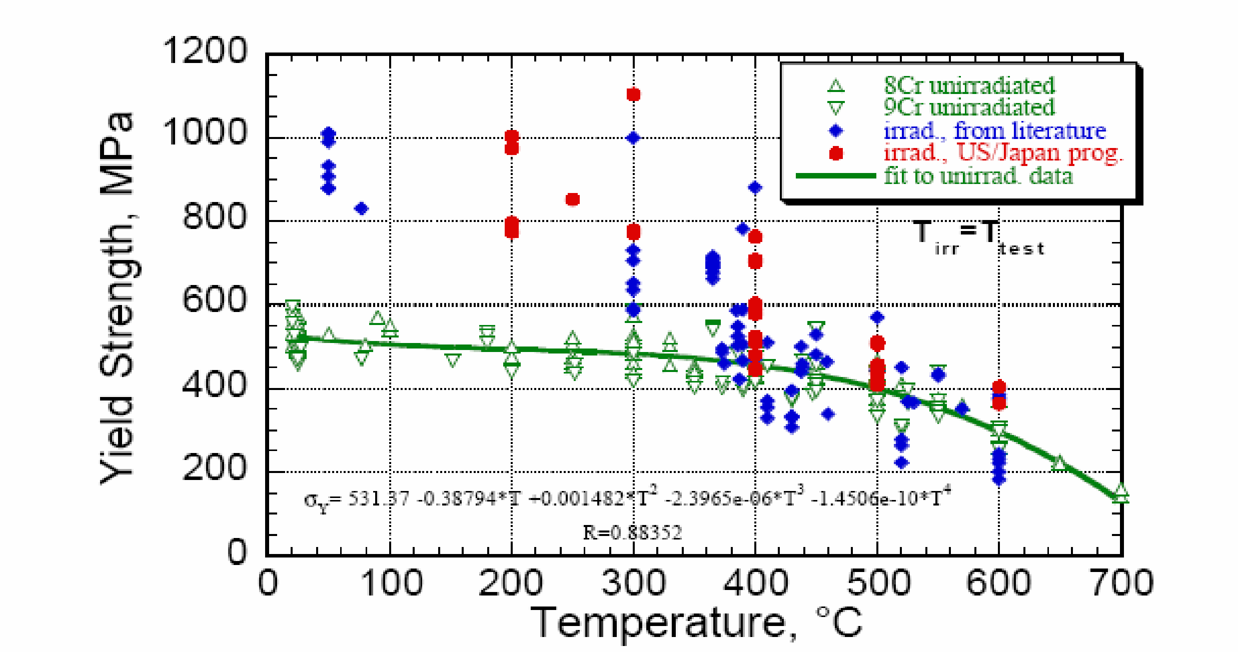
Material: BCC structural alloys
Property: Yield Strength vs. Temperature
Condition: Radiation Hardening
Data: Experimental

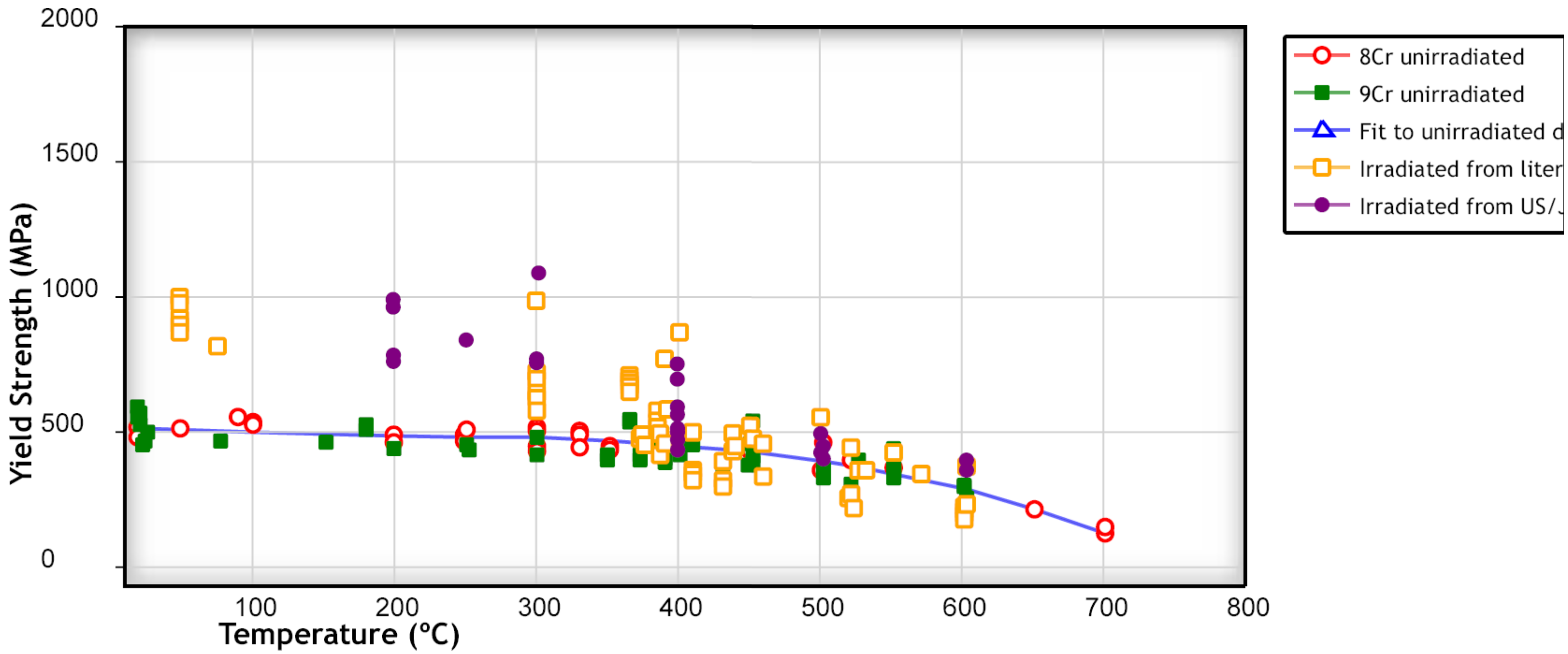


Source:
Fusion Materials Sciences Peer Review, University of California Santa Barbara (August 27-28, 2001)

Title of paper (or report) this figure appeared in:
Overview of Current BCC Structural Alloys

Author of paper or graph:
A.F. Rowcliffe

Caption:
Radiation Hardening in TMS (sigma_Y = 531.37 - 0.38794*T + 0.001482*T^2 - 2.3965e-06*T^3 - 1.4506e-10T^4; T_irr = T_test



Radiation Hardening in TMS (sigma_Y = 531.37 - 0.38794*T + 0.001482*T^2 - 2.3965e-06*T^3 - 1.4506e-10*T^4; T_irr = T_test)

Reference:

Author: *A.F. Rowcliffe*

Title: *Overview of Current BCC Structural Alloys*

Source: *Fusion Materials Sciences Peer Review, University of California Santa Barbara (August 27-28, 2001)*, [PDF]

View Data

Author Comments

Plot Format:

Y-Scale: ◉ linear ○ log ○ ln

X-Scale: ◉ linear ○ log ○ ln

Overview of Current BCC Structural Alloys

Presented by
A.F. Rowcliffe
Oak Ridge National Laboratory

Contributors:
N. Hashimoto, D.T. Hoelzer, R.L. Klueh, S.J. Zinkle (ORNL)
G.R. Odette (UCSB)
R.J. Kurtz (PNNL)
D.L. Smith (ANL)

Fusion Materials Sciences Peer Review
August 27th-28th, 2001
University of California Santa Barbara

Development of Current BCC Alloy Compositions

- Current alloy compositions evolved from strong U.S. leadership in the development of reduced activation options for Tempered Martensitic Steels (TMS) and Vanadium alloys
- Empirically-based development programs in the U.S., EU and Japan have addressed wide range of issues
  - reduced activation (safety, waste disposal)
  - fabrication/joining
  - mechanical behavior and thermophysical properties
  - radiation damage and helium effects
  - chemical compatibility and corrosion

Composition of Tempered Martensitic Steels (TMS)

- Current primary compositions have evolved empirically from studies on a wide range of compositions

USA	EU	Japan
2-9Cr-V	9Cr-W-V-Ta-N	2-15Cr-W
2-9Cr-W	12Cr-W-V-Ta-N	2-3Cr-W-V-Ta
2-12Cr-W-V	9-10Cr-W-V-Ta-Ti-Ce	7-9Cr-W-V-Ta
9Cr-W-Mn	9Cr-W-V-Mn-Ti	11Cr-W-V-Ta
9Cr-V-Mn		
12Cr-W-Mn		
12Cr-V-Mn		

Current Composition of US Program Model TMS

- Current compositions are all variants of the US-developed alloy
- 5000kg Heat of F82H is source of U.S. program model TMS

	Designation	Cr	W	V	Ta	Si	Mn	C	N
USA	9C-2WVTa	9.0	2.0	0.25	0.07	0.03	0.60	0.1	0.01
Japan	F82H	8.0	2.0	0.20	0.04	0.20	.050	0.1	<0.01
	JLF-1	9.0	2.0	0.20	0.07	0.08	0.65	0.1	0.05
EU	EUROFER	8.5	1.1	0.25	0.08	0.05	0.50	0.15	0.03

Composition of US Program Model Vanadium Alloy

- Model V-4Cr-4Ti, composition evolved empirically from US-led studies covering a wide range of compositions

Substitutional: Cr(O-20); Ti (1-15); Si(0-1) (wt%)

Interstitial: C(50-100); O(100-500); N(50-100) (wt.ppm)

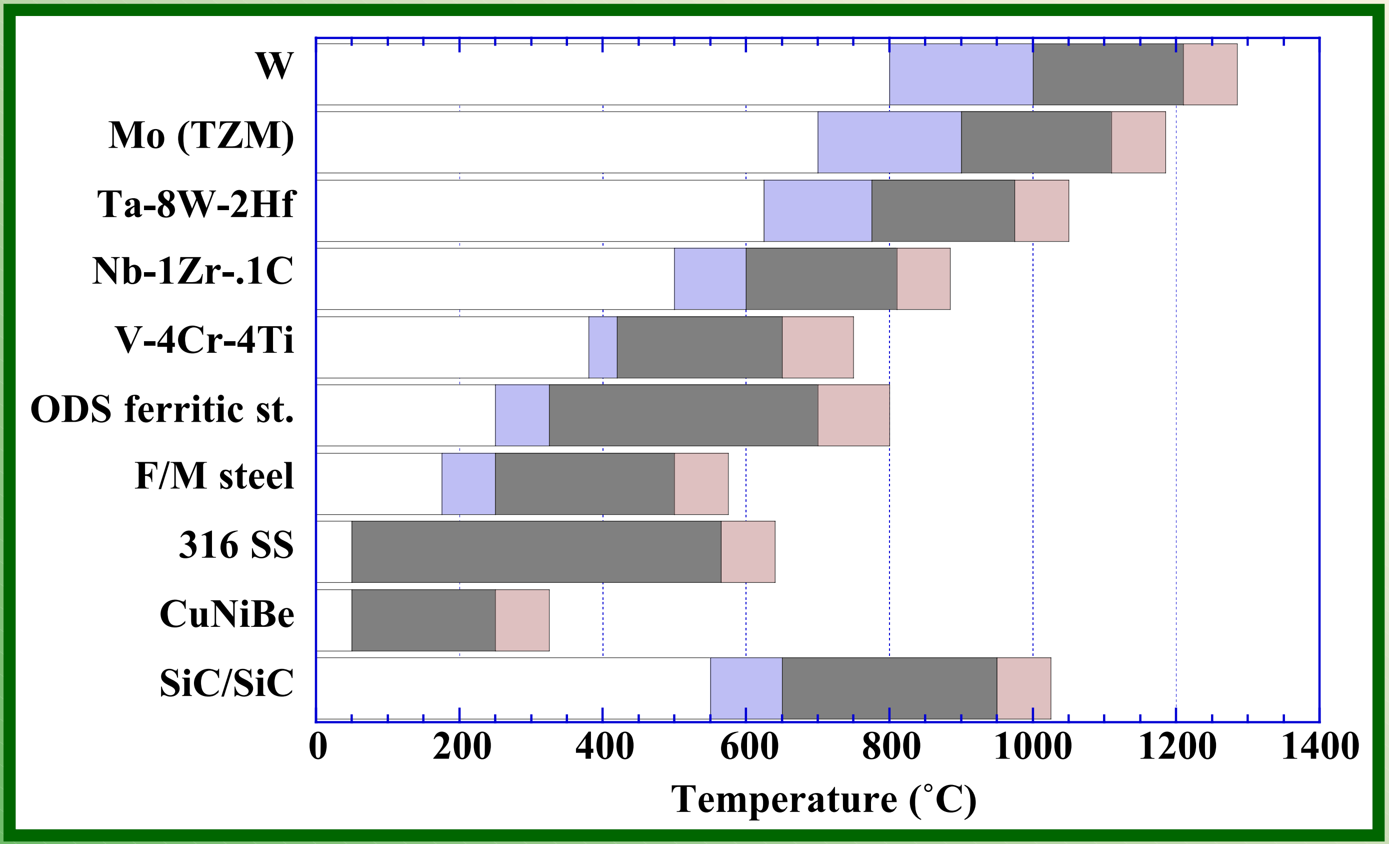
- Composition of U.S. 500kg heat

Cr	Ti	C	O	N
(wt%)		(wt.ppm)		
3.8	**3.9**	**80**	**310**	**85**

TMS and V alloys are the Focus of International Programs Co-ordinated through IEA Working Groups

