An Overview of Low to Intermediate Temperature Microstructural Evolution Processes in V-4Cr-4Ti and RAMS

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Fusion Materials Sciences Program
Strategic Planning Meeting

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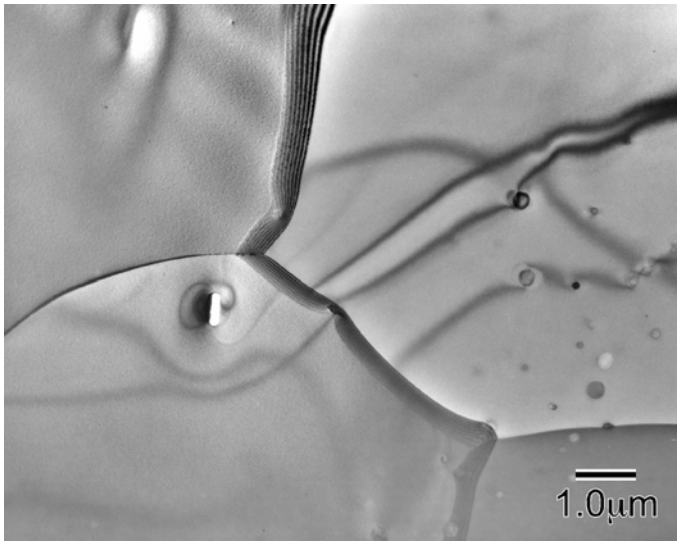
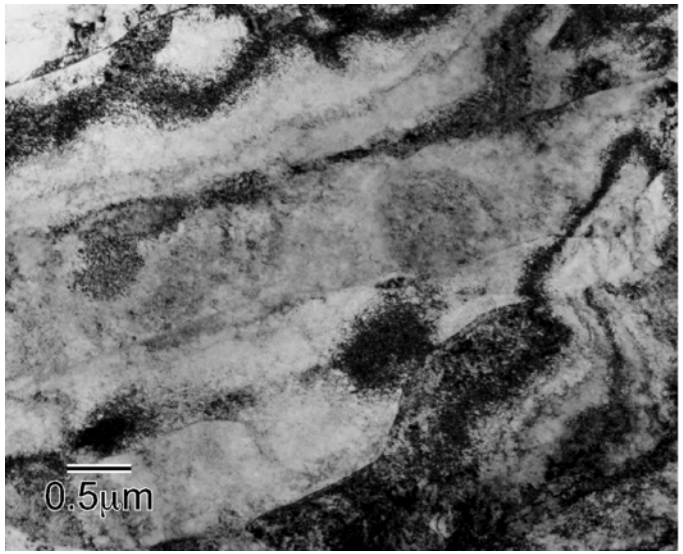
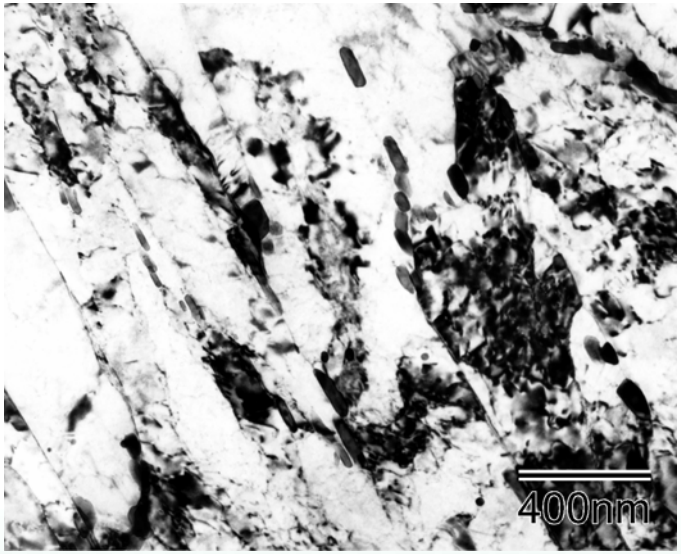
Representative TEM Images of the Structural Alloys



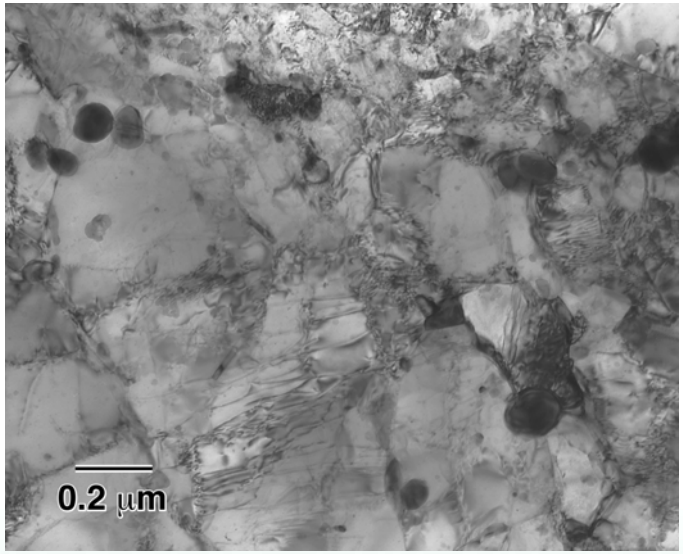
V-4Cr-4Ti



MA ODS Fe-12Cr-3W-0.4Ti +0.25Y_2O_3



F82H

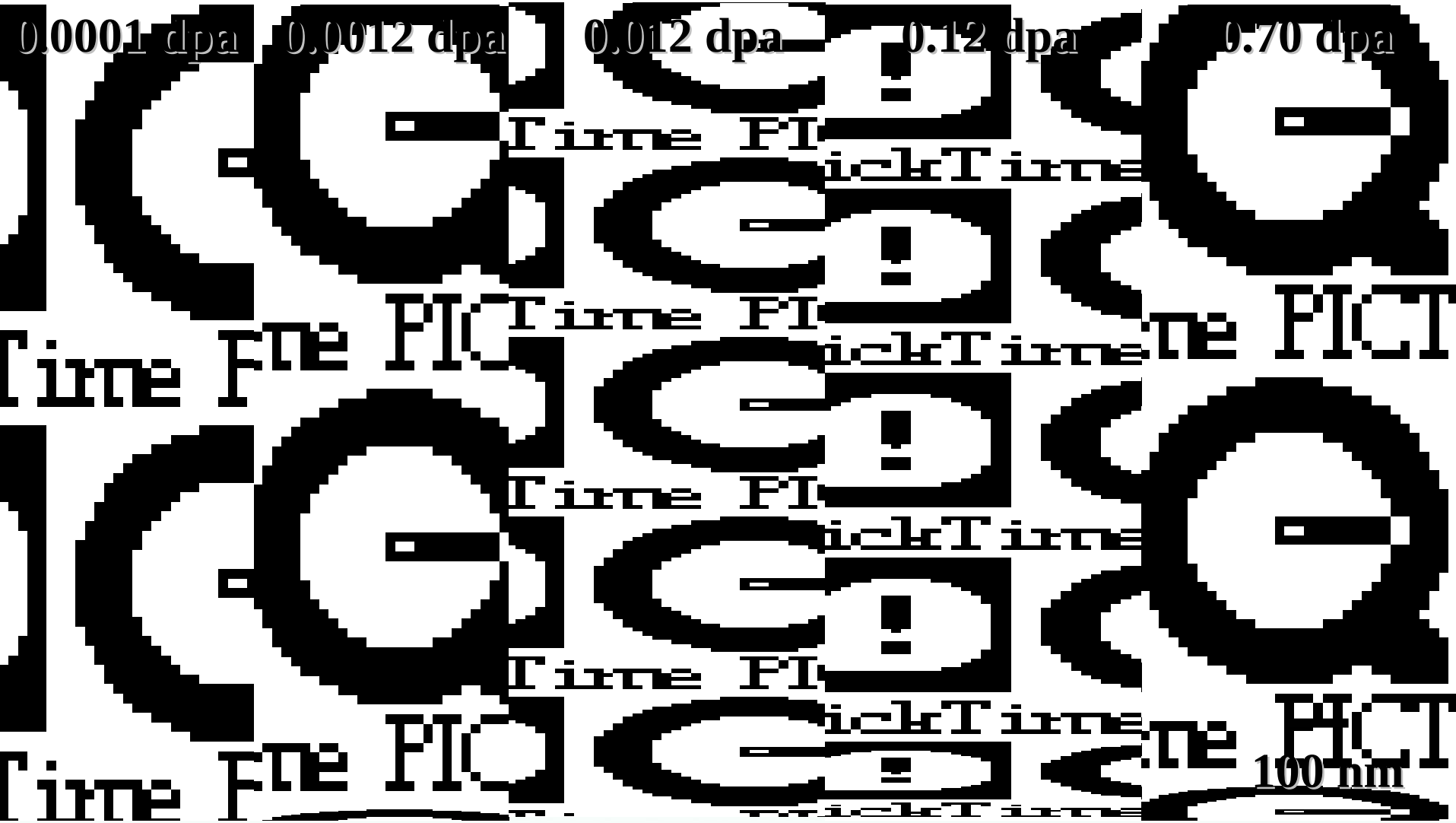


MA ODS Fe-9Cr-2W (0.5TiO_2 +0.5Y_2O_3)

