Overview of the ORNL Fusion Materials Science program

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Oak Ridge National Laboratory

Fusion Materials Sciences peer review

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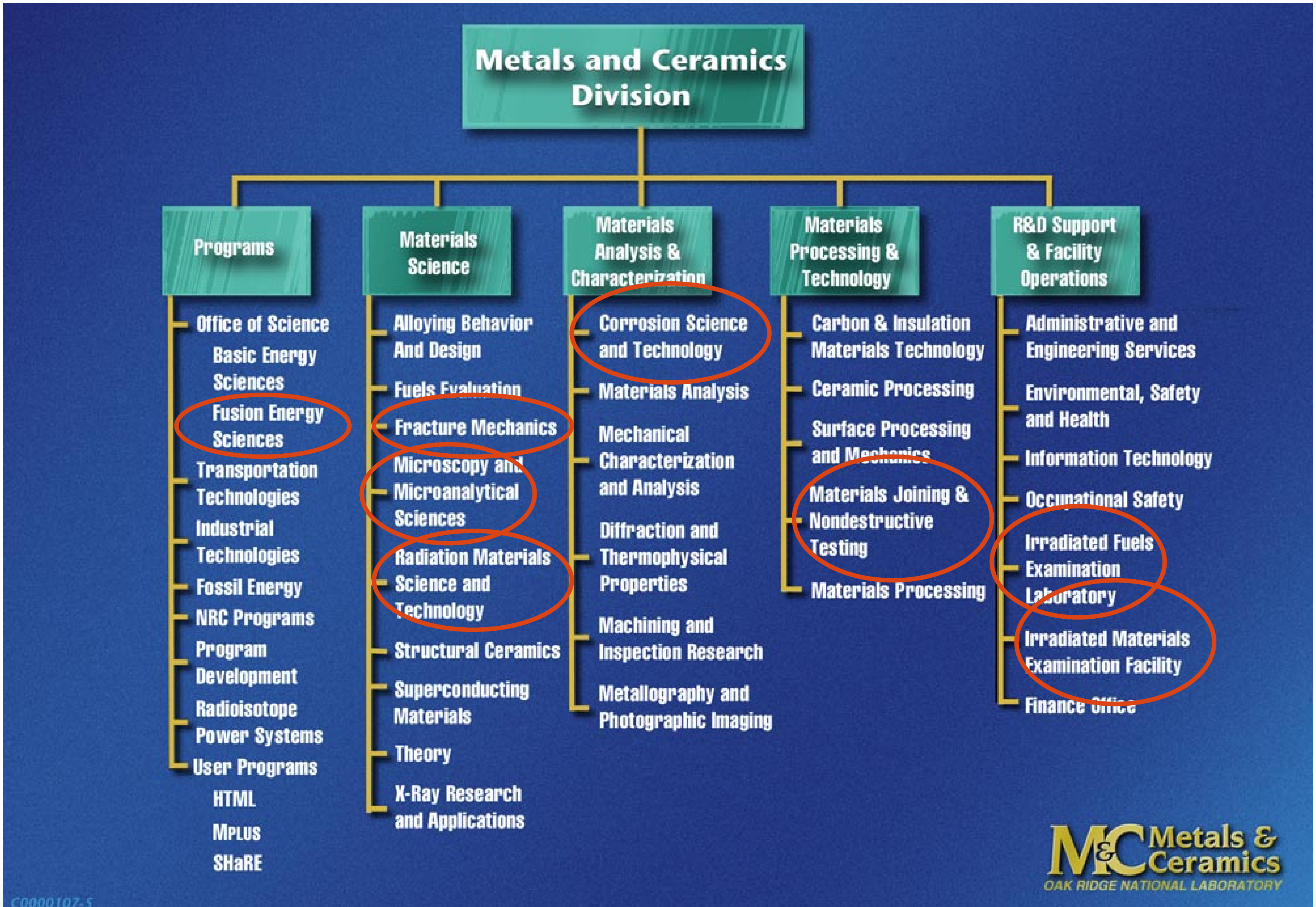
University of California-Santa Barbara

Fusion Materials Research Requires Multidisciplinary Effort



The ORNL fusion materials program has two complementary functions in the national program

- Fusion materials research (often in collaboration with US or foreign institutions)
  - Mechanical properties of structural materials (unirradiated and irradiated)
  - Microstructure-property investigations
  - Physical properties of selected materials (electrical and thermal conductivity of Cu alloys, ceramics)
  - Targeted R&D (compatibility of MHD insulators with Li, joining research, He accumulation and displacement damage modeling, etc.)
- Support services for national fusion materials program
  - Irradiation capsule design, assembly, surveillance, disassembly, specimen sorting and shipping
  - Host laboratory for DOE/JAERI collaboration on fusion materials
  - DOE/MEXT Jupiter-II collaboration on fusion blanket technology

The ORNL fusion materials program consists of 11 core research staff members*, 3 postdocs, 2 on-site Ph.D. students,

- 6 of the 11 core research staff members have been awarded Fellow status in professional societies (ASM, ANS, ASTM, AWS, ACerS)
- Metals & Ceramics Division fusion materials research staff
  - S.A. David (S.S. Babu, J.F. King): joining of materials
  - M.L. Grossbeck: mechanical properties
  - D.T. Hoelzer (electron microscopy, microstructure-property investigations
  - R.L. Klueh (physical metallurgy of steels)
  - B.A. Pint (P.F. Tortorelli): chemical compatibility
  - J.P. Robertson: tempered martensitic steels; hot cells research coordination
  - A.F. Rowcliffe: microstructure-property investigations
  - L.L. Snead (E. Lara-Curzio, R.A. Lowden, T.M. Besmann): ceramic composites
  - M.A. Sokolov (R.K. Nanstad)
  - R.E. Stoller: theory and modeling
  - S.J. Zinkle: microstructure-property investigations
  - N. Hashimoto (postdoc): electron microscopy
  - T.S. Byun (postdoc, shared with NERI): mechanical properties of materials
  - T. Hinoki (postdoc): ceramic composites microstructure-property investigations

