Advanced Materials for Fusion Technology

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OUTLINE

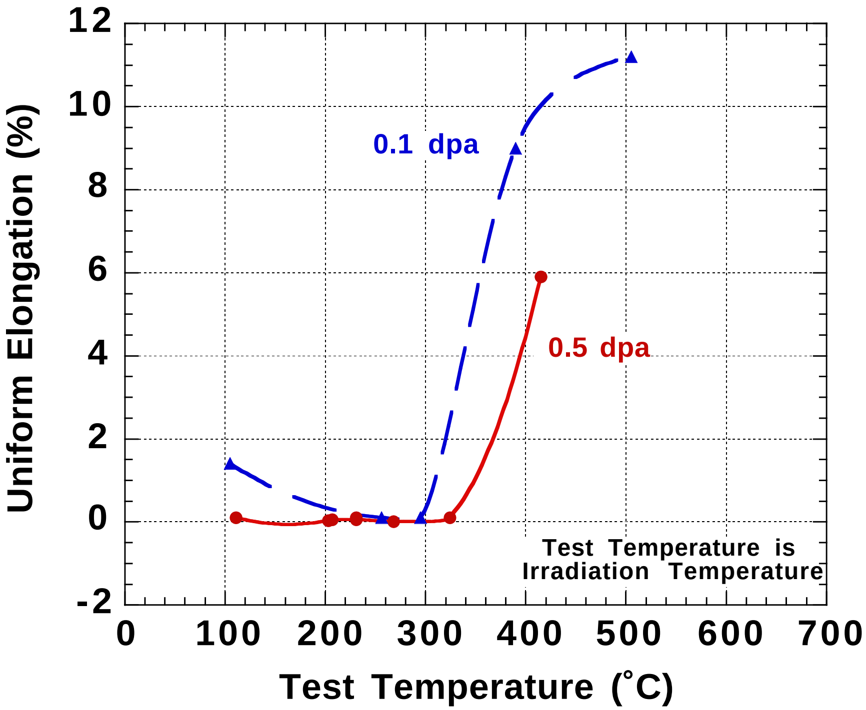
- **Development of Improved Materials**
  - **Advanced steels, including Nanocomposited ferritic steel**
  - **Refractory alloys (V, Mo, W alloys)**
  - **New welding technology**
  - **Ceramic composites**
- **Brief comments on prospects for improved Cu alloys and nonstructural materials**

INTRODUCTION

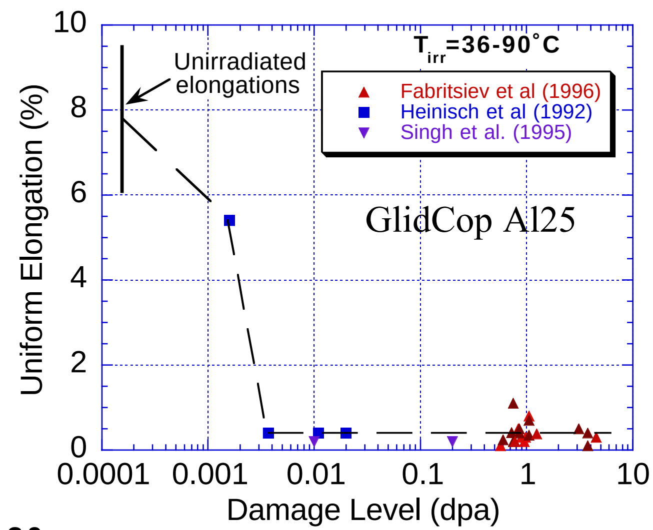
- **Major design criteria for structural alloys include**
  - **Resistance to He embrittlement & swelling from (n,α) reactions**
  - **high temperature strength**
  - **low temperature radiation embrittlement resistance**
  - **Safety and environmental (disposal) issues**
- **Major design criteria for ceramic composites include**
  - **Thermal conductivity degradation**
  - **Reduced-cost fabrication and joining techniques**
  - **Safety and environmental (disposal) issues**

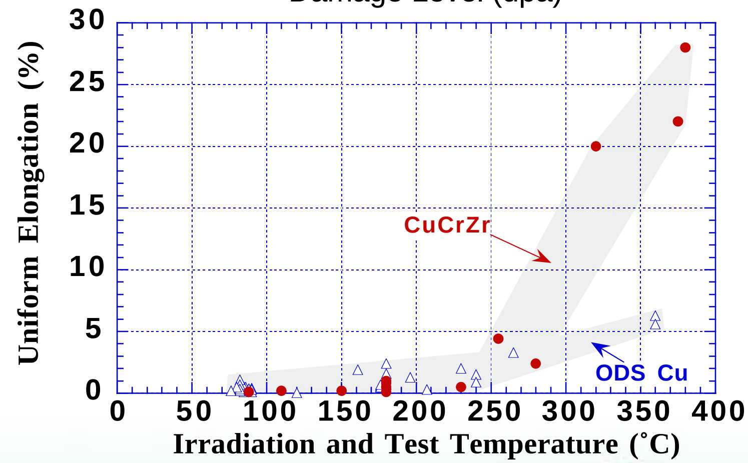
Low uniform elongations occur in many BCC and FCC metals after low-dose irradiation at low temperature

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

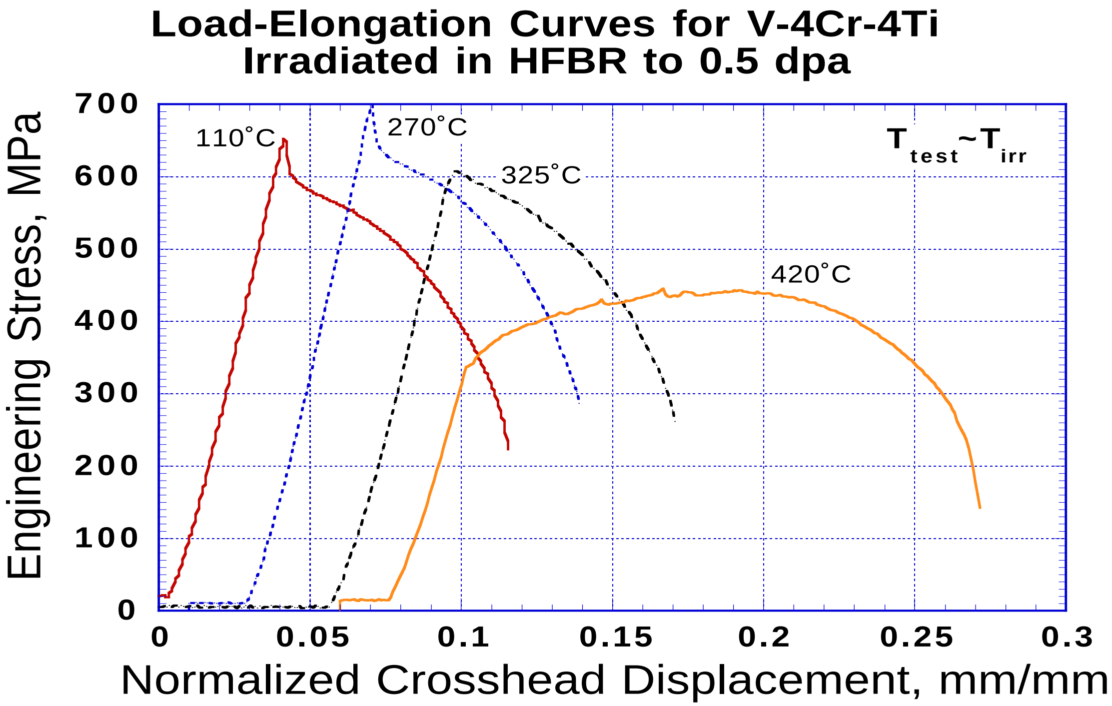


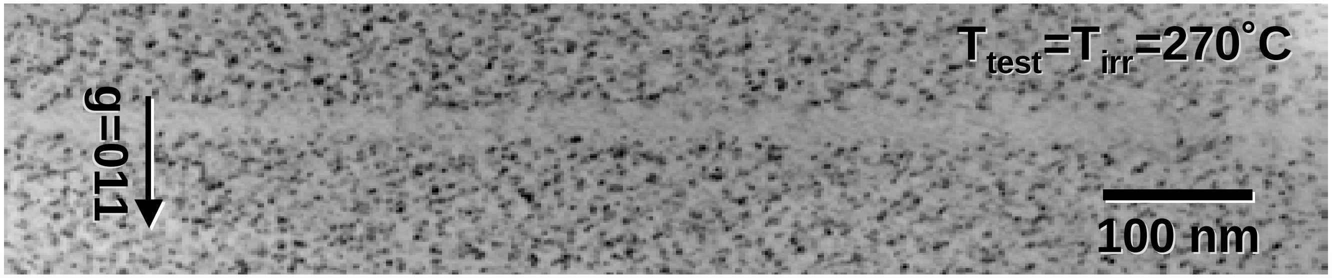
Uniform elongation of neutron-irradiated GlidCop Al25 and CuCrZr



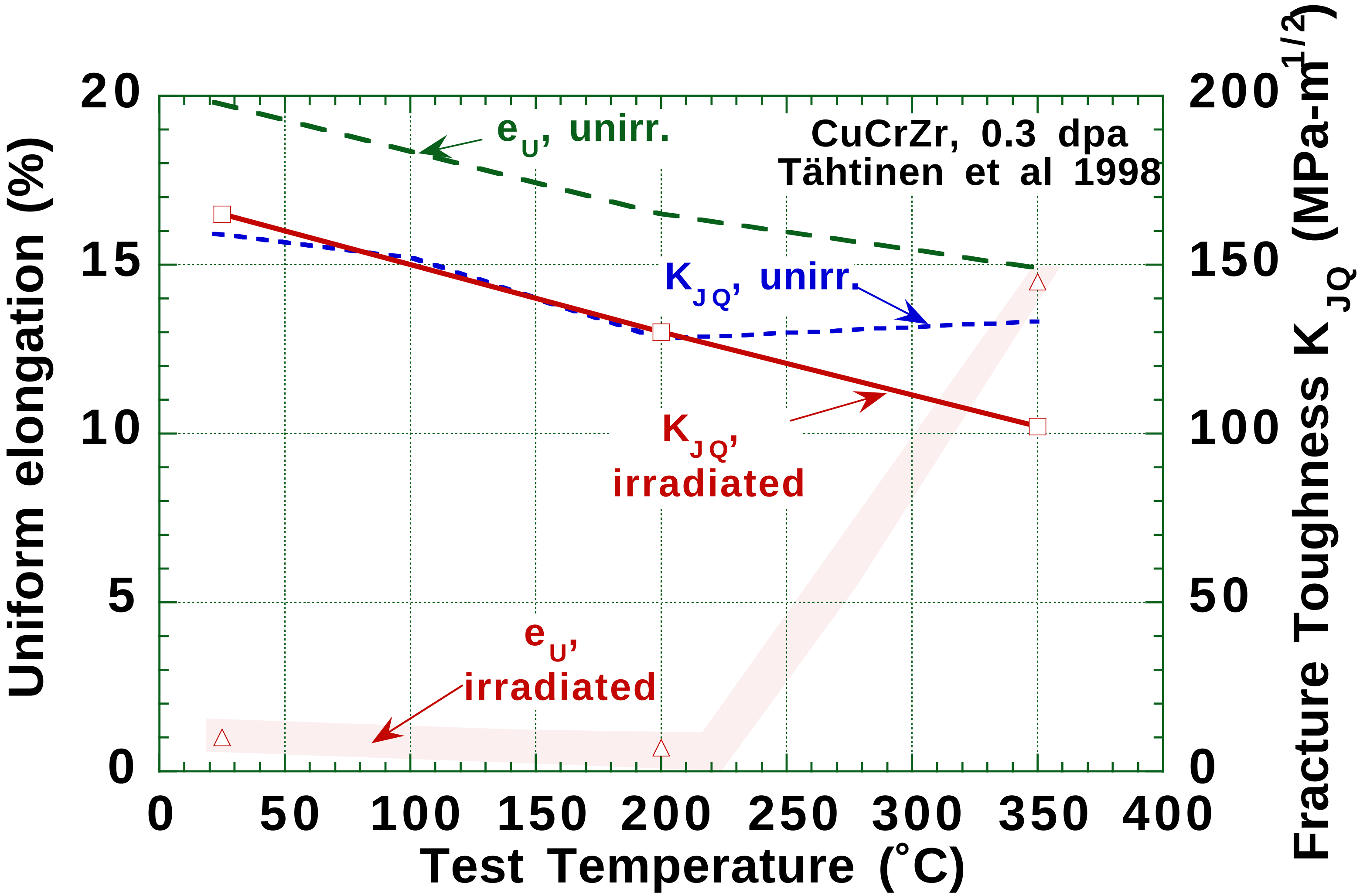


Irradiated Materials Suffer Plastic Instability due to Dislocation Channeling



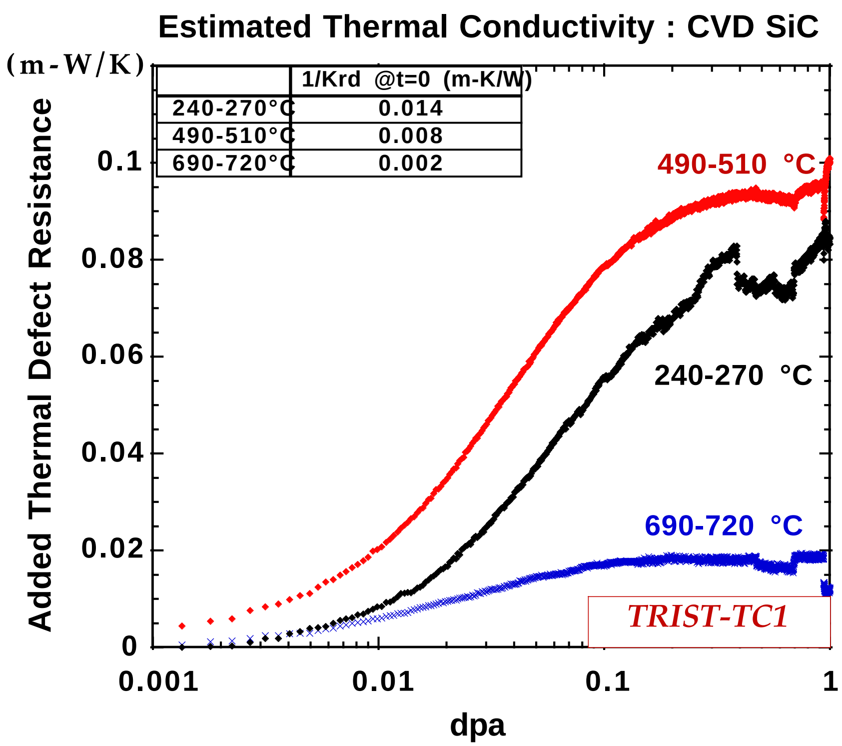


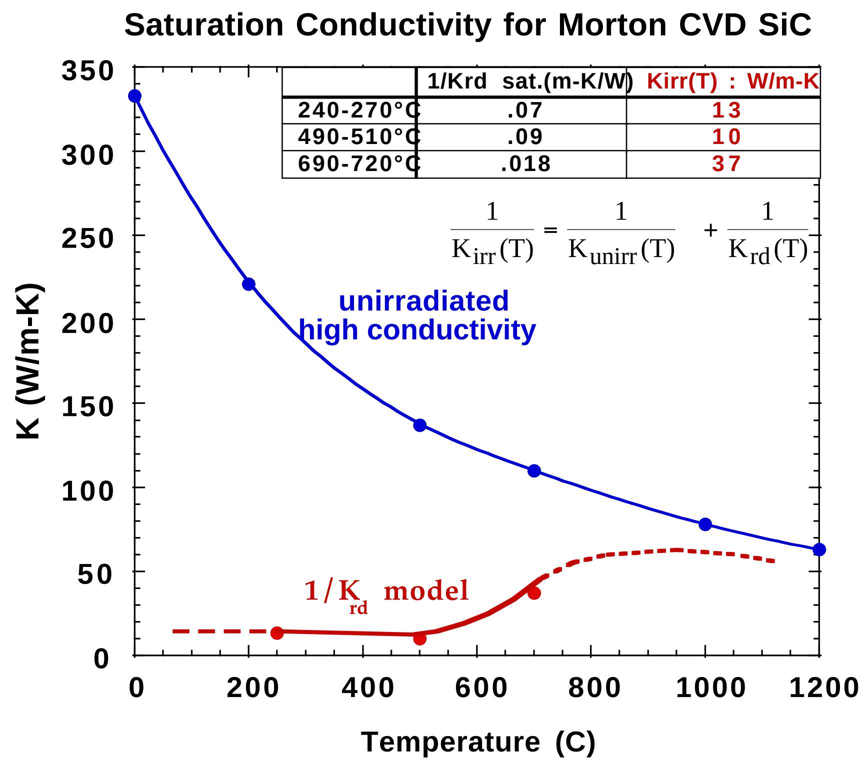
Radiation-induced Tensile "Embrittlement" does not Necessarily Produce Fracture Toughness Embrittlement



