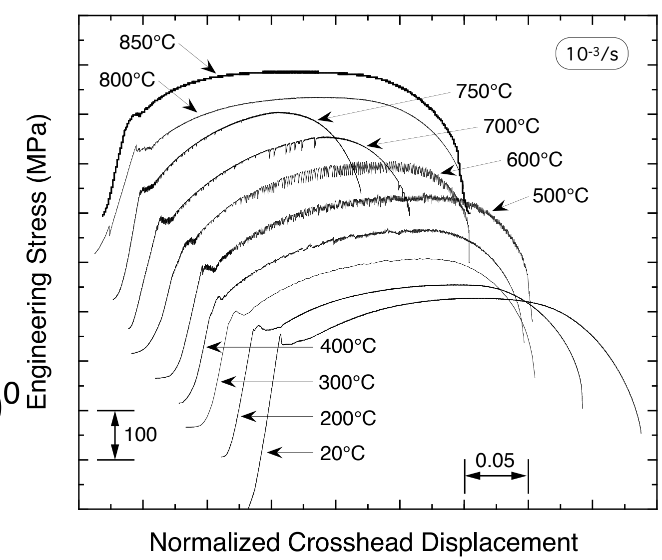


Radiation hardening controlled primarily by dislocation loops

Effect of Strain Rate and Temperature on Yield Strength Behavior of Unirradiated V-4Cr-4Ti

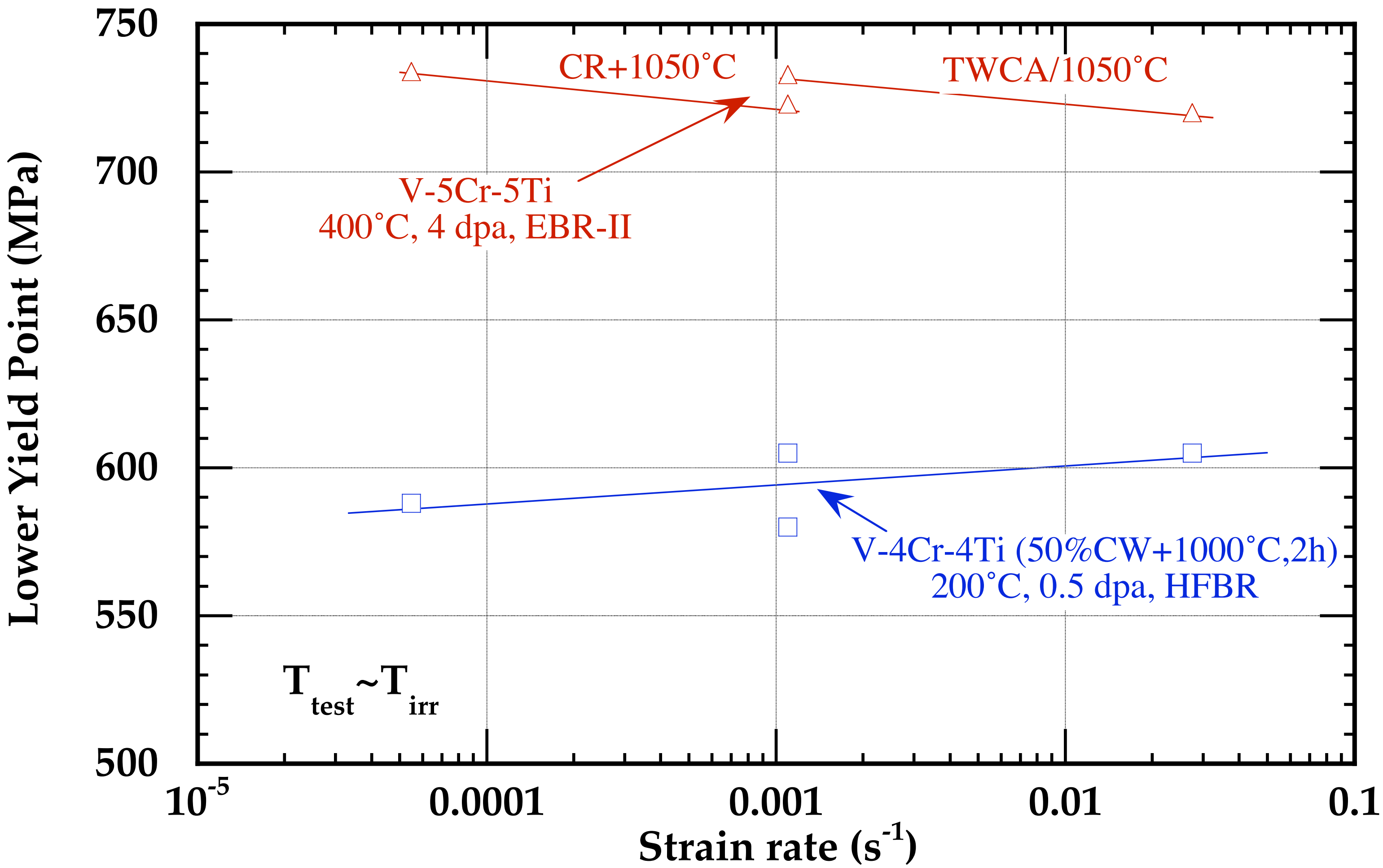






Negative strain rate exponent corresponds to dynamic strain aging regime

Effect of Strain Rate and Temperature on Yield Strength Behavior of Irradiated V-4Cr-4Ti

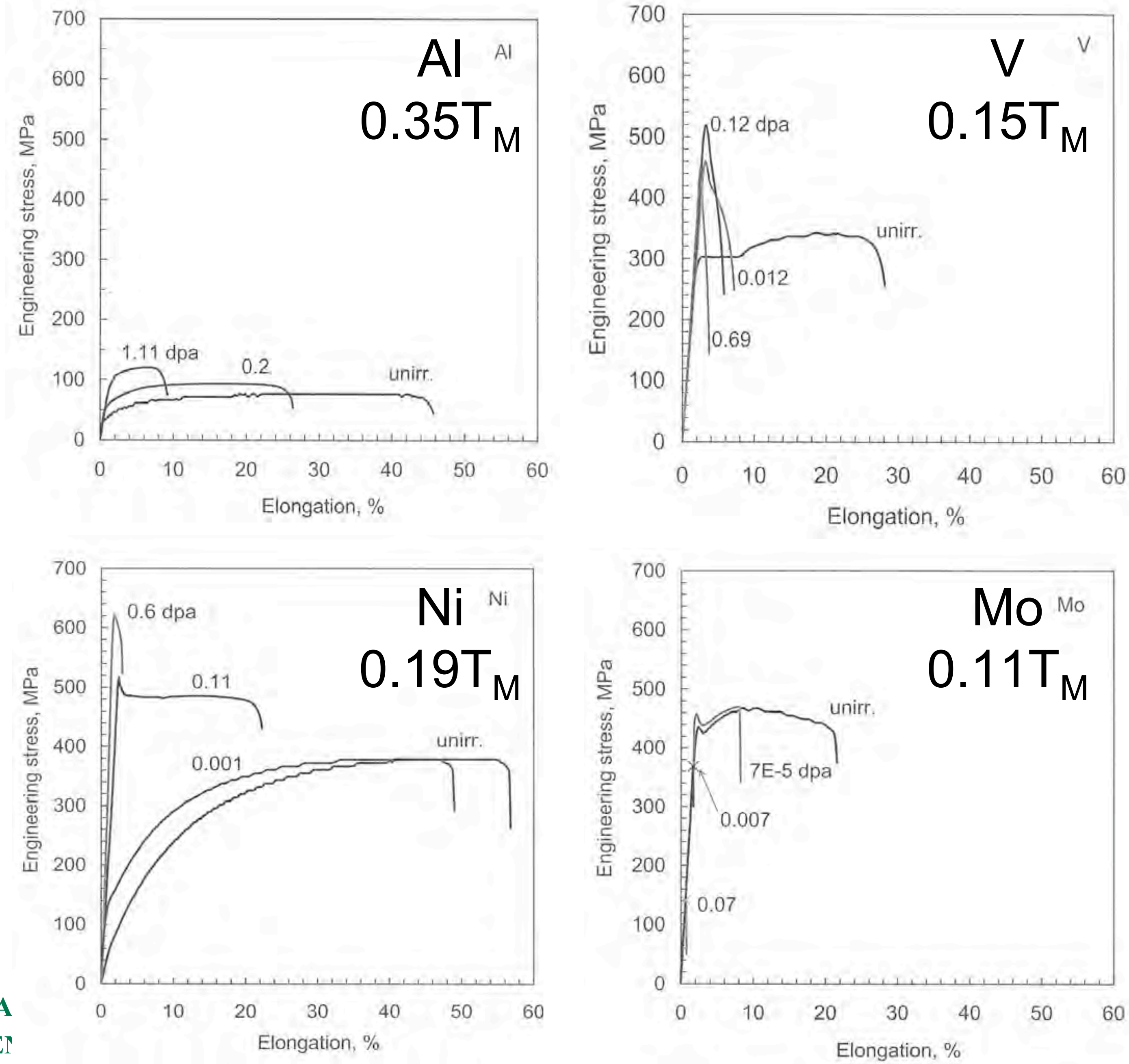


Strain rate exponent becomes negative in irradiated alloys at T_{test}>300°C even when dynamic strain aging serrations are not visible in stress-strain curves

What are the consequences of radiation hardening?

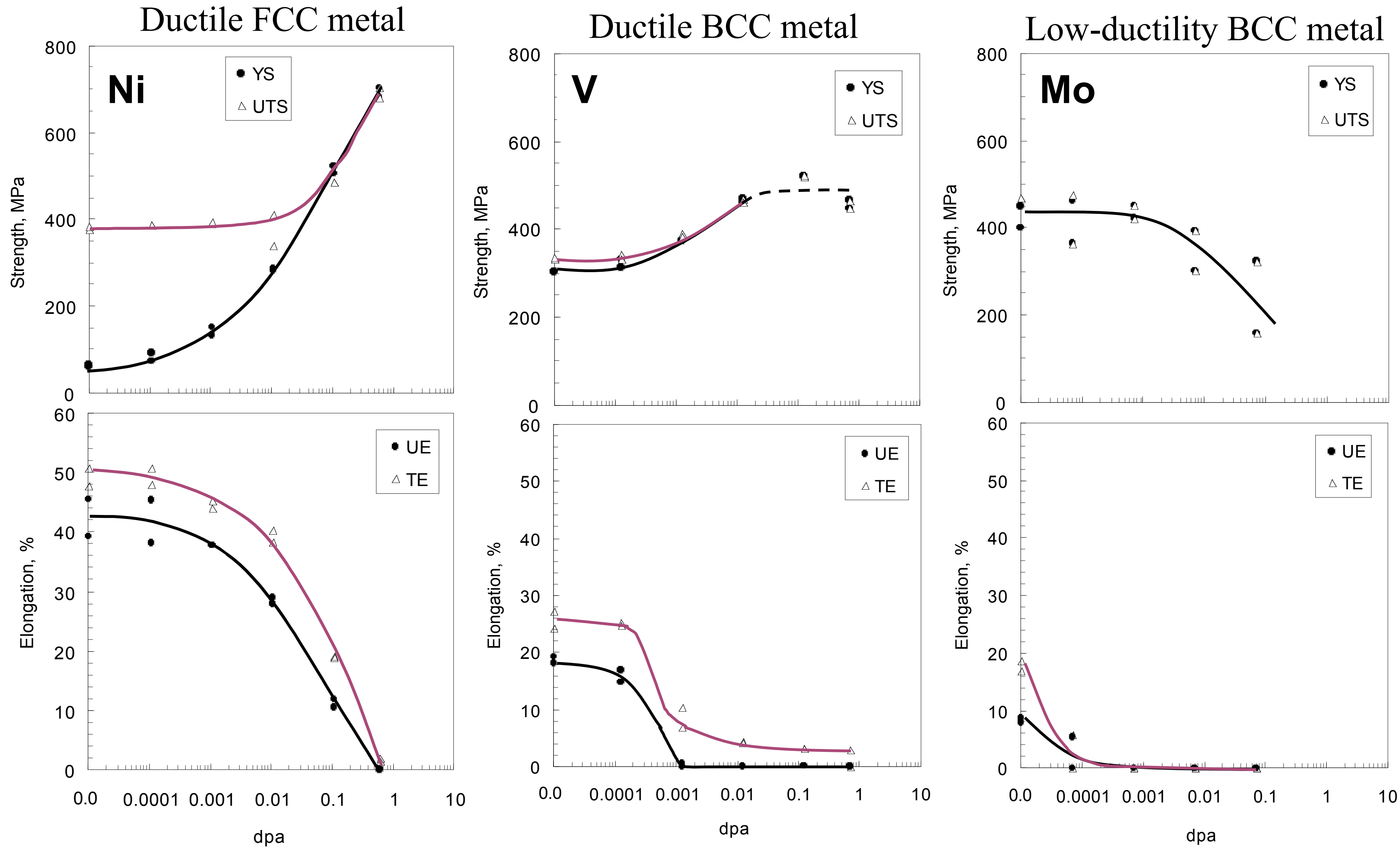
- Increased strength (good!)
- Decreased tensile elongation (bad!)
  - Practical impact/consequences: need to use more conservative structural design rules for uniform elongation <2%
- For BCC metals, increase in the ductile-brittle transition temperature and decrease of toughness in the “ductile” regime (can be catastrophic!)
  - Radiation hardening also tends to reduce the fracture toughness of FCC metals

Examples of tensile curves for pure metals irradiated at ~330 K



Effect of neutron irradiation near 70˚C on tensile properties

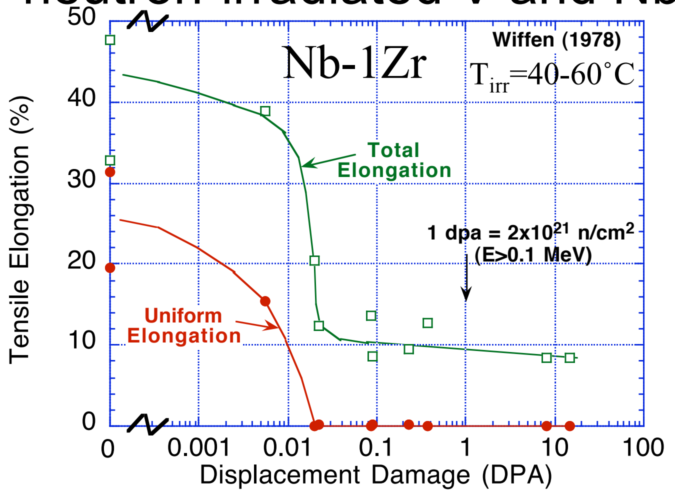
Reduction of uniform elongation to <2% typically occurs within 0.001 to 1 dpa

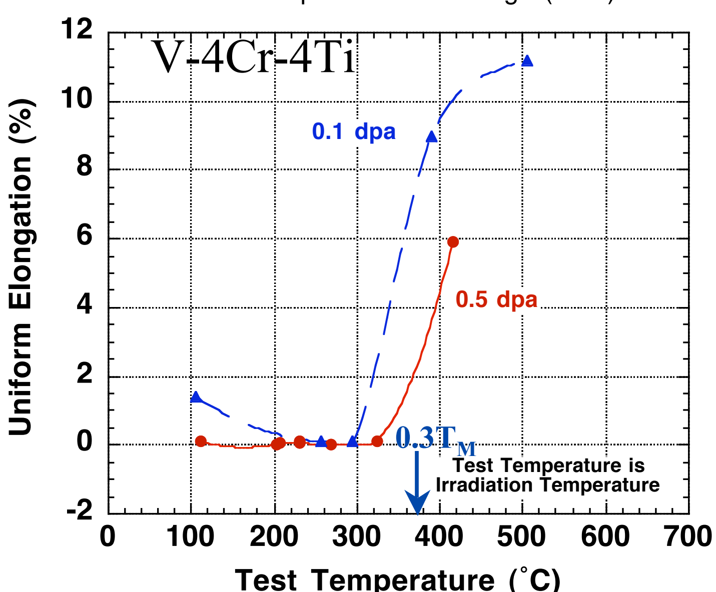


K. Farrell et al.

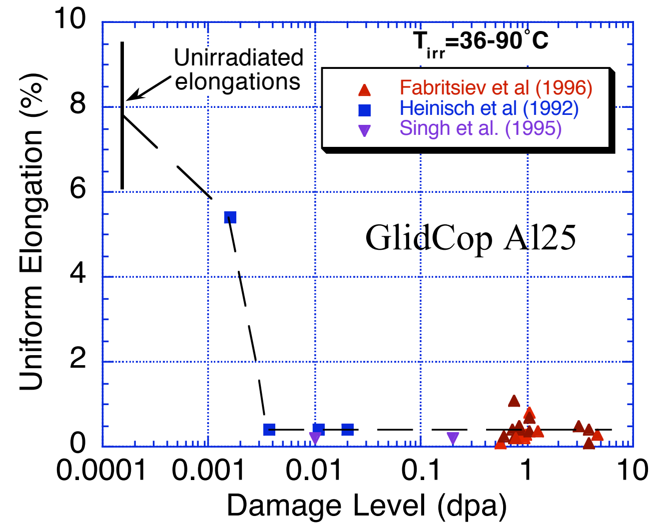
Low uniform elongations occur in many BCC and FCC metals after low-dose irradiation at low temperature

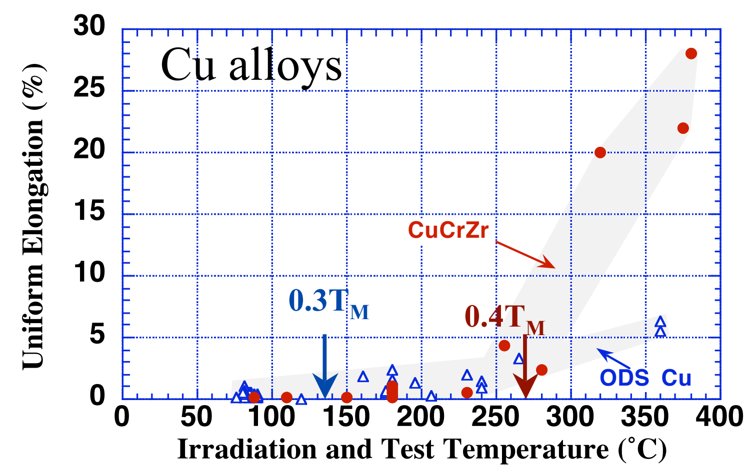
Uniform elongation of neutron-irradiated V and Nb





Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr





Low uniform elongation is induced after very small doses at low temperatures

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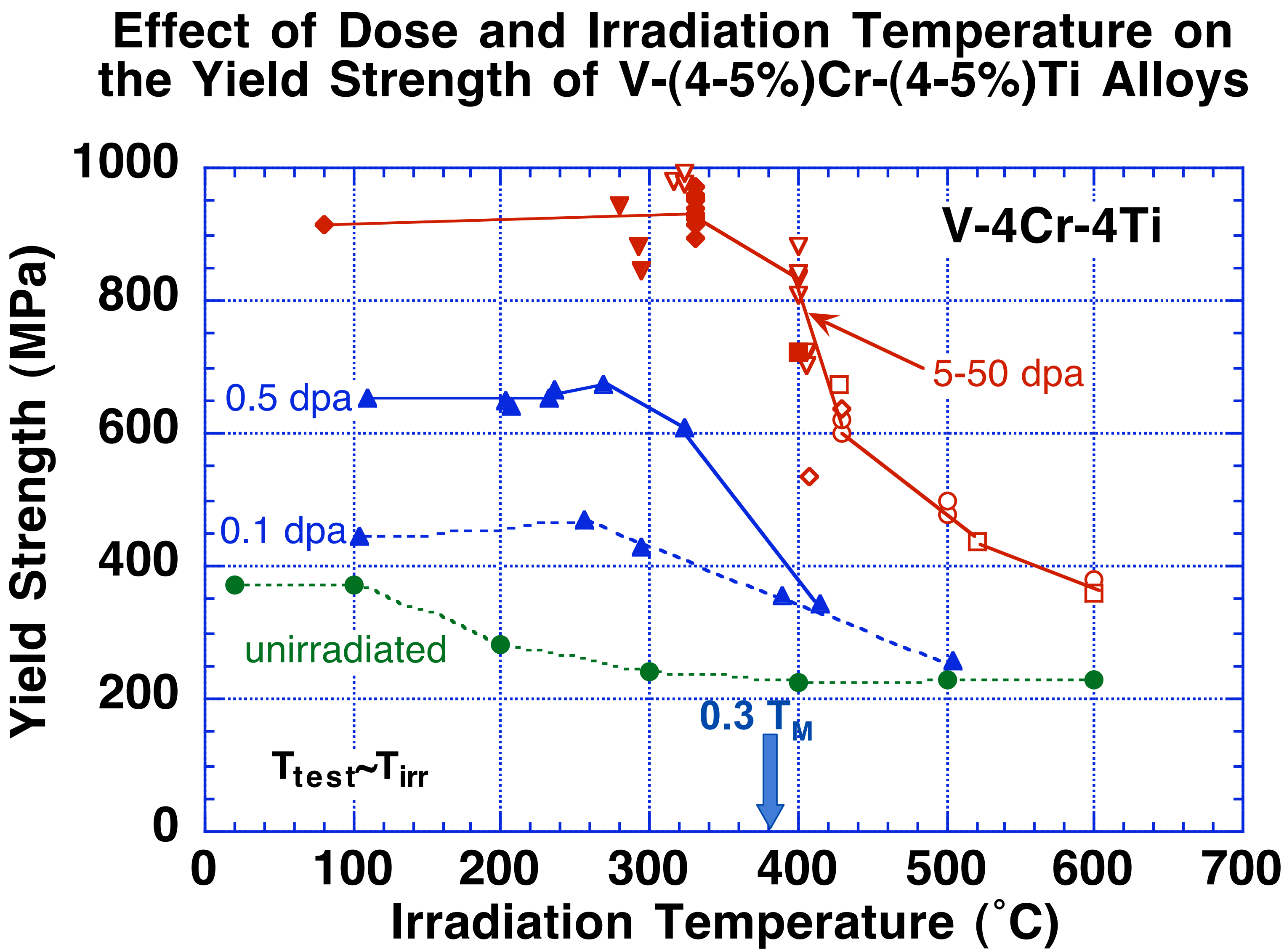
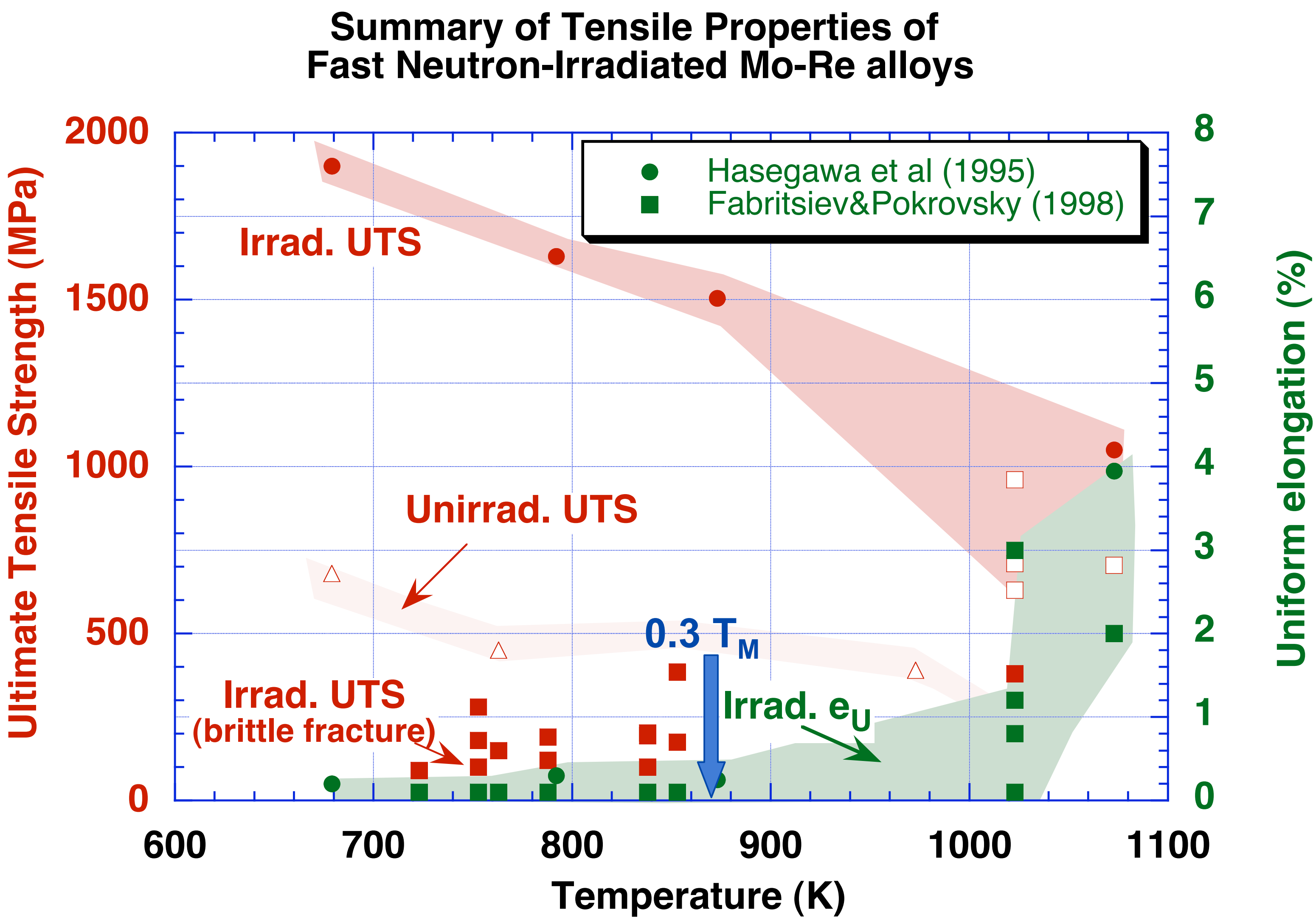
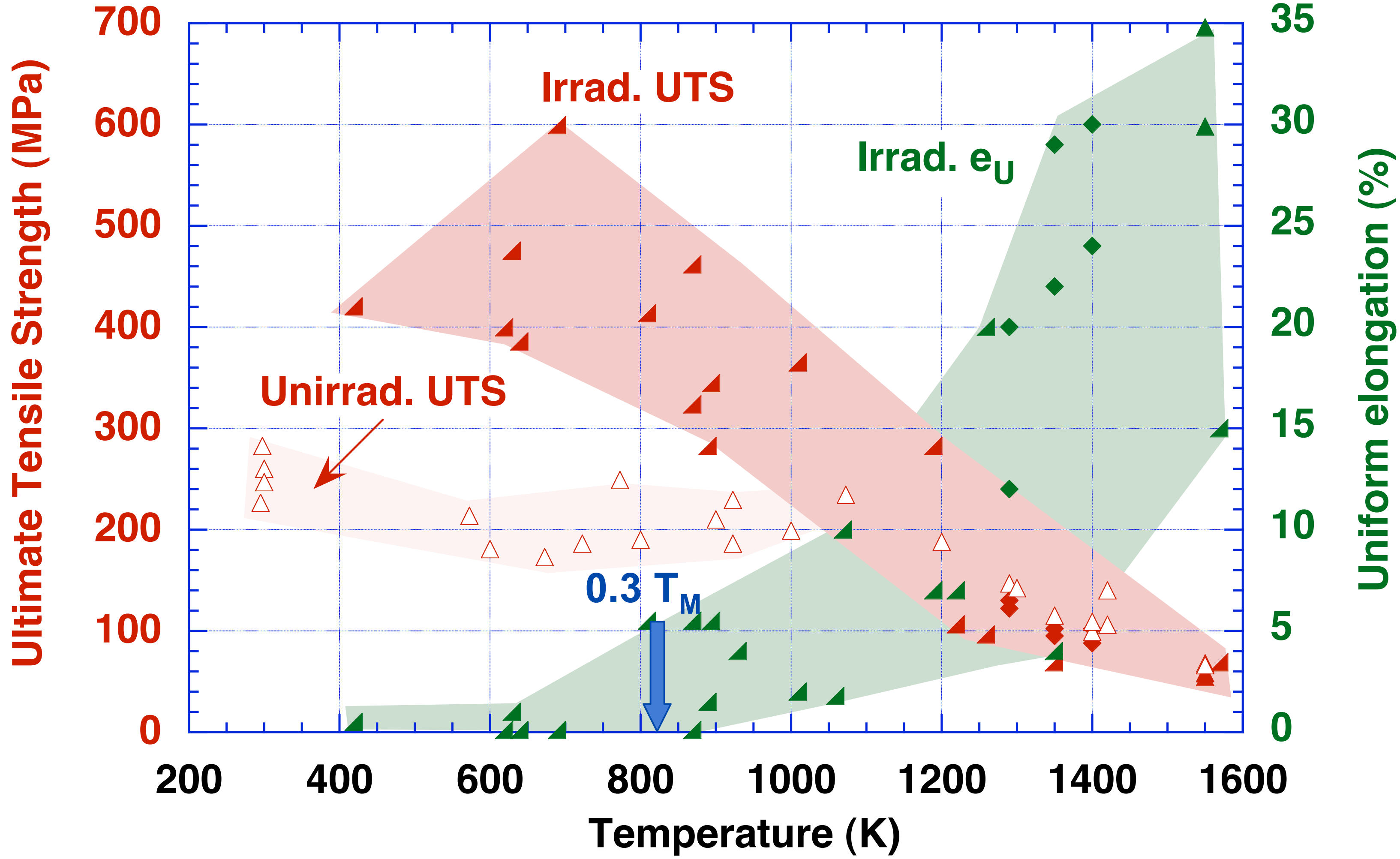
Radiation hardening in V-4Cr-4Ti



Neutron Irradiation Data Show Low Ductility and High Hardening of Mo-Re alloys up to 1070 K (0.37 T_M)



Summary of Tensile Properties of Neutron-irradiated Nb-1Zr in Li-bonded capsules



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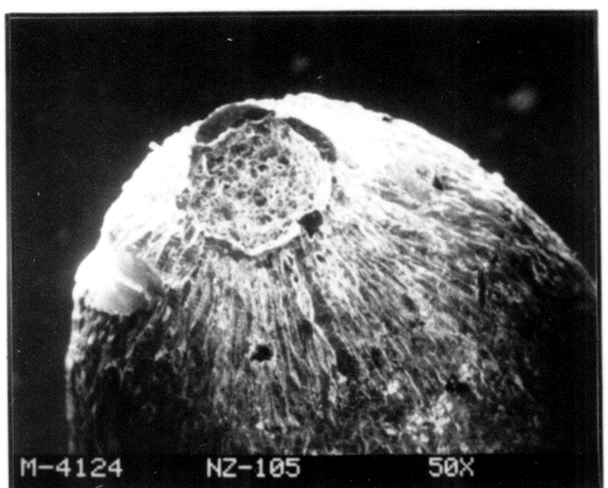
Fracture surface of Irradiated Nb-1Zr shows ductile behavior, despite low uniform elongation value

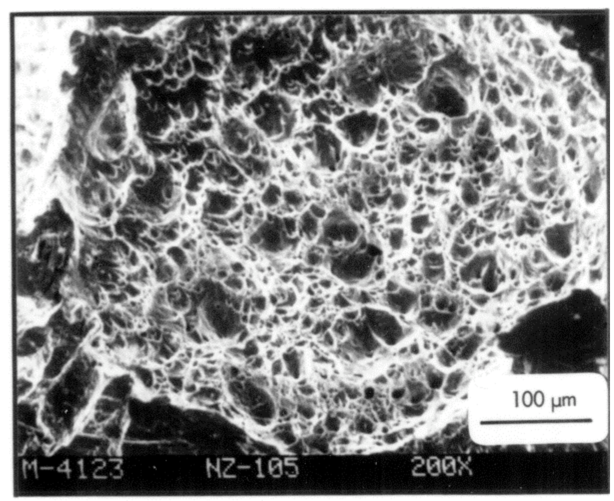
Nb-1 Zr

0.22 dpa at ~70°C
[4.5 x 10^{20} n/cm^2 (>0.1 MeV)]

Tensile Test at ~35°C

0.2 % Uniform Elongation
9.6% Total Elongation



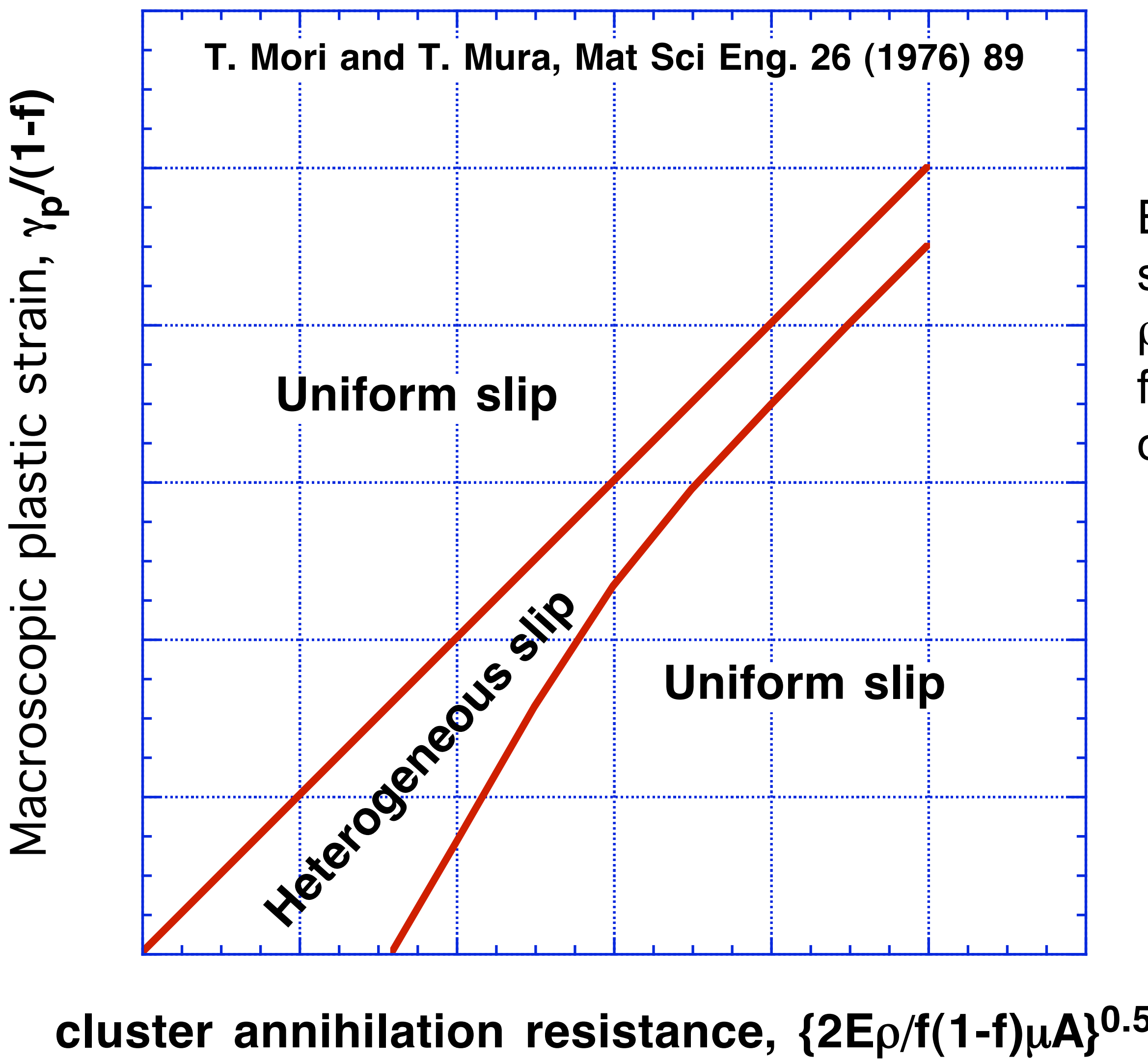


F.W. Wiffen, unpublished results

The issue of localized flow (planar slip) has been the subject of numerous materials science investigations (unirradiated metals)

