6th IEA & JUPITER Joint Workshop on Vanadium Alloys for Fusion Applications

Tucson, AZ
Jun 21-22, 2002

Hardening and Embrittlement

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A Concurrent Strategy

Material descriptions (constitutive, damage failure)
$\sigma(\varepsilon,\varepsilon',T)$, $K_e(T, \varepsilon')$,... = f_p(MVs, ϕt, T_i, dpa, He,...)
from empirically-calibrated microstructurally based multi-scale physical models and simulations

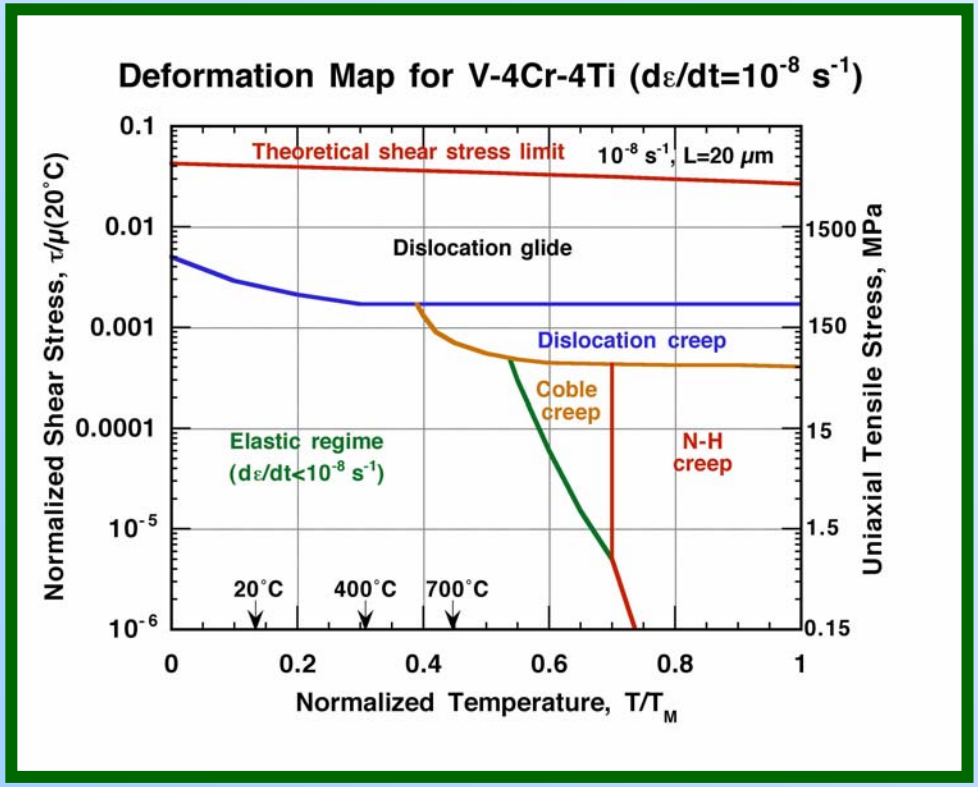
Advanced materials systems development

Performance maps

Advanced multiphysics (themalhydraulic/ inelastics stress…) FE codes for design, operation (ISI), safety and component lifing (benchmarks)

Analytical tools: plasticity laws, structural failure assessment methods and codes

Deformation Behavior



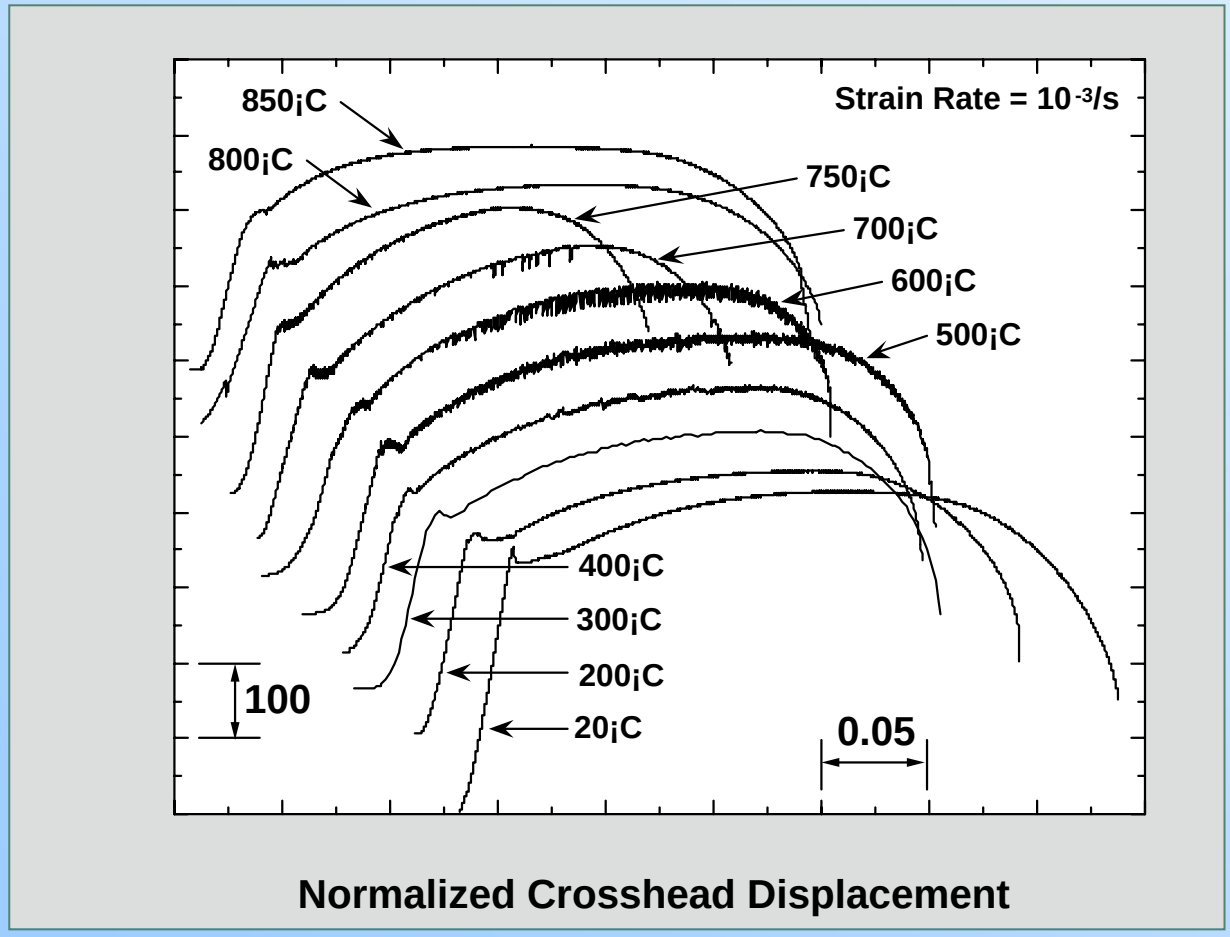
Dynamic Strain Aging In Vanadium

- At temperatures where interstitial solutes are mobile serrated yielding occurs in the Lüders extension and jerky flow (Portevin-Le Chatelier) occurs in the strain-hardening regime due to DSA.
- The DSA regime is bounded by certain values of temperature and strain rate and is characterized by negative strain rate sensitivity (SRS).
- Strain rate sensitivity parameter:

