Mechanical Property Changes in Metals due to Irradiation

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Outline

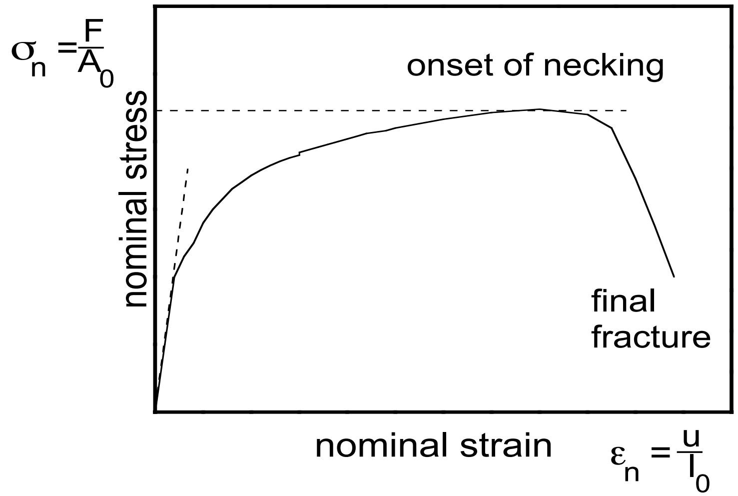
- Effect of low temperature (<0.3 T_M) irradiation on the tensile properties of metals
  - Dose and temperature dependence
  - FCC vs. BCC metal behavior
- Fracture toughness embrittlement in irradiated metals
- Overview of irradiation creep
- High temperature He embrittlement of grain boundaries
- Overview 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%

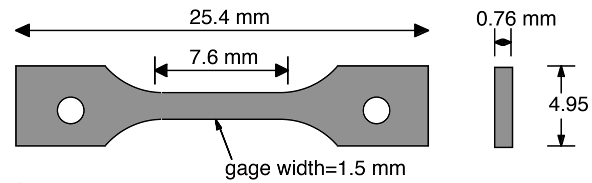
- Not covered: hardness, fatigue

Overview of tensile testing parameters

The plastic behaviour of a material is usually measured by conducting a tensile test. Tensile testing equipment produces a load/displacement (F/u) curve which is then converted into an engineering stress/nominal strain (σ / ε) curve, where

$\sigma = F/A_0$ and $\varepsilon = u/l_0$.





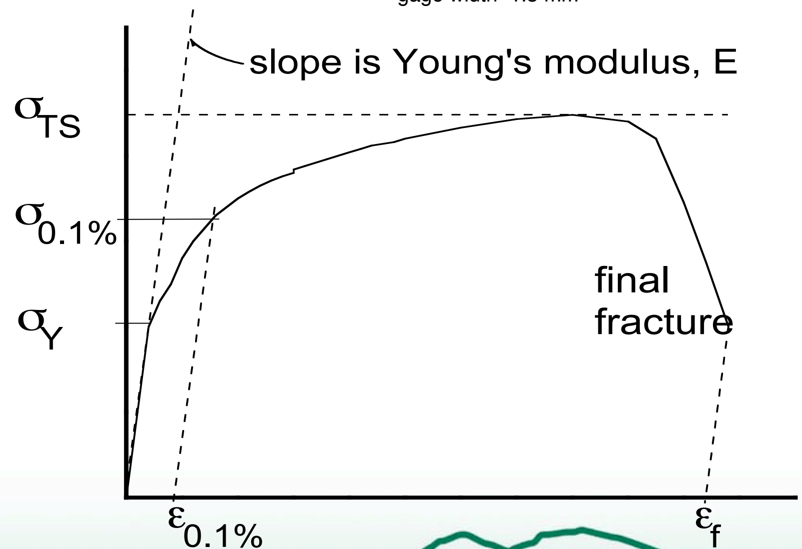
Definition of quantities usually listed as a result of a tensile test :

σ_y – yield stress (F/A_0 at onset of plastic flow)

$\sigma_{0.2\%}$ – 0.2% proof stress (F/A_0 at a permanent strain of 0.2% - when elastic strain ≈ plastic strain) (0.05-0.1% is sometime quoted)

σ_{TS} – tensile stress (F/A_0 at onset of necking)

e_{Tot} –– (plastic) strain after fracture, or tensile ductility.

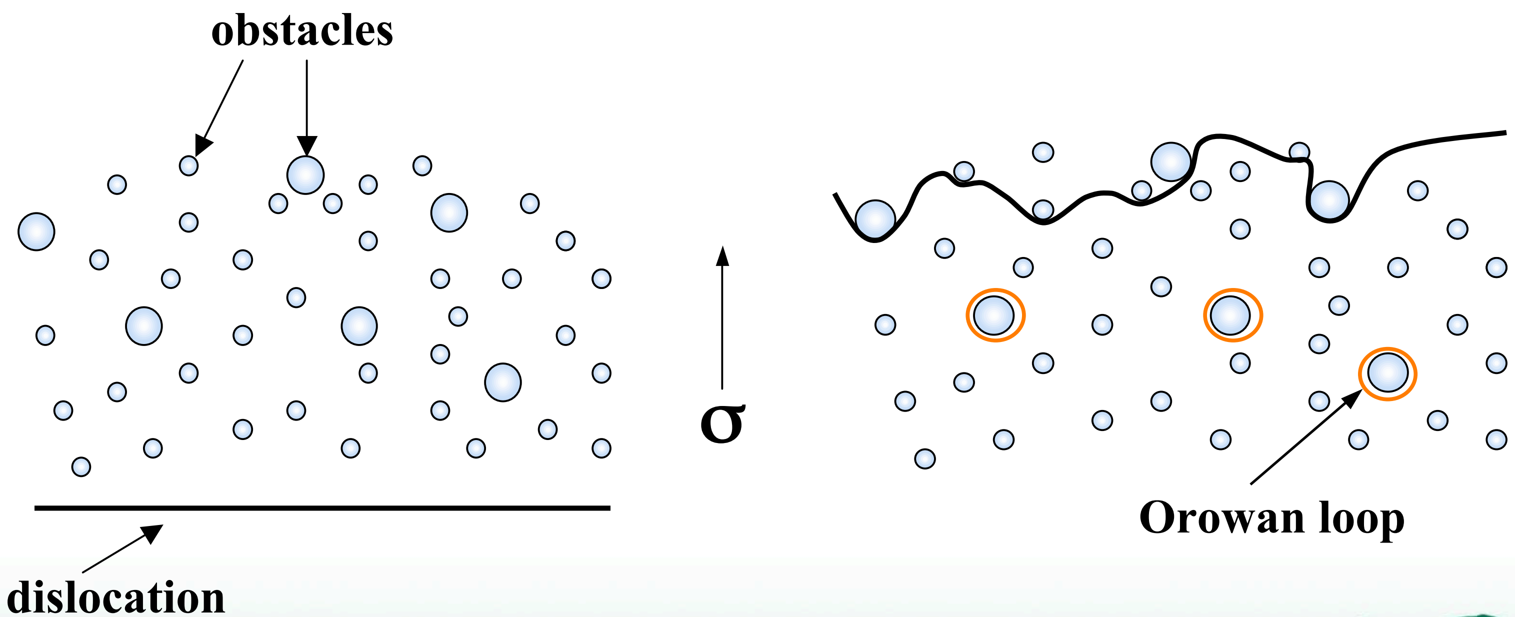


(ii) Mechanisms

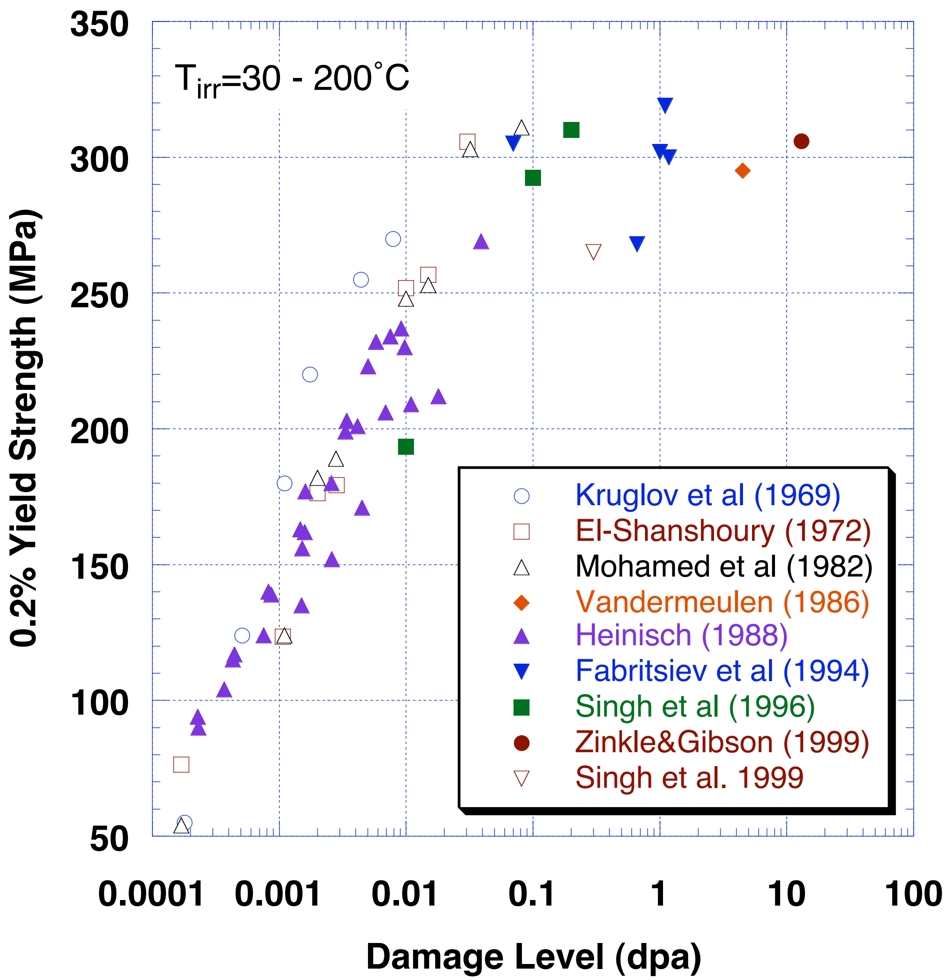
Radiation damage creates obstacles to dislocation motion

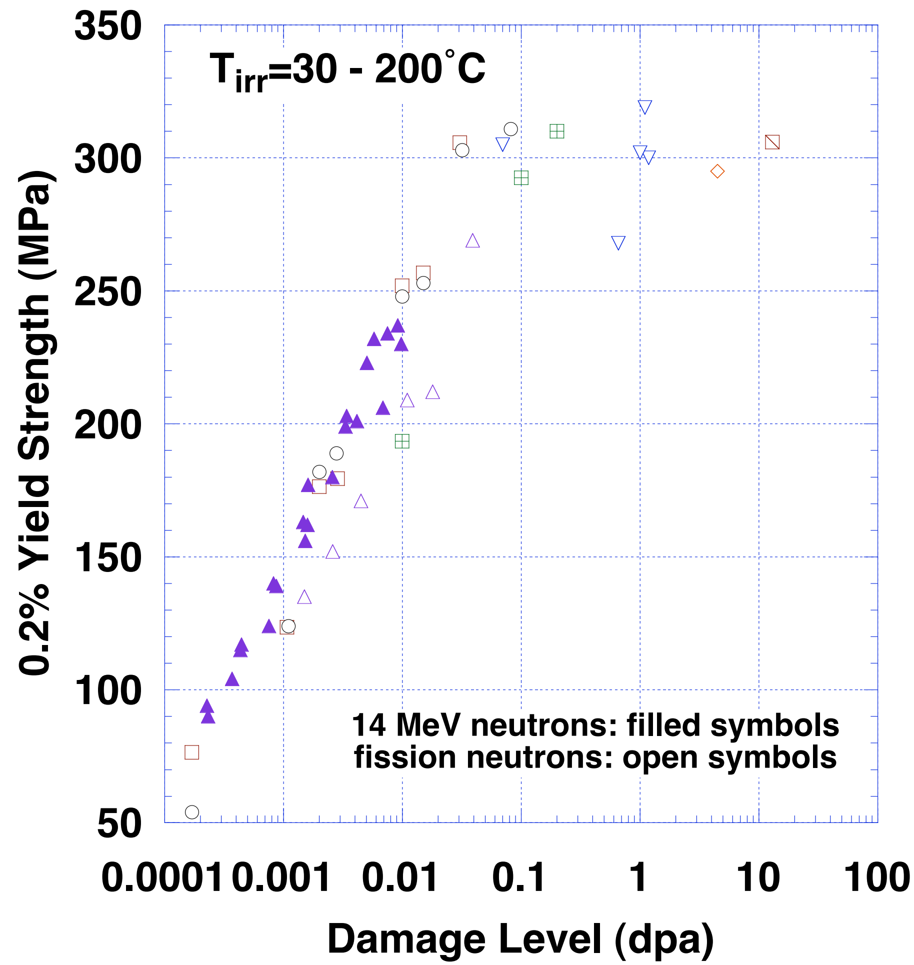
- **point defects (≡ solute strengthening in alloys)**
- **small clusters and precipitates (≡ precipitates in alloys)**
- **impenetrable clusters (≡ Orowan strengthening in alloys)**

- **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

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

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

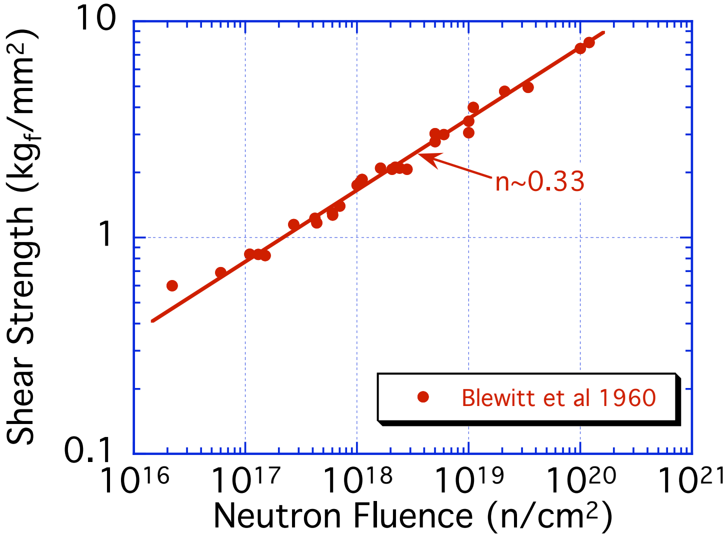
Where
M=Taylor factor
α=defect cluster barrier strength
μ=shear modulus
b=Burgers vector of glide dislocation
N, d=defect cluster density, diameter

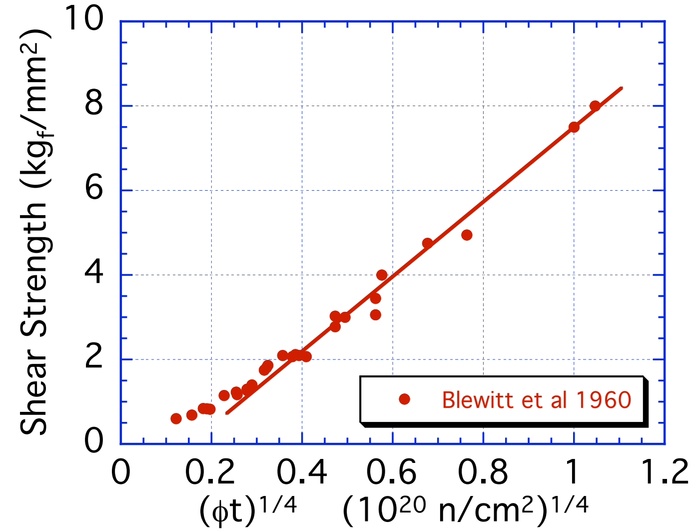
  - Friedel 1963 (also Kroupa and Hirsch 1964) weak barrier model:

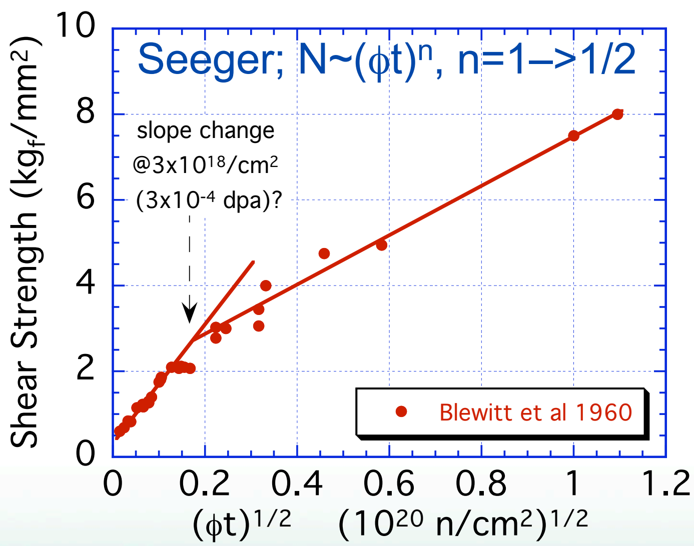
$$\Delta\sigma = \frac{1}{8} M\mu b d N^{2/3}$$

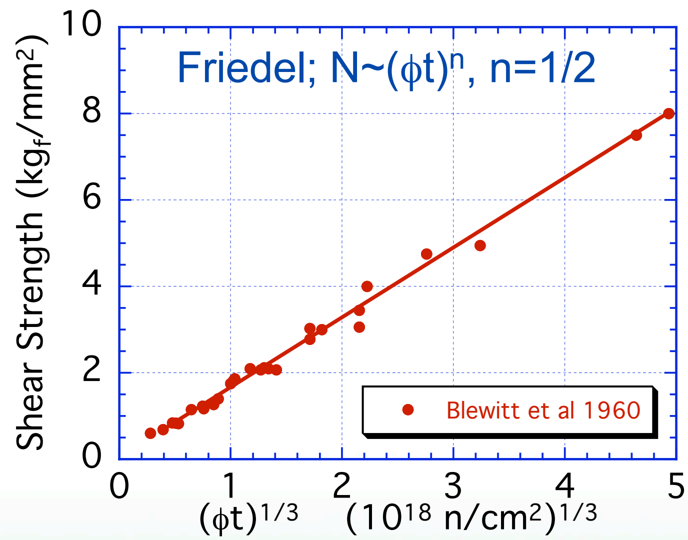
$$\Delta\sigma = M\alpha\mu b\sqrt{Nd} \quad \text{vs.} \quad \Delta\sigma = \frac{1}{8}M\mu bdN^{2/3}$$

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



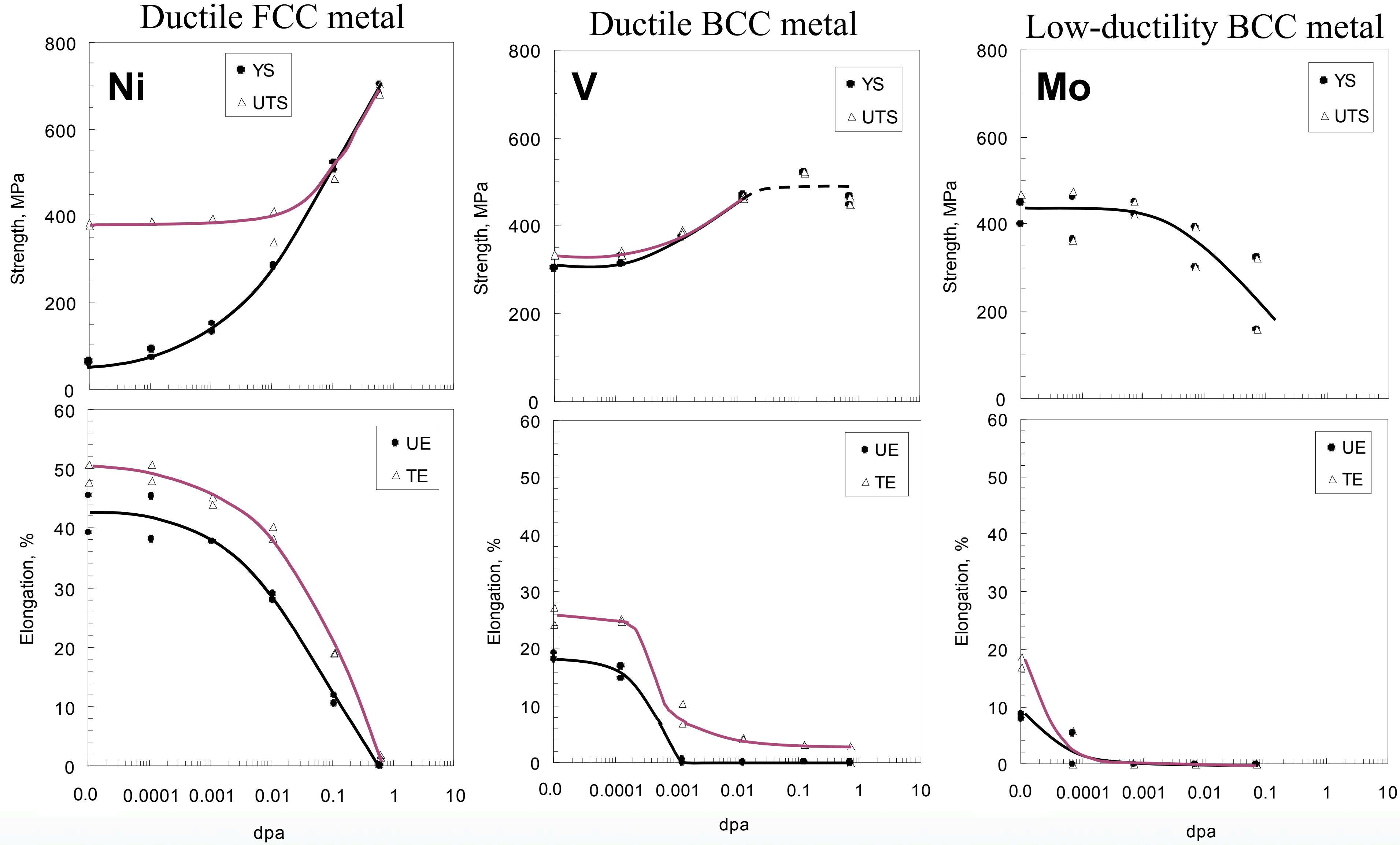






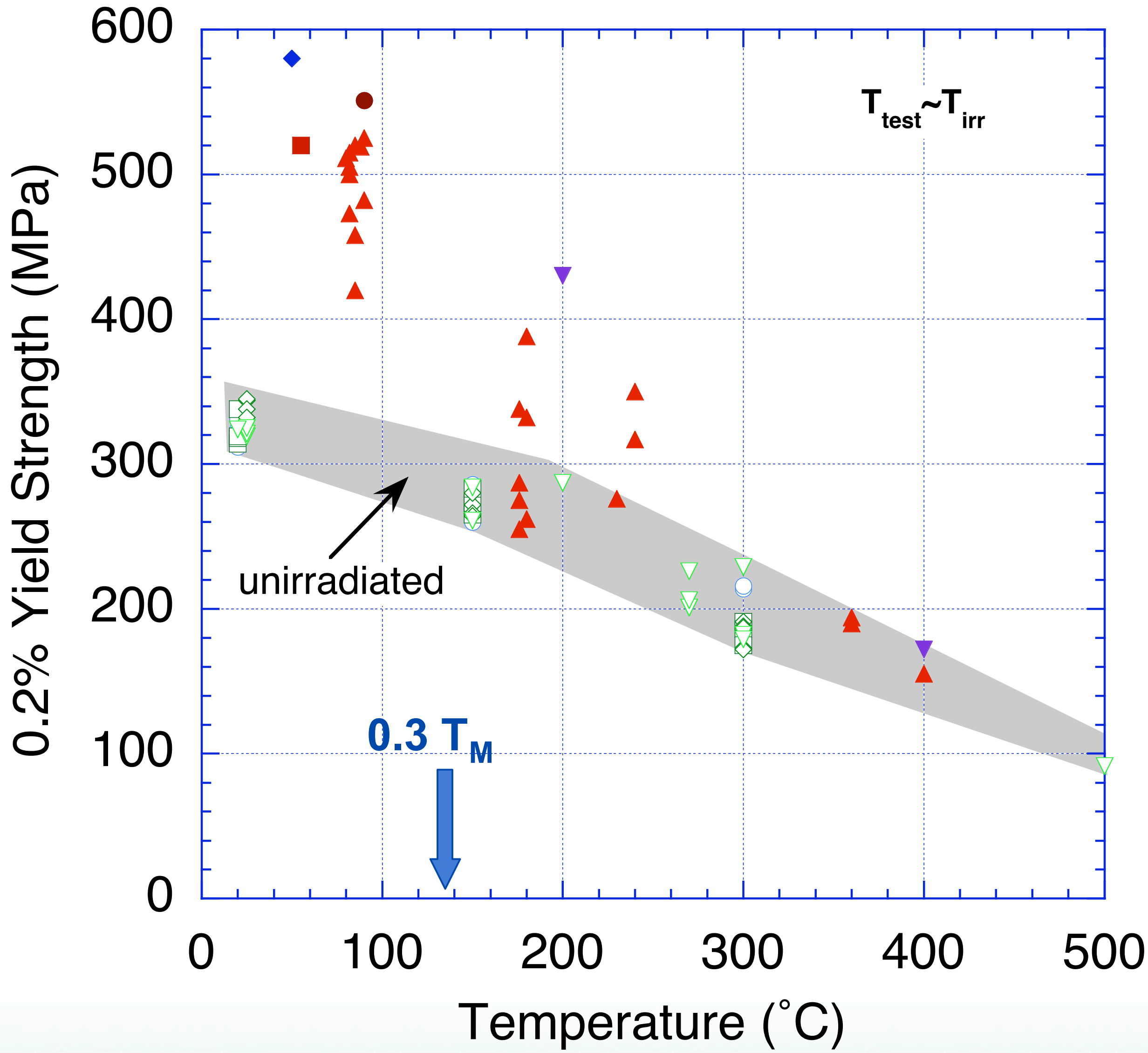
Effect of neutron irradiation near 70˚C on tensile properties

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



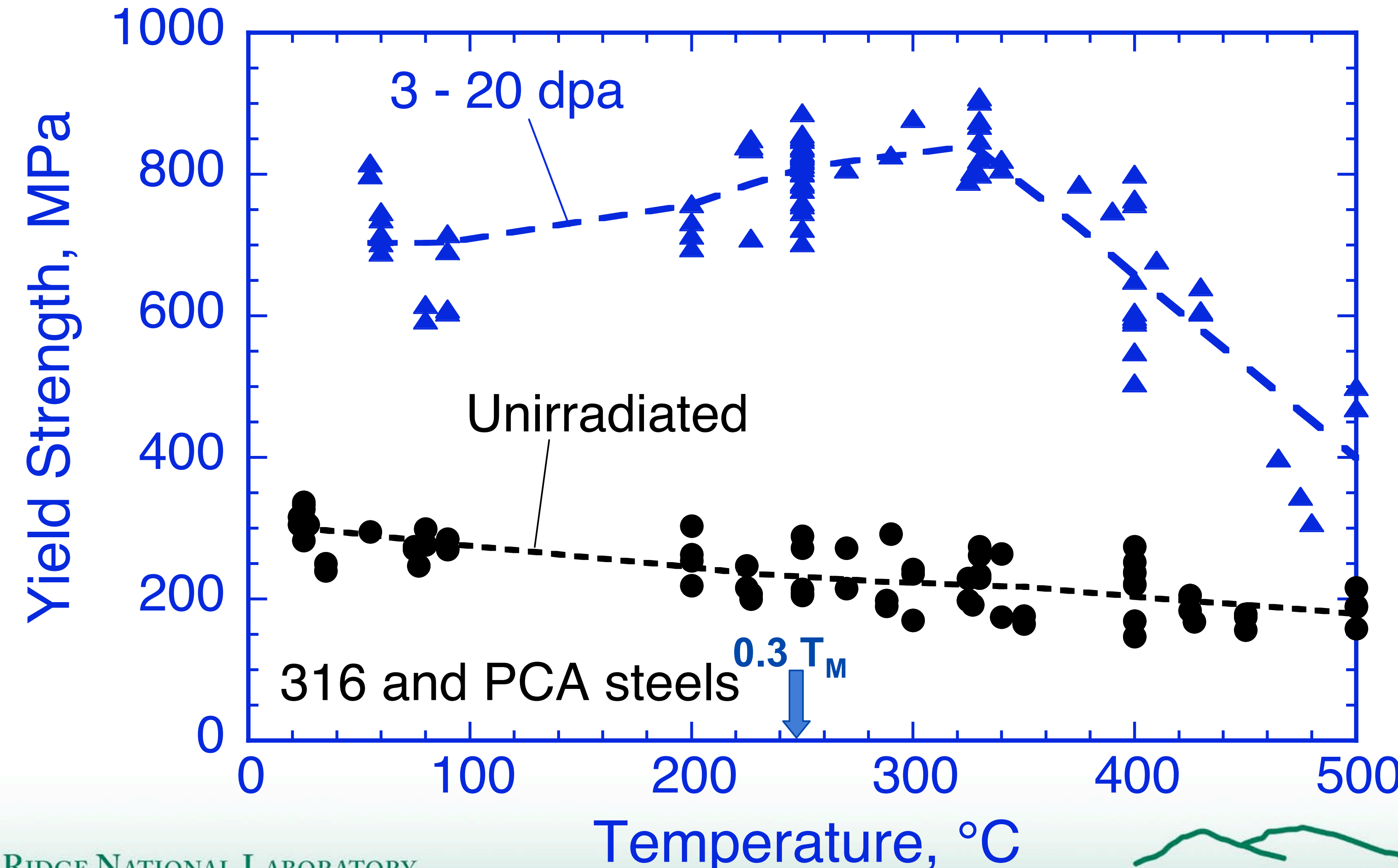
K. Farrell et al.