**core researcher defined as staff member supported ≥20% by fusion materials*

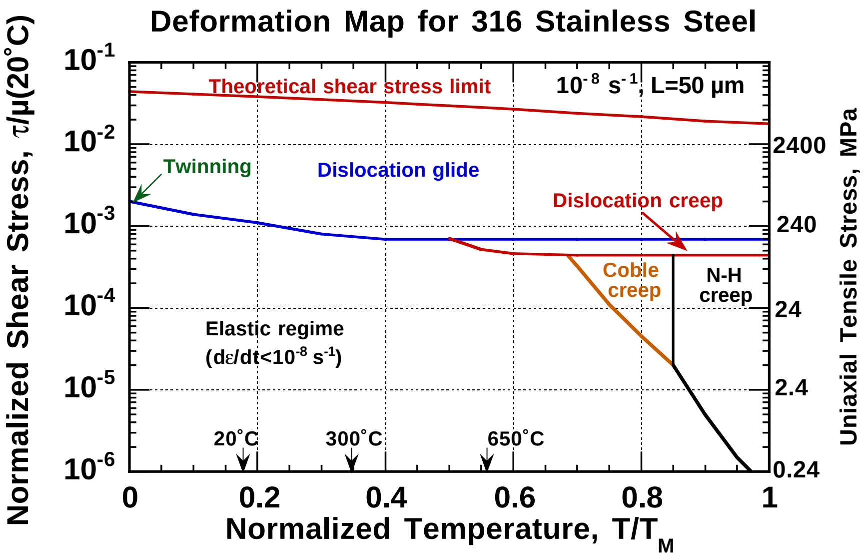
ORNL fusion materials staff, continued

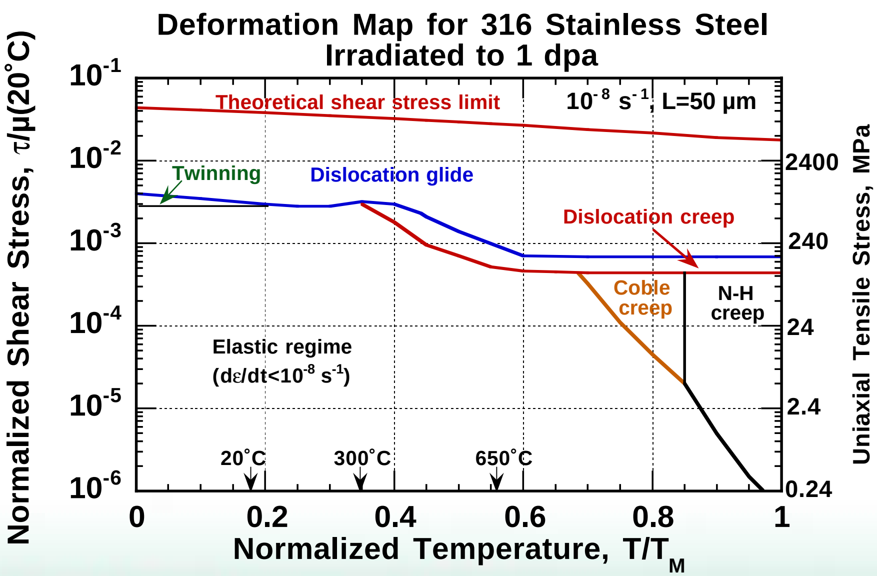
- On-site Ph.D. students
  - S.D. Connery (RPI): ceramic composites
  - M.K. West (U. Tennessee): mechanical properties of nanocomposited alloys

- Research support staff (Metals & Ceramics Division)
  - M.J. Gardner: specimen preparation, laser profilometry
  - L.T. Gibson: TEM specimen preparation, mechanical property testing
  - J.L. Bailey: low-level radioactive specimen testing
  - E.T. Manneschmidt: mechanical property testing (fracture mechanics)
  - P.S. Bishop, L.J. Turner, W.W. Bolinger, G.W. Parks: Hot cells staff
  - R.D. Godfrey: fusion program budgets, administrative support
  - J.L. Bishop: Administrative support

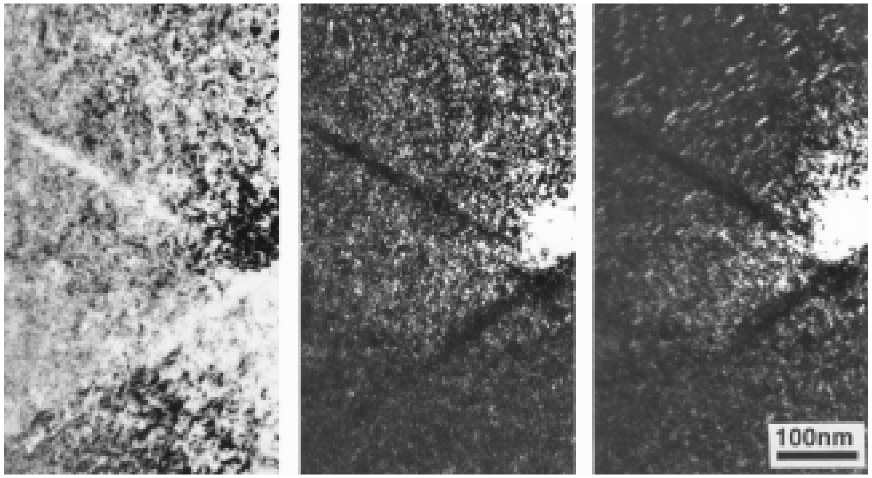
- Irradiation capsule support staff (Engineering Technology Division)
  - K.R. Thoms, A.L. Qualls : irradiation capsule design
  - D.W. Heatherly, R.G. Sitterson, R.L. Wallace: construction and surveillance of irradiation capsules
  - M. Hurst, D.G. Raby: irradiation capsule I&C

Deformation mechanisms in FCC metals

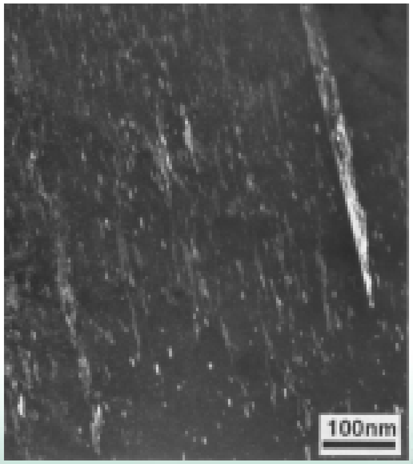




Irradiation is a useful tool to produce controlled microstructures for deformation mechanics studies

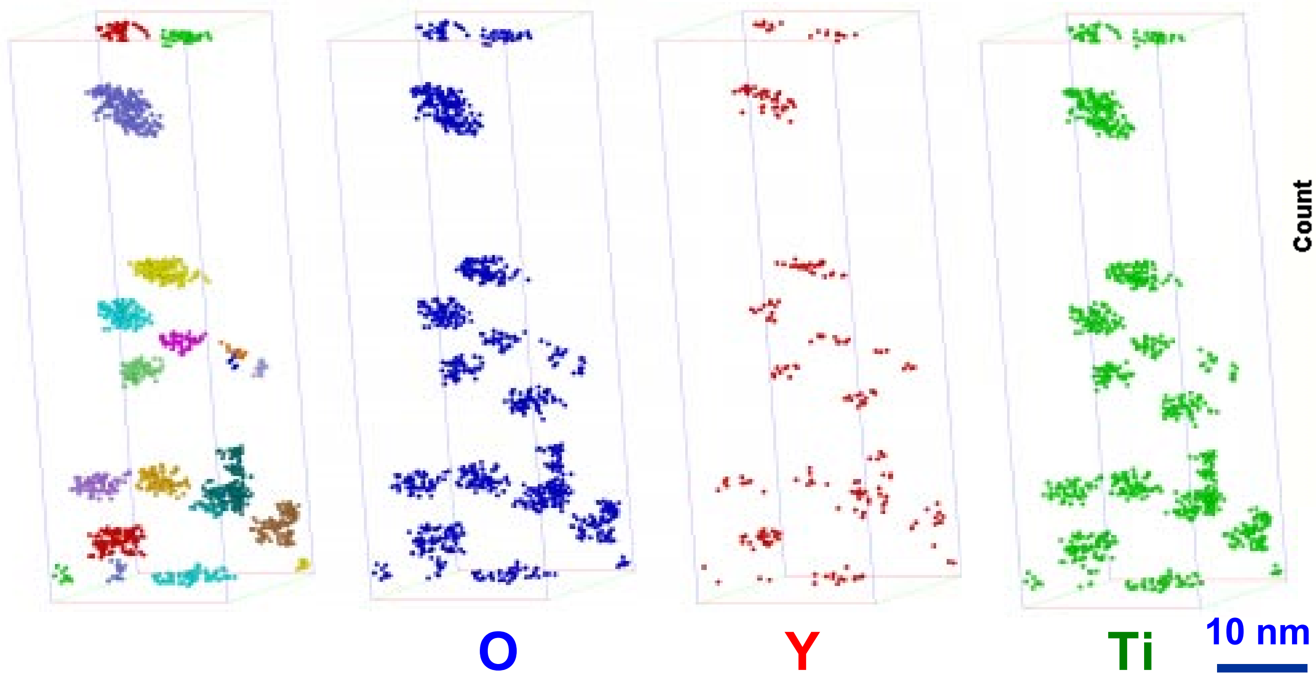


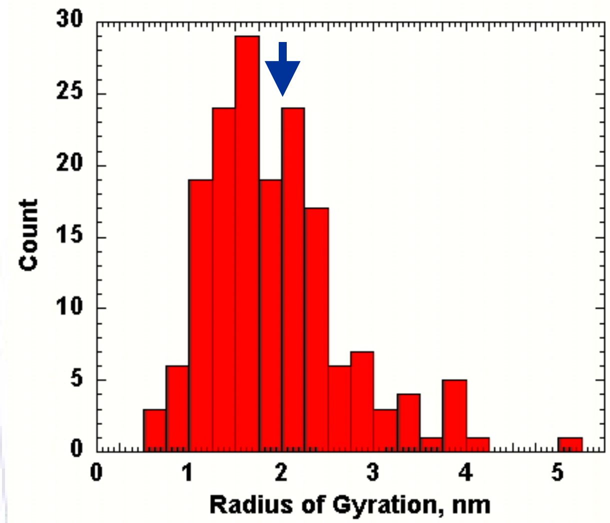
Channeling (Disln glide) occurs at higher temperatures (~300˚C)