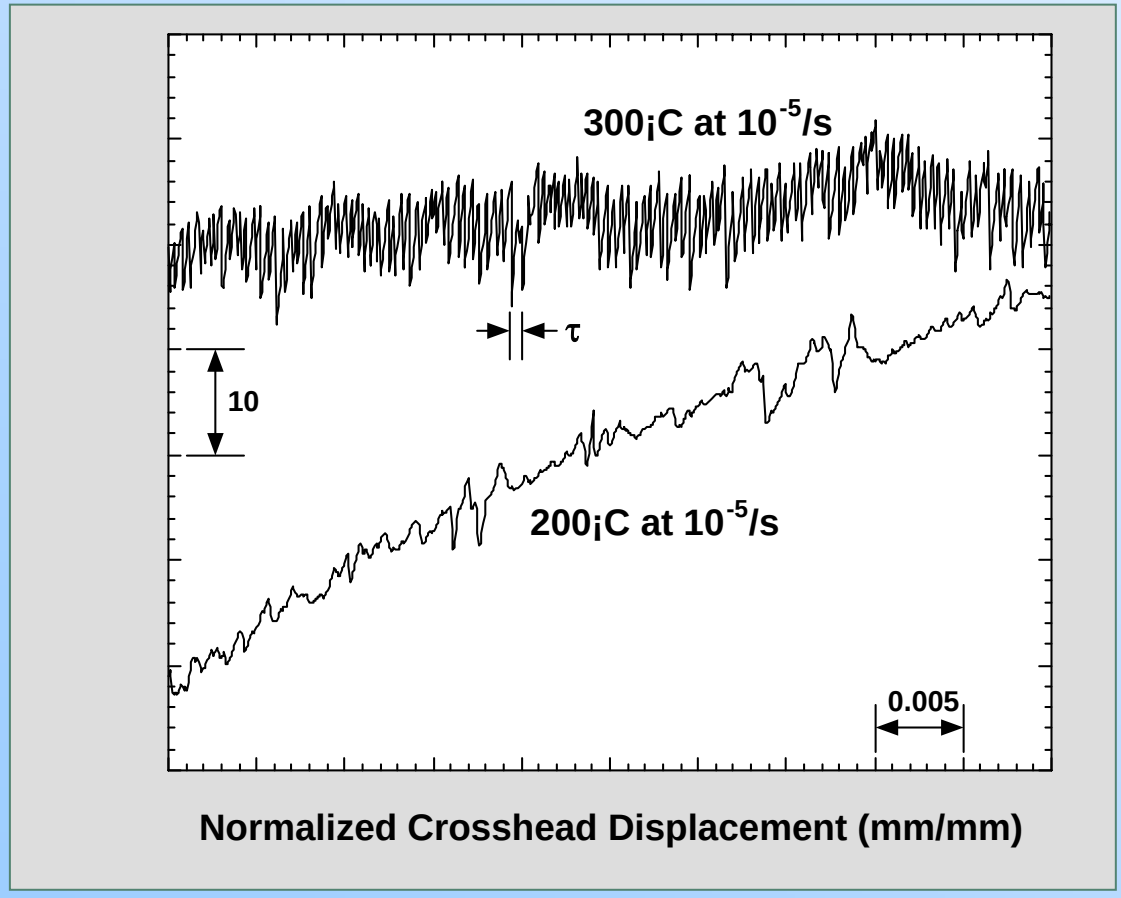
$$m = \frac{1}{\sigma} \frac{\delta\sigma}{\delta \ln \dot{\varepsilon}} \Big|_{\varepsilon, T}$$

Load-Elongation Curves For Annealed 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



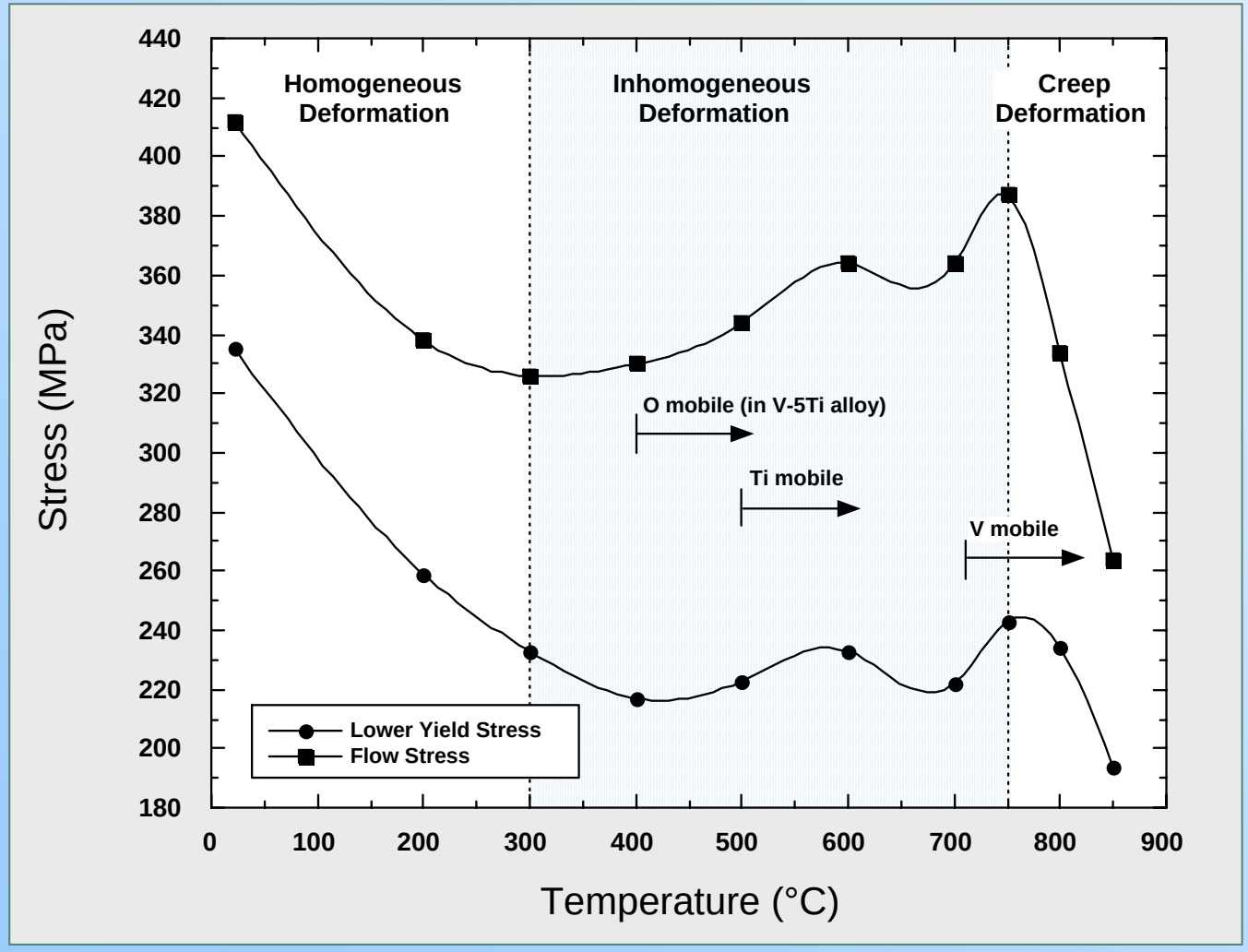
- **Estimate time for diffusion of interstitials**
  - **segregate to immobile and mobile dislocations**
  - **identify elements responsible for DSA**
- **Calculate average time between minima (τ)**
  - **300°C and 10^{-5}/s**

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

    τ = ~129s

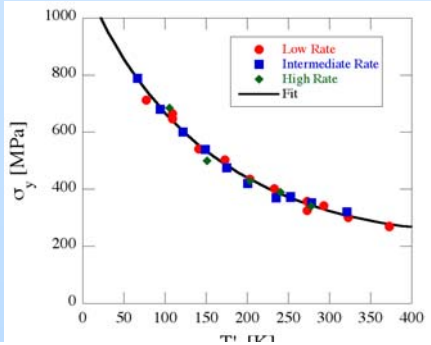
- Diffusivity calculations show:
  - Carbon and oxygen are primarily responsible for DSA effect below 300°C
  - Nitrogen has similar mobility at a higher temperature of 400°C