Application of Thermal Defect Resistance Model to Predict Conductivity of Irradiated SiC

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





- Maximum irradiated thermal conductivity for SiC is estimated to be ~ 10 W/m-K at 500°C, ~37 W/m-K at 700°C

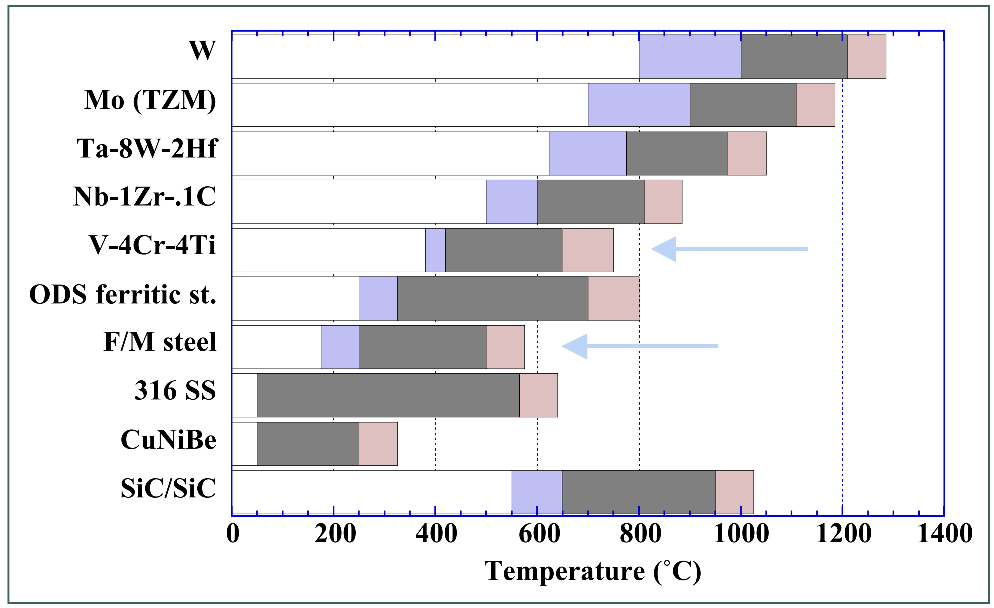
Current Alloy Systems Have Key Limitations

- V-4Cr-4Ti Alloy
  - Thermal creep limits
  - low temperature radiation hardening
  - possible He embrittlement
  - requires MHD coating
  - poor oxidation resistance

- Ferritic/Martensitic Steels
  - low temperature radiation hardening
  - Thermal creep limits
  - possible He embrittlement

- *Refractory Alloys*

Operating Temperature Windows



S.J. Zinkle and N.M. Ghoniem (2000)

Key Feasibility Issues for Ferritic Steels

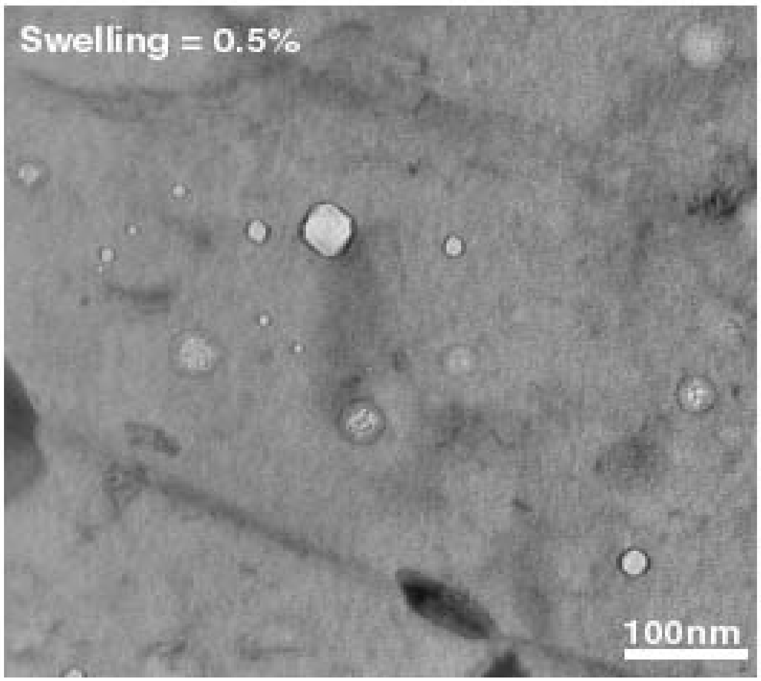
- Verify ferromagnetic structures are acceptable for MFE
- Expand low temperature operating limit (experiments and physical modeling, master curve methodology)
  - Development of alloys with improved resistance to low temperature (<350˚C) embrittlement
- Expand high-temperature and dose limits
  - Alloy development, including dispersion strengthened alloys
  - Effect of He on creep rupture
- Resolve system-specific compatibility issues (T barrier development, etc.)

IEA-integrated worldwide ferritic steel program is examining items 2 &3 (items 1&4 are being addressed by JA and EU programs)

Note: reduced-activation grades of Fe-9Cr ferritic/martensitic steels (e.g., F82H) have been developed with superior properties compared to commercial steels (e.g., HT9)

Void Swelling of Ferritic Steels is Low up to ~100 dpa (~10 MW-yr/m^2), Although Further Work is Needed to Examine He Effects

HFIR irradiation at 400˚C to 51 dpa

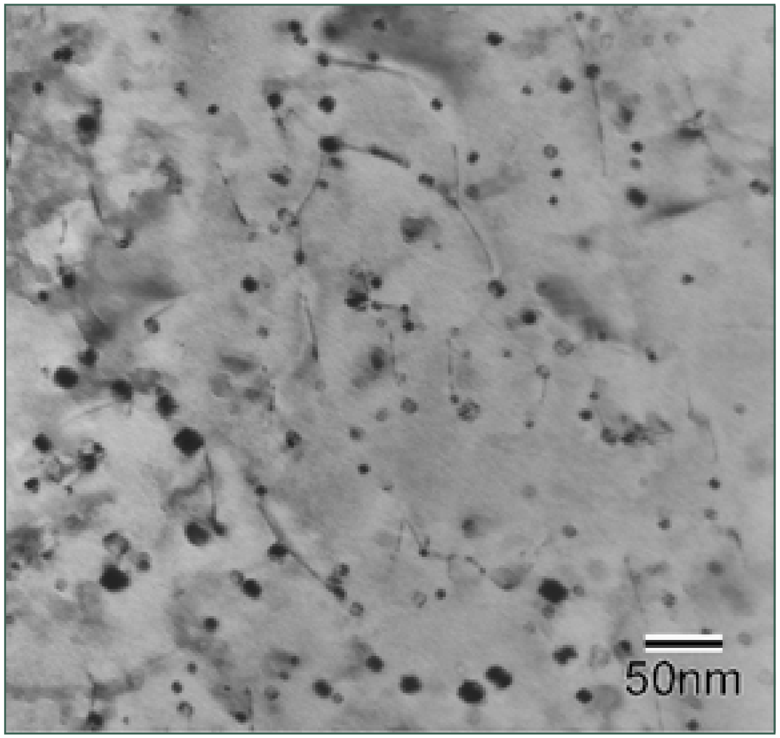


F82H (36 appm He)

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

Potential New Ferritic/Martensitic Alloy

- Dispersion-Strengthened Fe-9.5Cr-3Co-1Ni-0.6Mo-0.3Ti-0.07C steel
  - High number density of nano-size TiC precipitates
- Superior elevated-temperature strength and impact properties compared to conventional 9-12Cr steels
- Advantage over ODS steels: produced by conventional steel processing techniques
- Present composition not for nuclear applications; processing technique applicable to reduced-activation compositions

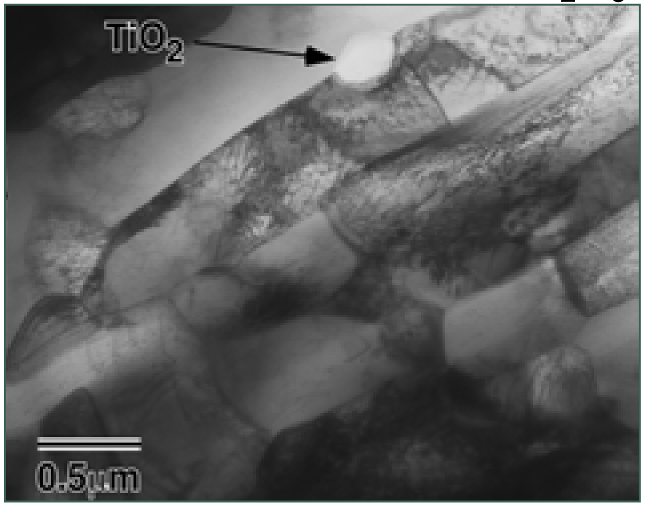


Klueh and Buck, J. Nucl. Mater. 283-287 (2000)

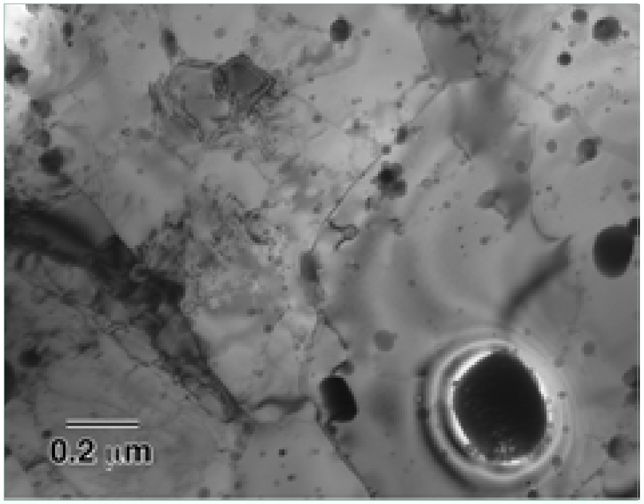
Oxide Dispersion Strengthening Approach

- Perspective
  - +50 year history
- Benefits
  - any desired combination of matrix composition and dispersoid
  - significant improvements in high temperature mechanical properties
- Problems
  - time-consuming & expensive
  - often produces materials with:
    - **anisotropic properties**
    - **coarse particles with non-uniform size and spatial distribution**
  - joining and fabrication
  - lack of understanding - experiment, theory, and modeling