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

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



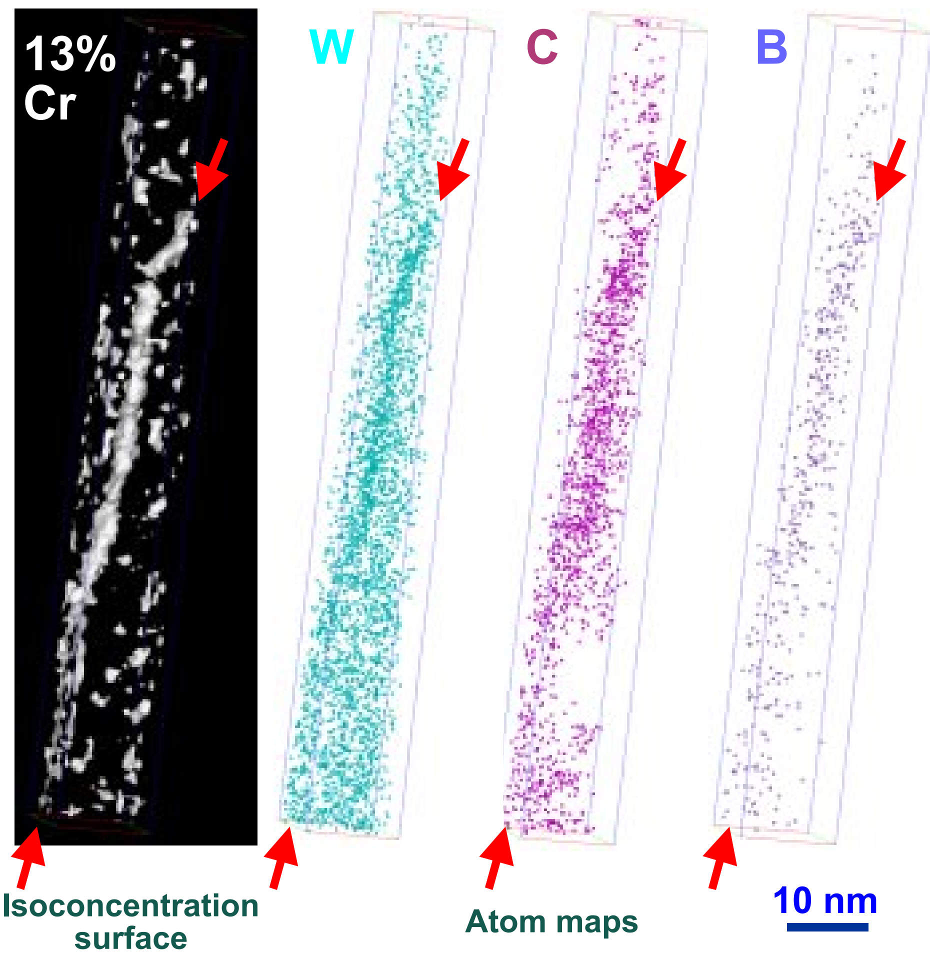


Atomic analysis of new nanocomposited ferritic steel (12YWT) provides clues to its outstanding creep strength (6 orders of magnitude lower creep rate than conventional steels at 600-900˚C)

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)

SOLUTE SEGREGATION TO DISLOCATIONS



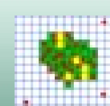
COMPOSITION OF SOLUTE-ENRICHED REGION AROUND DISLOCATION

analysis volume defined by a C + B atom maximum separation of 1.5 nm

	Alloy	Ferrite	Dislocation
Cr	13.3	12.3	15.9 ± 0.16
W	0.92	0.71	1.21 ± 0.05
Ti	0.46	0.08	0.44 ± 0.03
Y	0.13	0.01	0.16 ± 0.02
O	0.19	0.11	0.53 ± 0.03
C	trace	0.18	1.38 ± 0.05
B	trace	0.05	0.44 ± 0.03
N	trace	0.15	0.17 ± 0.02

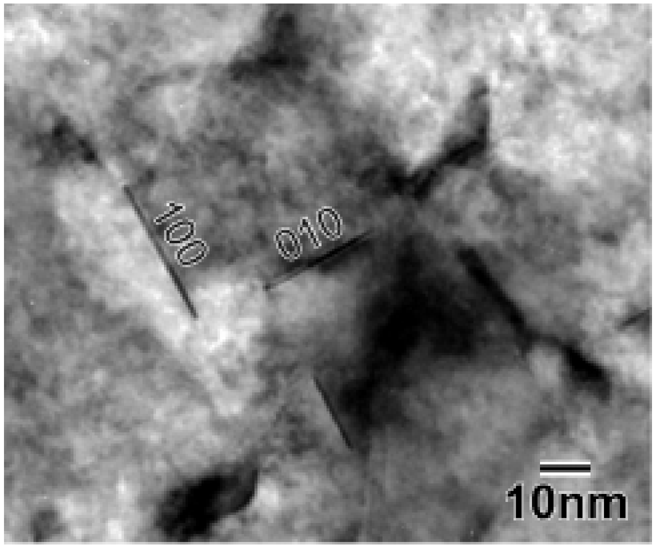
Enrichments of Cr, W, Ti, Y, O, C, B, and N were observed at dislocations. The Ti and Y enrichments could provide a mechanism for reduction in N_v. Dislocation pinning may contribute to the enhanced creep lifetimes.

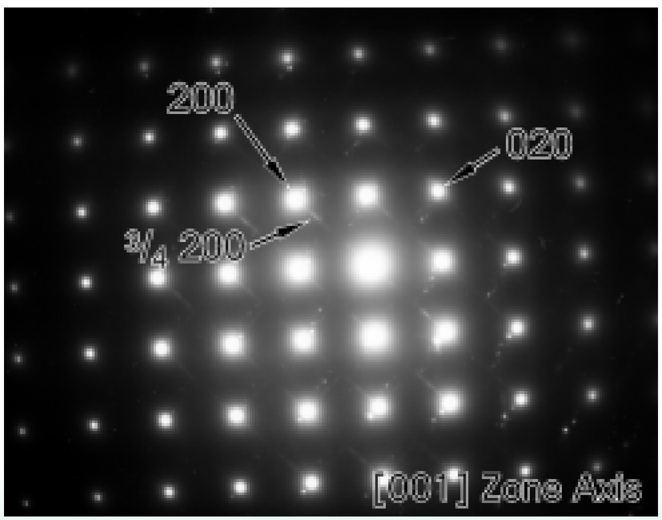
12YWT as-prepared



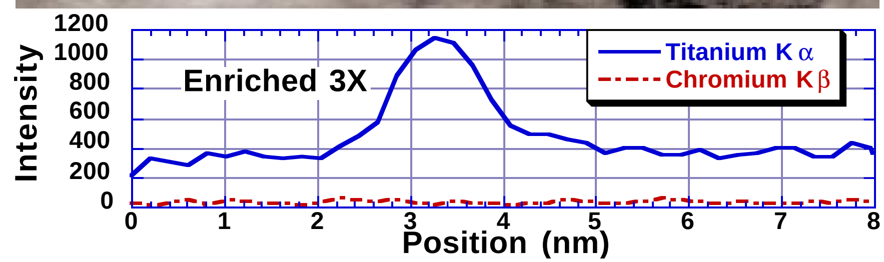
Maximum separation envelope method

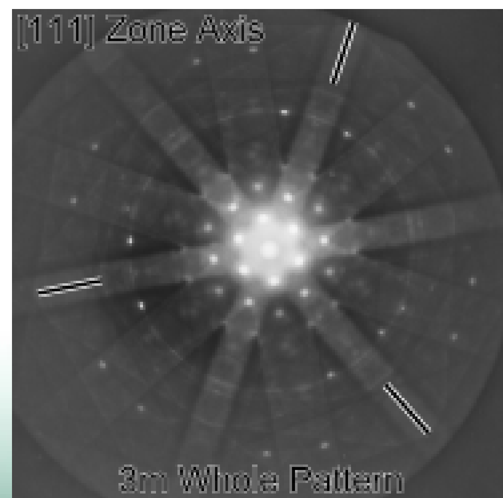
Advanced Analytical Electron Microscopy Techniques are being used to Examine Precipitates in V alloys