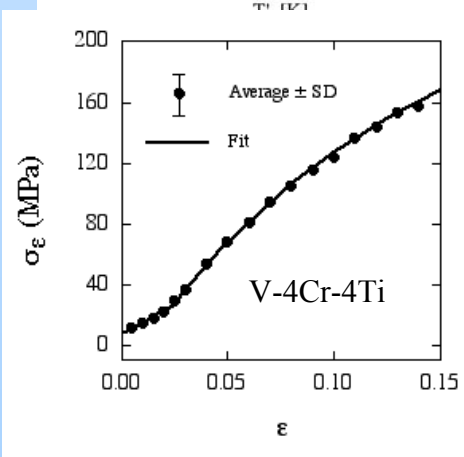
Temperature Dependence of σ_Y and σ_f For A Strain Rate of 10^{-3} s^{-1}



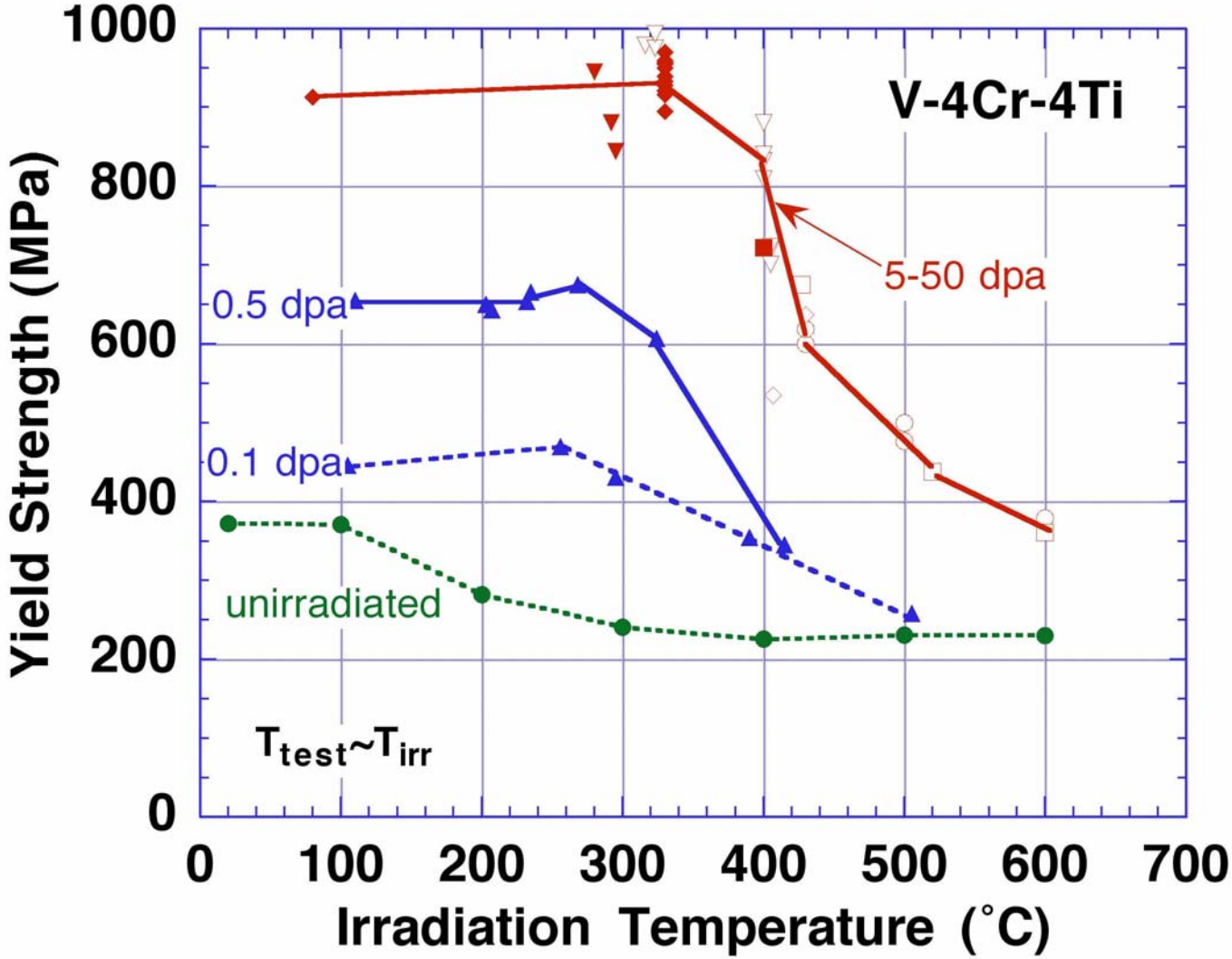
Constitutive Models

- Starting from a unified microstucture/dislocation mechanics-based constitutive model σ(ε, ε', T) for unirradiated bcc alloys, develop a multiscale model for irradiated alloys, ultimately incorporating results of atomistic and dislocation dynamics simulations.
- Unirradiated σ(ε, ε', T) for V-4Cr-4Ti with activated flow and dislocation production-recovery treatments of strain hardening are being integrated in a unified and comprehensive bcc model framework - including links to microstructure and effects such as dynamic strain aging.

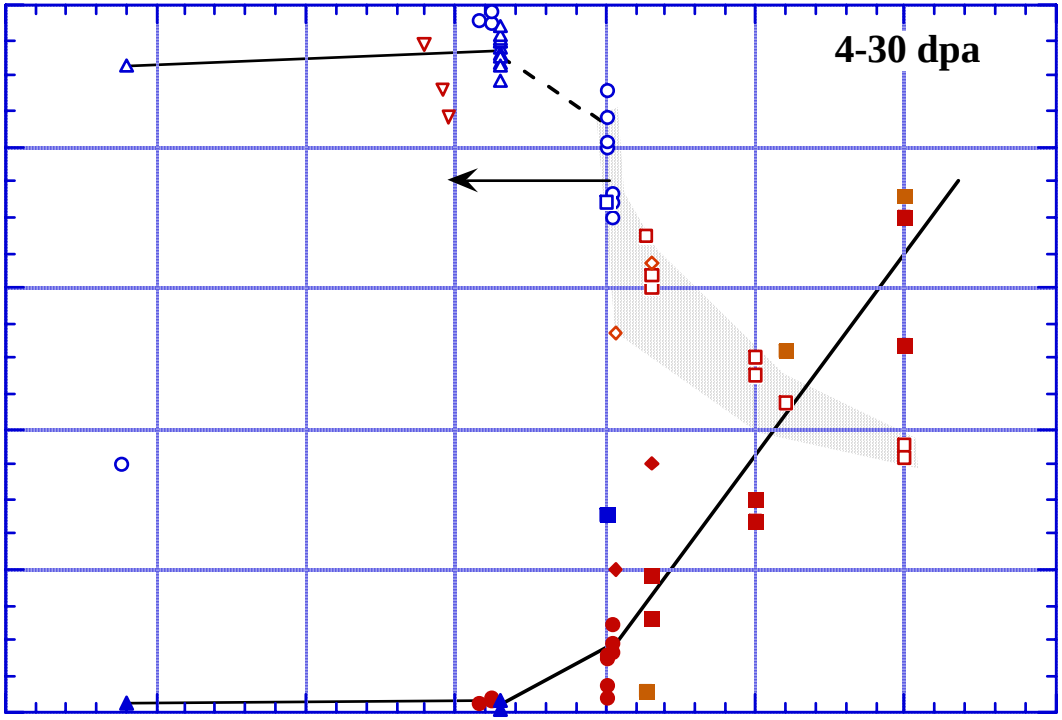




Effect of Dose and Irradiation Temperature on the Yield Strength of V-(4-5%)Cr-(4-5%)Ti Alloys