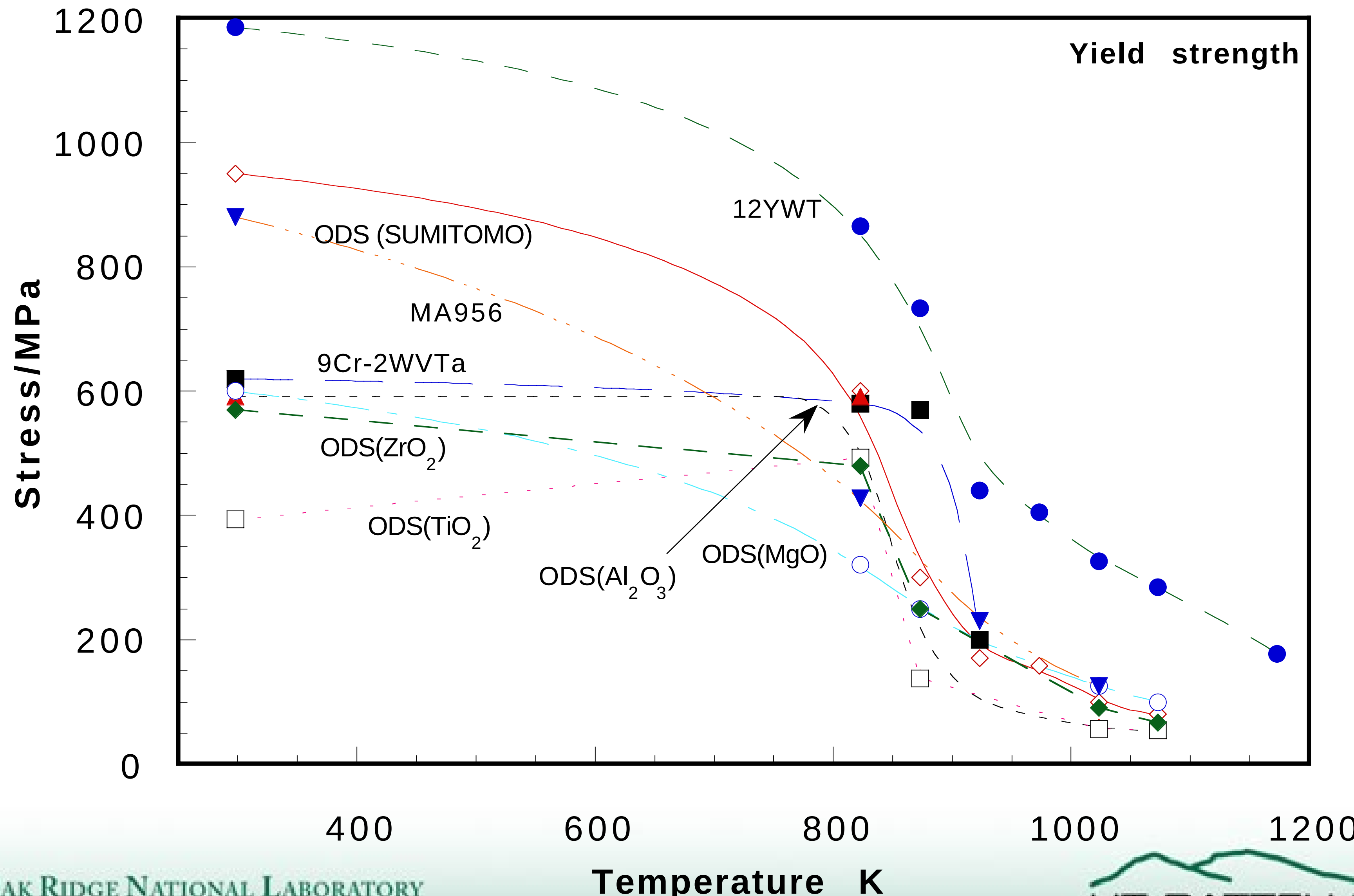
Fe-13Cr-3W-0.4Ti + 0.25Y_2O_3



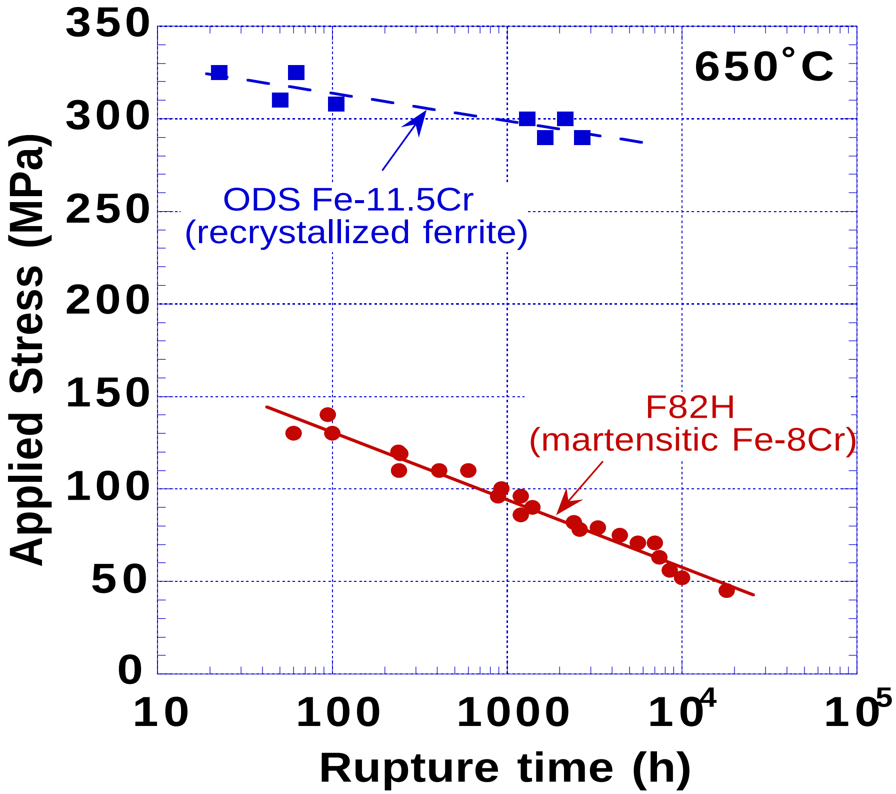
Fe-9Cr-2W + 0.33TiO_2 + 0.67Y_2O_3

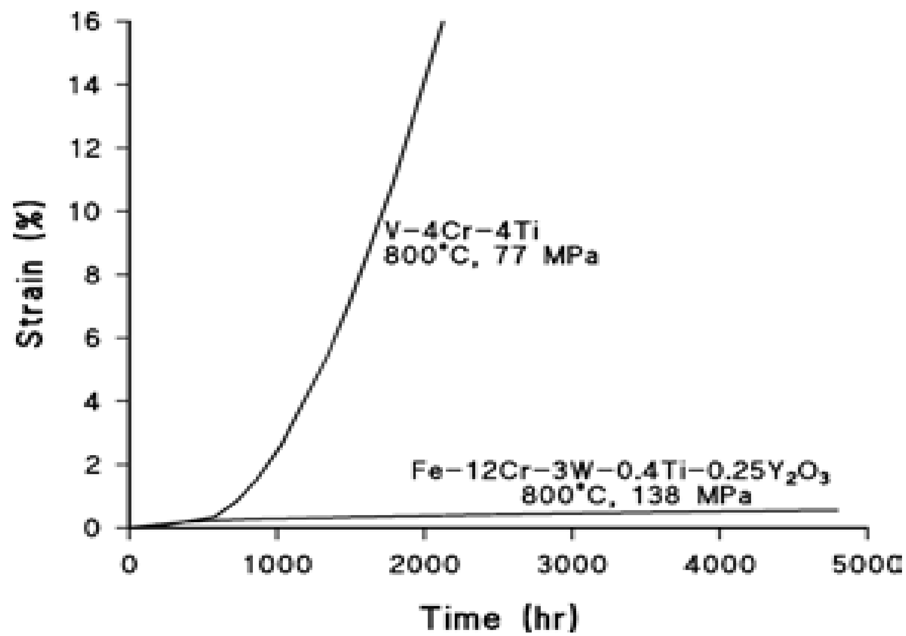


Comparison of Tensile strength of New 12YWT Nanocomposited Ferritic Steel vs. other ODS steels



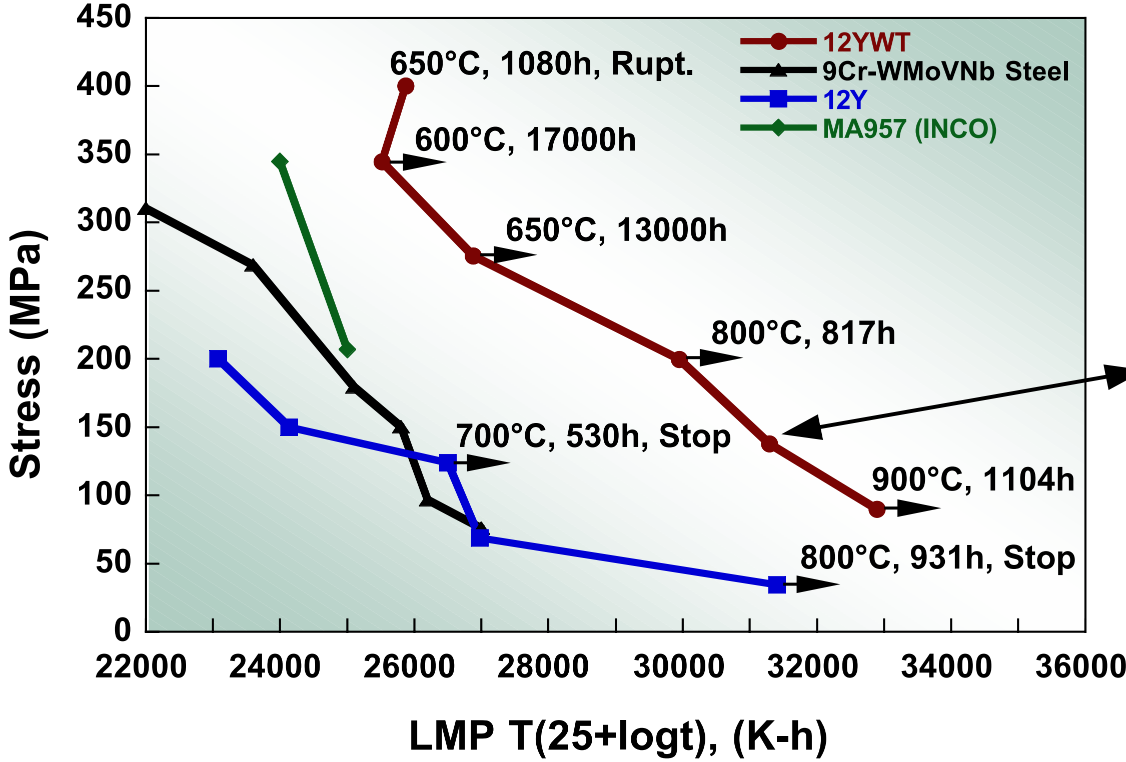
Recently Developed Isotropic Oxide Dispersion Strengthened Steels Offer Potential for Improved Performance

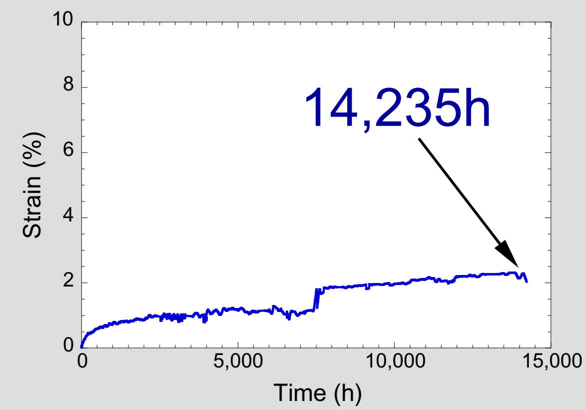




- Thermal creep temperature limit for martensitic Fe-8Cr steel is ~550˚C (vs. >700˚C for several grades of ODS steel, including Kobe Fe-12Cr-3W-0.4Ti-0.25Y_2O_3)

Nanocomposited 12YWT Ferritic Steel Exhibits Excellent High Temperature Creep Strength





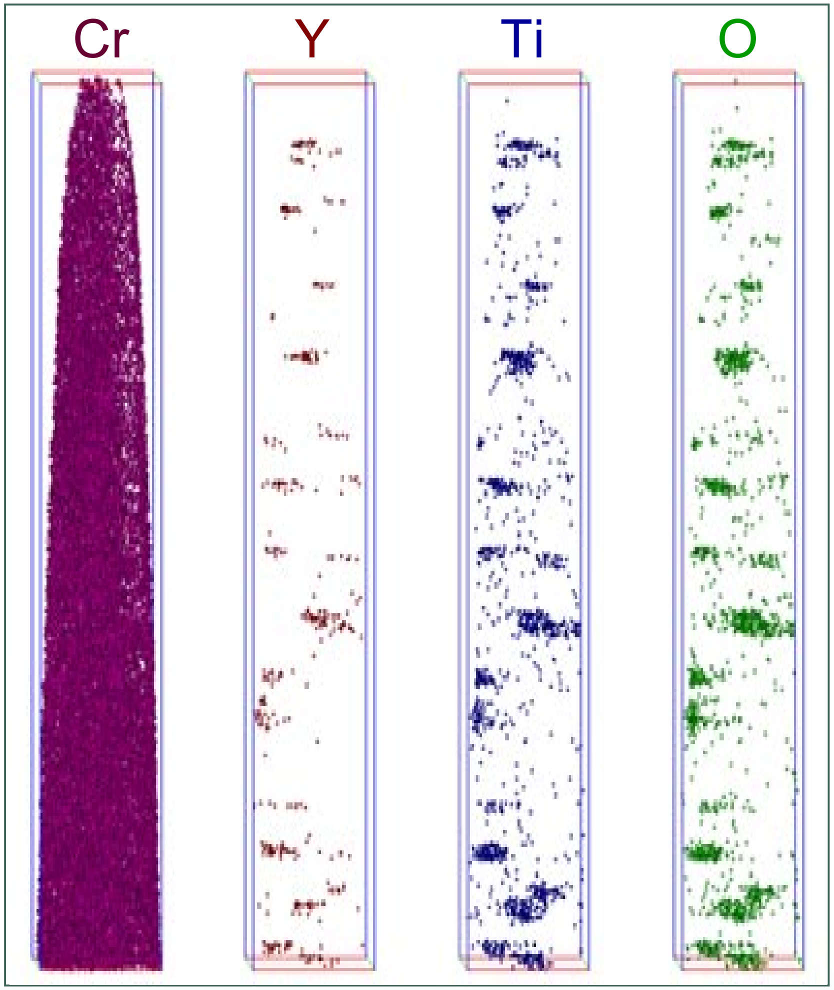
800°C and 138 MPa

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

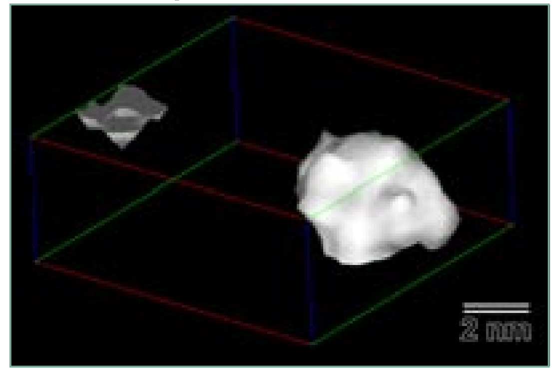
- Time to failure is increased by several orders of magnitude
- Potential for increasing the upper operating temperature of iron based alloys by ~200°C

Atom Probe Reveals the Presence of Nanoclusters in the Mechanically Alloyed 12YWT Ferritic Alloy

3-DAP Atomic Coordinates



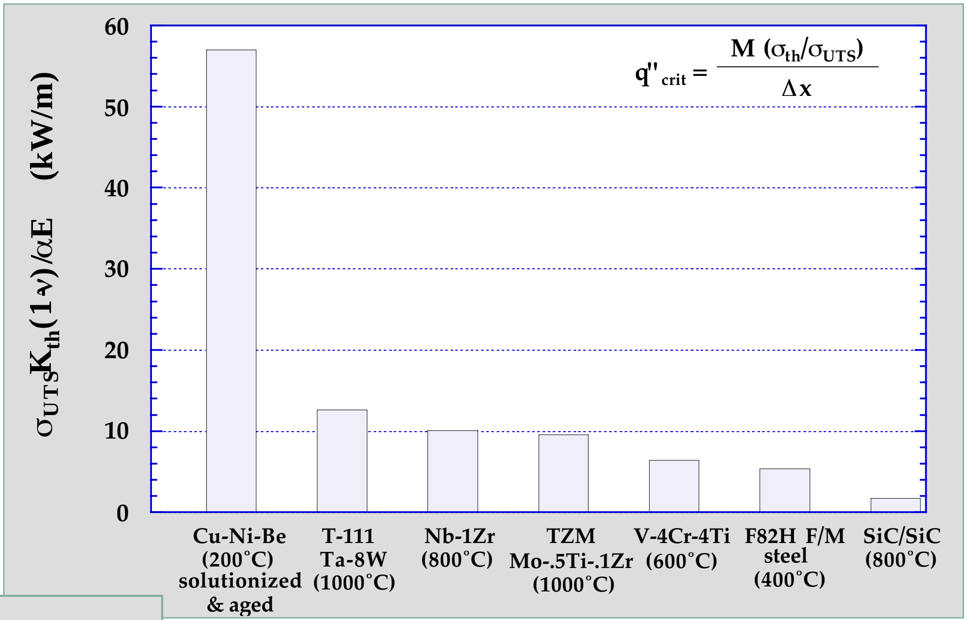
Isocompositional Surface

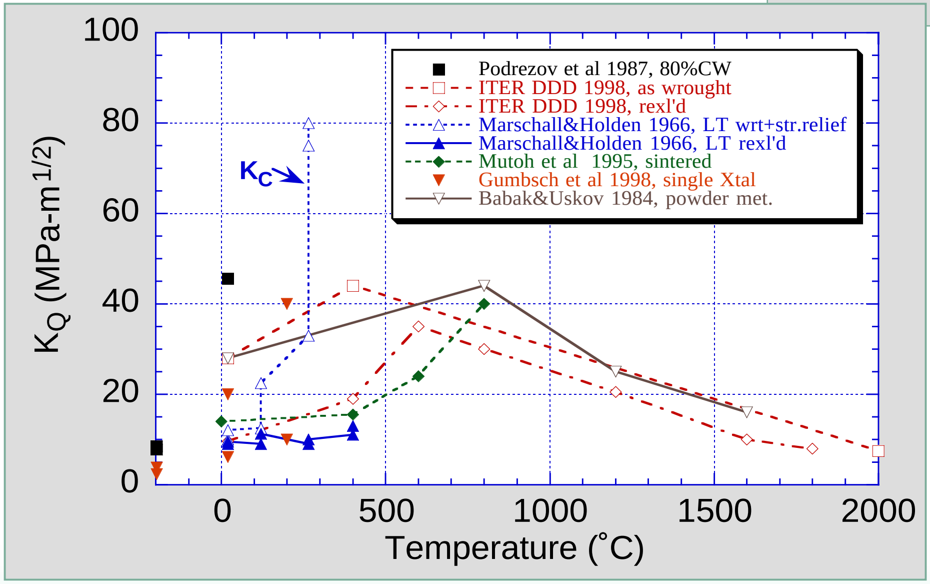


- Nano-size clusters
  - Average composition (at.%) :
    O - 23.6 ± 10.6
    Ti - 19.9 ± 8.7
    Y - 9.2 ± 7.8
  - Size : $r_g = 2.0 \pm 0.8$ nm
  - Number Density : $n_v = 1.4 \times 10^{24}/m^3$
- Original ~30 nm Y_2O_3 particles evolve to (Y,Ti,O) enriched nanoclusters
- Nanoclusters not present in ODS Fe-13Cr + 0.25Y_2O_3 alloy

Refractory Alloys

- Attractive Thermal/ Physical Properties
  - high temperature capabilities
  - thermal stress figure of merit
  - liquid metal compatibility (Li)





- Main problems
  - low fracture toughness
  - low oxidation resistance
  - poor mechanical properties of weldments

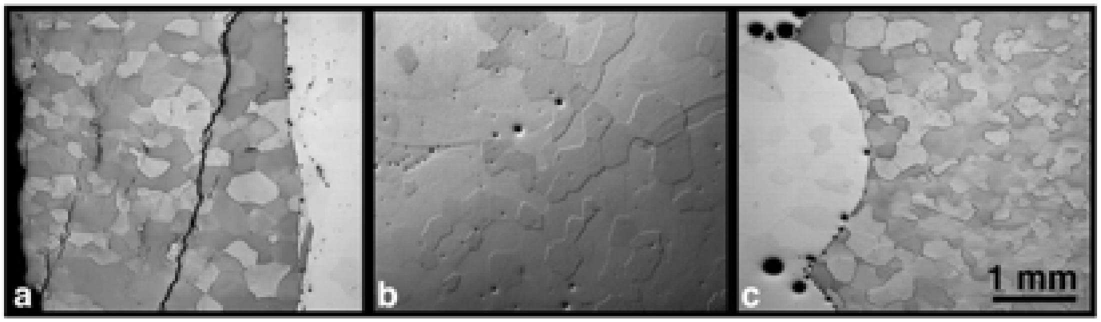
Recent research offers promise for developing refractory alloys with improved ductility

- Controlled (50-1600 appm) additions of Zr, B, C to molybdenum increases room temperature ductility of weldments from nearly zero to e_{tot}~20% (M.K.Miller and A.J.Bryhan, 2001)
- Mechanically alloyed W-0.3wt%Ti-0.05wt%C (H. Kurishita et al., ICFRM-10, Baden-Baden, Oct. 2001)
  - Avoid $(W,Ti)_2C$ brittle phase by limiting max concentration of carbon
  - Small grain size (~2 μm) helps to dilute harmful oxygen grain boundary segregation
  - TiC dispersed particles provide increased toughness (appropriate fracture mechanics tests needed to verify preliminary smooth bend bar results)

IMPROVEMENTS IN THE DUCTILITY OF MOLYBDENUM WELDMENTS BY ALLOYING ADDITIONS OF Zr, B and C

ALLOY COMPOSITION

Zr	**1600 appm**
C	**96 appm**
B	**53 appm**
O	**250 appm**
N	**178 appm**
Mo	**balance**



HAZ Weld HAZ

Fracture occurred predominantly in the heat affected zones

MECHANICAL PROPERTIES

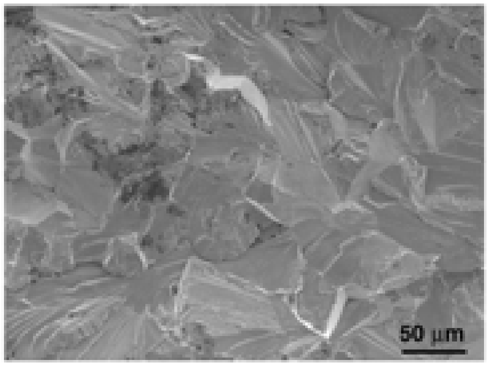
Strain rate: $8.3 \times 10^{-4}\ s^{-1}$

Mo- 30% Re filler

Ductility 19.5%

Yield Stress	481 MPa
UTS	544 MPa

Commercial Mo weld: 3% Ductility



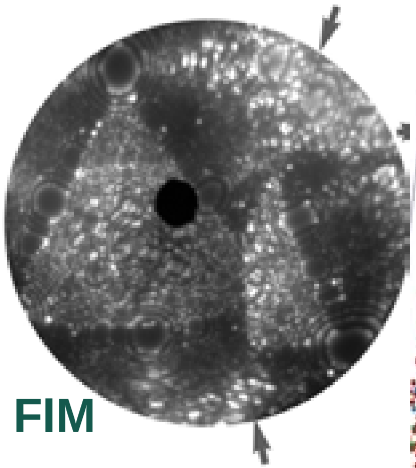
The fracture mode was transgranular cleavage with only small regions of intergranular fracture. This contrasts the intergranular fracture typically found in commercial Mo welds.