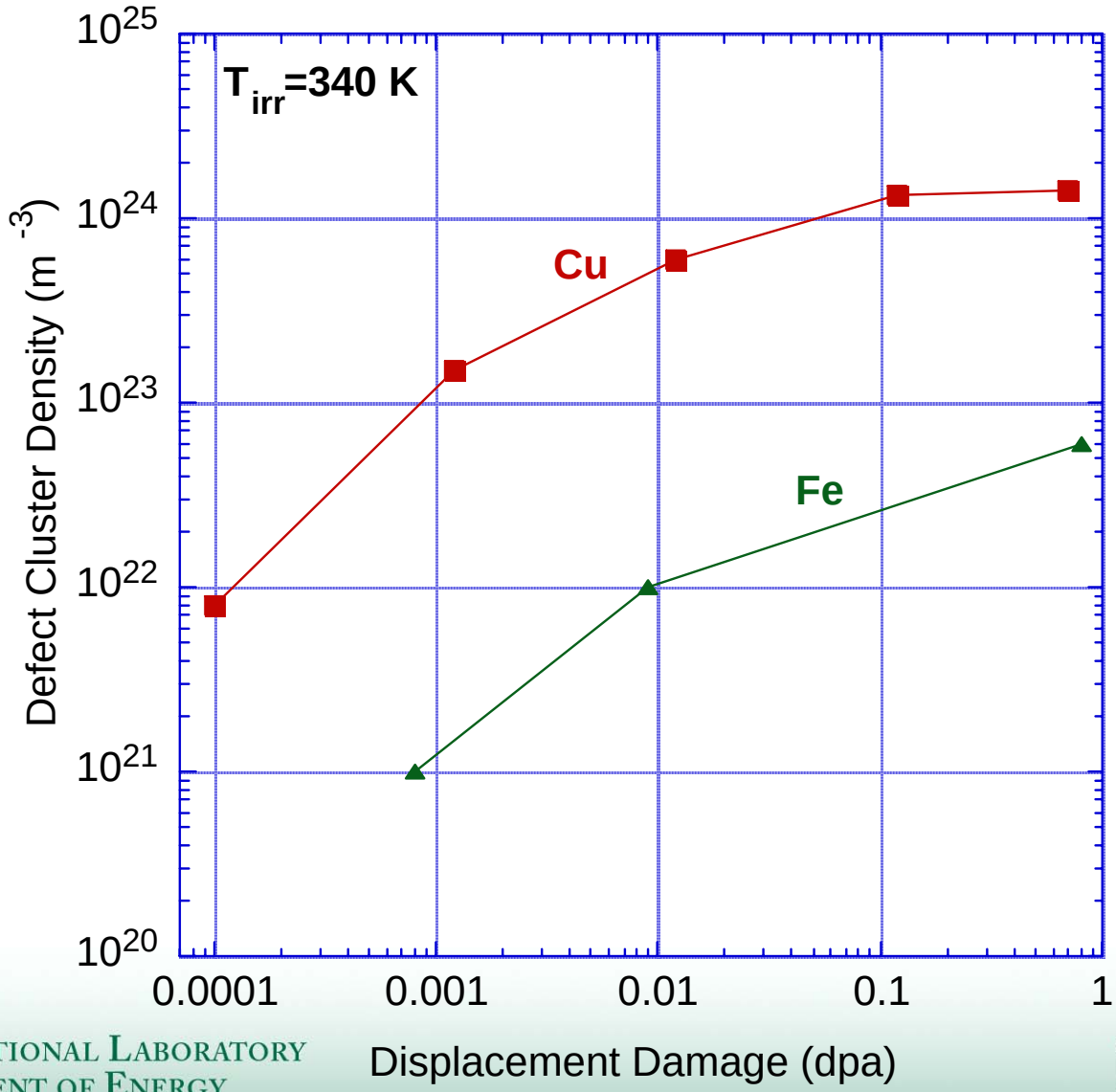
Dislocation loop evolution in neutron-irradiated Fe at 340 K

0.0001 dpa **0.0008 dpa** **0.009 dpa** **0.80 dpa**

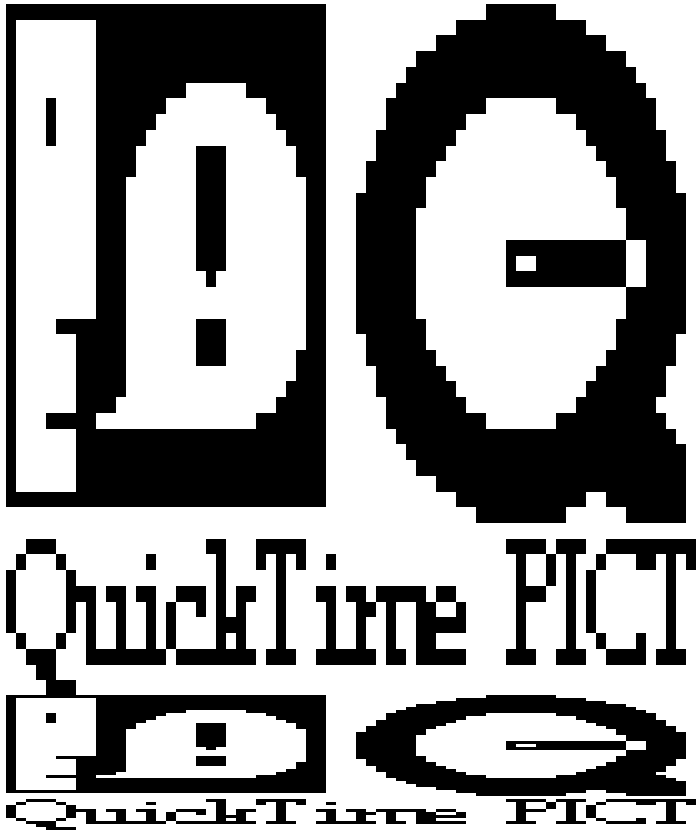
Dislocation loop evolution in neutron-irradiated Cu at 340 K



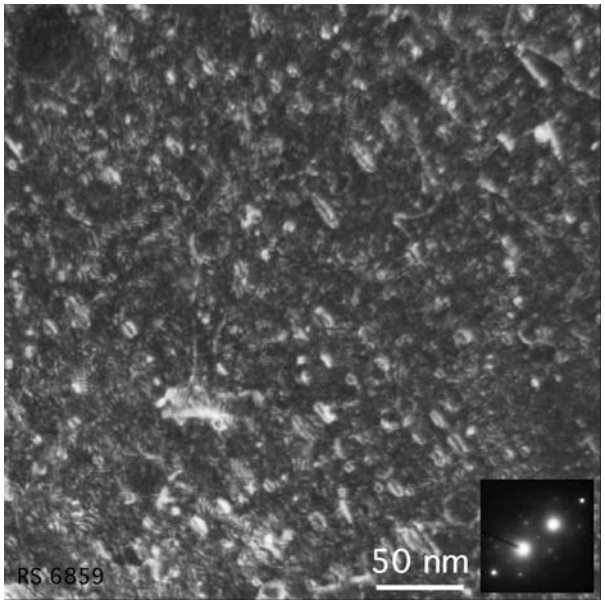
Comparison of the defect cluster accumulation behavior of Irradiated Cu and Fe



Formation of dislocation loop rafts in neutron-irradiated Fe at 0.8 dpa



Dislocation loop formation in ferritic steels



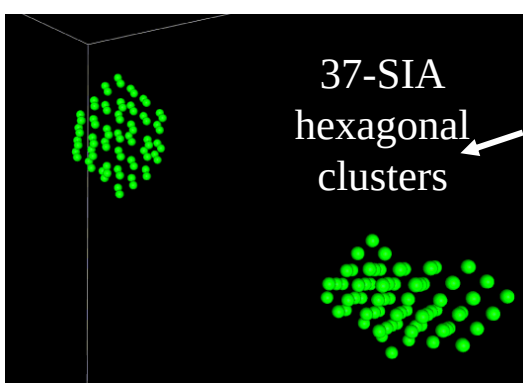
Irradiated ferritic steel (Fe-8Cr)
(experiment by R. Schäublin)

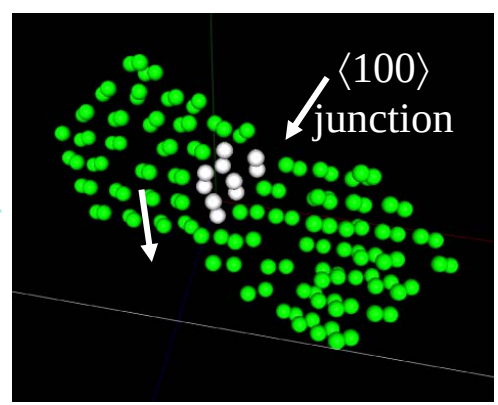
- **Large density of <100> loops observed (TEM) at high dose**
- **Previous model (Eyre & Bullough) suggests formation from faulted (<110>) platelets:**

$$\frac{a_o}{2}[110] + \frac{a_o}{2}[\bar{1}10] \rightarrow a_o[010]$$

- New insight: <100> junctions form through interaction of highly mobile, <111> loops:

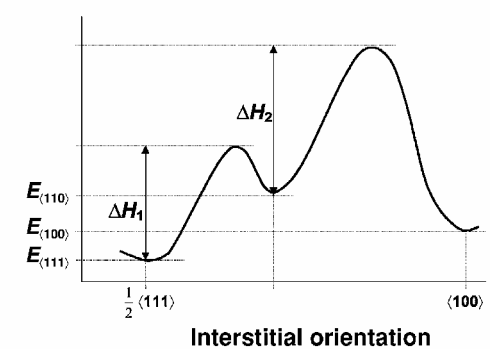
$$\frac{a_o}{2}[111] + \frac{a_o}{2}[1\bar{1}\bar{1}] \rightarrow a_o[100]$$





$\frac{1}{2}[111]$ $\frac{1}{2}[1\bar{1}\bar{1}]$ $\rightarrow$ $[100]$

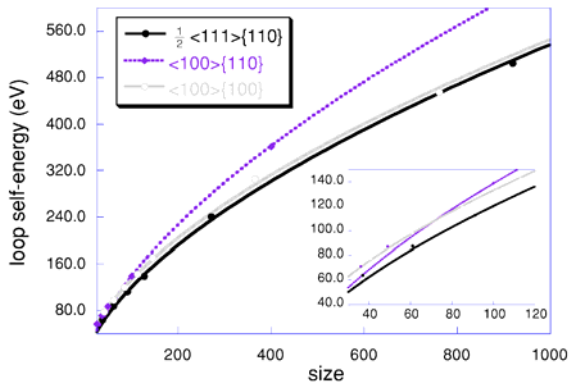
- Junction propagates or dissolves by 2-step mechanism