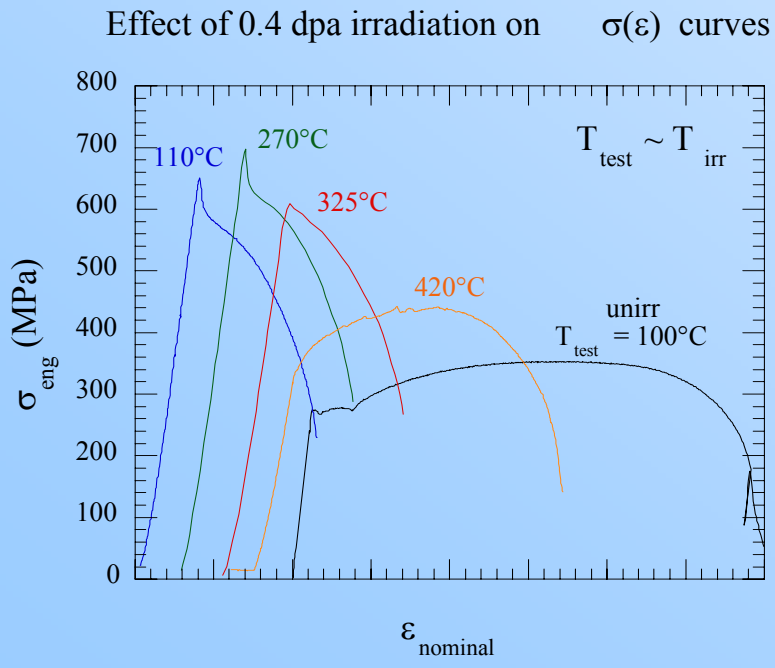


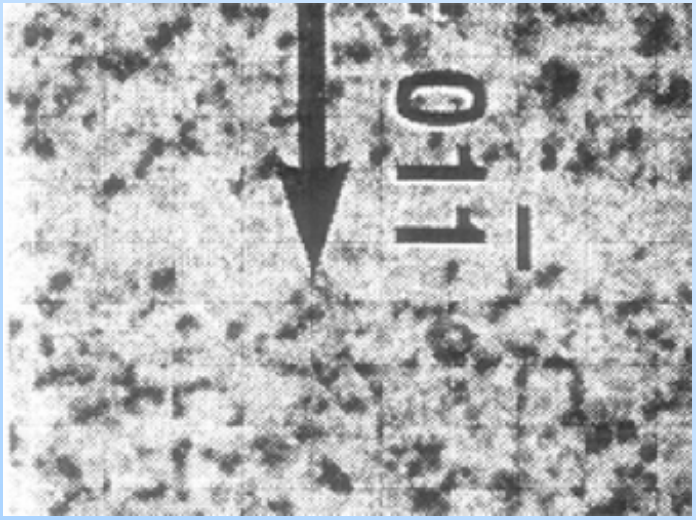
Yield Strength and Uniform Strain in Neutron-Irradiated V-4Cr-4Ti



Deformation

- Low to intermediate temperature irradiation results in substantial hardening ($\Delta\sigma_y$) and even more significant loss of uniform strain capacity ($\Delta\varepsilon_u$).
- The $\Delta\sigma_y$ and $\Delta\varepsilon_u$ are accompanied by varying degrees of flow localization

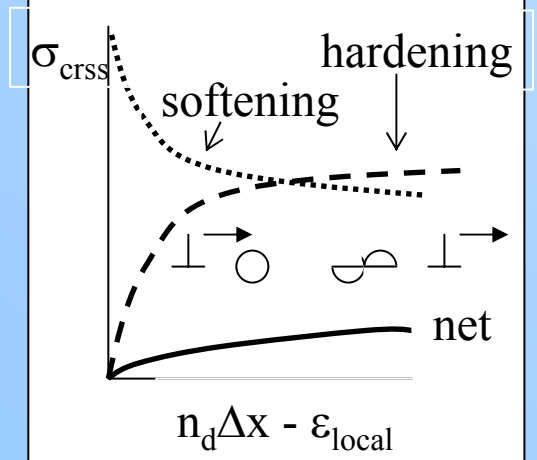




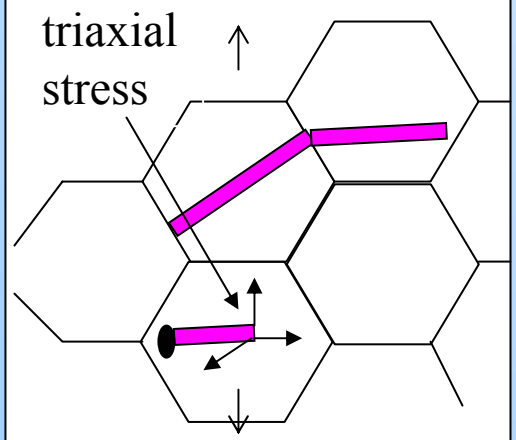
Deconvoluting Localization Effects

- Isolate and properly integrate *multiscale* parts - and determine what controls observables.

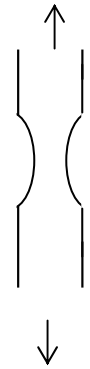
<u>Microconstitutive</u>
dislocation-obstacle interactions and processes controlling local $\sigma_{crss}(\varepsilon_{local})$



<u>Micromechanics</u>
deformation patterns and localization- depend on σ, σ-state redistribution

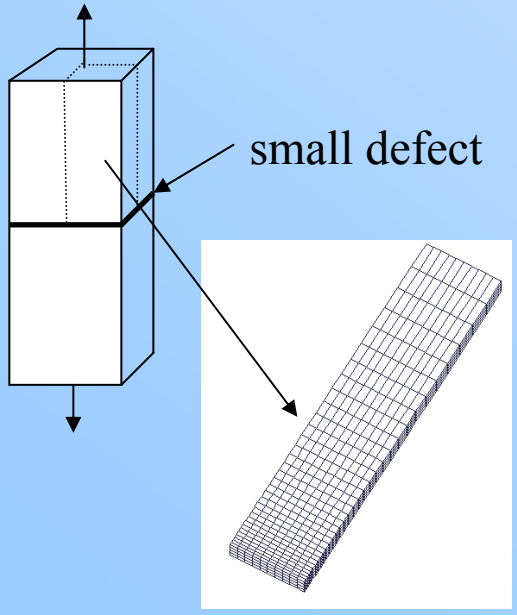


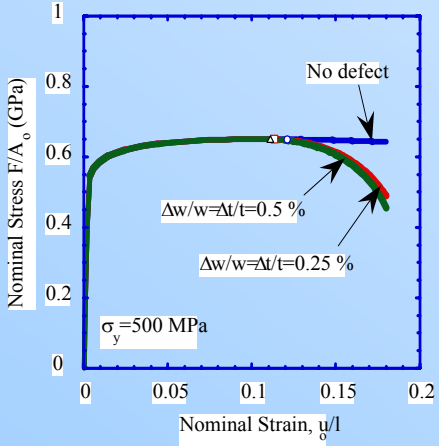
<u>Continuum Mechanics</u>
large geometry-change deformation & load- instability- necking

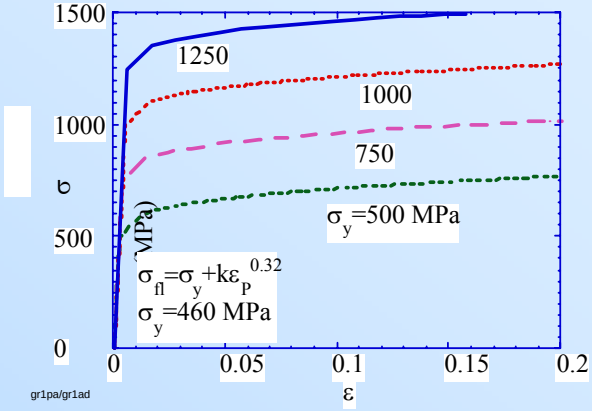


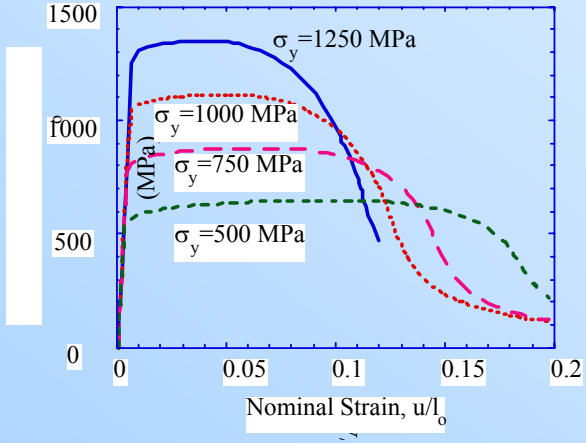
Modeling the Tensile Test

- ABAQUS 1320 8-noded brick elements on 4x1x0.2 1/8 symmetry plate using J_2 incremental flow theory.



