Flow Localization and Channeling in Irradiated Alloys

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Fusion Materials Sciences Program Strategic Planning Meeting

August 26-30, 2002

Univ. California-Santa Barbara

Introduction

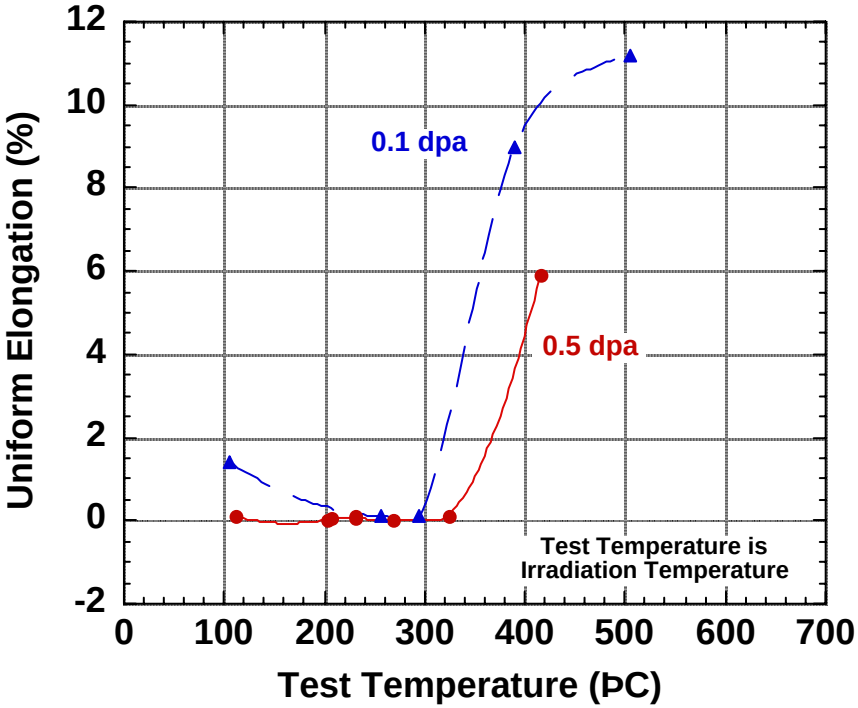
- Overview of flow localization in irradiated & unirradiated metals: main features of engineering stress-strain curve; yield drop, Luders band, work hardening exponent, etc.
  - Practical impact/consequences: e.g., ITER structural design criteria rules for uniform elongations <2%
  - Theoretical challenge: deformation mechanisms in materials

- **Outstanding questions:**
- **What governs the appearance of a yield point?**
- **What governs the dose dependence of yield point onset?**
- **What governs dislocation channel initiation?**
- **What governs dislocation channel growth? (cross-slip in fcc metals is not well understood)**
- **What controls channel width?**

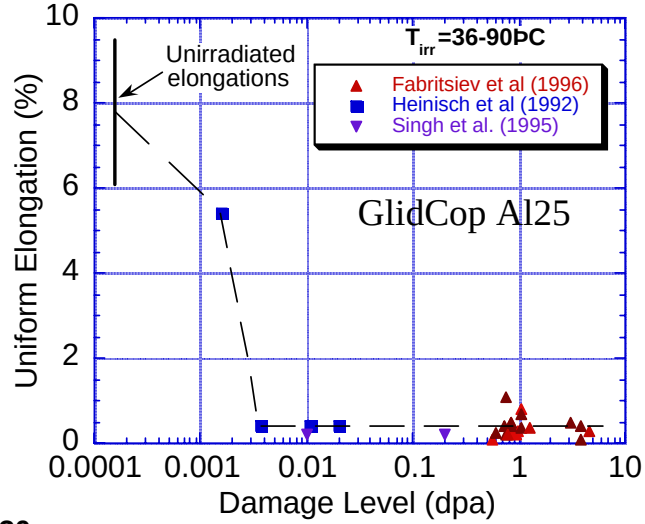
- summary of observations on conditions for channeling (base alloys and their microstructures, irradiation microstructures, test details), observational methods, the characteristics of localized deformation (channel/band characteristics, distributions, dislocation structures and their distributions, strain distributions, triggering features), underlying mechanisms and models - experiments and models needed to address the issue for candidate fusion alloys

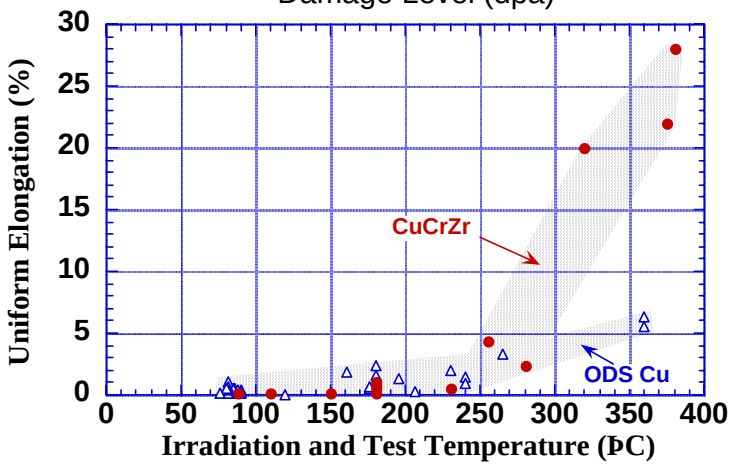
Low uniform elongations occur in many BCC and FCC metals after low-dose irradiation at low temperature