Temperature-dependent radiation hardening in oxide dispersion strengthened copper

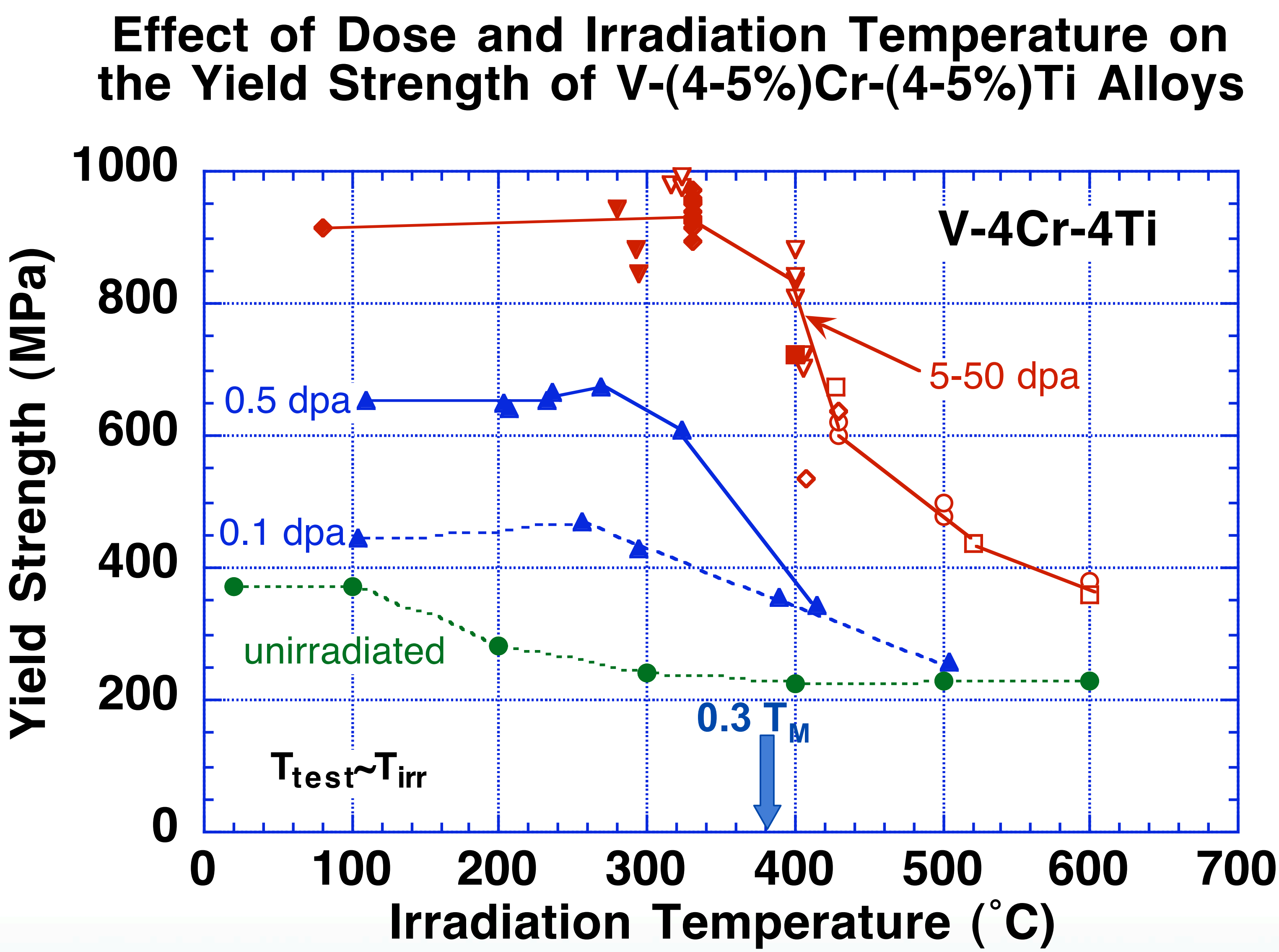


Irradiation of Austenitic Stainless Steel in Mixed Spectrum Reactors produces significant hardening up to 500˚C, with peak hardening at ~300˚C

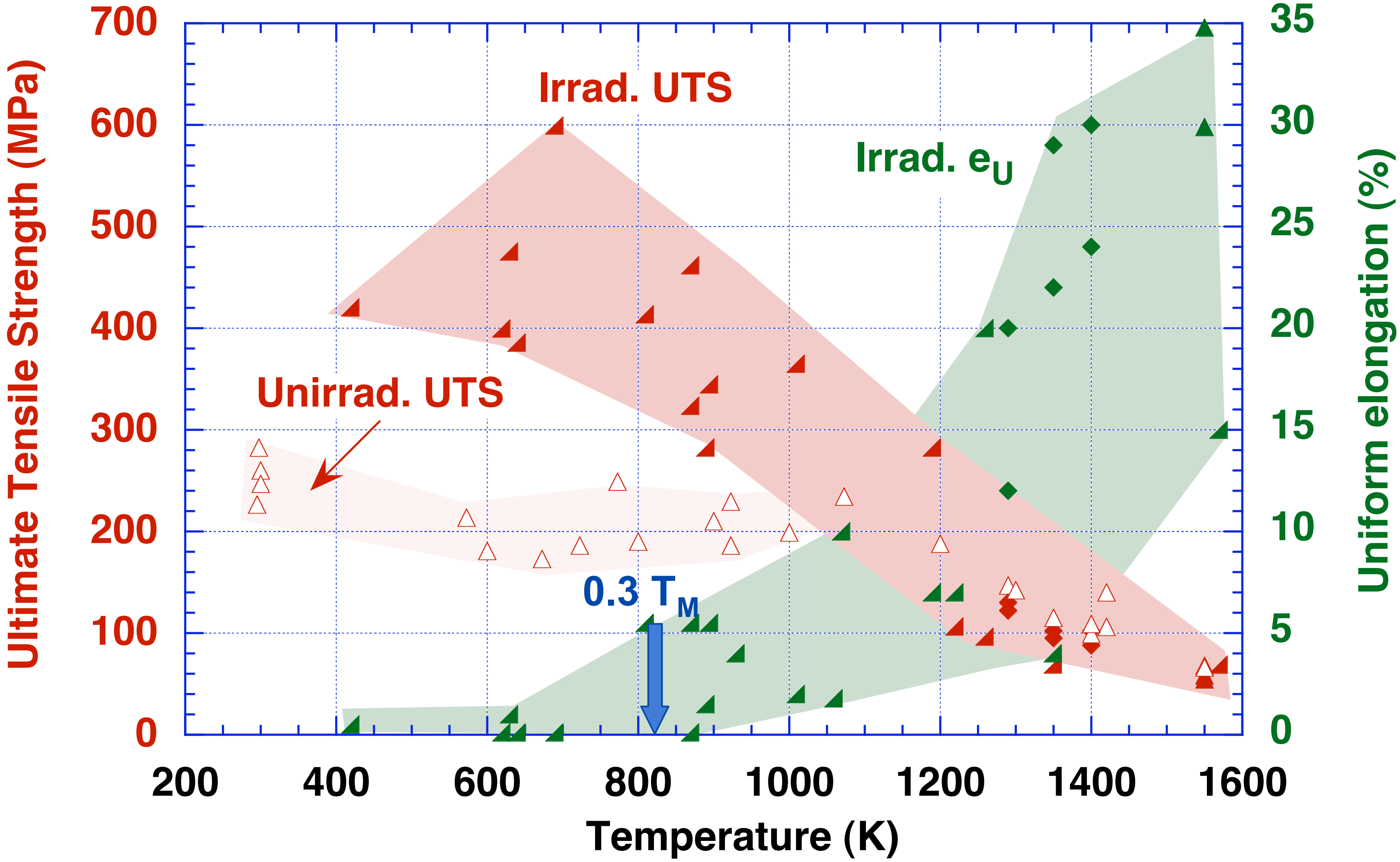
Hardening at 290-400˚C is dominated by He bubbles



Radiation hardening in V-4Cr-4Ti

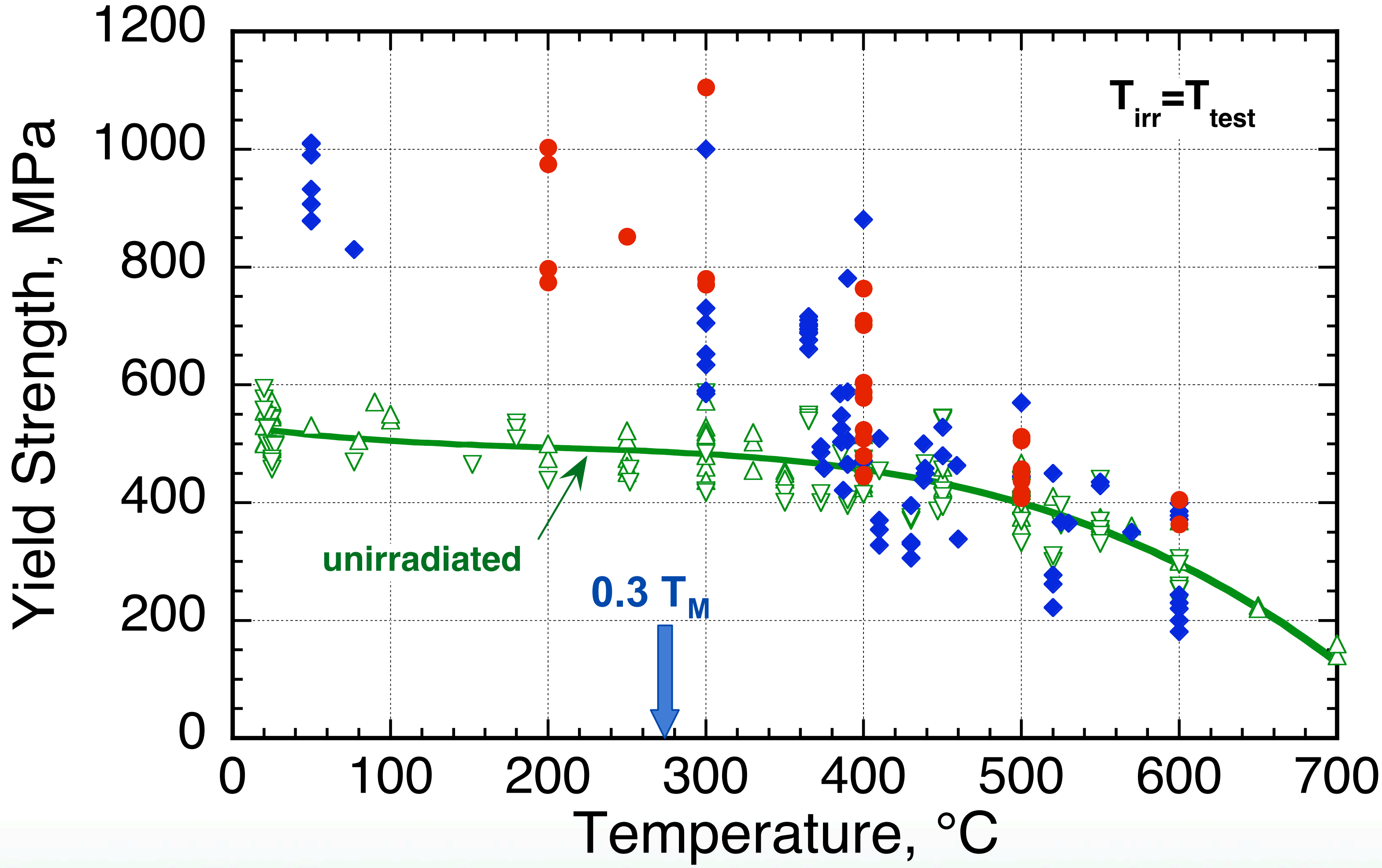


Summary of Tensile Properties of Neutron-irradiated Nb-1Zr in Li-bonded capsules

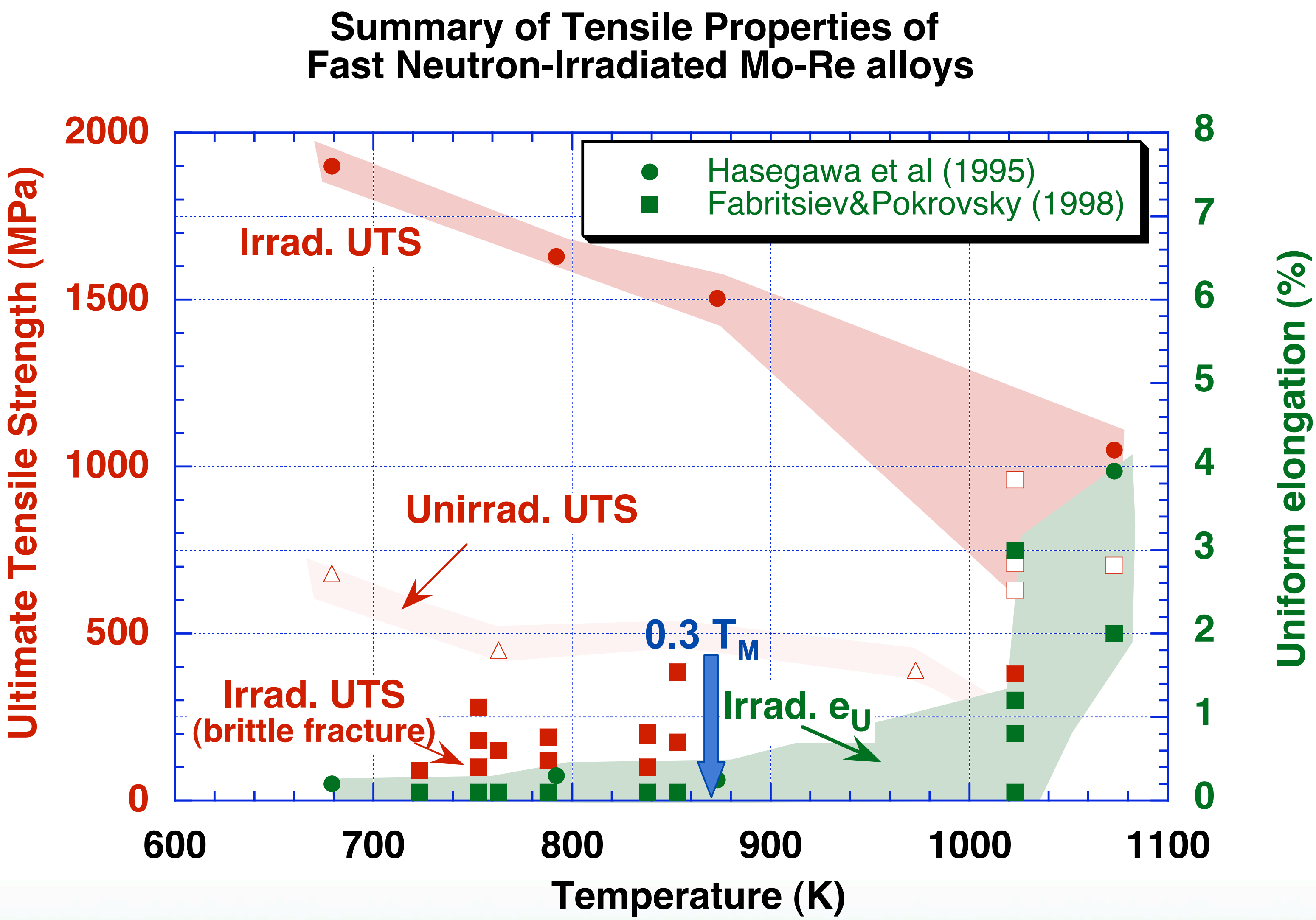


Radiation hardening in Fe-(8-9%Cr) steels

8-9Cr Steels: Yield Strength as Function of Temperature, 0.1 - 94 dpa



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

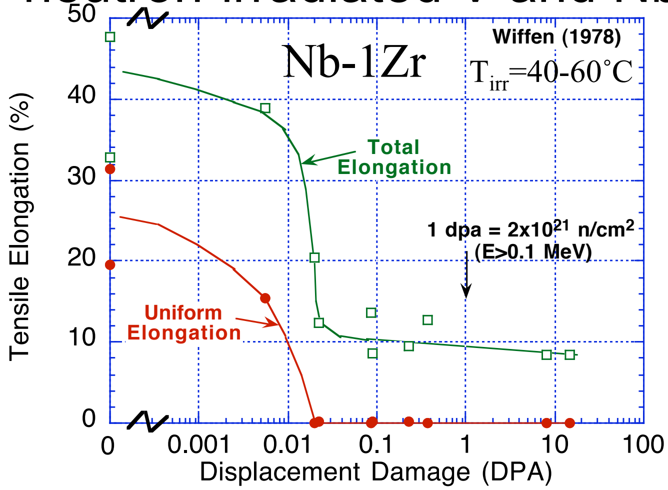


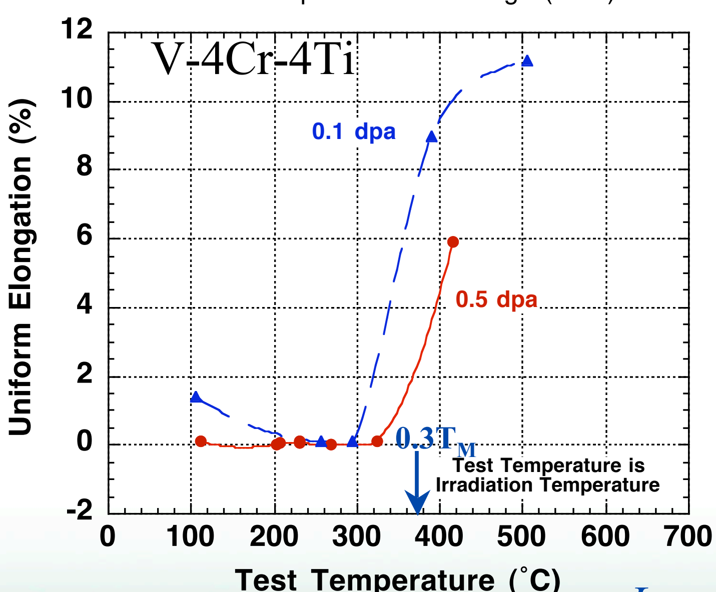
What are the consequences of radiation hardening?

- 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

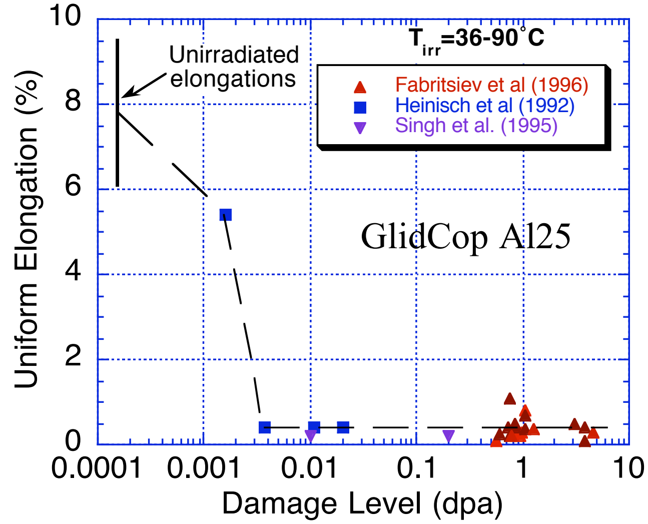
Low uniform elongations occur in many BCC and FCC metals after low-dose irradiation at low temperature

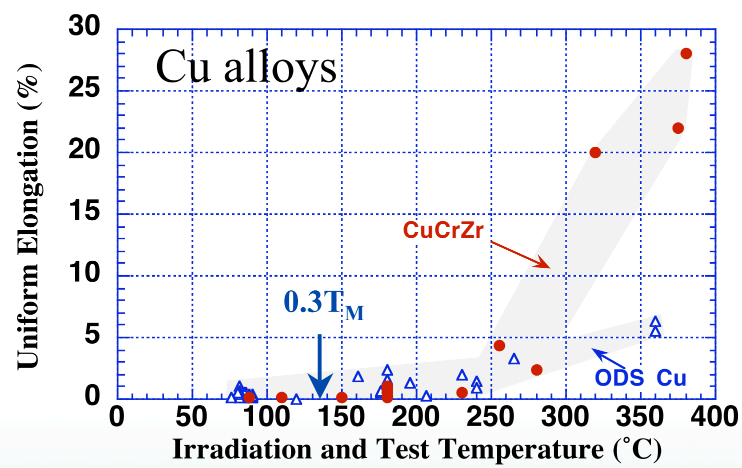
Uniform elongation of neutron-irradiated V and Nb





Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr

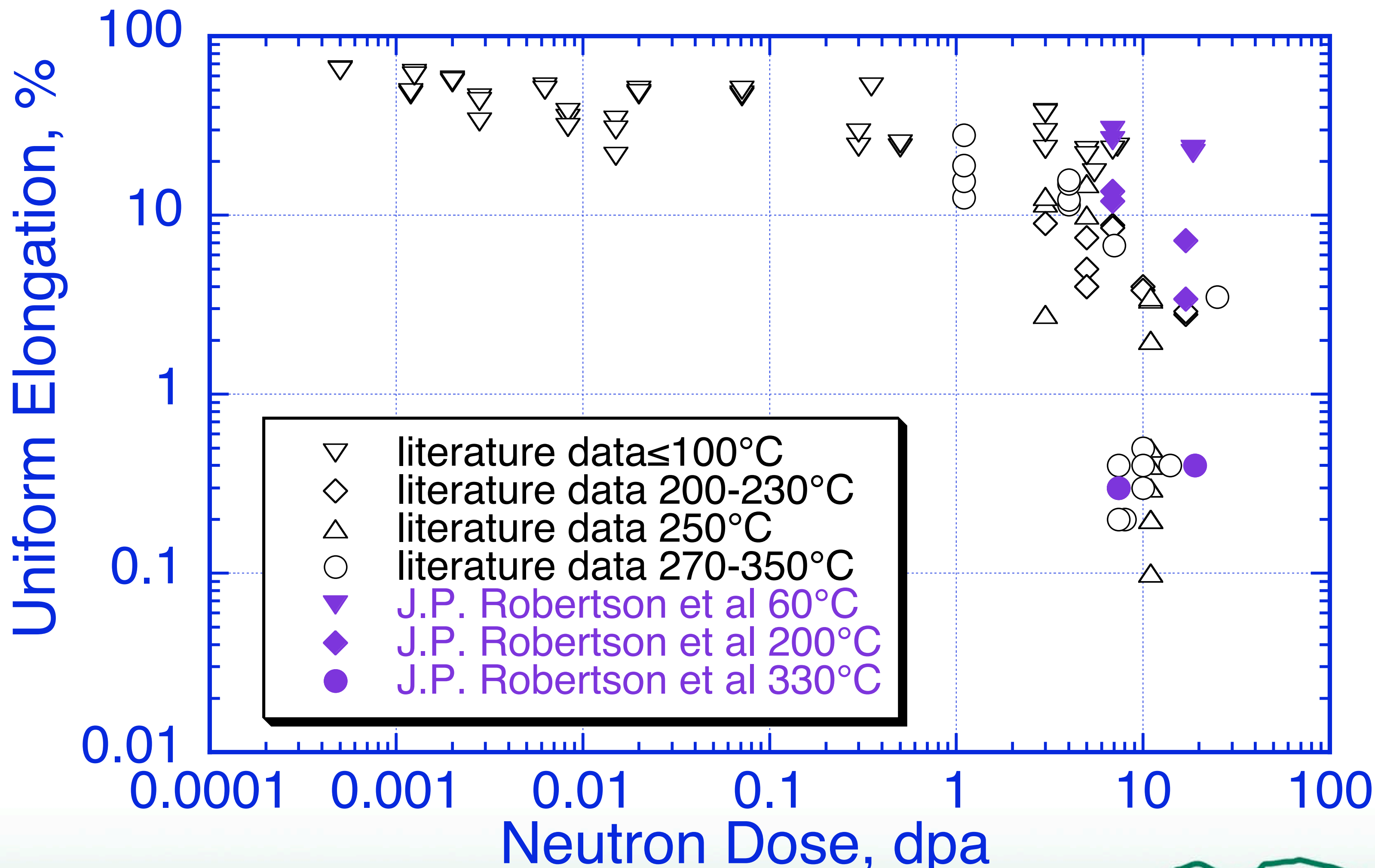




Low uniform elongation is induced after very small doses at low temperatures

Austenitic Stainless Steel exhibits low uniform elongation after irradiation at temperatures up to ~400˚C

Reduction in uniform elongation requires higher doses than in simple metals (e.g. Cu, Ni)



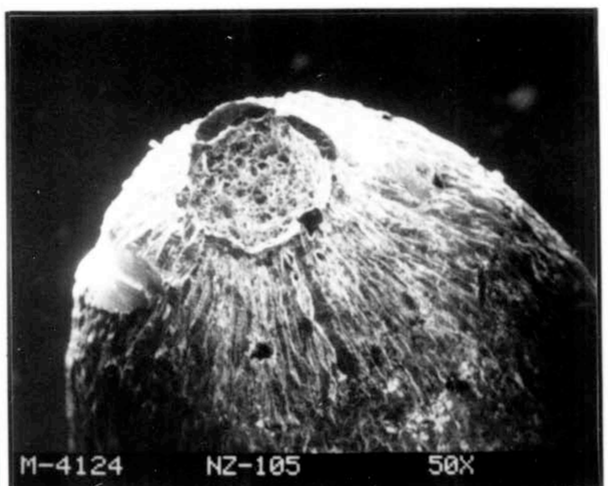
Fracture surface of Irradiated Nb-1Zr shows ductile behavior, despite low uniform elongation value

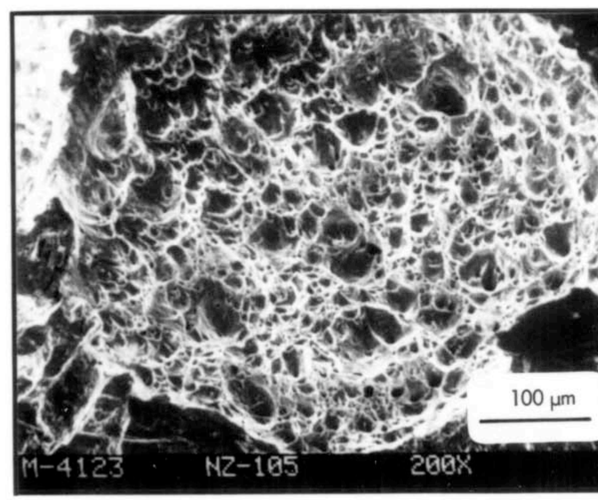
Nb-1 Zr

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

Tensile Test at ~35 °C

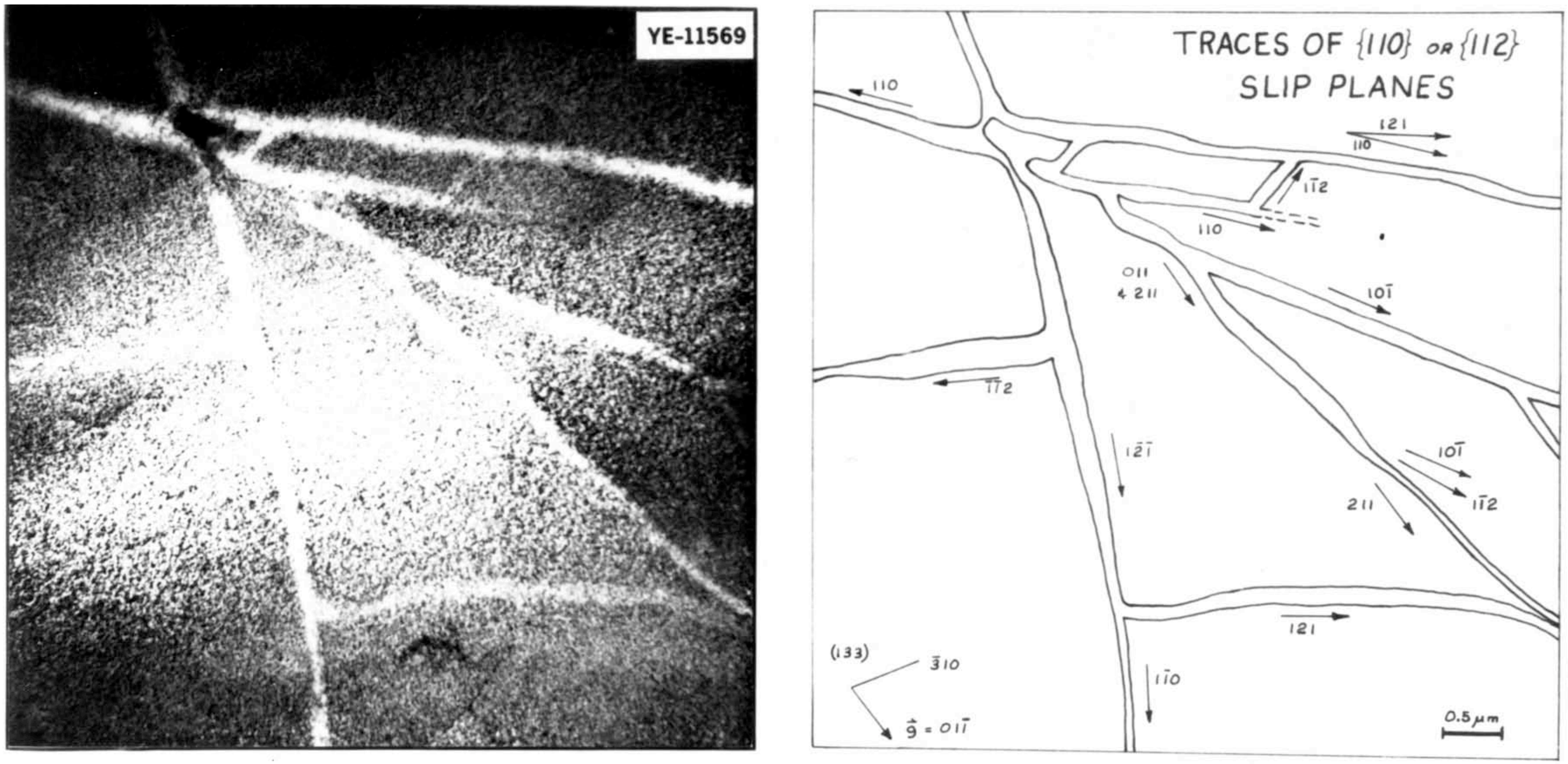
0.2 % Uniform Elongation
9.6% Total Elongation





F.W. Wiffen, unpublished results

Low uniform elongation in Nb1Zr is associated with dislocation channeling (localized deformation)