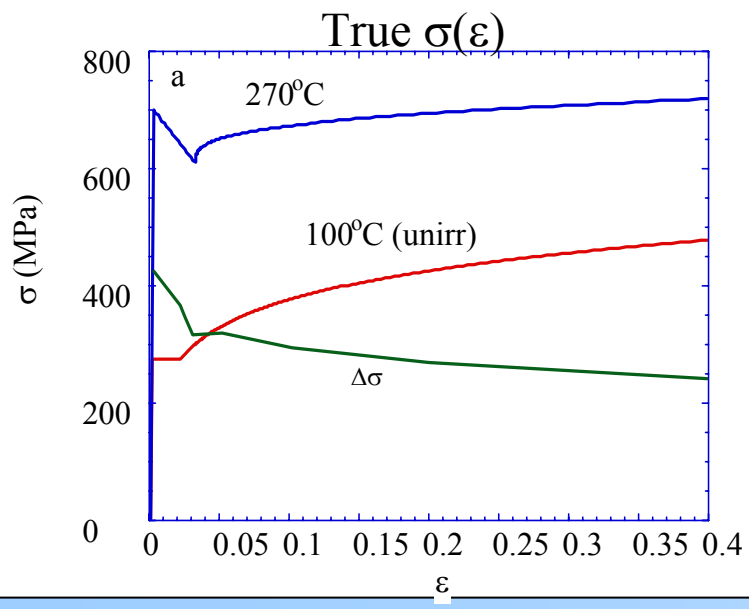


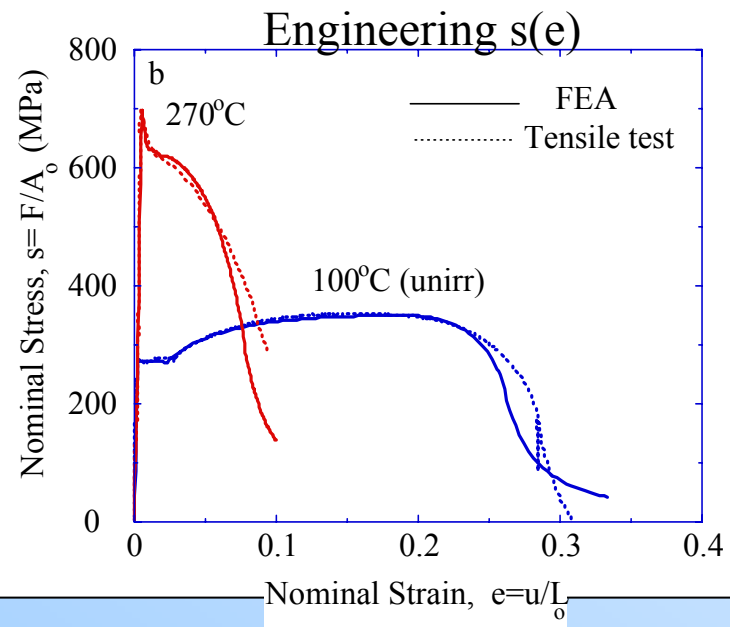




Strain Softening-Hardening

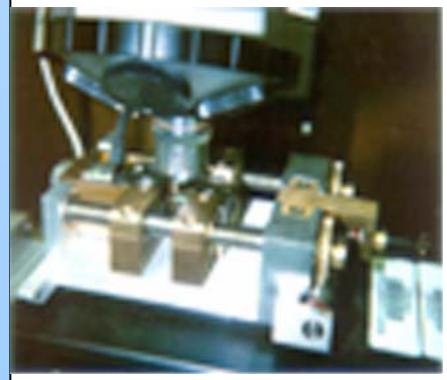
- s(e) data fit by $\sigma_{fl}(\varepsilon)$ with a gradual yield drop softening followed by hardening. Estimate of the minimum $\Delta\sigma_{fl}$ shows a persistence of irradiation hardening to high ε.

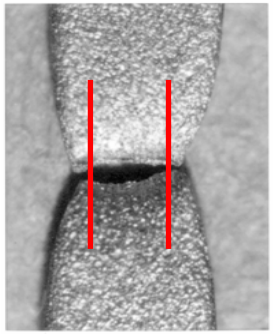


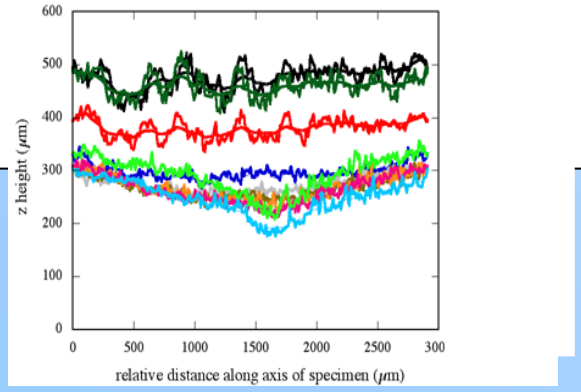


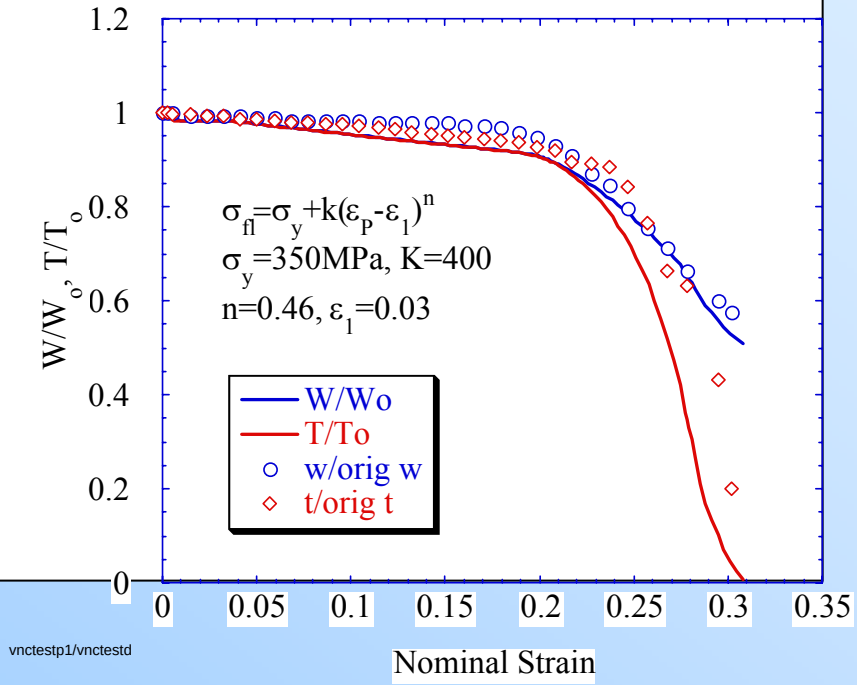
Characterization of Necking Strains

- Combine confocal and optical microscopy for in-situ tensile test imaging to compare with FEA results. Also interrupted/post-test examination.