Uniform elongation of neutron-irradiated V-4Cr-4Ti

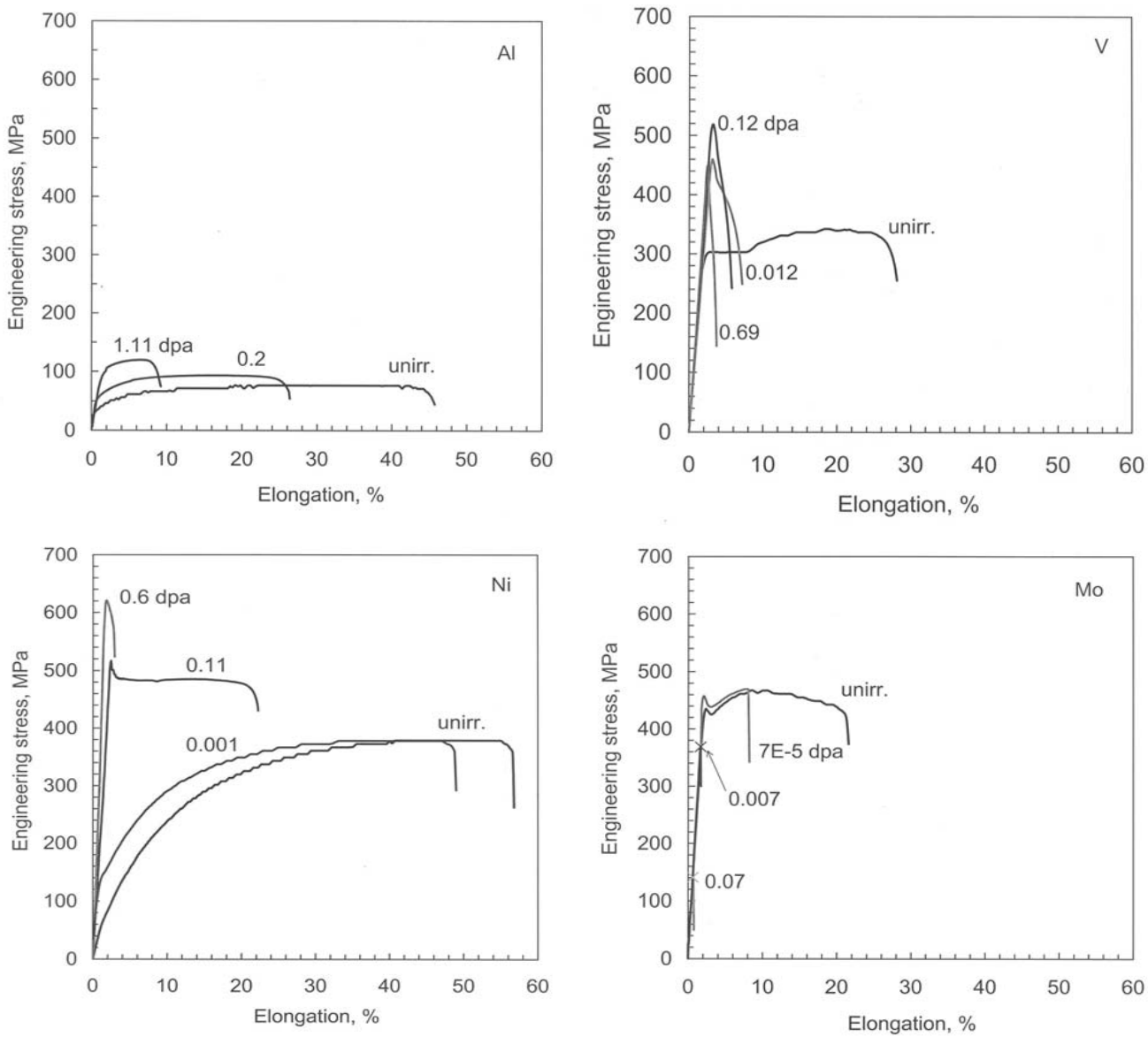


Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr

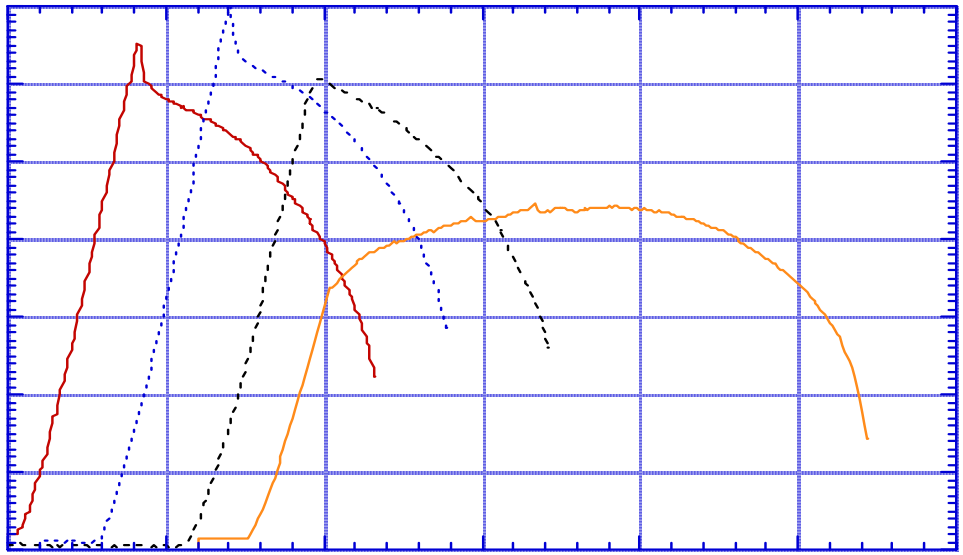


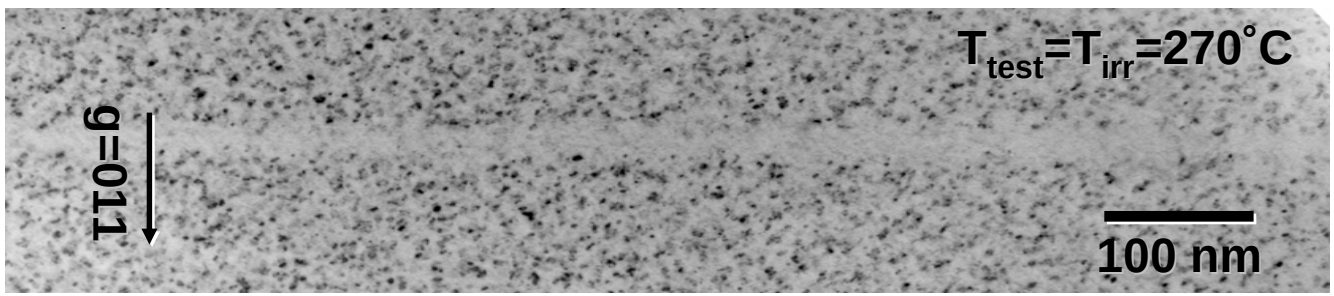


Examples of tensile curves

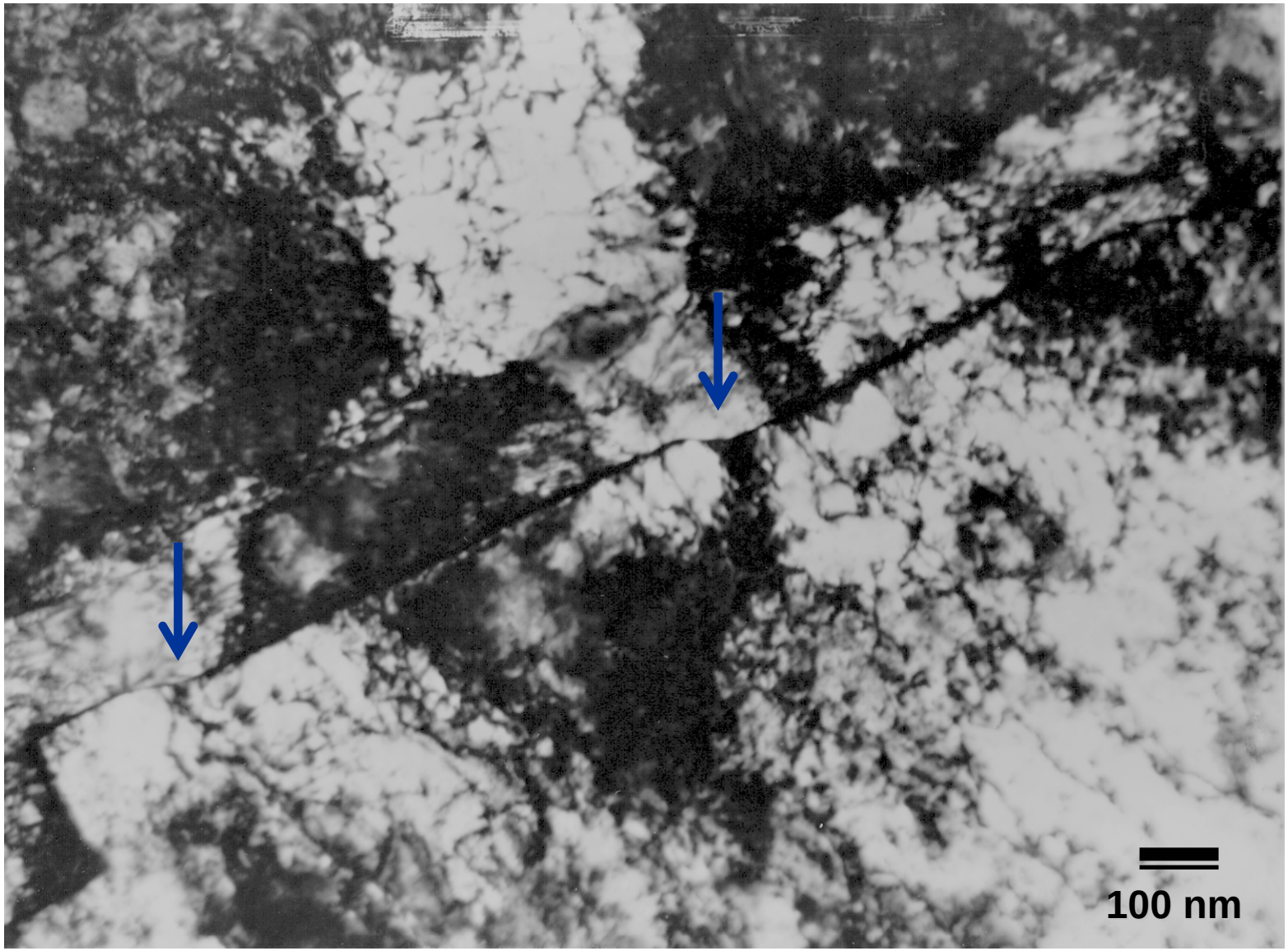


Irradiated Materials Suffer Plastic Instability due to Dislocation Channeling



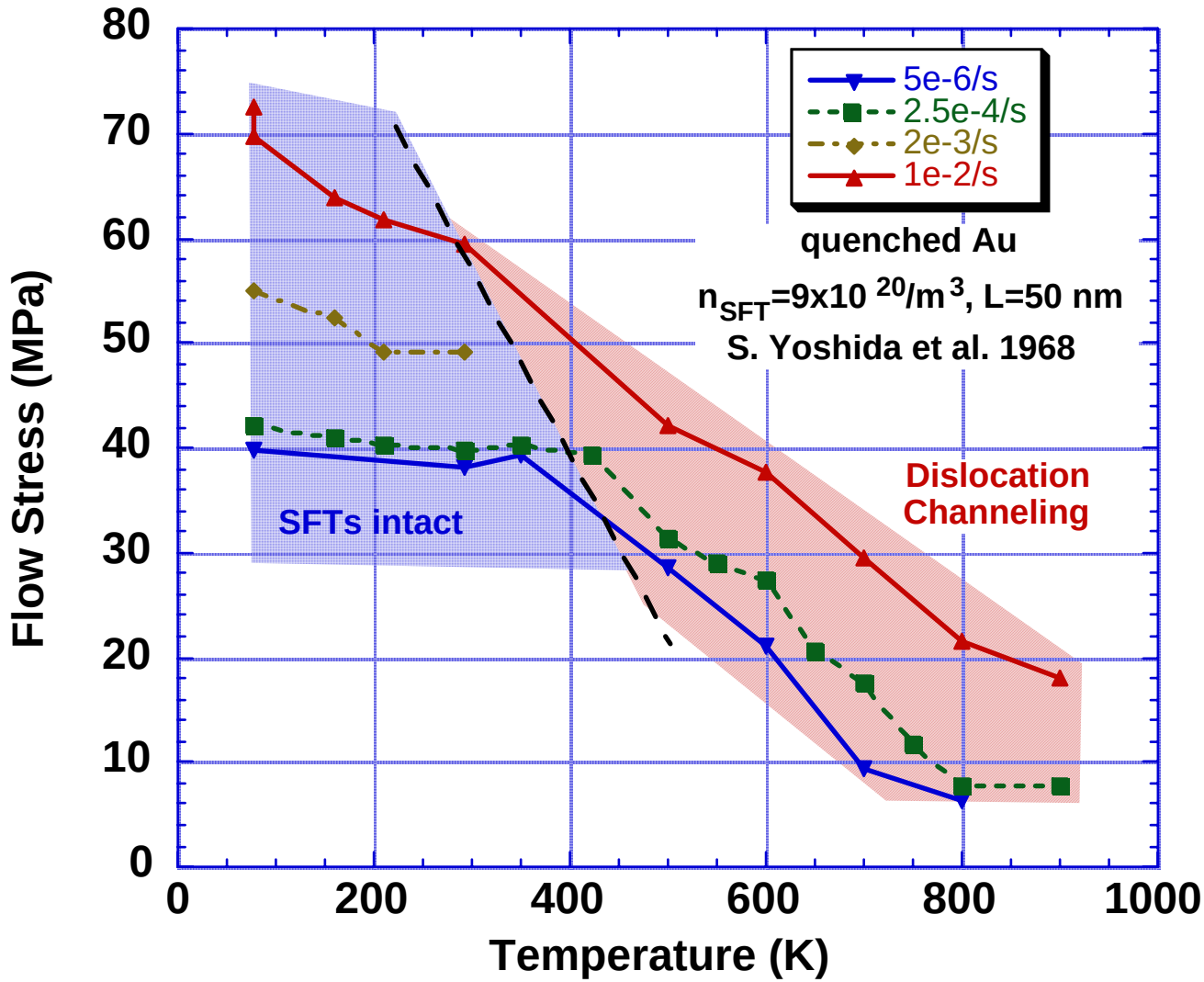


Dislocation channel steps observed along twin boundary



Tensile Properties and Deformation Mode in Quenched Au

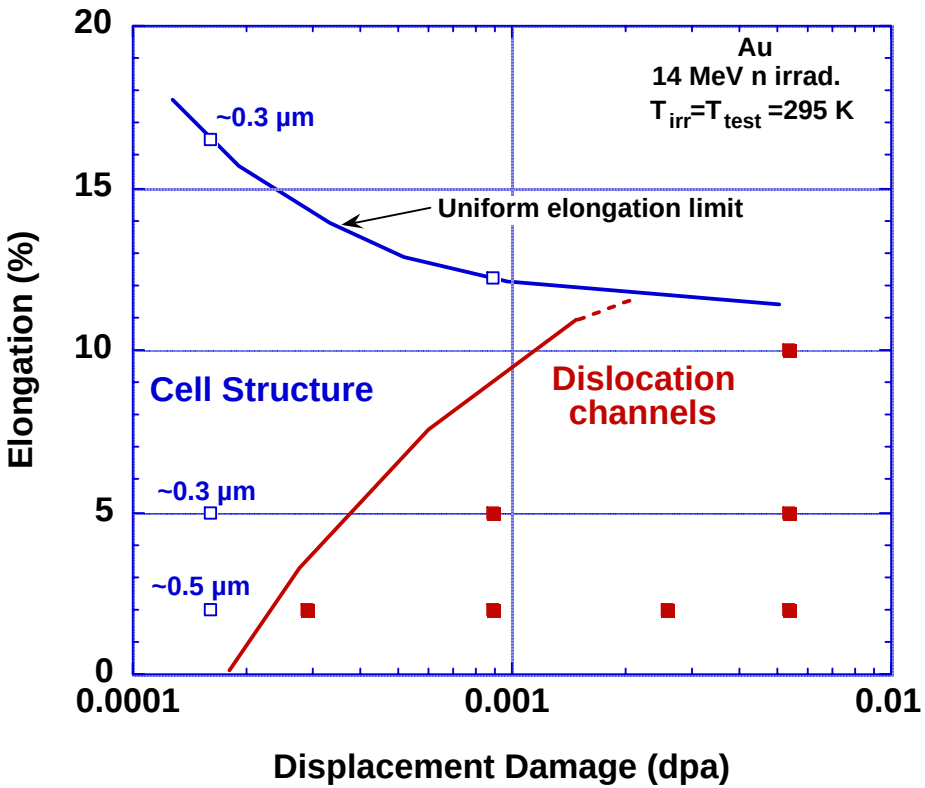
S. Yoshida et al., Trans. JIM 9 suppl. (1968) 83