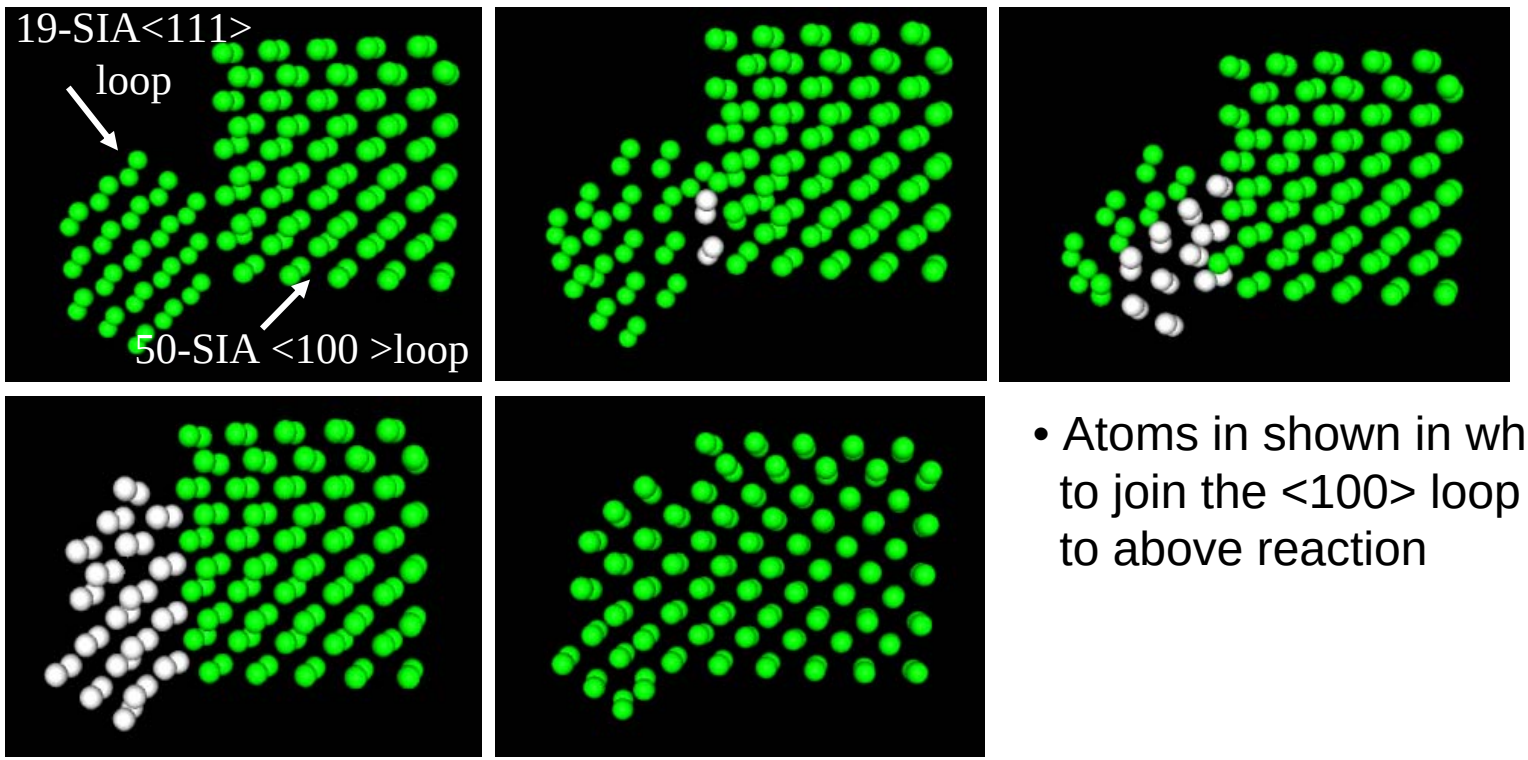
Energy landscape favors <100> growth

Growth mechanisms of <100> loops

- **Despite being metastable with respect to <111> loops, <100> loops grow by absorption of smaller <111> loops**



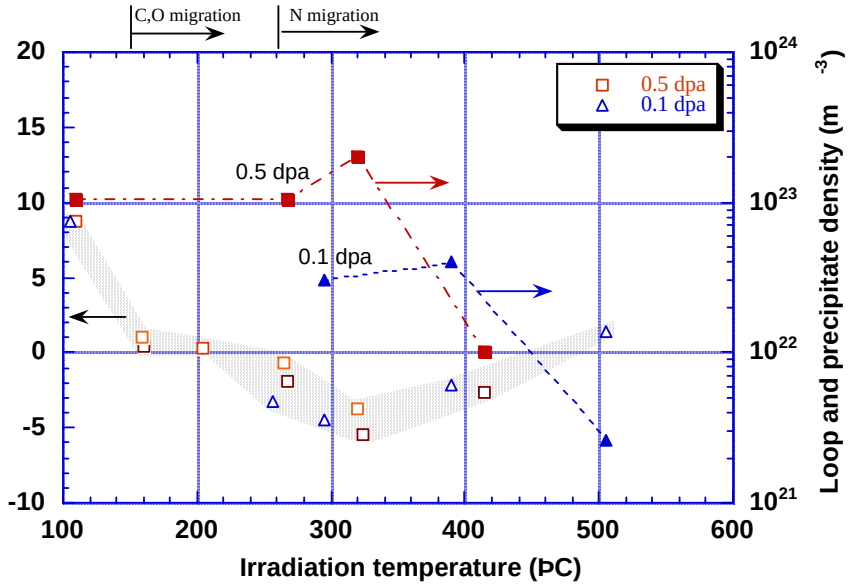
$$\Downarrow \langle 100\rangle \frac{1}{2} \quad \langle 111\rangle \rightarrow \langle 211\rangle \rightarrow \langle 100\rangle$$

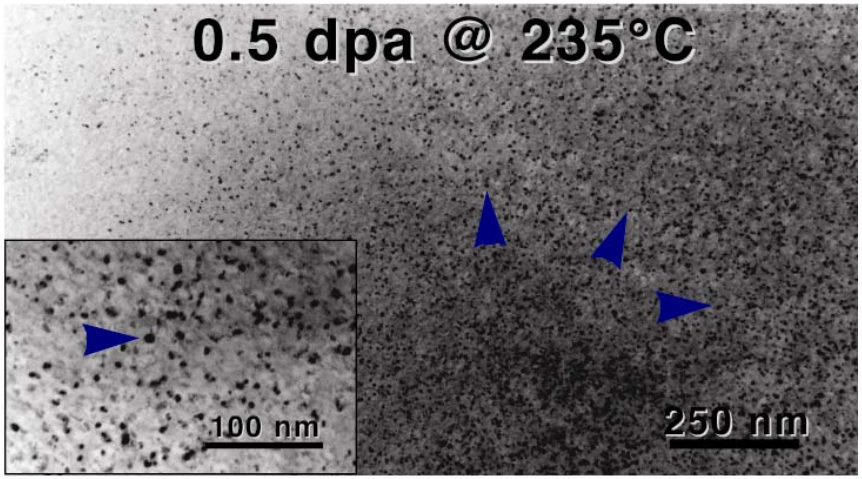


- Atoms in shown in white, are rotating to join the <100> loop according to above reaction

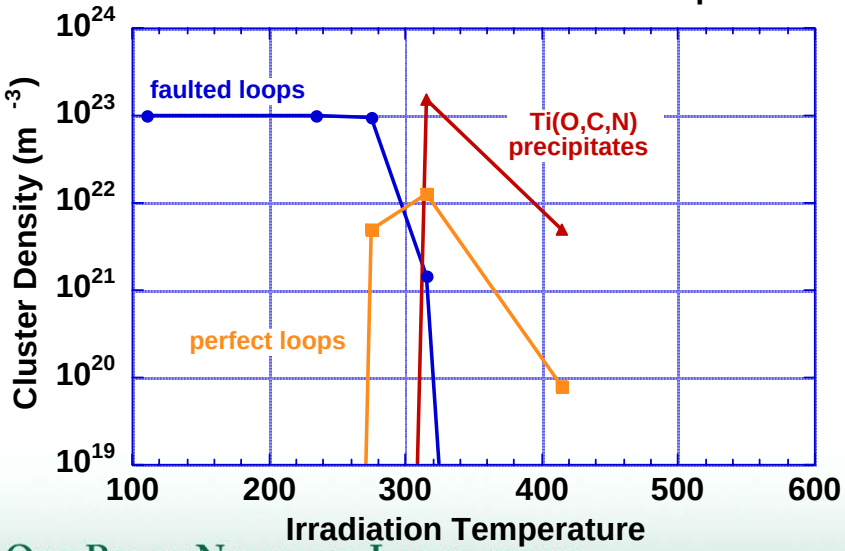
Microstructure of Neutron-irradiated V-4Cr-4Ti

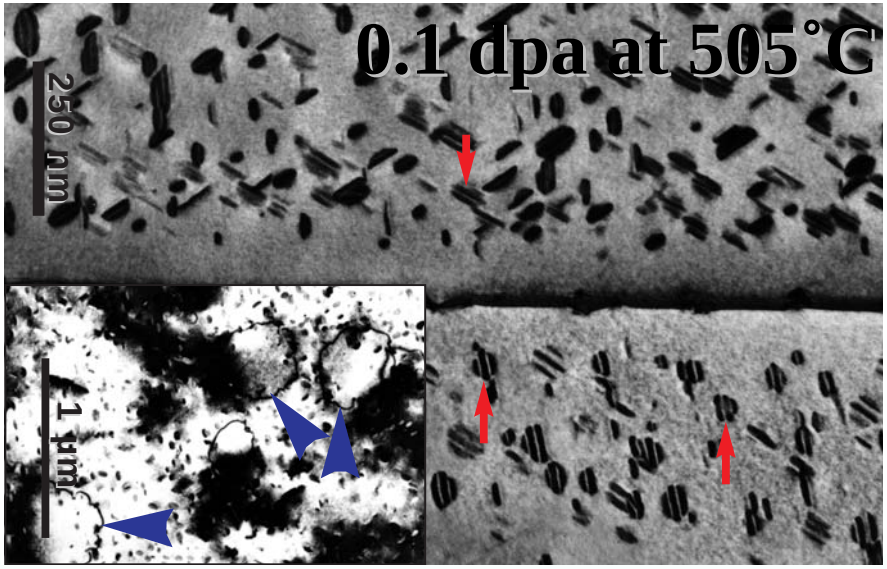
Effect of Irradiation Temperature on the Electrical Resistivity and Total Defect Cluster Density in V-4Cr-4Ti Irradiated in HFBR