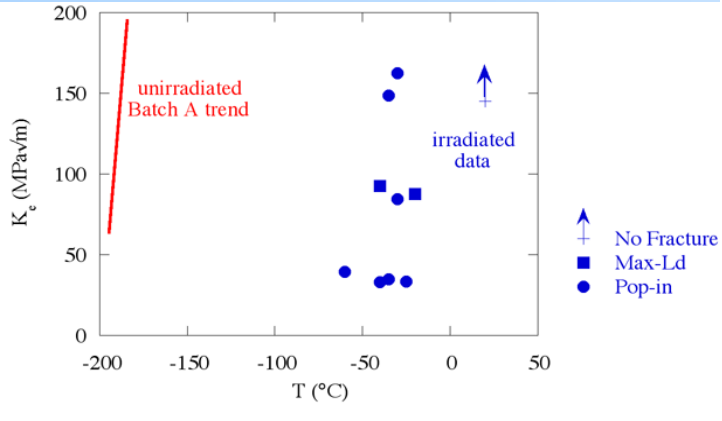
vnctestp1/vnctestd

Implications of FE σ(ε)-s(e) Modeling

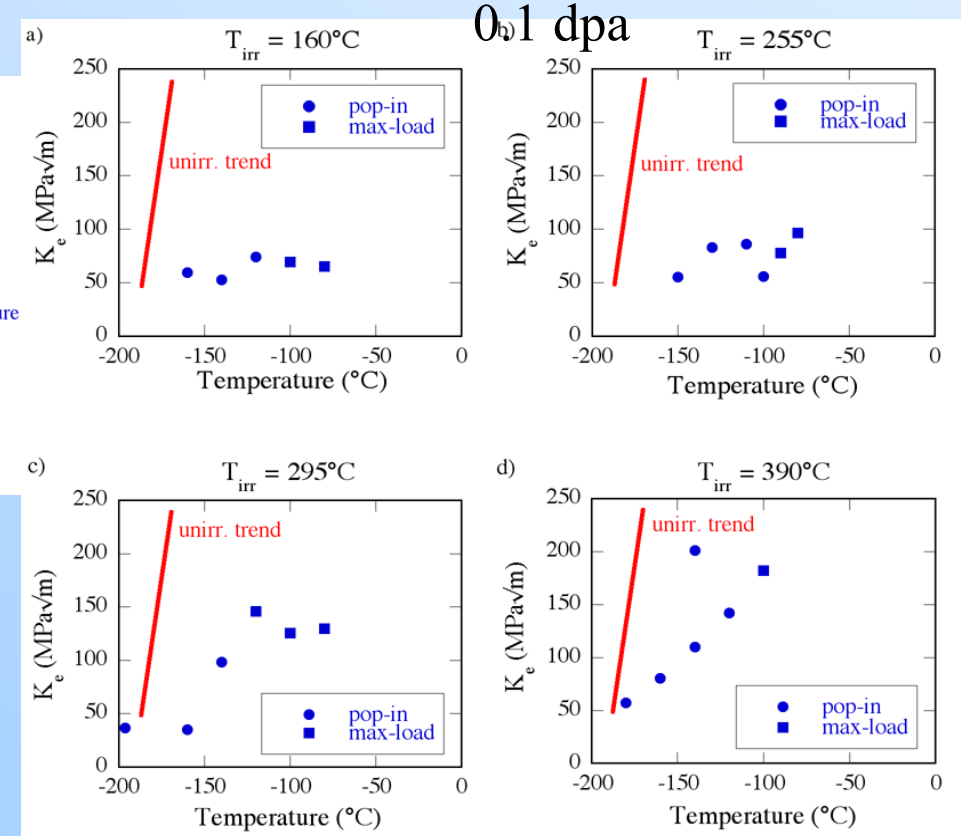
- Effects of irradiation on the s(e) curves can reproduced in FE simulations using continuum, incremental flow (J_2) laws.
- Competition of initial softening followed by modest hardening - significant irradiation hardening persists to high ε.
- Role of micro-localization on macro constitutive behavior may be modest, depending on the situation (if not shear dominated?). Guide for MS-modeling and experiment (what to look for), including compatibility micromechanics of localization, dislocation dynamics and structure evolution with ε and the local mechanics of defect softening.