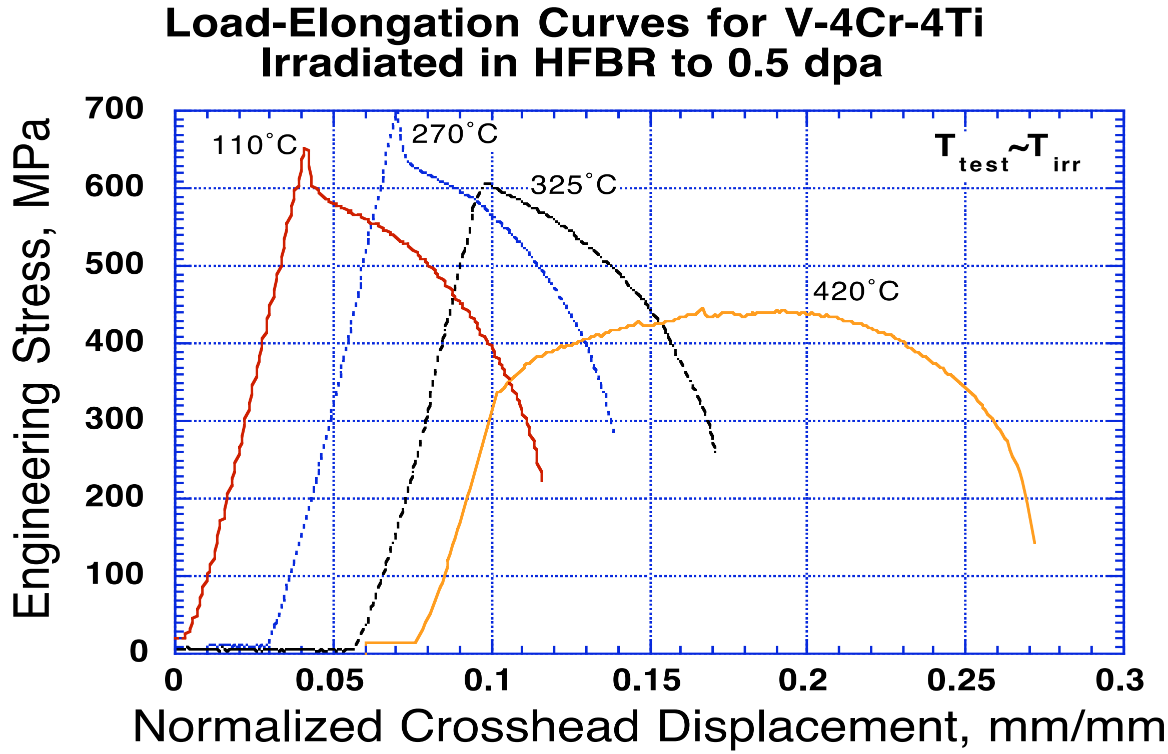
- Three general parameters may be considered to influence planar slip (e.g., Gerold & Karnthaler Acta Met. 39 (1989) 2177; Basinski et al. Phil Mag. A 76 (1997) 743):
  - Stacking fault energy (weak effect)
  - Value of yield stress (weak effect)
  - Occurrence of short range ordering (solid solution alloys) or ordered precipitates that are shearable (generally dominant effect)

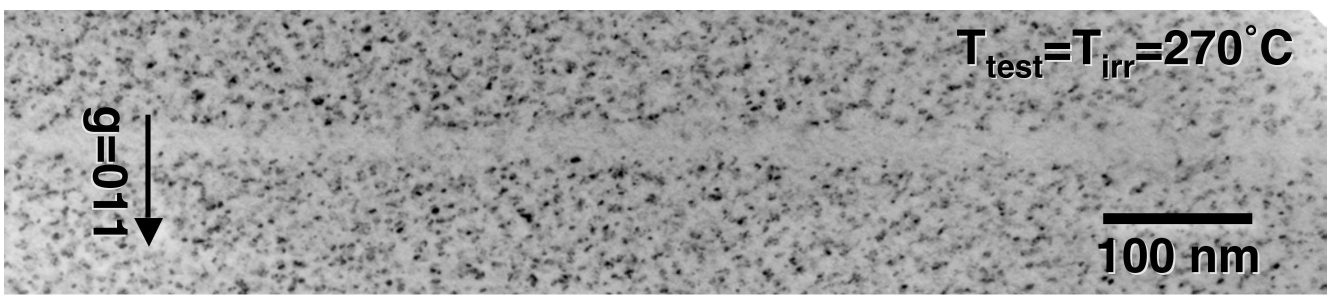
Plastic deformation mechanisms for dispersion hardened materials containing work-softening obstacles



E_e=elastic energy stored by one obstacle
ρ=obstacle density
f=vol. fraction of obstacles

Irradiated Materials Suffer Plastic Instability (due to Dislocation Channeling?)





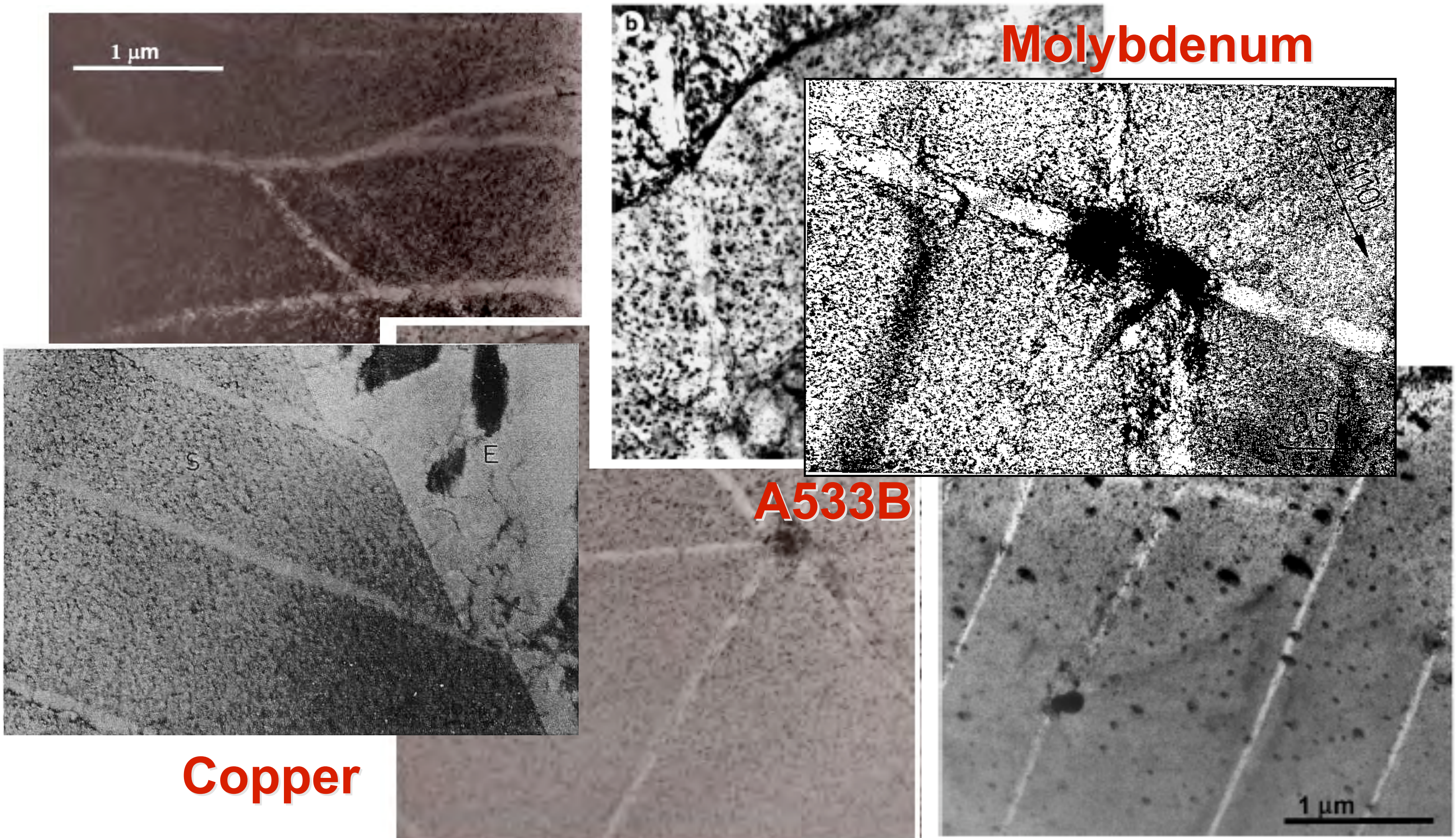
Overview of dislocation channeling

- Dislocation channeling is a viable mechanism to locally work soften the matrix
  - Shearable obstacles
- Channeling involves localized flow and therefore inhibits dislocation multiplication
  - Limited interaction between dislocation sources

However, ...

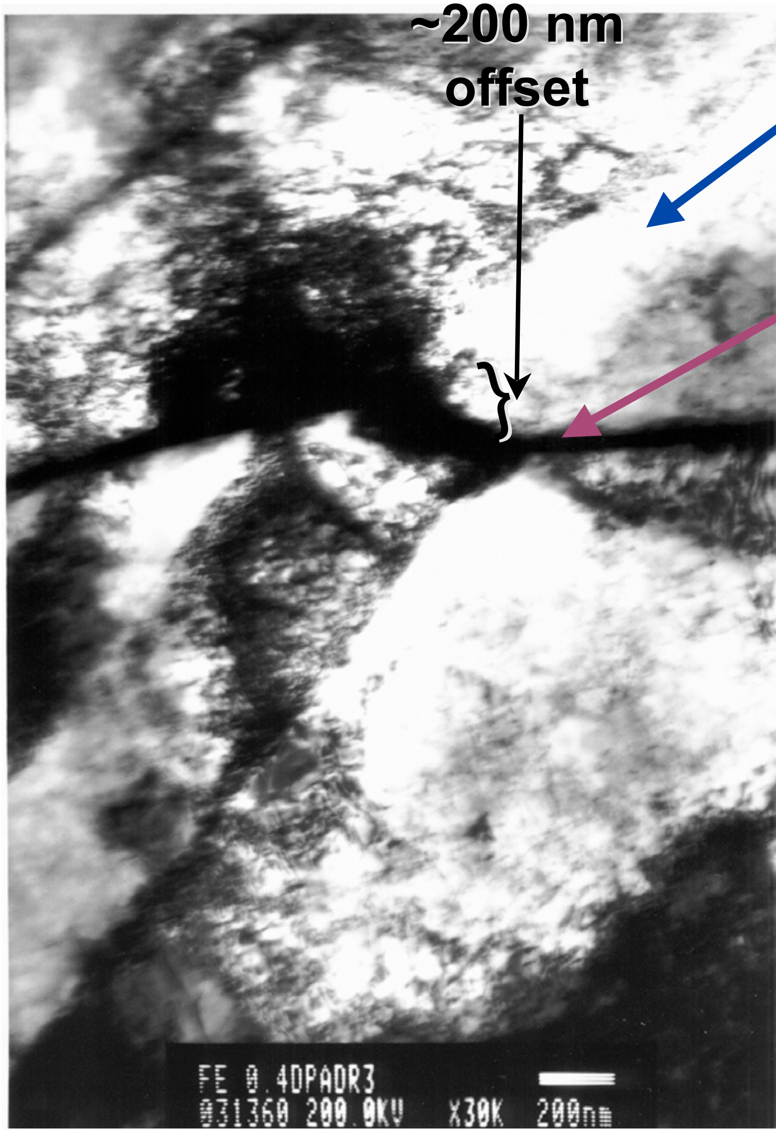
- It is not generally established that the catastophic reduction in tensile elongation is directly due to dislocation channeling
  - High tensile elongations and significant work hardening rates can occur in irradiated metals that exhibit dislocation channeling

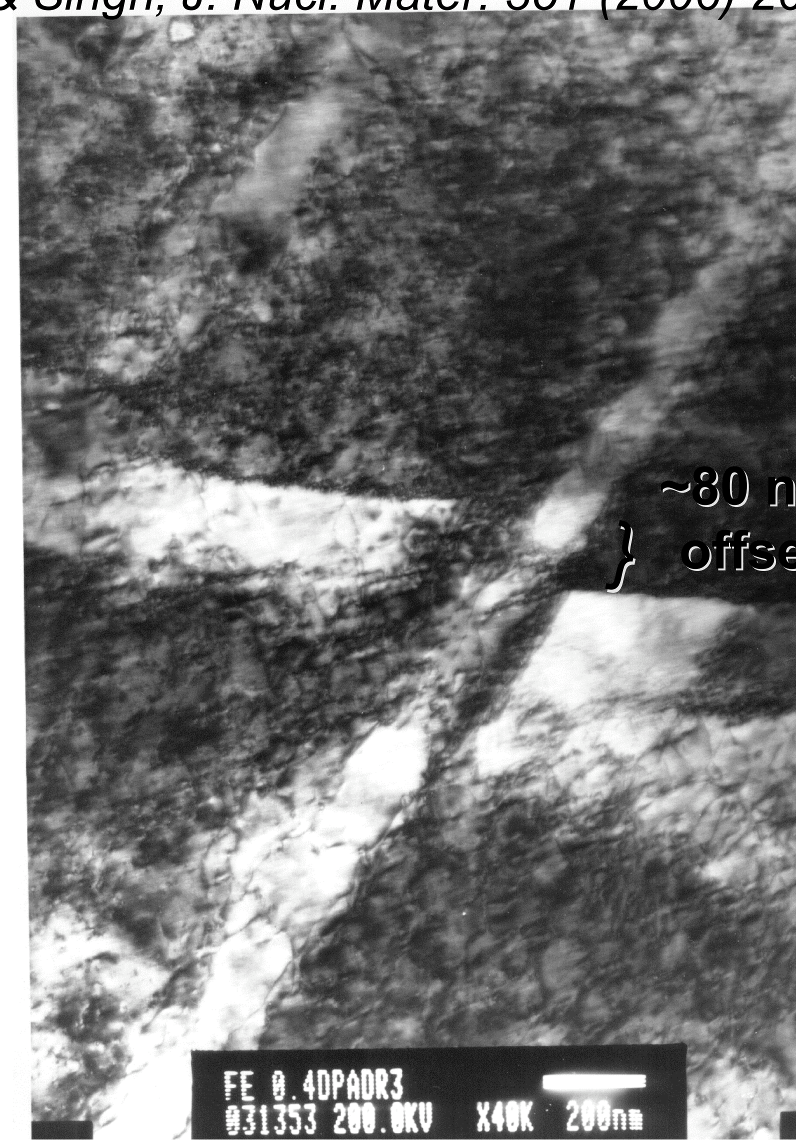
Localized deformation (and dislocation channeling) occurs in many irradiated material systems



Dislocation channel interactions in Fe deformed following neutron irradiation at 70°C to 0.8 dpa

Zinkle & Singh, J. Nucl. Mater. 351 (2006) 269





Need well-engineered materials to mitigate neutron radiation effects

Summary of Dislocation Channeling Parameters

Material	Dose (dpa)	Irrad. Temperature	Test Temperature	Channel width (nm)	Channel spacing	Reference
Cu	~0.001-0.5	313-323 K	295 K	~50-200	0.5-2.3 μm	9 research groups
Cu	~0.5	~50˚C	50 K 77 K 295 K	50 70 100	0.8-1.2 μm	Howe 1974
CuCrZr	0.3	323 K	323 K	100-300		Singh & Stubbins fatigue
Cu-0.8%Co	~0.001	~50˚C	295 K	160	1.2-2.3 μm	Sharp 1974
Cu-0.05%Al	~0.001	~50˚C	295 K	240	1.2-2.3 μm	Sharp 1974 (channels not observed in Cu-4%Al)
Au	~0.003	20˚C	295 K	~100		Okada 1989
Ni		~50˚C	295 K	~300		Noda 1977
Pd	0.3			~50-100		Victoria et al 2000
304L SS	5 (ions) "	500˚C "	563 K 295 K	15 50-200 (twins)		Brimhall 1995
Fe-10%Cr-30%Mn	~0.005	300˚C		~100?		F. Abe 1992
α-Fe	~0.38	323 K	323 K	50-200		Singh et al.;Victoria et al 2000
Nb	~0.002			~400		Tucker 1969
V	0.1-0.8	330 K	295 K	20-80	0.5-2.5 μm	Arsenault 1977; Farrell 2002
V-4Cr-4Ti	0.5-5	500-673 K	295-673 K	~50-100		Rice&Zinkle 1998, Gazda 1998
Mo	~0.2	323 K	323 K	~500		Luft 1991; Singh et al.
TZM	~0.2	373 K	373 K	100-200		Singh et al.
Re						Pitt 1980
Zircaloy-2,4		425-563 K	293-573 K	40-100		Coleman 1972, Onchi 1980
Au	quenched			160-500		Yoshida 1968, Bapna 1974
Al	quenched			650-1000		Mori 1969; Tokuno 1987