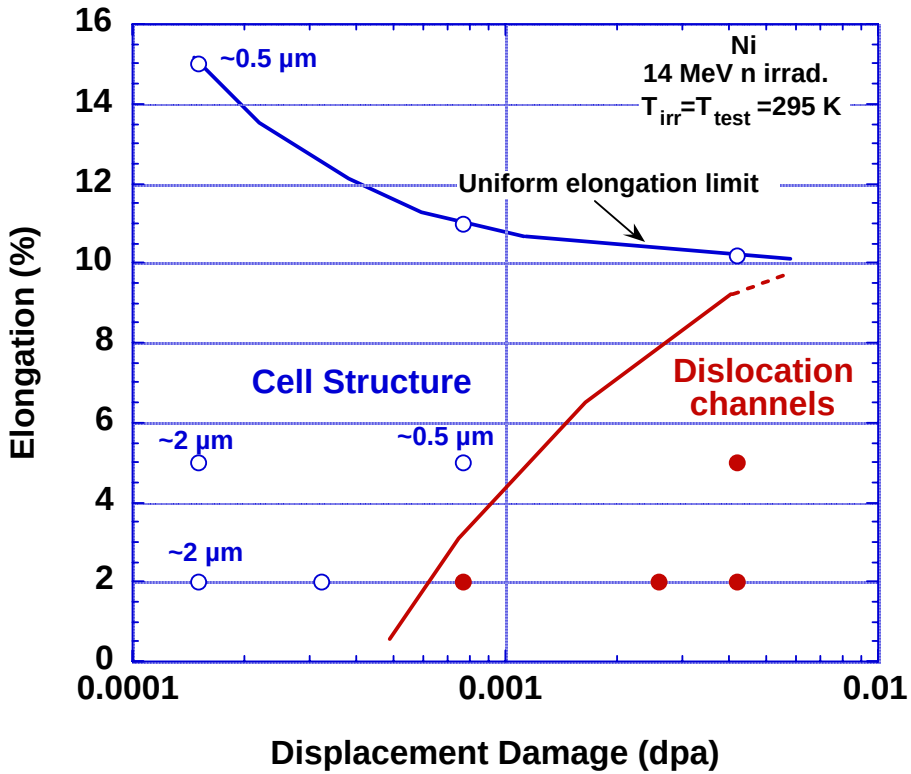
Effect of Irradiation Dose and Strain on Deformation Modes of FCC Metals

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

Deformation Mode Diagram for Neutron-irradiated Au

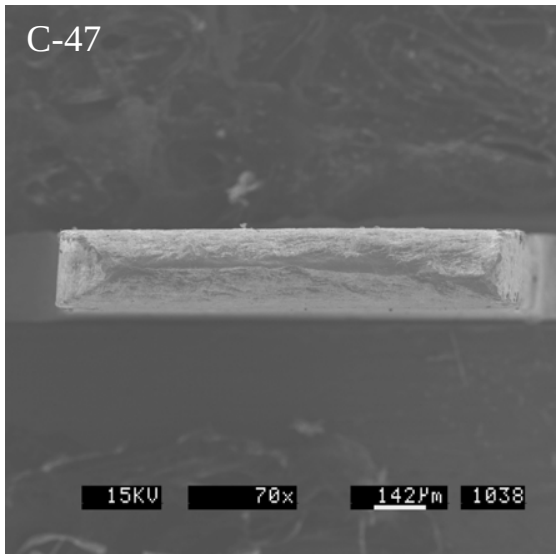


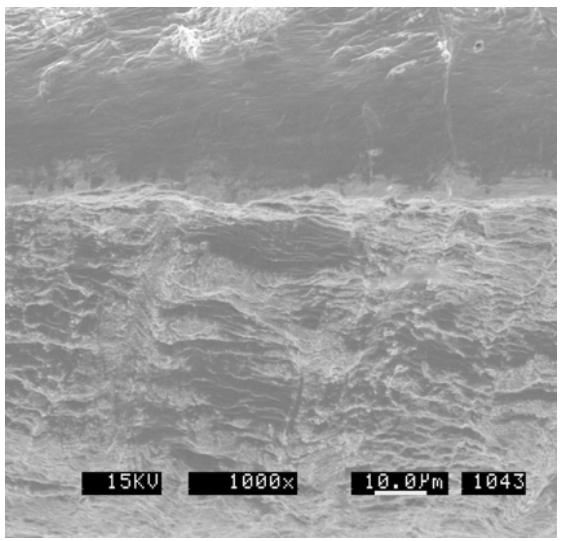
Deformation Mode Diagram for Neutron-irradiated Ni

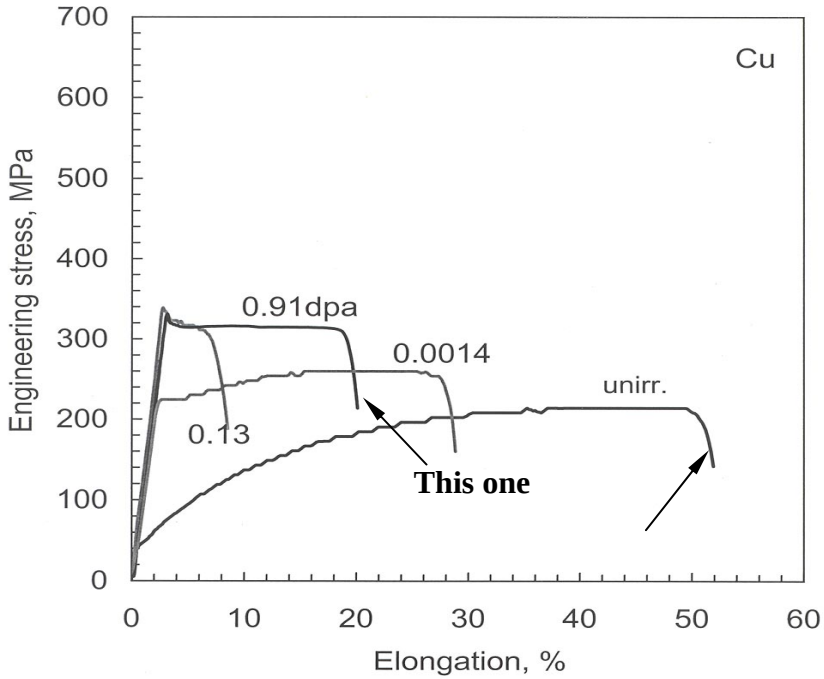


Irradiation does not affect strain in the neck

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

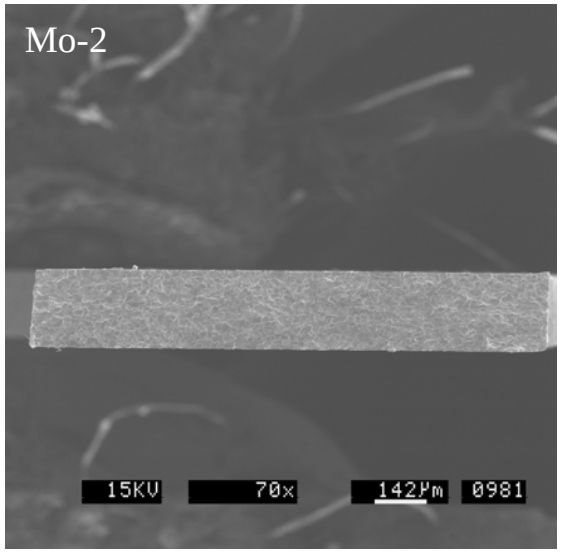


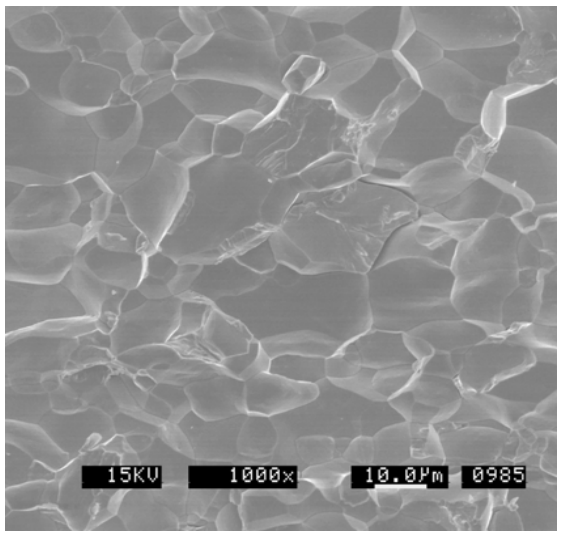


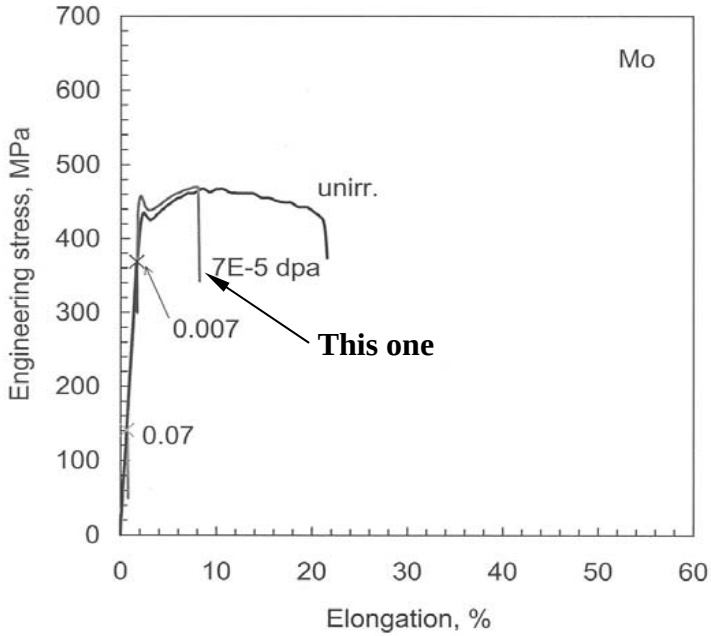


In all materials except Mo the reduction in area at fracture was the same in irradiated and unirradiated specimens despite considerable differences in uniform elongation. The implication is that much work hardening lost in uniaxial mode is restored when multiaxial loading prevails.

Brittle intergranular failure with little or no necking occurred in Mo at low dose



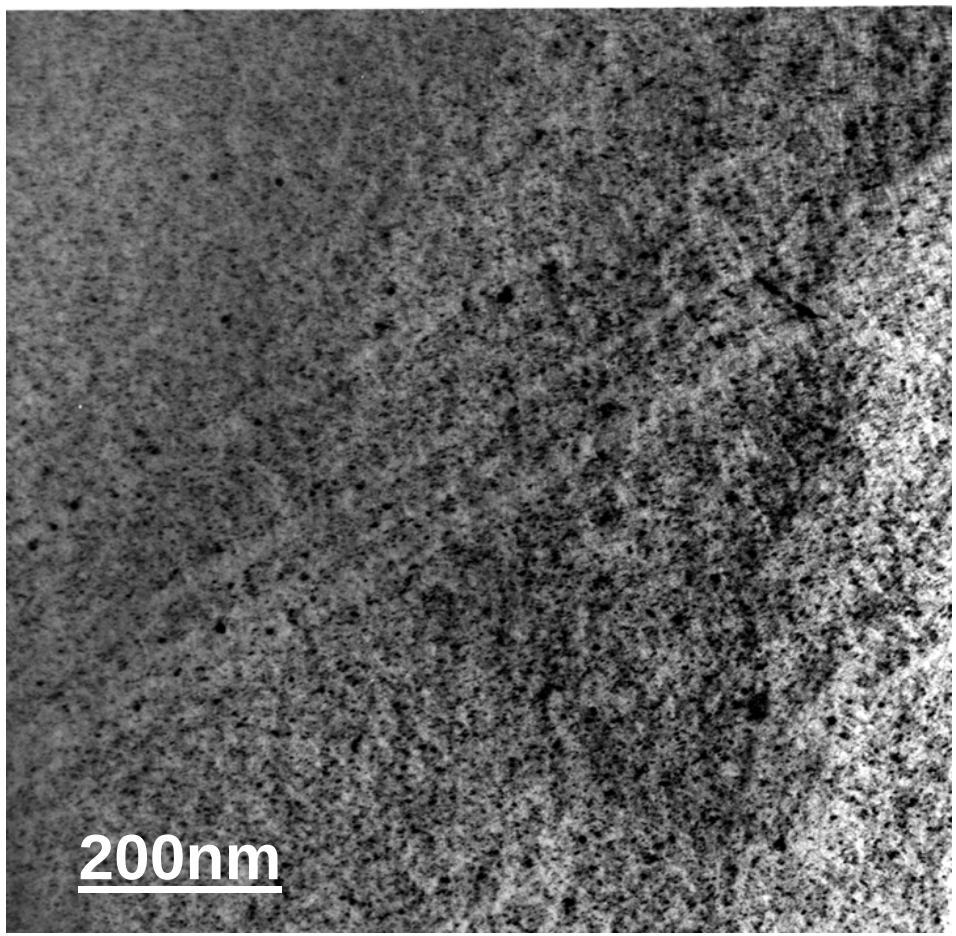




Mo was produced by a powder metallurgy route. The example was irradiated to the lowest dose. It showed 6% R in A versus about 16% for the unirradiated case. The more highly irradiated specimens broke in the elastic region with no R in A.