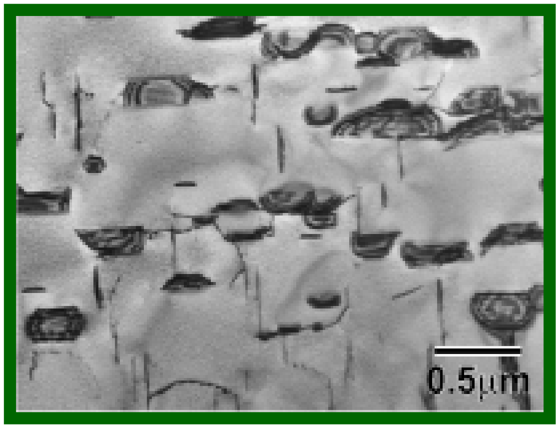
Solute Segregation Was Detected in V-4Cr-4Ti Following Neutron Irradiation to 0.5 dpa at Elevated Temperatures





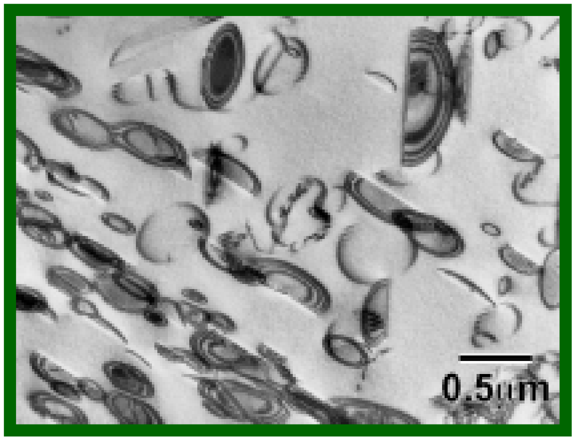
Analytical microscopy reveals Ti-rich precipitates with Fm3m space group
(Baker-Nutting precipitate-matrix orientation)

Plate Formation on {001} Habit in V-4Cr-4Ti



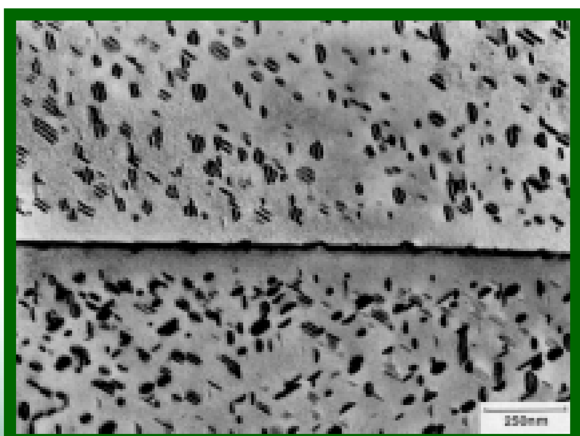
GTA Weld

- $Ti_{16}(O_3N_3C_2)$



Oxidized

- $Ti_{58.2}(O_{12.8}C_{24.1}N_{4.9})$



Neutron Irradiated

- $Ti_{>90}(O,N)_{<10}$ [No C]

UT-BATTELLE

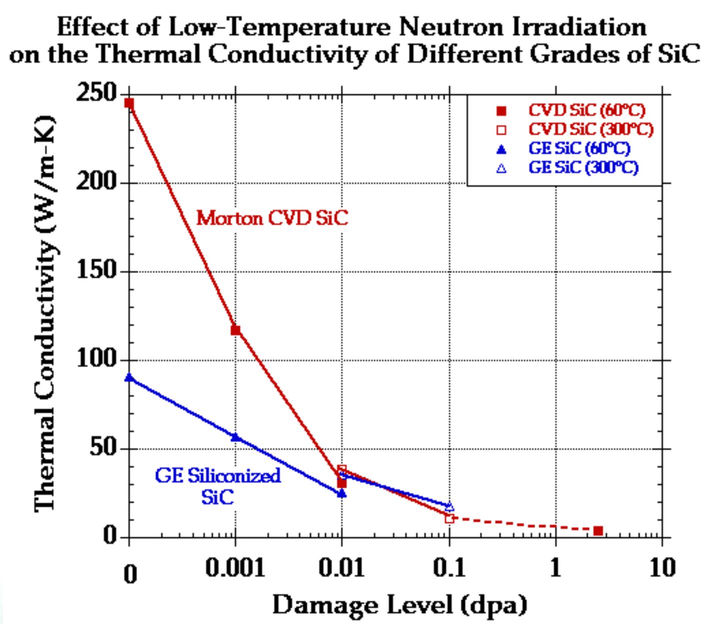
Physics of phonon transport & scattering are being investigated in neutron-irradiated ceramics

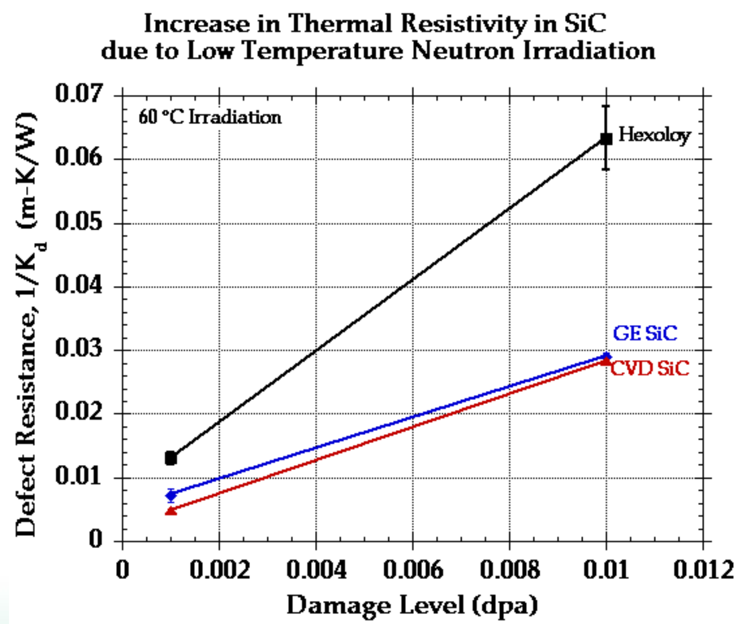
$$[K(T)]^{-1} = \left[\frac{1}{K_u(T)} + \frac{1}{K_{gb}(T)} + \frac{1}{K_{d0}} + \frac{1}{K_{rd}}\right]$$

Thermal resistance of different phonon scattering centers can be simply added if their characteristic phonon interaction frequencies are well-separated from one another

$$\frac{K_{irr}}{K_{unirr}} = \left(\frac{2h\upsilon^2}{18\pi^2\Omega\Theta_D K_{unirr} C_v}\right)^{1/2} \tan^{-1}\left(\frac{2h\upsilon^2}{18\pi^2\Omega\Theta_D K_{unirr} C_v}\right)^{-1/2}$$