- **EU**
  - Large program on TMS
  - Materials engineering data base for 2010 DEMO breeding blanket, Pb-Li and water-cooled options
  - No technological interest in V
- **Japan**
  - Program on TMS led by JAERI
  - Materials engineering data base for 2015 DEMO, Water-cooled blanket (SSTR)
  - Program on V Alloys led by MONBUSHO
  - Materials development phase for a Li-cooled blanket (ARIES-RS)
- **US**
  - Advancement of materials science base for BCC model structural alloys; integrated theory/modeling/experimental approach to resolve feasibility issues; development of innovative materials

Operating Temperature Windows for Structural Alloys in Fusion Reactors



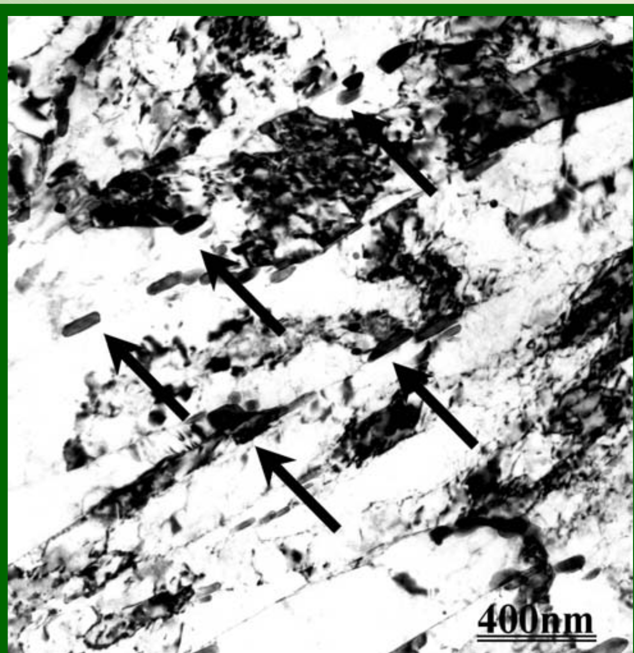
- Lower temperature limit of alloys based on radiation hardening/ fracture toughness embrittlement (K_{1C}< ~30 MPa-$m^{1/2}$)—large uncertainty for W, Mo due to lack of data
- Upper temperature limit based on 150 MPa creep strength (1% in 1000 h); chemical compatibility considerations may cause further decreases in the max operating temp.

Critical Performance-Limiting Phenomena in BCC Alloys

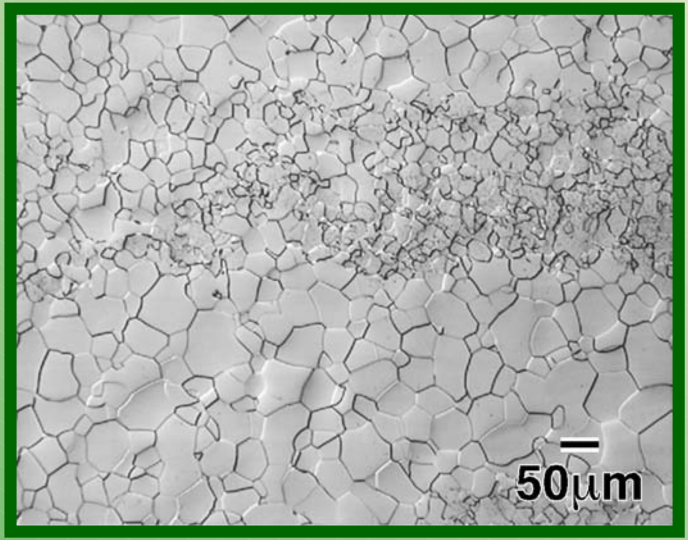
- **Low Temperature Regime:**
  - Radiation hardening and flow localization
  - Hardening-induced shifts in fracture toughness transition temperature
  - Effects of helium and hydrogen generation on fracture properties
- **High Temperature Regime:**
  - Loss of creep strength in TMS due to recovery of martensite structure
  - Loss of creep strength in V-4CrO4Ti; low barrier density
  - Helium-induced swelling and grain-boundary embrittlement

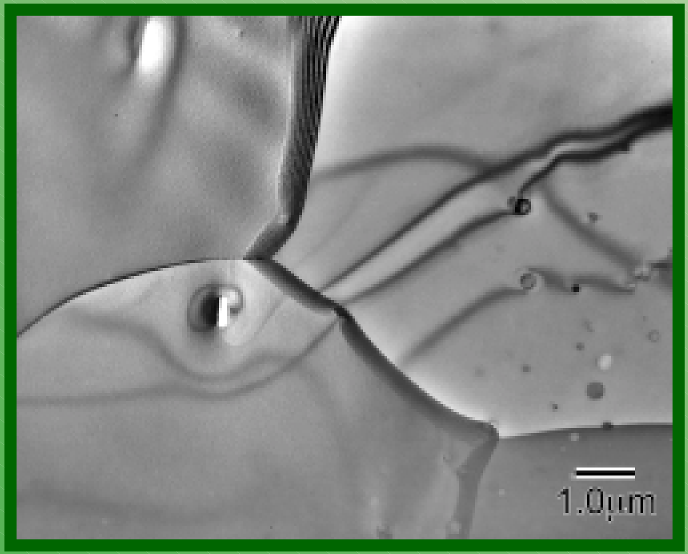
Processing and Start-of-Life Microstructure for F82H

- **Processing**
  - Hot rolling in the austenite range at 1200ºC-1050ºC
  - Normalizing at 1040ºC (fully austenitic); martensitic transformation on cooling; tempering at 740ºC (below Ac).
- **Microstructure**
  - Prior austenite grain size ~100μ; lath packets/partially recovered dislocation structure; precipitation of $M_{23}C_6$;
  - Dislocation density $\sim 5x10^{14} m^{-2}$
  - $M_{23}C_6$ number density $\sim 1x10^{20} m^{-3}$



Processing and Start-of-Life Microstructures for V-4Cr-4Ti

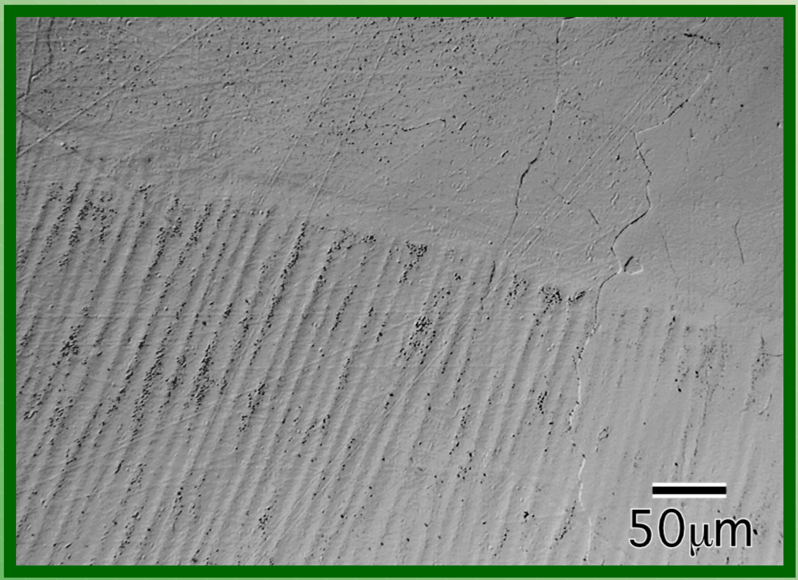




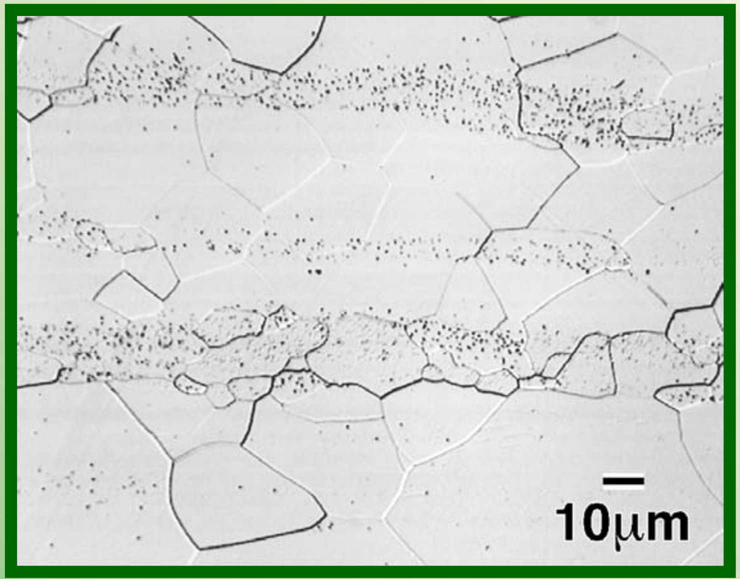
- **Processing**
  - 500kg ingot hot extruded at 1100ºC
  - Cold rolling and recrystallization in the range 950ºC-1050ºC
  - Primary globular Ti(OCN) phase solvus temperature >1150ºC
- **Microstructure**
  - Ti segregation during ingot solidification results in formation of bands of Ti(OCN) during extrusion
  - Recrystallized grain size 20-30µm; low sink strength microstructure