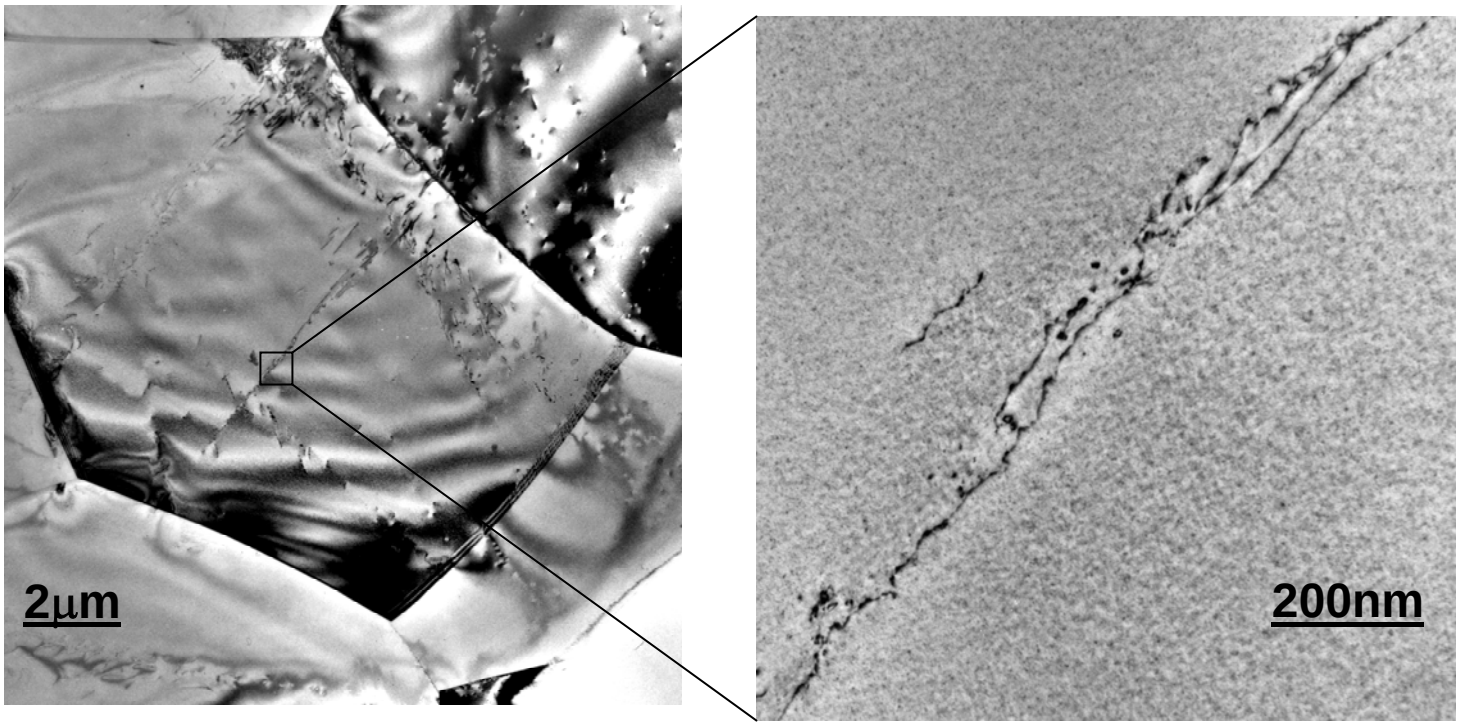
Molybdenum. Narrow channels are present in brittle specimens that broke before the yield strength was reached. Suggests that stress and strain intensification in the channels is sufficient to initiate brittle fracture.

0.007 dpa, ε_u = 0.01%

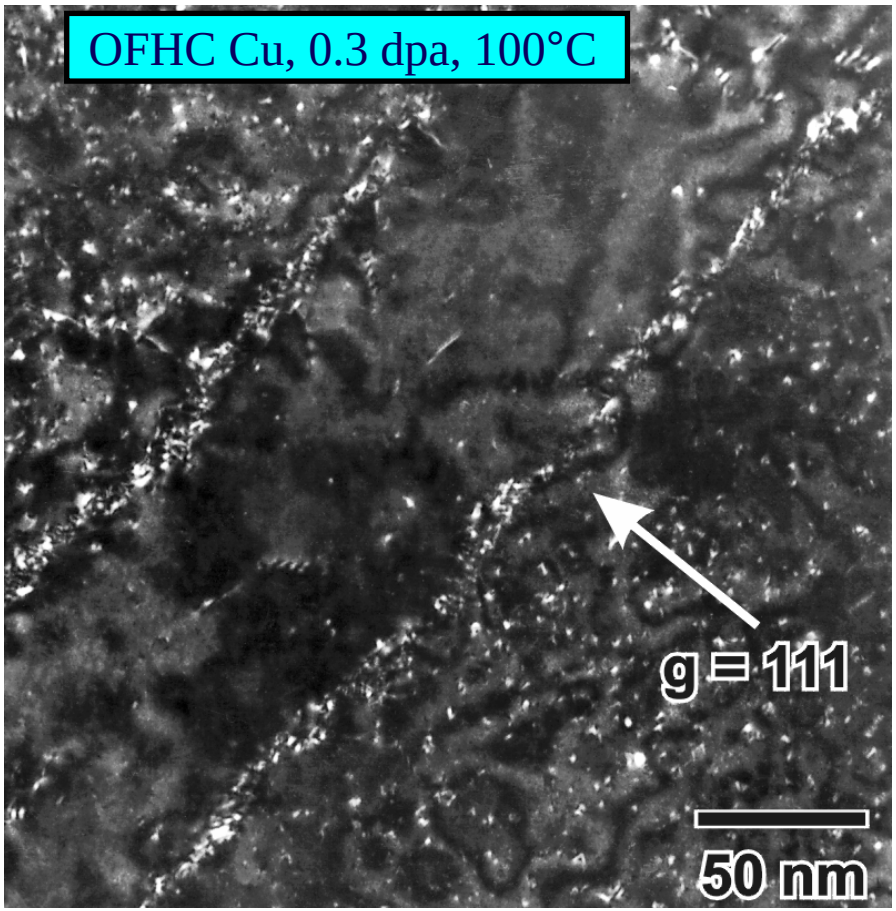


Channels in V (0.01 dpa) are not fully cleared; they contain elongated dislocations and loop-like debris