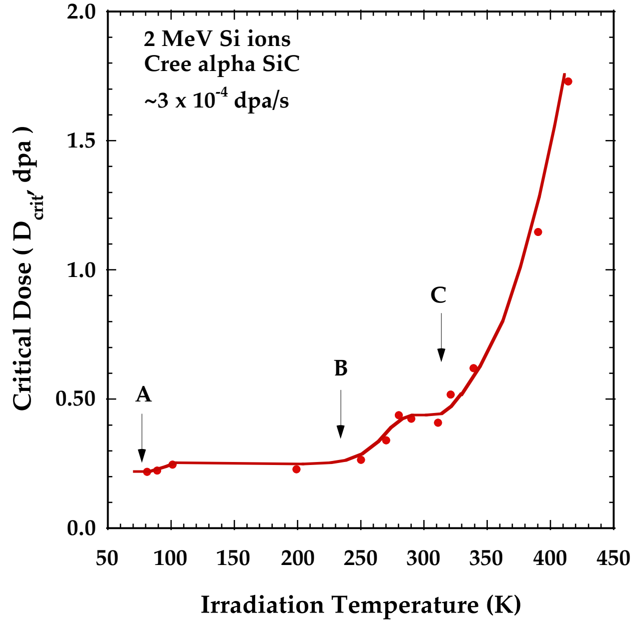
Thermal resistance due to radiation-induced defects (vacancies, dislocation loops, etc.) is proportional to their concentration

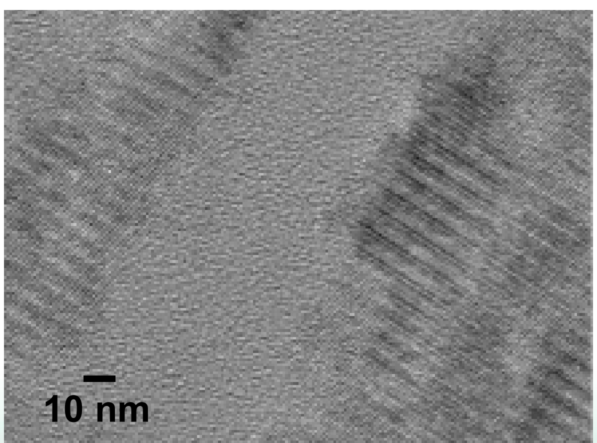




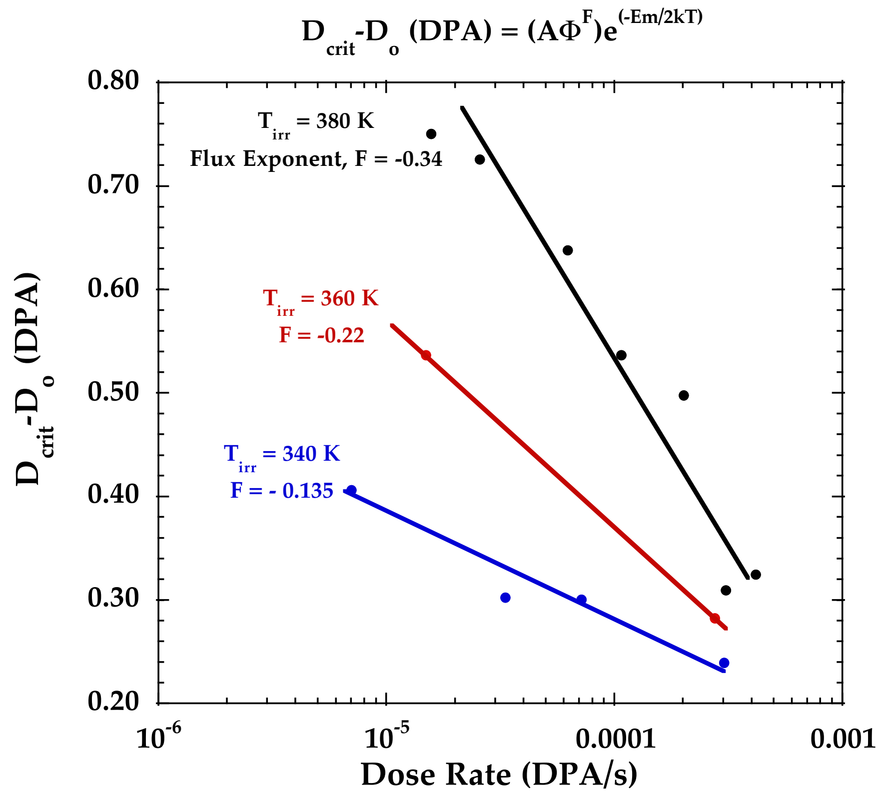
SiC Amorphization

3 recovery substages are observed below 320 K



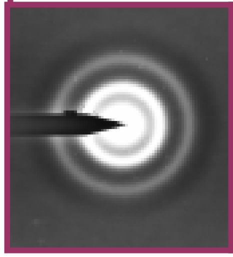


Analysis of flux dependence shows recovery substages are not associated with long range point defect migration (F<0.5 up to 380 K)

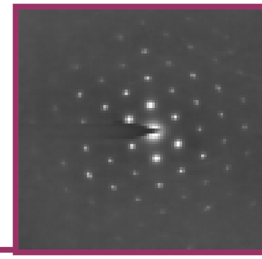
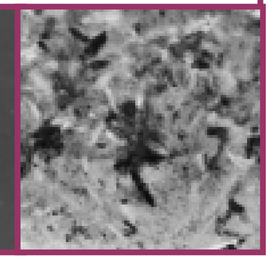


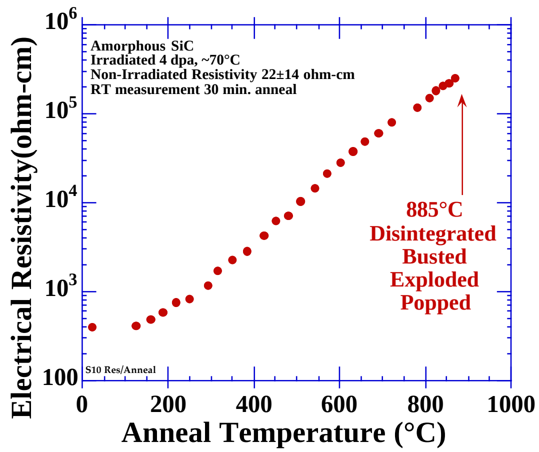
➡ **Implies that both vacancies and interstitials are immobile in SiC up to 100˚C (interstitials are mobile in many other ceramics at room temperature)**

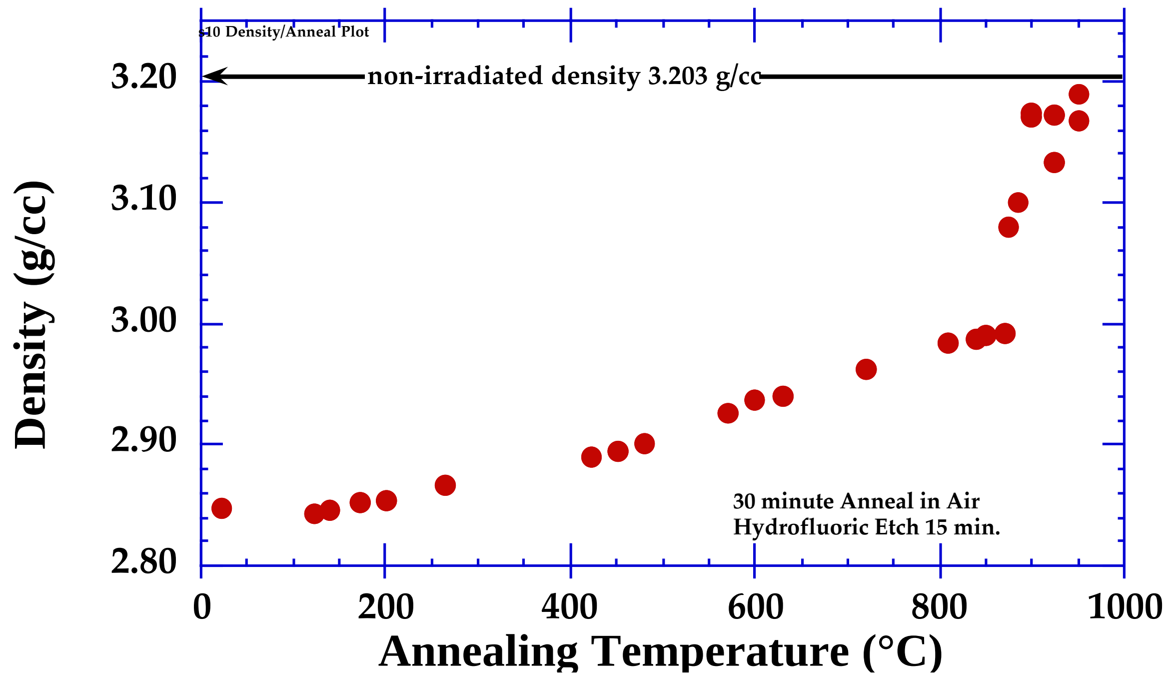
Effect of annealing on the properties of bulk amorphous SiC