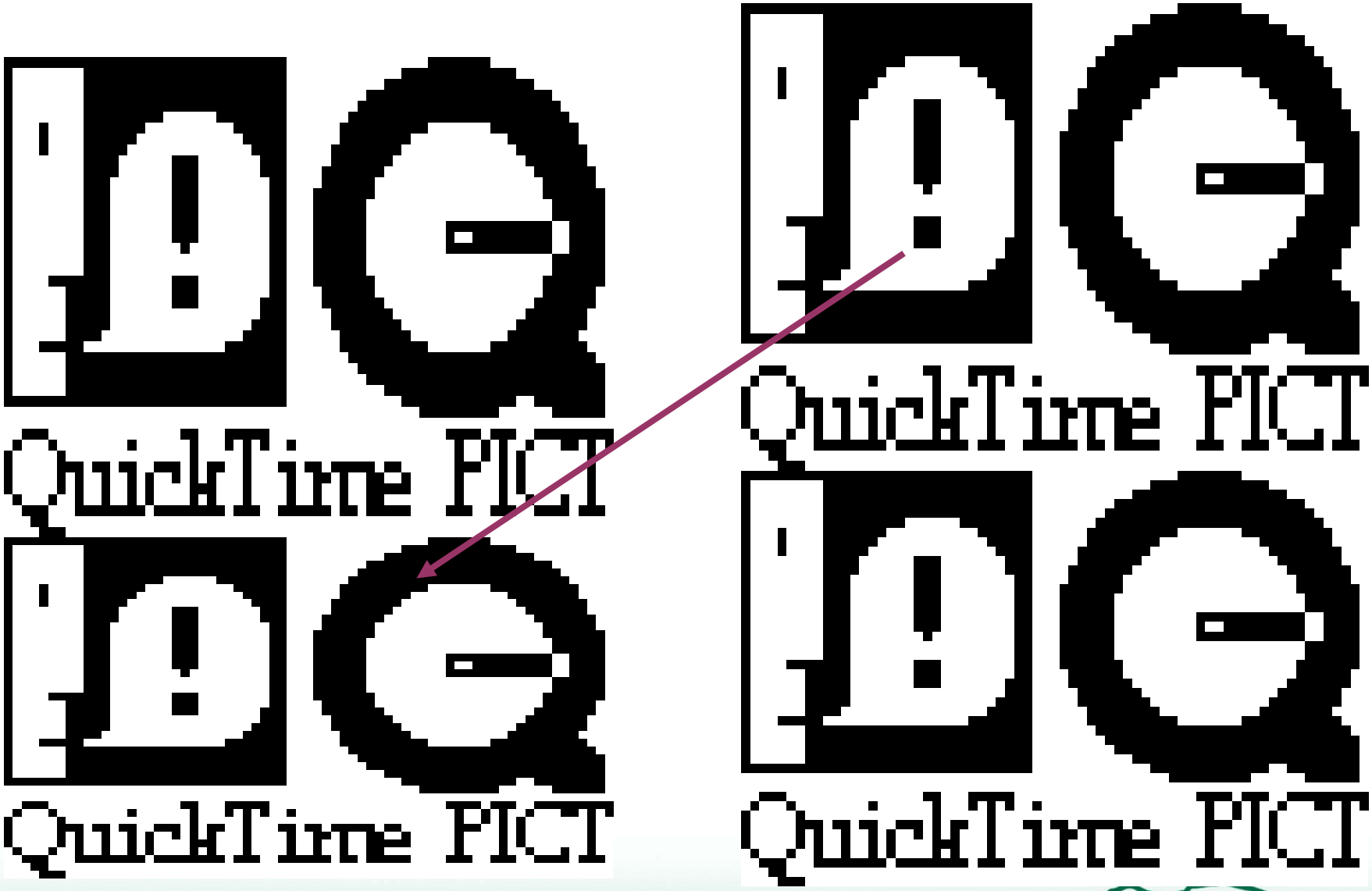


Measured Defect Cluster Densities in V-4Cr-4Ti Neutron-irradiated to 0.5 dpa



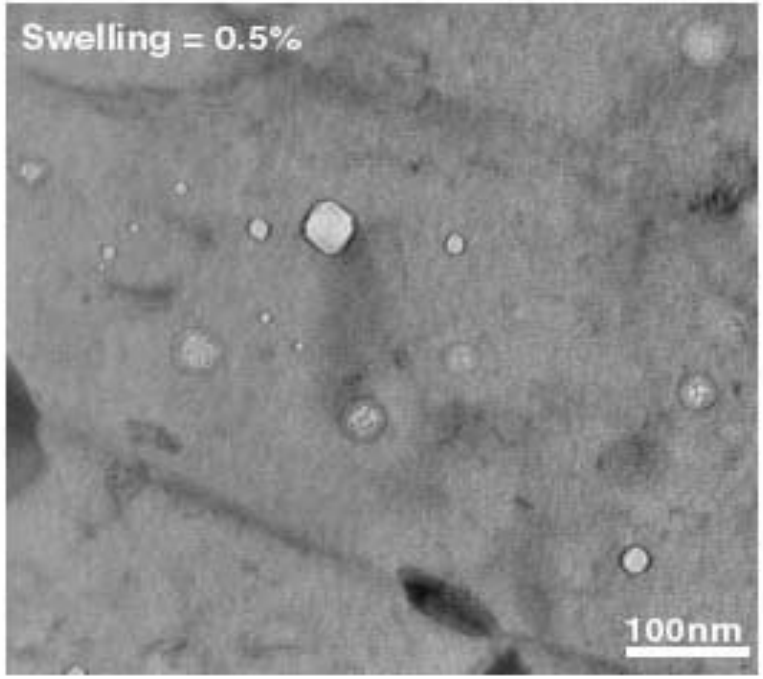


Dislocation channeling in 0.8 dpa neutron-irradiated Fe

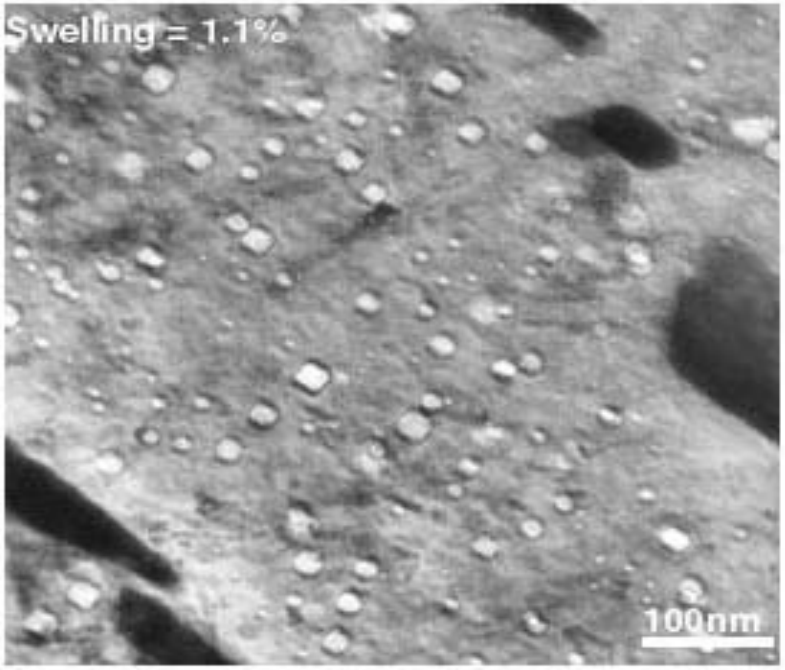


Void Swelling of Ferritic Steels is Low up to ~50 dpa (~5 MW-yr/m^2), Although Further Work is Needed to Examine He Effects

HFIR irradiation at 400˚C to 51 dpa

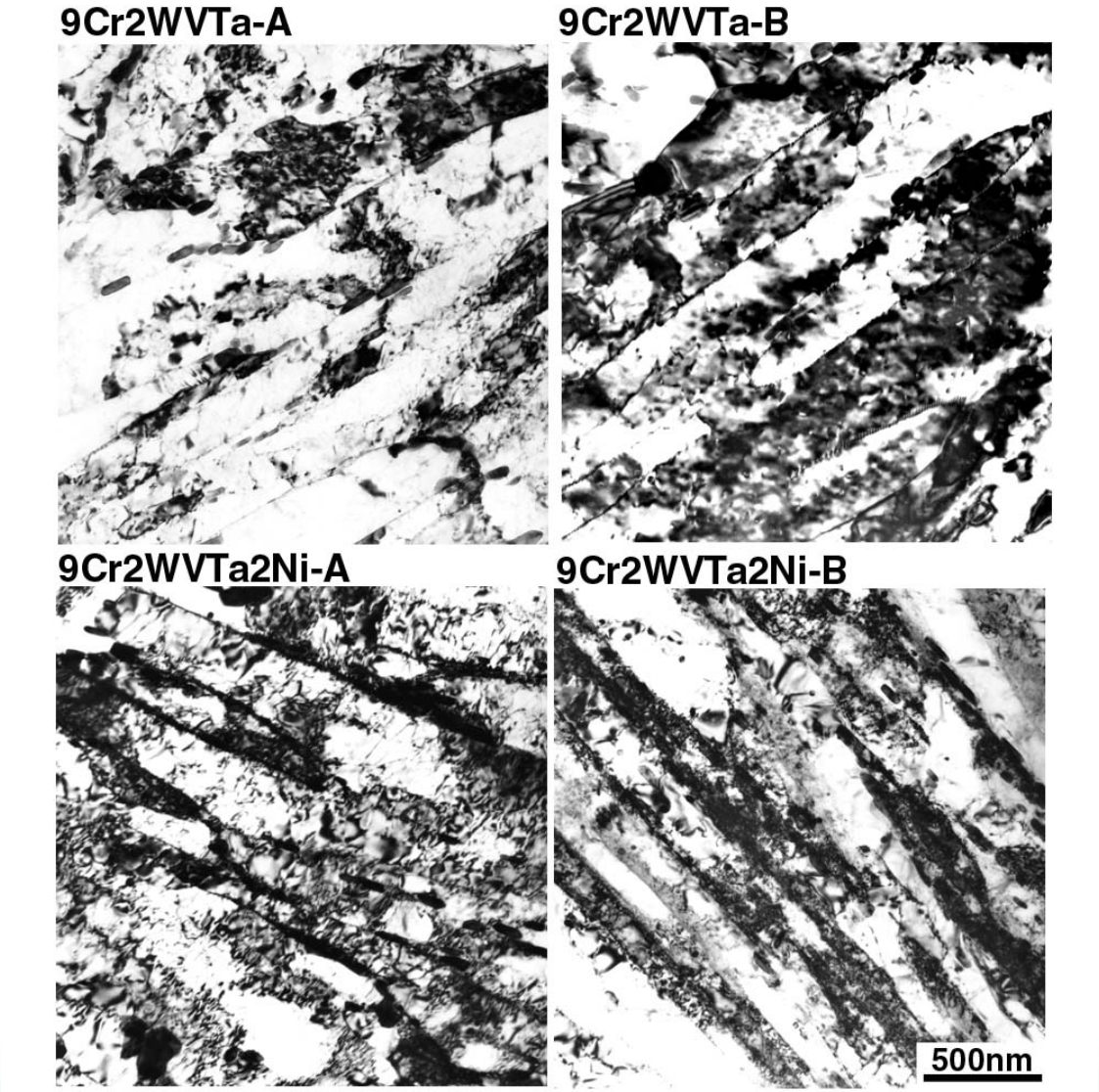


F82H (36 appm He)