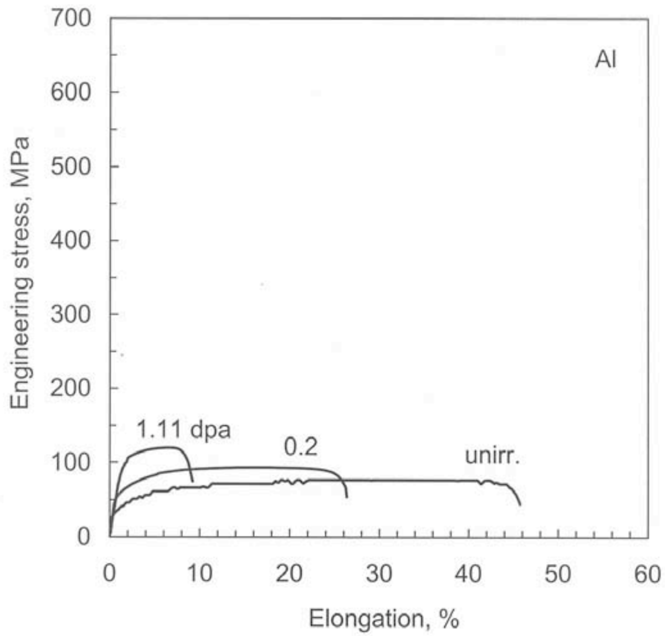
CHANNELING DEFORMATION IN Nb-1 Zr

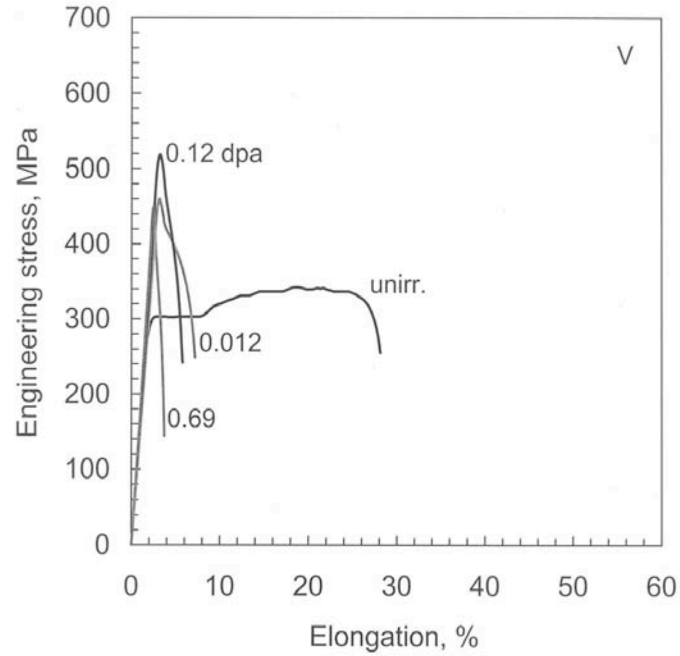
Irradiated to 7.5 × 10^{20} n/cm^2 (> 0.1 MeV) at ~ 70°C [0.36 dpa]

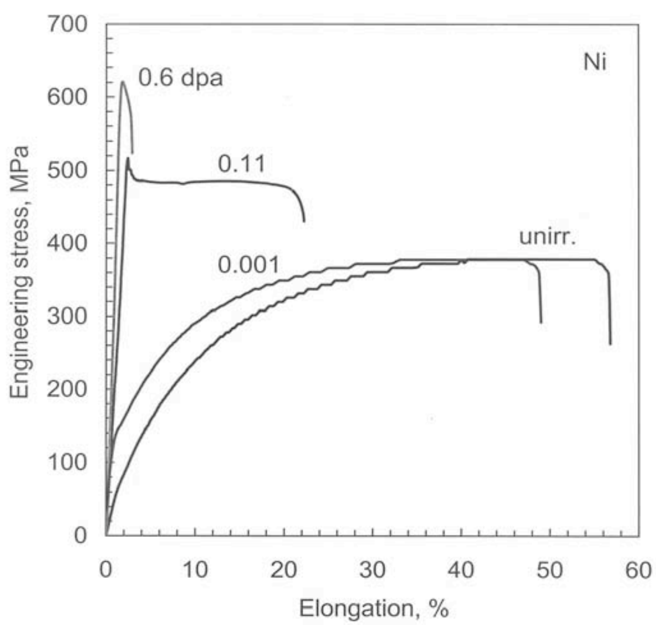
Tensile test at ~35°C, 0.1% uniform elongation, 12.7% total elongation

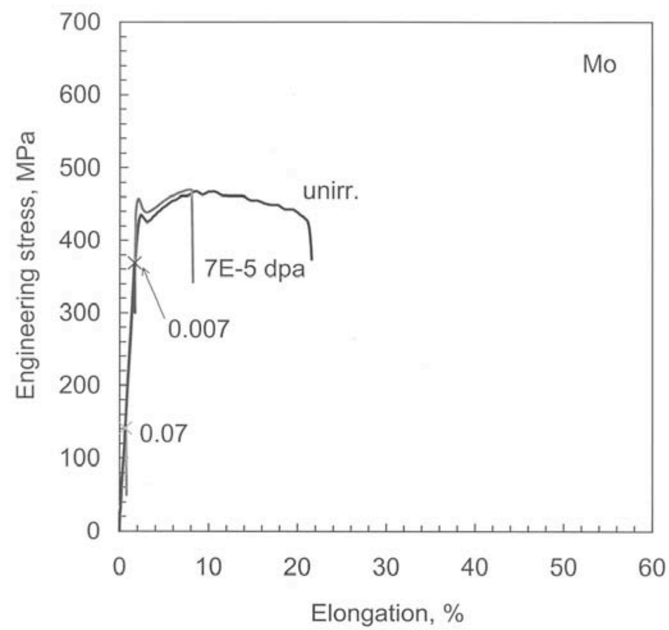
F.W. Wiffen, unpublished results

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

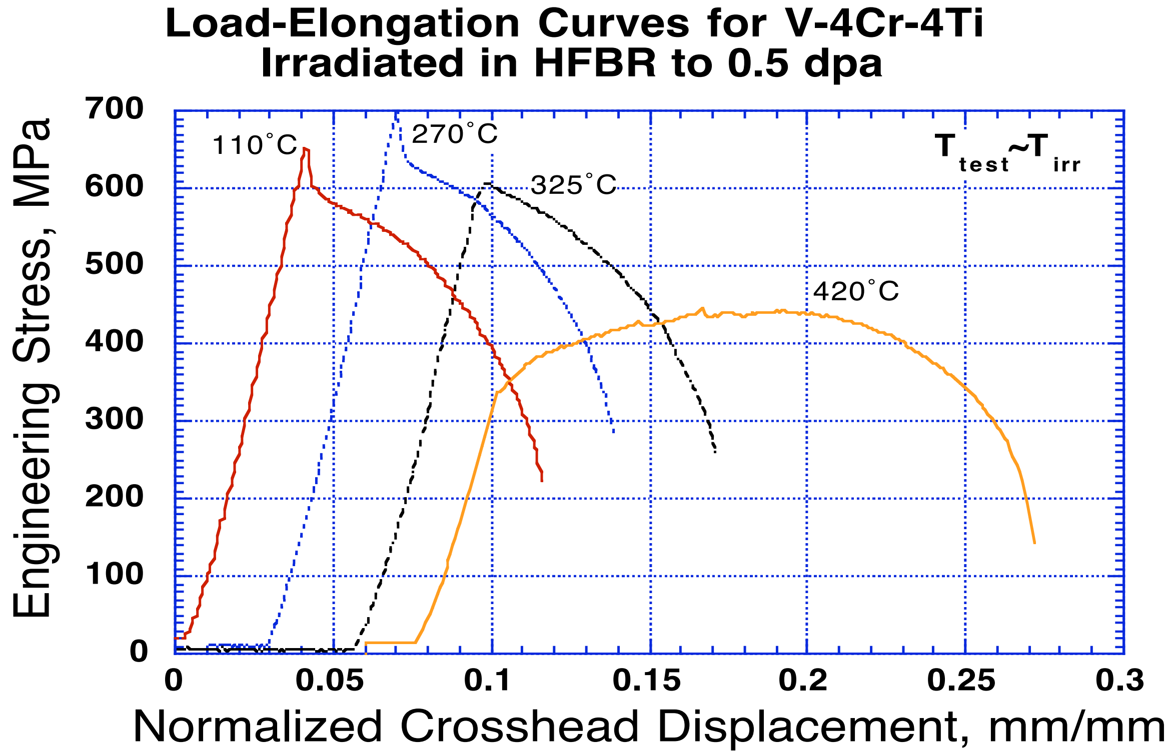


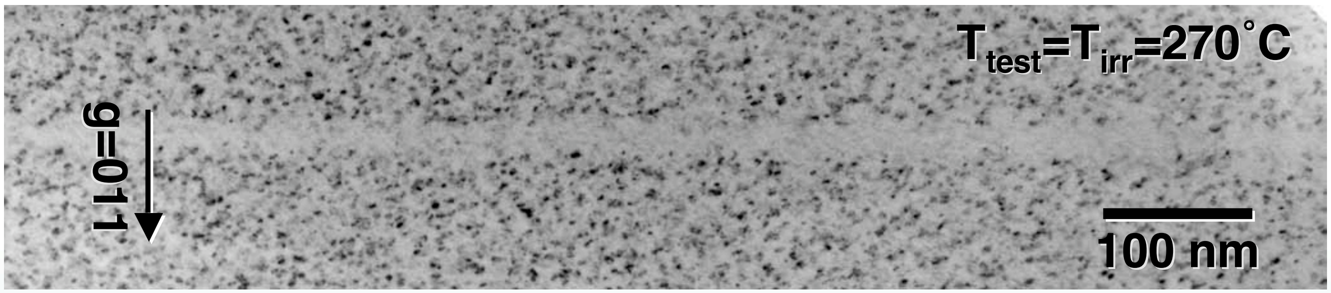






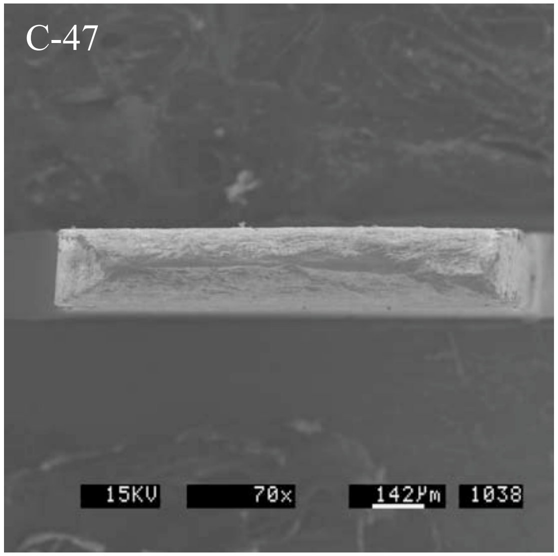
Irradiated Materials Suffer Plastic Instability (due to Dislocation Channeling?)

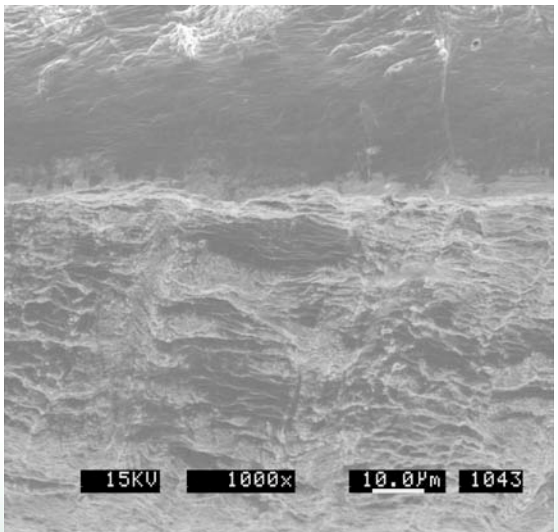


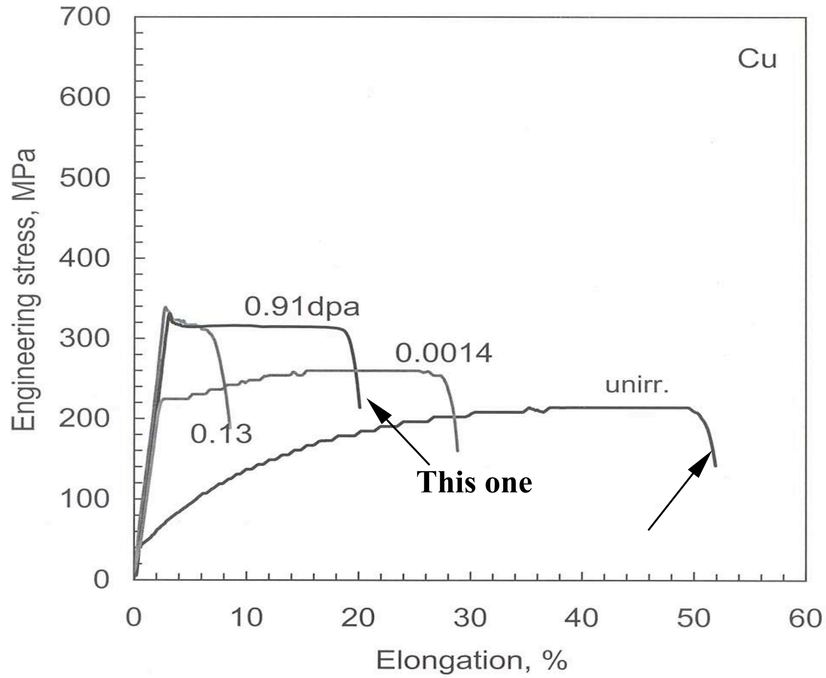


Irradiation does not affect strain in the neck

Example: knife-edge fracture (100%R in A) in Cu







In all materials except Mo the reduction in area at fracture was the same in irradiated and unirradiated specimens despite considerable differences in uniform elongation. The implication is that much work hardening lost in uniaxial mode is restored when multiaxial loading prevails.

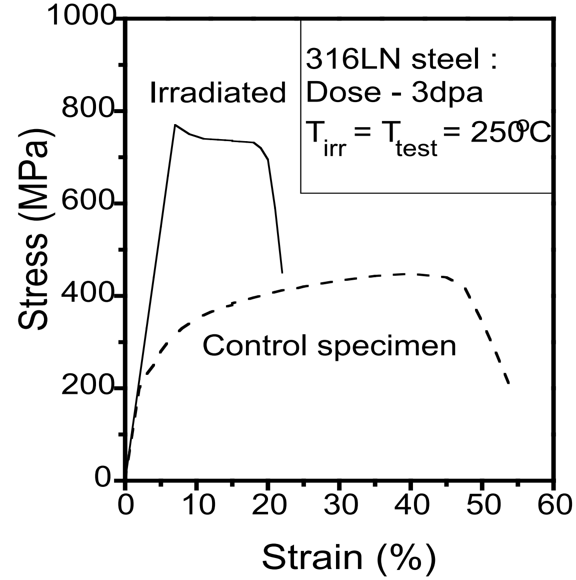
Irradiation hardening and embrittlement ($T<0.5T_M$)

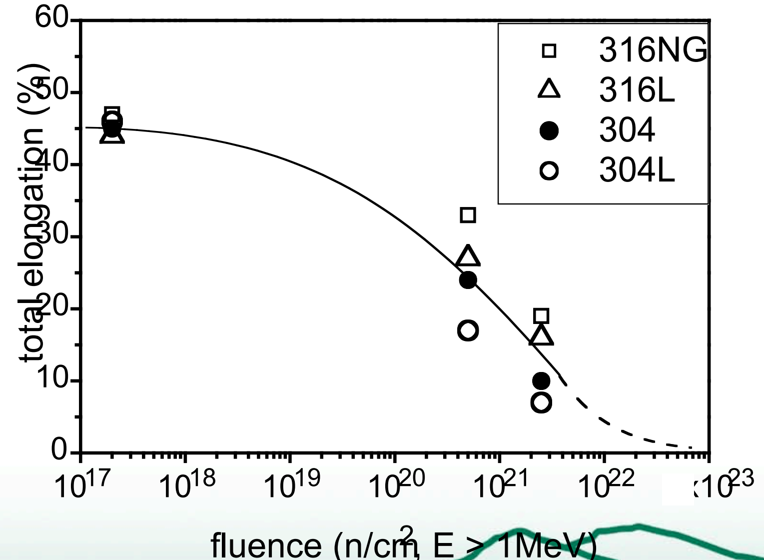
(i) Phenomenon

- **<u>Ferritic and austenitic steels</u>**

  - increase in yield stress σ_y and UTS (Ultimate Tensile Strength)

  - decrease in elongation to failure





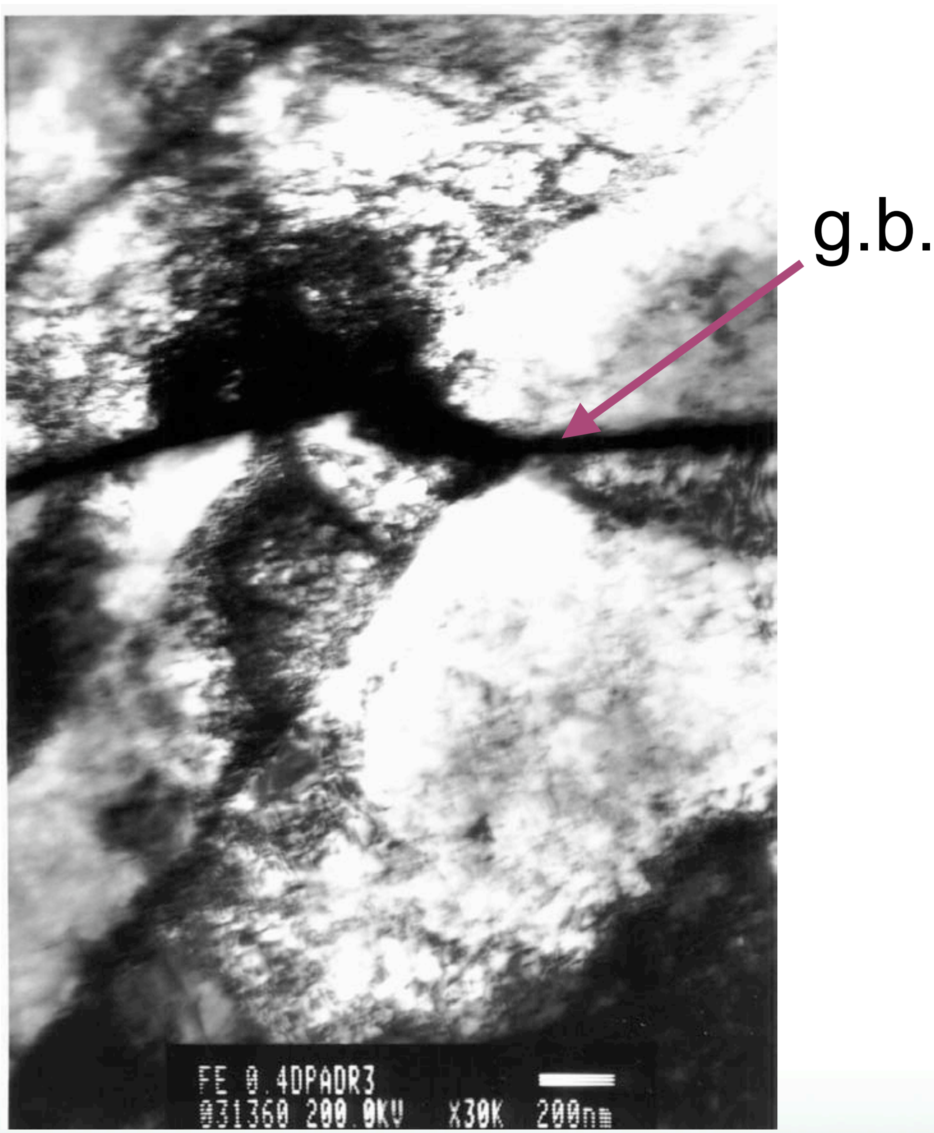
Overview of dislocation channeling

- 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, …………….

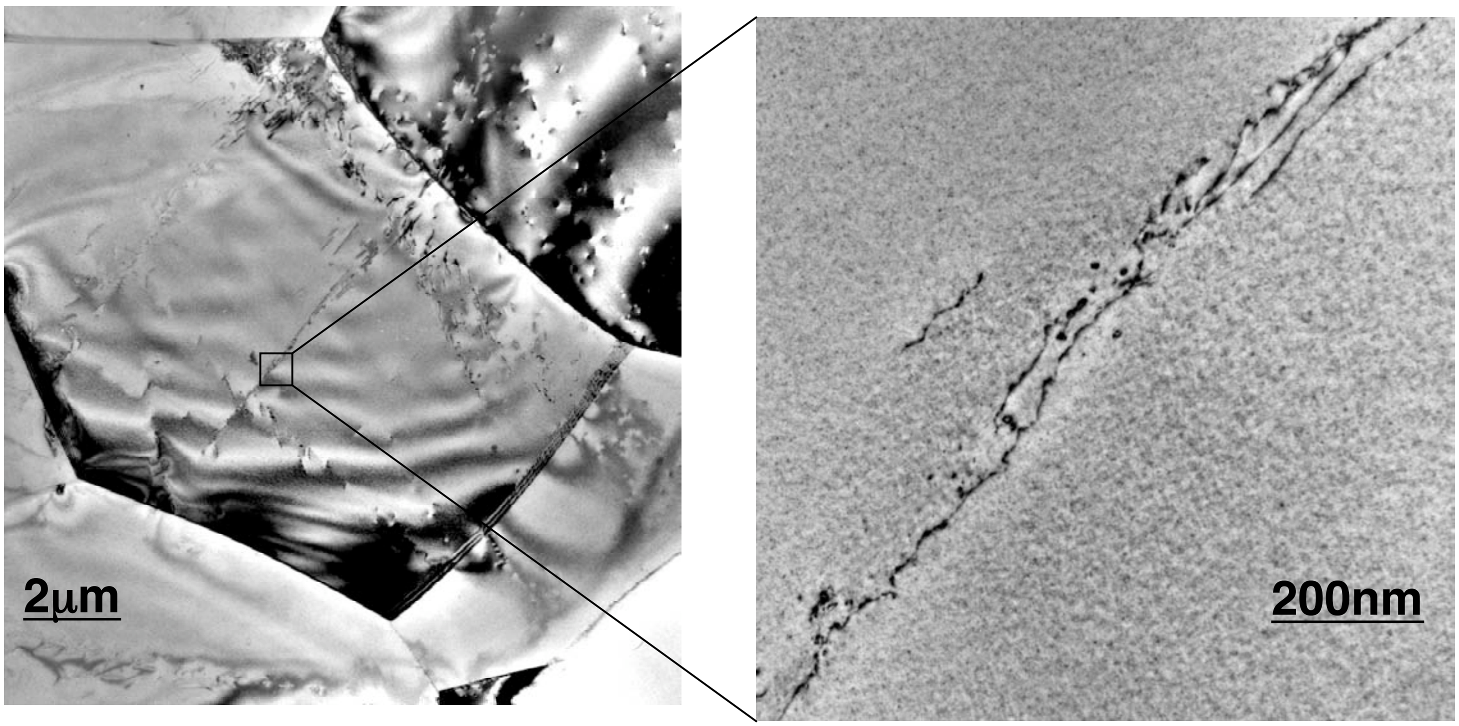
- It is not generally established that the catastophic reduction in tensile elongation is directly due to dislocation channeling
  - High tensile elongations and significant work hardening rates can occur in irradiated metals that exhibit dislocation channeling

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



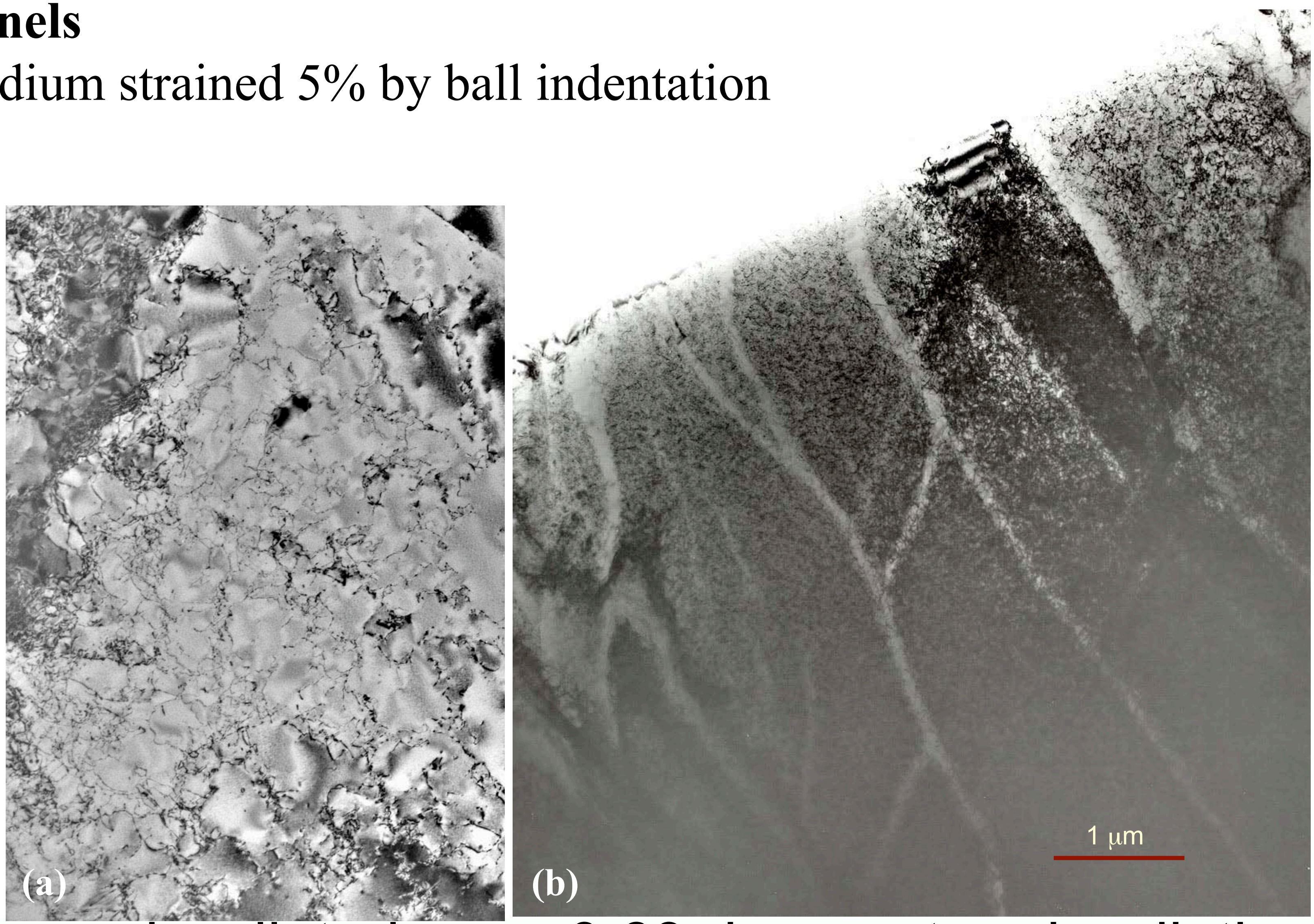
Channels in V (0.01 dpa) are not fully cleared; they contain elongated dislocations and loop-like debris

0.012 dpa, 0.1% ε_u



Multiaxial loading causes bending, twisting and bifurcation of channels

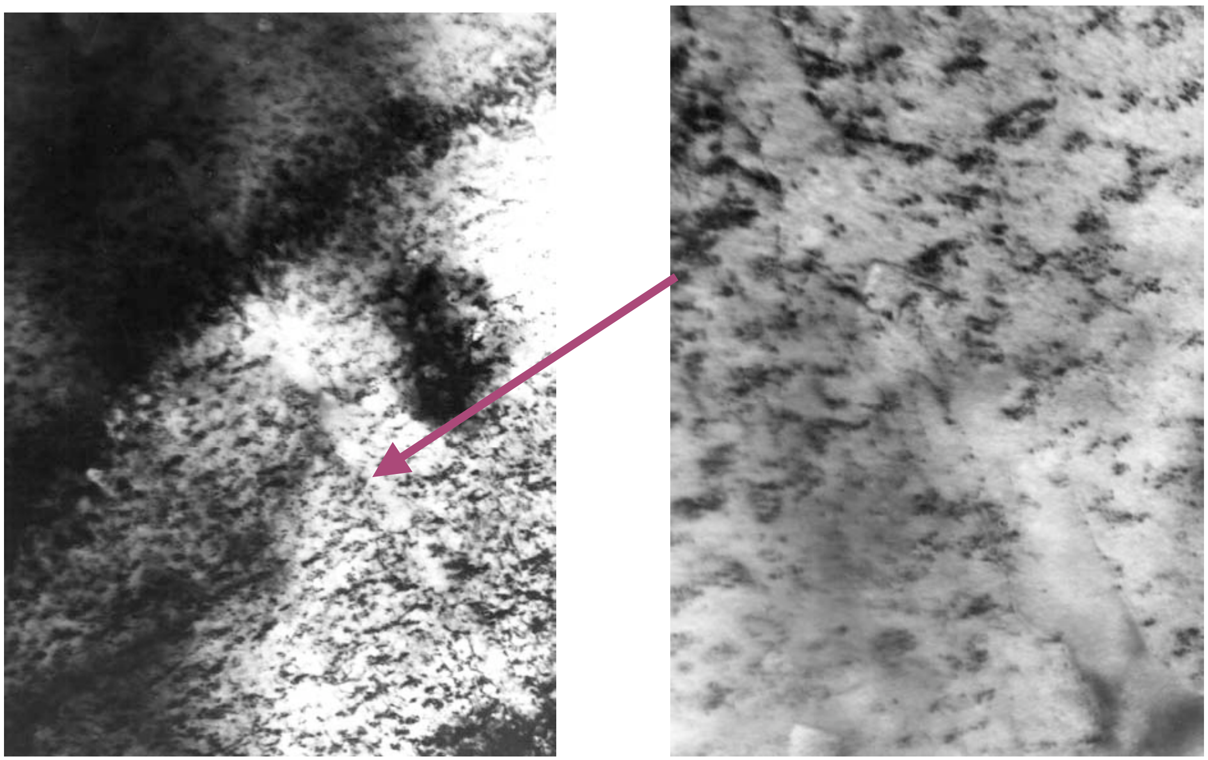
Vanadium strained 5% by ball indentation



unirradiated   0.69 dpa neutron irradiation

Dislocation channeling in Fe deformed following neutron irradiation at 70˚C to 0.8 dpa