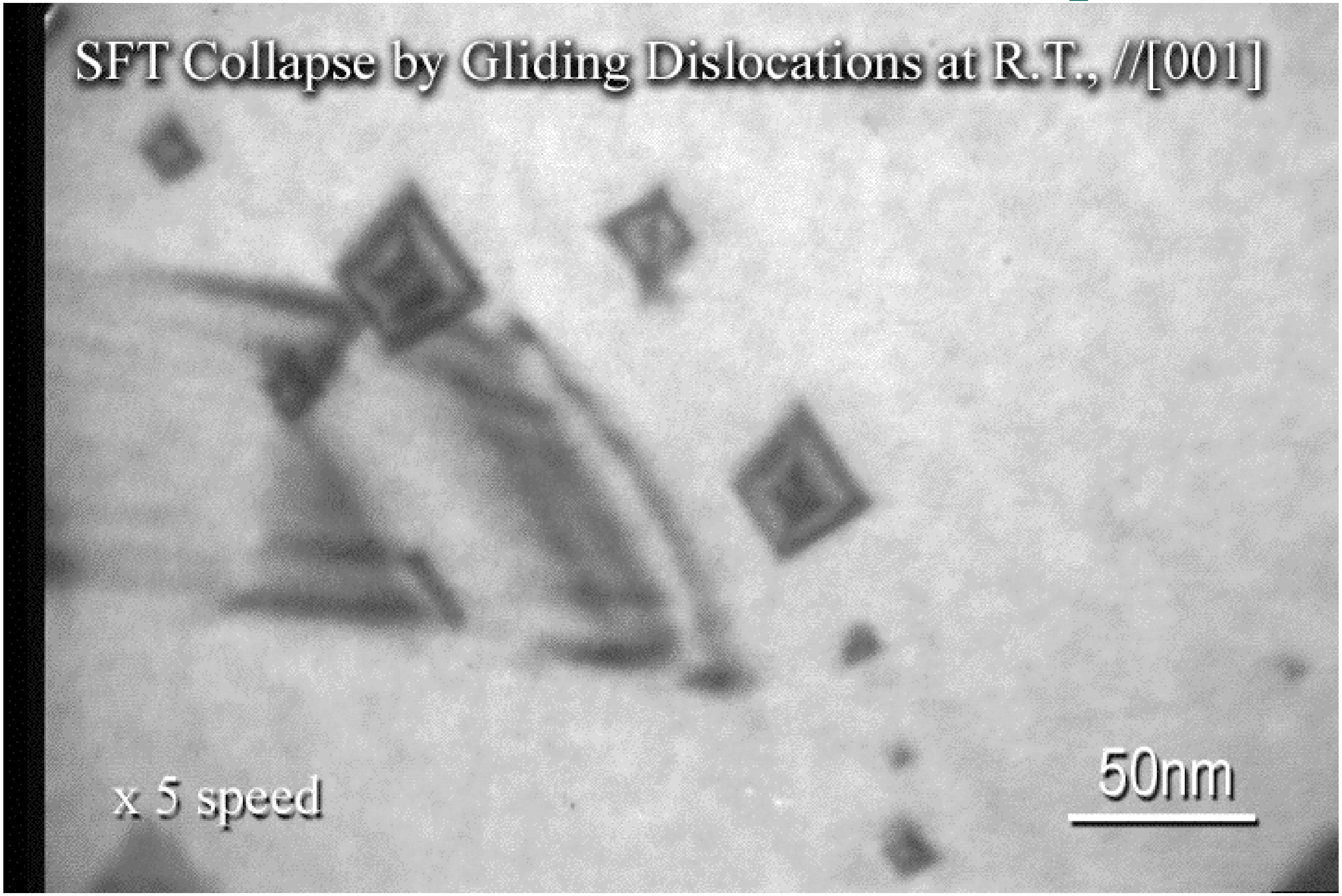
Dislocation channel width is ~100 nm for a wide range of experimental conditions

Investigation of dislocation interactions with SFTs

SFT annihilation by a single dislocation (remnant apex)

Y. Matsukawa, ORNL

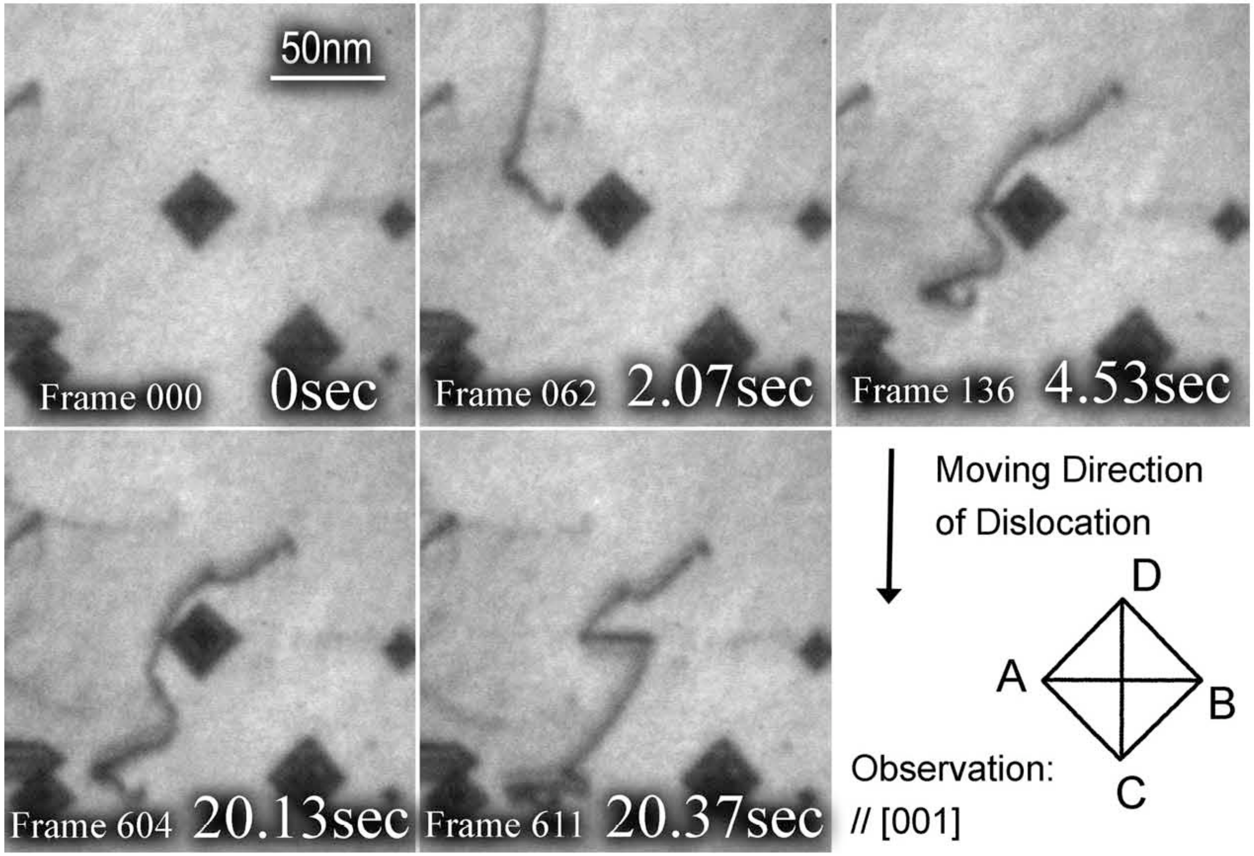
Dislocation interaction with SFTs in quenched Au



- Type 1 interaction (Frank loop formation) at room temperature

Matsukawa, Stoller, Osetsky & Zinkle
J. Nucl. Mater. 351 (2006) 285

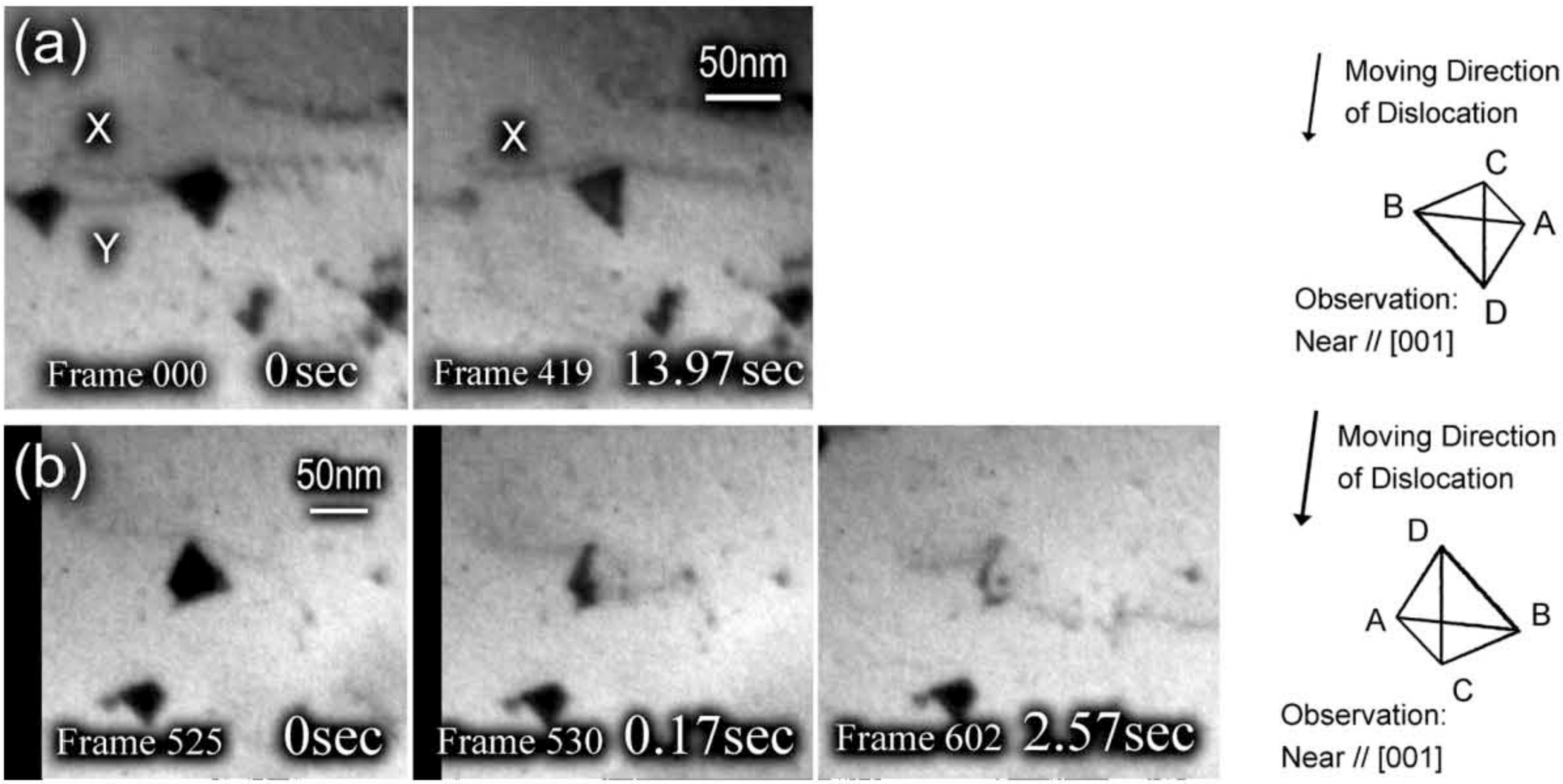
Dislocation interaction with SFTs in quenched Au



- Type 2 interaction at room temperature (superjog creation with no SFT remnant)

Matsukawa, Stoller, Osetsky & Zinkle
J. Nucl. Mater. 351 (2006) 285

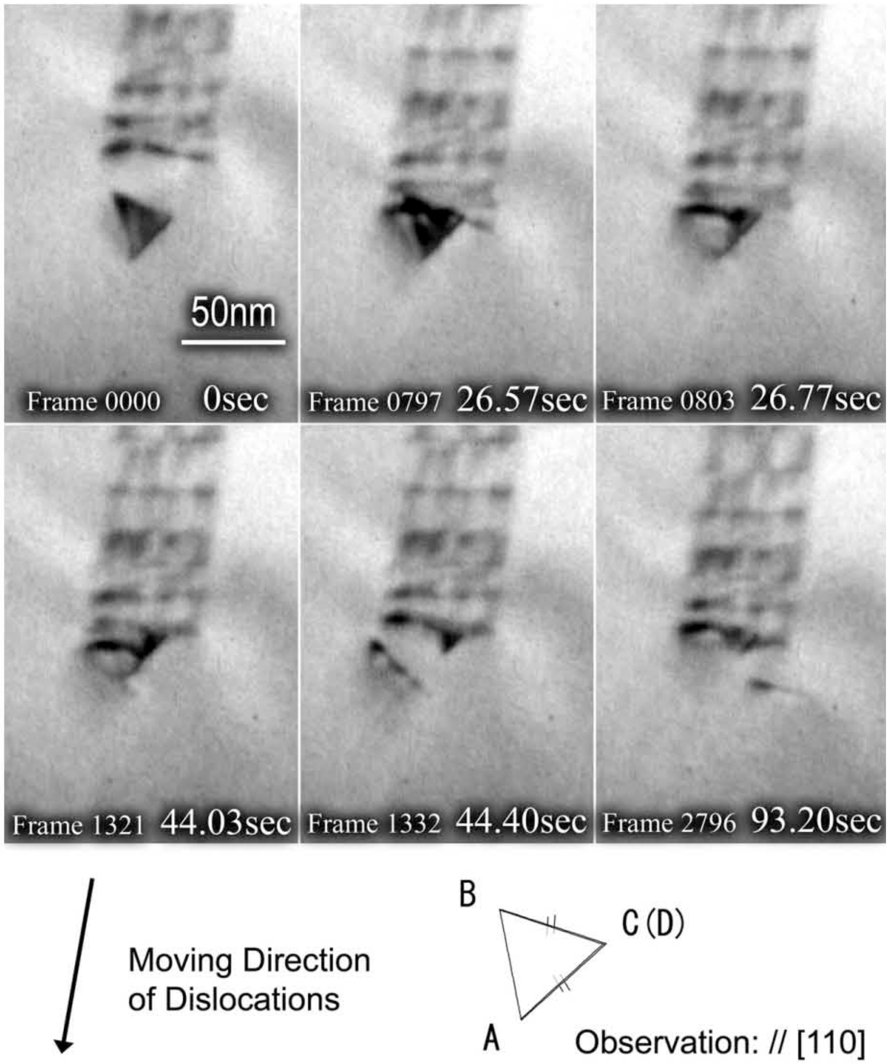
Dislocation interaction with SFTs in quenched Au

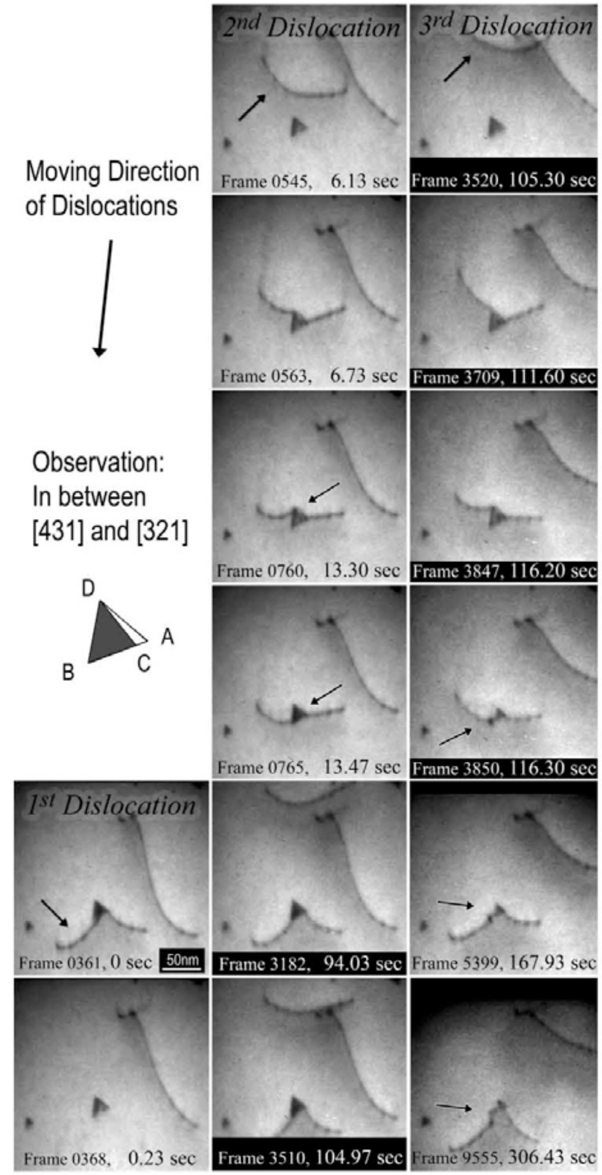


- Types 1(a) & 2(b) interactions also occur at 100 K

Matsukawa, Stoller, Osetsky & Zinkle
J. Nucl. Mater. 351 (2006) 285

Dislocation interaction with SFTs in quenched Au



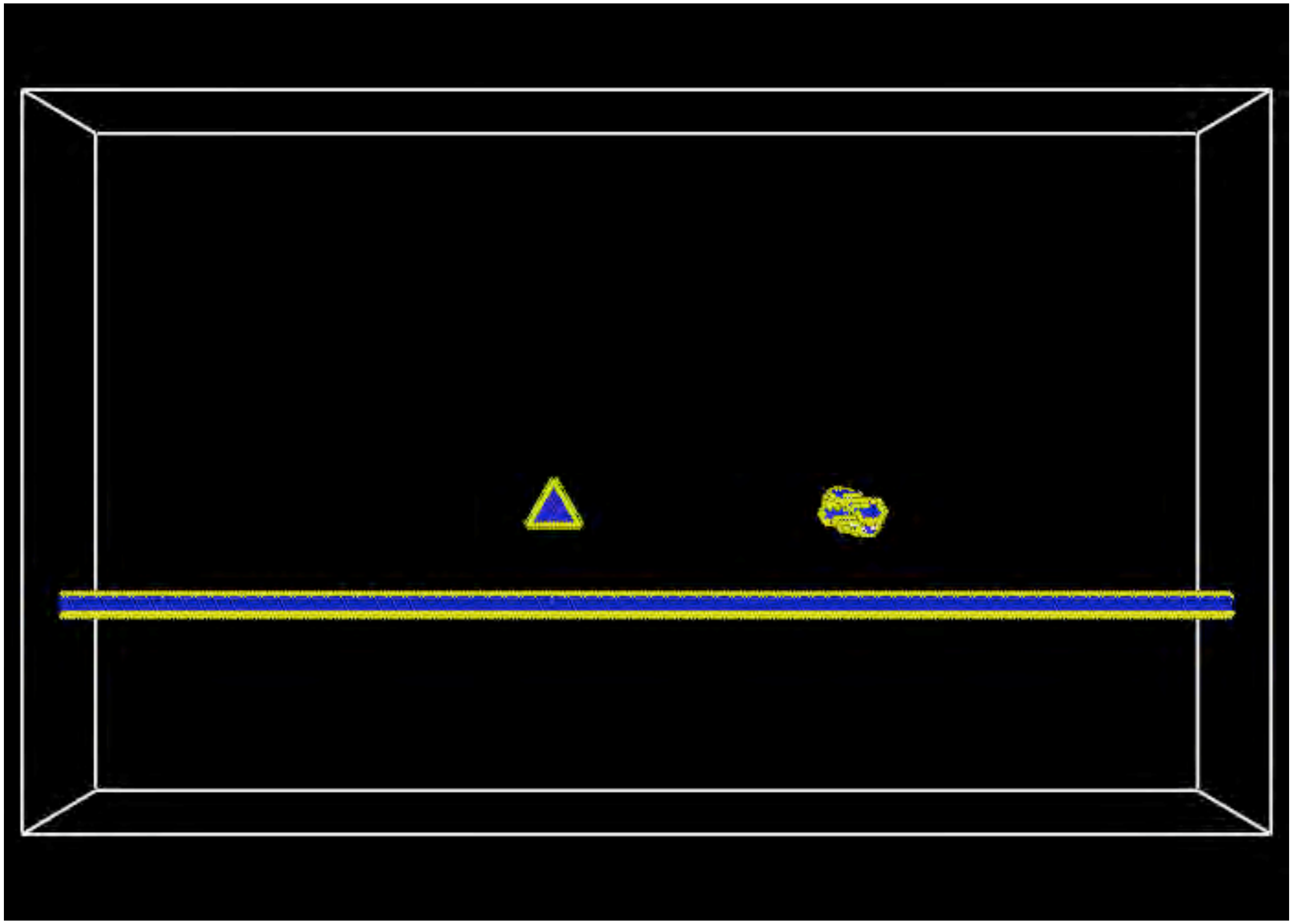


- Type 3 interactions at room temperature (SFT apex remains); not observed at 100 K