Formation of Banded Microstructures in V-4Cr-4Ti

GTA Weld



Recrystallized at 1000°C

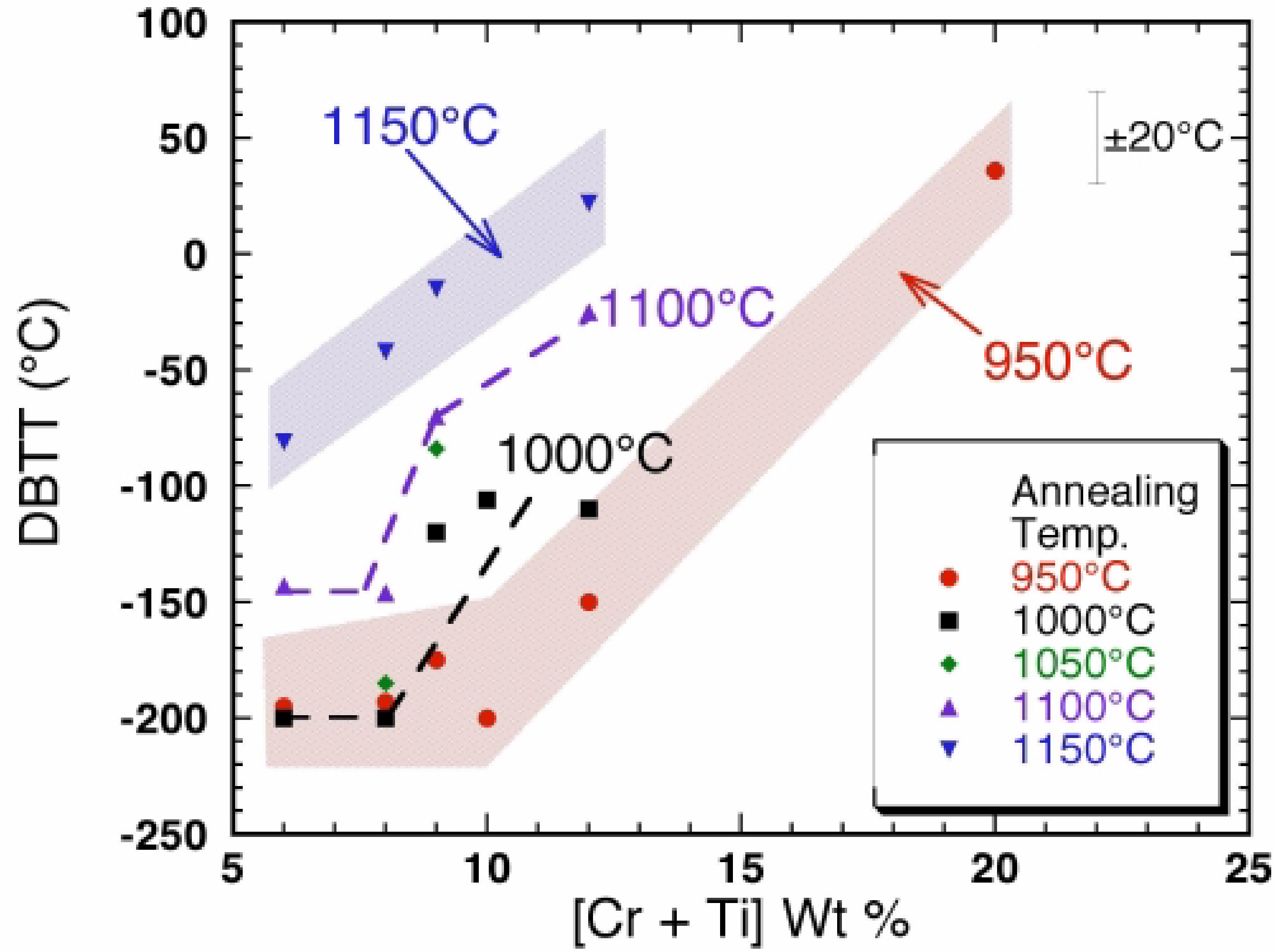


- Evidence for Ti segregation during solidification in GTA weld zones and also from microprobe analysis of ingots prepared in RF
- Globular Ti(OCN) develops in Ti-rich regions; bands of particles form during hot extrusion

Sensitivity of Fracture Properties to SOL Microstructures

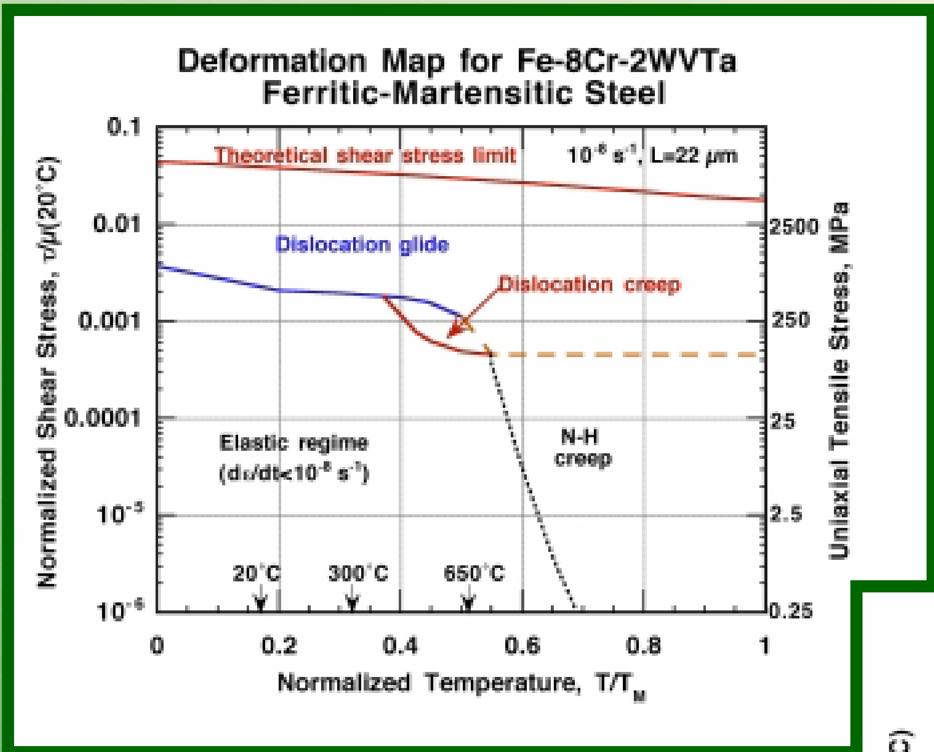
- Fracture properties of V-4Cr-4Ti strongly dependent on final heat treatment conditions
  - DBTT variations >200ºC due to change in grain size and interstitial content
- Fracture properties of TMS much less sensitive to SOL microstructure
  - DBTT variations 10º-50ºC produced by variations in prior austenite grain size and final tempering conditions.

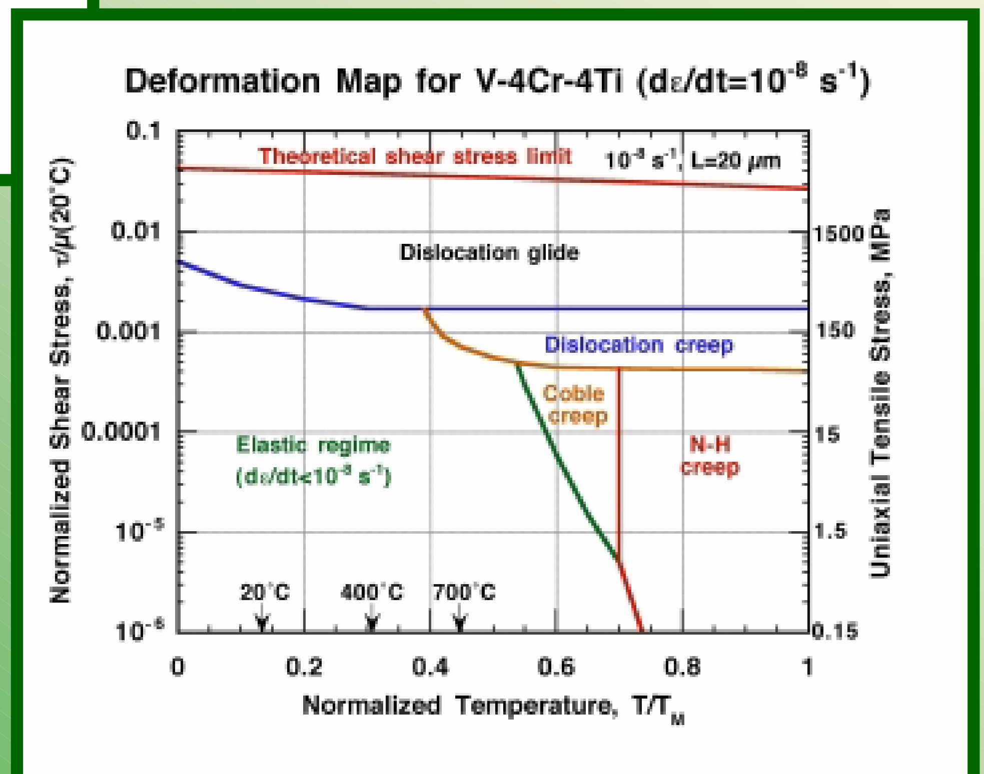
Summary of Effect of Heat Treatment and [Cr+Ti] Concentration on Impact Properties



- Optimal impact properties are produced at annealing temperature of 950-1000°C for a wide range of V-Cr-Ti solid solution alloys