Research performed by
M. K. Miller, Oak Ridge National Laboratory
and A. J. Bryhan, Applied Materials

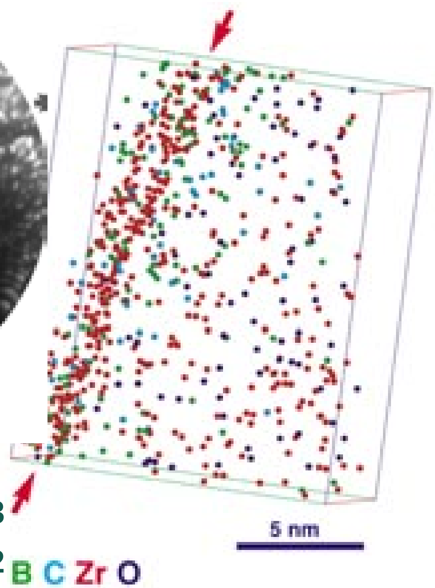
ATOM PROBE TOMOGRAPHY REVEALS
Zr, B and C SEGREGATION TO THE GRAIN BOUNDARIES

- **Base metal: Zr, C and B enrichments and O depletion**
- **HAZ: Heavy B and moderate Zr enrichments**

BASE METAL



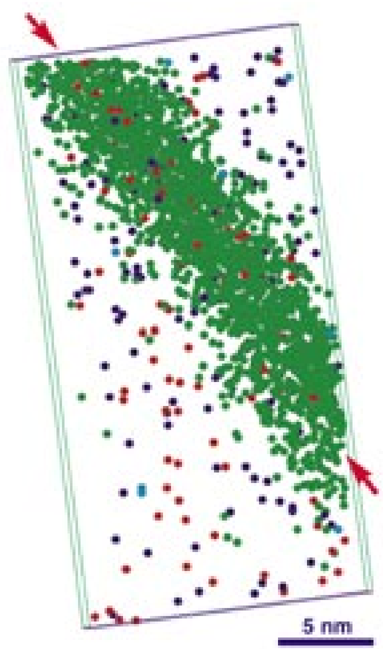
FIM



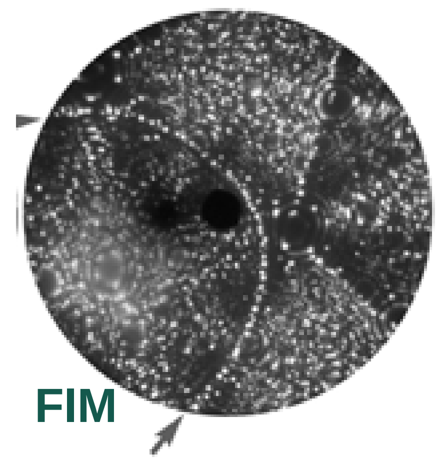
GIE (atoms m^{-2})

Zr	7.6×10^{13}
B	7.3×10^{12}
C	1.1×10^{13}
O	-3.9×10^{12}

HEAT AFFECTED ZONE



APT atom maps



FIM

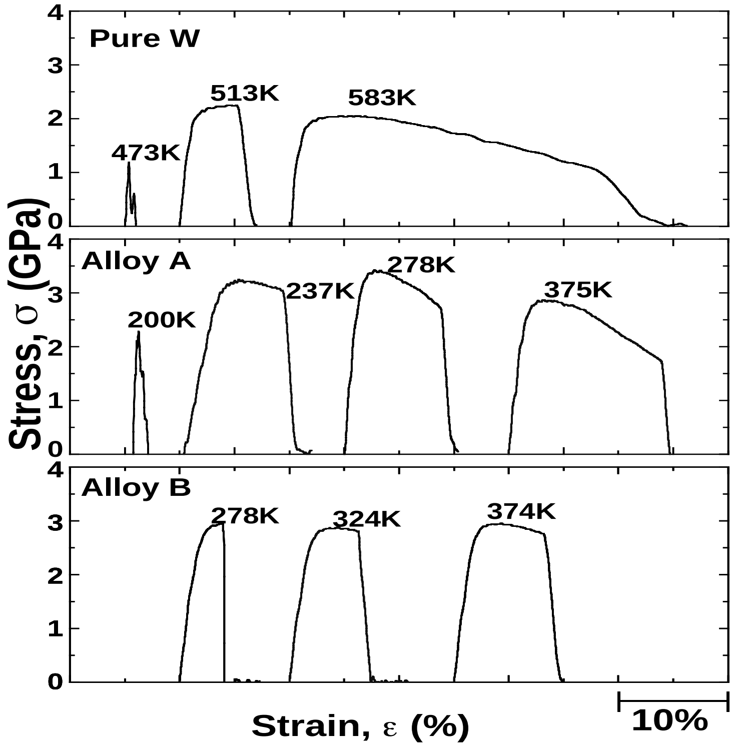
GIE (atoms m^{-2})

Zr	1.3×10^{13}
B	9.9×10^{14}
C	9.9×10^{11}
O	1.1×10^{13}

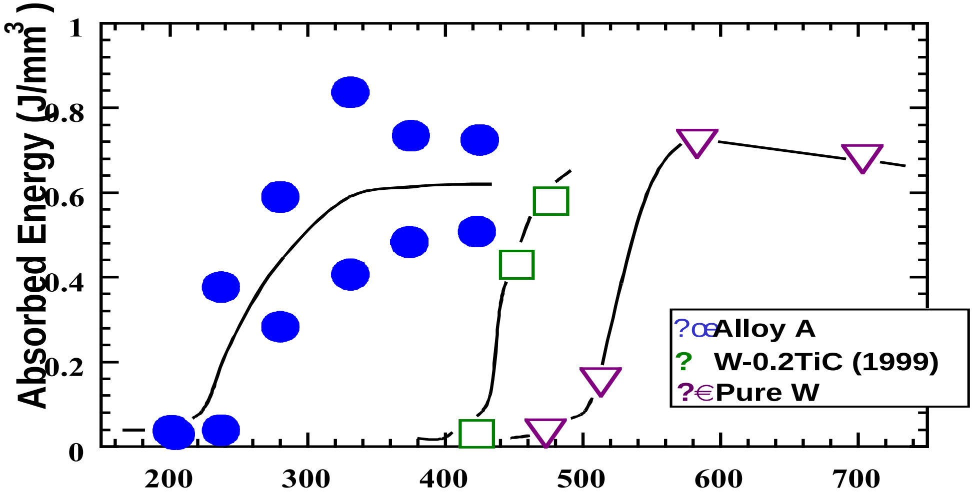
Research performed by
M. K. Miller, Oak Ridge National Laboratory
and A. J. Bryhan, Applied Materials

Mechanically alloyed W-0.3wt%Ti-0.05wt%C exhibits good low temperature ductility

Example of the as-rolled sheets.



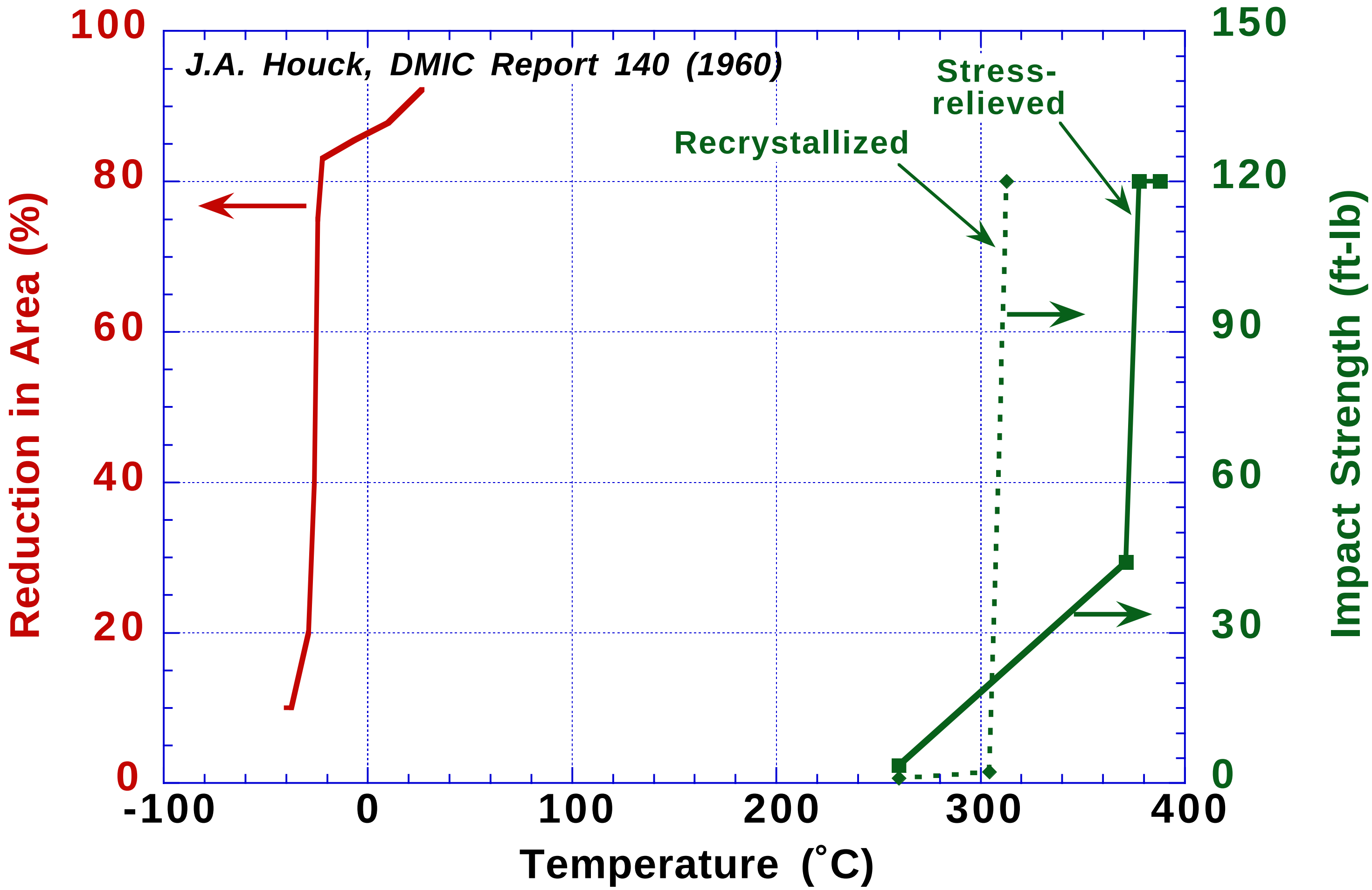
Three-point bending stress-strain curves for pure tungsten and developed alloys A and B.



Comparison of test temperature dependence of total absorbed energy and maximum strength among alloy A, W-0.2wt%TiC and pure tungsten (un-notched bend bar impact tests).

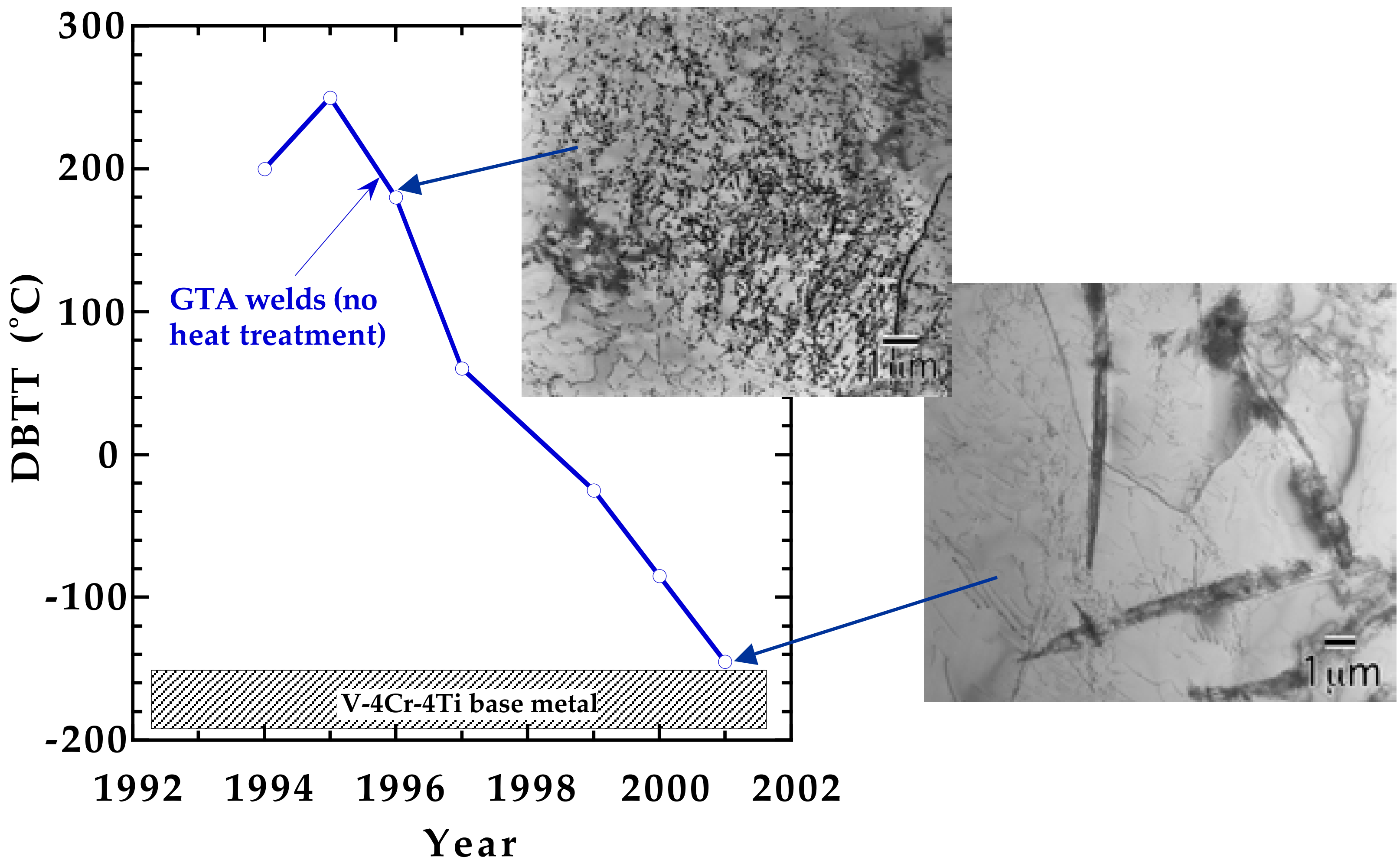
H. Kurishita et al., 2001

Comparison of Tensile (Red. in area) and Charpy Impact Ductile-Brittle Transition Behavior of Mo-0.5Ti