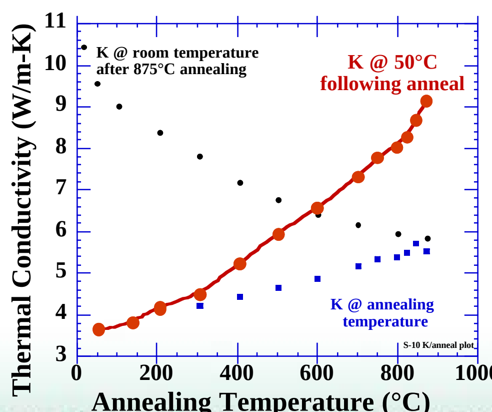



- Amorphization causes large changes
  - --> density change, -10.8 %
  - --> hardness change, -46 %
  - --> elastic modulus change, -45 %

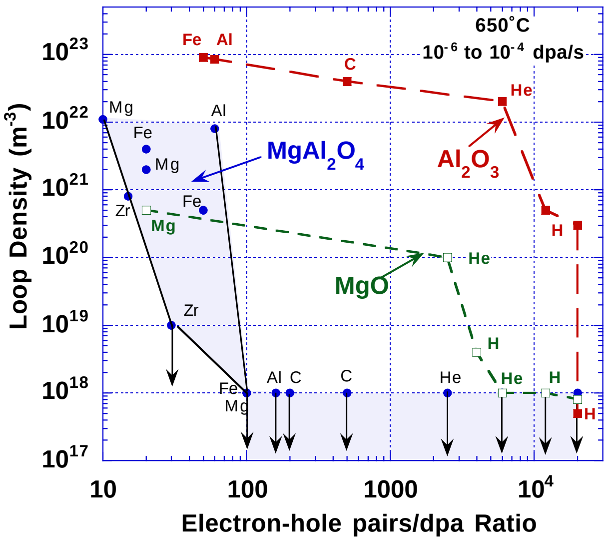


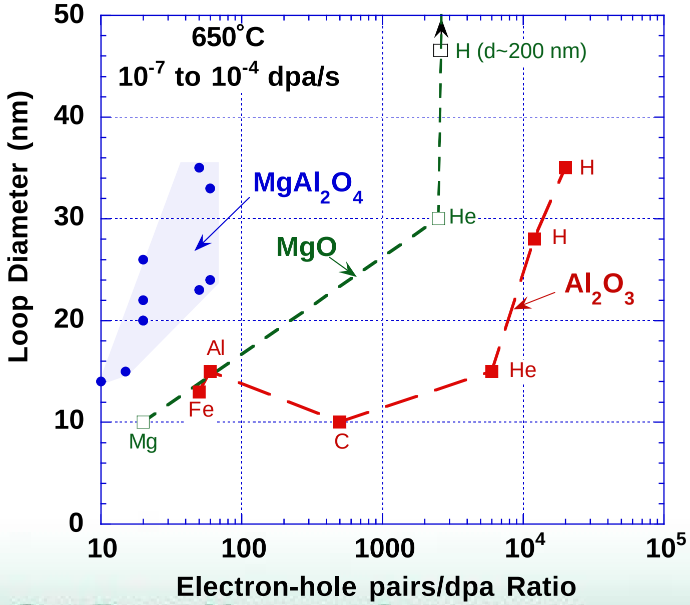




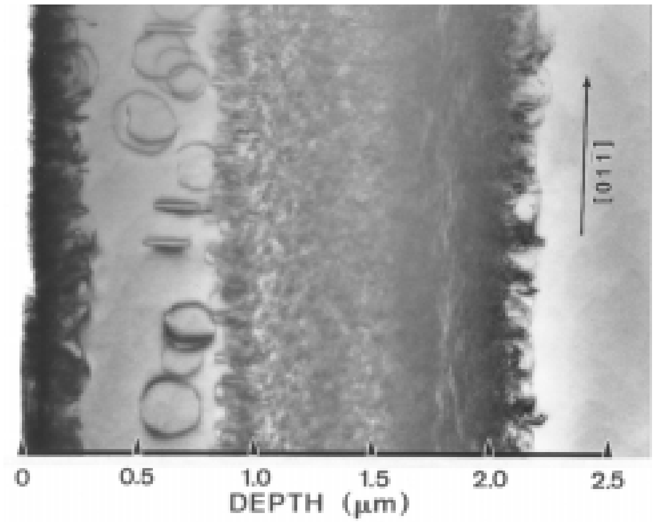
A continuum of short-range ordered states is observed in amorphous SiC during annealing up to 850˚C (recrystallization occurs above 875˚C)

Investigation of ionization-induced diffusion in ceramics

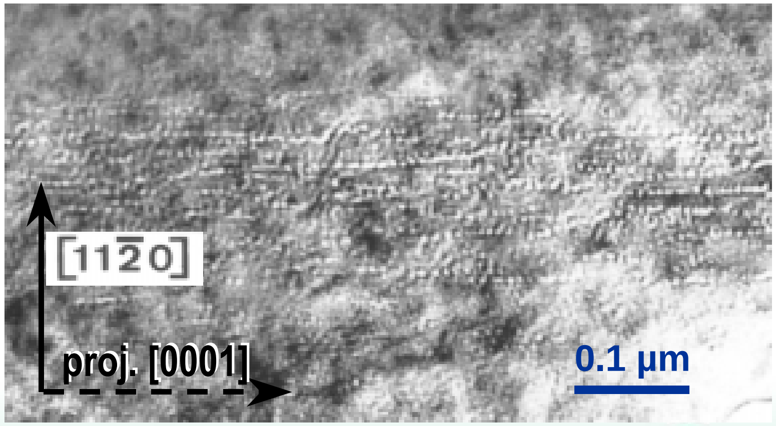




Large interstitial loops in $MgAl_2O_4$ ion-irradiated at 25˚C for regions with >100 eln.-hole pairs per dpa