Matsukawa, Stoller, Osetsky & Zinkle
J. Nucl. Mater. 351 (2006) 285

Interaction of a screw dislocation with 78-vacancy SFT and 91-intersitital cluster in Cu thin foil

300 K



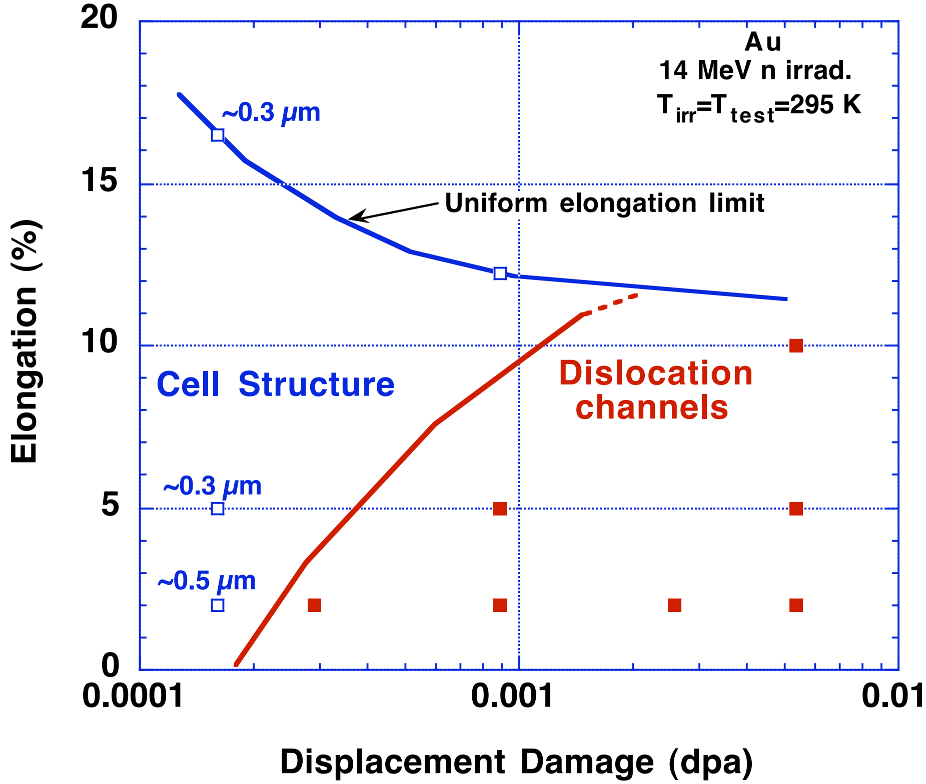
Cooperative effects may be important for annihilation of sessile defect clusters by gliding dislocations during deformation

Yu.N. Osetsky

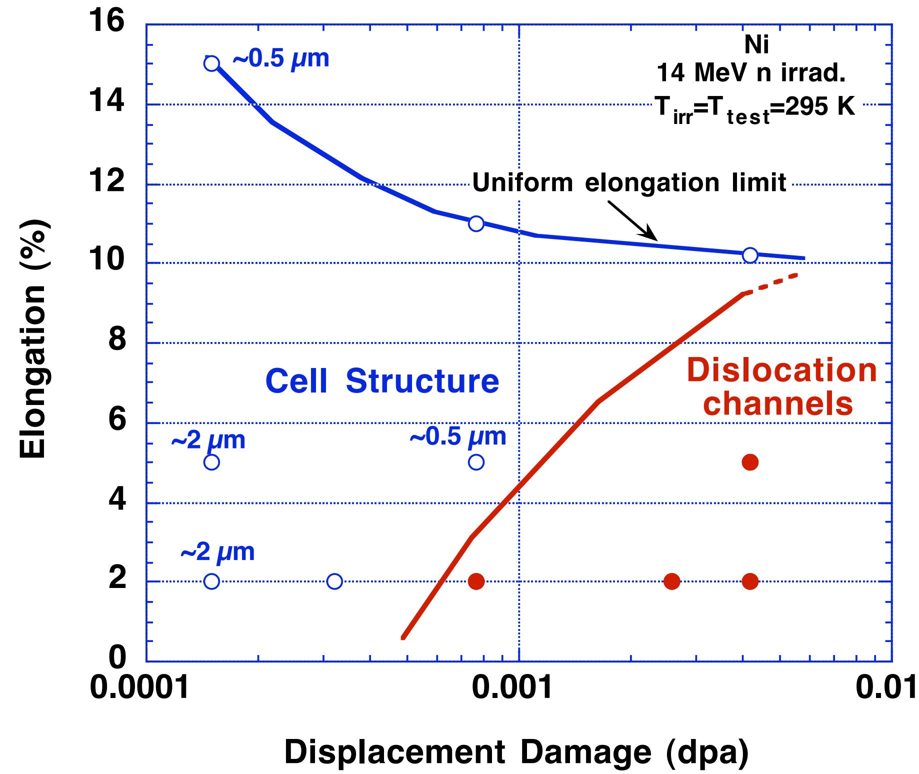
Effect of Irradiation Dose and Strain on Deformation Modes of FCC Metals

A. Okada et al. Mater. Trans. JIM 30 (1989) 265

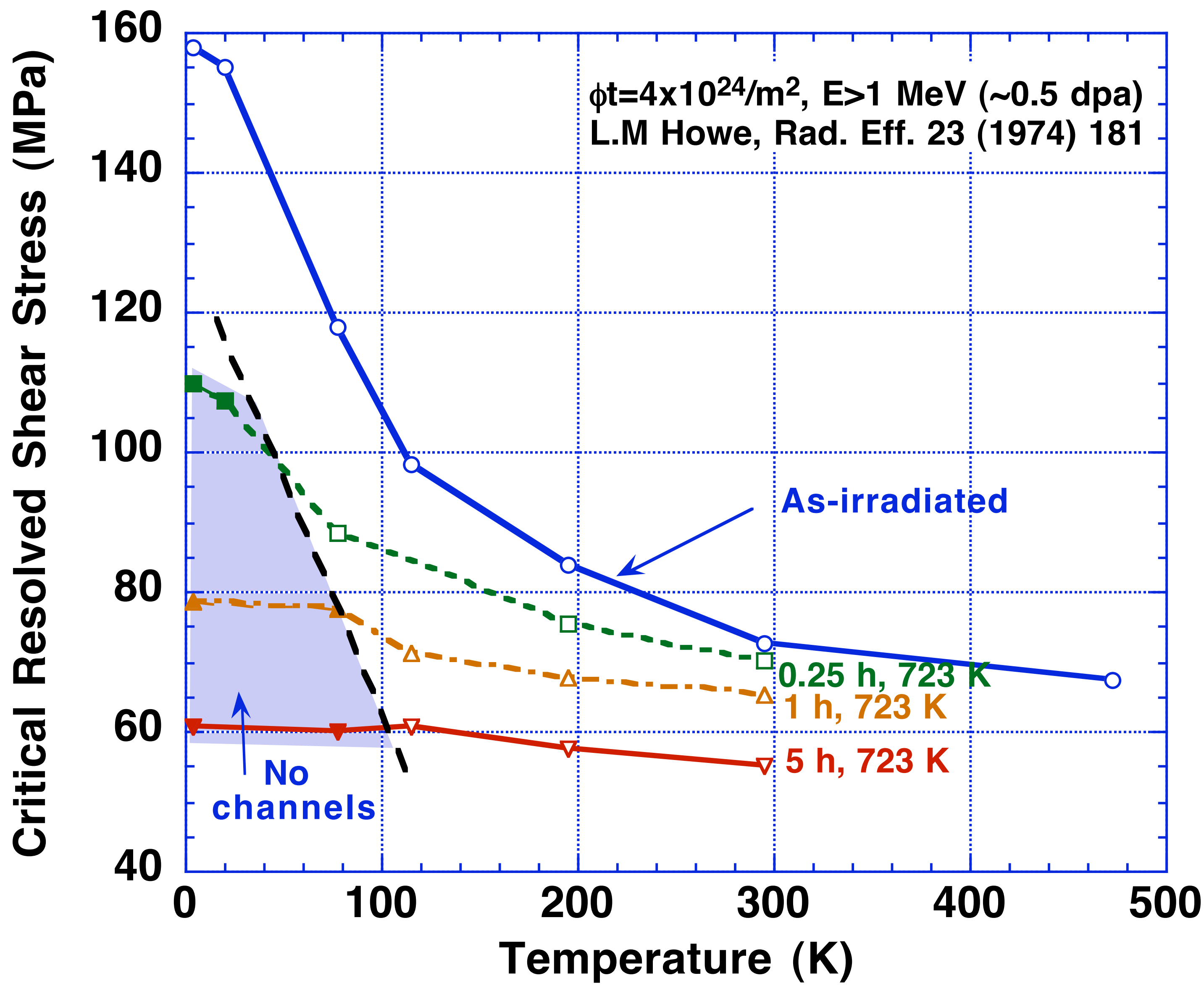
Deformation Mode Diagram for Neutron-irradiated Au



Deformation Mode Diagram for Neutron-irradiated Ni



Tensile Deformation Behavior in Irradiated Cu



Similar behavior observed in quenched Au
(S. Yoshida, Trans. JIM 9 suppl. (1968)83)

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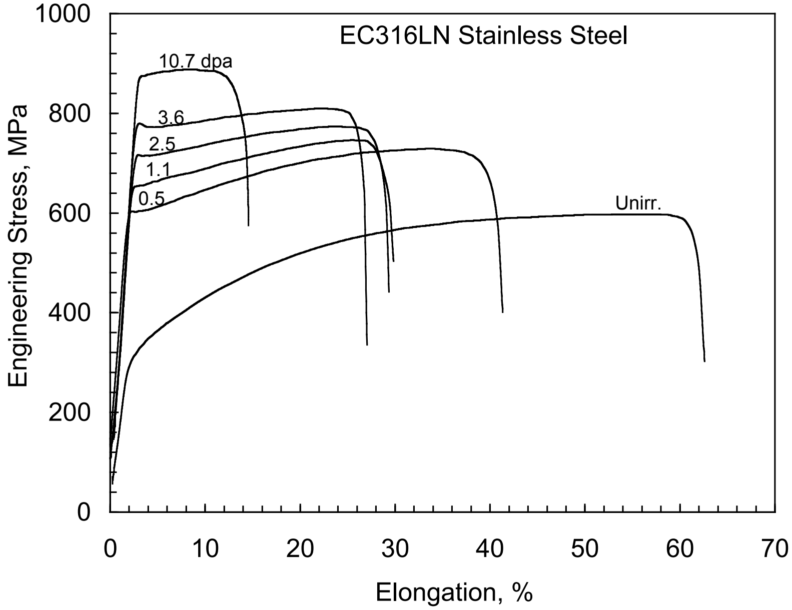
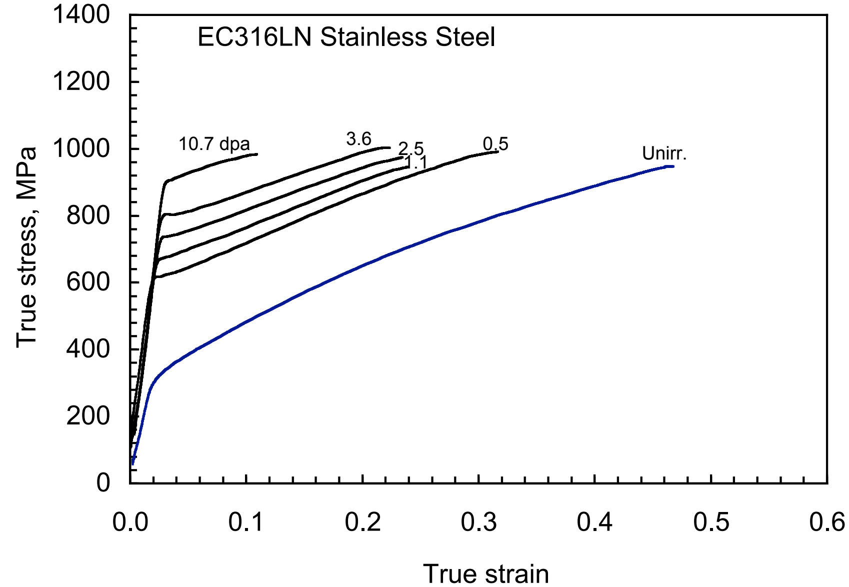
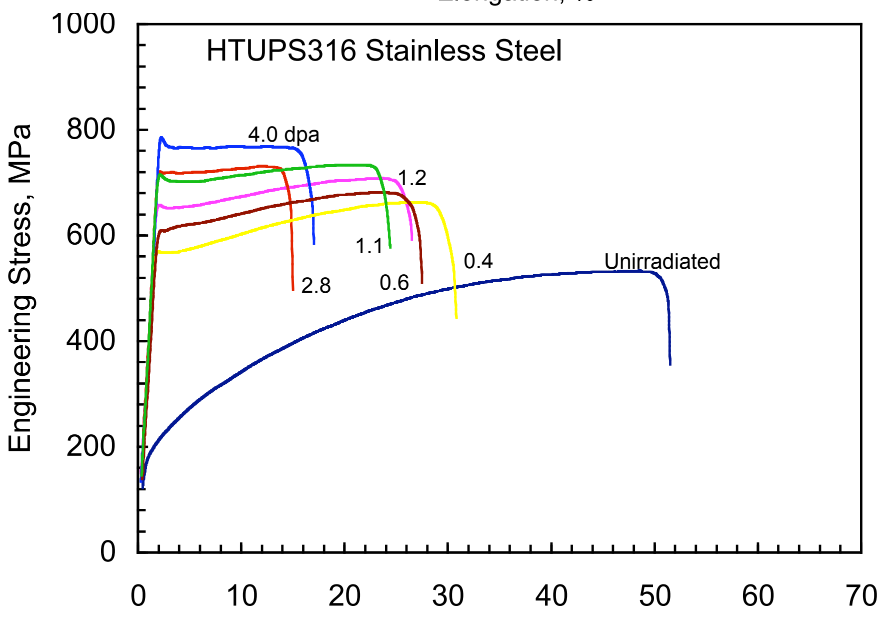
UT-BATTELLE

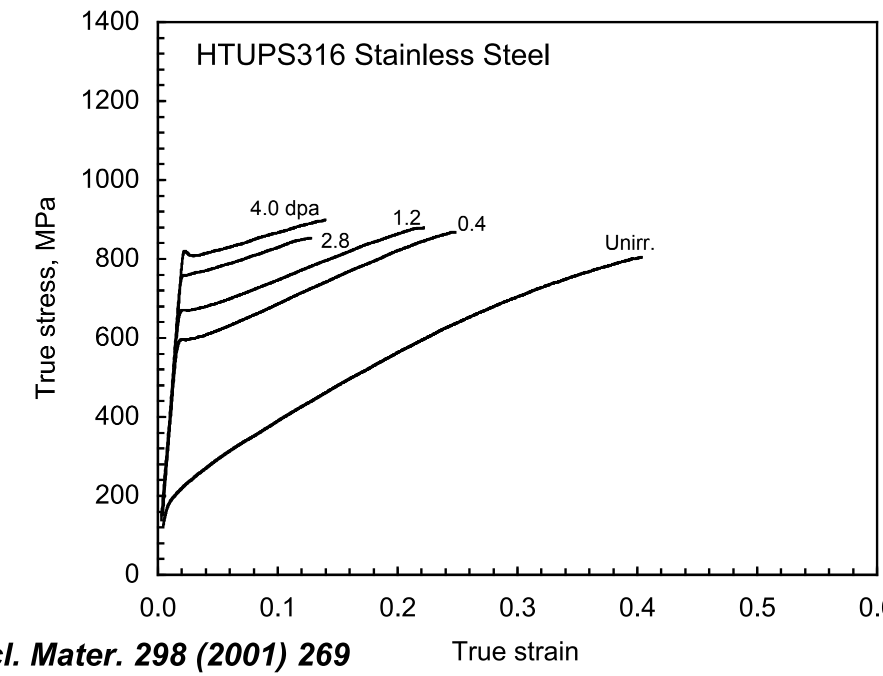
Engineering and true stress-strain tensile curves for stainless steel before and after spallation irradiation at ~100°C