Mechanical Behavior of BCC Structural Alloys

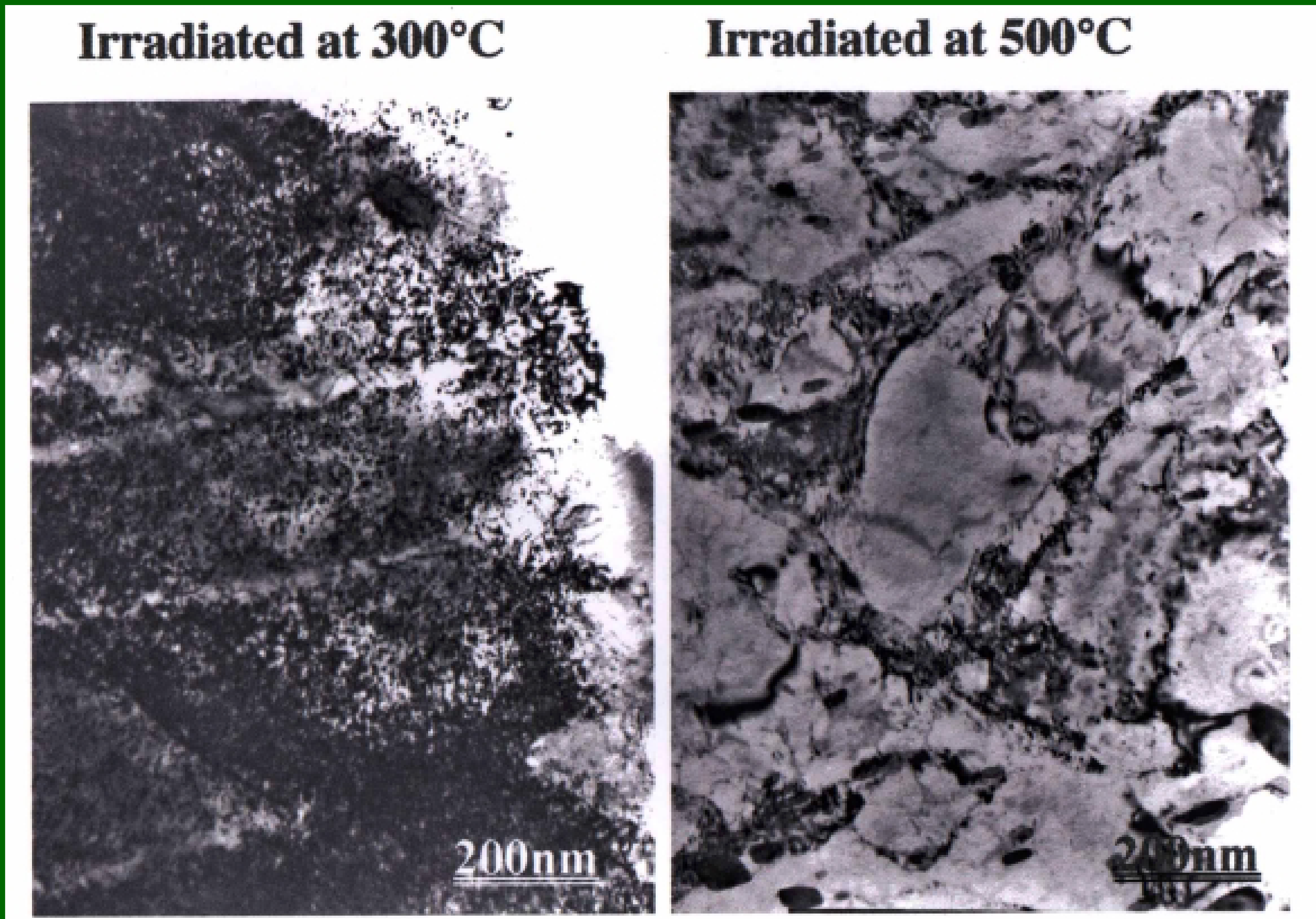




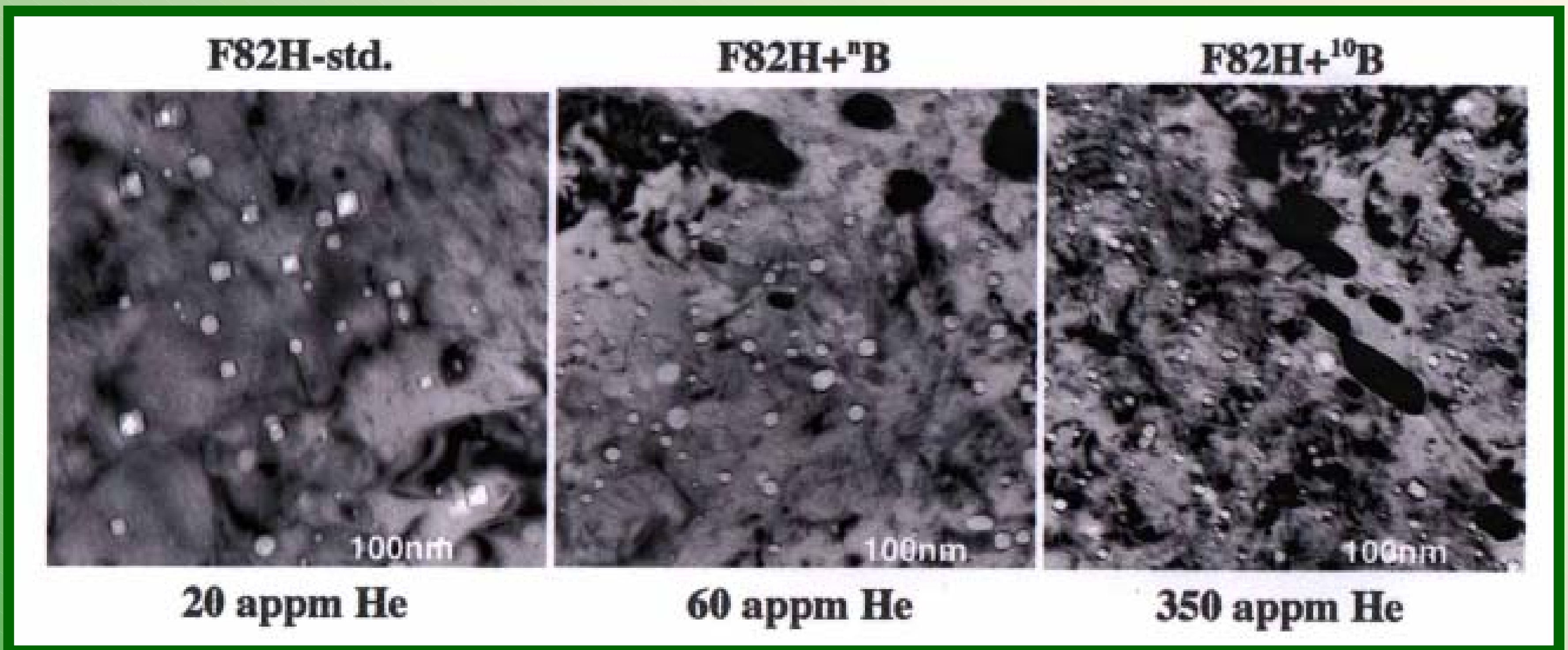
Microstructural Stability in F82H

- **Thermal**
  - Tempered martensite structure relatively stable up to 550ºC (5000h)
  - Intermetallic Laves phase develops > 600ºC after 10^4 hours
- **Irradiation**
  - Lath, dislocation and precipitate structure relatively stable during neutron irradiation up to 500ºC
  - Populations of a_0<100> and $(a_0/2)$<111> loops are the principal source of hardening 100ºC - 400ºC
- **Helium Generation**
  - Doping with Ni or B produces fairly uniform distributions of helium bubbles via (n,α) reactions between ^{58}Ni, ^{10}B and thermal neutrons

Microstructure of F82H Irradiated to 5 dpa and Tensile Tested at R.T.

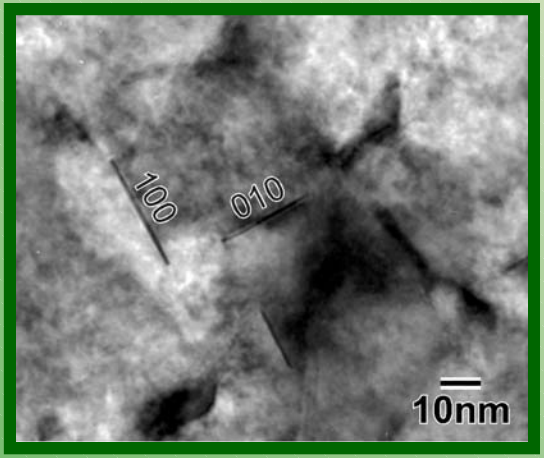


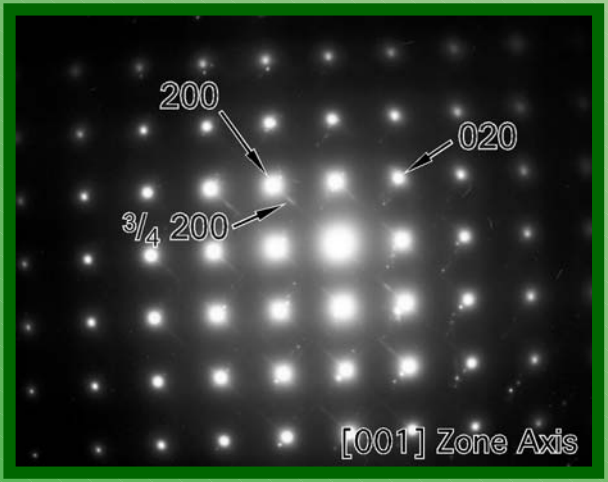
Microstructure of F82H Irradiated at 400ºC to 52 dpa in HFIR

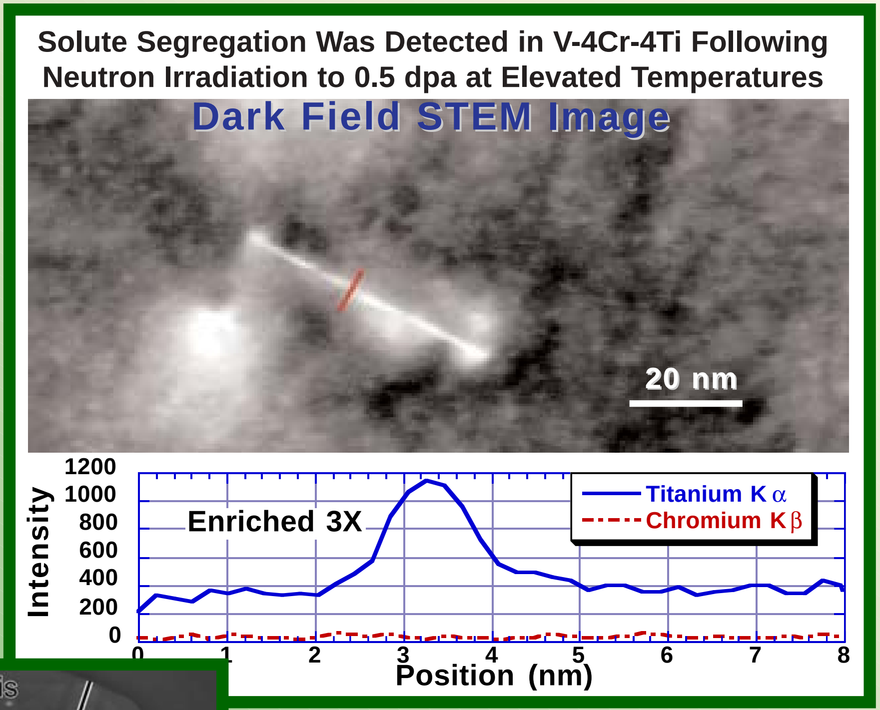


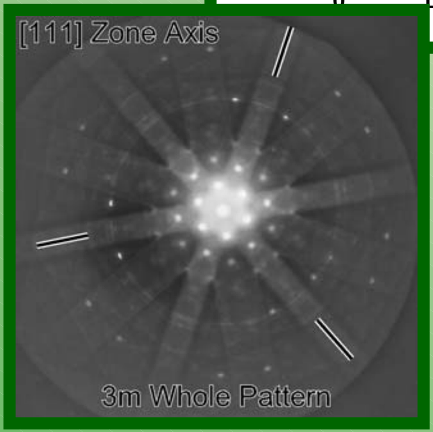
- Doping with B produces fairly uniform bubble distributions and provides an important means of investigating the effect of helium on fracture behavior.