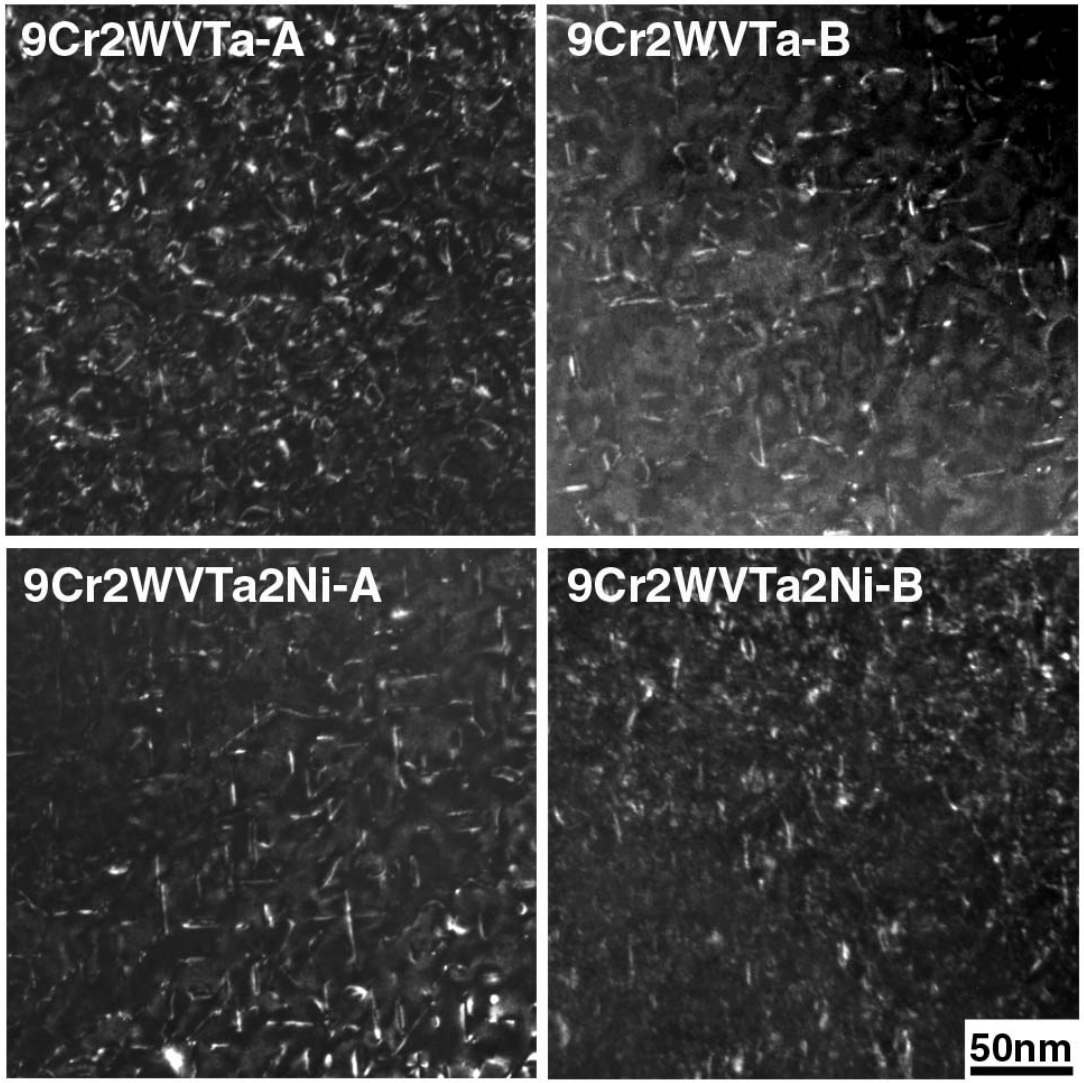
^{10}B-doped F82H (330 appm He)

Comparison of unirradiated microstructures of B- and Ni-doped 9Cr martensitic steels



Tempered 1h at 700˚C (A) or 750˚C (B)

Comparison of microstructures of 9Cr martensitic steels following neutron irradiation at 400˚C, 12 dpa



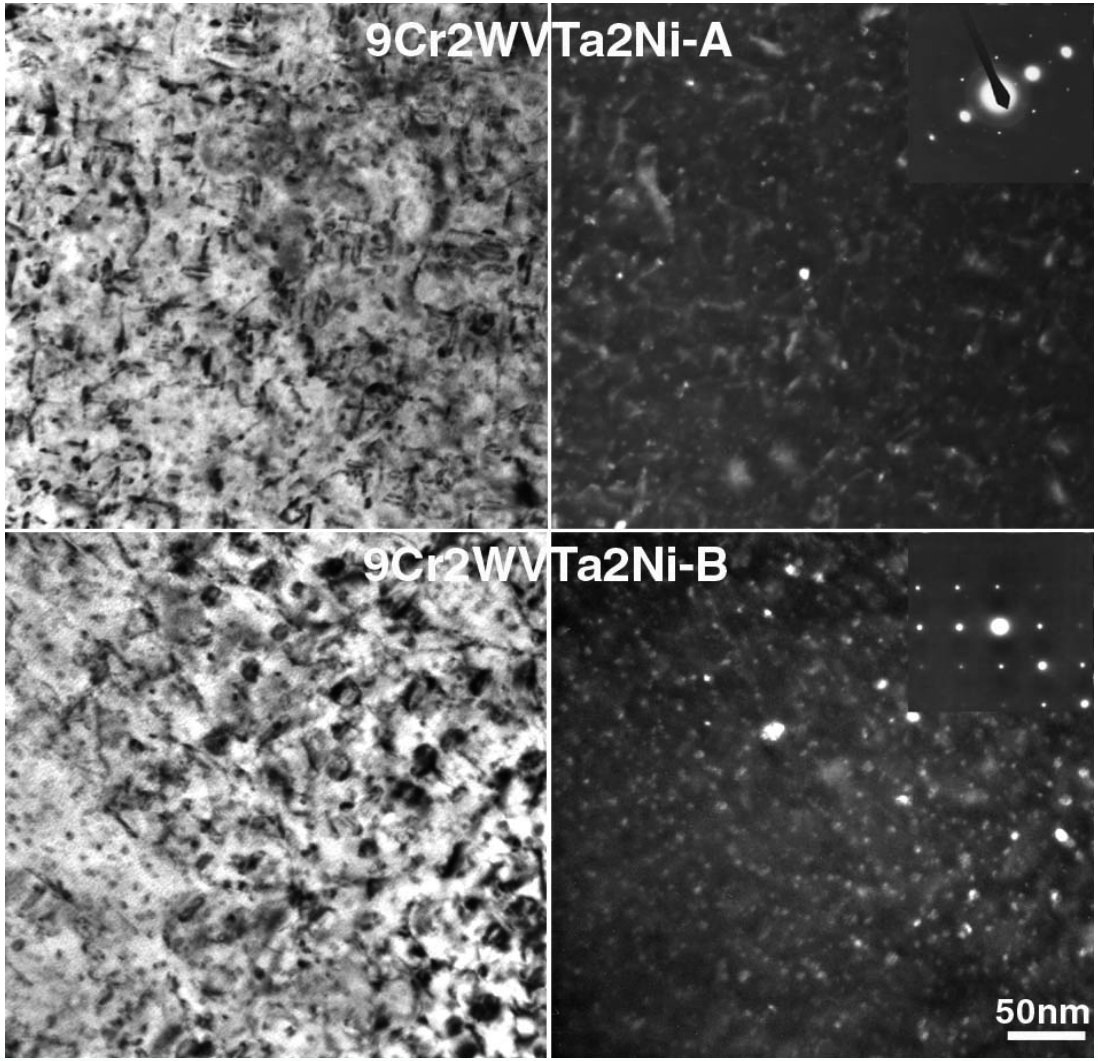
Tempered 1h at 700˚C (A) or 750˚C (B)

Dislocation Densities:

$1 \times 10^{22}/m^3$ a<100>

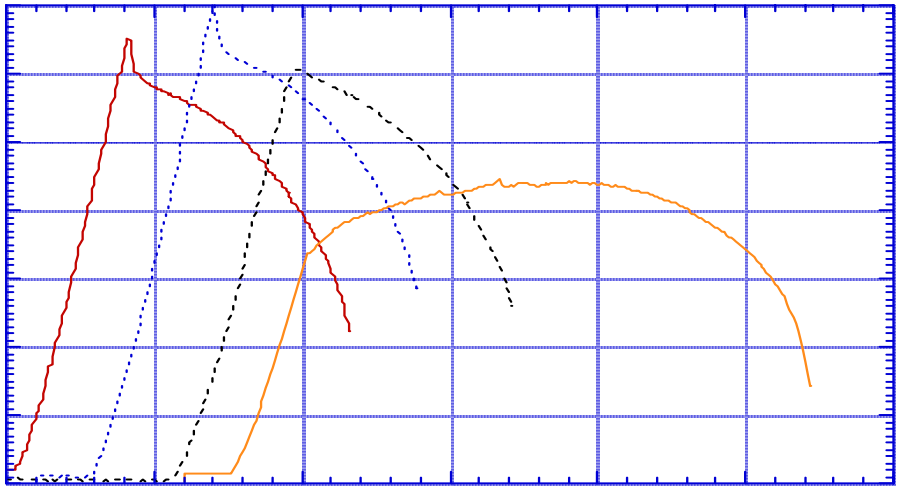
$4\text{-}6 \times 10^{21}/m^3$ a/2<111>

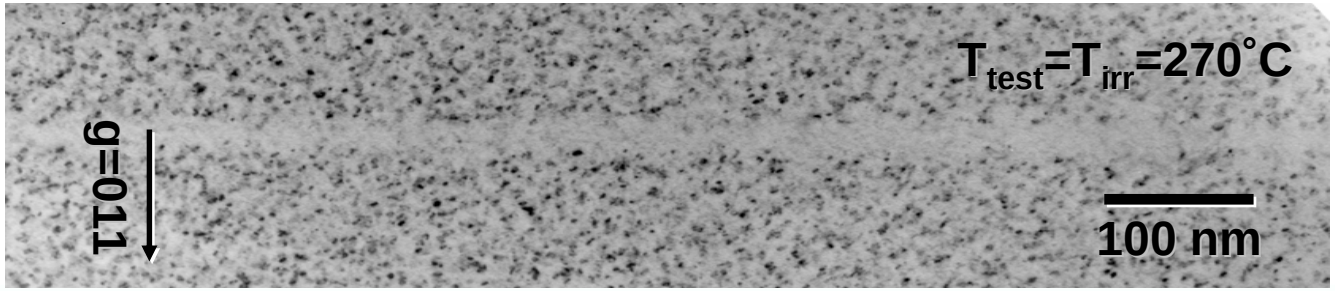
M_6C (η) precipitates in Ni-doped 9Cr martensitic steels following neutron irradiation at 400˚C,12 dpa