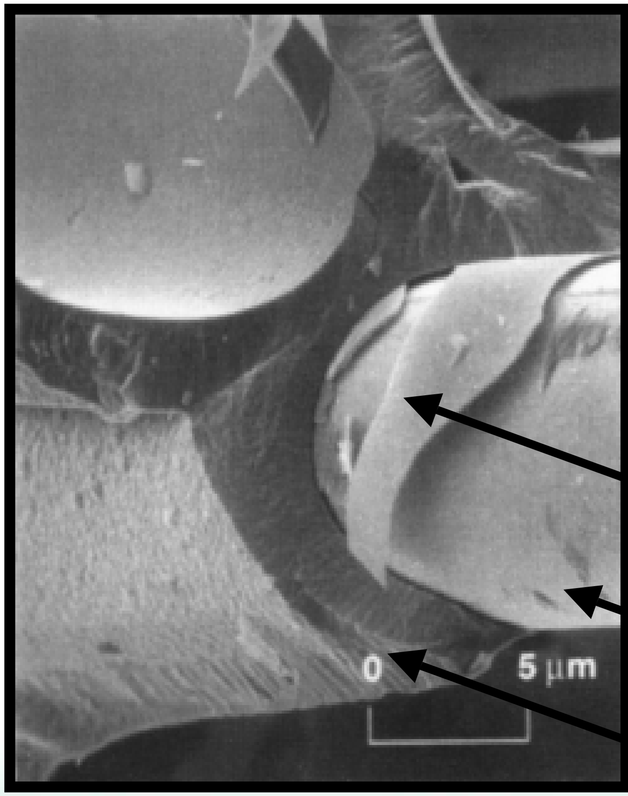
Aligned cavities in Al_2O_3 ion-irradiated at 25˚C (Al/O/He ion irradiation, >500 eln.-hole pairs per dpa)



Silicon Carbide Composites for Fusion Structures

Silicon carbide composite is the least-developed structural material studied in the US Magnetic Fusion Materials Program, but it has the **greatest potential**

Very Low Radioactivation - Very High Temperature Use

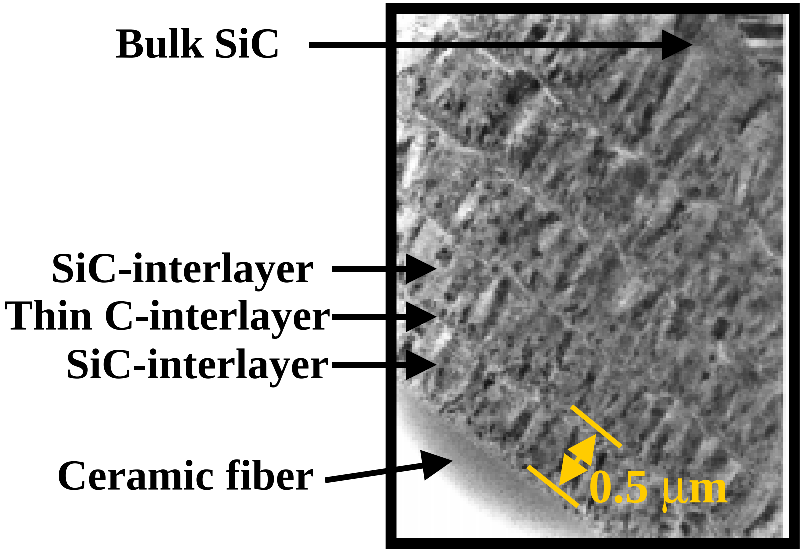


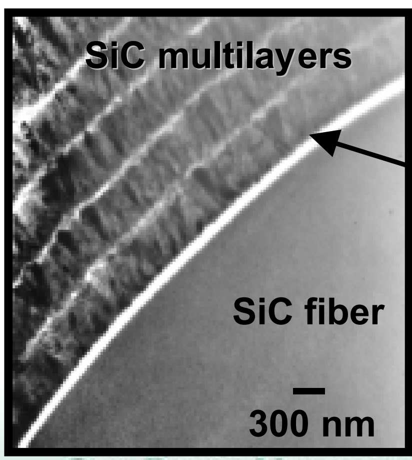
Areas being actively studied

- Radiation Hardened Composite Development
- Effects of Helium on Mechanical Properties
- Radiation Degradation of Thermal Conductivity
- Swelling, Amorphization and Defect Fundamentals

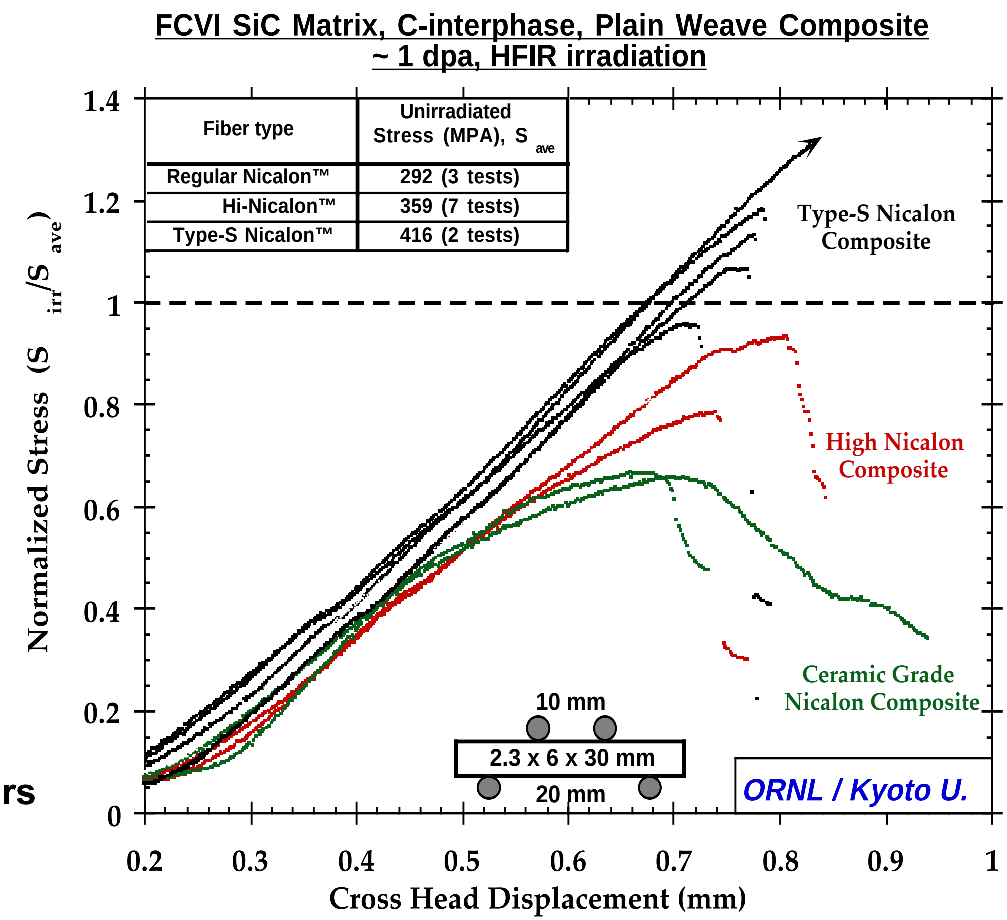
Development of Radiation-Resistant Silicon Carbide Composites

Until recently, SiC/SiC composites underwent significant degradation in mechanical properties due to non-SiC impurities in fibers causing interfacial debonding.