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



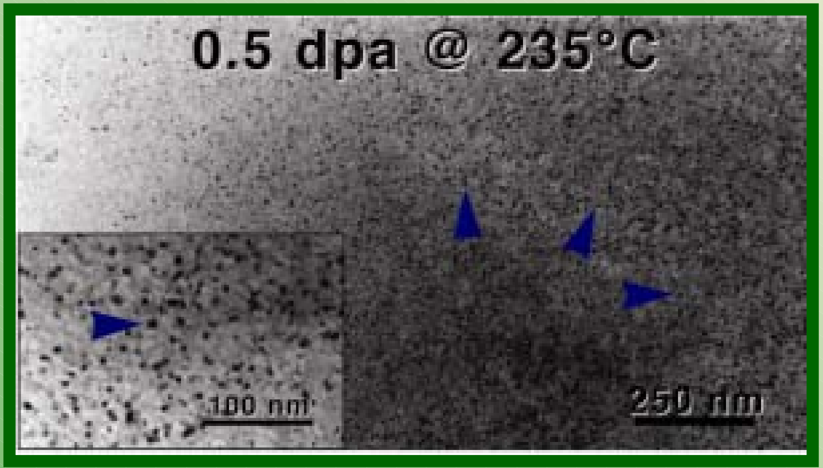


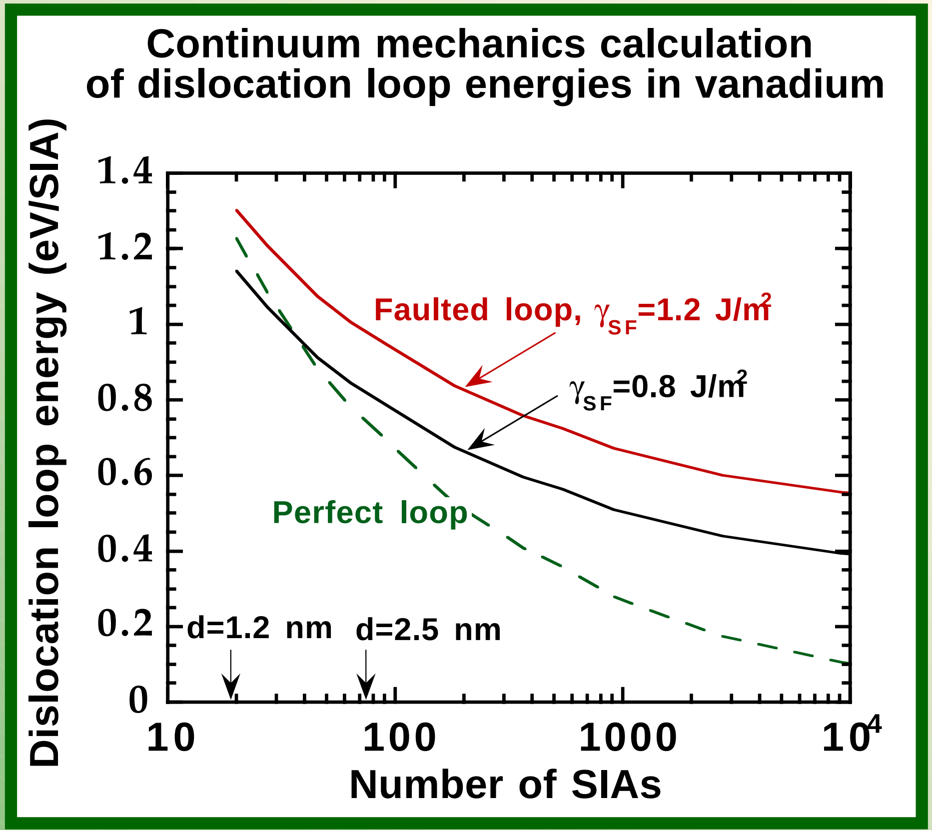


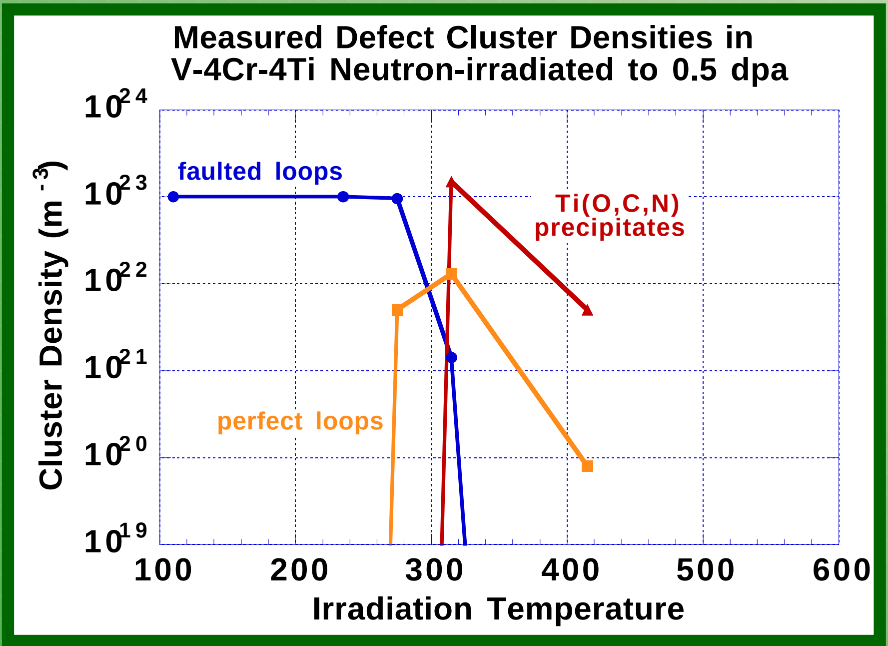


- Analytical microscopy reveals Ti-rich precipitates with Fm3m space group

Experimental investigation of stacking fault energies of BCC metals



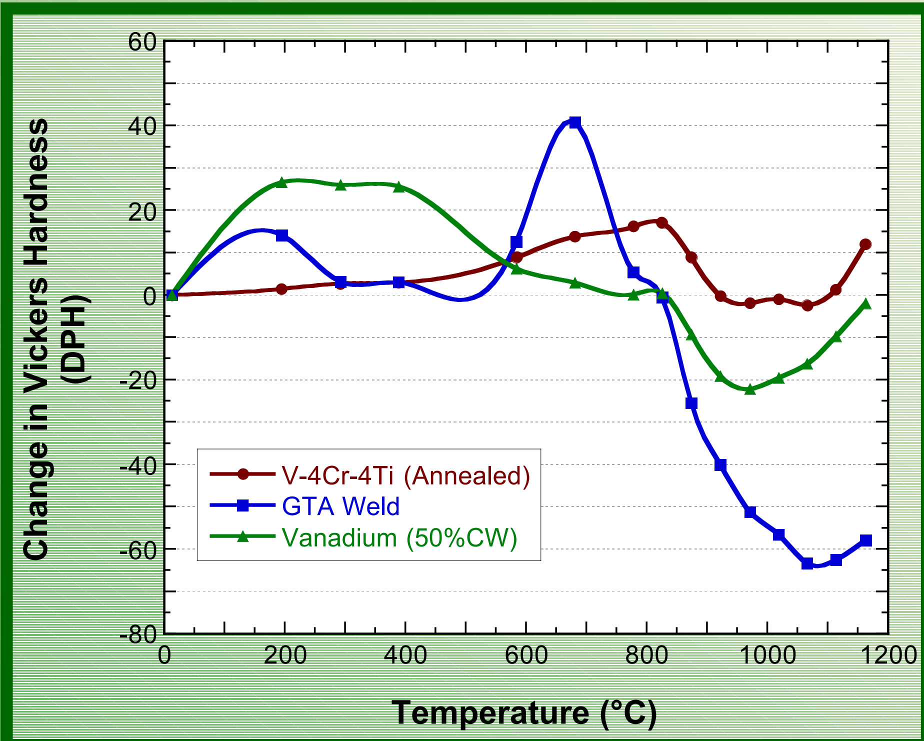


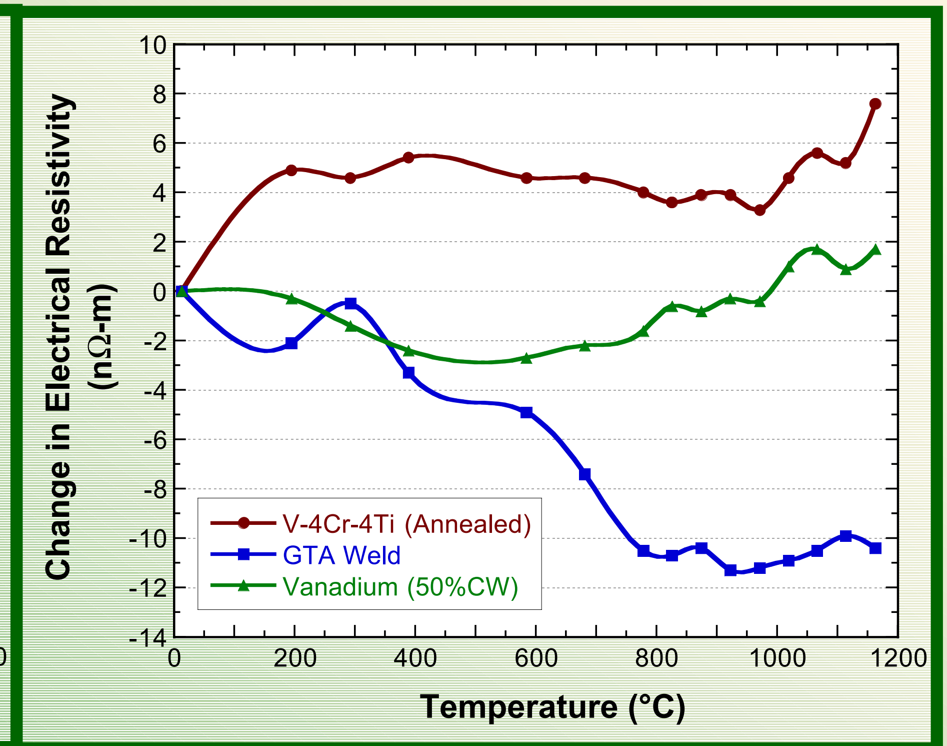


Microstructural Stability in V-4Cr-4Ti

- **Thermal**
  - Segregation of interstitials to dislocations beginning at ~200ºC (static and dynamic strain aging)
  - Precipitation of a range of plate shaped Ti(OCN) phase 700º-950ºC
- **Irradiation**
  - <110> faulted and <111> perfect interstitial loops primarily responsible for radiation hardening 60º-350ºC
  - Ti-enriched <001> defects develop 300º-400ºC; Ti-rich oxycarbonitride plates develop 400º-550ºC

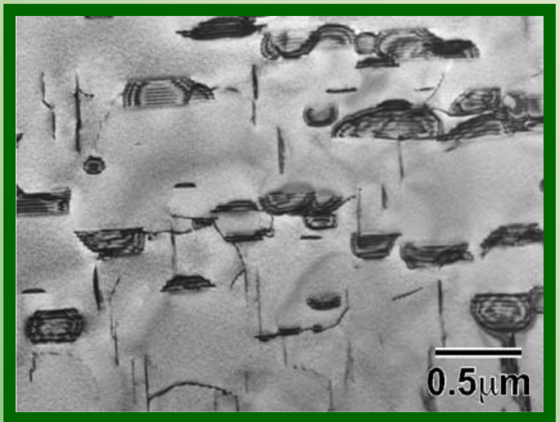
Electrical Resistivity and Hardness in V-4Cr-4Ti as a Function of Temperature





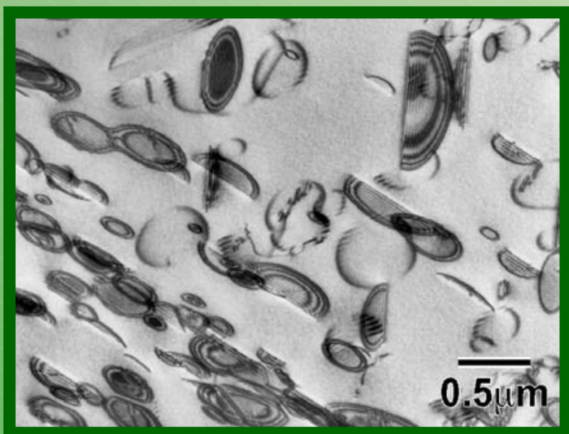
- Variations in electrical resistivity and hardness reflect mobility of interstitials and interactions with Ti and provide information relevant to DSA, recovery and recrystallization processes and precipitation reactions