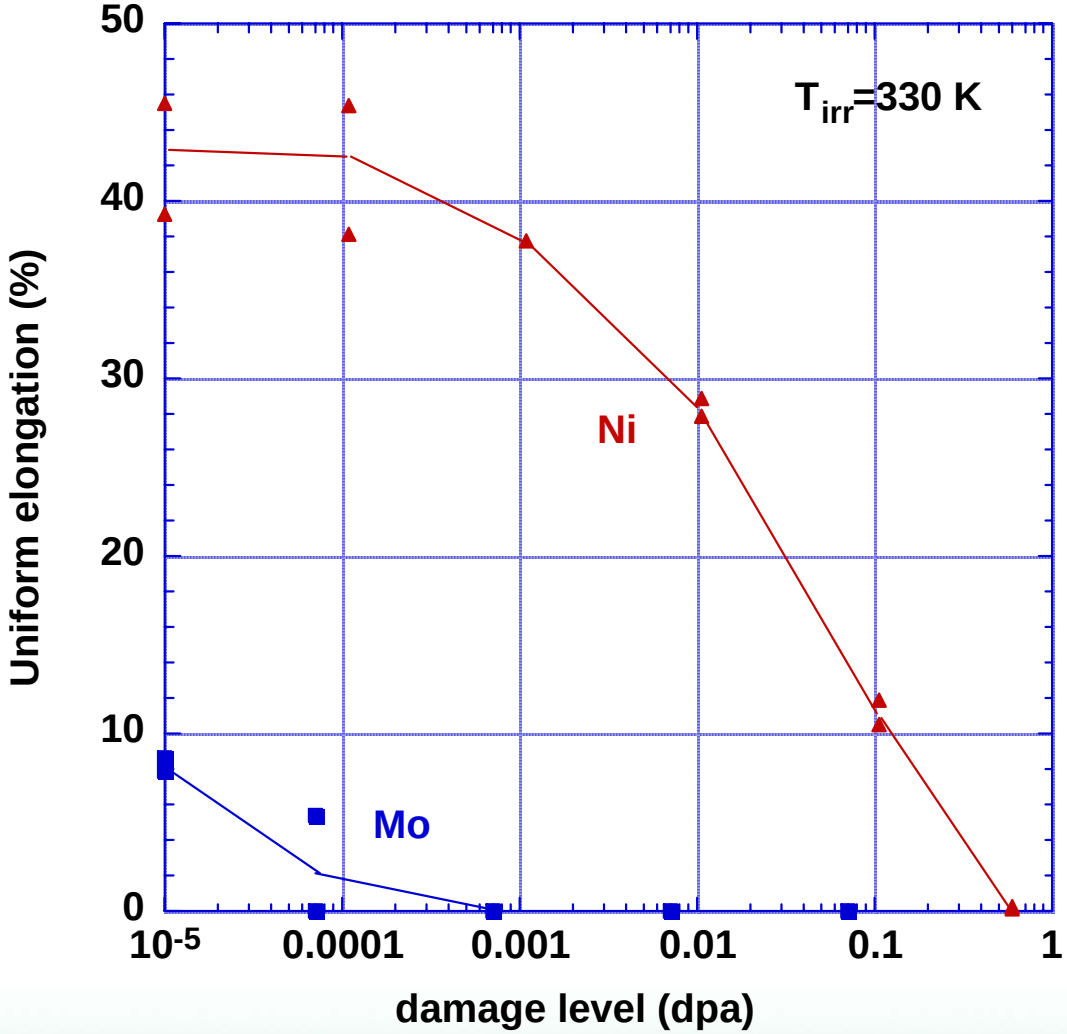
Tempered 1h at 700˚C (A) or 750˚C (B)

Irradiated Materials Suffer Plastic Instability due to Dislocation Channeling



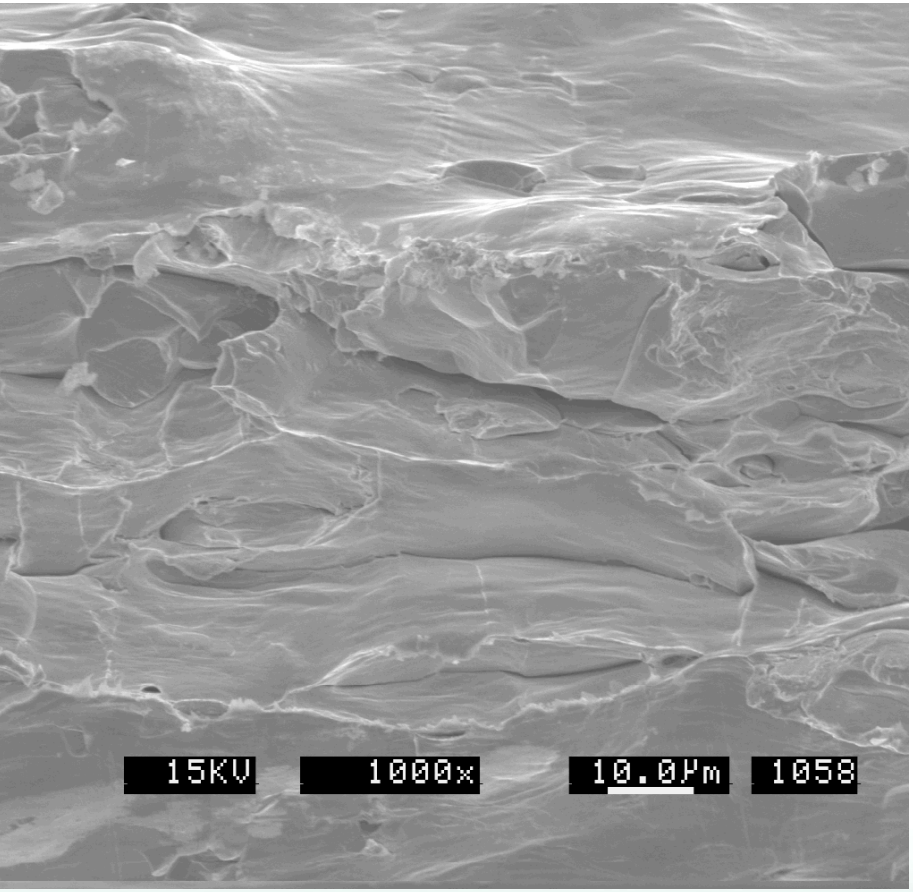


Irradiation near room temperature causes rapid degradation in the uniform elongation of Mo

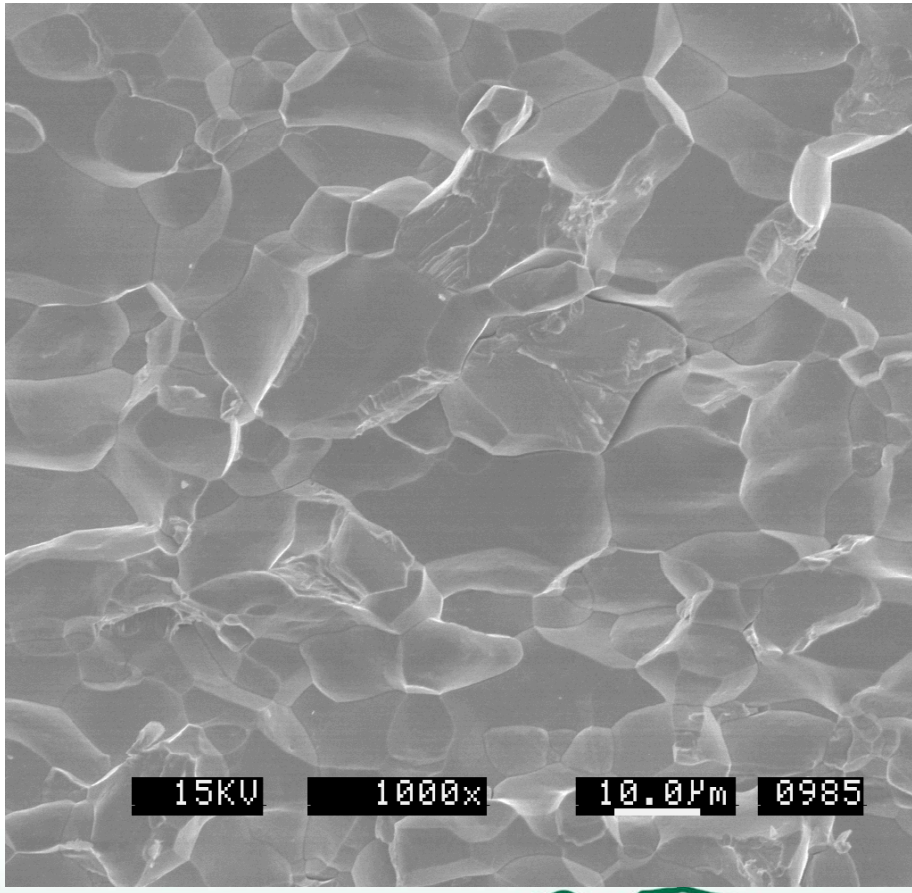


Grain boundary engineering is a key challenge for the successful development of Mo alloys in radiation environments