Multiaxial stresses in necked region induce operation of numerous dislocation sources compared to uniaxial stress case



Uniform strain region

Necked region

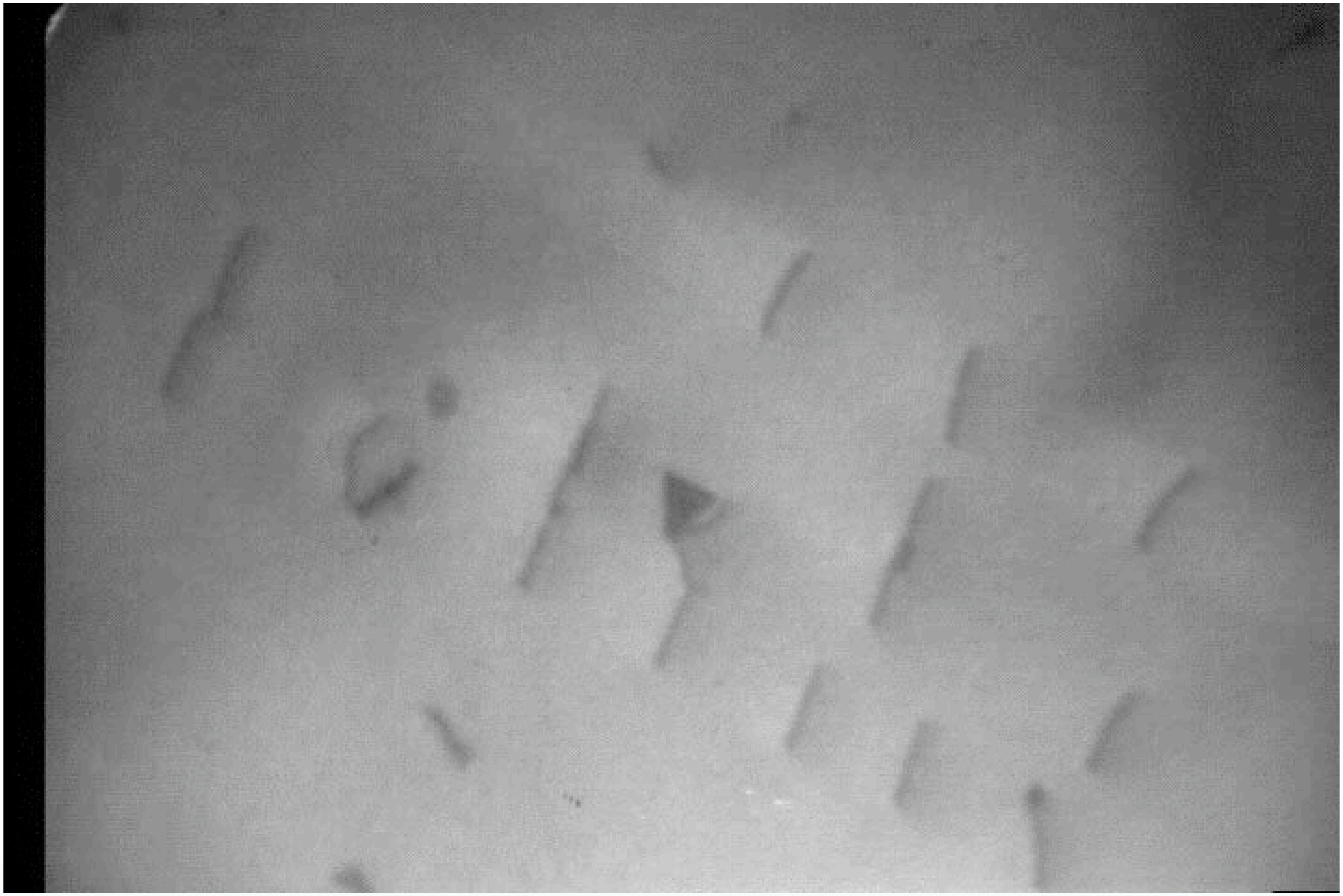
Summary of Dislocation Channeling Parameters

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

In-situ TEM deformation study of dislocation-defect cluster interactions in quenched gold containing SFTs

- Dislocation pinning and defect cluster annihilation



Y. Matsukawa

Investigation of dislocation interactions with SFTs

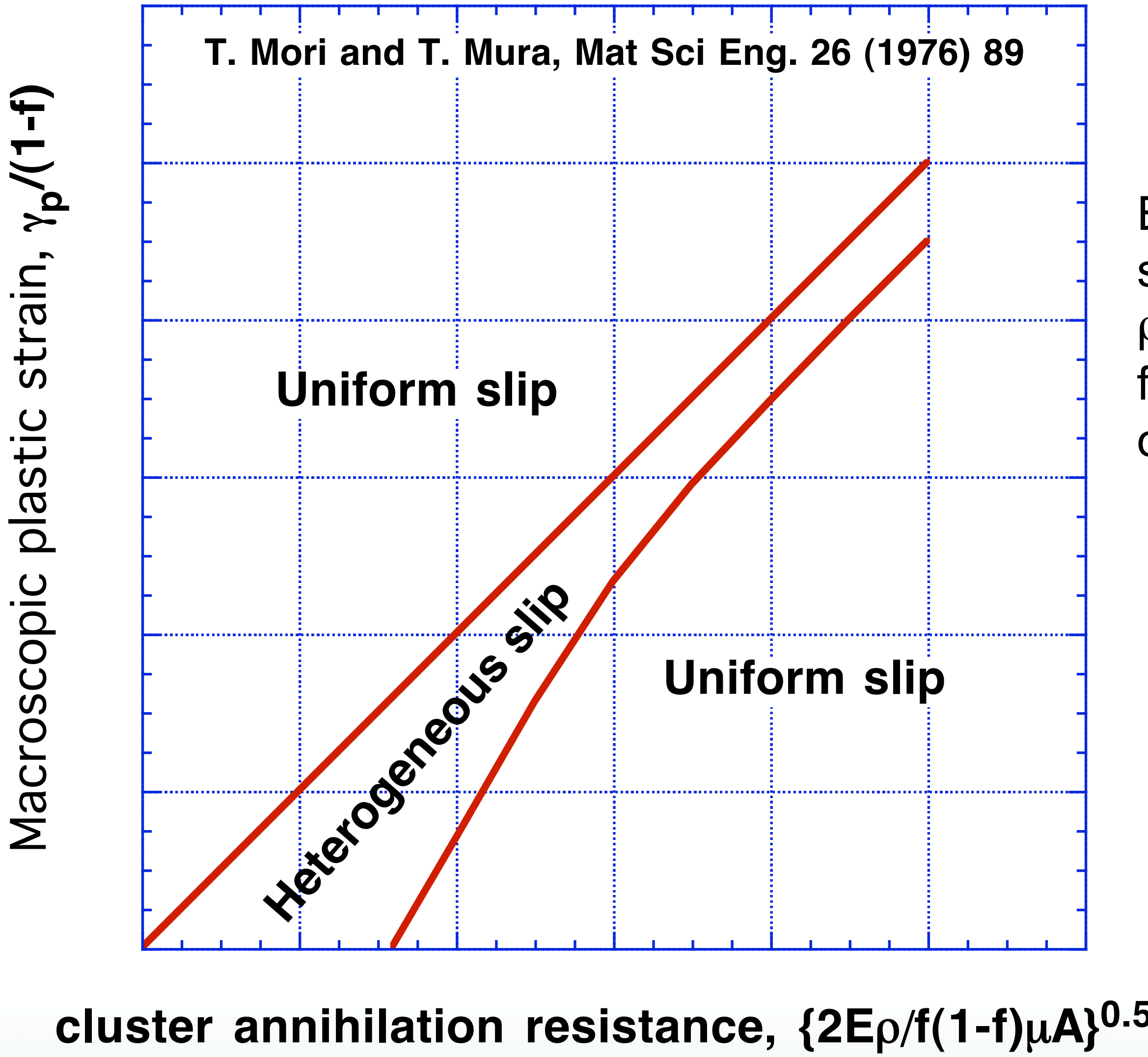
SFT annihilation by a single dislocation

Y. Matsukawa

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)

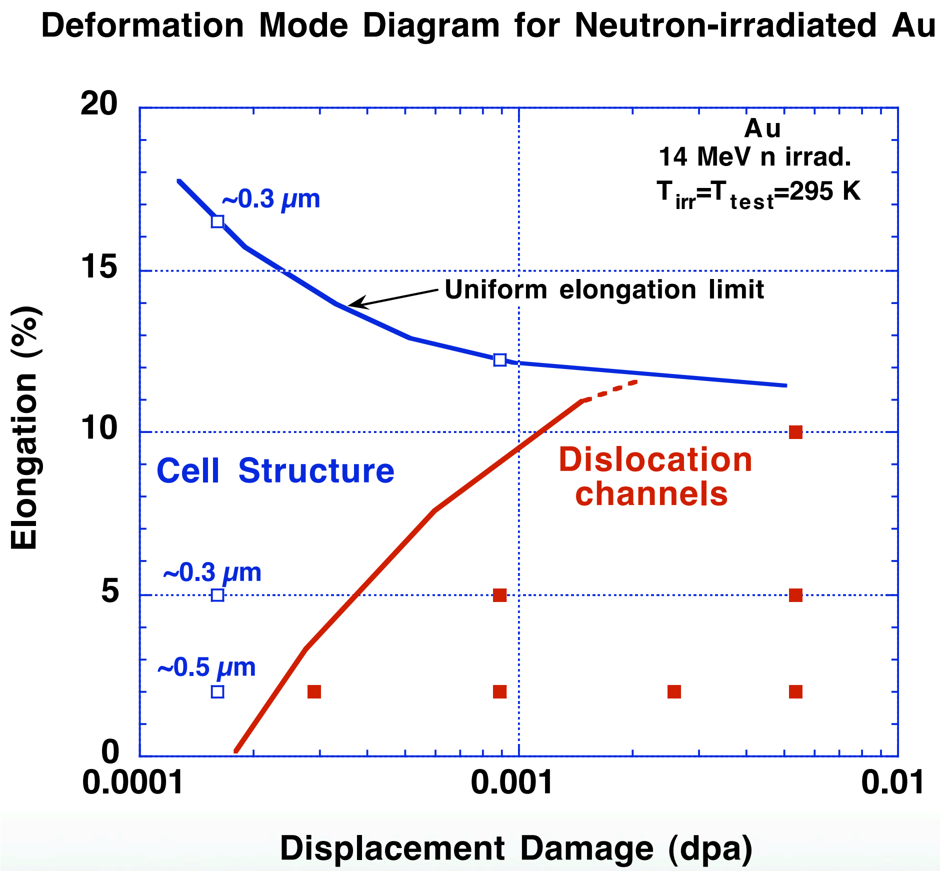
Plastic deformation mechanisms for dispersion hardened materials containing work-softening obstacles

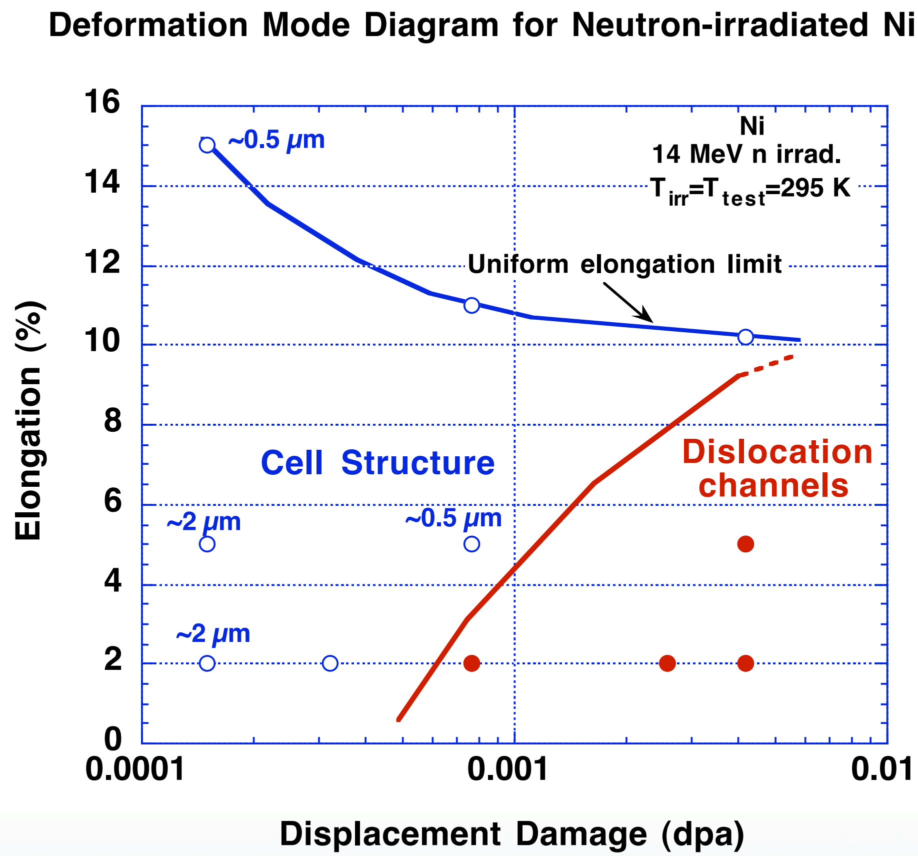


E_e=elastic energy stored by one obstacle
ρ=obstacle density
f=vol. fraction of obstacles

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

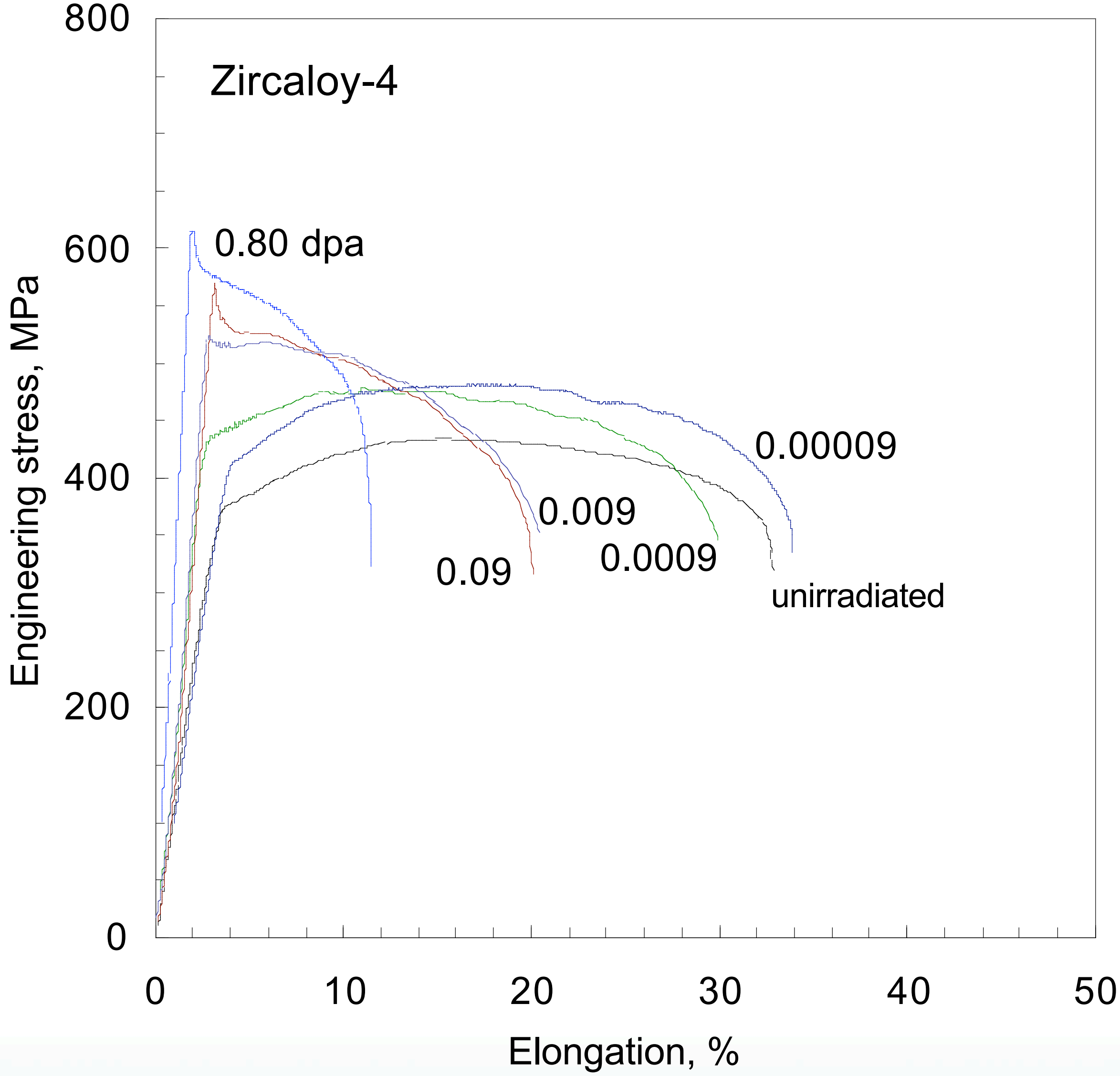
A. Okada et al. Mater. Trans. JIM 30 (1989) 265





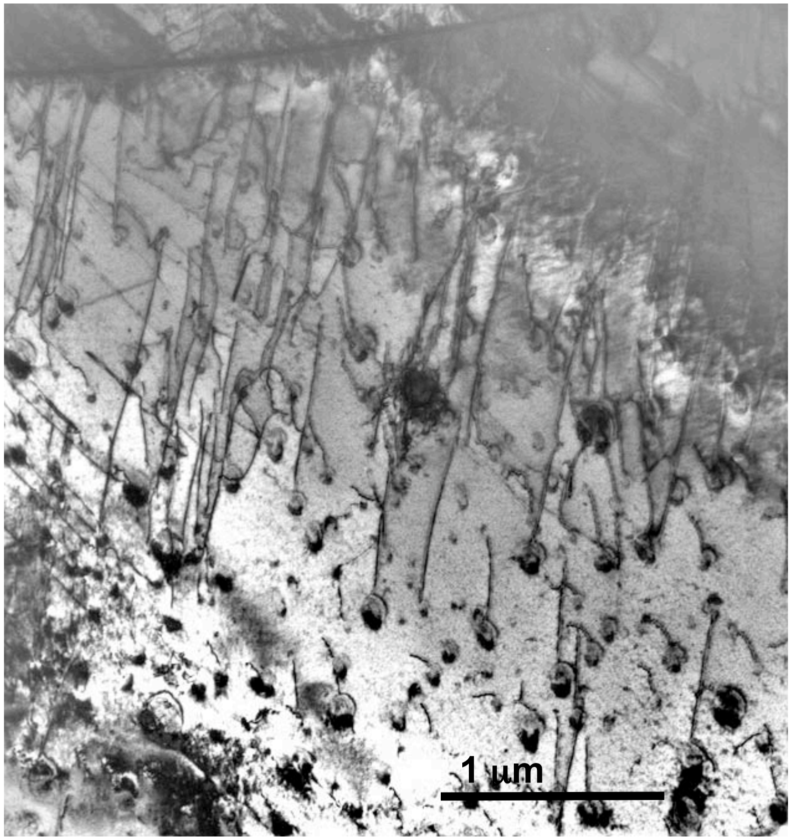
Tensile test curves for Zircaloy-4

K. Farrell et al. ORNL/TM-2002/66 (2002)

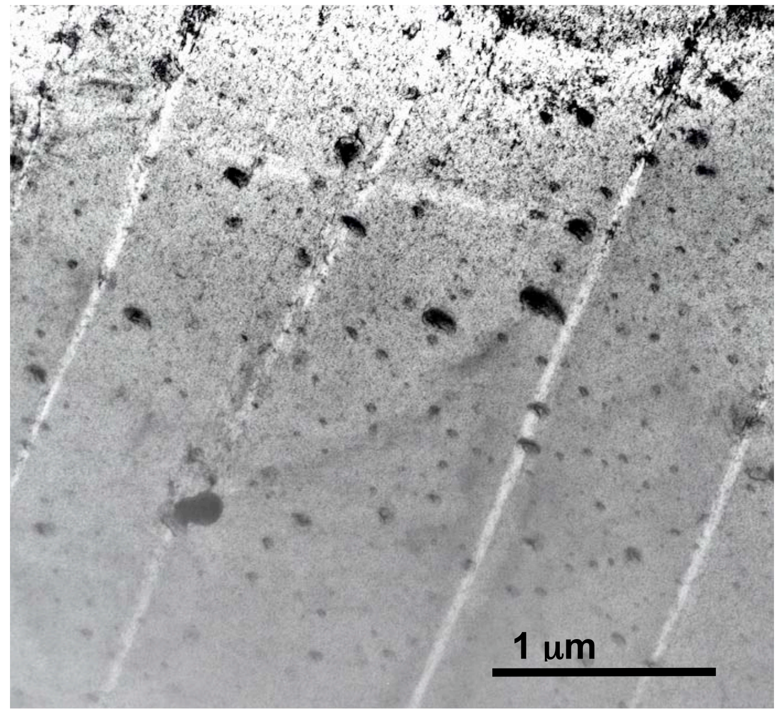


Deformation microstructure in Zircaloy-4 after room temperature tensile deformation

K. Farrell et al. ORNL/TM-2002/66 (2002)



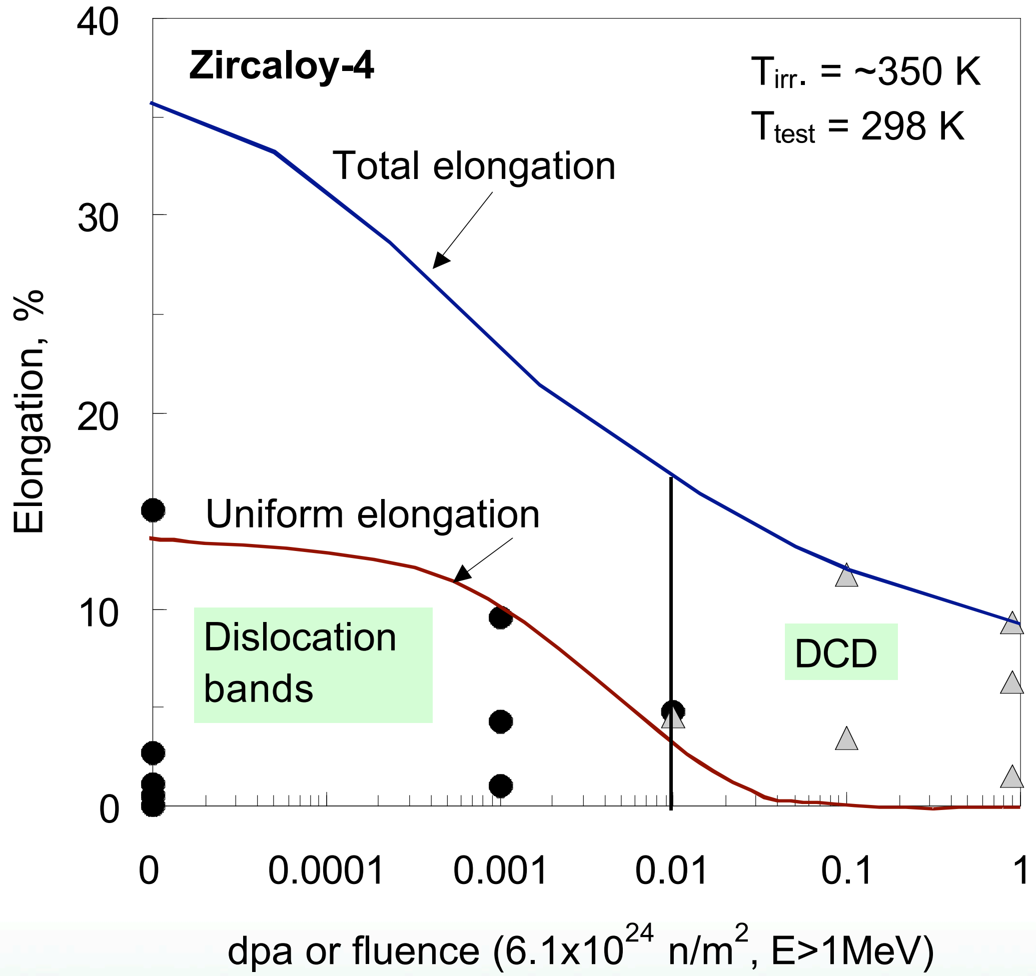
unirradiated, ε=3%



0.8 dpa, ε=6.3%
(dislocation channels)

Deformation mode map for Zircaloy-4 neutron-irradiated at 65-100°C and tested at 25°C

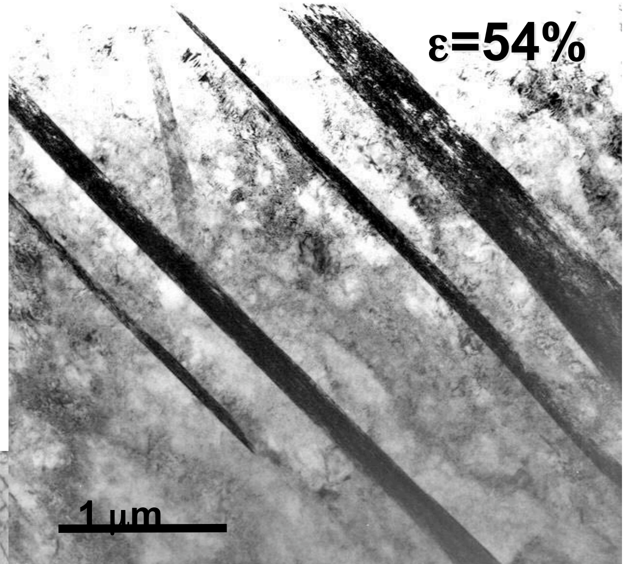
K. Farrell et al. ORNL/TM-2002/66 (2002)

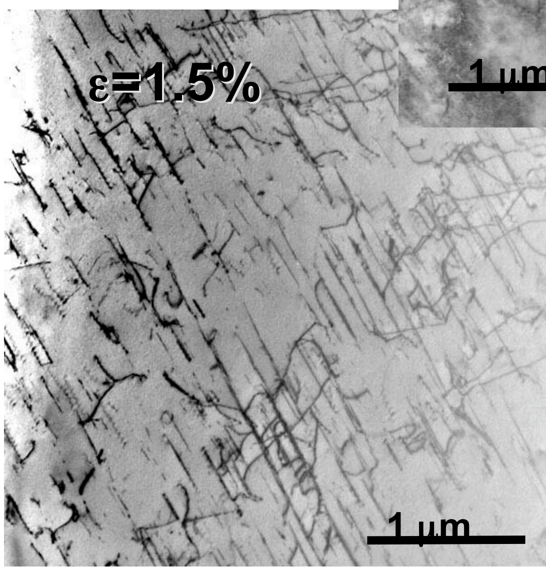


Deformation microstructures in 316 stainless steel after room temperature tensile deformation

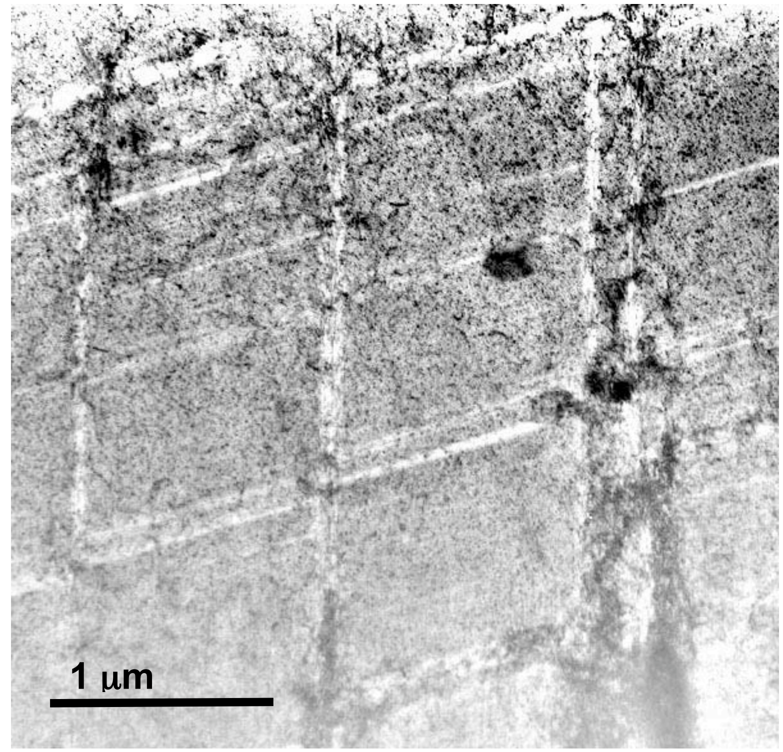
K. Farrell et al. ORNL/TM-2002/66 (2002)