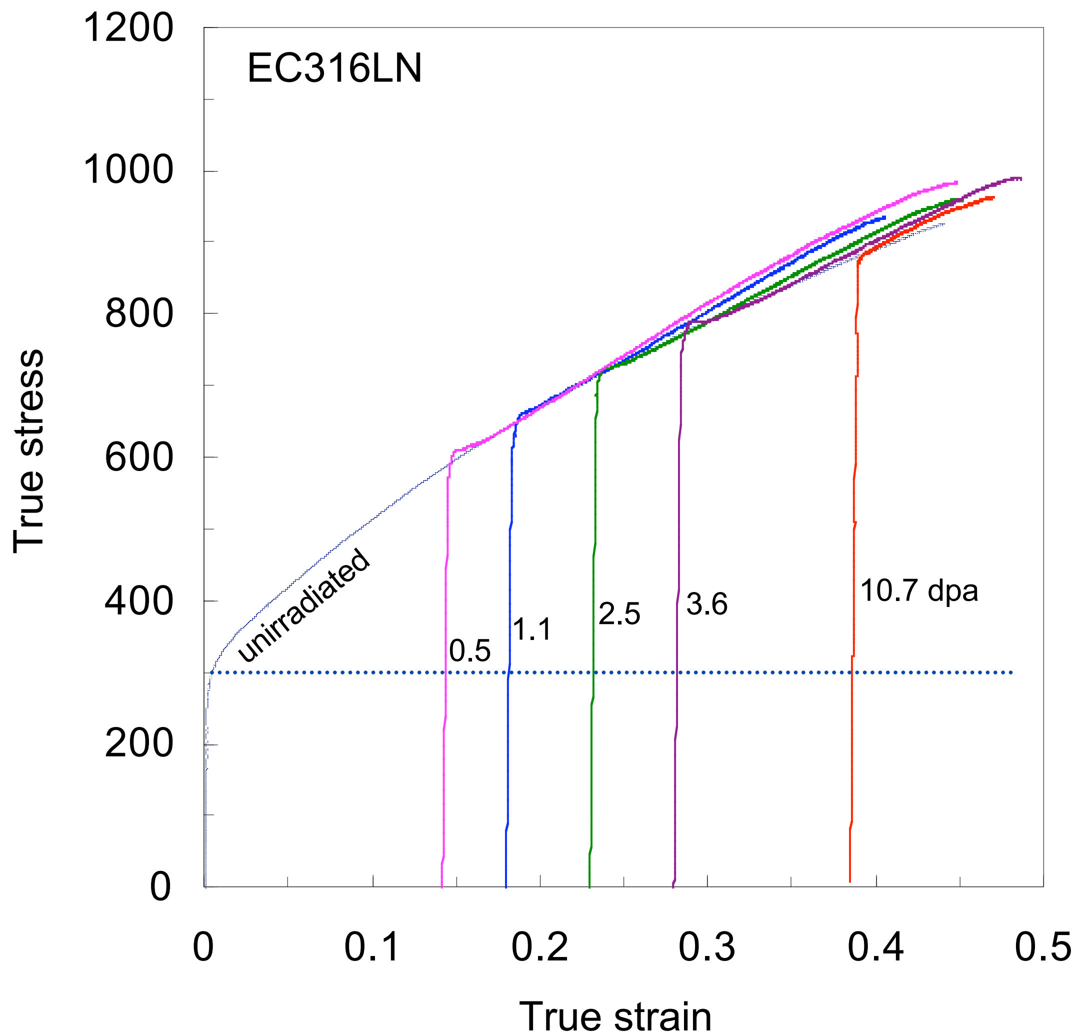




T.S. Byun et al., J. Nucl. Mater. 298 (2001) 269



Radiation Effect in True Stress-True Strain Curve (FCC)



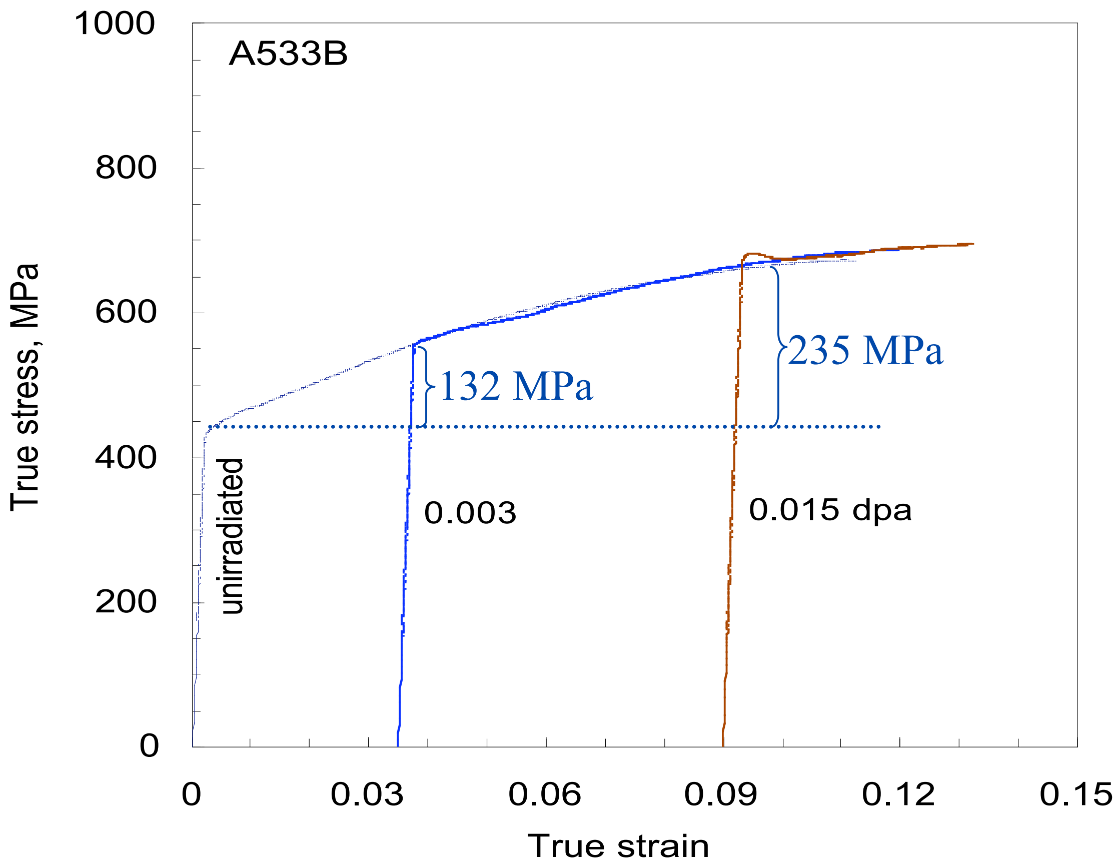
True stress-true strain curves for EC316LN stainless steel; the curves of irradiated specimens are shifted in the positive direction by strains of 0.14, 0.18, 0.23, 0.28, and 0.385, respectively, to superimpose on the curve of unirradiated material. Irradiation-induced increases in yield stress were 305, 358, 421, 485, and 587 MPa, respectively.

Further work is need to determine importance of dislocation channeling in observed exhaustion of initial strain hardening capacity

T.S. Byun & K. Farrell,
Acta Mater. 52 (2004) 1597

Radiation Effect on True Stress-True Strain Curve (BCC)

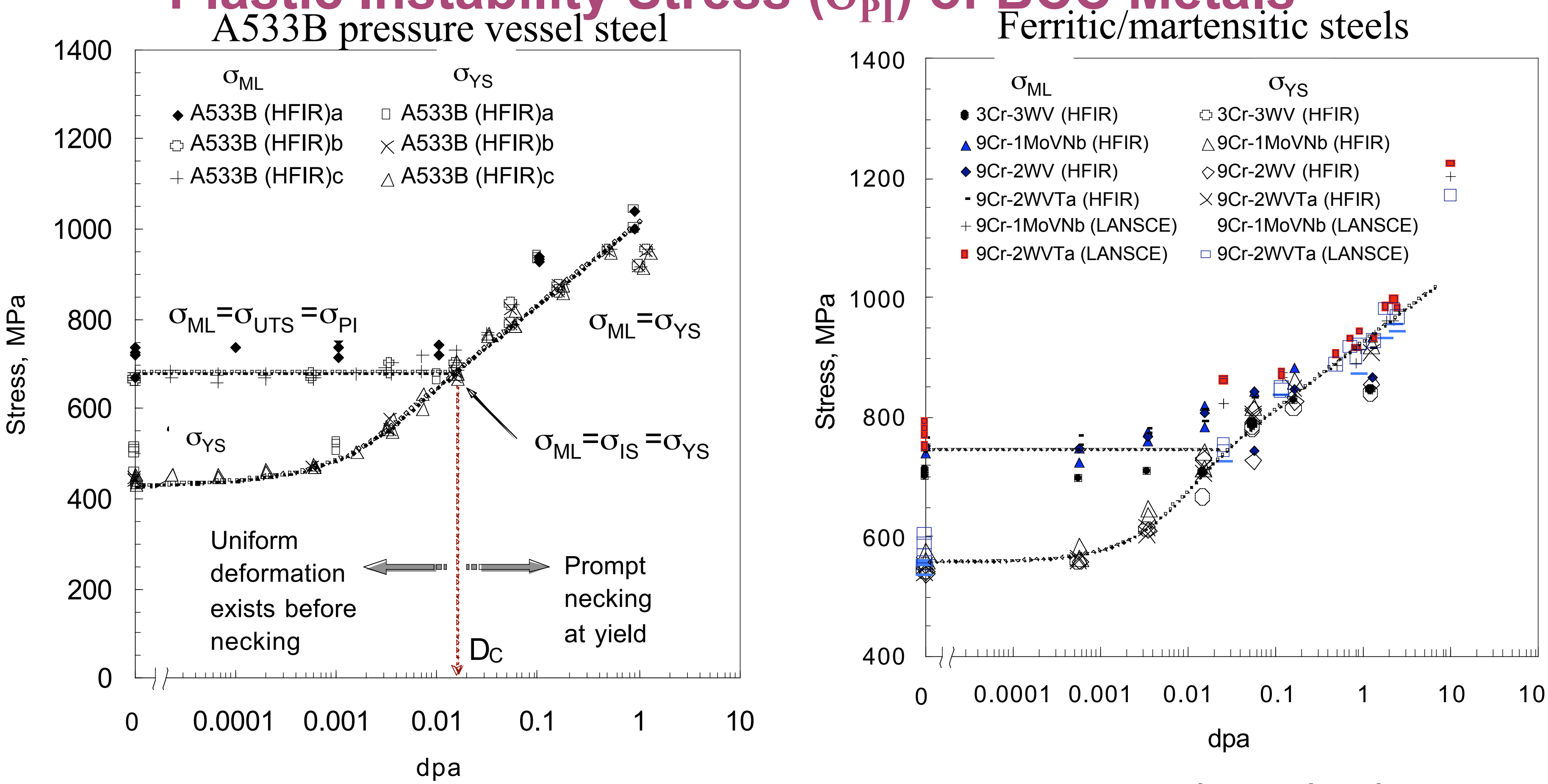
- True stress- true strain curve for irradiated material coincides with unirradiated curve, after translation to account for radiation hardening
  - Suggests main effect of radiation hardening is to partially exhaust strain hardening capacity



True stress-true strain curves for A533B steel; the curves of irradiated specimens are shifted in the positive direction by strains of 0.035 and 0.09, respectively, to superimpose on the curve of unirradiated material. Irradiation-induced increases in yield stress were 132 and 235 MPa, respectively.

T.S. Byun & K. Farrell, Acta Mater. 52 (2004) 1597

Plastic Instability Stress (σ_{PI}) of BCC Metals

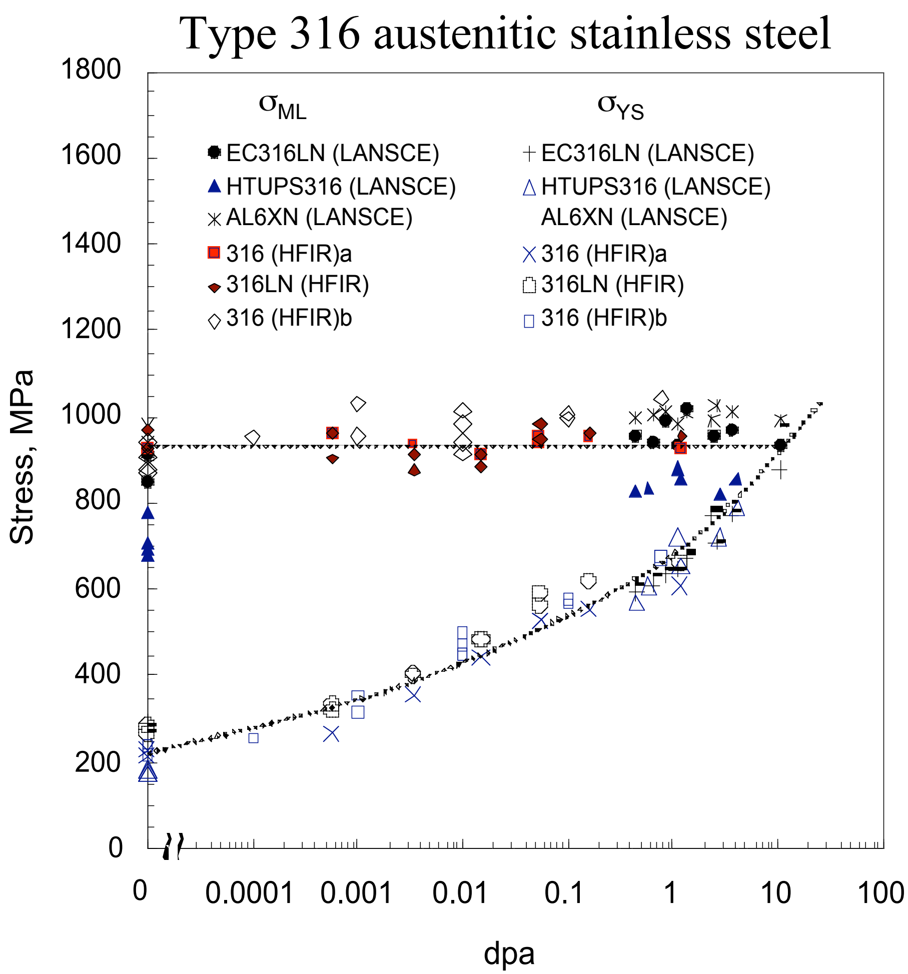


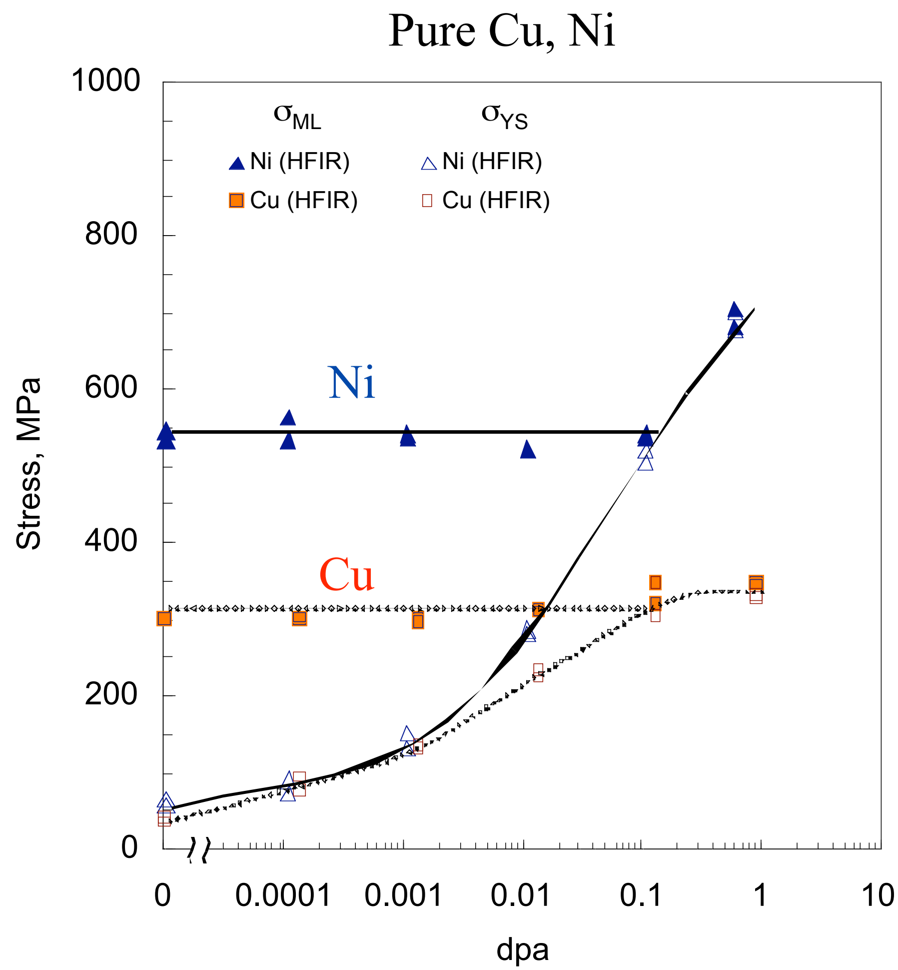
σ_{ML}=true stress at maximum load

- **Plastic Instability Stress (σ_{PI}) = the true stress version of Ultimate Tensile Stress**
- **Plastic Instability Stress is independent of dose when yield stress < σ_{PI}.**
- **Yield stress can be > σ_{PI}, which is defined only when uniform deformation exists.**
- **σ_{PI} is considered to be a material constant, independent of initial cold-work or radiation-induced defect clusters**