Unirradiated Mo tensile, T_{test}=295 K

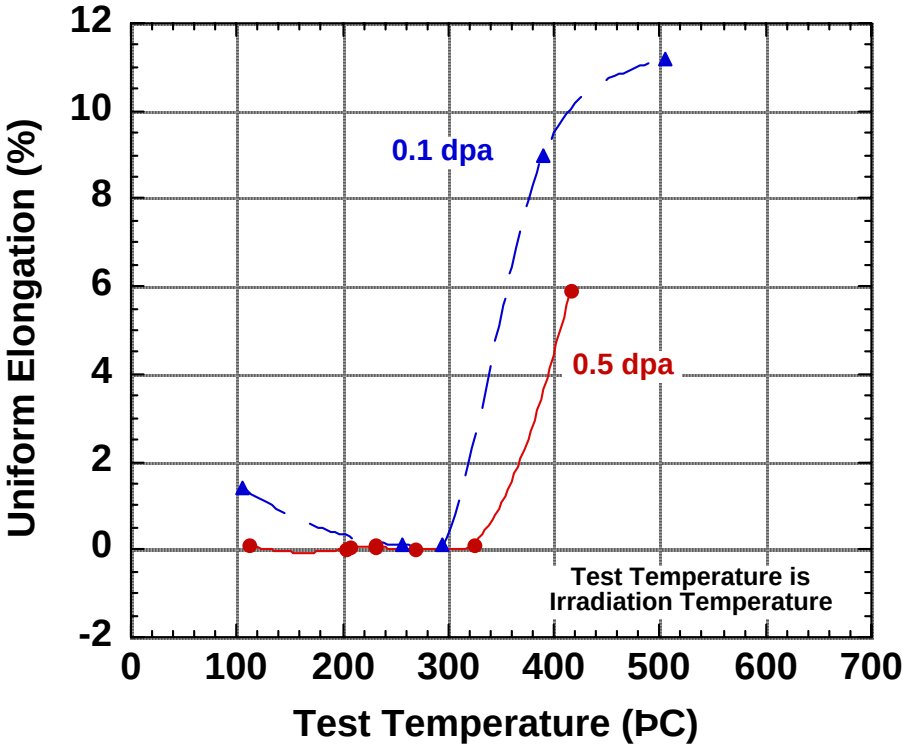


Irrad. Mo 1x10^{-4} dpa, 330K; T_{test}=295 K

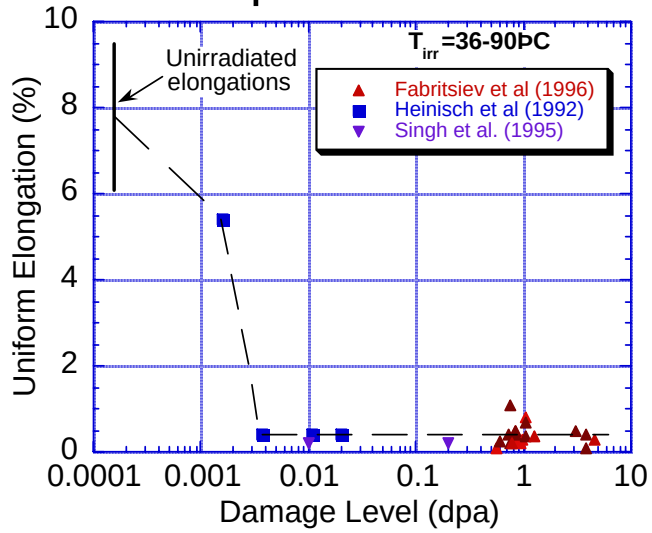


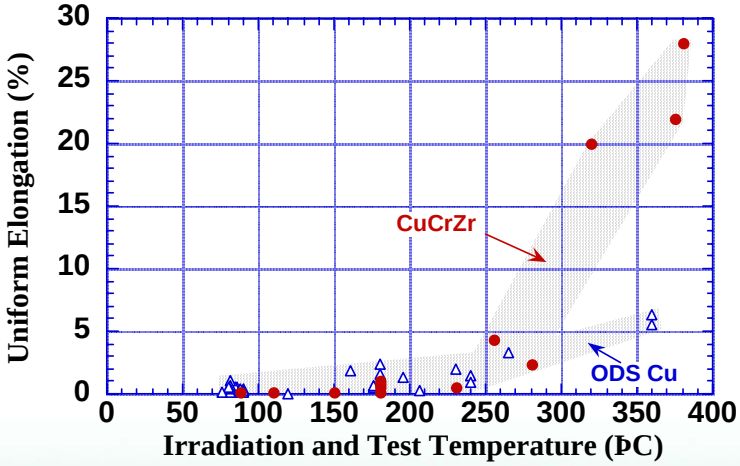
Low uniform elongations occur in many FCC and BCC metals after low-dose irradiation at low temperature

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

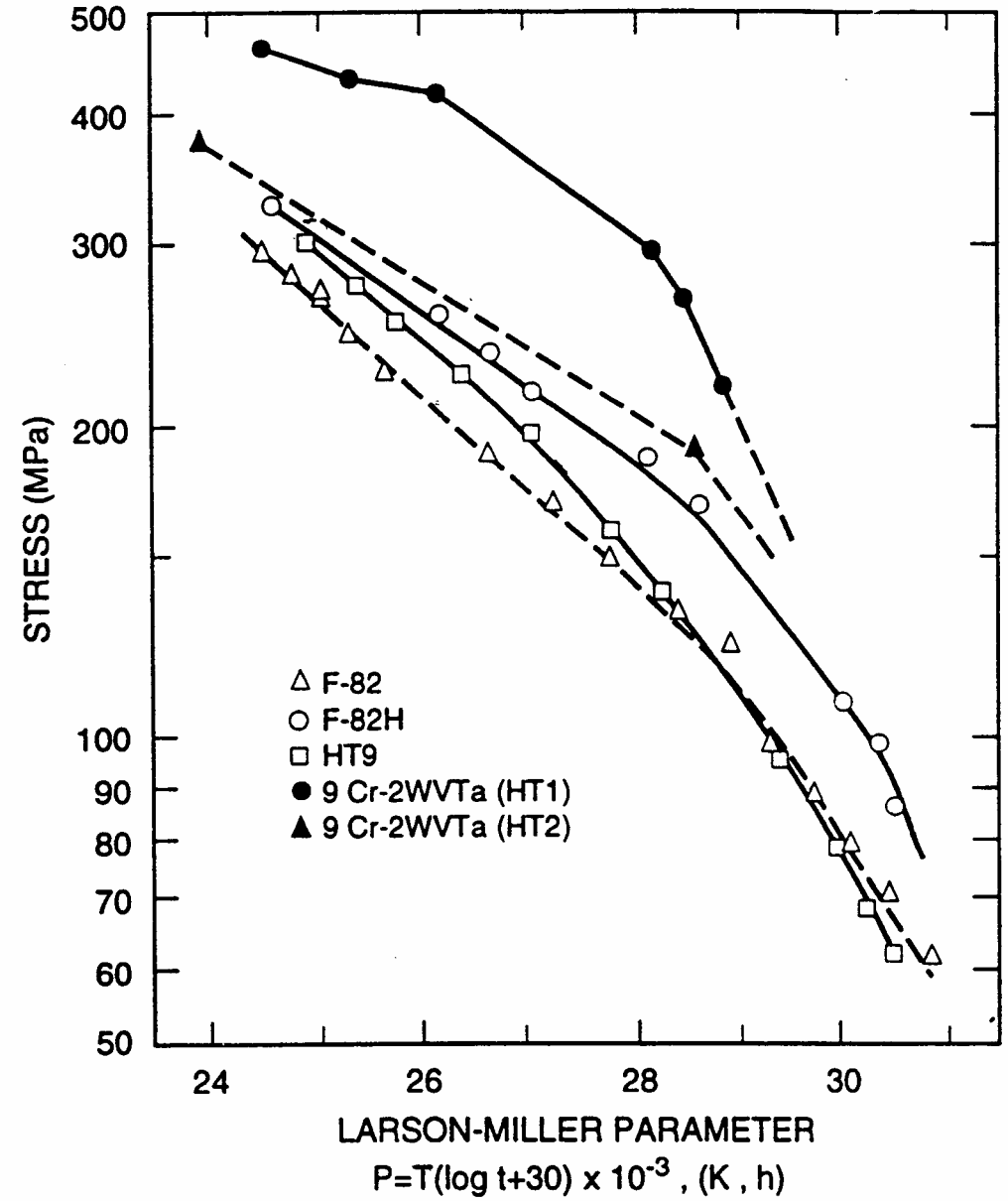


Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr





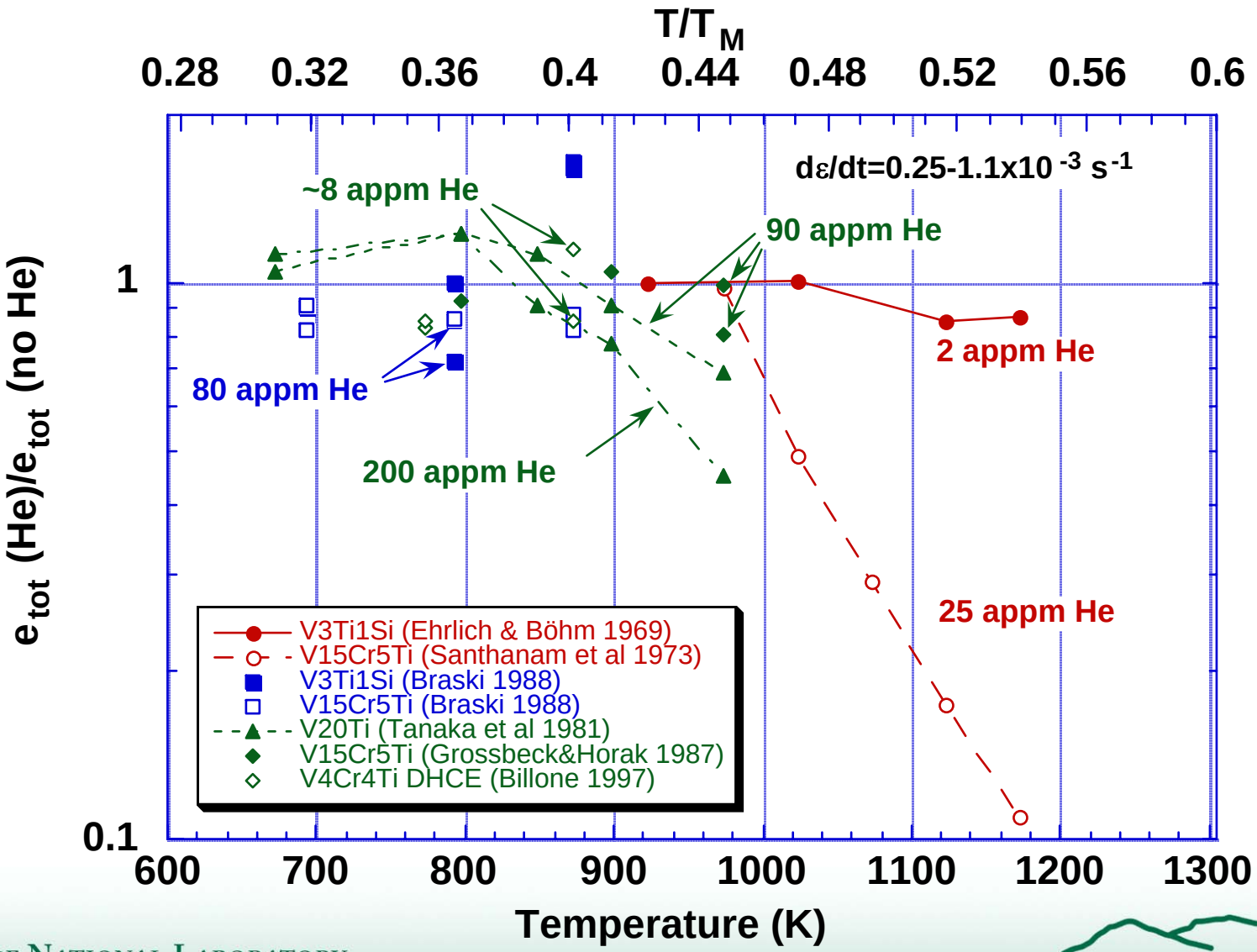
Comparison of Creep Rupture of Ferritic Alloys