Twinning occurs at high strains





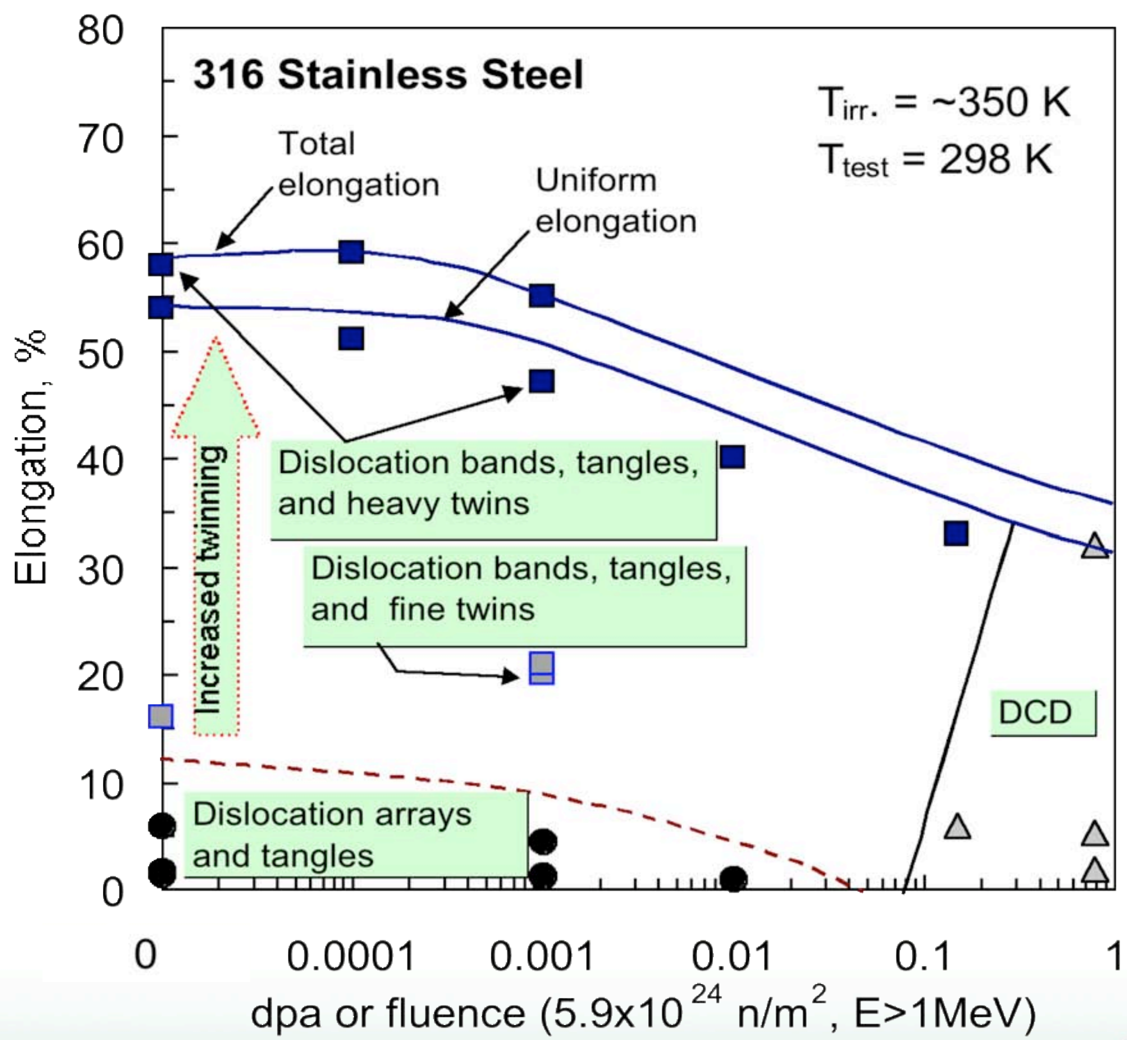
unirradiated, ε=1.5 - 54%



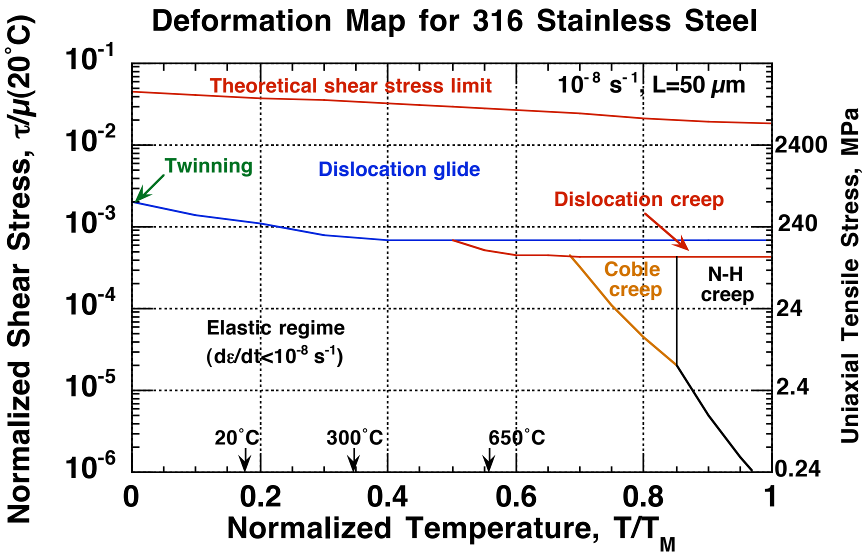
0.78 dpa, ε=32%
(dislocation channels)

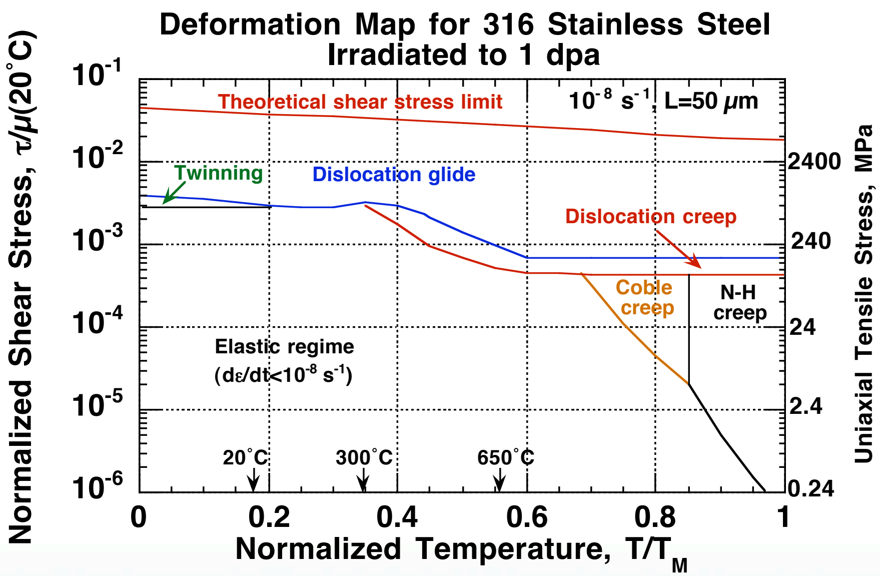
Deformation mode map for 316 SS neutron-irradiated at 65-100^{o}C and tested at 25°C

K. Farrell et al. ORNL/TM-2002/66 (2002)

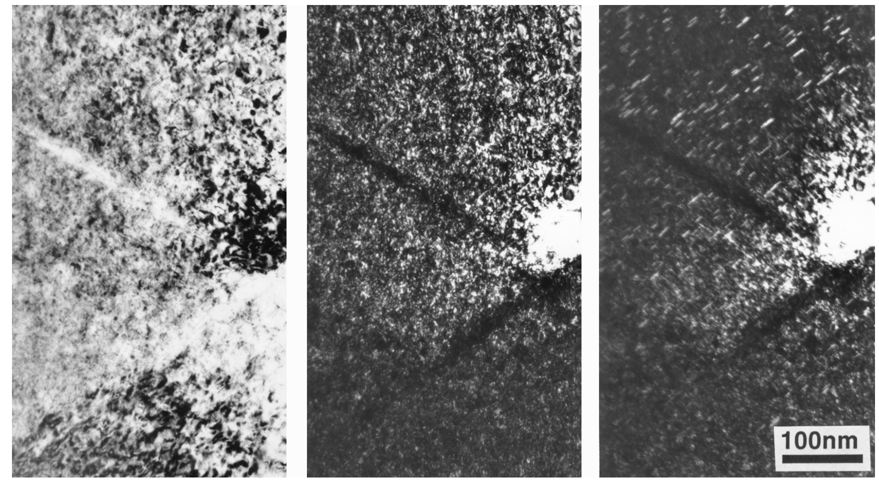


Deformation mechanisms in stainless steel

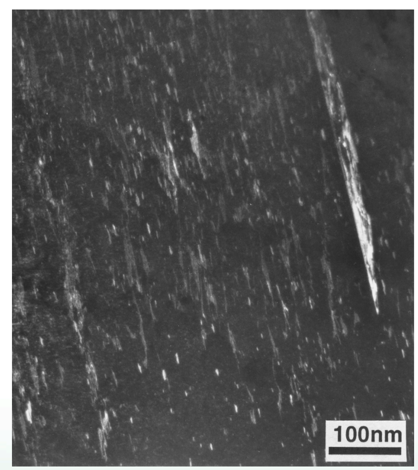




Irradiation is a useful tool to produce controlled microstructures for deformation mechanics studies

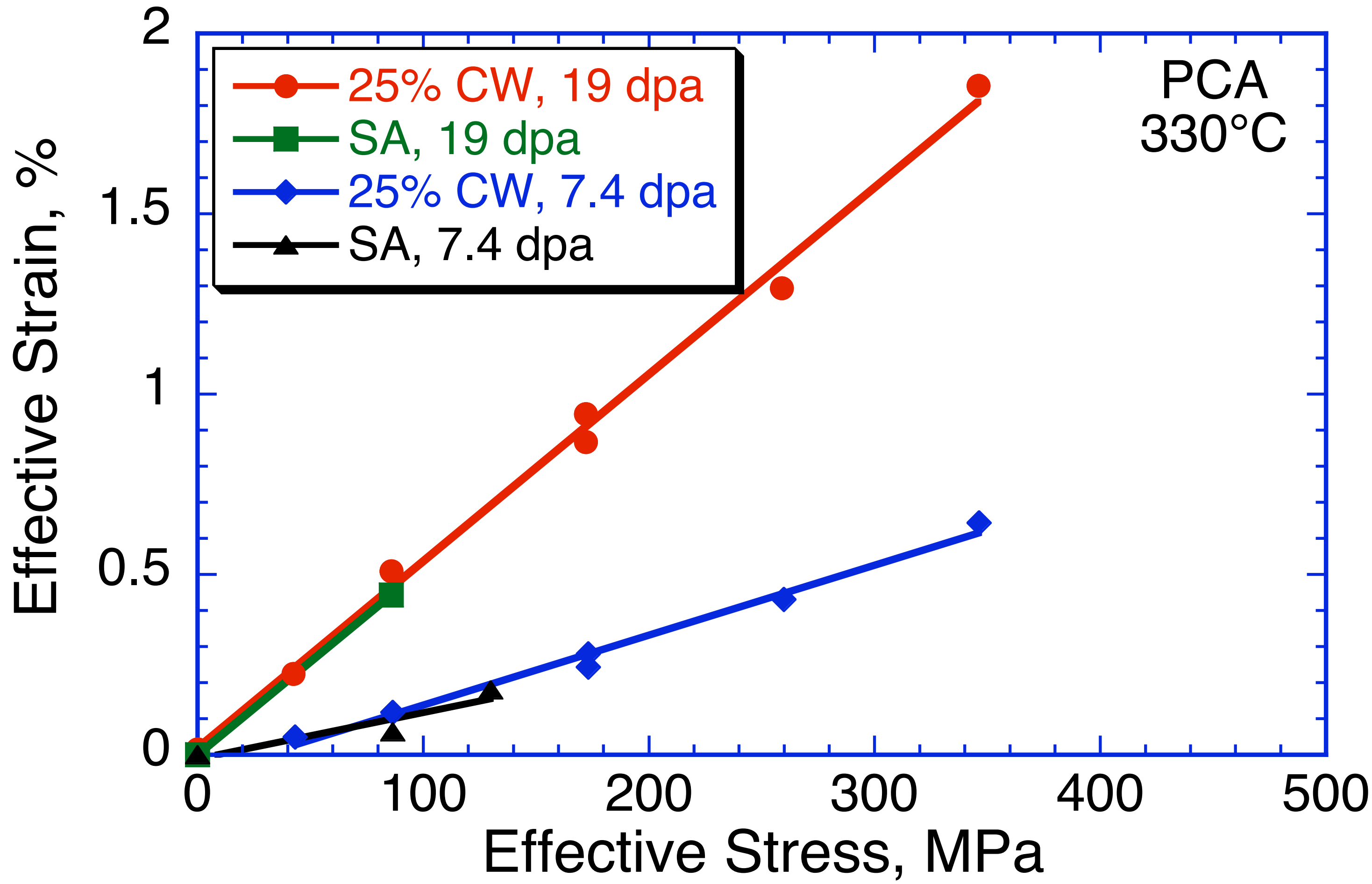


Channeling (Disln glide) occurs at higher temperatures (~300˚C)



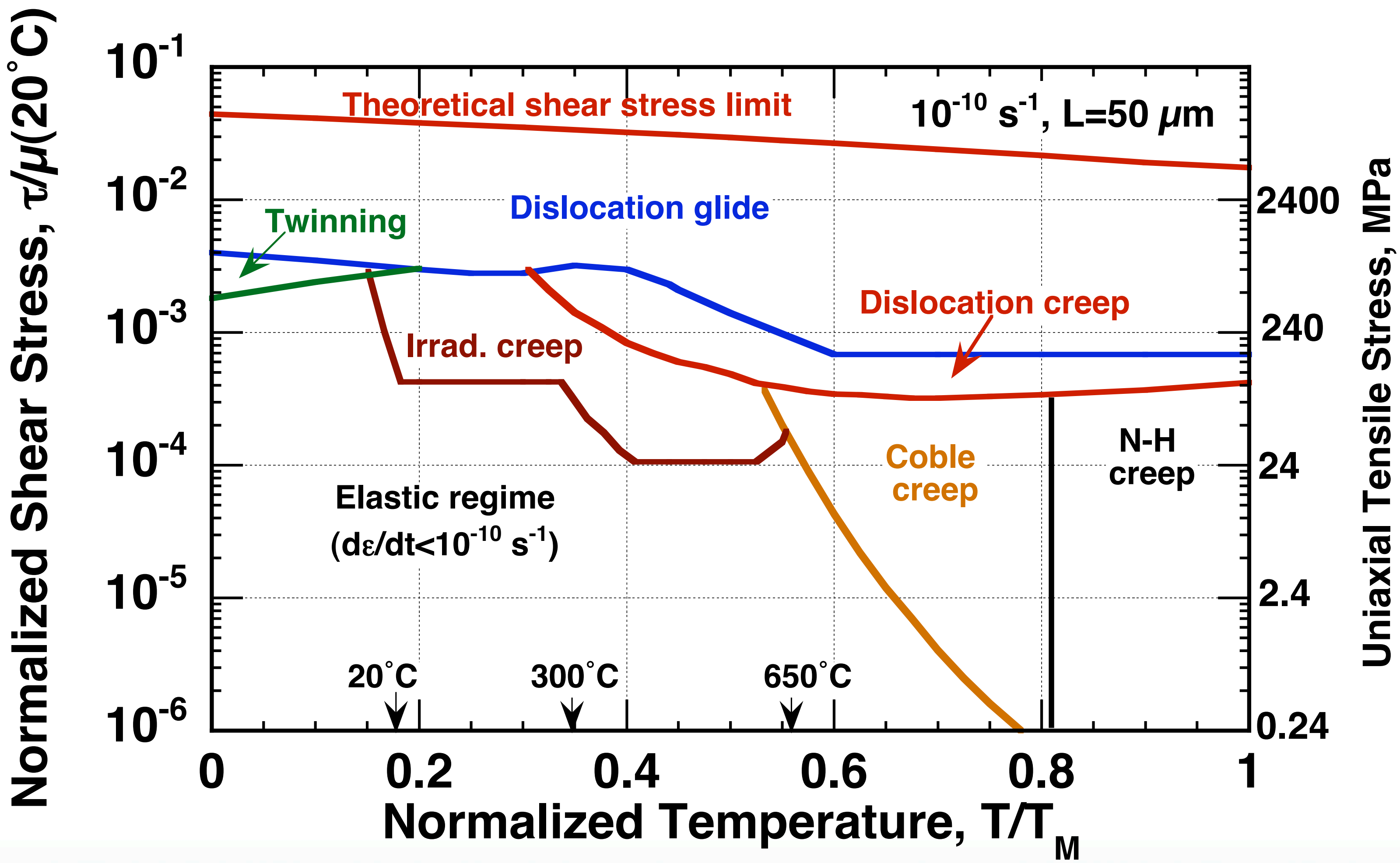
Twinning occurs at lower temperatures (<200˚C) and high strain rates

Irradiation Creep of Austenitic Stainless Steel will Generally be of Concern only for High Fluence (>20 dpa), High Stress Environments



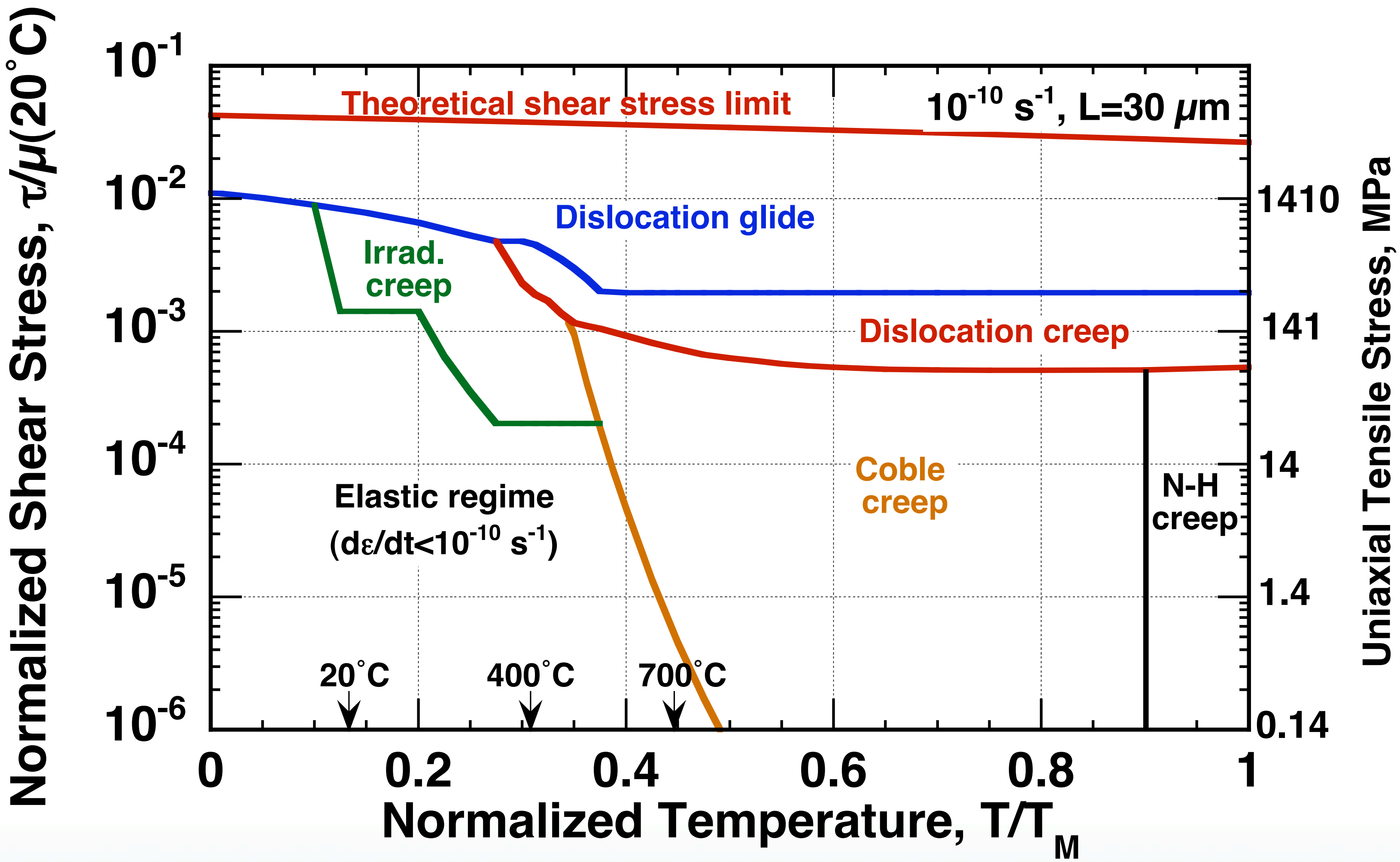
Calculated irradiated Ashby deformation map for Type 316 stainless steel at low strain rates

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

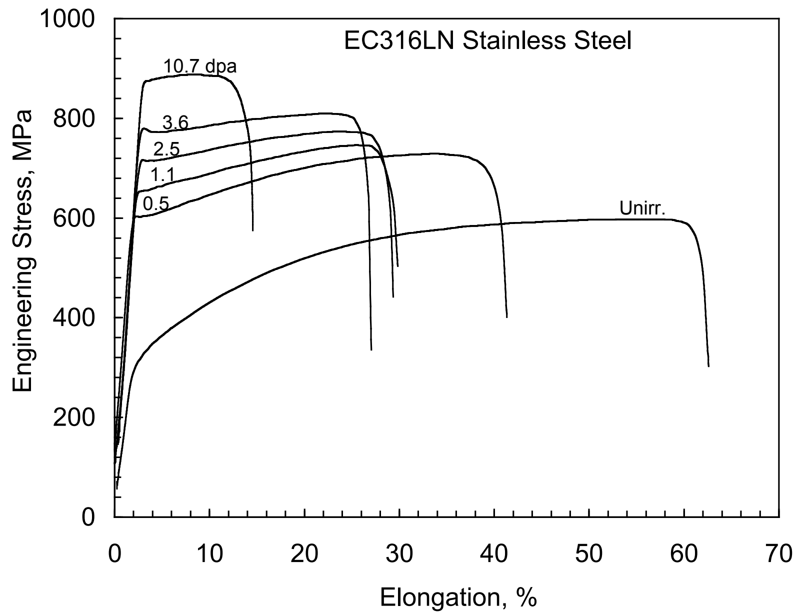


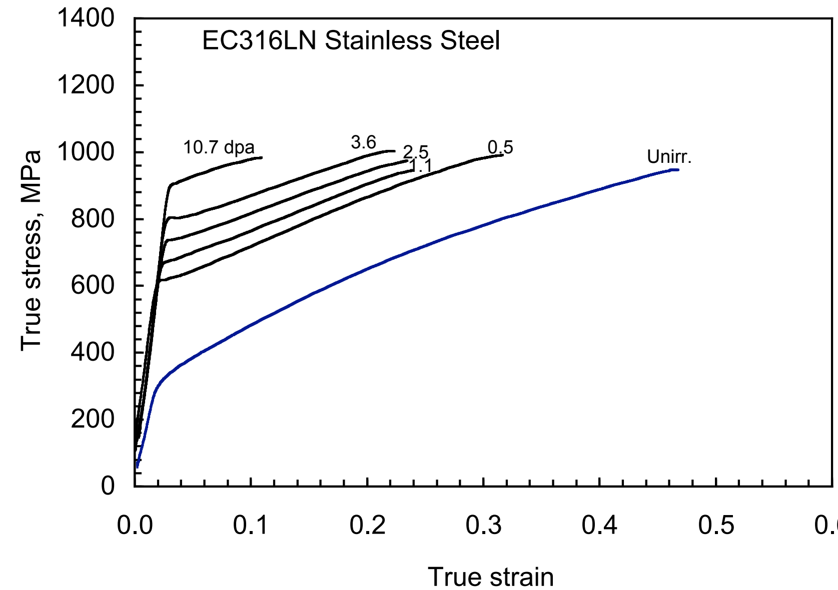
Calculated irradiated Ashby deformation map for V-4%Cr-4%Ti

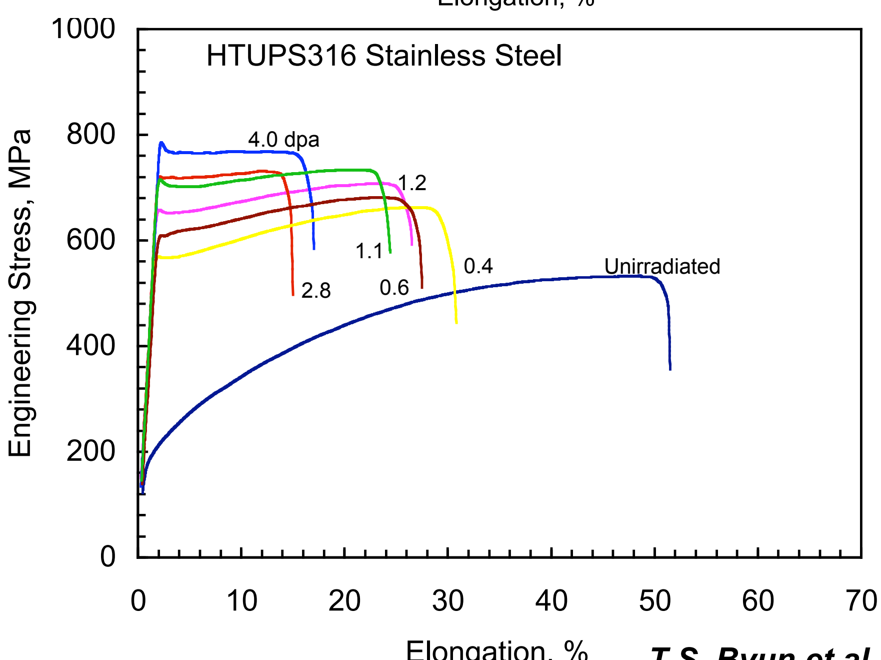
Damage rate = 10^{-6} dpa/s

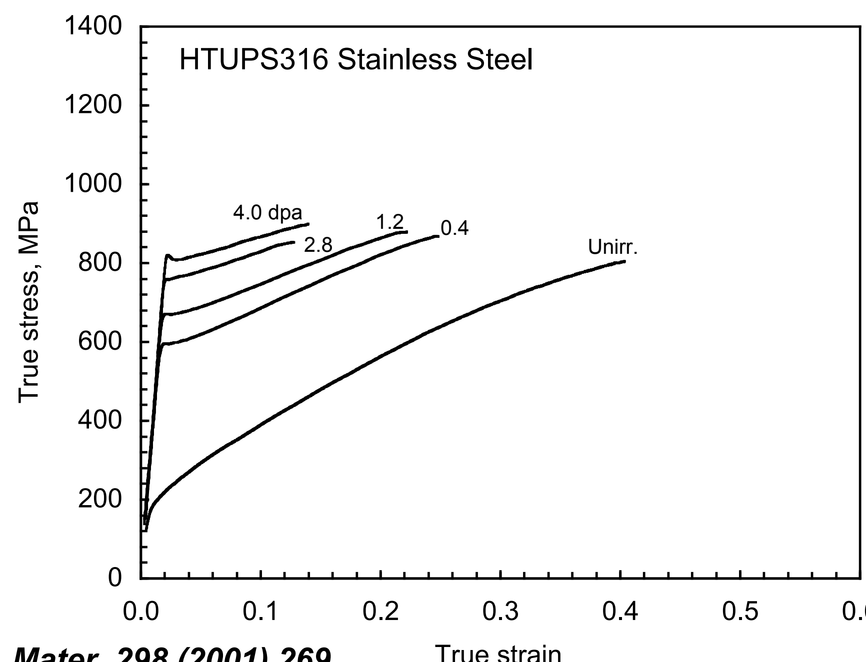


Engineering and true stress-strain tensile curves for stainless steel before and after spallation irradiation at ~100°C