• *The DBTT is dependent on numerous factors, including strain rate and notch acuity ("tensile DBTT" is not a meaningful design parameter)*

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

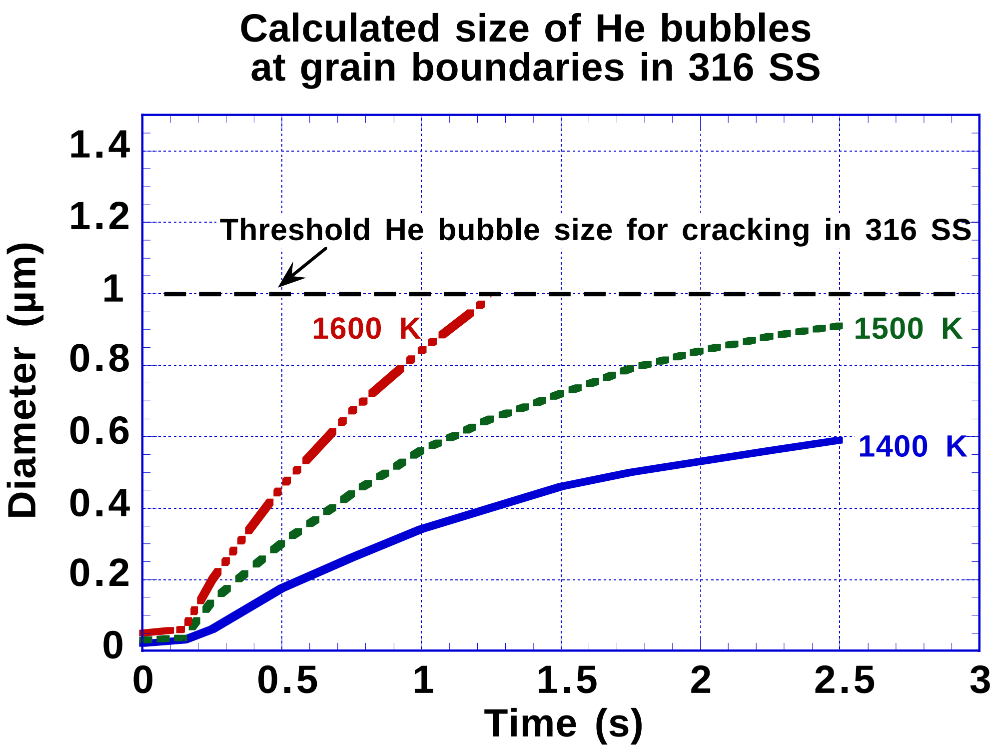


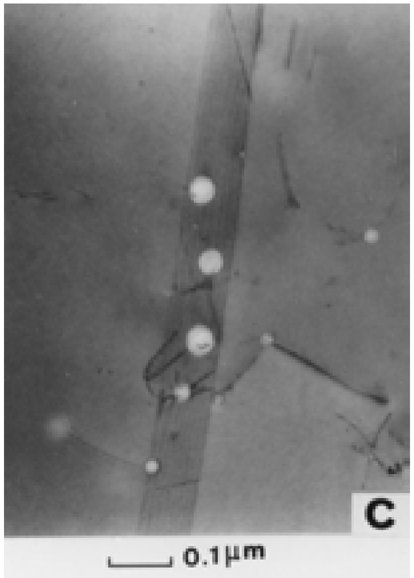
Success is due to simultaneous control of impurity pickup, grain size

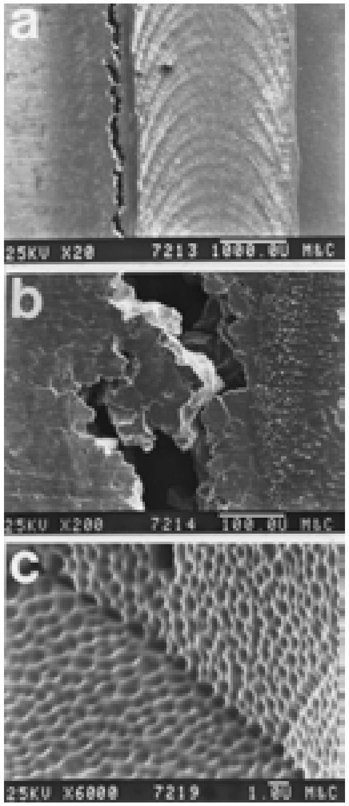
- **Results are applicable to other Group V refractory alloys (Nb, Ta)**
- **Use of ultra-high purity weld wire may reduce atmospheric purity requirements**

Motivation for pursuing Friction Stir Welding (FSW)

- A solid-state joining process such as FSW may enable field welding of refractory alloys (V, Mo, W), due to reduced pickup of atmospheric contaminants
- 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



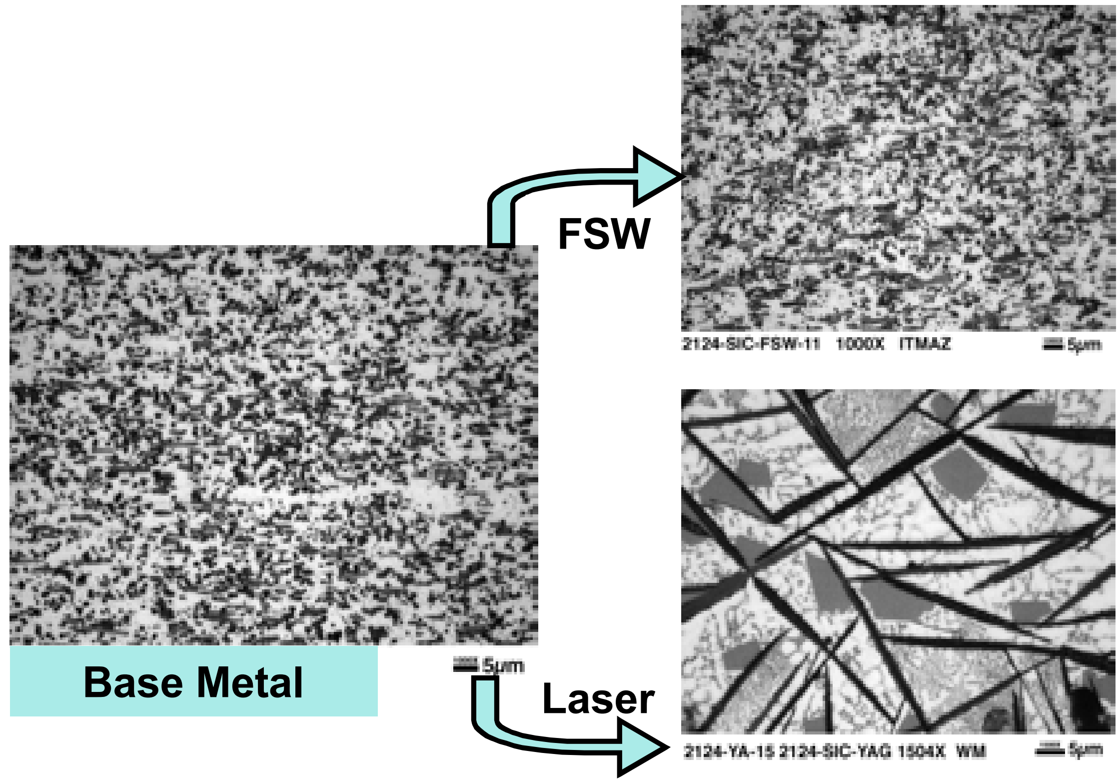




Advanced materials can be successfully joined with friction stir welding (FSW) process

- **Metal matrix composites (MMC) and oxide dispersion strengthened (ODS) alloys are difficult to join using conventional fusion welding processes.**
  - **Particle / fiber reinforcement deteriorate in MMCs due to melting.**
  - **In Al-SiC MMC laser welds, SiC decomposes and forms Al_4C_3 carbides.**

- **Friction stir welding (FSW) uses plastic deformation to join materials.**
  - **Homogeneous microstructure and properties are achieved.**
  - **SiC fibers were uniformly distributed.**

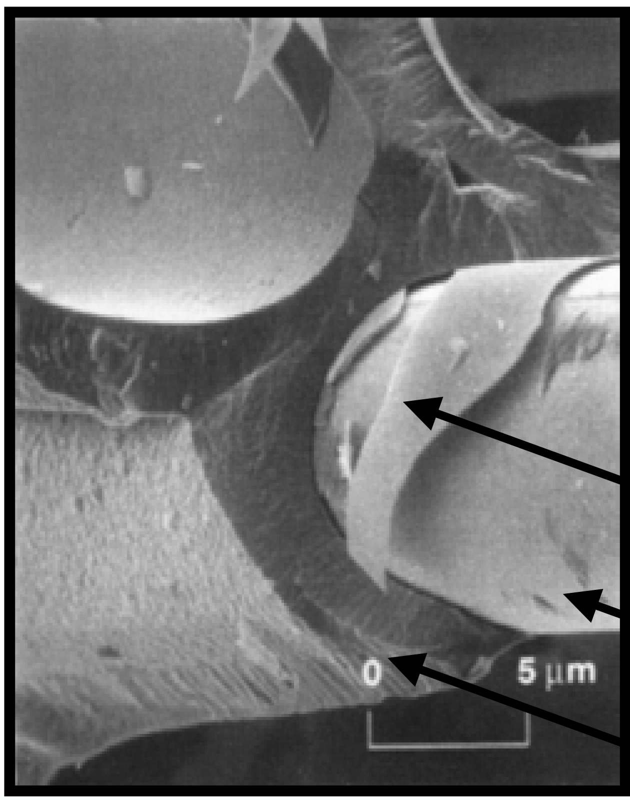


Sponsor: DOE Office of Transportation Technologies
Office of Heavy Vehicle Technologies

Silicon Carbide Composite Development

Silicon carbide composite is the least-developed of the 3 main structural materials being studied in the Fusion Materials Program, but it has the **greatest potential**

Very Low Radioactivation - Very High Temperature Use

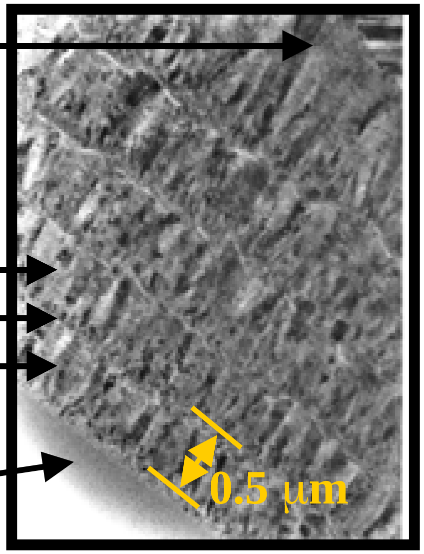


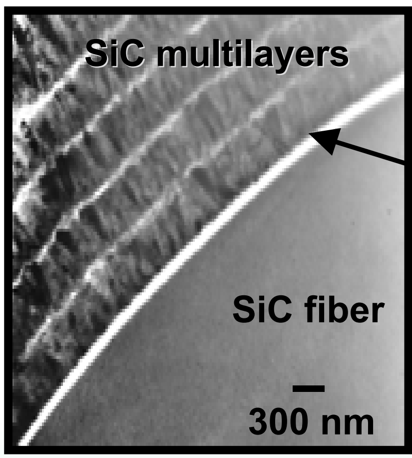
Areas being actively studied

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

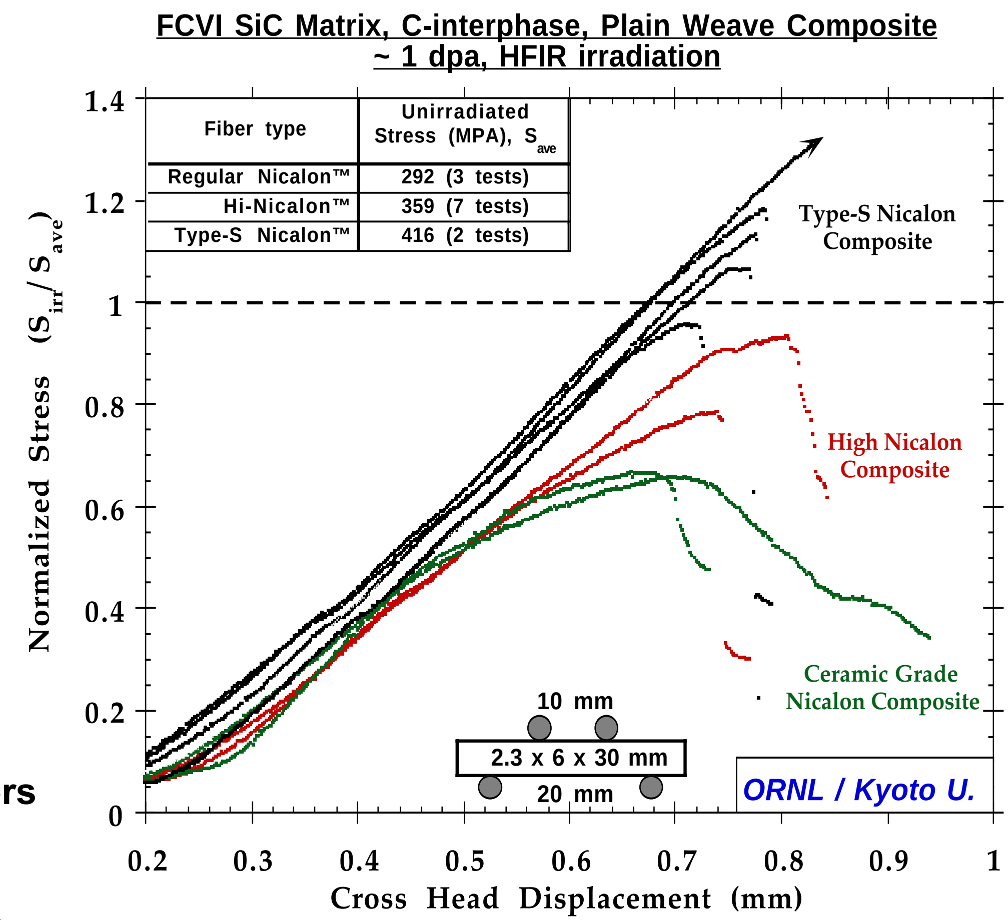
Development of Radiation-Resistant SiC Composites