Significant improvements in the performance of ferritic/martensitic steels can be achieved by further optimization of the microstructure

R.L. Klueh

He embrittlement in V alloys occurs for C_{He} >100 appm and/or test temperatures >700˚C

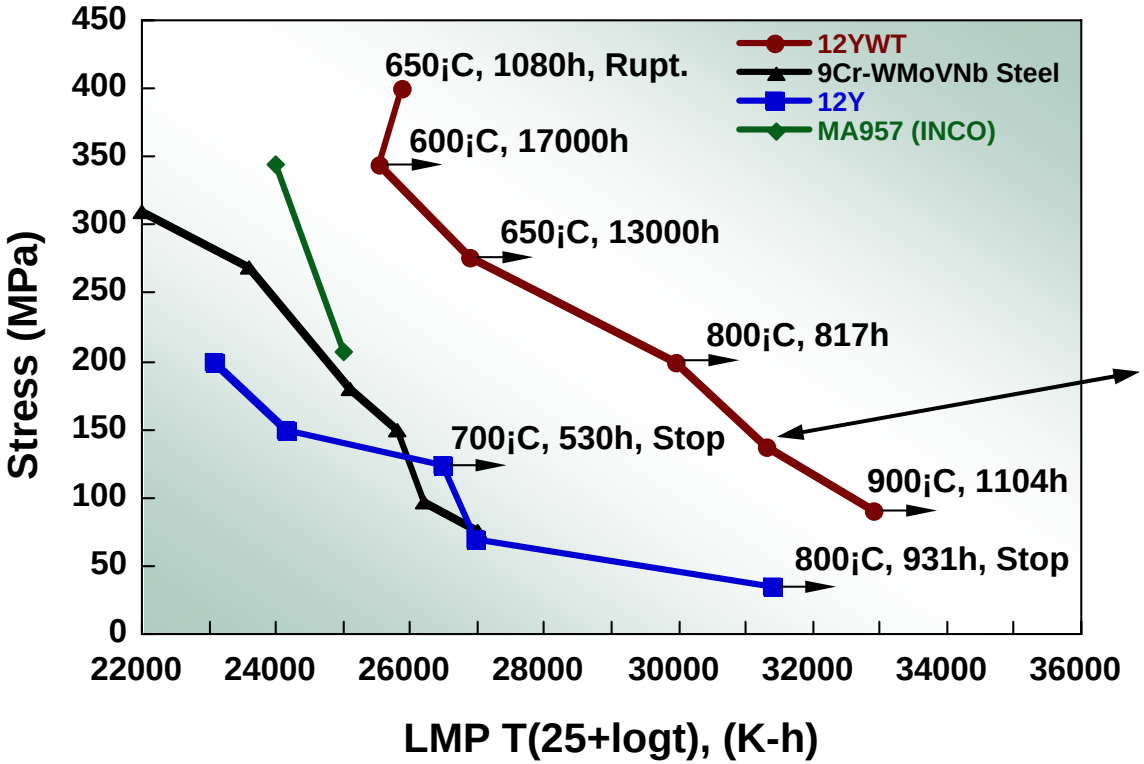


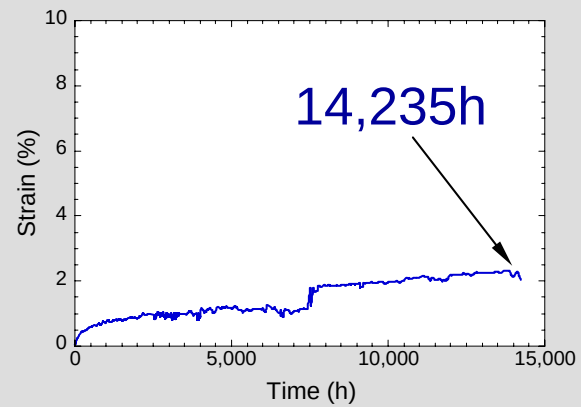
He embrittlement: Unresolved Questions

- **Effect of grain boundary type on He bubble density and size**
- **Quantitative dependence of He flux to grain boundaries on:**
  - **He production rate (n=0.75?)**
  - **Matrix sink density**
  - **Temperature (transition temperatures for bubble migration and coalescence vs. Ostwald ripening, etc.)**

=> need improved teaming between experimentalists and modeling community in order to develop robust experimentally-validated models covering all aspects of He embrittlement

Nanocomposited 12YWT Ferritic Steel Exhibits Excellent High Temperature Creep Strength



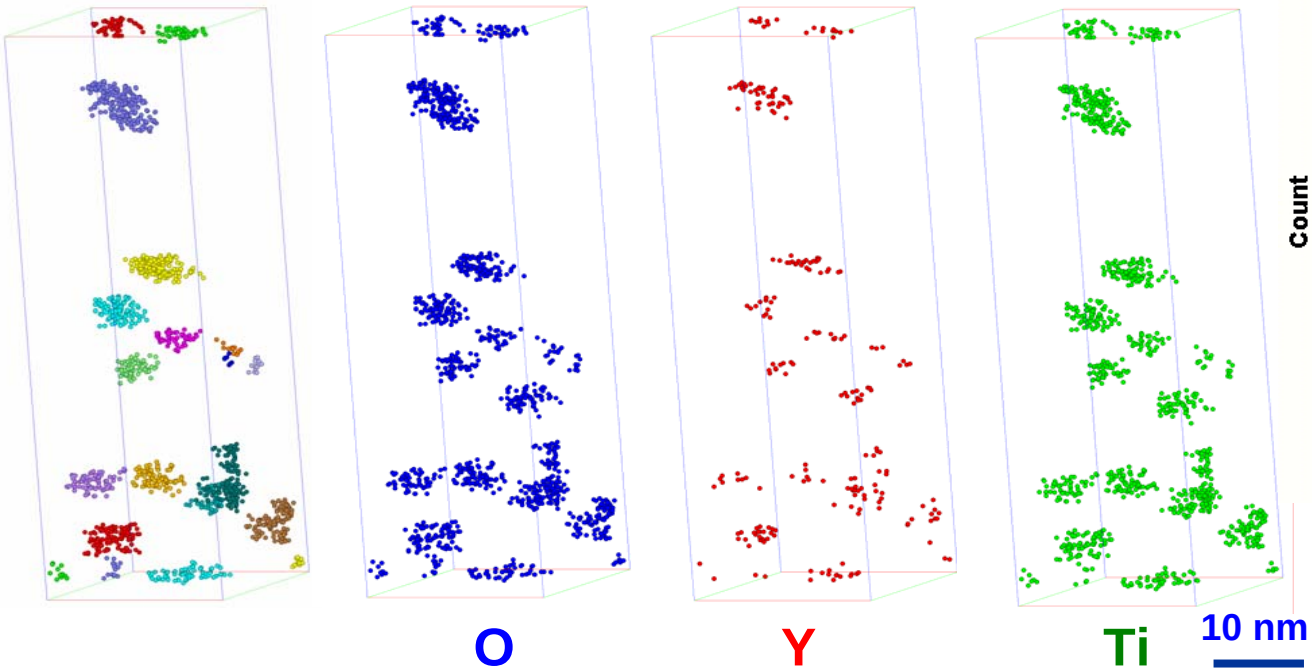


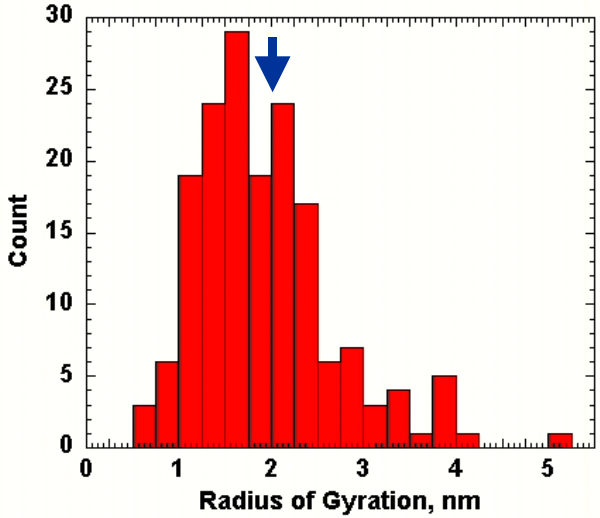
800°C and 138 MPa

- minimum creep rate
  $2.13 \times 10^{-10} s^{-1}$
- total strain
  2.03%

- Time to failure is increased by several orders of magnitude
- Potential for increasing the upper operating temperature of iron based alloys by ~200°C

Recent work suggests that thermodynamics may be significantly altered at the nanoscale





Atomic analysis of new nanocomposited ferritic steel (12YWT) provides clues to its outstanding creep strength (6 orders of magnitude lower creep rate than conventional steels at 600-900˚C)

Original Y_2O_3 particles convert to thermally stable nanoscale (Ti,Y, Cr, O) particles during processing

(Ti ,Y,Cr)mixed oxide: R=2.0 nm; N=1.4x10^{24}/m^3 (before and after thermal creep testing)

Unresolved Fusion Materials Issues (partial list)

- Primary damage and microstructural evolution in irradiated materials
  - Role of glissile interstitial clusters on microstructural evolution
    - Maximum glissile size, migration energies, reaction kinetics
  - Effect of O,C,N on microstructural evolution in BCC alloys (vanadium)
  - Why doesn't V exhibit a void lattice?
  - Why does Fe form <100> and <111> loops, whereas other BCC metals only form a/2<111> loops
  - Do we need to resurrect modeling effort on ballistic dissolution, radiation induced/enhanced/modified segregation, radiation induced/enhanced/modified precipitation
- Deformation (flow localization, thermal and irradiation creep)
  - Possibility of new Cottrell atmosphere mechanism to suppress thermal creep in nanocomposited ferritic steels?
  - What controls initiation, propagation of dislocation channels
  - Role of source vs lattice hardening
  - Effect of alloy composition on irradiation creep

Unresolved Fusion Materials Issues (partial list)

- Fracture mechanisms
  - Fracture/matrix strength constitutive equations: beyond semi-empirical
- Helium embrittlement
  - Optimum 2nd phase microstructure for He trapping (appropriate efficieny for He trapping, cf. fine phosphide vs. bulky MC particles in stainless steel)
- Alloy development/materials by design
  - Potential for evolutionary improvements in materials properties (ferritic steels, etc.)
  - Potential for revolutionary improvements
  - Can ductile refractory alloys be formulated?
- What are the major He effects R&D issues for metallic, ceramic materials
  - Need to develop national coordinated research program
- What is maximum dose that we have confidence can be achieved in current reference reduced activation materials
  - What are controlling physical process that limit the lifetime