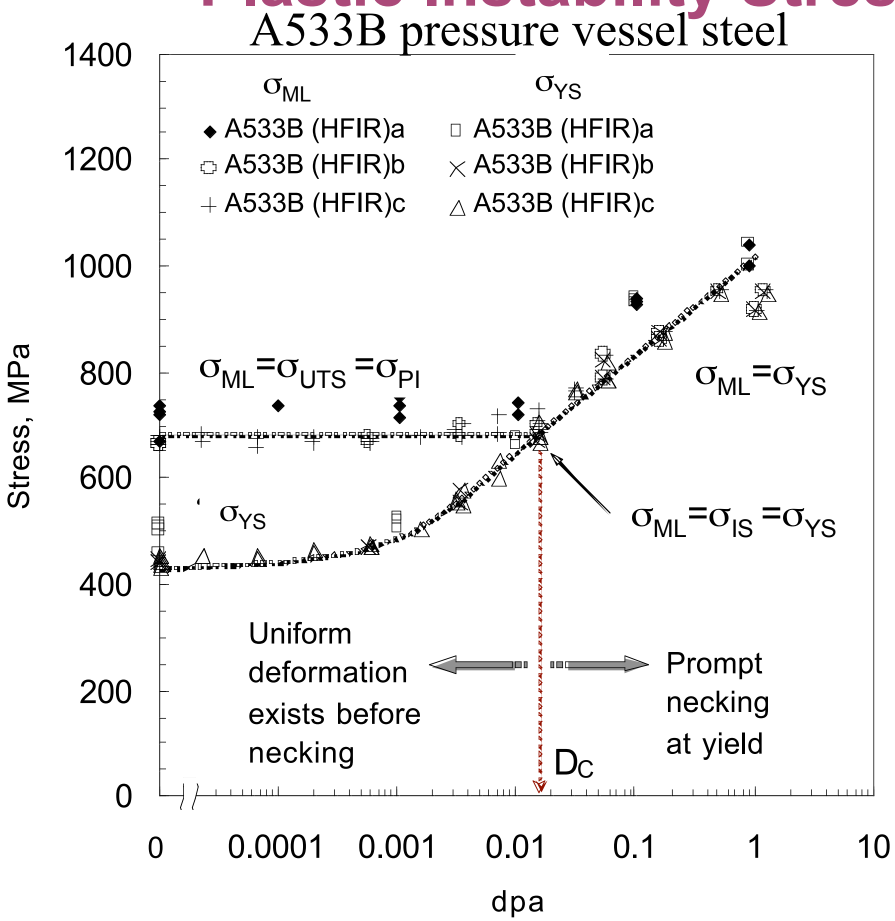


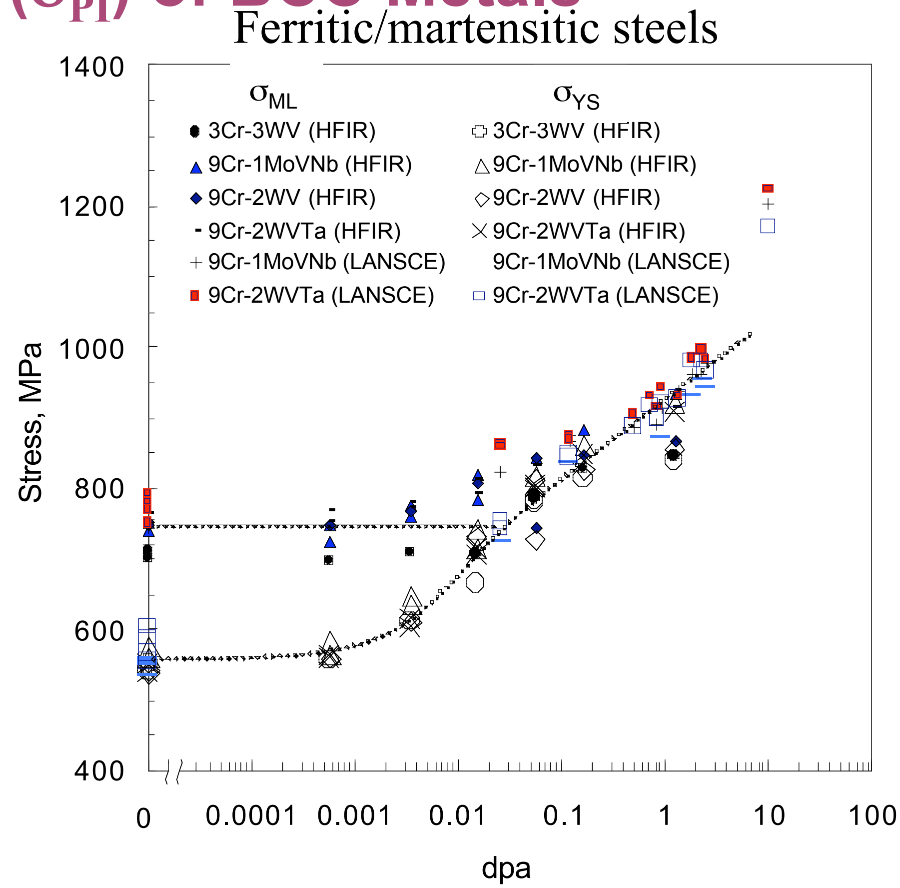




T.S. Byun et al., J. Nucl. Mater. 298 (2001) 269

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



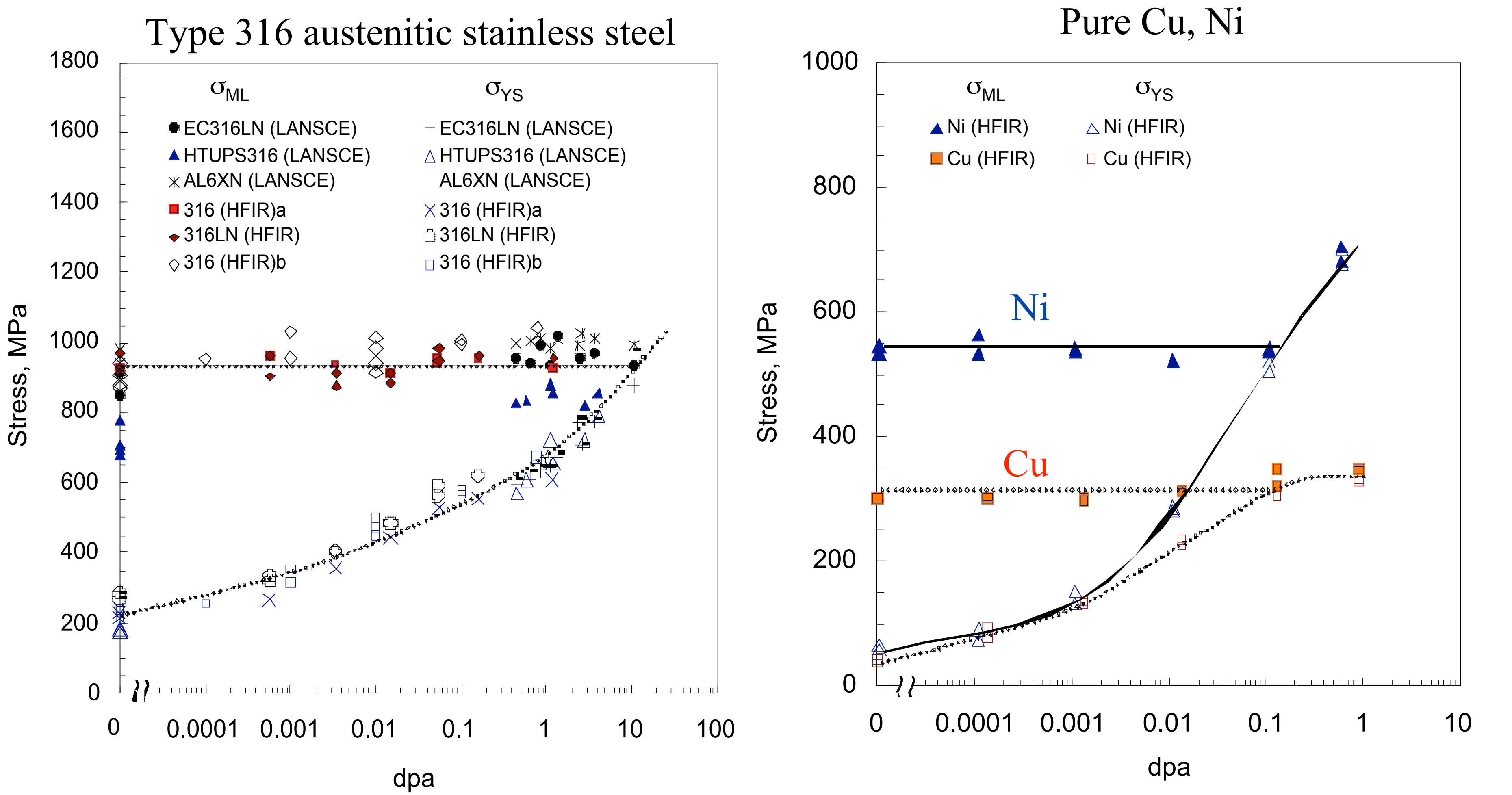


σ_{ML}=true stress at maximum load

- **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**

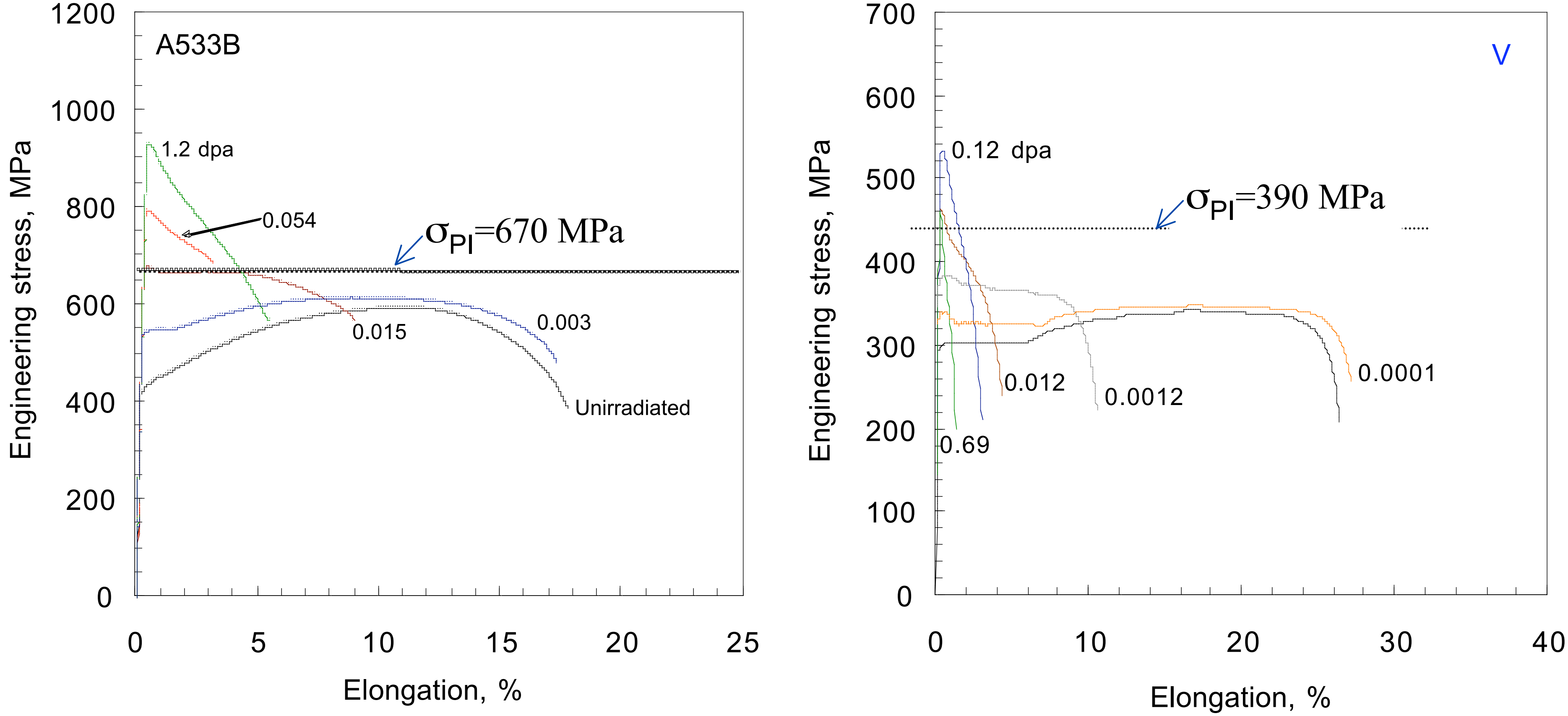
T.S. Byun & K. Farrell, Acta Mater. 52 (2004) 1597

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



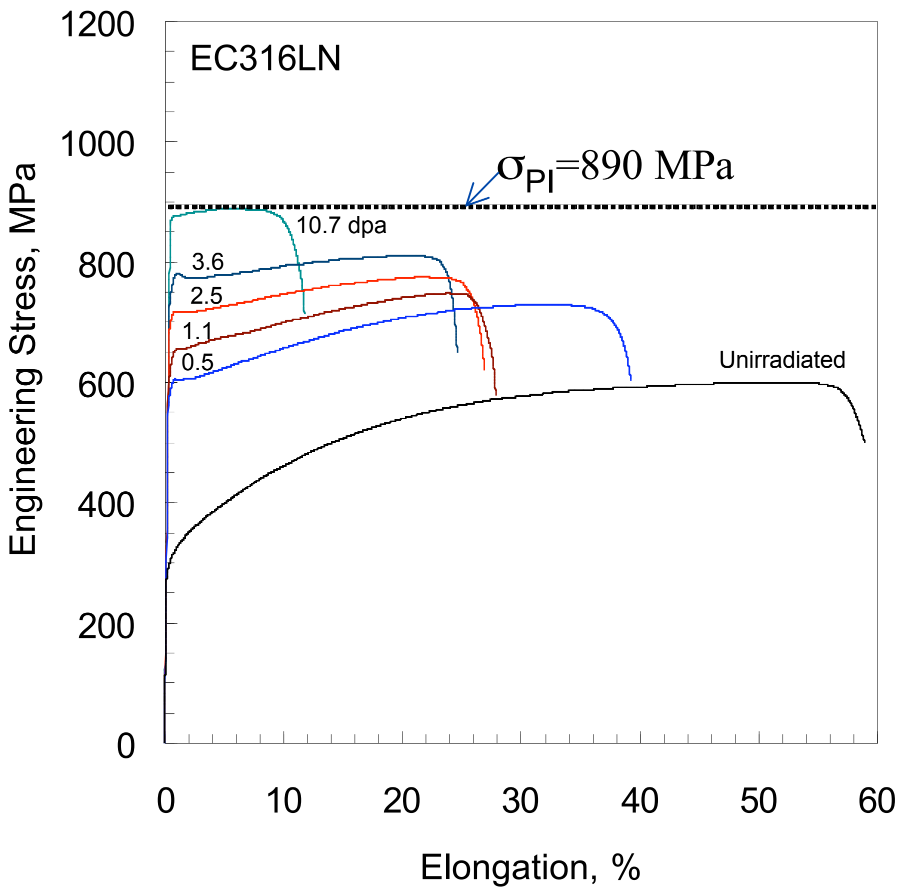
T.S. Byun & K. Farrell,
Acta Mater. 52 (2004) 1597

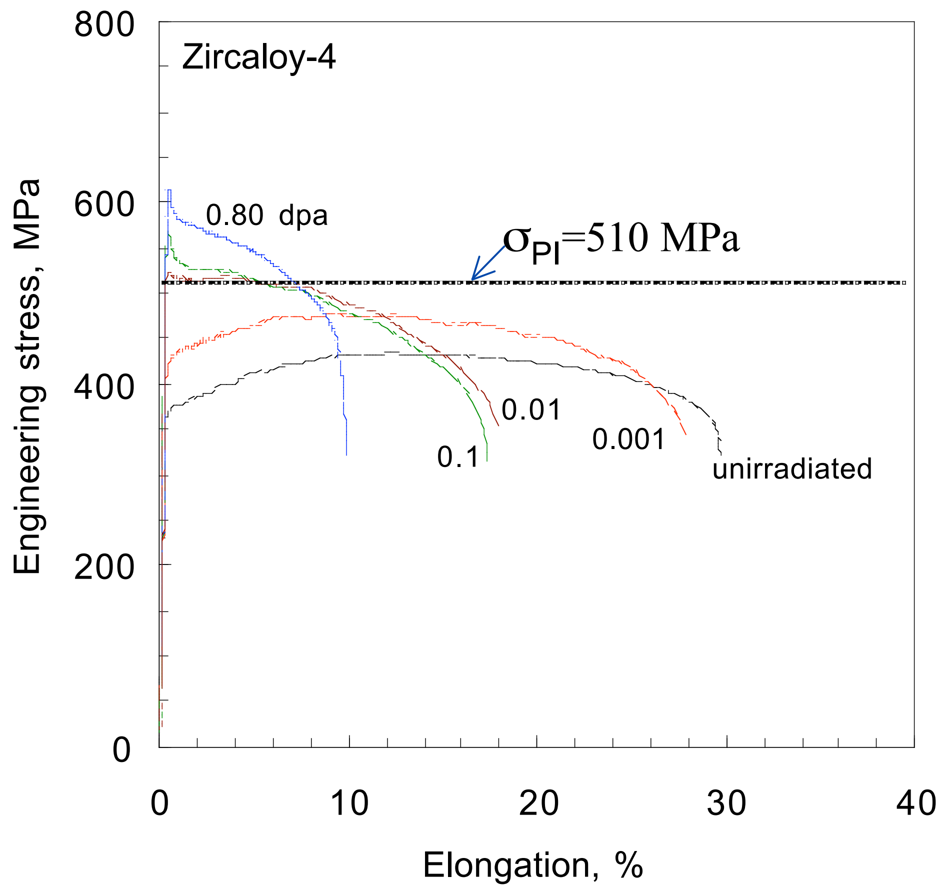
Plastic Instability Criterion for BCC metals irradiated near 70˚C



- 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

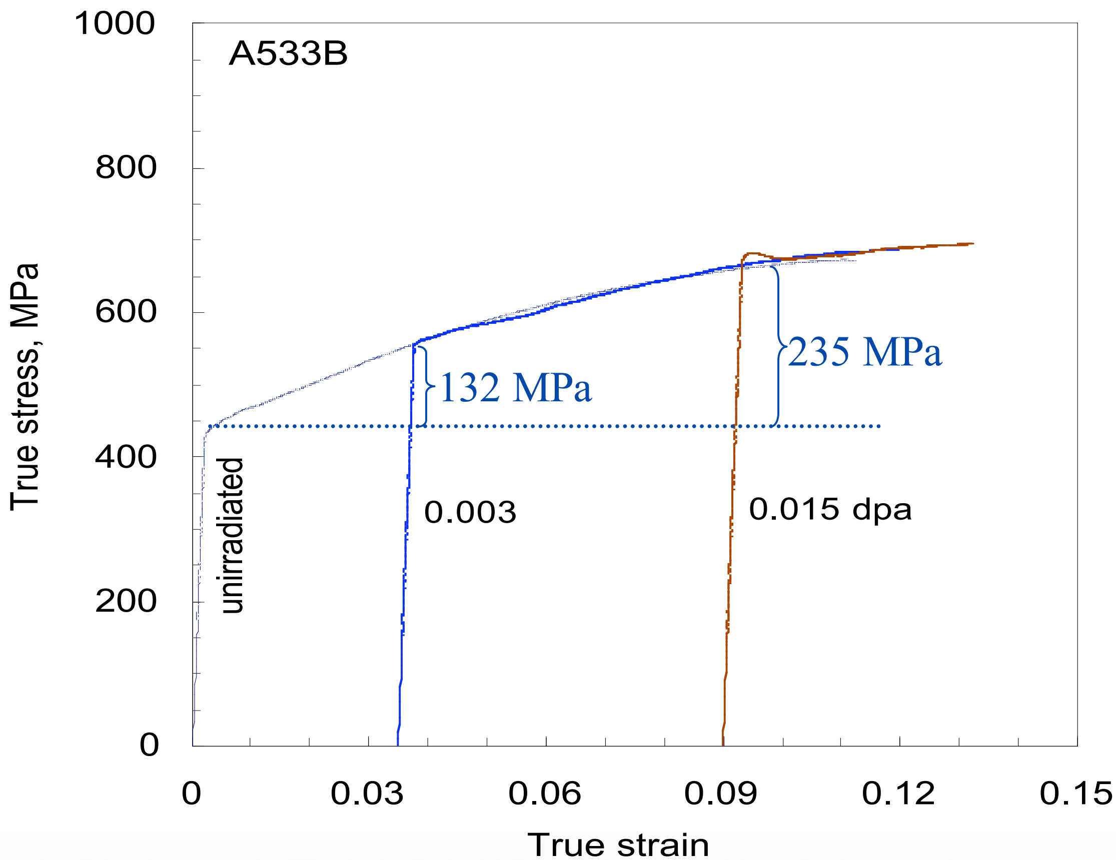
Plastic Instability Criterion (FCC & HCP) irradiated at ~70˚C





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

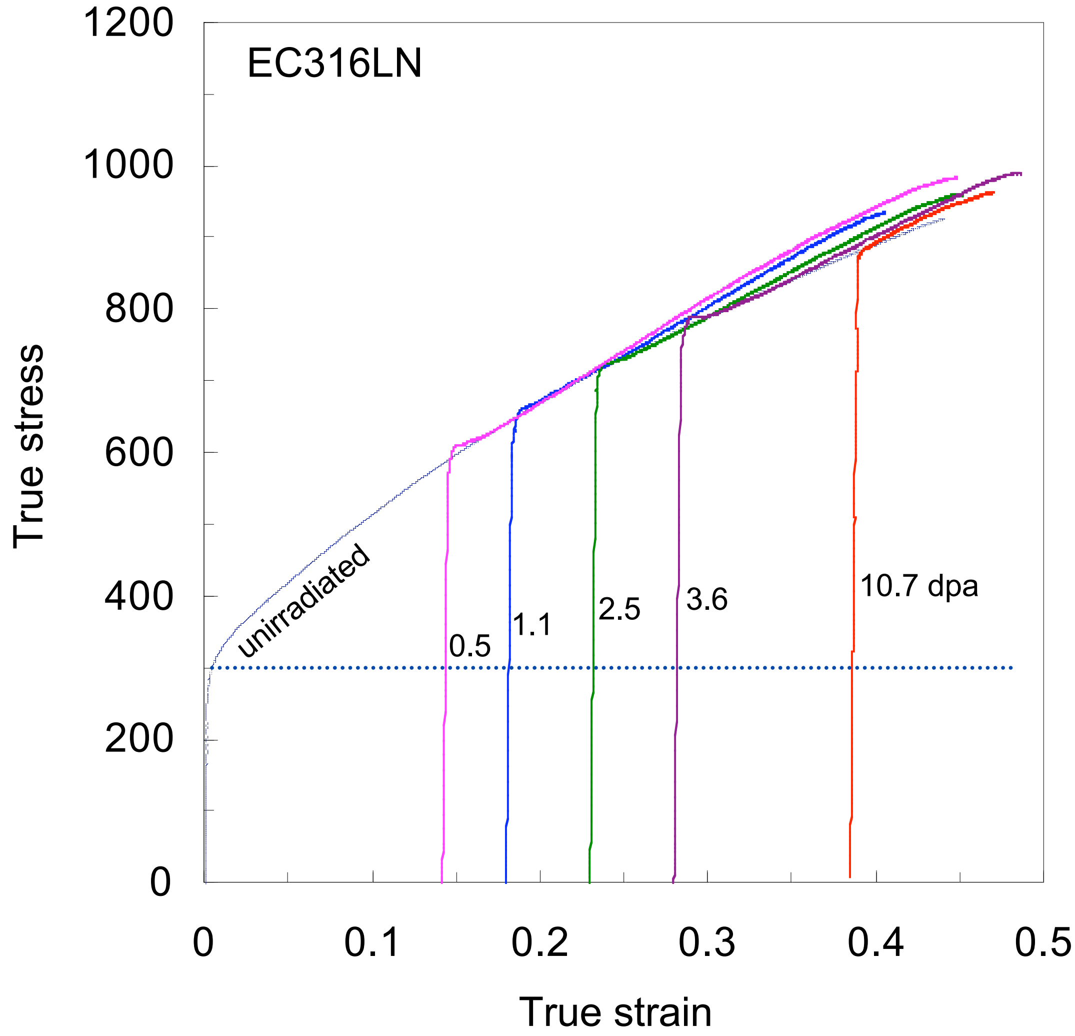
- True stress- true strain curve for irradiated material coincides with unirradiated curve, after translation to account for radiation hardening
  - Suggests main effect of radiation hardening is to partially exhaust strain hardening capacity



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

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



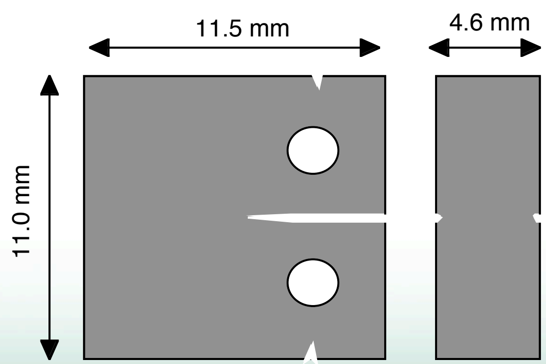
True stress-true strain curves for EC316LN stainless steel; the curves of irradiated specimens are shifted in the positive direction by strains of 0.14, 0.18, 0.23, 0.28, and 0.385, respectively, to superimpose on the curve of unirradiated material. Irradiation-induced increases in yield stress were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

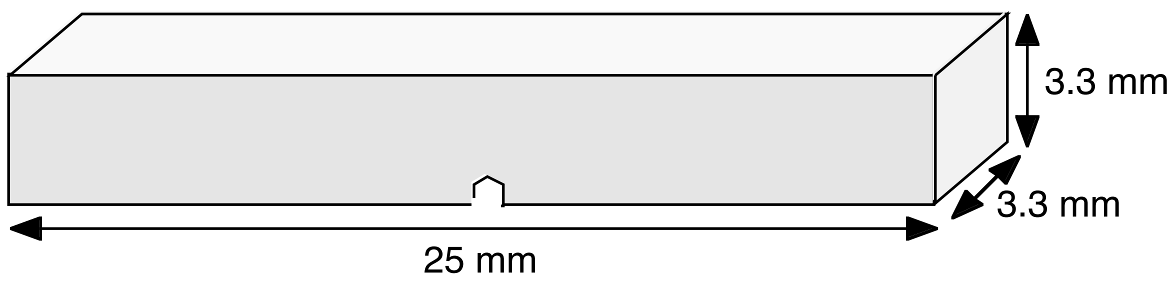
Introduction to Fracture Mechanics of Irradiated Metals

- Crack propagation can lead to failure of structural materials
- The fracture toughness of a material is a direct measure of its resistance to crack propagation
- For body-centered cubic metals, there is a transition near a critical temperature from low resistance to crack propagation (brittle) at low temperature to high toughness at high temperature
  - This transition temperature is known as the ductile to brittle transition temperature (DBTT)
    - Sometimes also referred to as "nil ductility temperature", NDT
- The quantitative value of the fracture toughness of materials is best measured using dedicated fracture toughness specimens
  - Example of a miniaturized compact tension specimen:



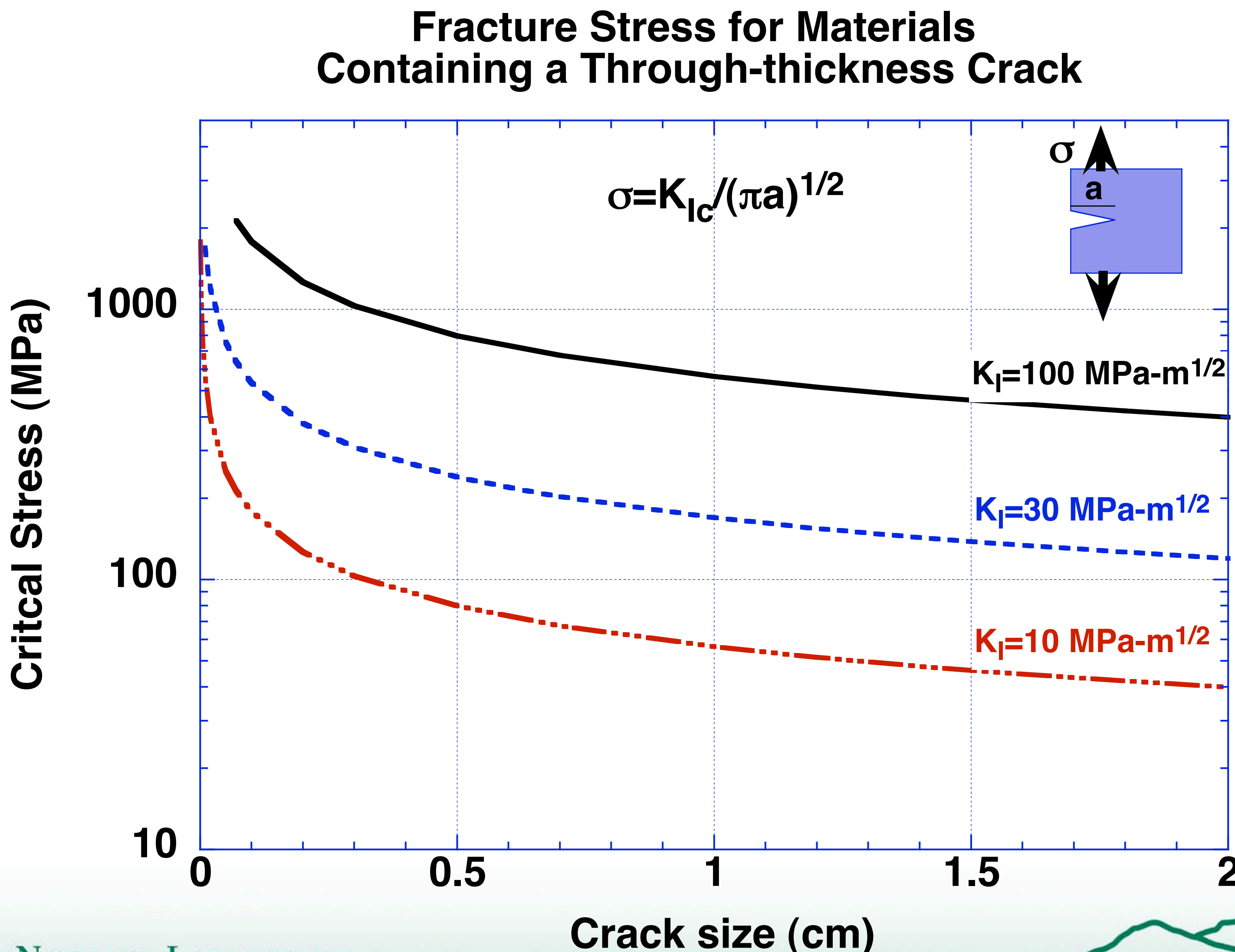
Introduction to Fracture Mechanics of Irradiated Metals
(continued)

- Accurate measurement of the fracture toughness behavior of a material at a single irradiation condition requires >10 specimens
  - Typically requires >1 h testing time per specimen
- A useful semi-quantitative monitor of the fracture toughness behavior can be obtained from notched Charpy impact tests
  - Example of a miniaturized notched Charpy impact specimen:

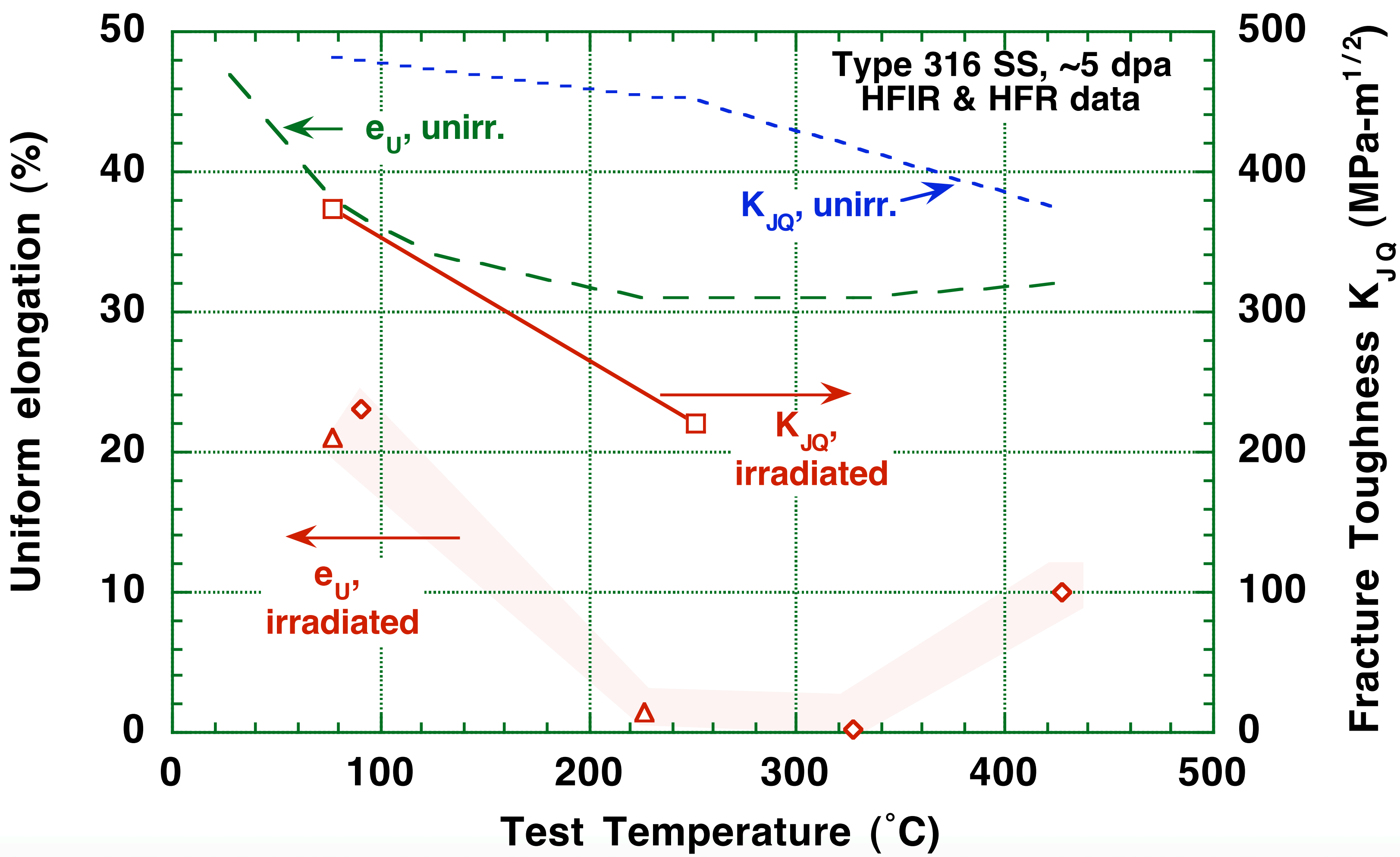


Fracture Stress for Materials Containing a Through-thickness Crack

Introduction to fracture toughness

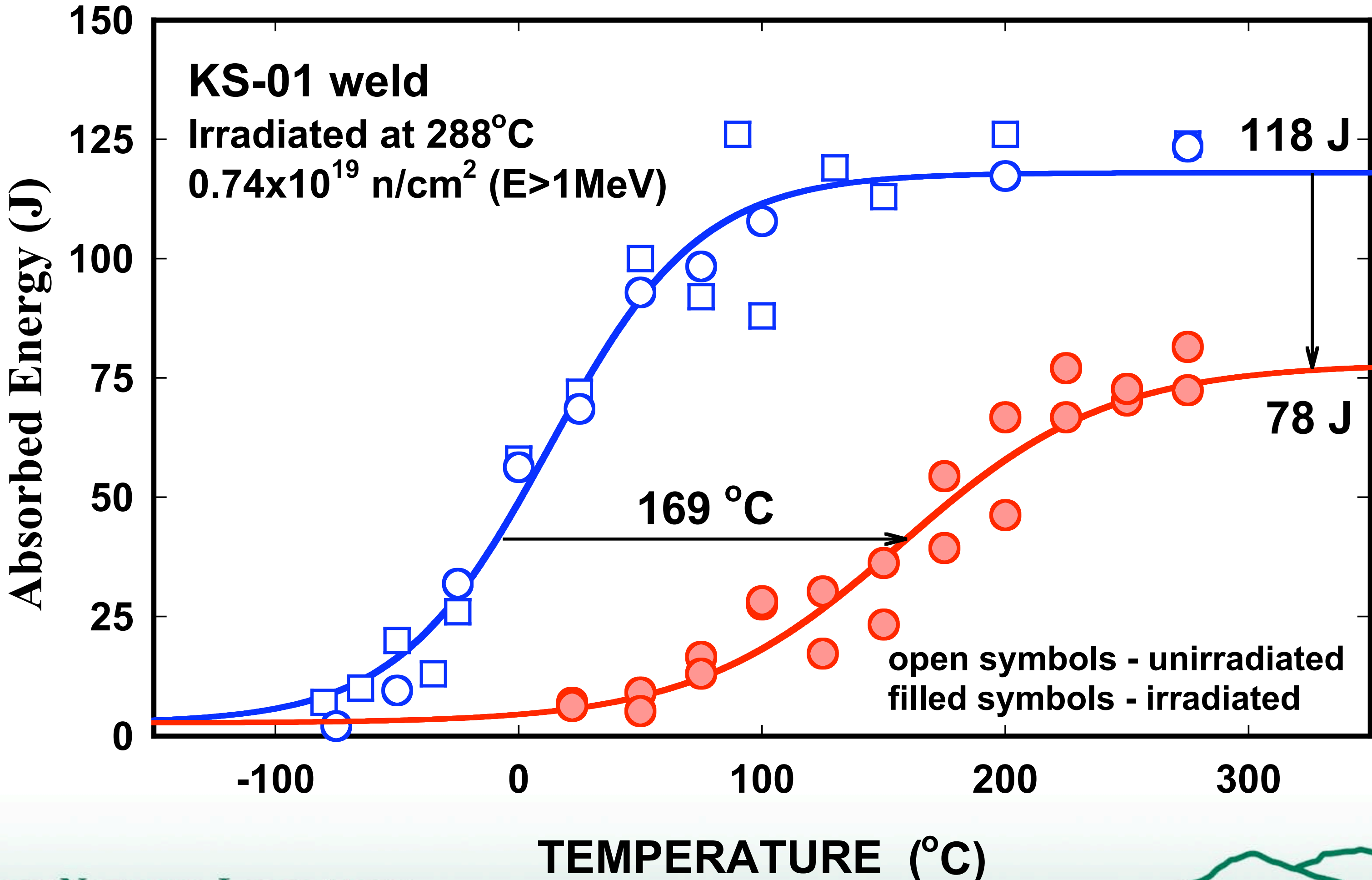


Irradiation of Austenitic Stainless Steel in Mixed Spectrum Reactors causes Pronounced Loss in Elongation and Significant Reduction in Fracture Toughness



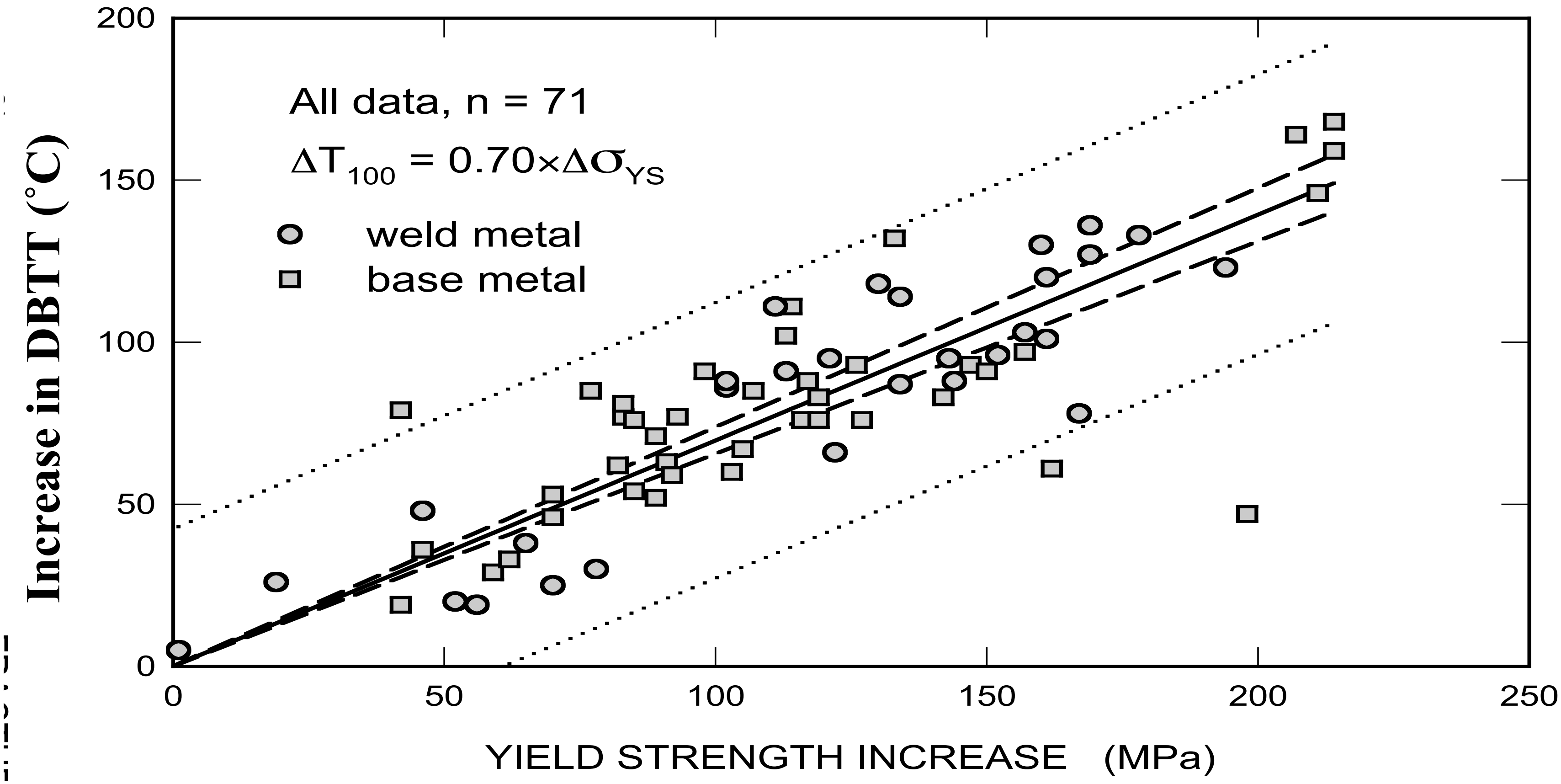
Irradiation of BCC Metals Results in Significant Decrease of Upper-Shelf Energy and Increase (Shift) of Ductile-to-Brittle Transition Temperature (DBTT)

Example for pressure vessel steel



There is a linear correlation between shift of transition temperature and hardening for BCC metals

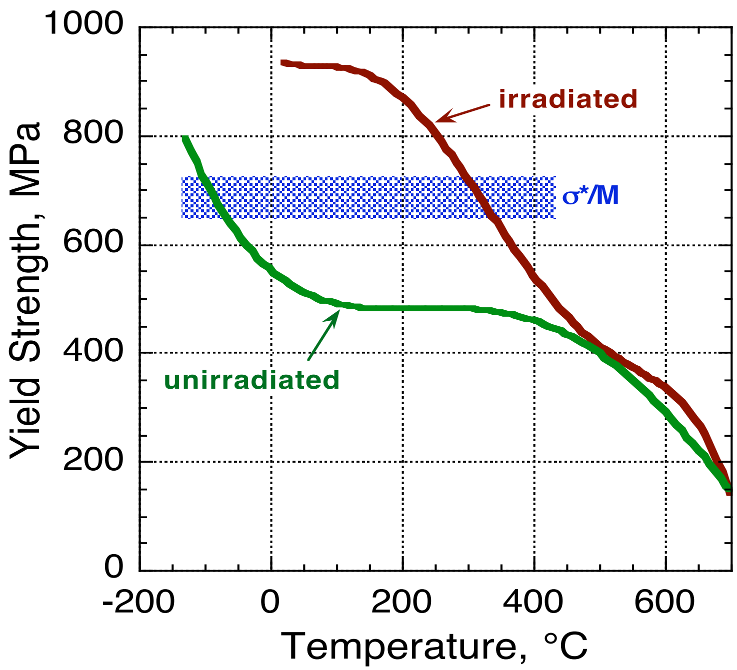
Example for reactor pressure vessel steel



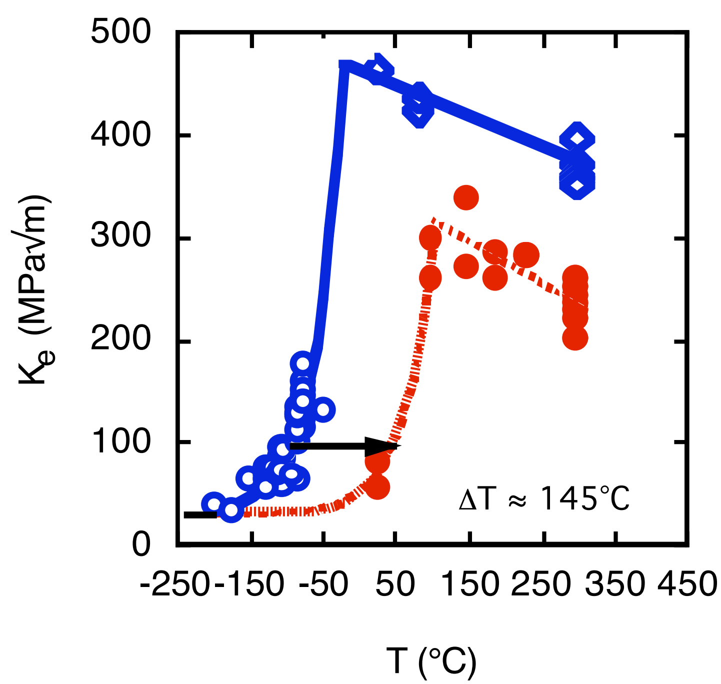
Fracture Toughness of BCC Metals: Master Curve Approach

• 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

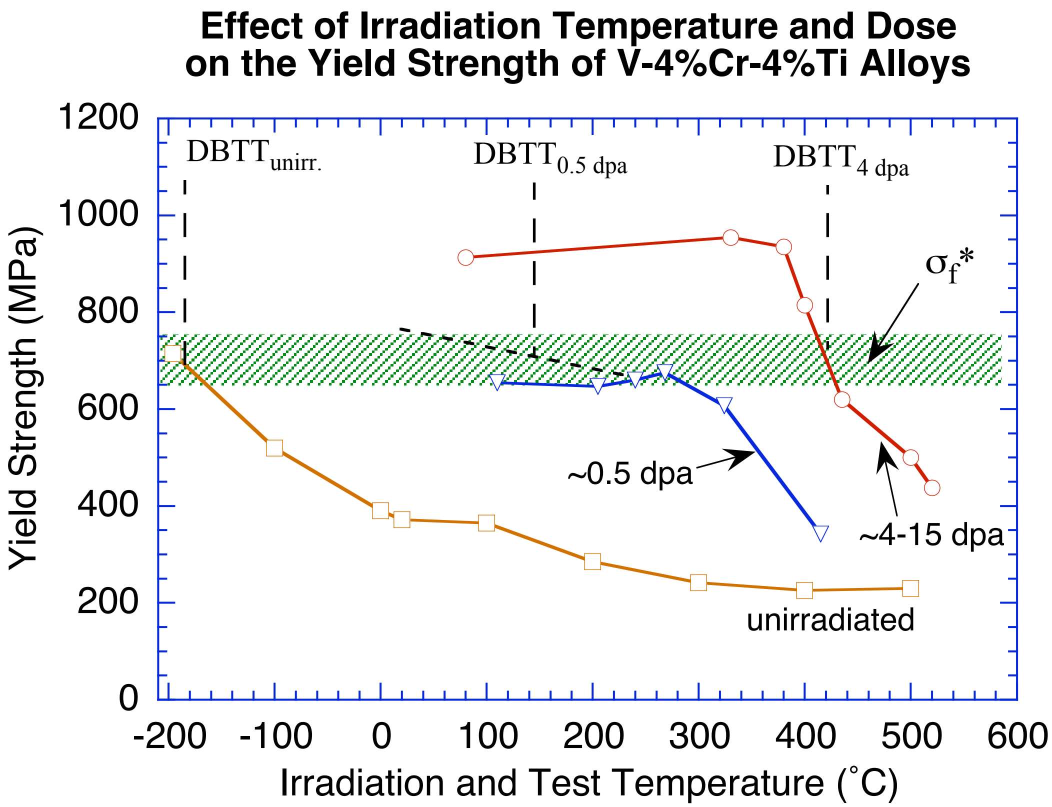


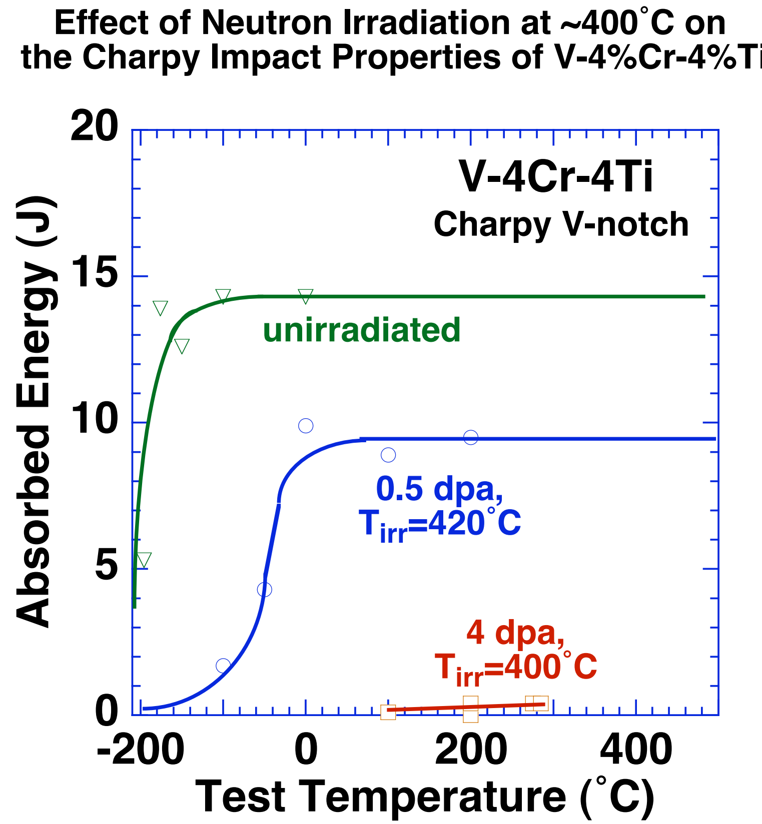
- Important parameters such as constraint and strain rate are included in recent advanced approaches (Master curve)



UCSB

Low temperature radiation hardening causes fracture toughness embrittlement in BCC metals





The Operating Window for BCC metals can be Divided into Four Regimes (red values are relevant for Nb1Zr)

I, II: Low Temperature Radiation Embrittlement Regimes

- Fracture toughness (K_J) embrittlement: high radiation hardening causes low resistance to crack propagation (occurs when S_U>500-700 MPa)
  - Regimes which cause K_J<30 MPa-m$^{1/2}$ should be avoided (T_{irr}< ~600 K ?)
- Loss of ductility: localized plastic deformation requires use of more conservative engineering design rules for primary+secondary stress (S_e)

$$S_e = \begin{cases} \frac{1}{3} S_u & \varepsilon_U<0.02 \\ \frac{1}{3}\left[S_u + \frac{E(\varepsilon_U - 0.02)}{8}\right] & \varepsilon_U>0.02 \end{cases}$$

(T_{irr}< ~900-1270 K)

where ε_U is uniform elongation, S_U is ultimate tensile strength, E is elastic modulus (additional design rules also need to be considered)

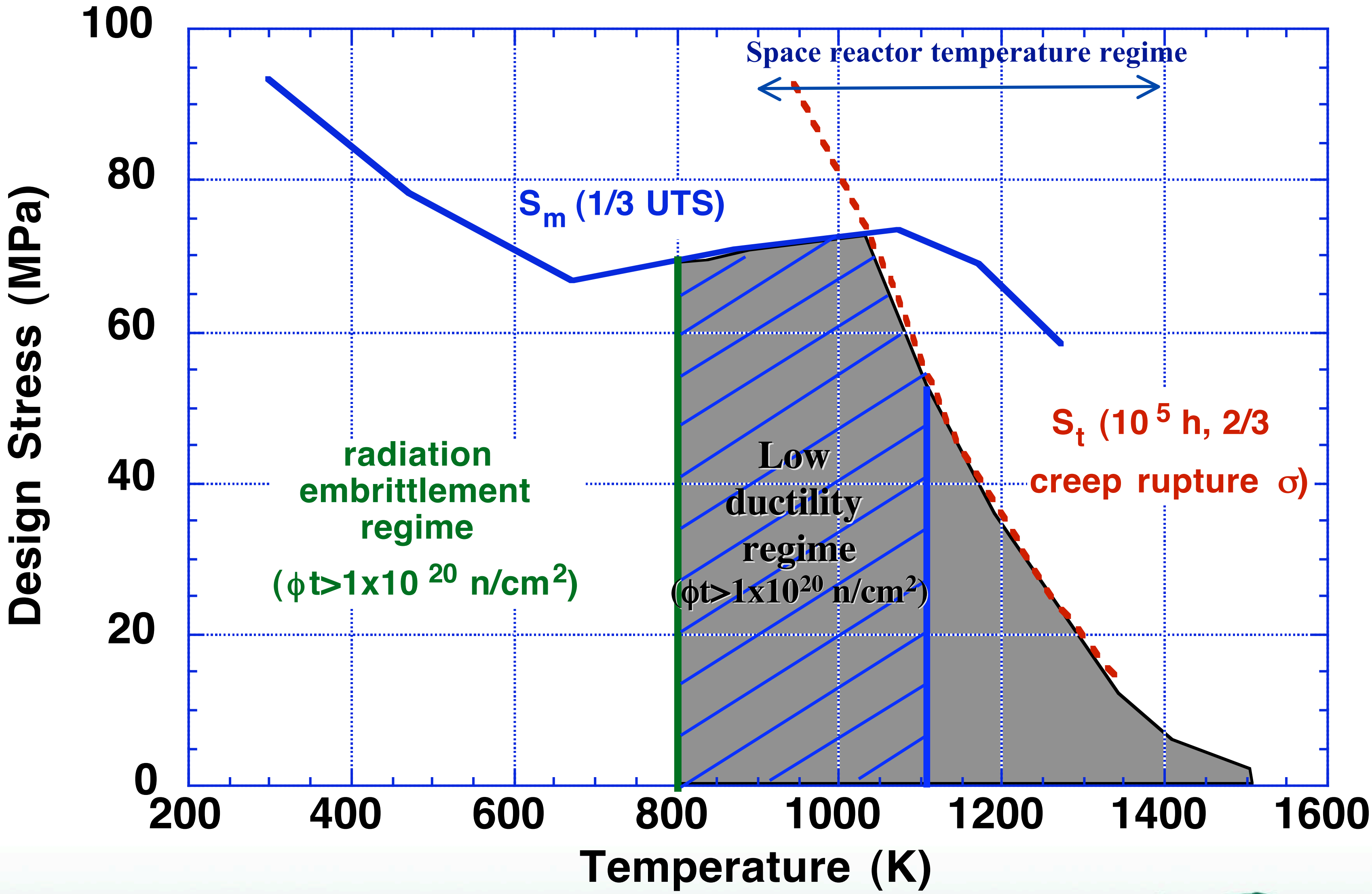
III: Ductile Yield and Ultimate Tensile Strength Regime (e_U>0.02)

- Sets allowable stress at intermediate temperature (very small regime for Nb-1Zr)

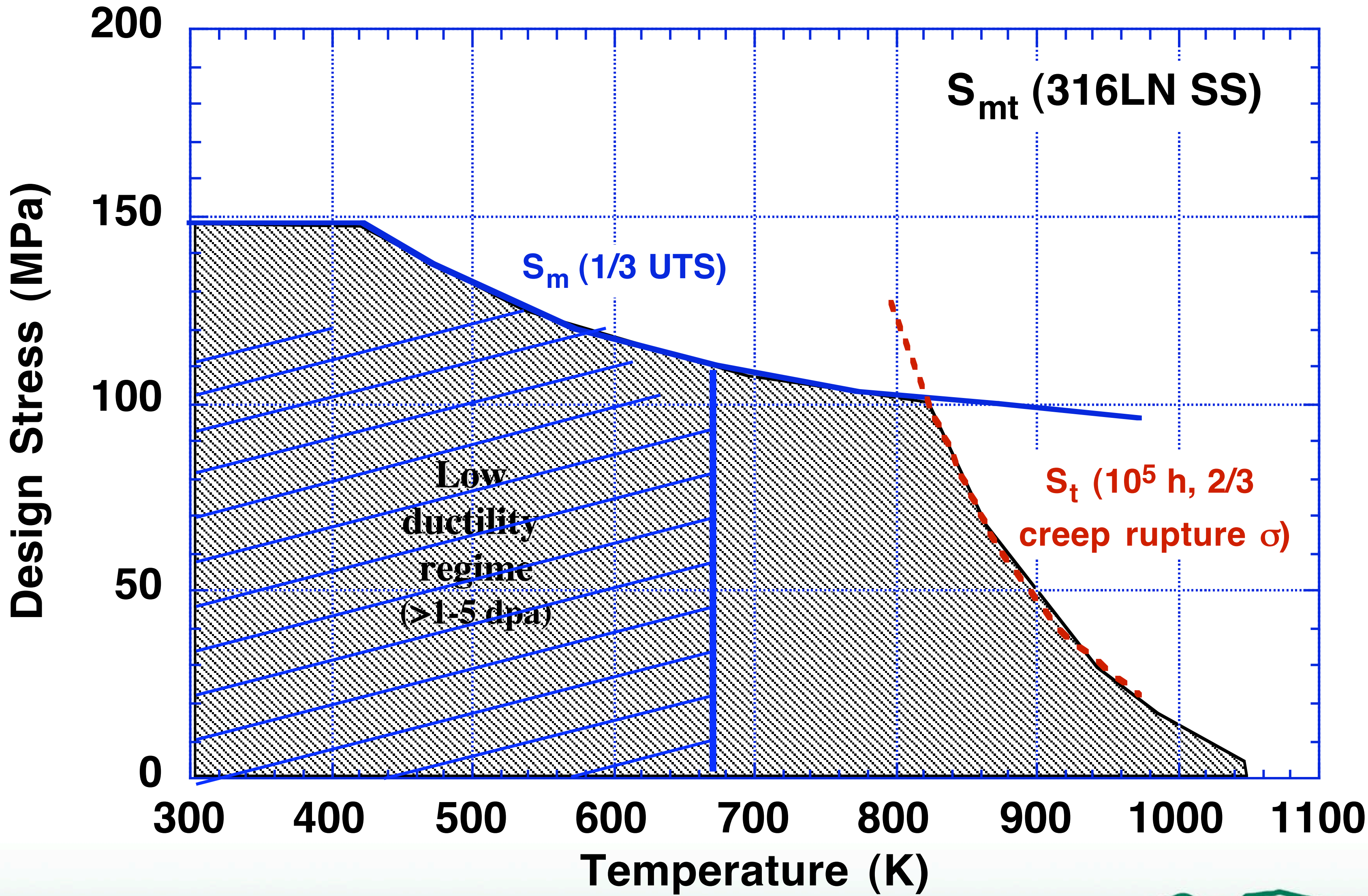
IV: High Temperature Thermal Creep Regime (T>~1050 K)

- Deformation limit depends on engineering application (common metrics are 1% deformation and complete rupture)

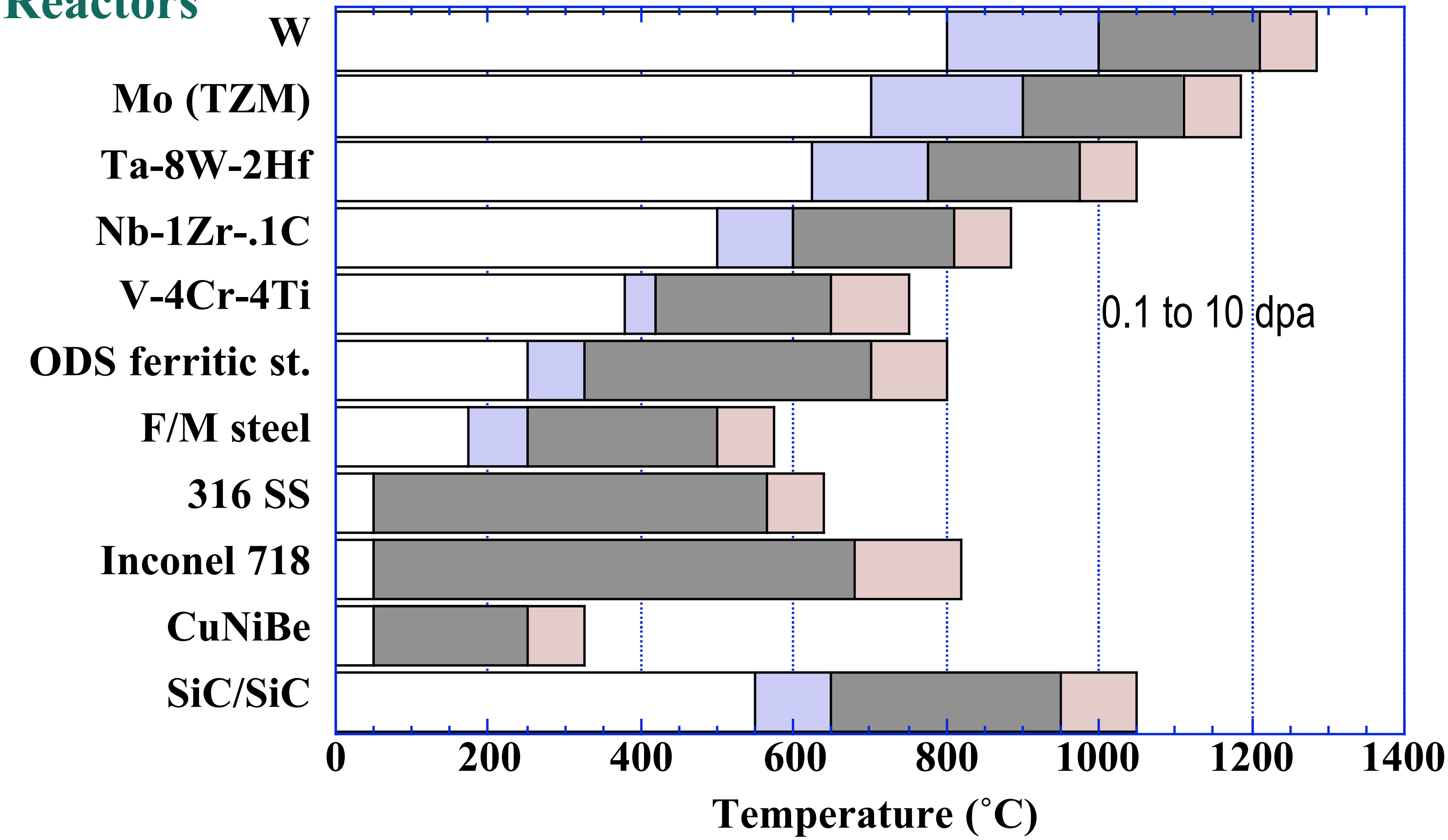
Stress-Temperature Design Window for Nb-1Zr



Stress-Temperature Design Window for Unirradiated Type 316 Stainless Steel



Operating Temperature Windows for Structural Alloys in Fusion Reactors

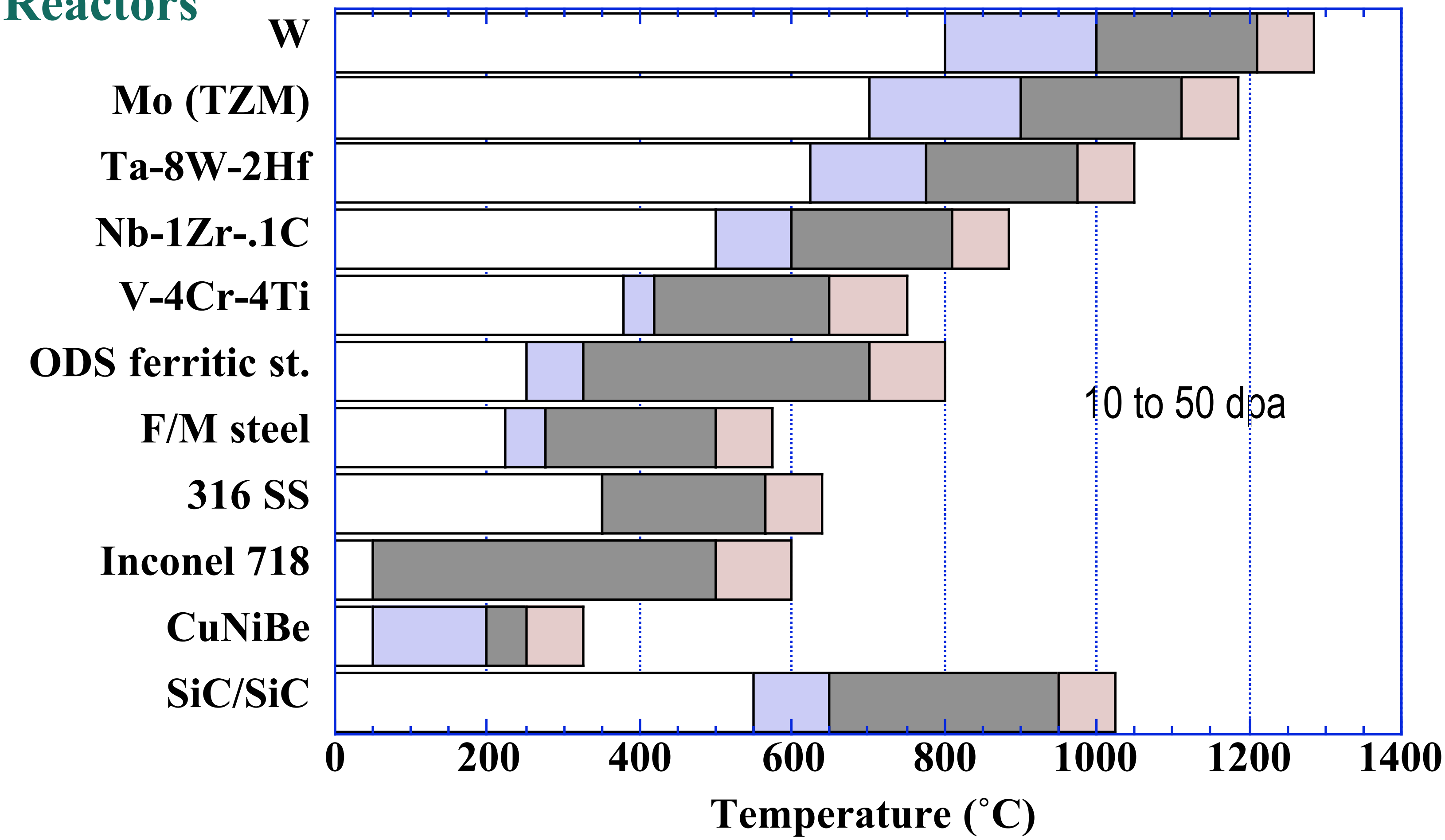


• Lower temperature limit of alloys based on radiation hardening/ fracture toughness embrittlement (K_{1C}< ~30 MPa-$m^{1/2}$)—large uncertainty for W,Mo due to lack of data

• Upper temperature limit based on 150 MPa creep strength (1% in 1000 h); chemical compatibility considerations may cause further decreases in the max operating temp.