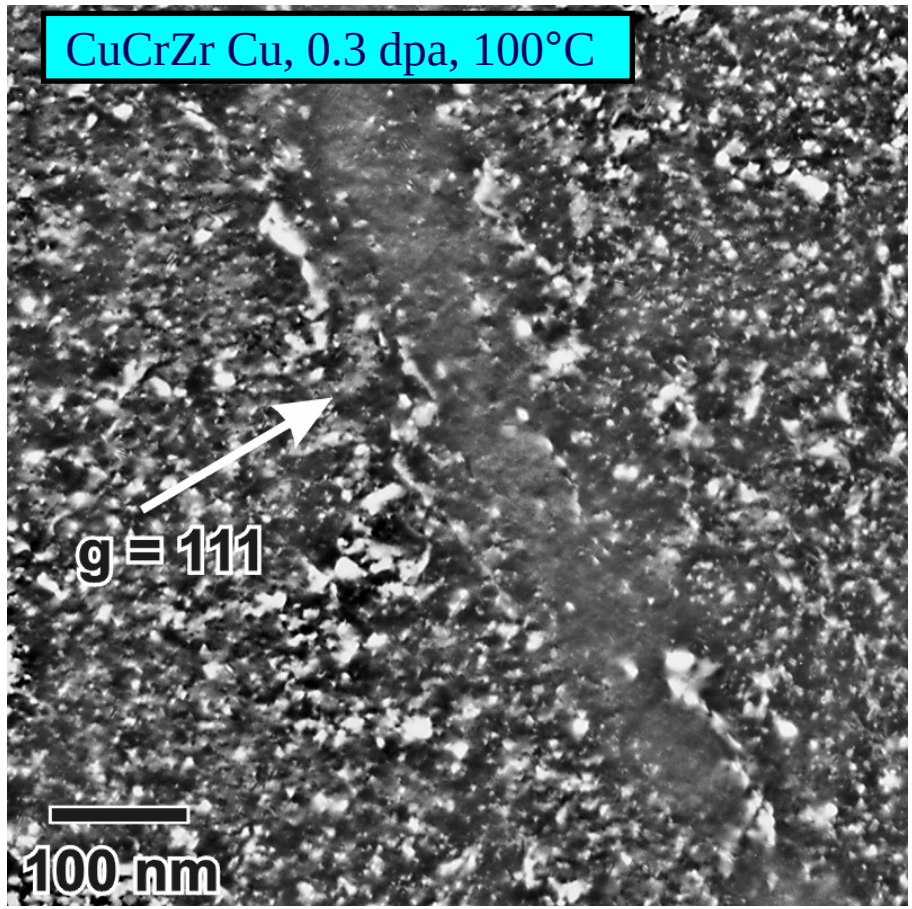
0.012 dpa, 0.1% ε_u



Defect Clearing in Channels in Irradiated OFHC Cu and CuCrZr

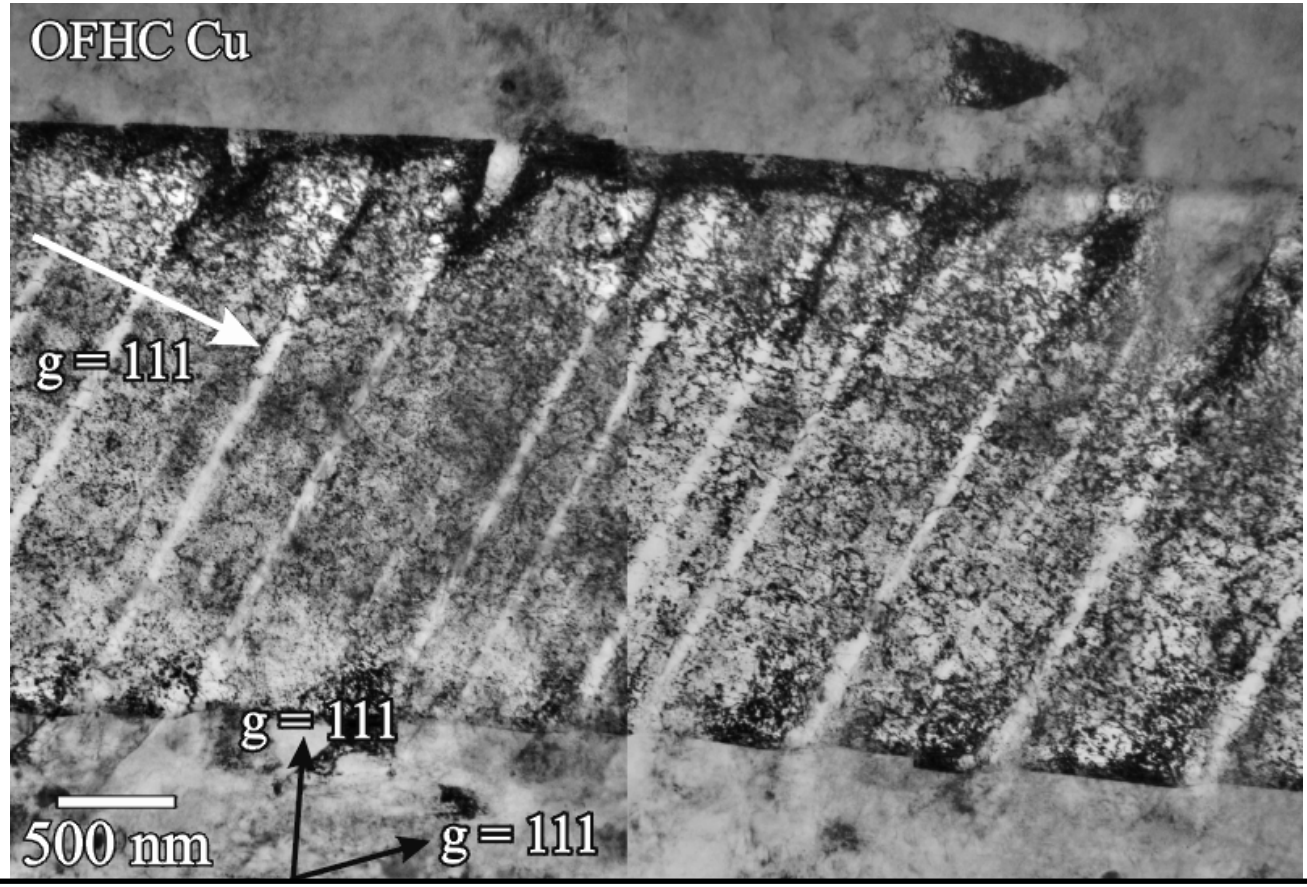


Defects “ploughed” to the side of the channels, not common



Channel not completely defect free, ppts. may be responsible.

Initiation and Propagation of Dislocation Channels

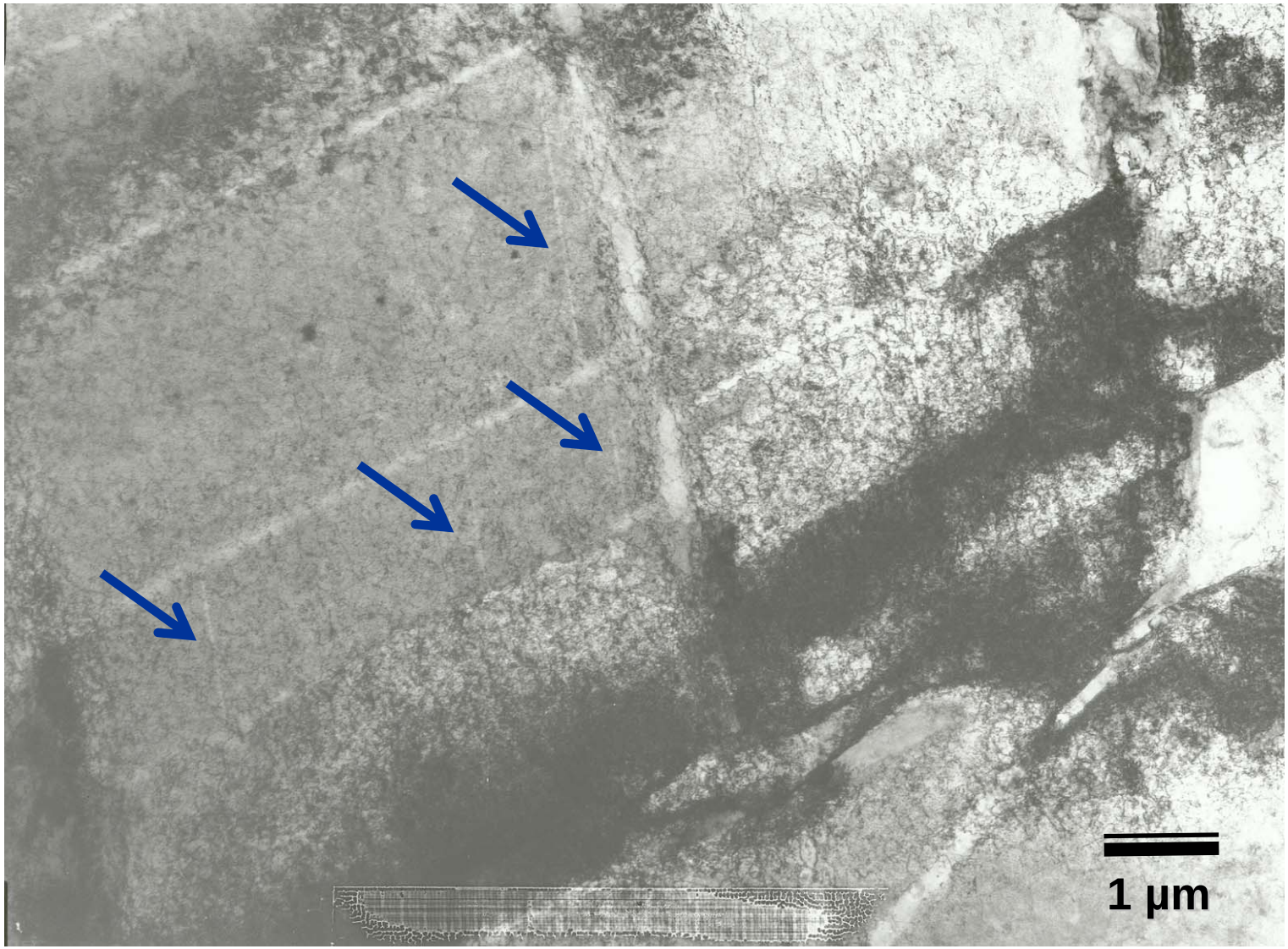


As-Irradiated OFHC Cu

- Channels found to initiate from twin boundaries and grain boundaries
- Stress concentrations play a critical role in where the channels form
- Twin boundary is thought to have periodic steps in the interface that can act as stress concentrators and set off channels
- Channels free of radiation-induced defects, but dipoles and debris remain

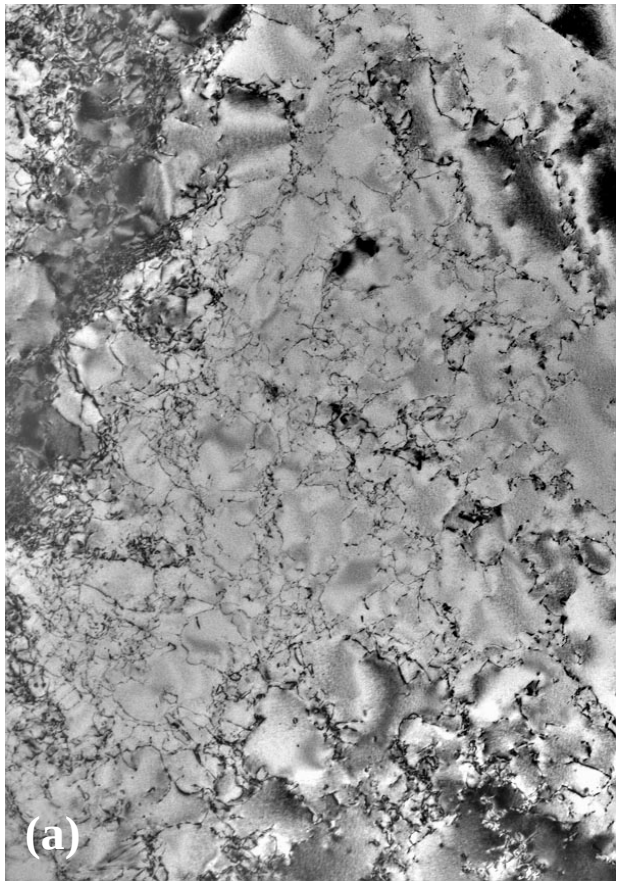
Dislocation Channel Interactions with Twin Boundaries in Cu

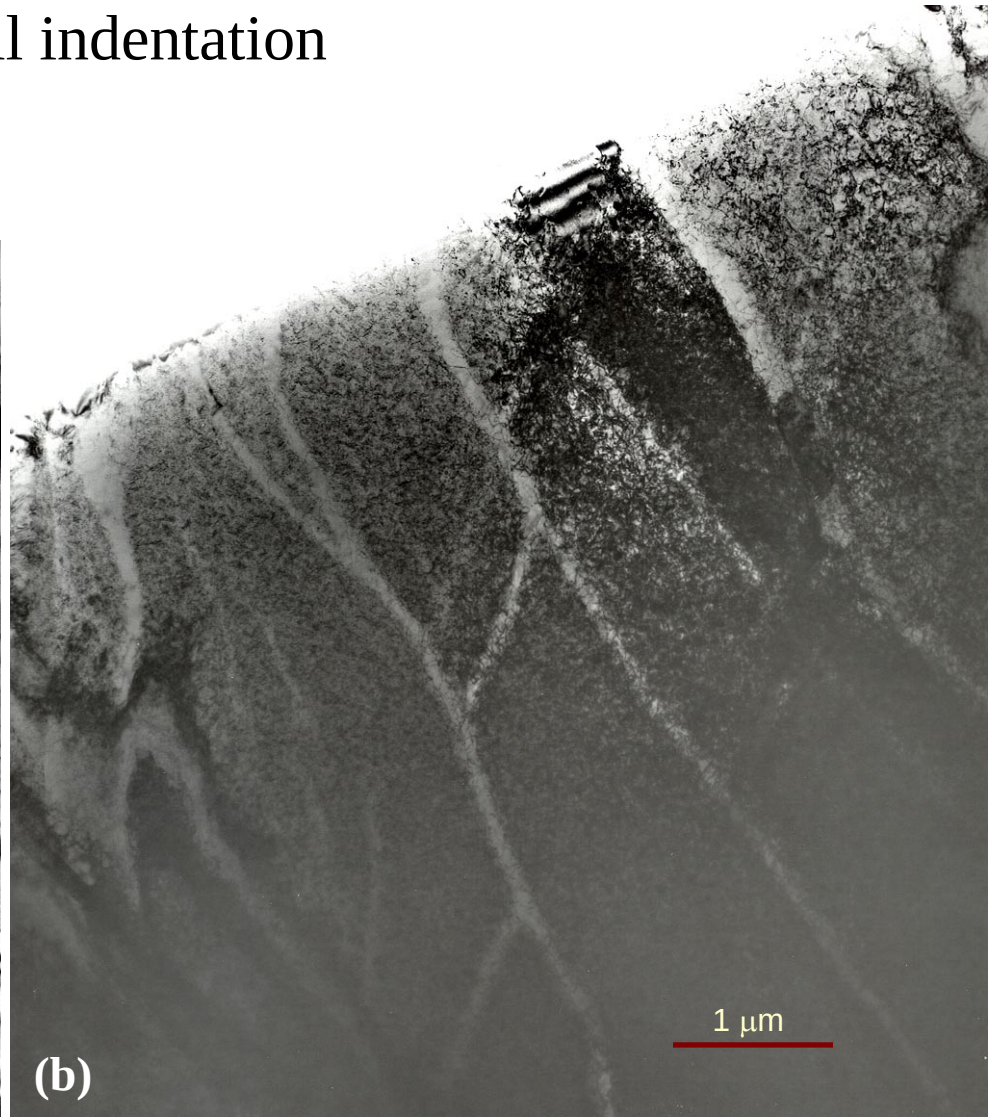
Fine-scale Dislocation channels in Irradiated Cu