T.S. Byun & K. Farrell,
Acta Mater. 52 (2004) 1597

Plastic Instability Stress (σ_{PI}) of FCC Metals irradiated near 70˚C





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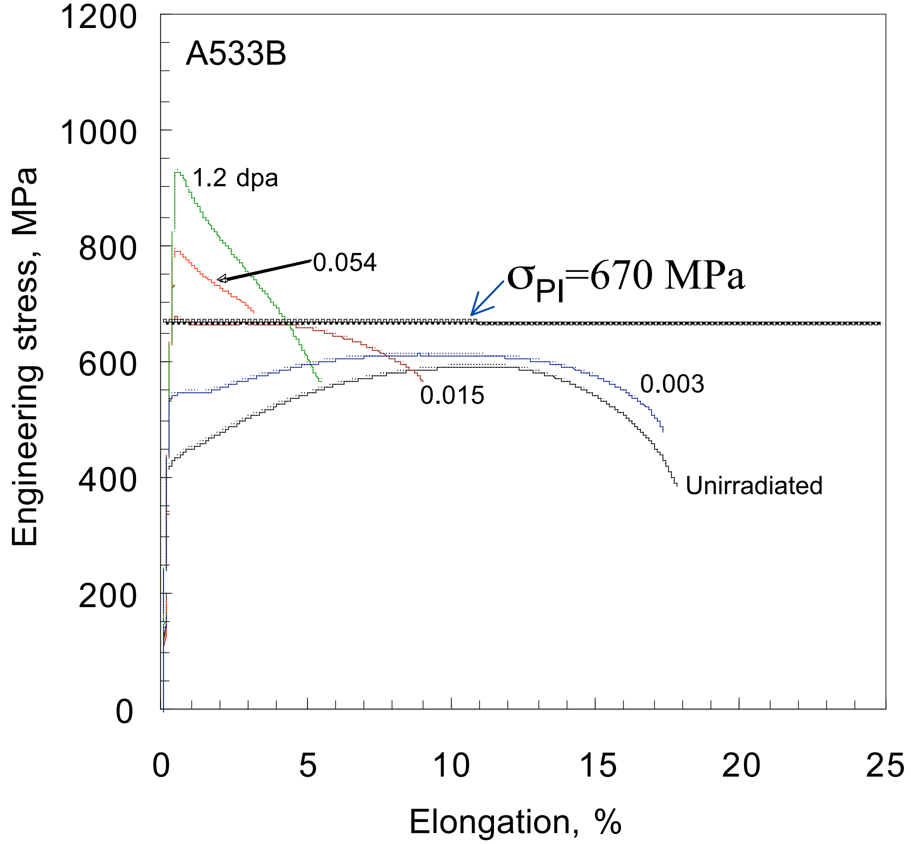
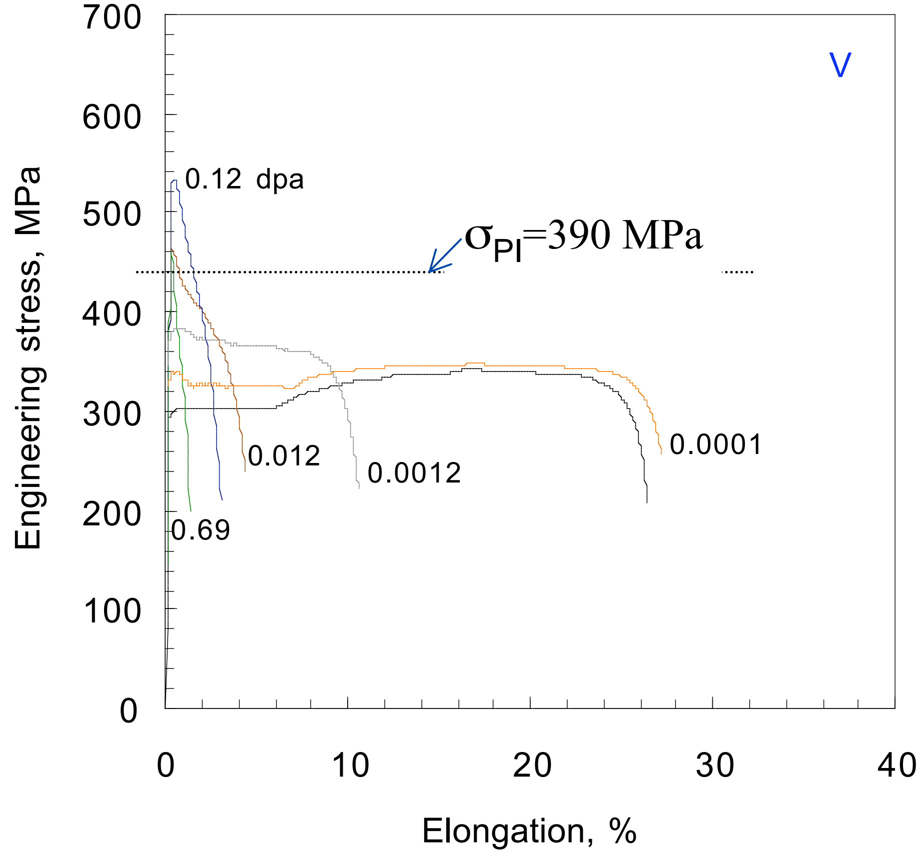
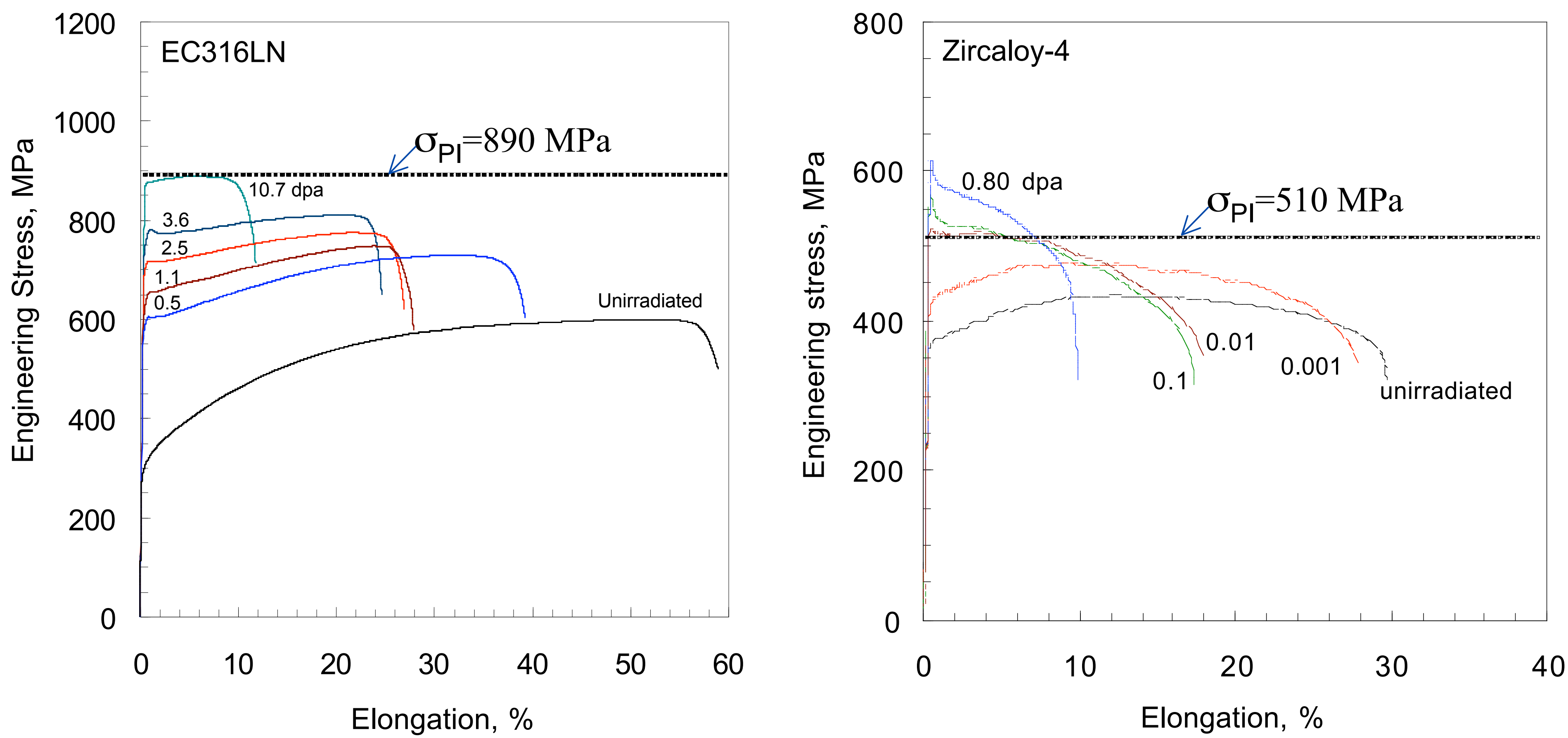
Plastic Instability Criterion for BCC metals irradiated near 70˚C



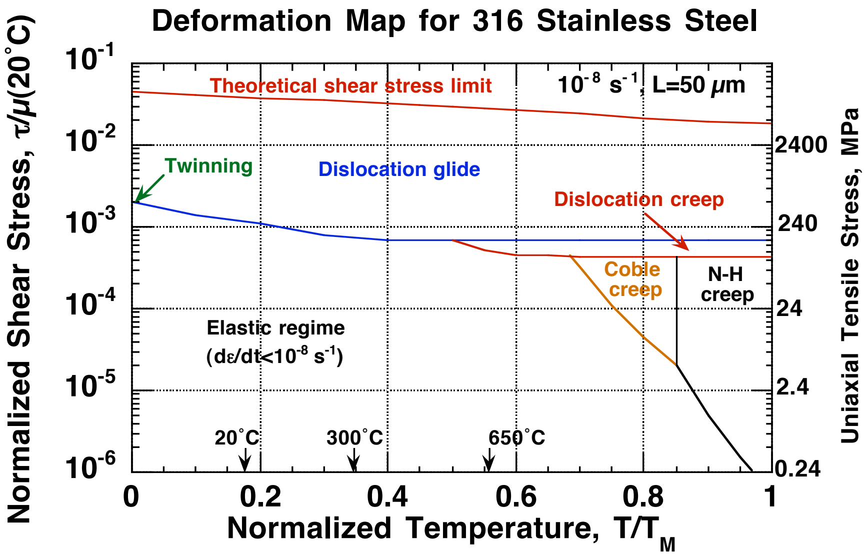


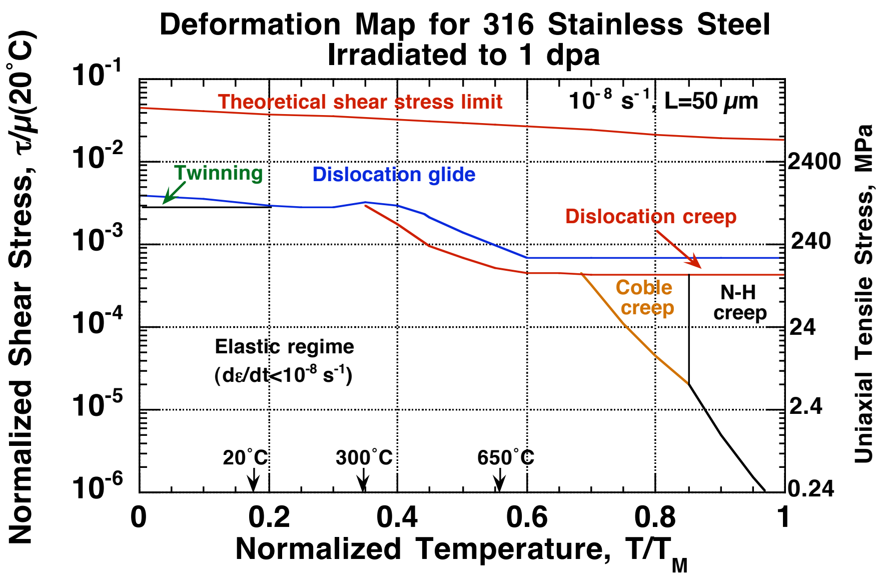
- Prompt plastic instability at yield occurs when yield stress > σ_{PI}.
- σ_{PI} is constant for unirradiated and irradiated conditions; implies that σ_{PI} is a criterion for plastic instability

Plastic Instability Criterion (FCC & HCP) irradiated at ~70˚C

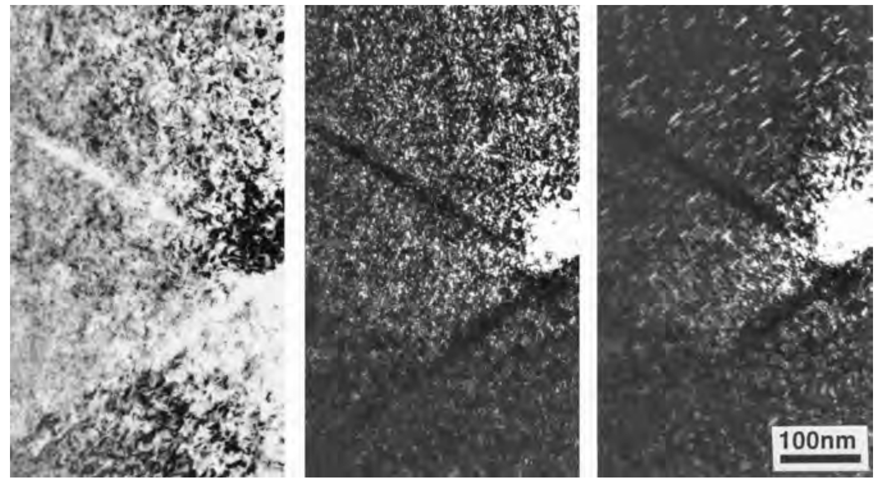


Deformation mechanisms in stainless steel

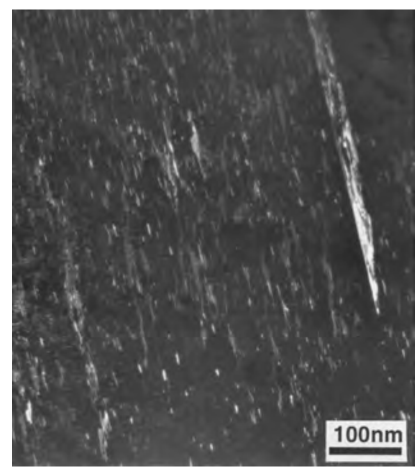




Irradiation induces changes in controlling deformation mechanisms



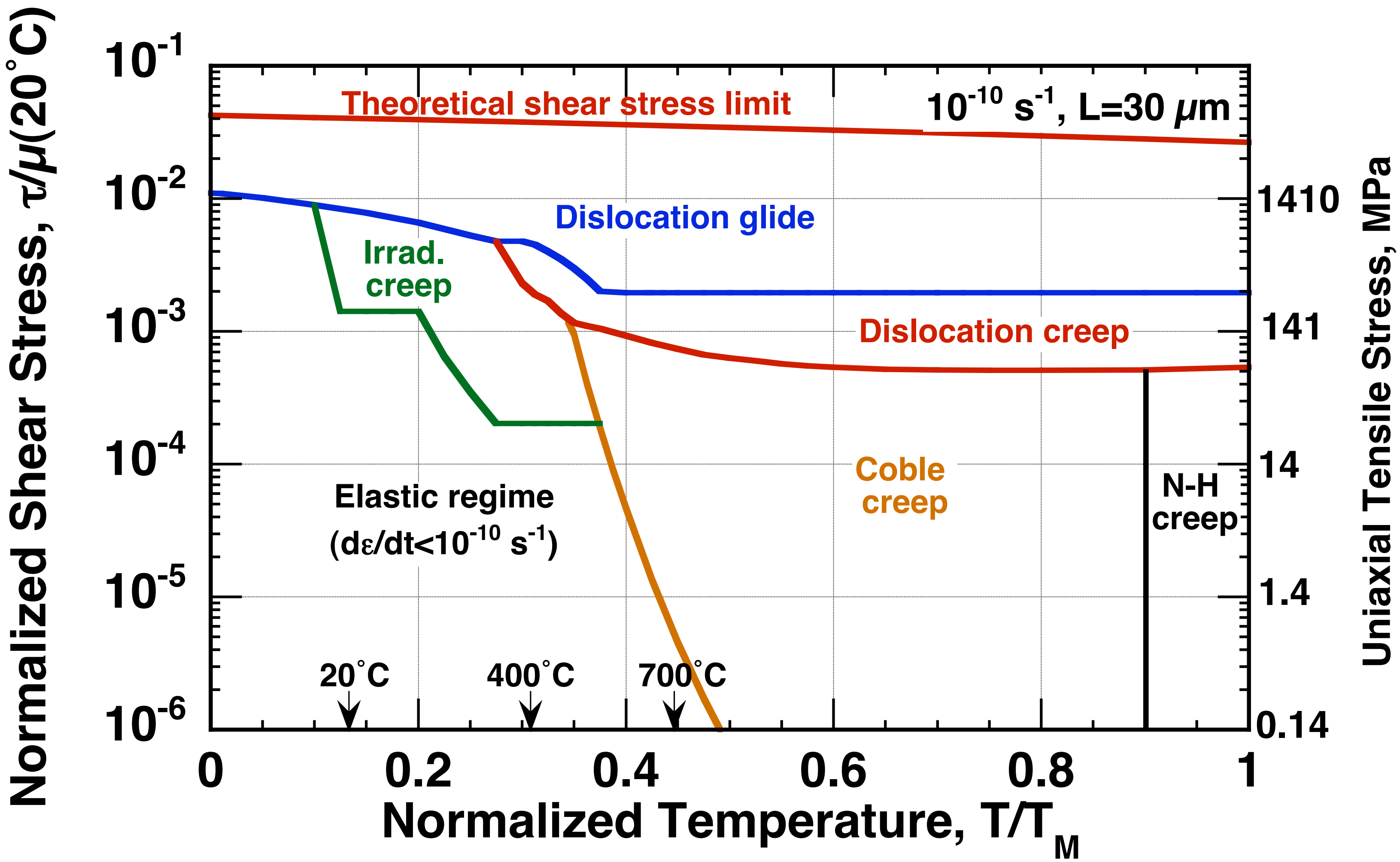
Channeling (Disln glide) occurs at higher temperatures (~300˚C)



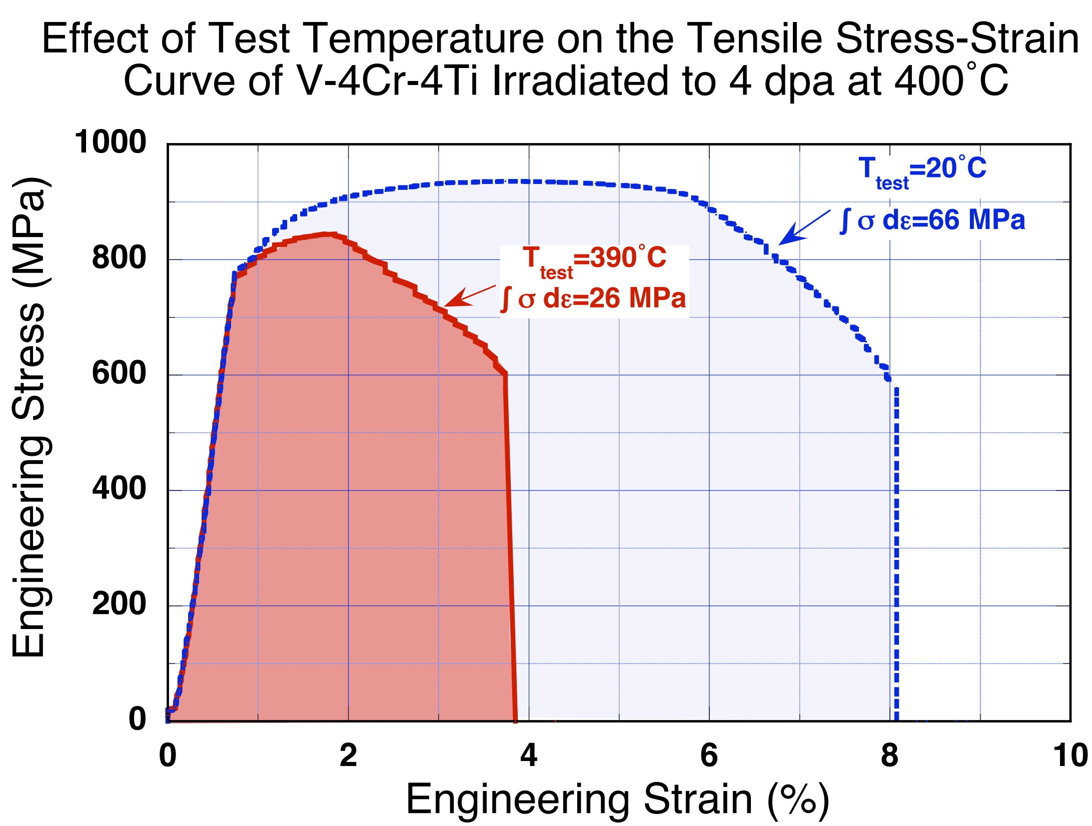
Twinning occurs at lower temperatures (<200˚C) and high strain rates