S.J. Zinkle and N.M. Ghoniem, Fus. Eng. Des. 51-52 (2000) 55; S.J. Zinkle et al. STAIF2002

Operating Temperature Windows for Structural Alloys in Fusion Reactors



- Lower temperature limit of alloys based on radiation hardening/ fracture toughness embrittlement ($K_{1C} < \sim 30$ MPa-m$^{1/2}$)—large uncertainty for W,Mo due to lack of data
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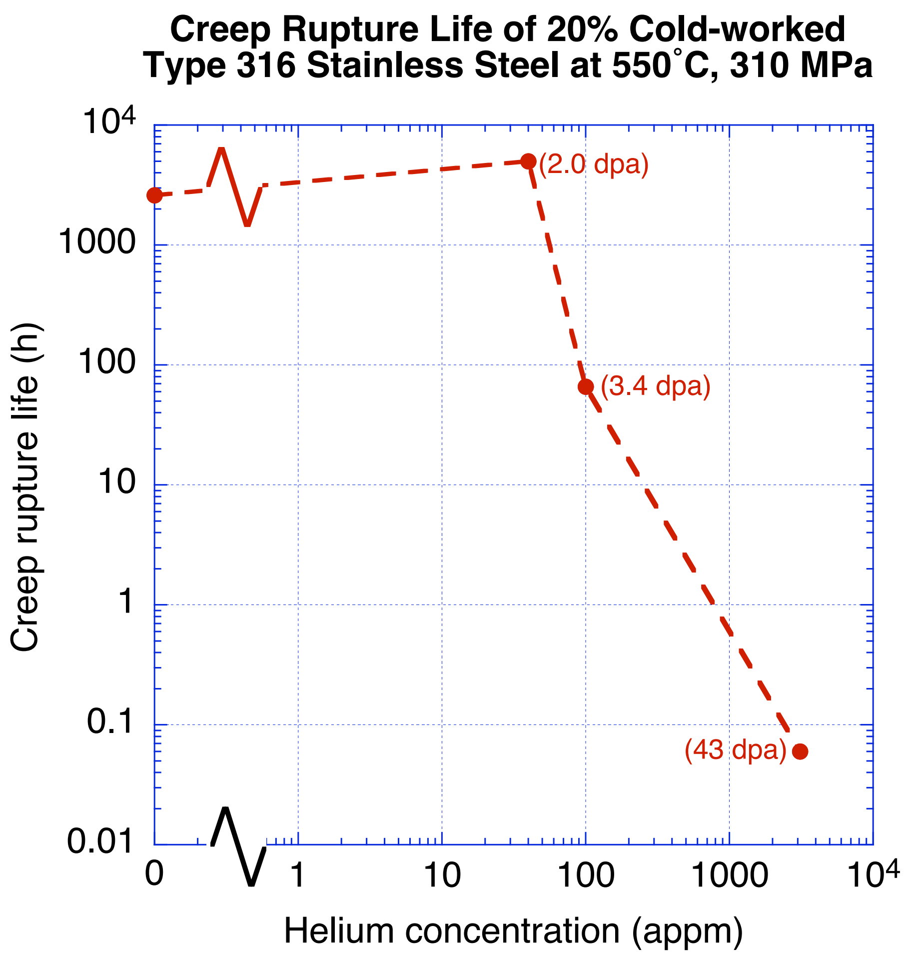
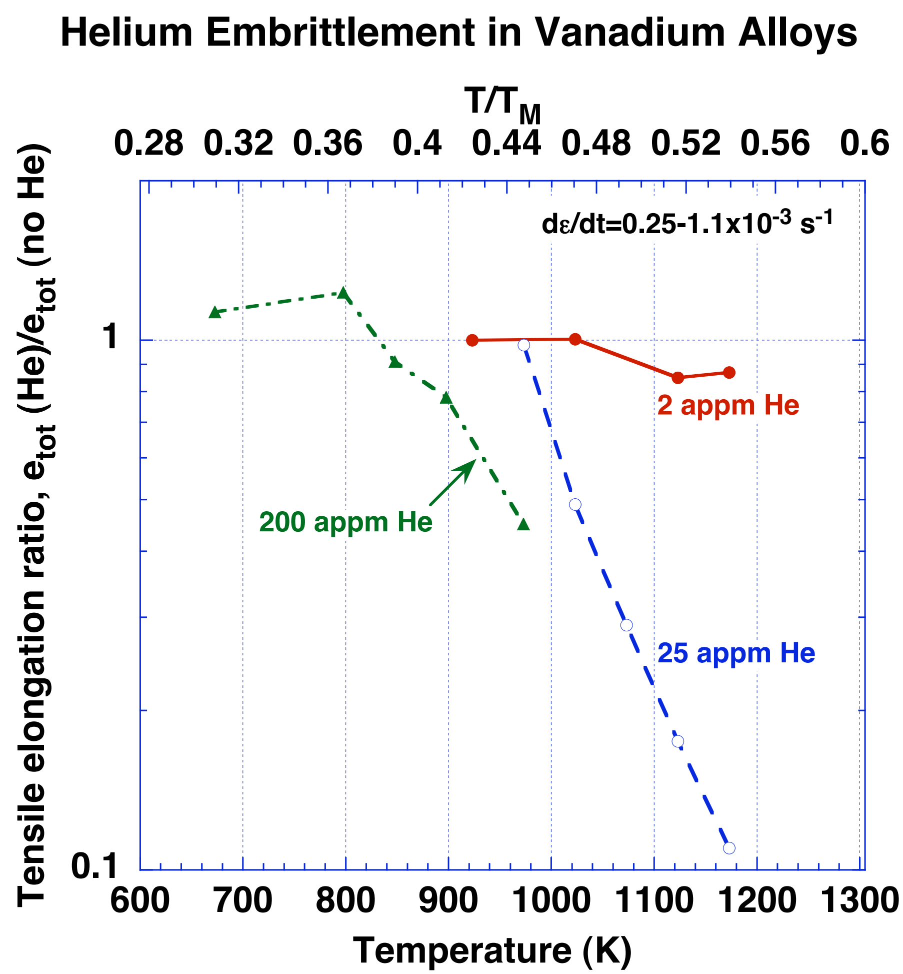
S.J. Zinkle and N.M. Ghoniem, Fus. Eng. Des. 51-52 (2000) 55; S.J. Zinkle et al. STAIF2002

Helium Embrittlement of Grain Boundaries is of concern at High Temperatures

The Degradation of Creep-Rupture Properties and Ductility Can Be Catastrophic

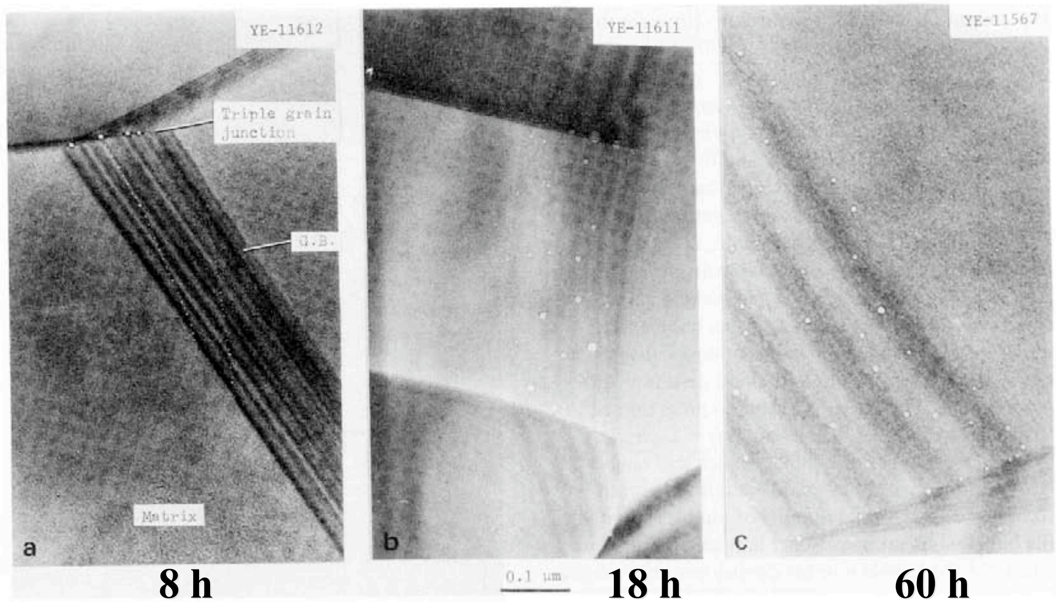




He trapping at nanoscale precipitates within grains is key for inhibiting He embrittlement

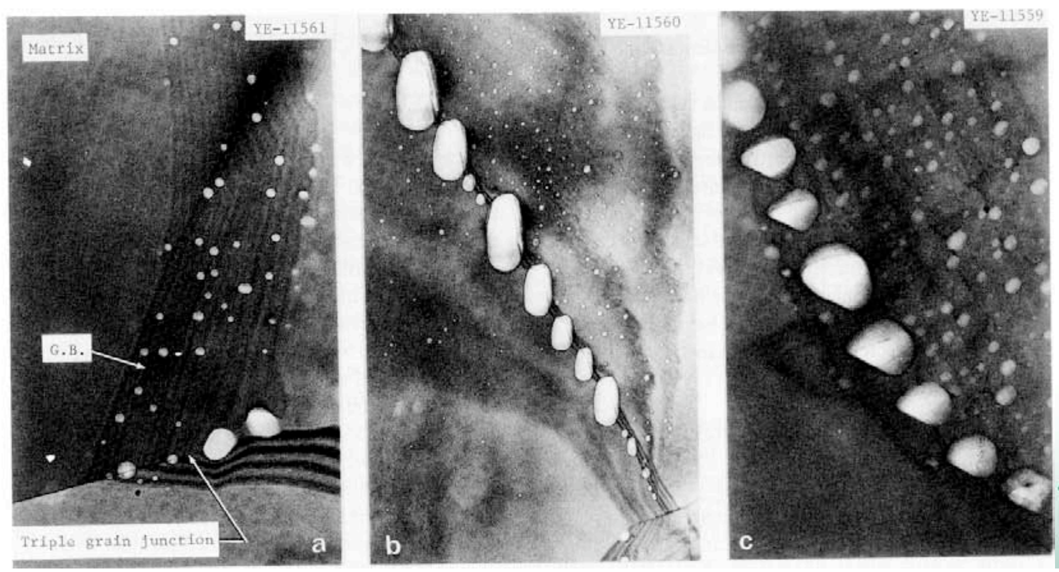
However…….. The formation and microstructural stability of these precipitates is strongly affected by irradiation parameters, in particular the He/dpa ratio

He grain boundary cavities in austenitic stainless steel: effect of annealing time and applied stress at 750˚C



0 MPa

Fig. 2. Growth of helium bubbles in unstressed Fe–17 Cr–17 Ni specimens after annealing at 1023 K for (s) 2.88×10^4 s, (b) 6.48×10^4 s and (c) 21.60×10^4 s.

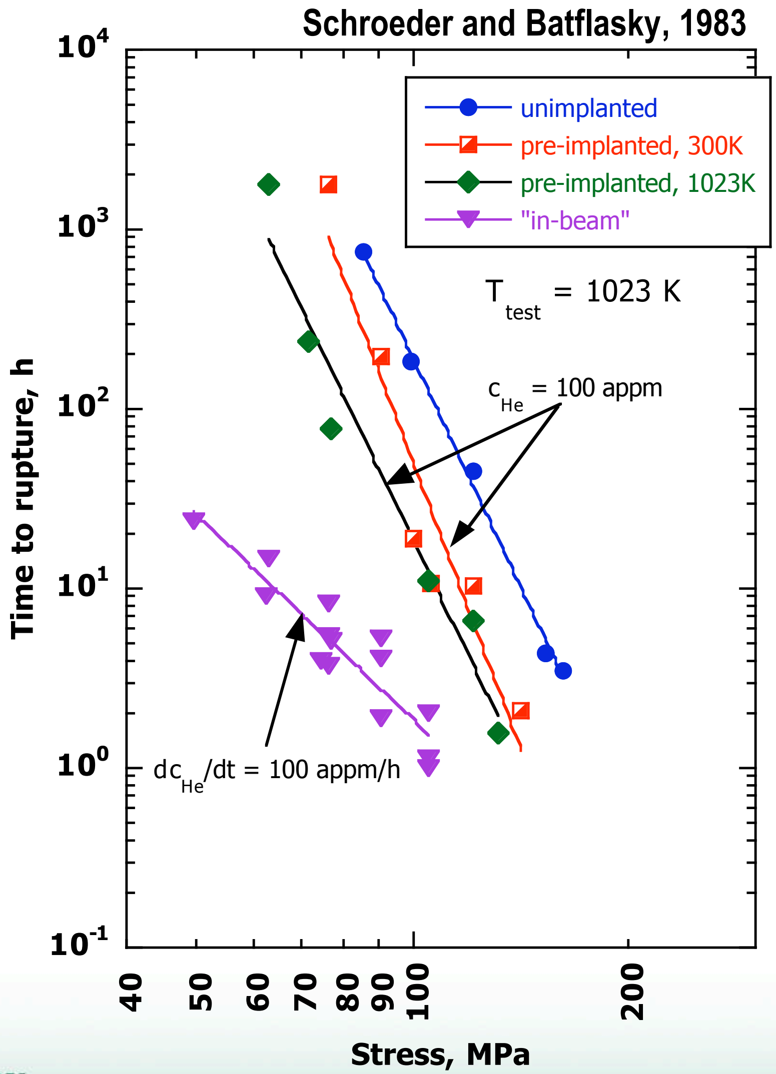


19.6 MPa

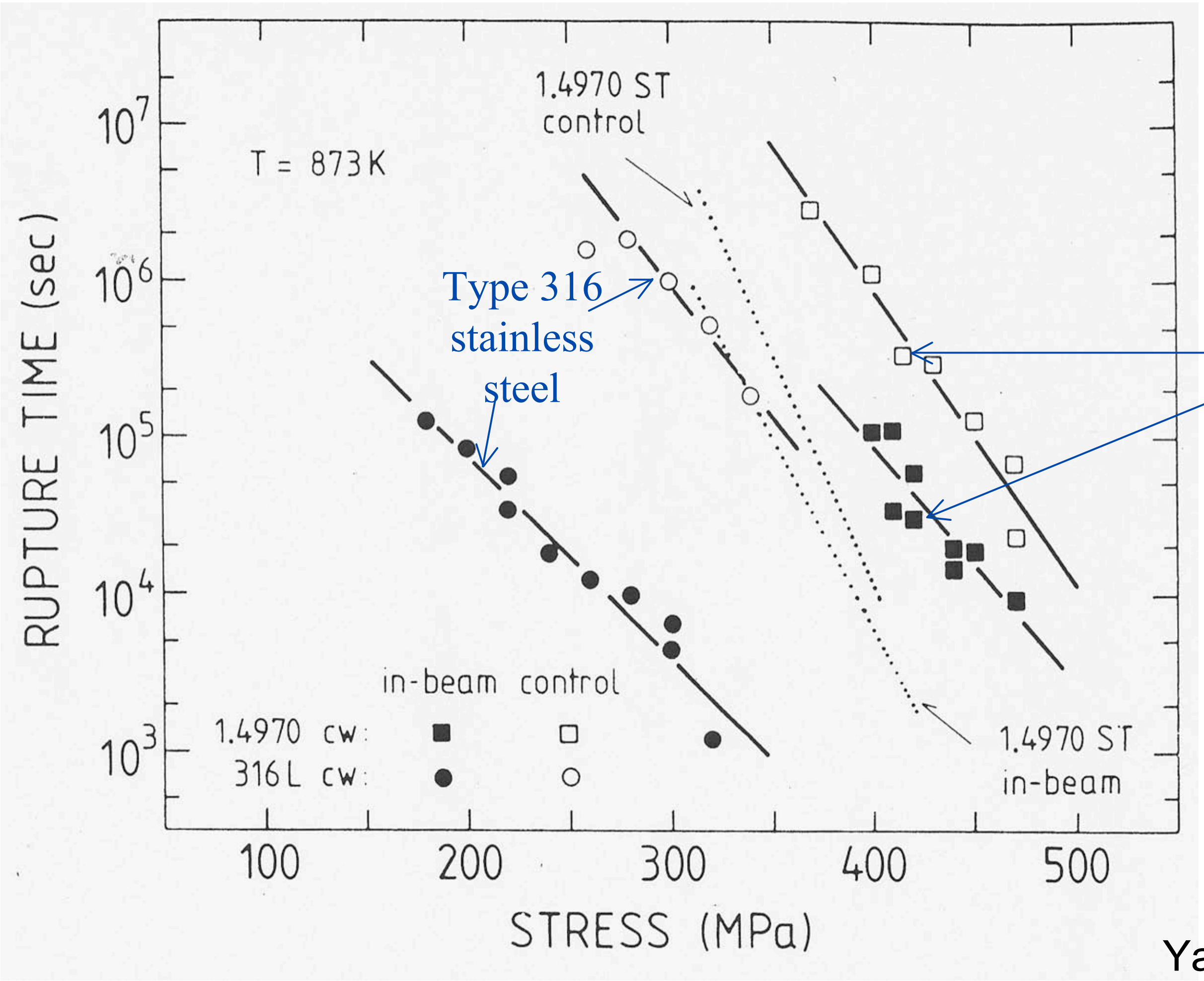
D.N. Braski

Effect of applied stress on the rupture lifetime of austenitic stainless steel annealed at 750˚C

- 100 appm He reduces rupture lifetime of stainless steel at 750˚C by 10-100X due to formation of grain boundary He cavities



Fine-scale matrix precipitates can trap He and provide greatly improved He embrittlement resistance



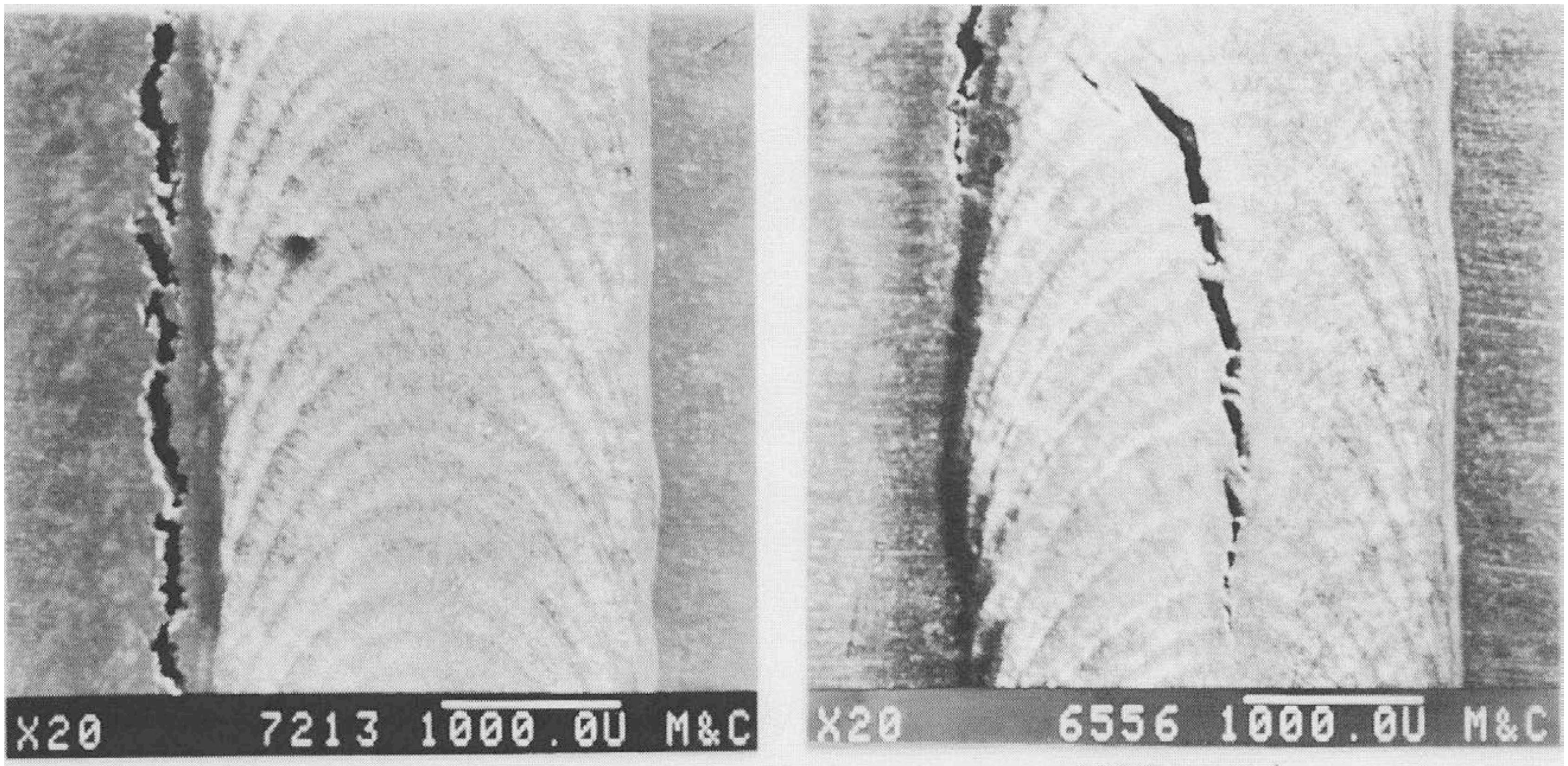
Improved stainless steel containing fine-scale precipitates

Yamamoto & Schroeder J.Nucl. Mat. 155-157 (1988)

Cracking is observed in welded metals containing He (from nuclear transmutations)

Occurs in heat affected zone for low He concentrations

At high He concentrations, cracking also occurs in the fusion zone (weld bead)

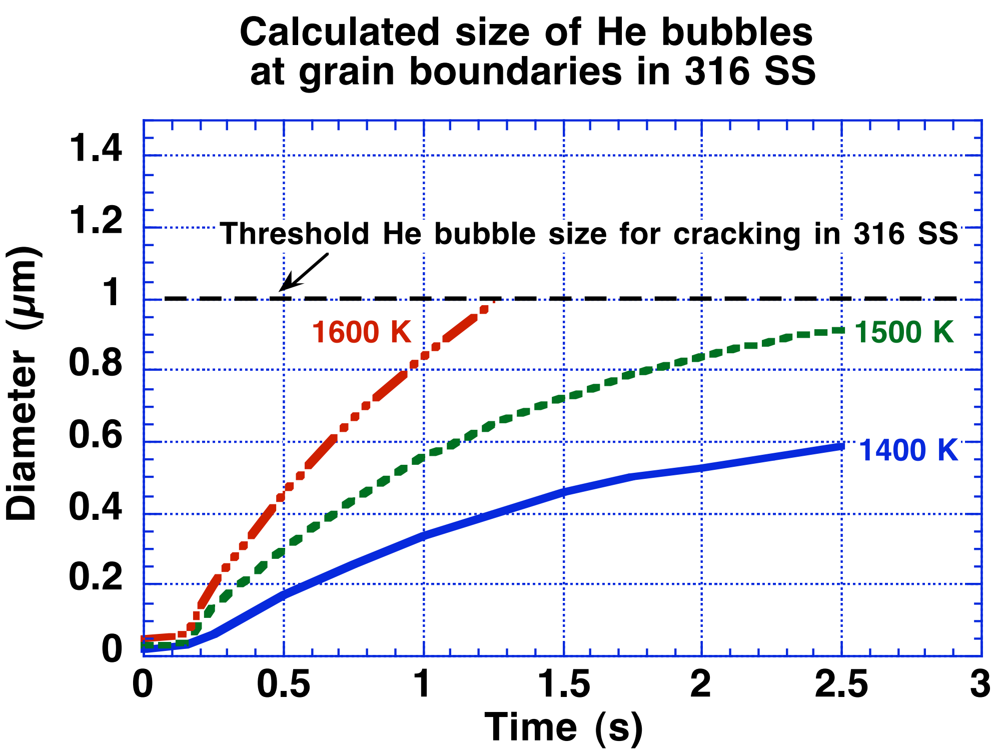


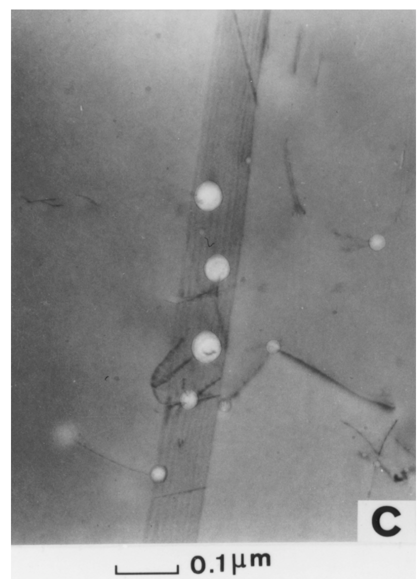
(2.5 appm) (105 appm)

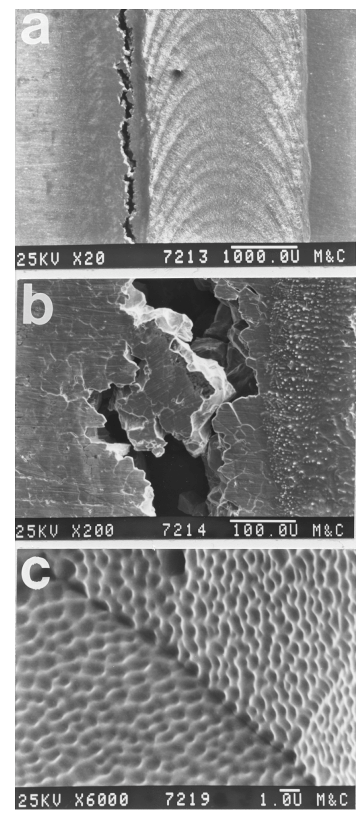
Heat affected zone (HAZ) — Weld bead — HAZ

Effect of transmutant He on welding behavior of metals

- Irradiated materials with He contents above ~1 appm cannot be fusion-welded due to cracking associated with He bubble growth; the lower temperatures associated with FSW may allow repair joining of irradiated materials







Summary and Conclusions

- **Low temperature (<0.3 T_M) irradiation causes rapid hardening and reduction in uniform elongation of metals**
  - **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**
- **Irradiation creep is typically of concern for structural materials irradiated to doses above ~10 dpa at intermediate temperatures**
- **High temperature He embrittlement of grain boundaries generally becomes important for transmutant He levels above 10-100 appm at temperatures above 0.5 T_M**
  - **Mechanism based on critical number of gas atoms for unconstrained cavity growth**