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



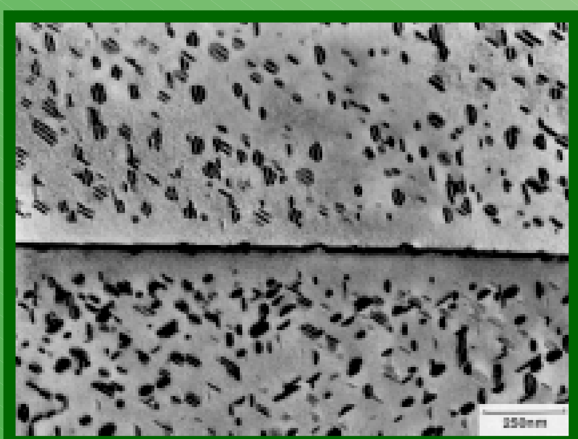
GTA Weld

- $Ti_{16}(O_3N_3C_2)$



Oxidized

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

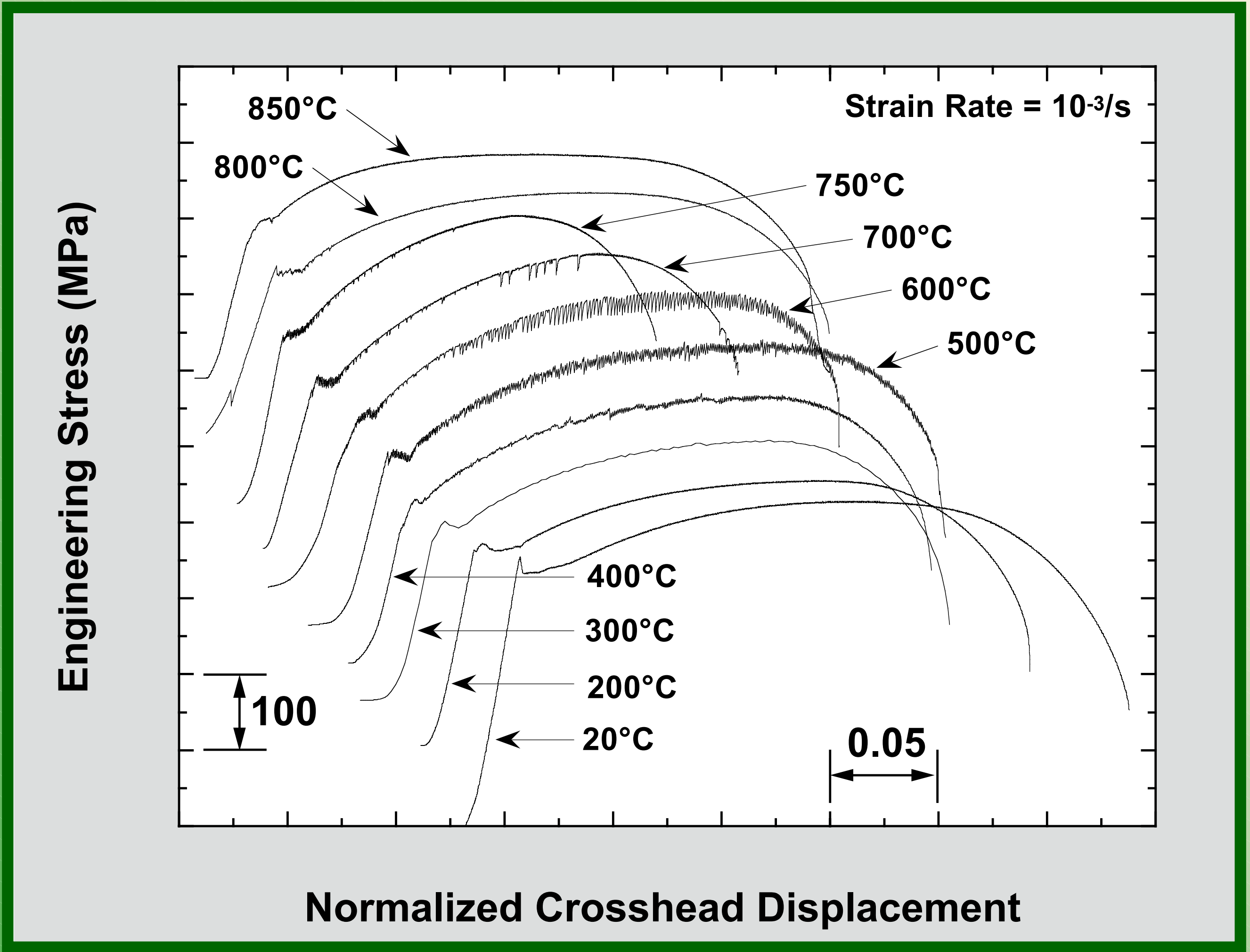


Neutron Irradiated

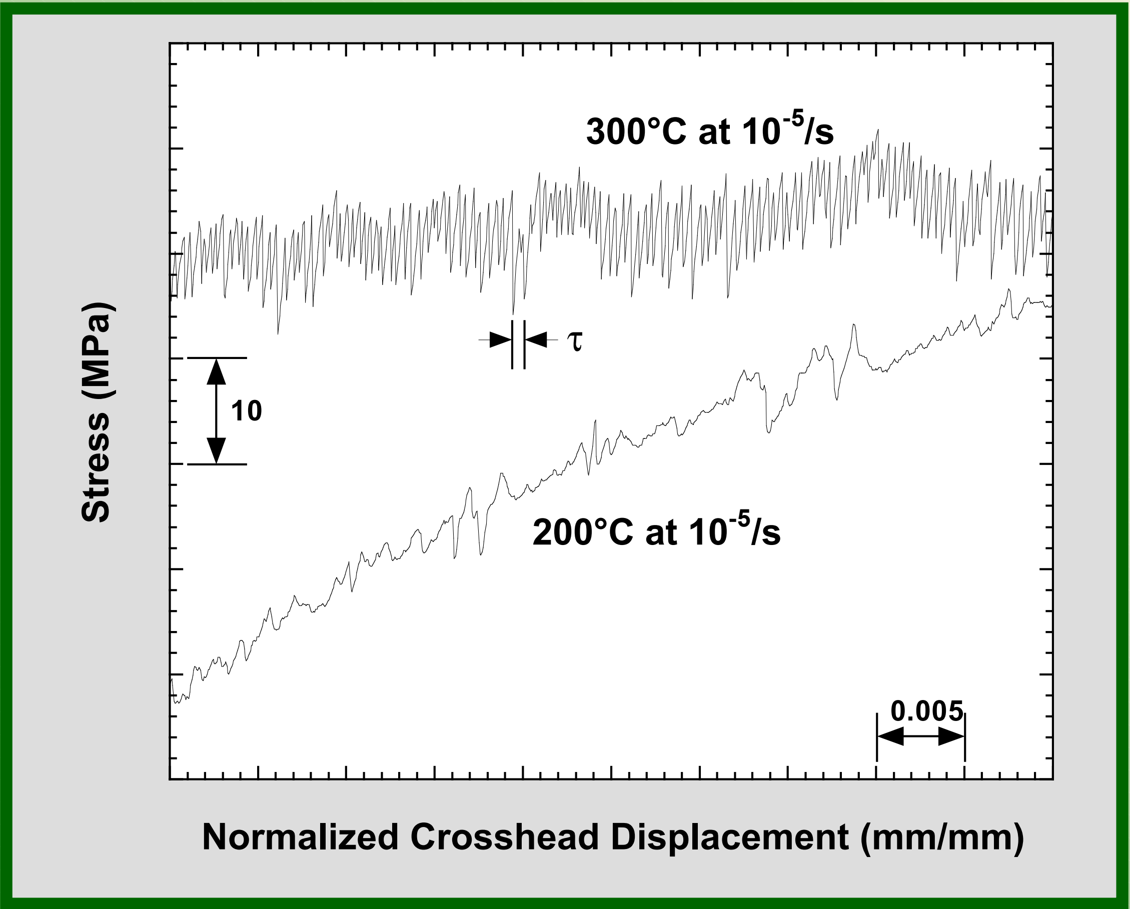
- $Ti_{>90}(O,N)_{<10}$ [No C]

Dynamic Strain Aging in V-4Cr-4Ti

- Maximum in strain-rate sensitivity occurs at 600°C in V-4Cr-4Ti



Magnified View of Serrated and Jerky Flow Behavior in Vanadium



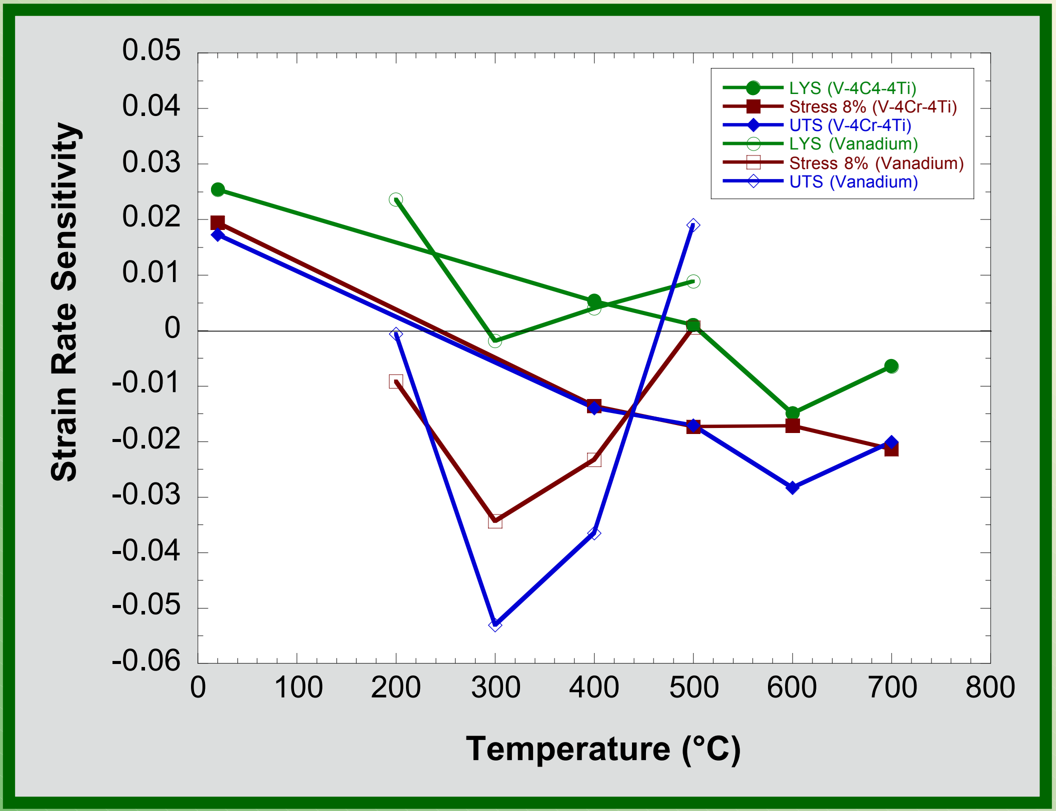
- **Estimate time for diffusion of interstitials**
  - **segregate to immobile and mobile dislocations**
  - **identify elements responsible for DSA**
- **Calculate average time between minima (t)**
  - **300°C and 10^{-5}/s**

    τ = ~37.5s
  - **200°C and 10^{-5}/s**

    τ = ~129s

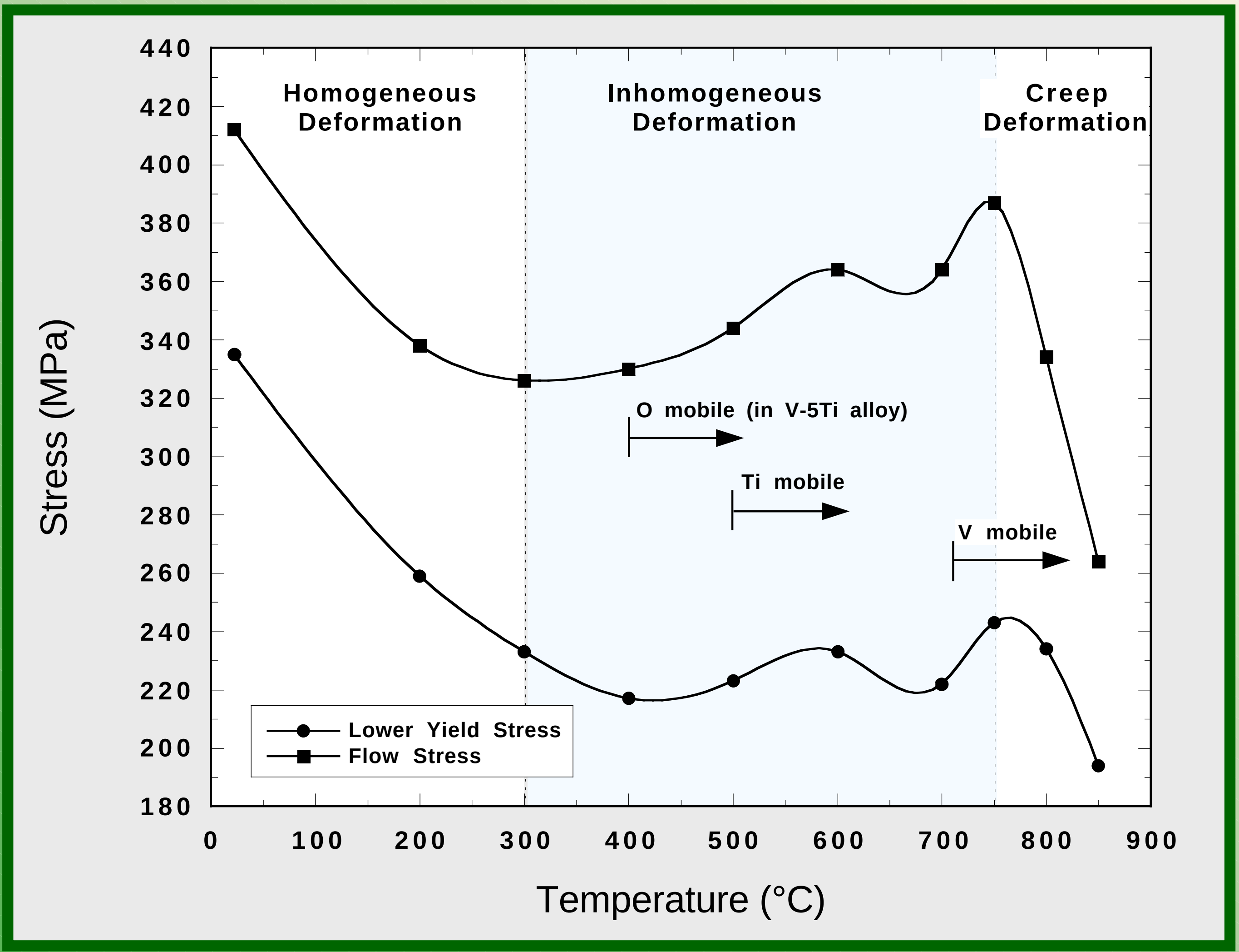
- Diffusivity calculations show:
  - Carbon and oxygen are primarily responsible for DSA effect below 300°C
  - Nitrogen has similar mobility at a higher temperature of 400°C