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

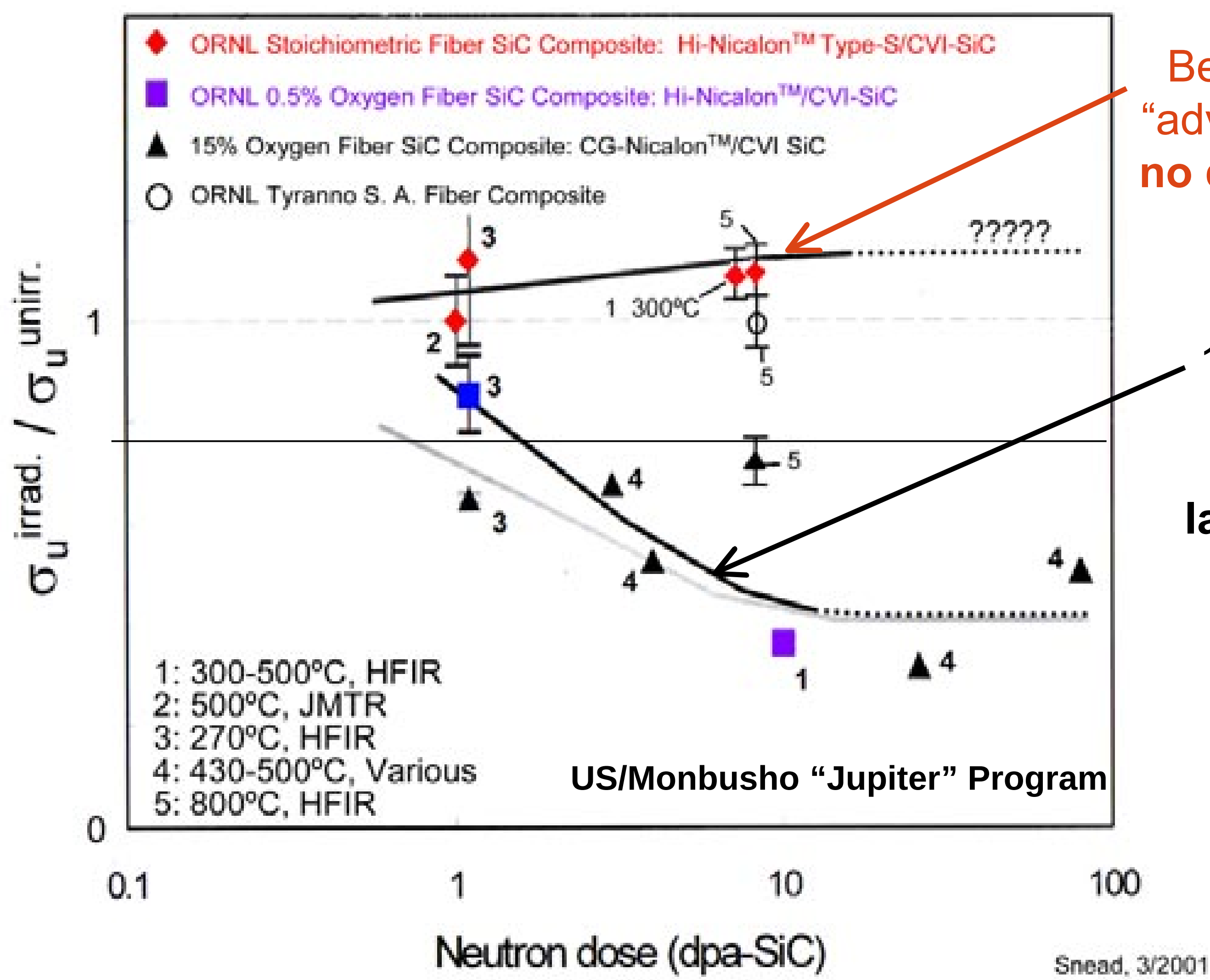




Upon irradiation, if fibers densify, fiber/matrix interfaces debonds -->strength degrades



We Now Have First Radiation-Resistant SiC Composite

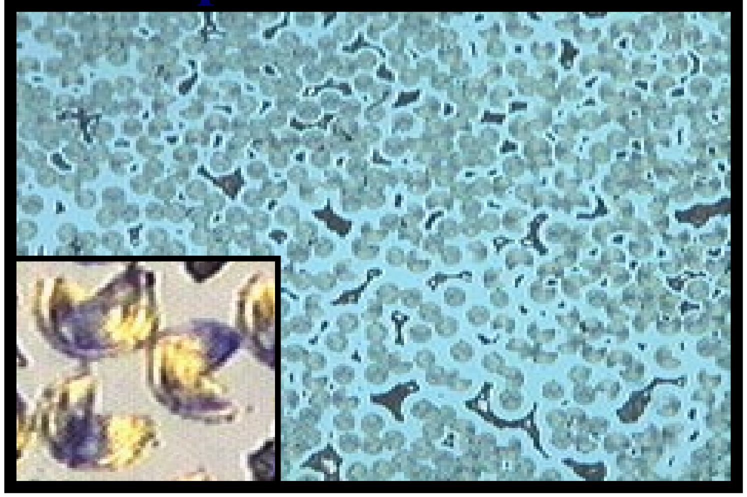


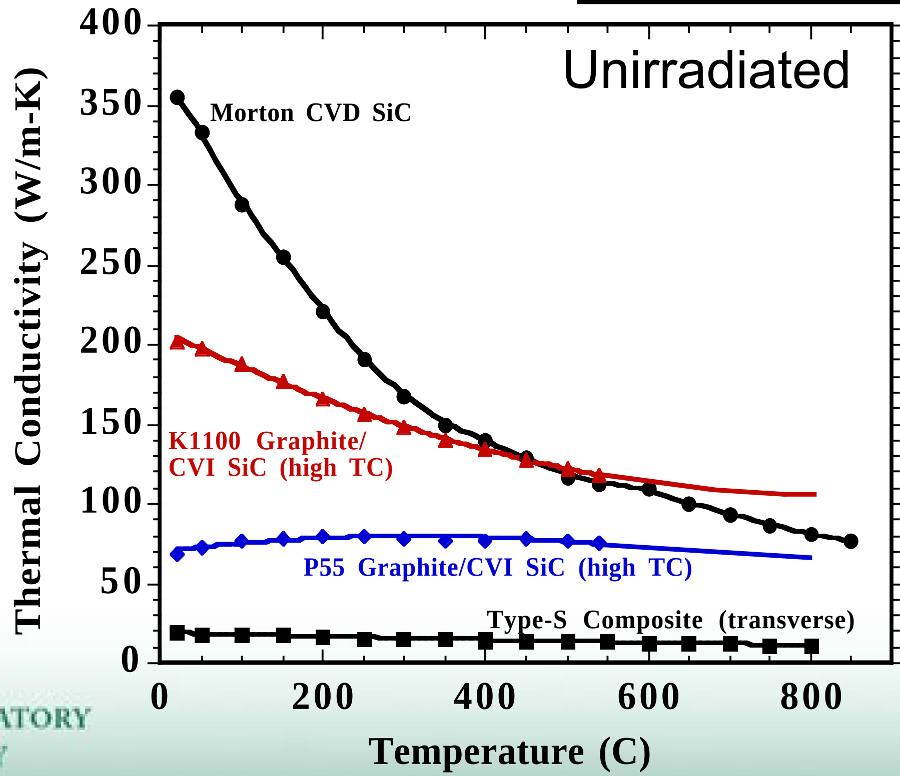
Bend strength of irradiated "advanced" composites show **no degradation** up to 10 dpa

1st- and 2nd generation irradiated SiC/SiC composites show **large strength loss** after doses >1 dpa

High Thermal Conductivity SiC/G Composites offer potential for improved thermomechanical performance

Fiber	K-1100	P-55	Nicalon Type-S
Kth (W/m-K@RT)	~950	120	15
Diameter (micron)	10	10	13
Tensile Strength (GPa)	3.1	1.9	2.6
Tensile Modulus (GPa)	965	379	420
Density (g/cc)	2.2	2.0	3.2





Predicted irradiated conductivity of SiC/G is higher than monolithic SiC

New Developments in SiC/SiC Fabrication:
Nano-Powder Infiltration and Transient Eutectoid (NITE) Process

Institute of Advanced Energy, Kyoto University

- **Reinforcement**
  - **Tyranno™-SA grade-3 (Ube Industries, Ltd.)**
  - **Uni-directional**
  - **PyC coating, 800nm-thick nominal**
- **Matrix raw materials**
  - **Beta-SiC Nano-powder (110m²/g) *and submicron (~40m²/g) powders***
  - **Al_2O_3-Y_2O_3 complex as sintering additive**
  - **Pre-ceramic polymer inclusion for intra-bundle densification**
- **Transient eutectoid process**
  - **Uni-axial hot-pressing**
  - **$T_p \leq 1800°C$**
  - **$P_p \leq 20MPa$**

Flow Chart of the “NITE” Process

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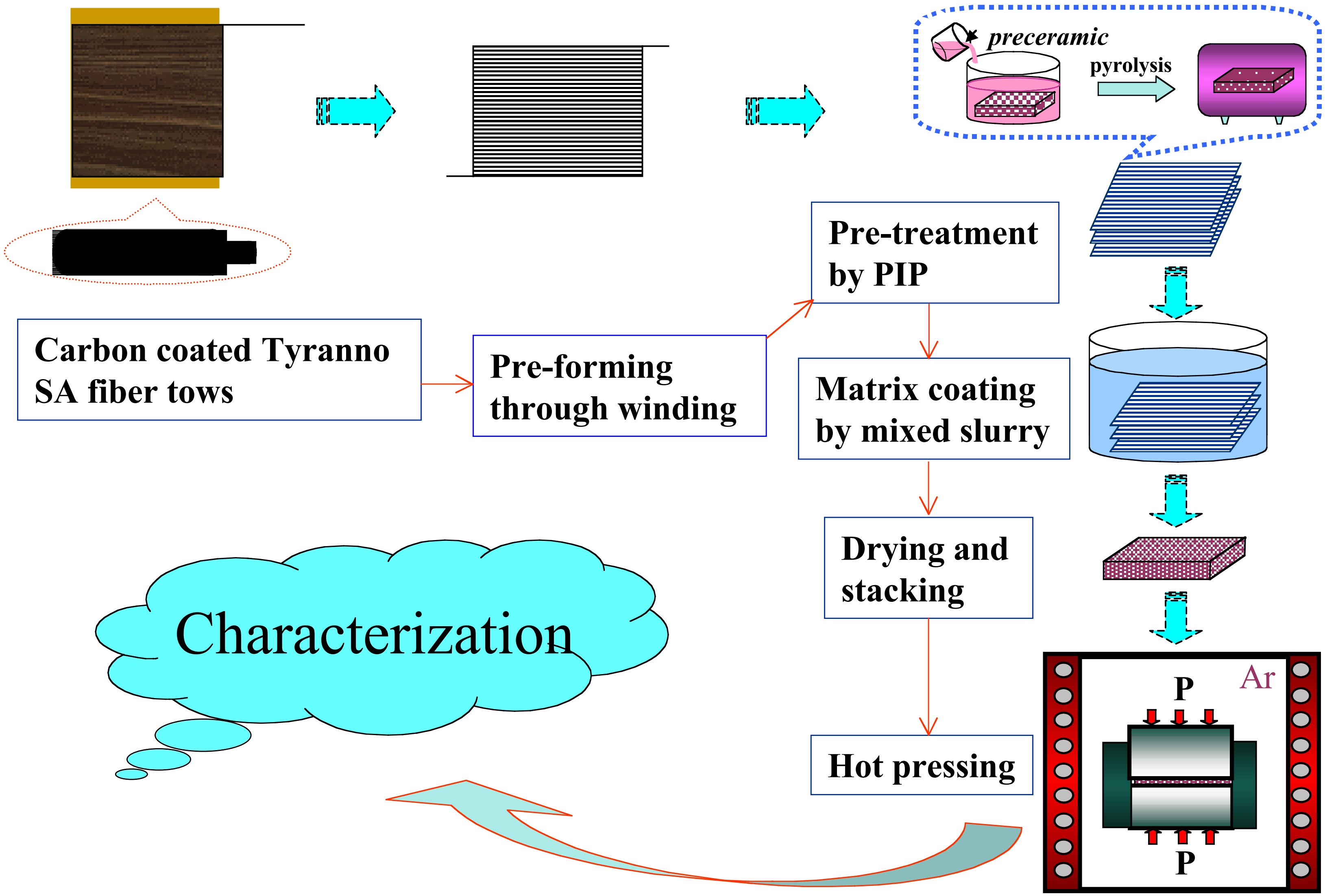
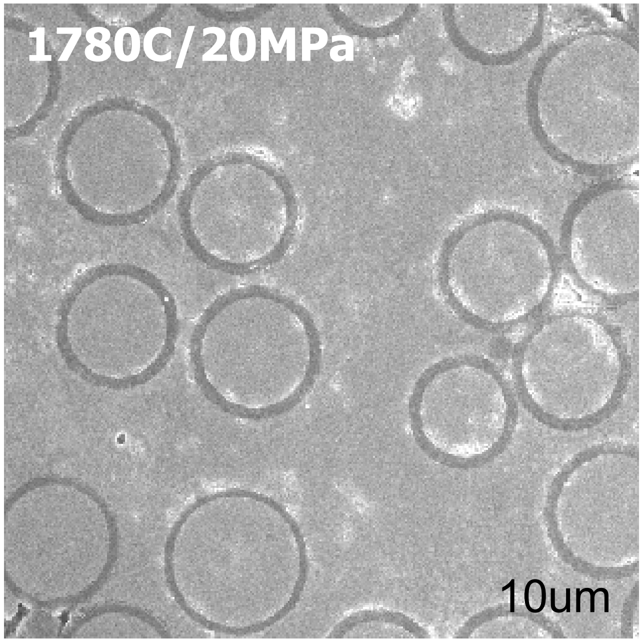
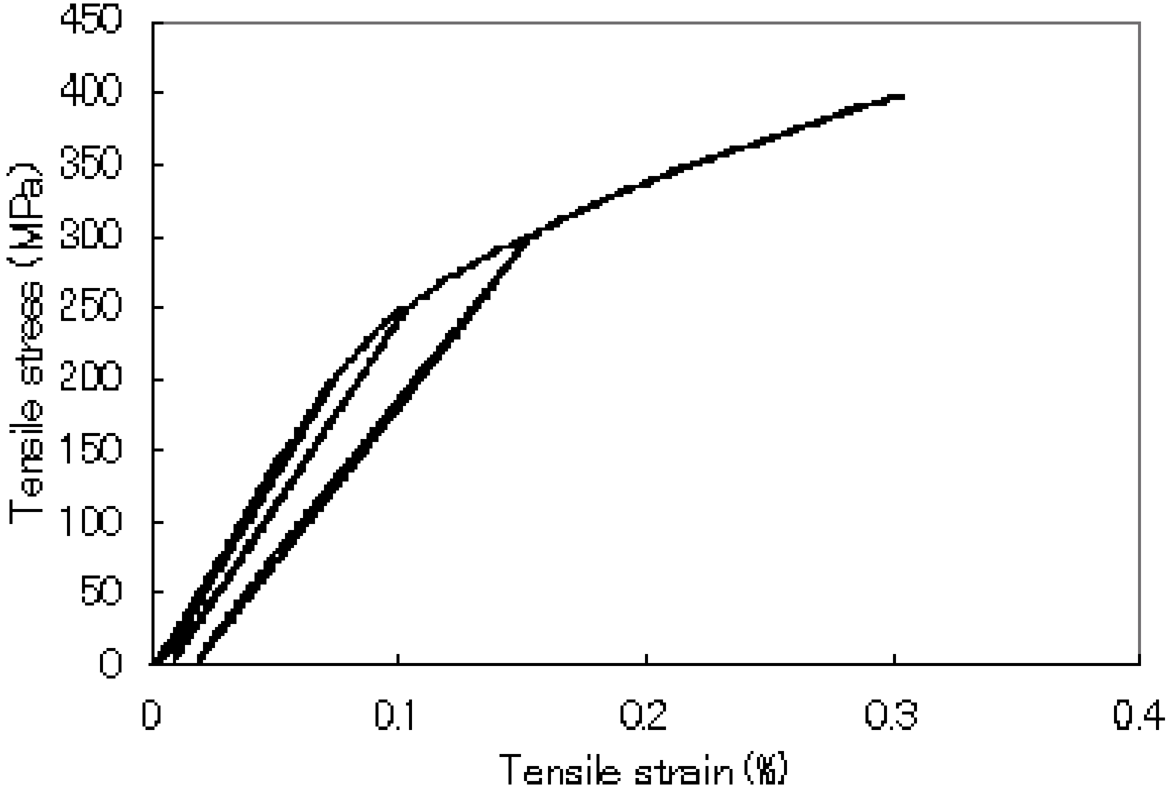