Multiaxial loading causes bending, twisting and bifurcation of channels

Vanadium strained 5% by ball indentation

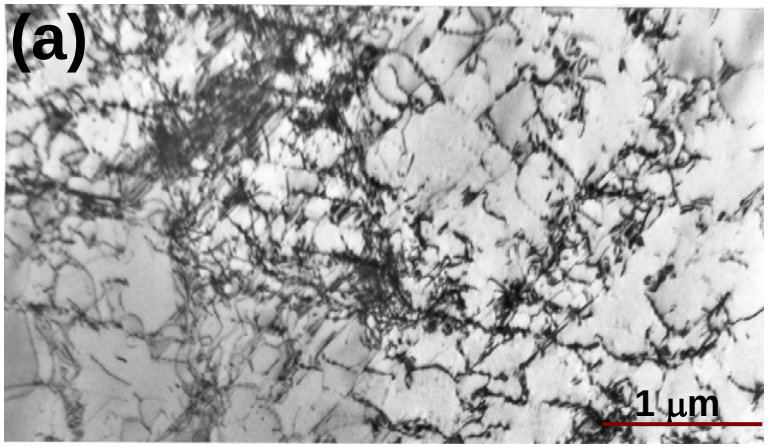


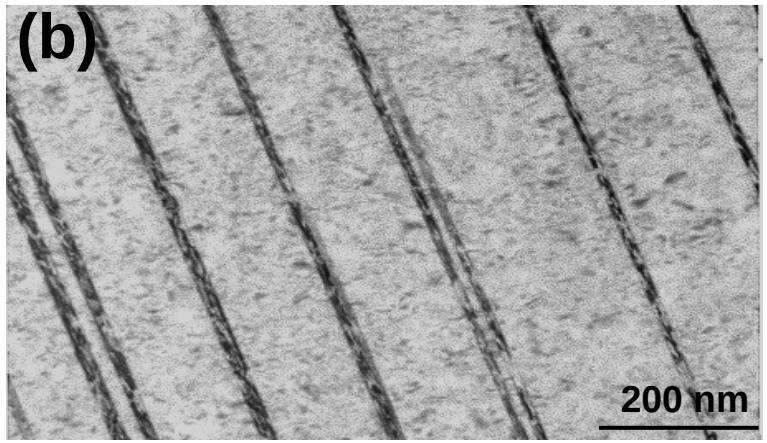


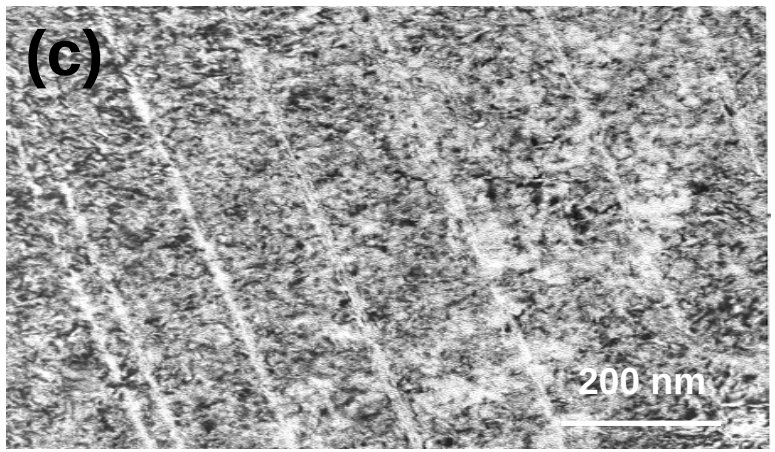
unirradiated

0.69 dpa neutron irradiation

Change in deformation microstructure by irradiation

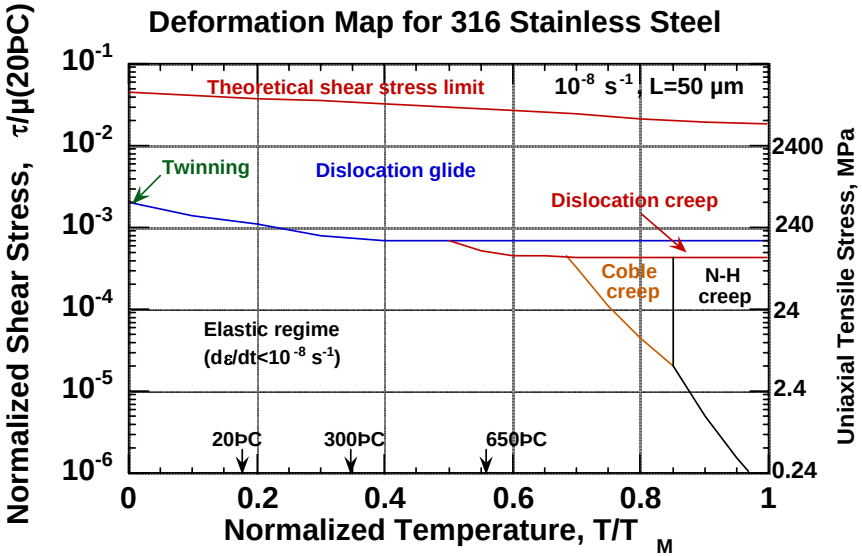


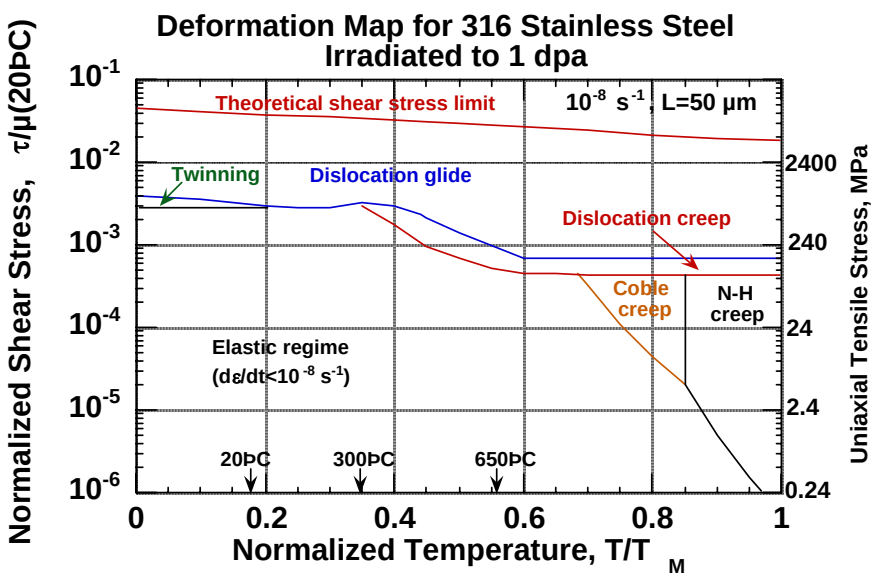




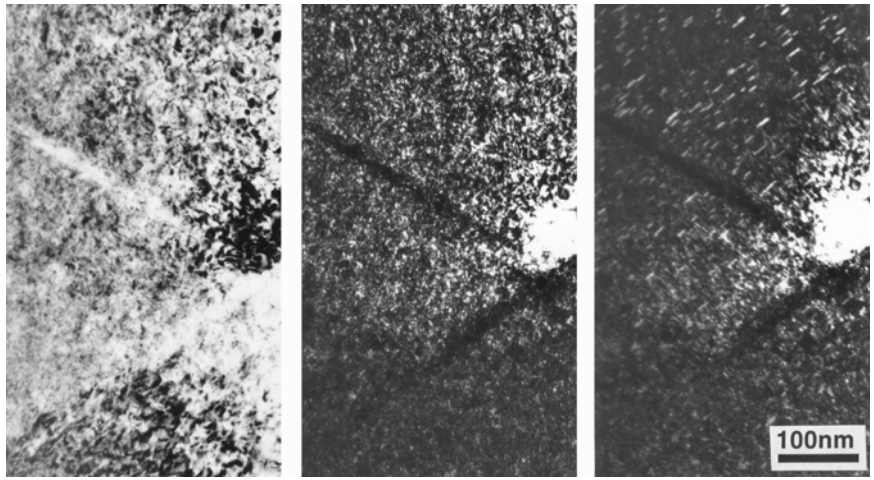
Deformation microstructures in 10% strained 316LN stainless steel (a) before and (b), (c) after irradiation to 7.5 dpa (10 at.%) with He ions. Channels with reduced defects in (c) were imaged edge-on by tilting the twin bands in (b).

Deformation mechanisms in stainless steel

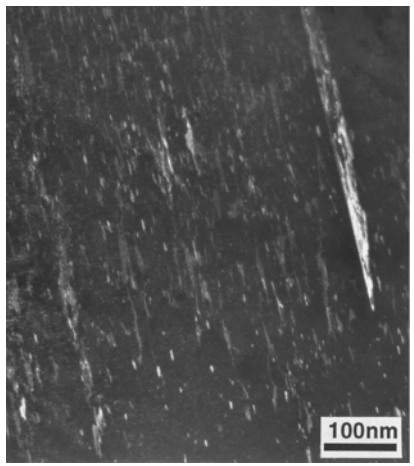




Irradiation is a useful tool to produce controlled microstructures for deformation mechanics studies