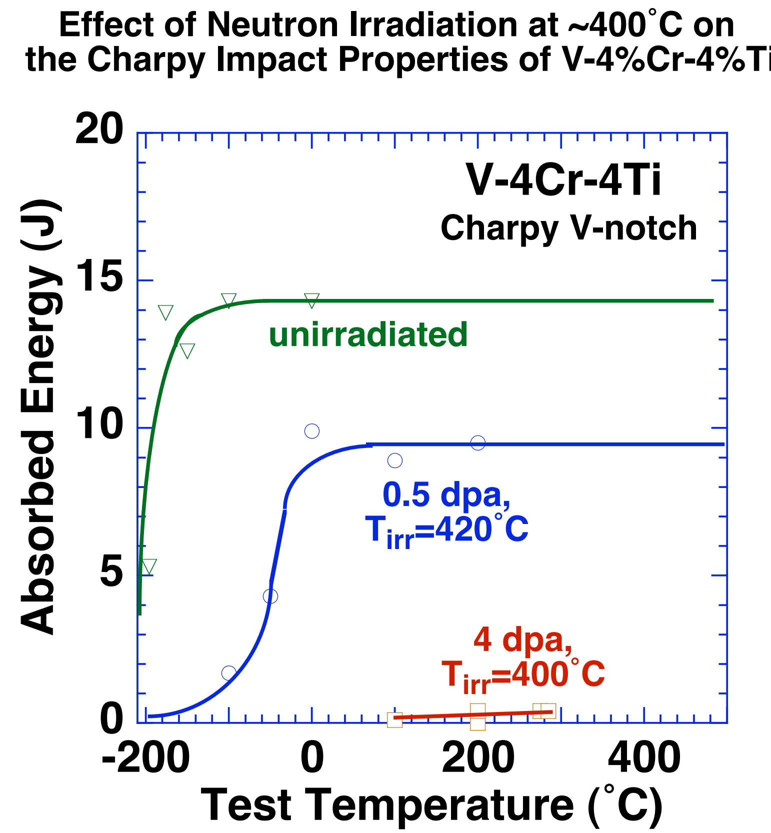
Calculated irradiated Ashby deformation map for V-4%Cr-4%Ti

Damage rate = 10^{-6} dpa/s



Tensile toughness is not a reliable indicator of fracture toughness in BCC metals



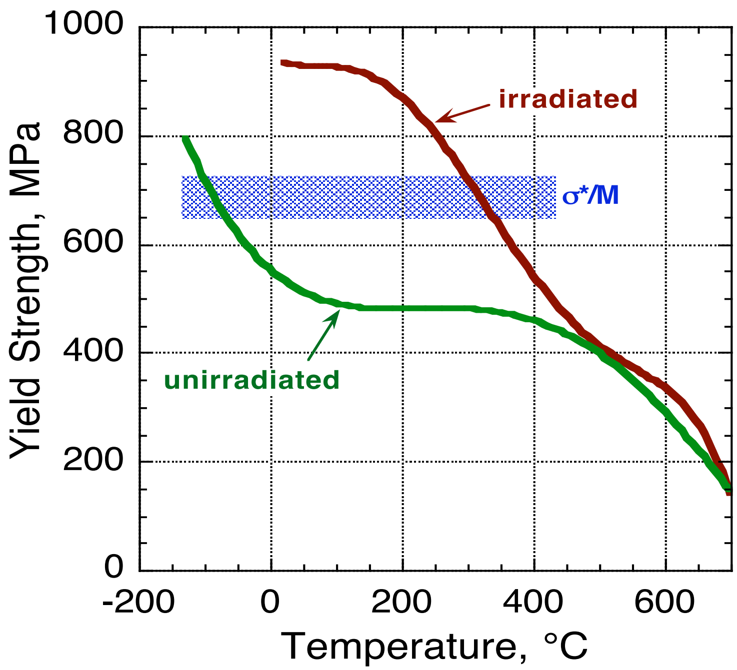


- Magnitude of radiation hardening (overall matrix strength) is most important parameter for fracture toughness in BCC metals

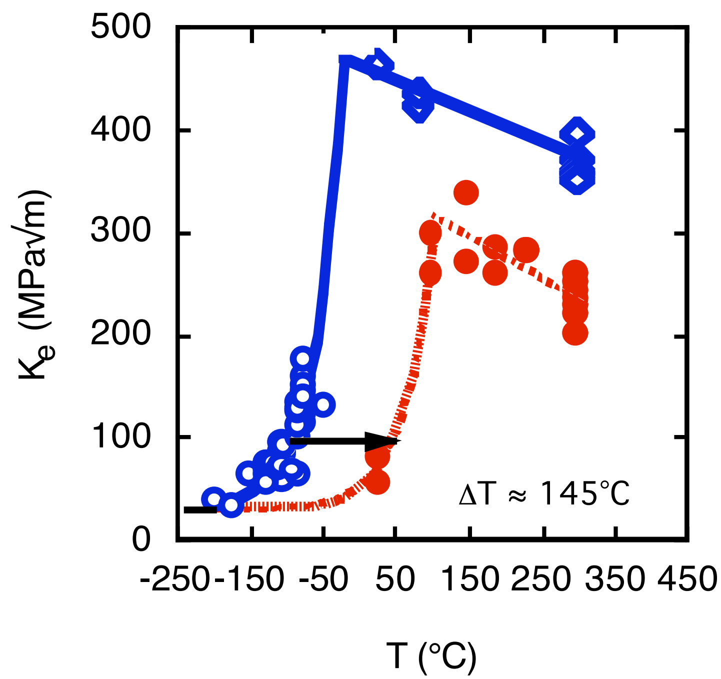
Fracture Toughness of BCC Metals: Master Curve Approach

• The measured DBTT depends on numerous parameters, including strain rate and amount of physical constraint in cracked sample

- Ludwig-Davidenkov relation provides a rough estimation of embrittlement due to radiation hardening



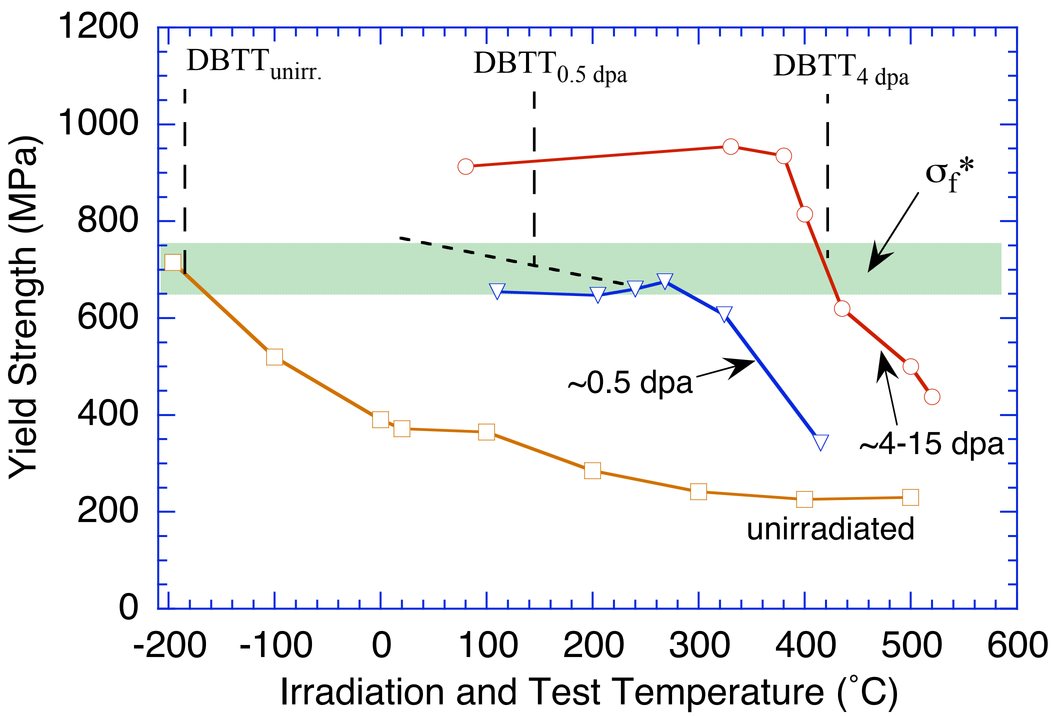
- Important parameters such as constraint and strain rate are included in recent advanced approaches (Master curve)



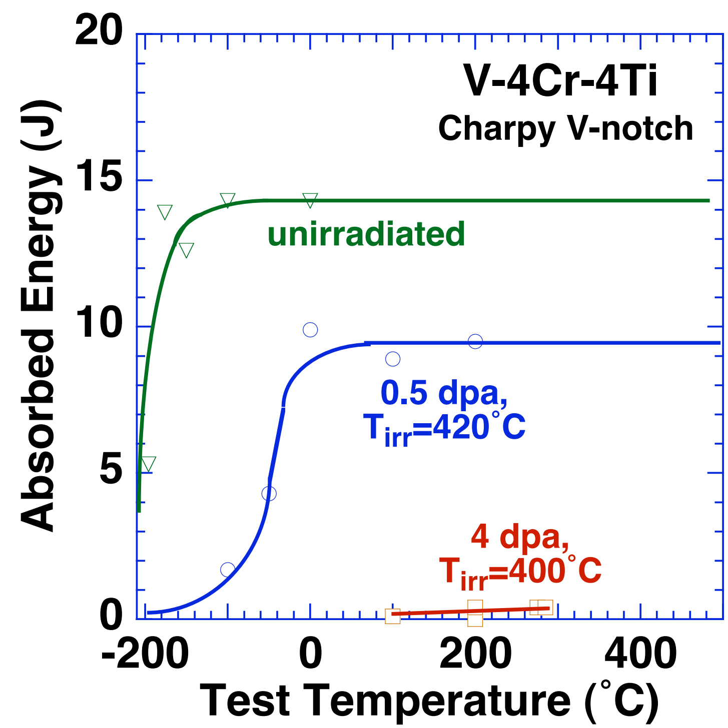
UCSB

Low temperature radiation hardening causes fracture toughness embrittlement in BCC metals

Effect of Irradiation Temperature and Dose on the Yield Strength of V-4%Cr-4%Ti Alloys



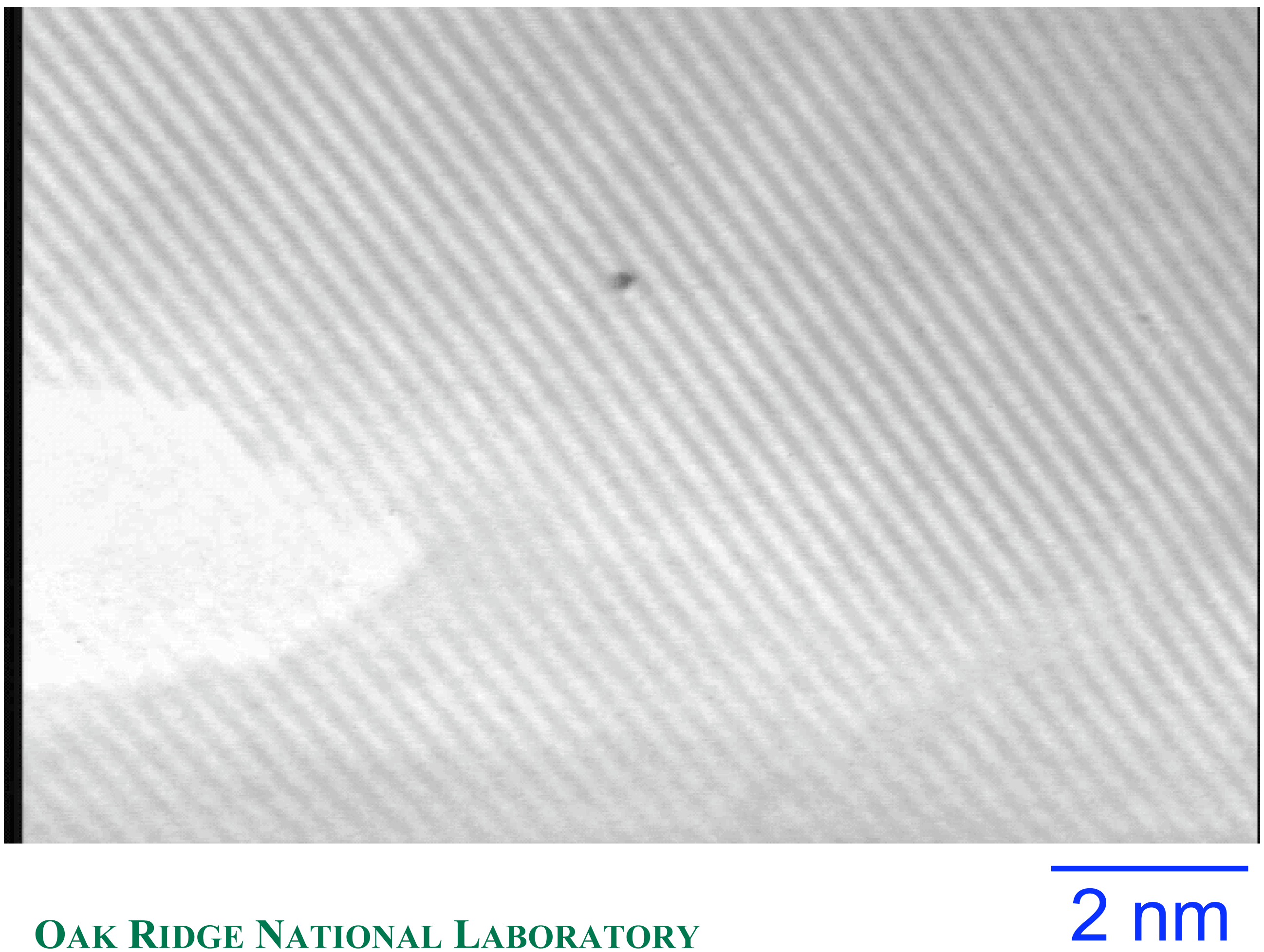
Effect of Neutron Irradiation at ~400˚C on the Charpy Impact Properties of V-4%Cr-4%Ti

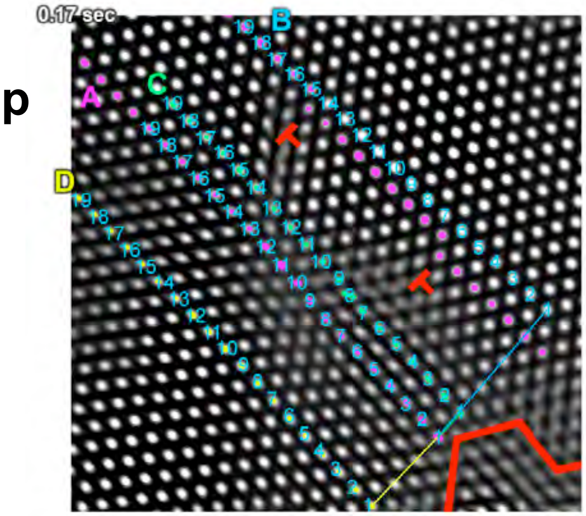


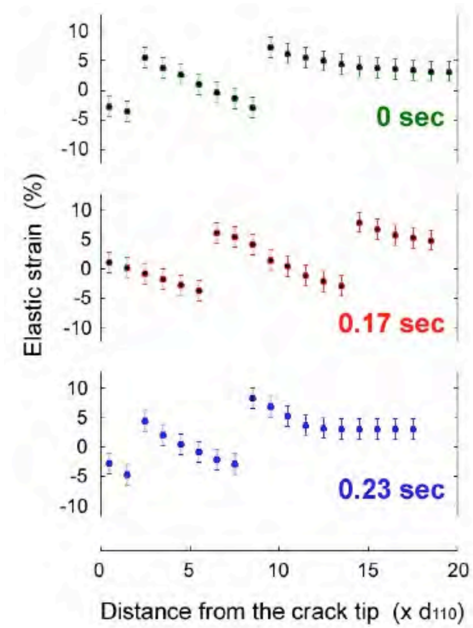
TEM in-situ deformation studies can be used to provide insight on fundamental fracture processes

Atomic resolution imaging of ductile crack propagation (plane stress)

- **Macroscopic Mode I fracture is composed of coordinated Mode III shear displacements at the crack tip**







Y. Matsukawa, ORNL

Summary and Conclusions

- **Low temperature (<0.3 T_M) irradiation causes rapid hardening and reduction in uniform elongation of metals**
  - When radiation hardening increment becomes a significant fraction of the unirradiated strength, new dependencies on test temperature and strain rate may occur
  - Uniform elongation is typically reduced to <1% after doses of ~0.1 dpa
  - Responsible mechanisms for loss of tensile ductility (dislocation channeling, radiation hardening) are currently being investigated
- **Radiation hardening causes fracture toughness embrittlement and increases in the ductile-to-brittle-transition temperature in irradiated BCC metals**
  - Can be mitigated by alloying additions that reduce radiation hardening or increase σ^*