"NITE"-Fabricated SiC/SiC





Microstructure of “NITE”-Fabricated SiC/SiC

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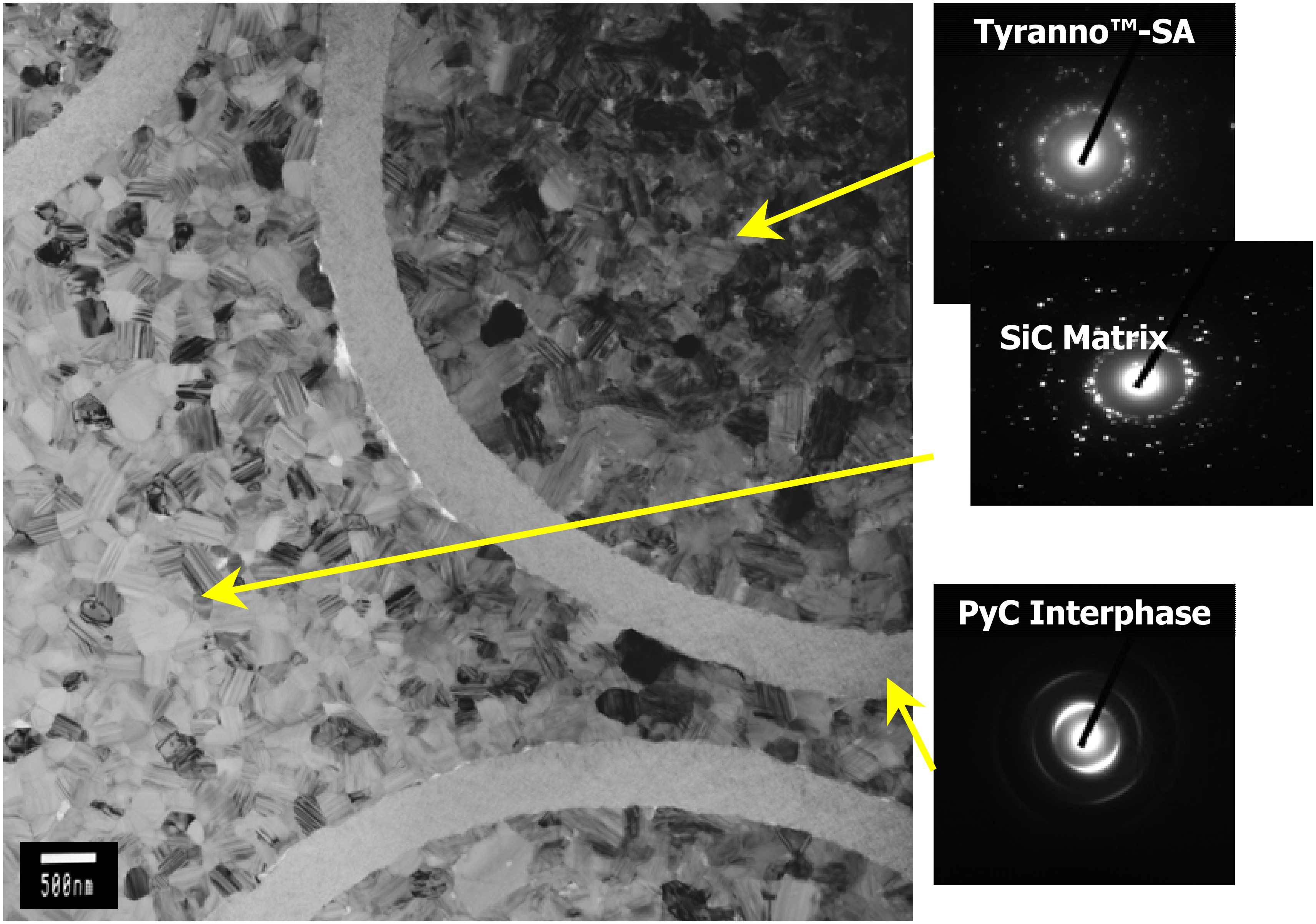

Fabrication Cost of SiC/SiC by Various Processes

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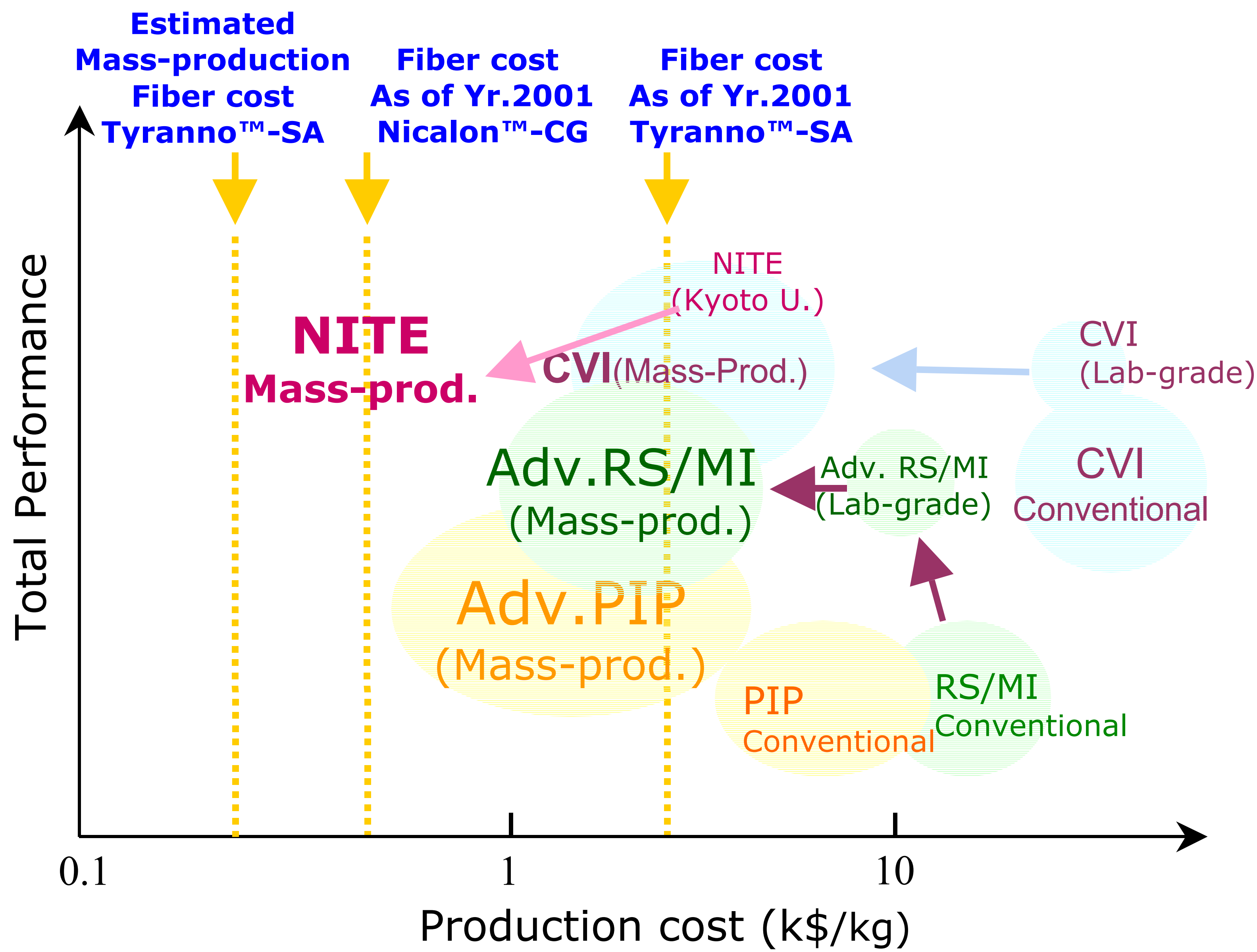

Permeability of He in SiC/SiC

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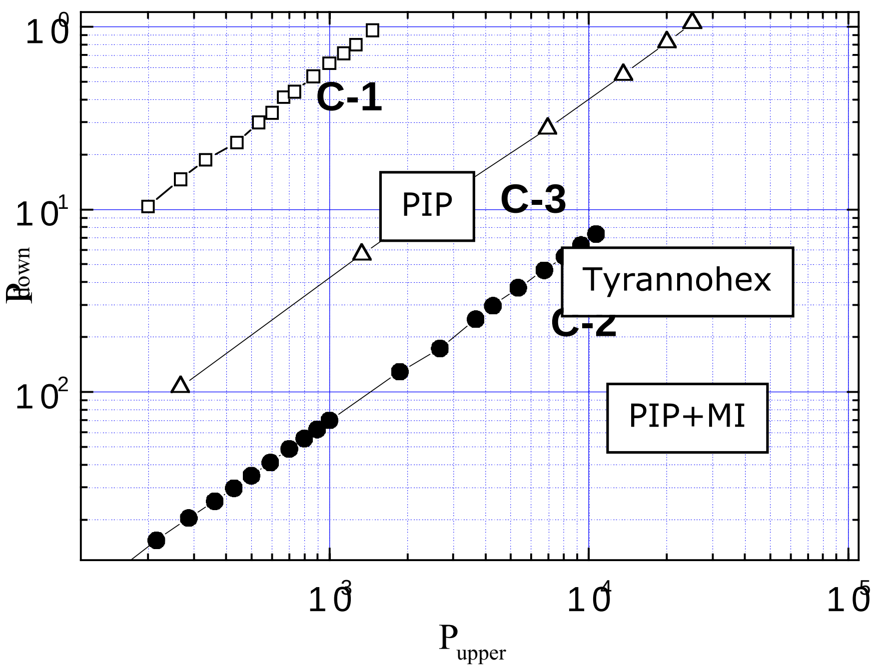
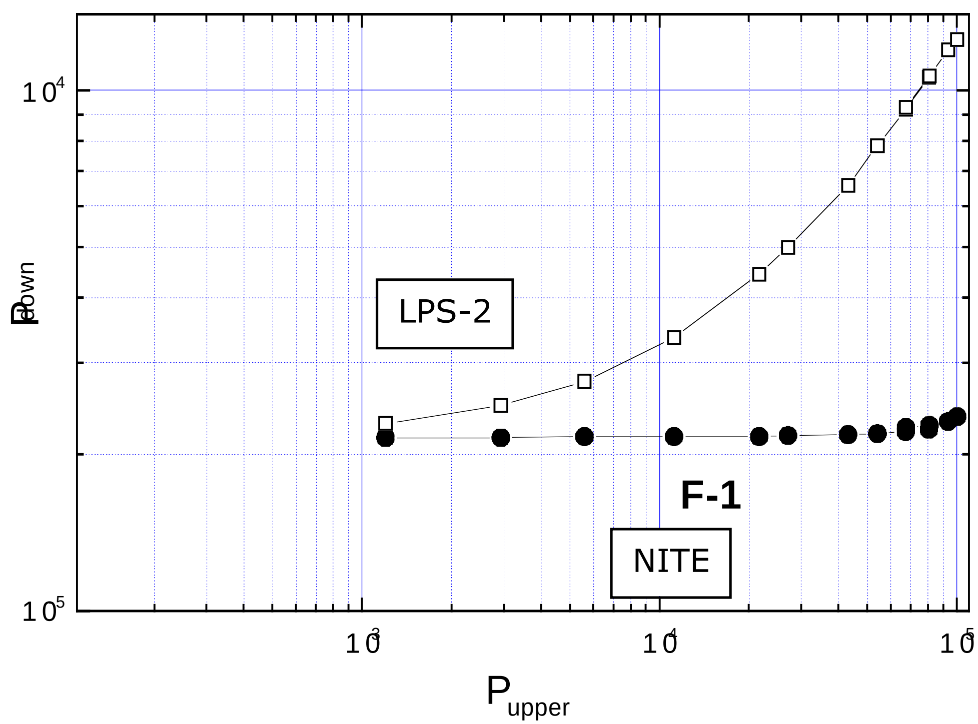
Conventional SiC/SiC and Bonded-SiC-Fiber Ceramics



Tubes by LPS (Kyoto University)



Comparison of Thermal Conductivity of SiC/SiC

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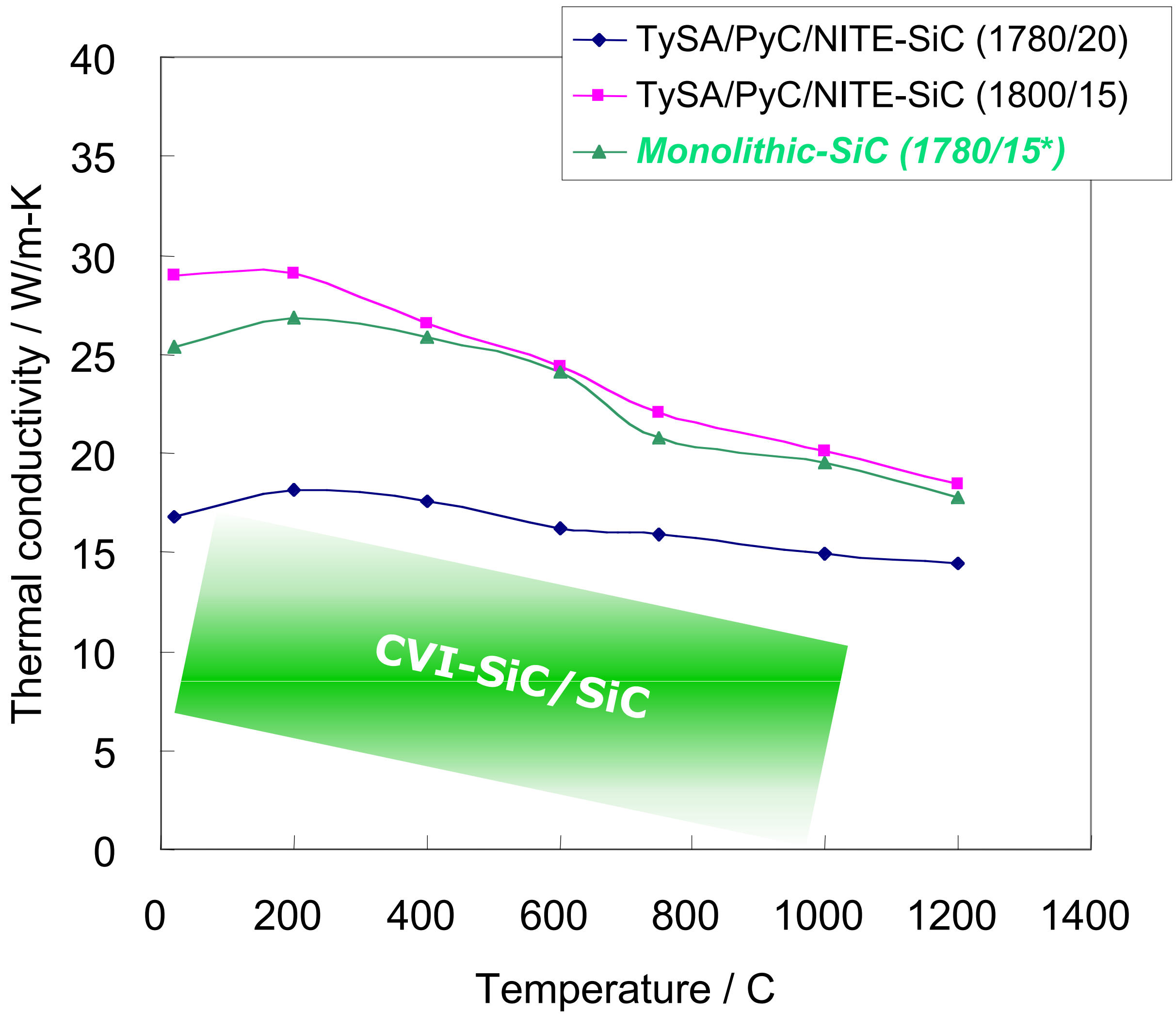
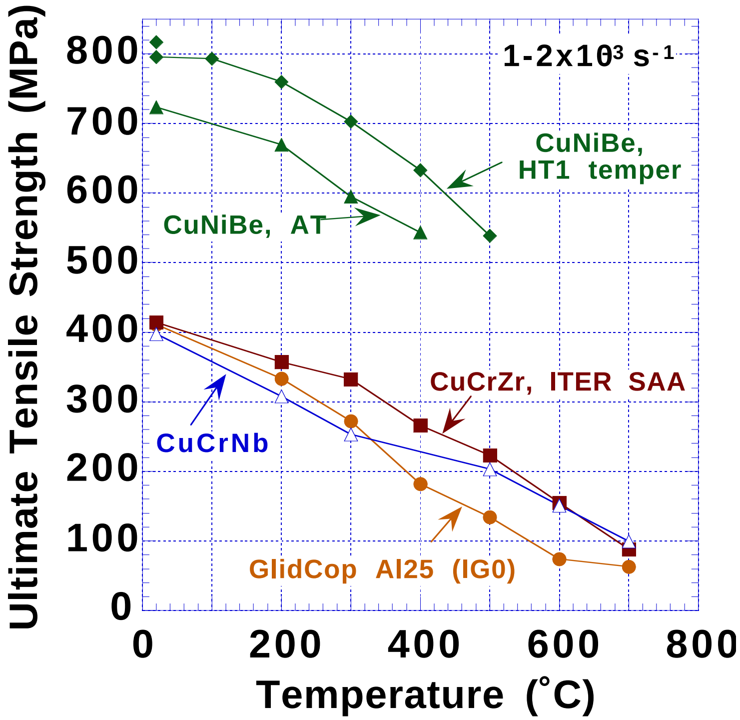
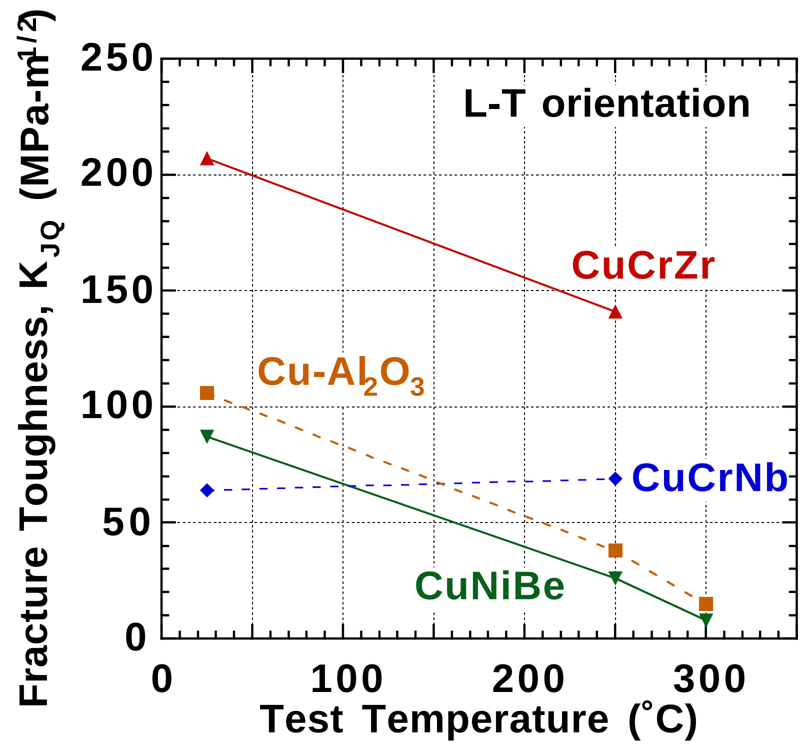