Strain Rate Sensitivity for V and V-4Cr-4Ti

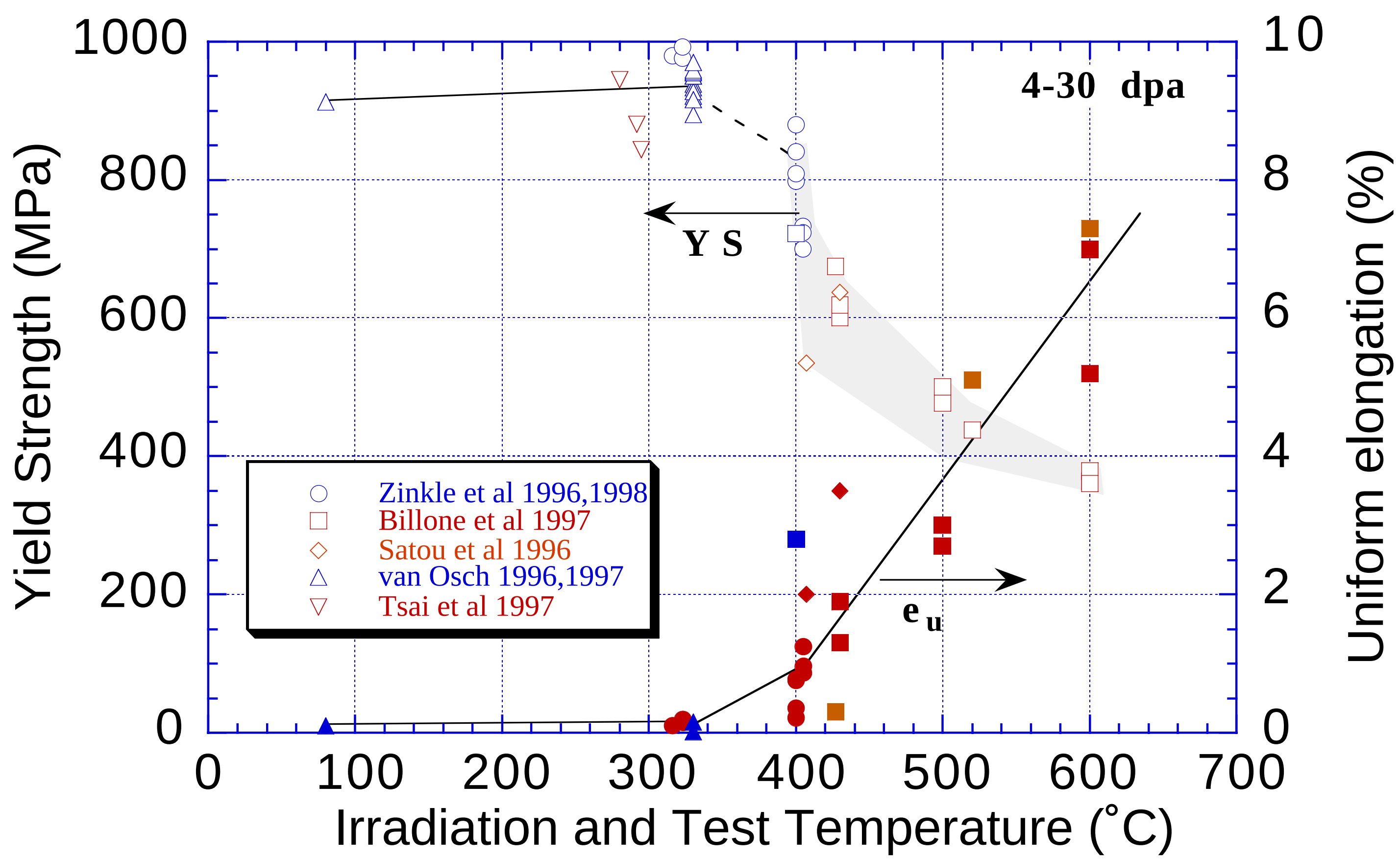


- Alloying with Ti shifts the maximum negative SRS by ~300°C
- Calculations based on stereology measurements indicate that ~50% of the interstitials are retained in the globular Ti(OCN)
  - mobility of the remaining interstitial content is reduced by interactions with Ti
- Possible benefits of lowering Ti concentration are being investigated

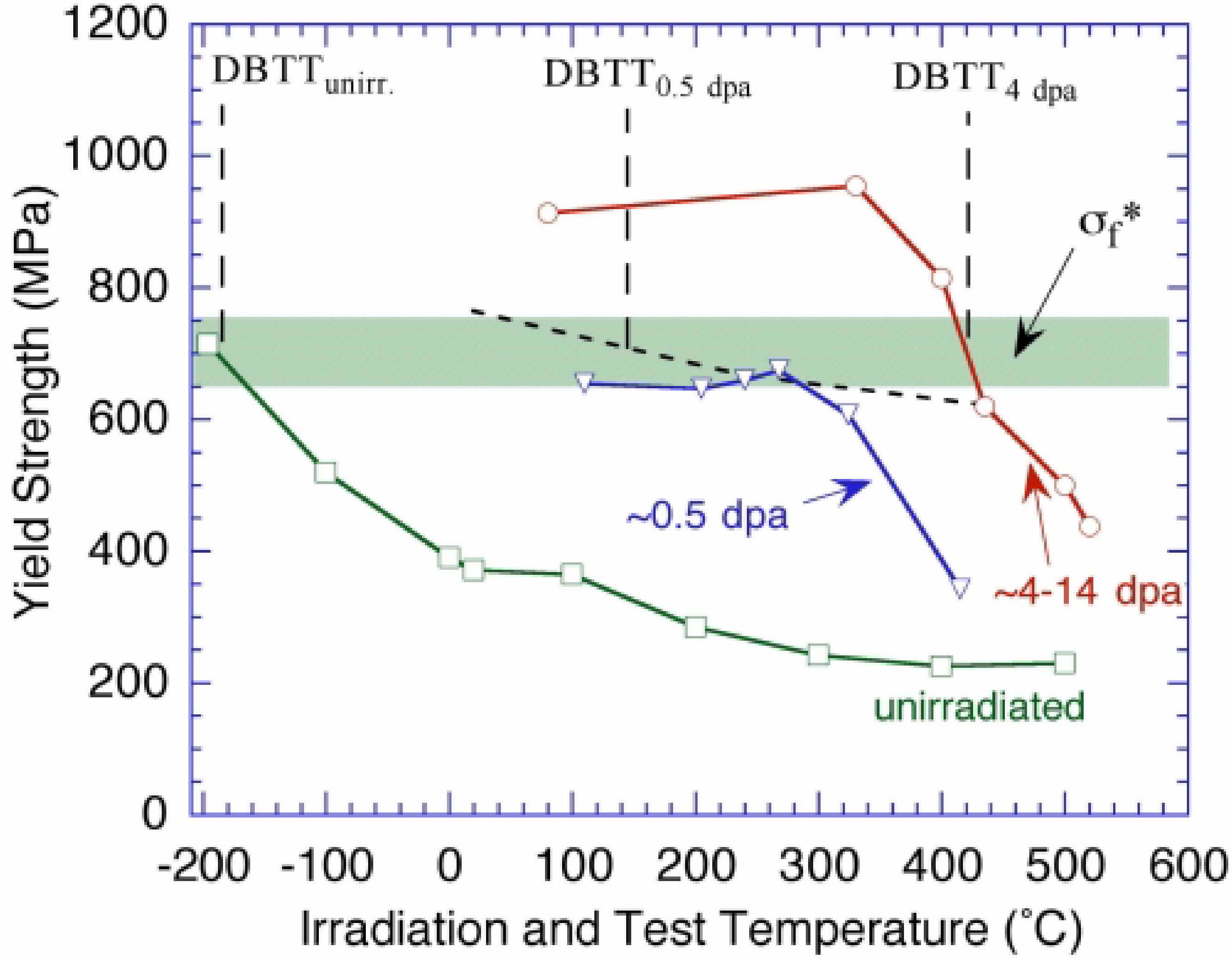
Temperature Dependence of σ_Y and σ_f at 10^{-3} s^{-1}



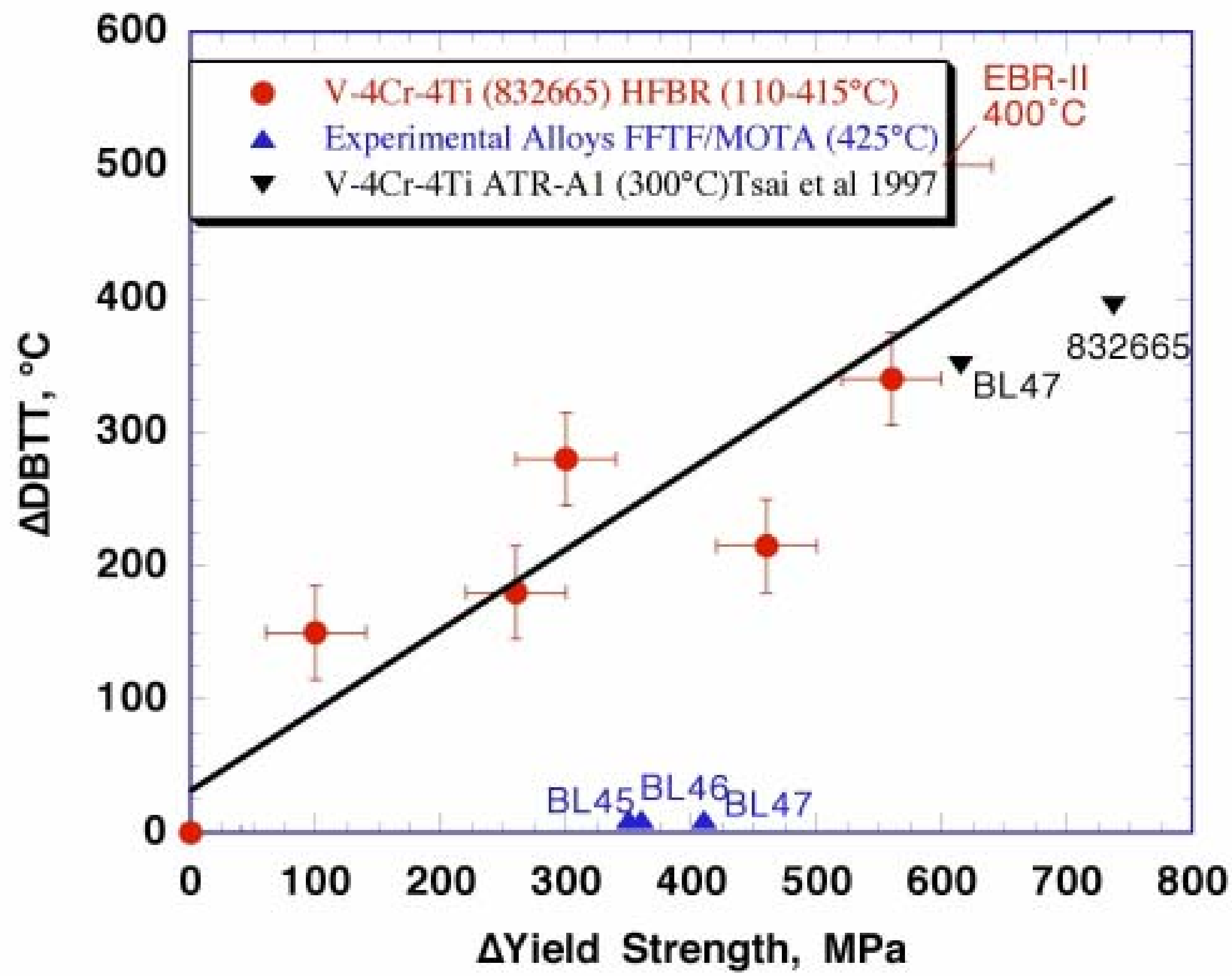
Yield Strength and Uniform Strain in Neutron-Irradiated V-4Cr-4Ti