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

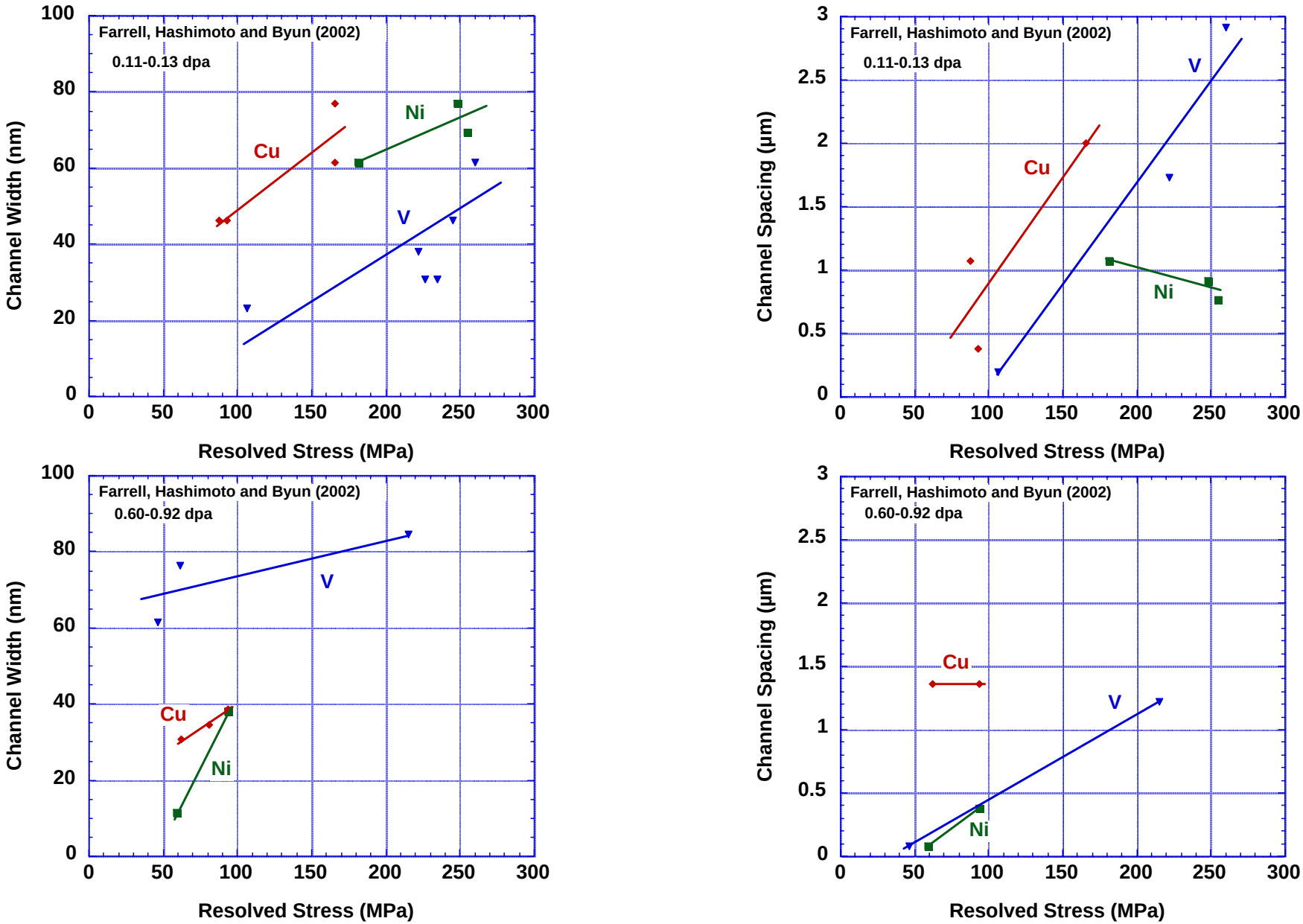


Twinning occurs at lower temperatures (<200˚C) and high strain rates

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	~50ÞC	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	~50ÞC	295 K	160	1.2-2.3 µm	Sharp 1974
Cu-0.05%Al	~0.001	~50ÞC	295 K	240	1.2-2.3 µm	Sharp 1974 (channels not observed in Cu-4%Al)
Au	~0.003	20ÞC	295 K	~100		Okada 1989
Ni						
Pd	0.3			~50-100		Victoria et al 2000
304L SS	5 (ions) “	500ÞC “	563 K 295 K	15 50-200 (twins)		Brimhall 1995
Fe-10%Cr-30%Mn	~0.005	300ÞC		~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	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		Bapna 1974
Al	quenched			1000		Mori 1969; Tokuno 1987

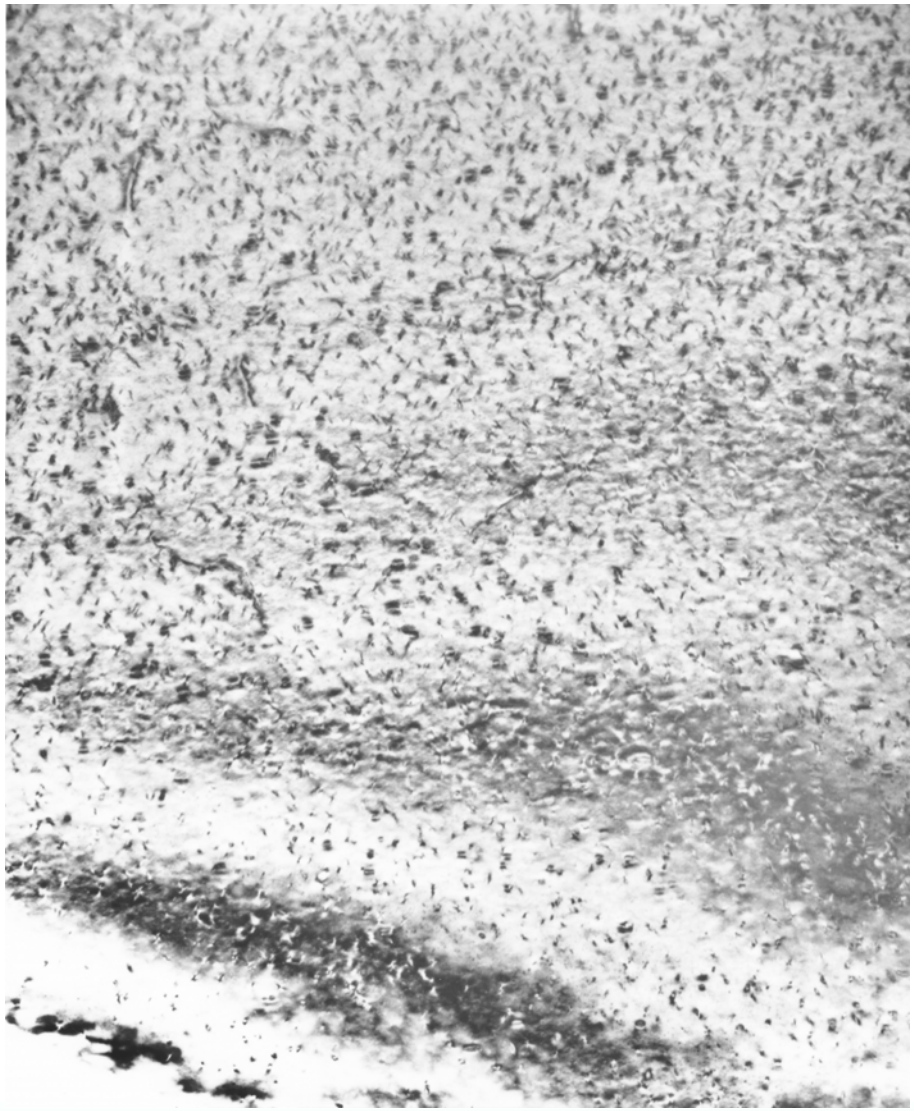
Dislocation Channel Parameters in Pure Metals Irradiated at 330 K and Tensile Tested at 295 K

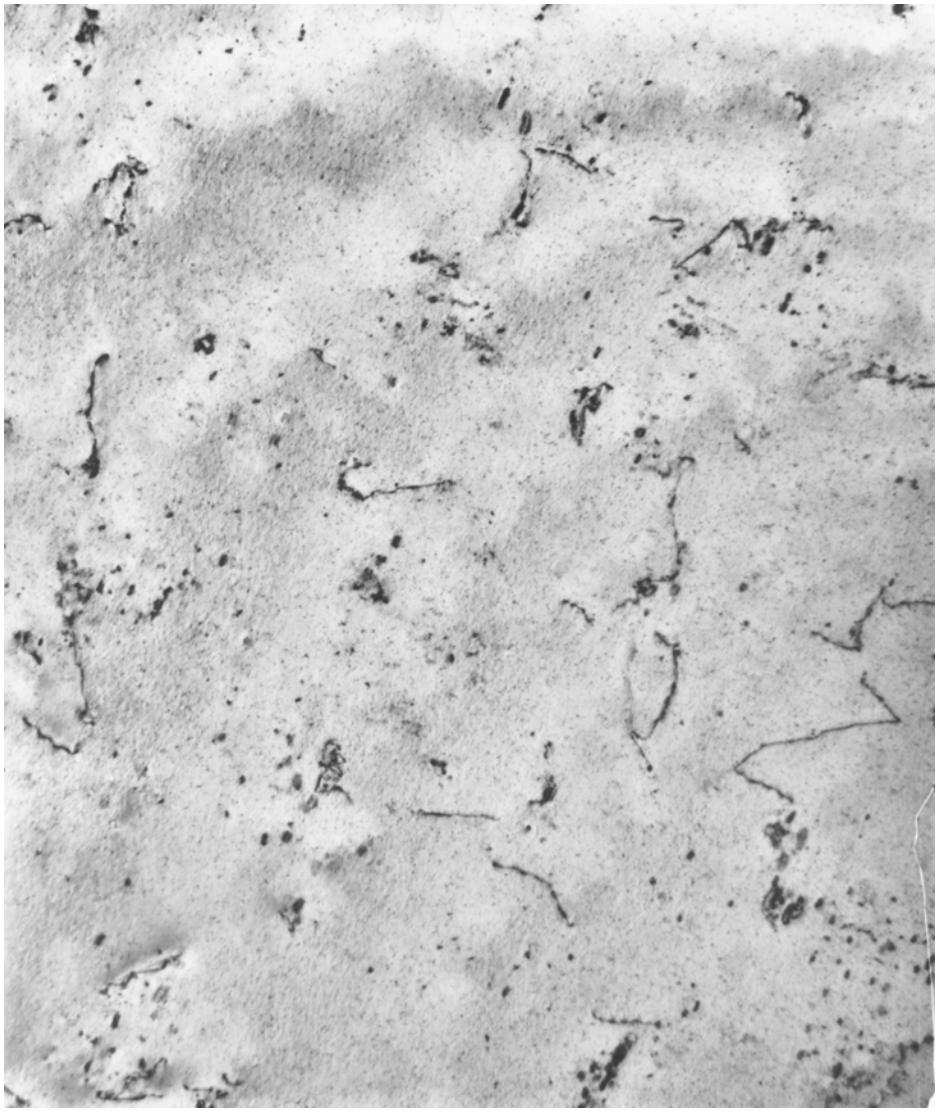


Discussion and Conclusions

- Flow localization is a common feature in unirradiated, quenched, and irradiated metals and alloys
  - role of intrinsic material parameters (stacking fault energy, etc.) and extrinsic effects (specimen geometry, etc.) needs to be understood
- Numerous outstanding issues need to be resolved in order to obtain a comprehensive model for flow localization in deformed materials
  - Role of dislocation channeling on flow localization phenomena
  - Effects of SFTs vs. dislocation loops on defect cluster annihilation by dislocations; mechanisms for defect cluster annihilation
  - Transmission of dislocation channels through grain boundaries
  - Location of dislocation sources (grain boundaries, inclusions, etc.)
  - Stress and defect cluster spacing effects on flow localization
  - Effect of resolved stress on channel width and spacing
  - Effect of impurity segregation (pre-existing and neutron transmutatation)
- Additional work using a combination of single crystal and polycrystal specimens would improve our knowledge base (multiple slip systems in polycrystal specimens complicates analysis)

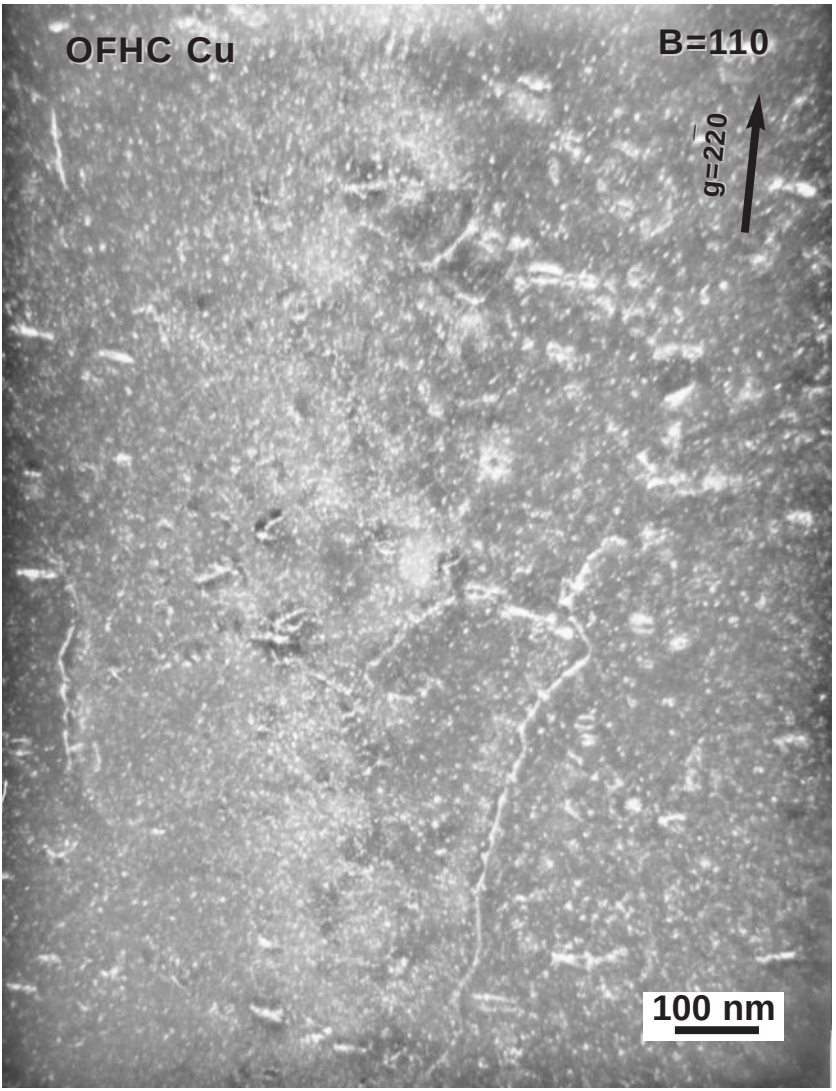
Defect cluster decoration of irradiated copper is not a common feature (assumption of original Cascade induced source hardening model)