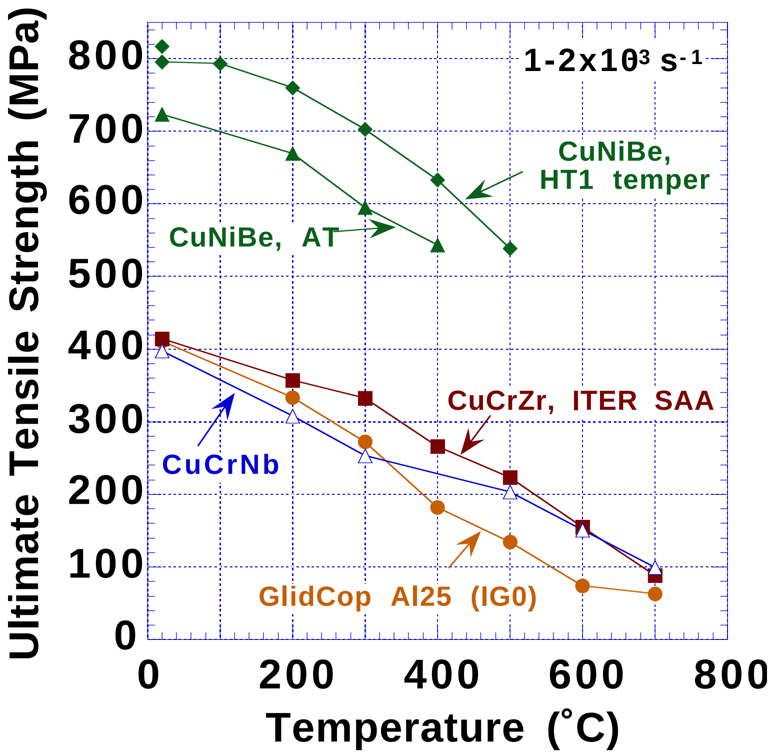
Mechanical behavior of a wide range of copper alloys has been investigated vs. strain rate and temperature (constitutive equations for deformation and fracture)

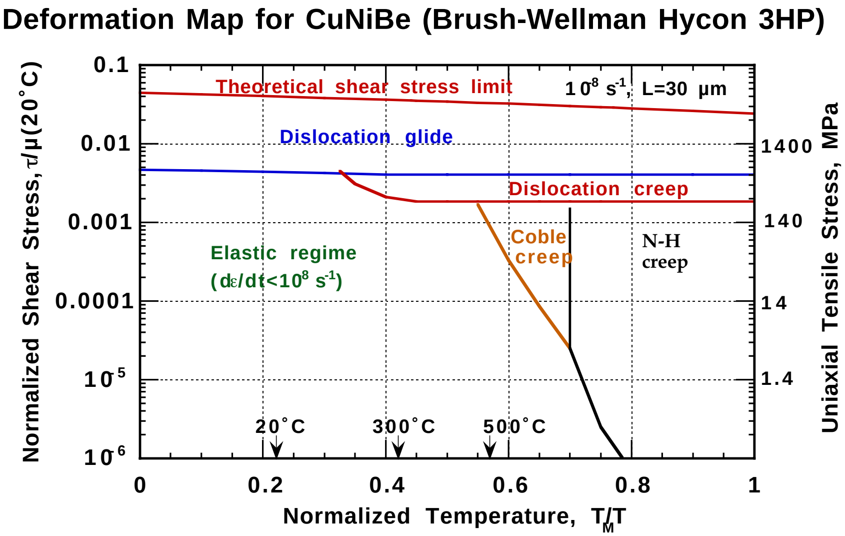


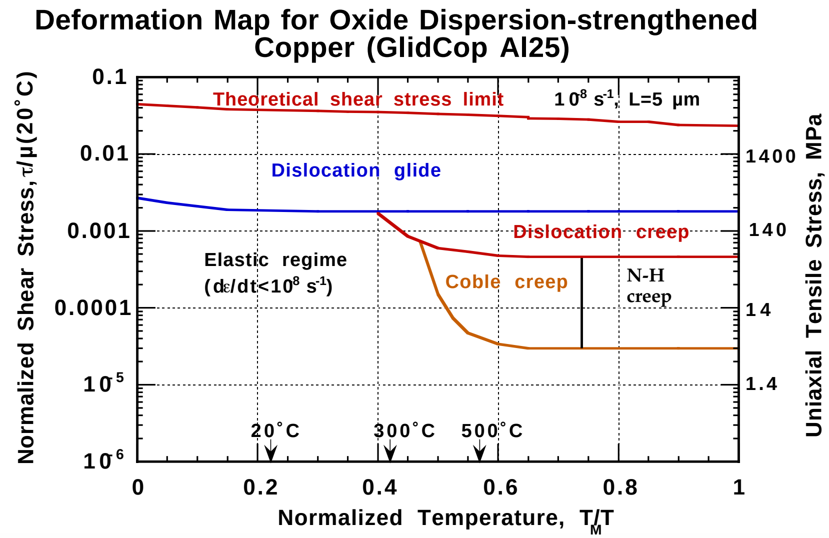


- CuNiBe has superior properties below 100˚C; CuCrZr and Cu-Al_2O_3 have best properties at intermediate temperatures
- high temperature limits in CuNiBe and Cu-Al_2O_3 alloys are associated with grain boundary phenomena

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





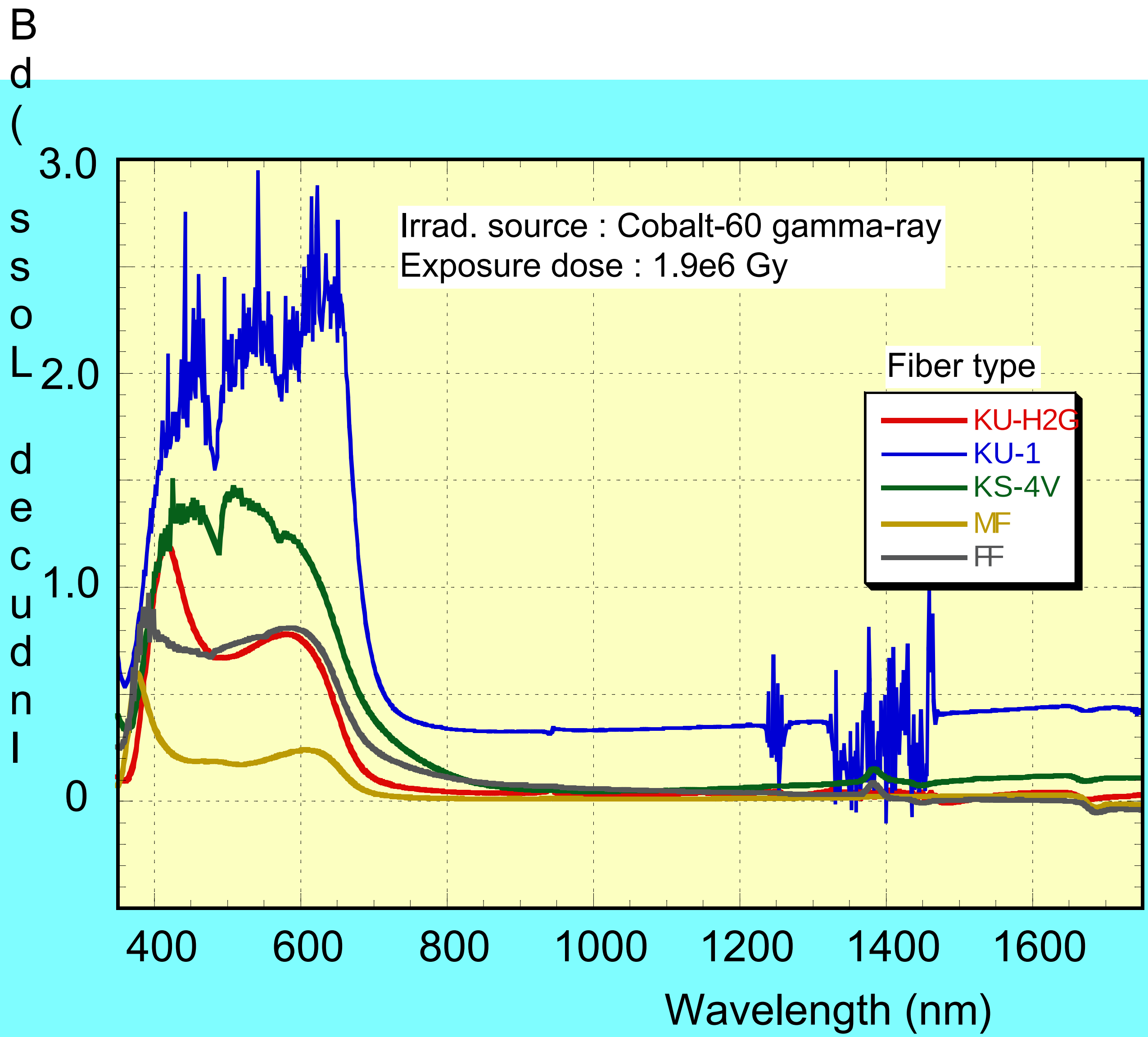


Applications to US industry (e.g., USCAR) as well as fusion energy sciences program

Optical fibers for ITER round robin irradiation tests

Team	Fiber Type	Supplier	Diameter(μm)		Remarks
			core	clad.	
RF	KS-4V	FORC	200	250	Pure silica core, OH & Cl free
	KU-1	FORC	200	250	Original, OH:800ppm
	KU-H2G	FORC	200	250	Improved, Hydrogen treated OH:800ppm
JPN	F F	Fujikura Ltd.	200	250	Fluorine doped silica core, OH-free
	M F	Mitsubishi Cable	200	250	Fluorine doped silica core, OH-free

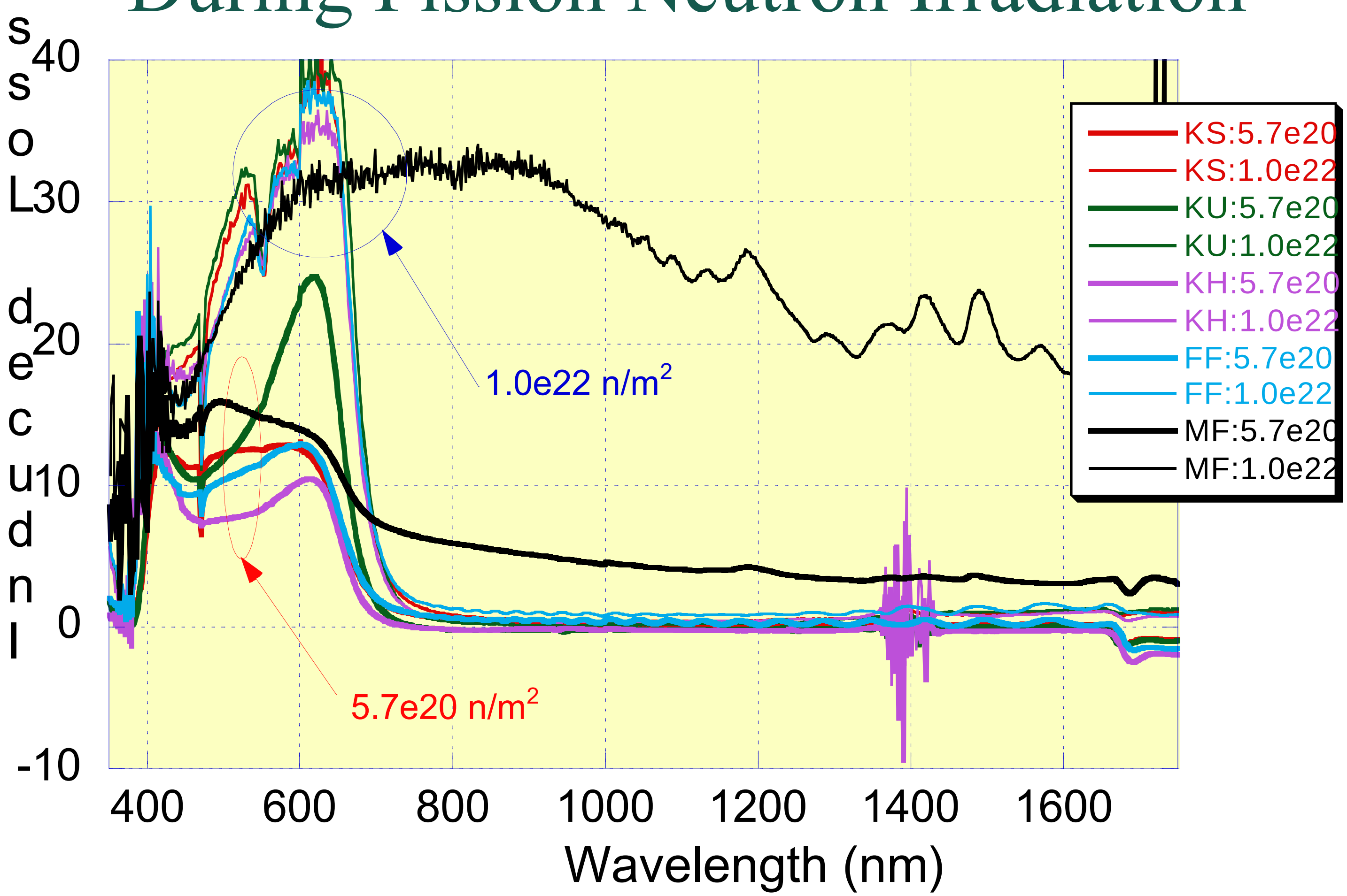
T. Kakuta et al., ICFRM11 (2001)



Comparison of increased absorption in ITER round robin fibers at gamma-ray irradiation of 1.9e6 Gy.

T. Kakuta et al., ICFRM11 (2001)

Observed Absorption of Optical Fibers During Fission Neutron Irradiation



High loss in MF fiber may be due to neutron radiation-induced microcracking

T. Kakuta et al., ICFRM11 (2001)

Conclusions

- There is a strong prospect for improvements in the capabilities of fusion structural materials based on ongoing research
  - Nanocomposited ferritic steels
  - Ductile Mo and W alloys
  - Hermetic, high conductivity, radiation-resistant, lower cost SiC composites
- Improved joining techniques are being applied to fusion materials
  - Gas tungsten arc welding of V alloys
  - Friction stir welding
- Materials which can be categorized as "reduced-activation" have properties comparable or superior to their commercial (high-activation) counterparts
  - e.g., Fe-9Cr ferritic/martensitic steels developed for fusion
- Additional screening studies are needed to identify the most promising nonstructural materials for fusion (organic insulators, optical materials, etc.)