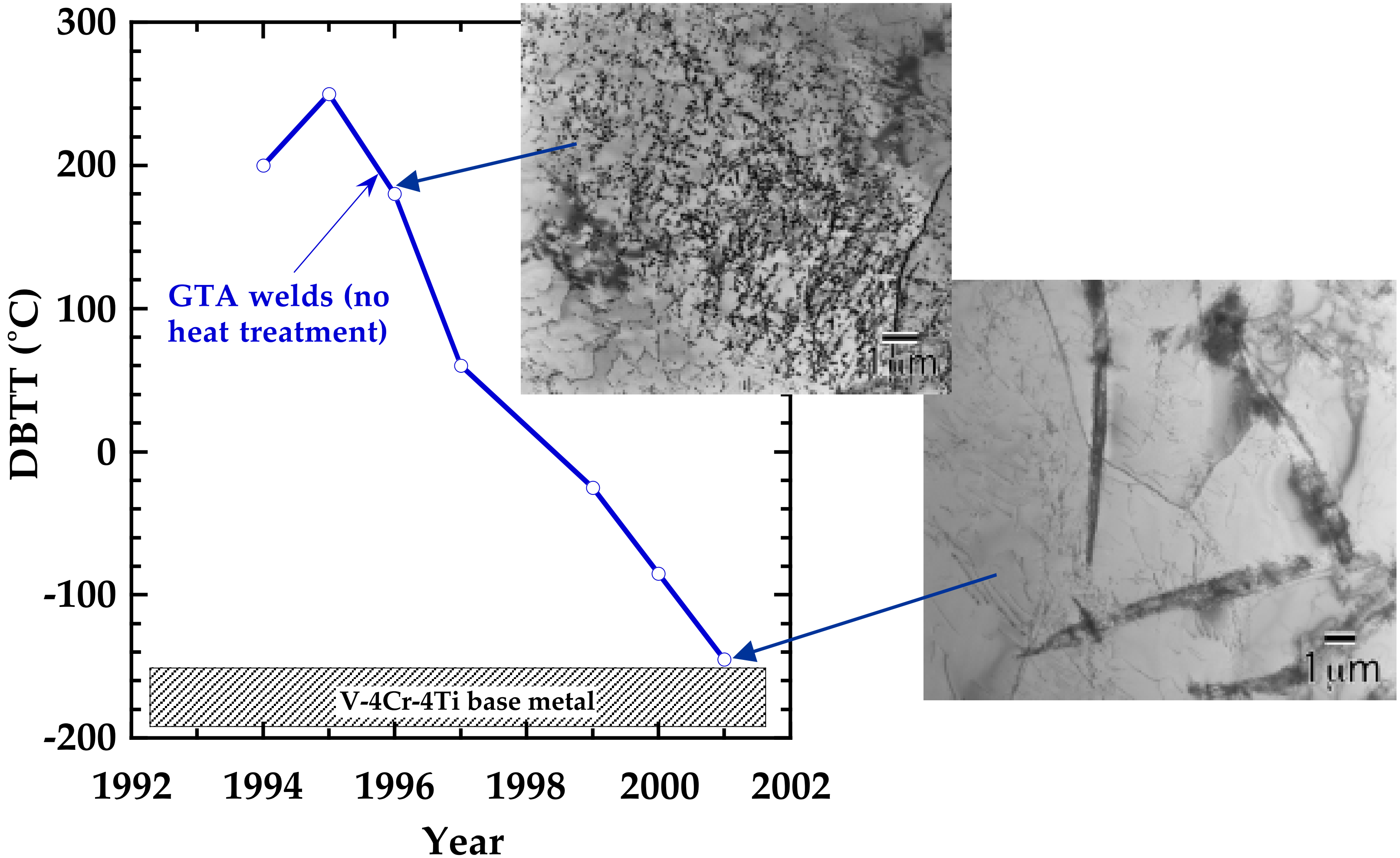




Upon irradiation, if fibers densify, fiber/matrix interfaces debonds -->strength degrades



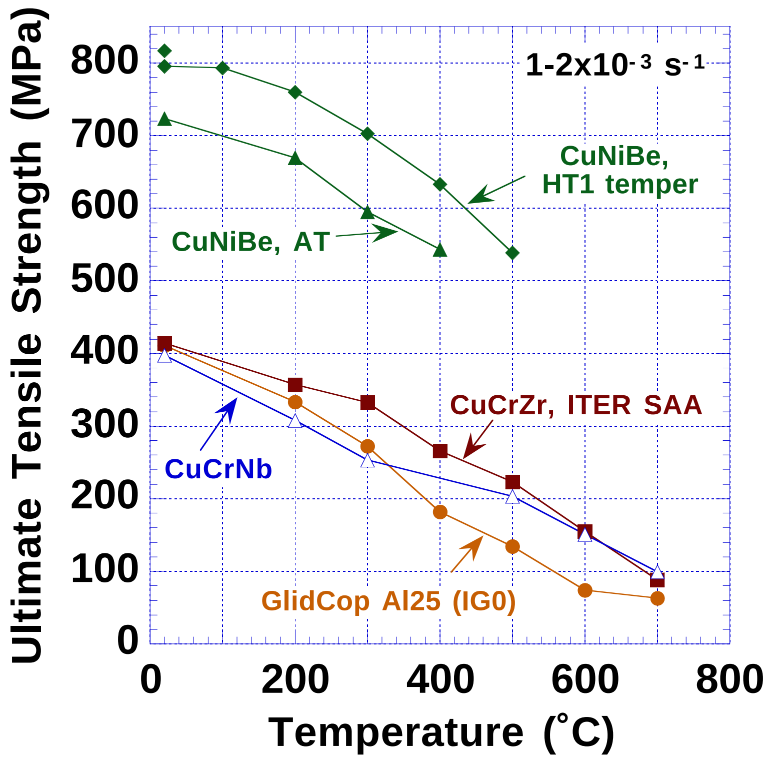
The fusion materials welding program has successfully resolved one of the key feasibility issues for V alloys



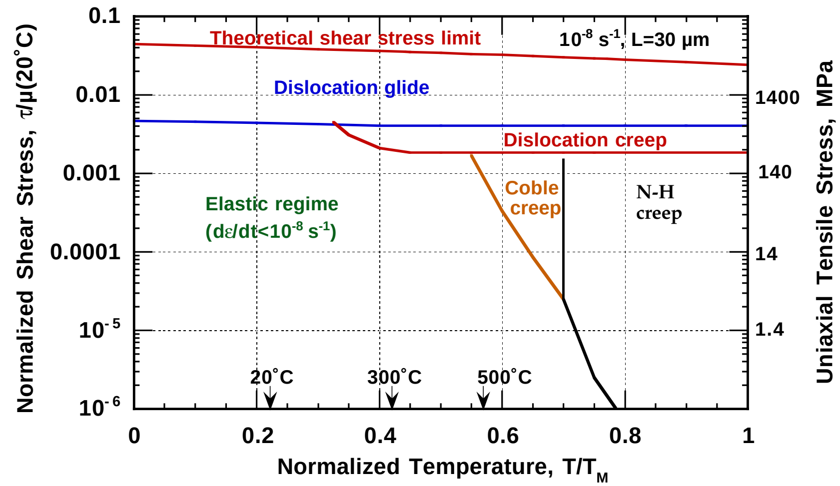
Success is due to simultaneous control of impurity pickup, grain size

- Results are applicable to other Group V refractory alloys (Nb, Ta)
- Use of ultra-high purity weld wire may reduce atmospheric purity requirements

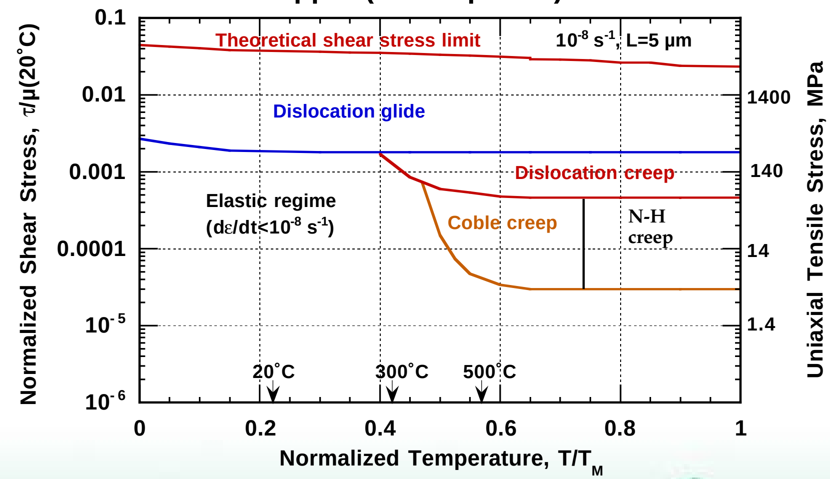
Mechanical behavior of copper alloys can be understood on the basis of current materials science models of deformation



Deformation Map for CuNiBe (Brush-Wellman Hycon 3HP)



Deformation Map for Oxide Dispersion-strengthened Copper (GlidCop Al25)



Applications to US industry (e.g., USCAR) as well as fusion energy sciences program