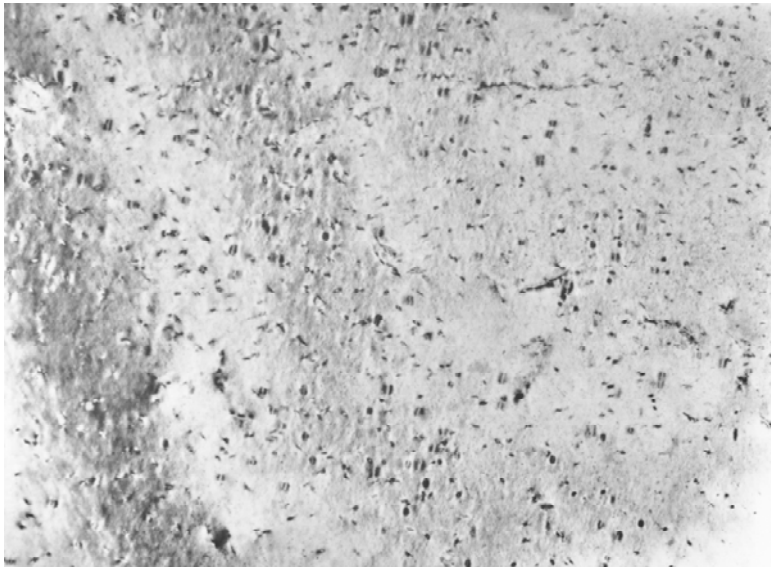


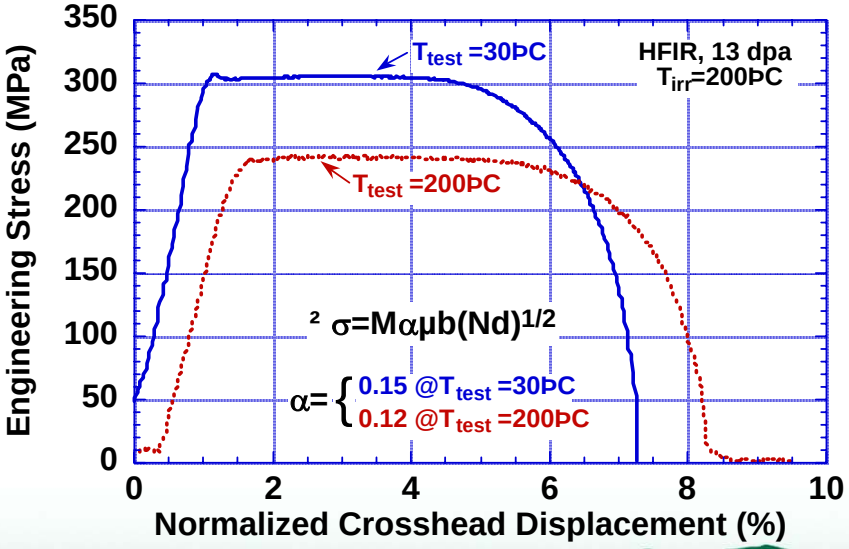


HFIR-irradiated copper, 13 dpa, 200˚C

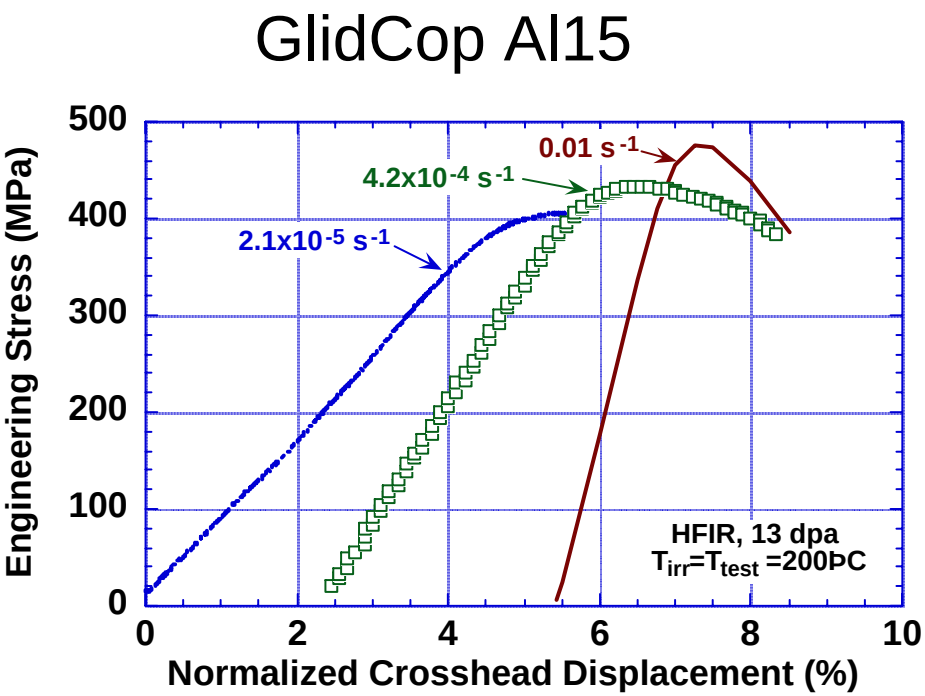
Dislocation decoration by defect clusters is not generally responsible for yield drop

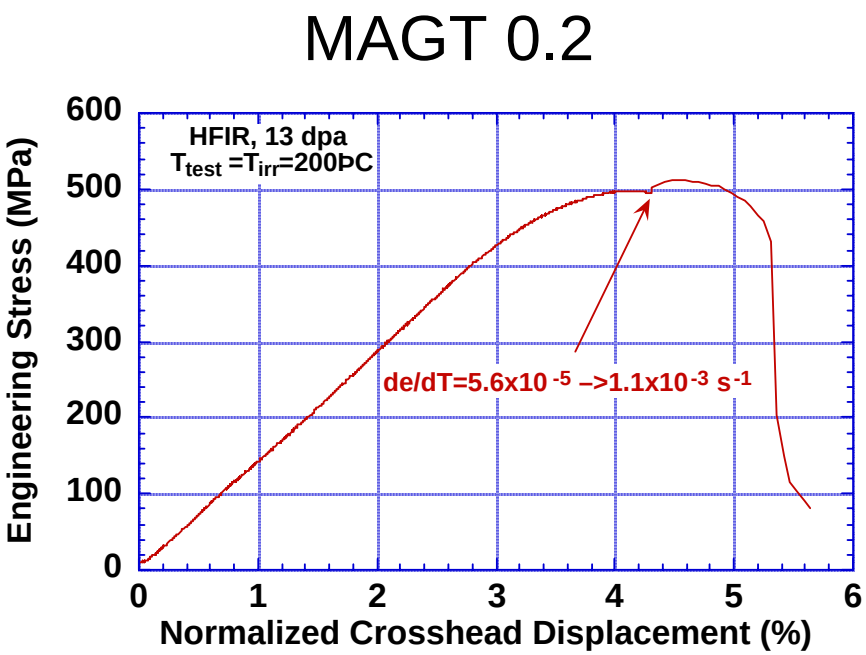




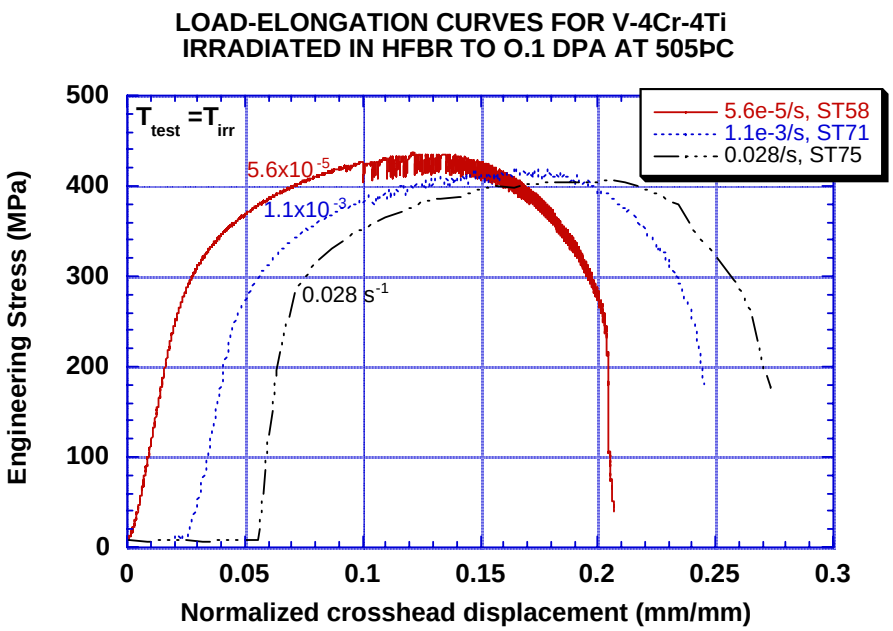


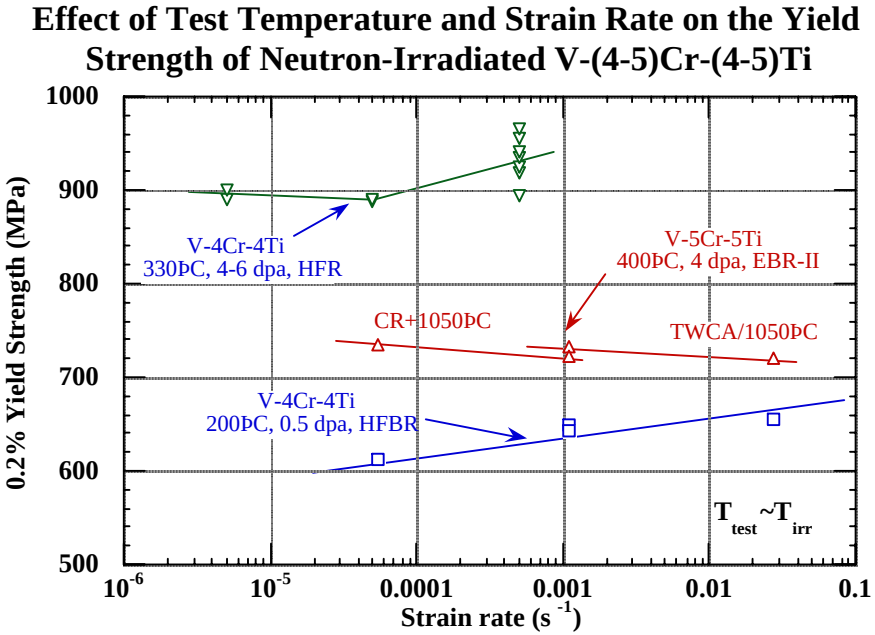
Comparison of strain rate dependence of tensile strength of irradiated dispersion strengthened Cu





Strain rate dependence of tensile strength of irradiated V4Cr4Ti





- Strain rate exponent becomes negative in irradiated alloys at Ttest>330ÞC even when serrated stress-strain behavior is not visible due to dislocation channeling