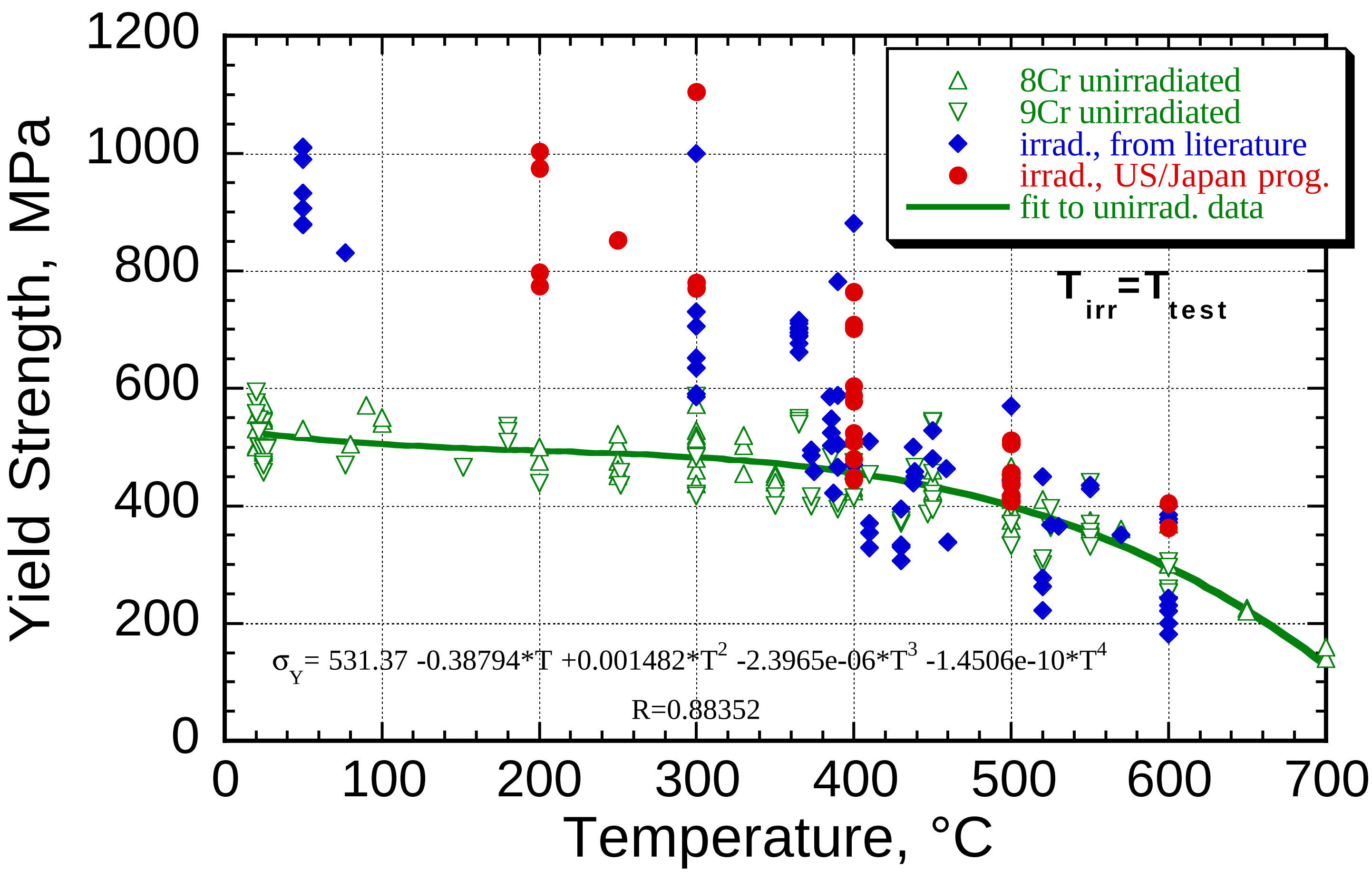
Low-Temperature Radiation Hardening Causes a Large Increase in the Ductile-to-Brittle-Transition Temperature in V-4%Cr-4%Ti Alloys



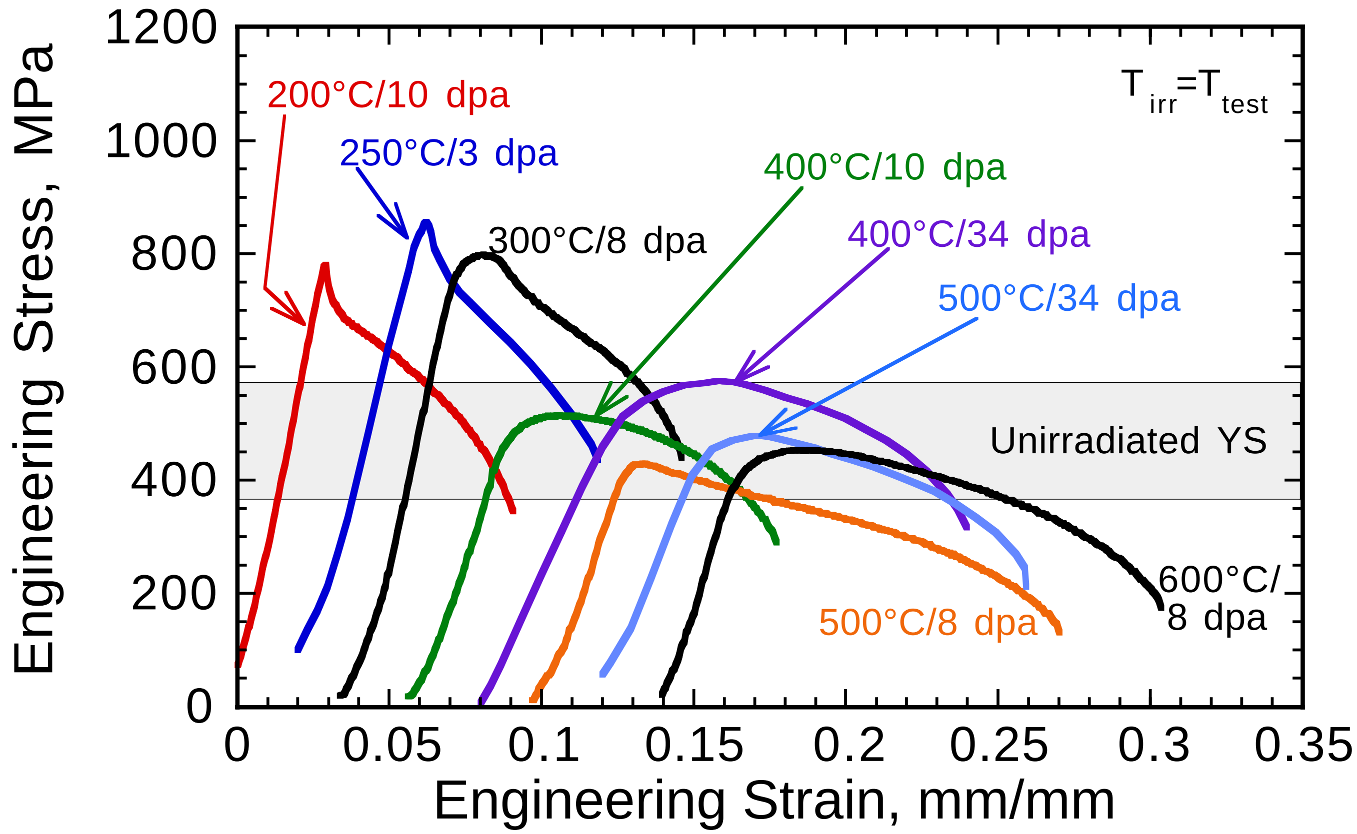
Relationship Between Radiation Hardening and DBTT Shift for V-4Cr-4Ti Irradiated in Various Reactors



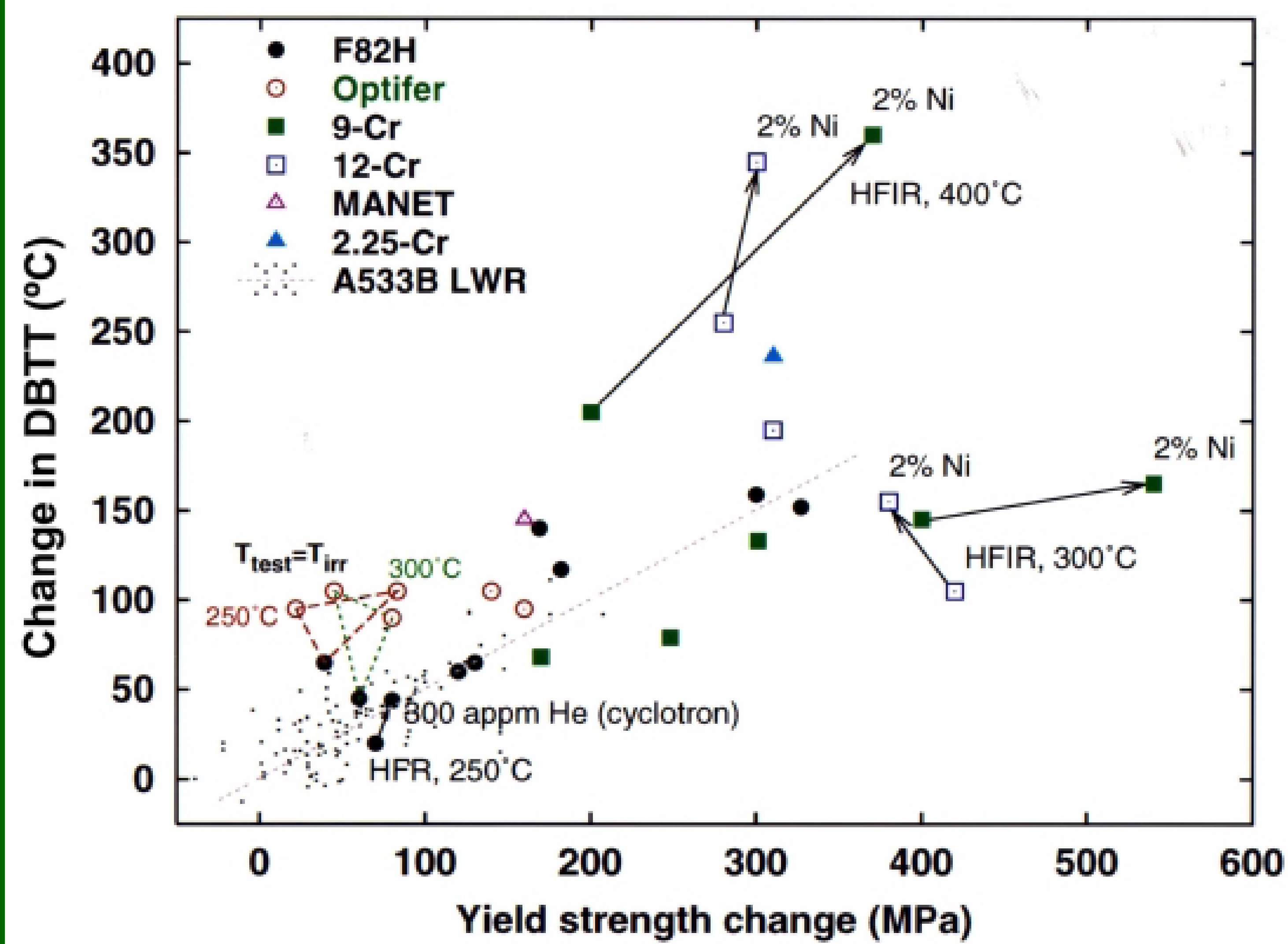
Radiation Hardening in TMS



Stress - Strain Curves for Neutron Irradiated F82H



Radiation Hardening-DBTT Shifts Relationship for TMS Including Helium Effects



Future Work

- Investigation of performance limiting, radiation-induced phenomena in model alloys
  - Broad portfolio of miniaturized property measurements and characterization methods
  - Fully integrated with theory/modeling activities
- Fundamental issues of flow and fracture in TMS and V-4Cr-4Ti model alloys including helium effects at 300º-400ºC
- Fundamental issues related to helium migration, trapping and bubble formation in TMS and V-4Cr-4Ti model alloys at 400º-650ºC
- Initial studies of dispersoid and nanocluster stability, helium trapping in advanced alloys at 300º-800ºC

Future Work

- Irradiation program to be carried out under a 5-year shared-cost program with JAERI/MONBUSHO
  - 5 Li-bonded small volume HFIR experiments ($25cm^3$ specimens/capsule)
  - Temperature monitored and controlled; neutron doses (1-10 dpa)
  - Spectrally tailored and isotopically- doped to vary helium production
- Continuing investigation of substitutional solute-interstitial interactions in V-4Cr-4Ti model alloy
  - Immobilization of interstitials in uniformly-dispersed oxycarbonitride phases
  - Improved creep strength and helium management
- Expanding upper temperature operating limits of TMS through nano-phase engineering