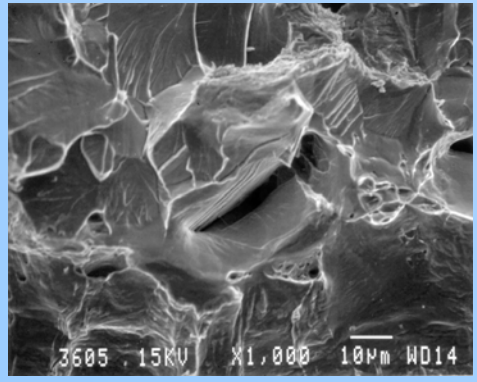
Irradiation Effects of V-4Cr-4Ti

T_{irr} = 200°C, 0.4 dpa

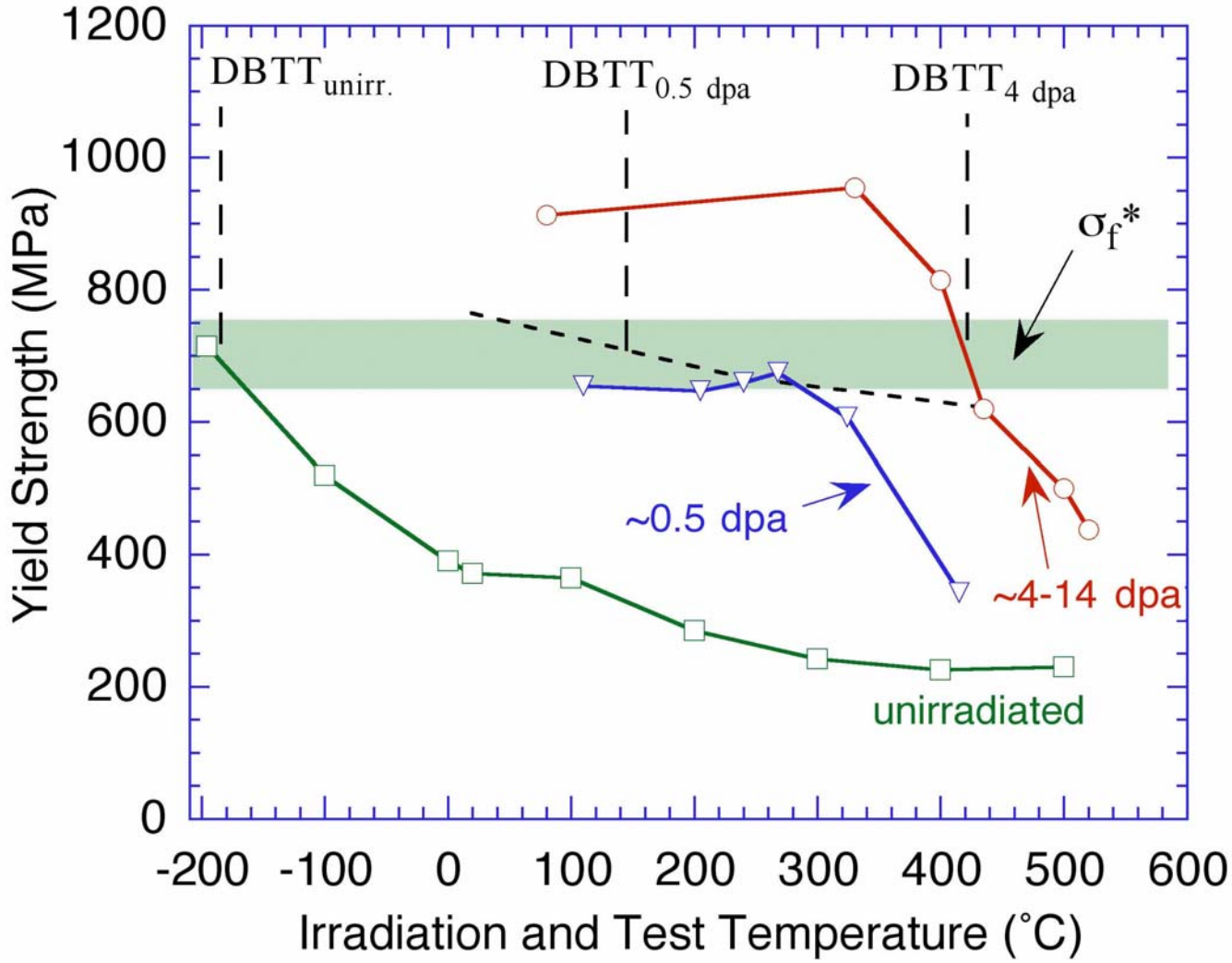


0.1 dpa

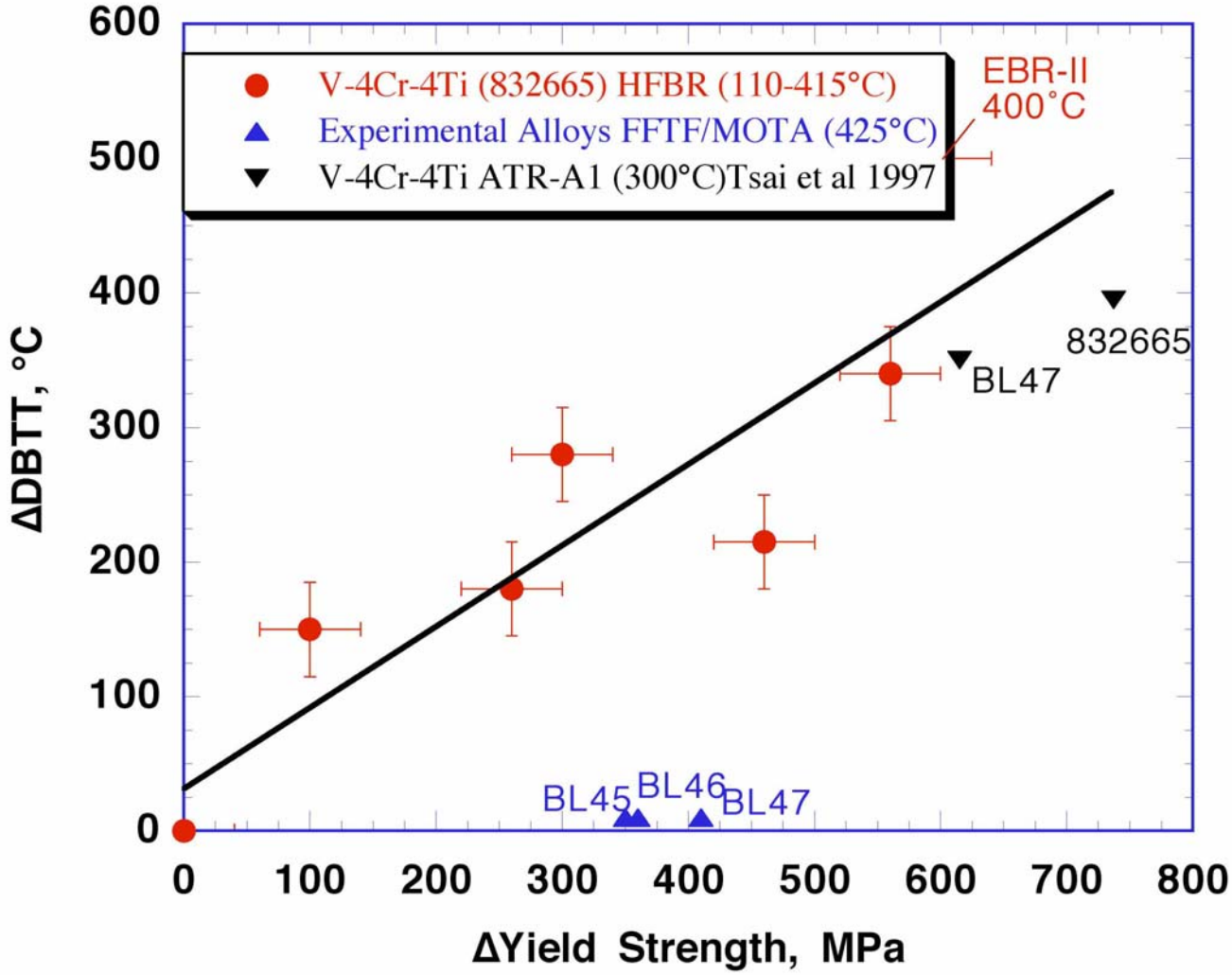




Low-Temperature Radiation Hardening Causes a Large Increase in the Ductile-to-Brittle-Transition Temperature in V-4%Cr-4%Ti Alloys



Relationship Between Radiation Hardening and DBTT Shift for V-4Cr-4Ti Irradiated in HFBR, ATR, EBR-II, and FFTF



The MC-ΔT Method

- Combinations of many variables control embrittlement - it is prohibitive to 'measure' a huge number of toughness-temperature K(T) curves - must use (very) small specimens.
- MC-ΔT method measures a *reference toughness- temperature* (T_o) with a small number of small specimens for small family of fixed $K_{eff}(T-T_o)$ curve *shapes*.
- Use K_{eff} shapes and T_o shifts (ΔT_o) to account for loading rate, irradiation, size and geometry, statistical effects and margins in both testing and application.
- The ΔT_o can be independently measured, assessed with tensile data and modeled.
- Specific to thin-fusion structures (vs. heavy-section fracture mechanics).

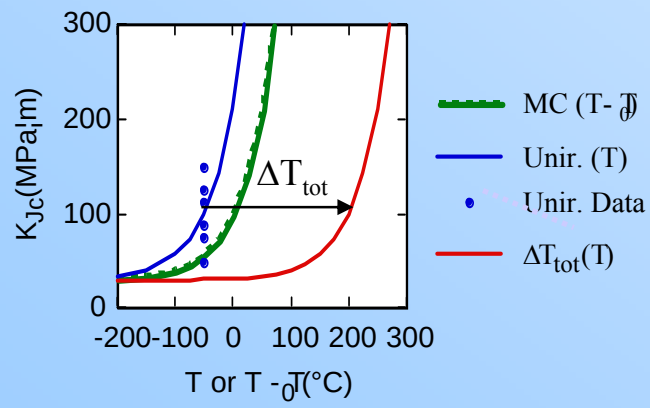
QuickTime™ and a
TIFF decompressor
are needed to see this picture.

RPV Steels

MC-ΔT Method

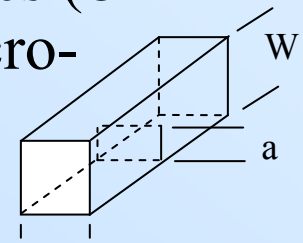
- $K(T-T_o)$ shape & $\Delta T_{tot} \approx \Delta T_{irr}+\Delta T_{rate}+\Delta T_{size/geom}+\Delta T_{stat.}+\Delta T_{marg}$
- Seek rigorous physical basis (limits) for MC-shape(s), size effects (statistical and constraint mechanics), links of shape & ΔT to fundamental properties & microstructure (irradiated).
- Major progress and MC-ΔT subject of international research (irradiation studies include: US-Euope, US-JAERI, US-MEXT)

Concept



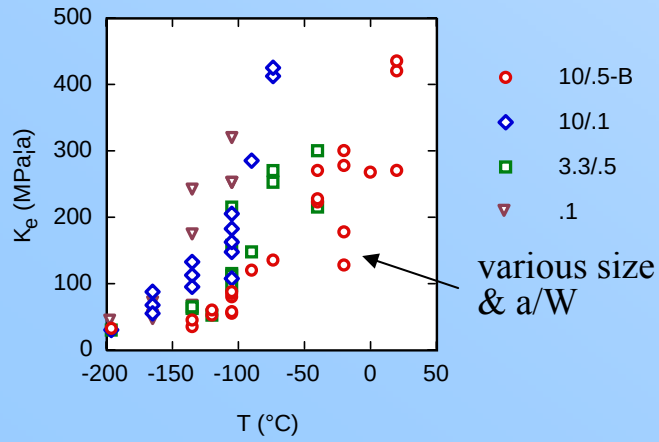
Micromechanical Models

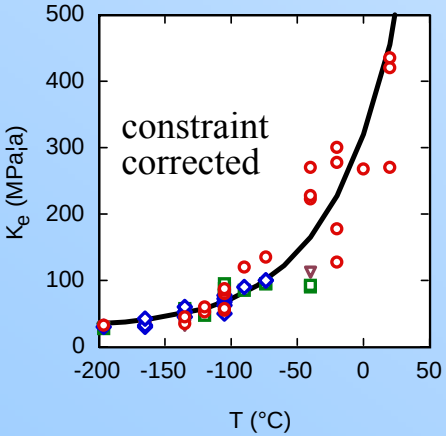
- Models of cleavage combine $\sigma(\varepsilon, \varepsilon', T)$ in FE simulations of crack tip σ-ε fields with local fracture properties (σ^*-A^*/V^* or σ_w, m) mediated by trigger particle micro-structures & intrinsic ferrite toughness to treat:

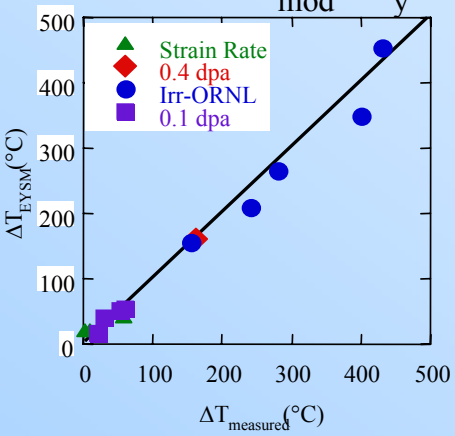


  - constraint-statistical(W,a/W,B) size effects (small specimens to structures) on K(T□) and T_o
  - loading rate and irradiation on ΔT_o [$\Delta\sigma(\varepsilon)$ and $\Delta\sigma^*$]
  - invariance of K_{ssy}(□T) for small scale yielding

$$\Delta T = C_{mod}\Delta\sigma_y$$







FE $\sigma(\varepsilon)$-$\sigma^*(A^*)$ Model

Cracked Body Geometry

FE - $A(\sigma_n/\sigma_y, K_{Jap})$

$\sigma(\varepsilon, \varepsilon', T)$ model

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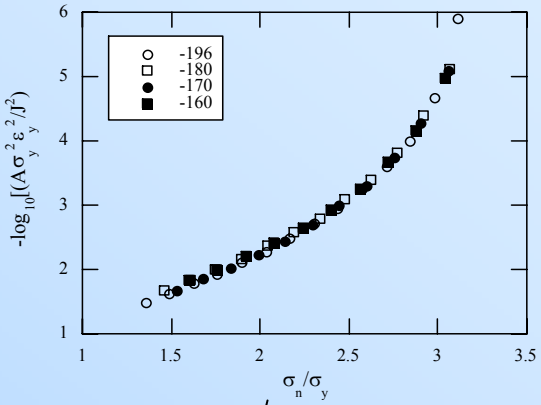
n

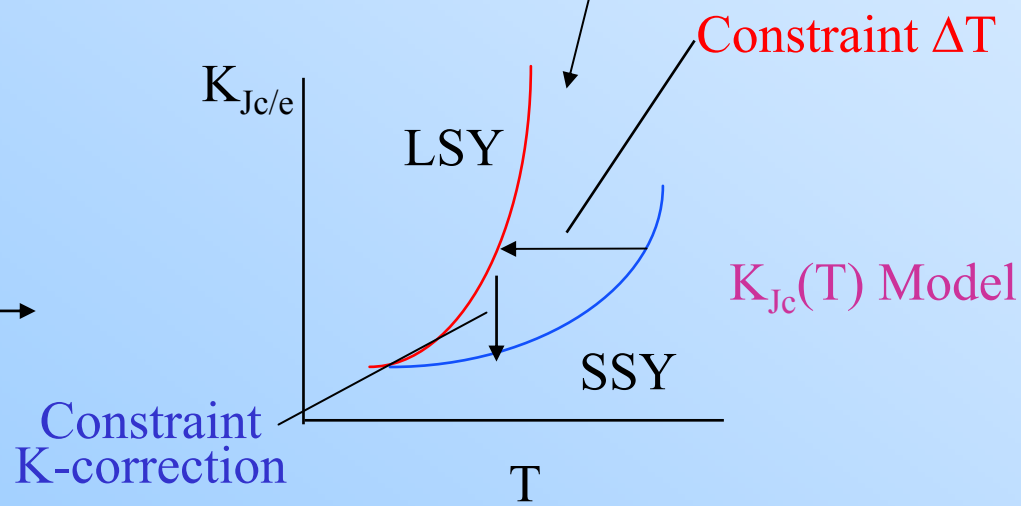
d_p

$A=f[K_J,\sigma_n, \sigma(\varepsilon)]$



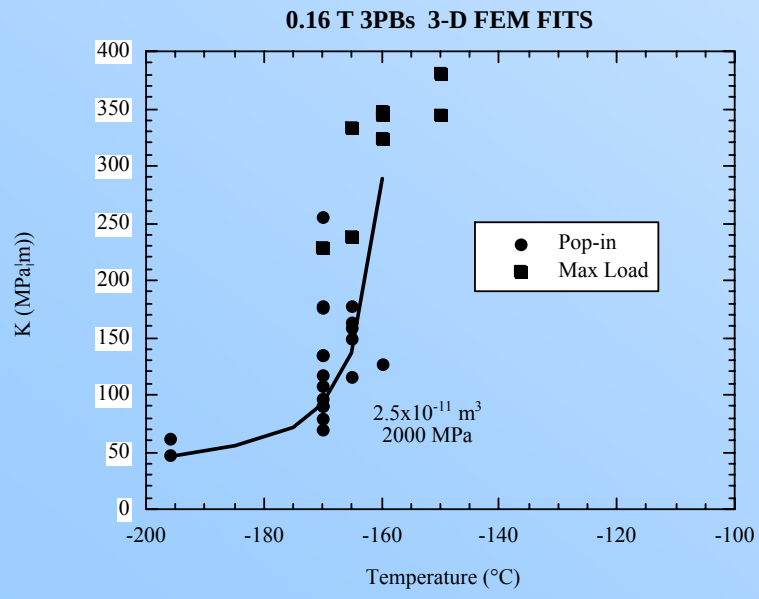
Micromechanics

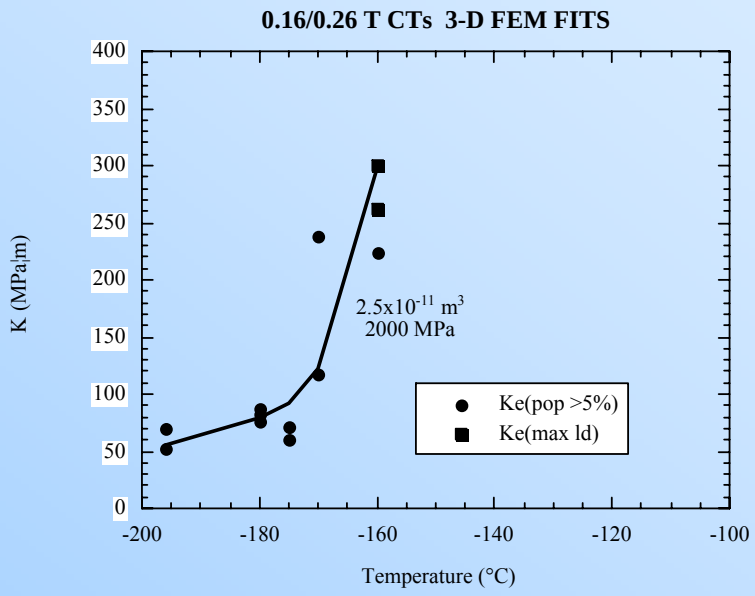
$A(\sigma_n = \sigma^*, K_{Jc/e}) = A^*$



3D FEA

- $K_e(T)$ curves can be fit using a combination of 3D FEA, tensile-derived $\sigma(\varepsilon,T)$, and a σ^*-A^* criterion for cleavage fracture



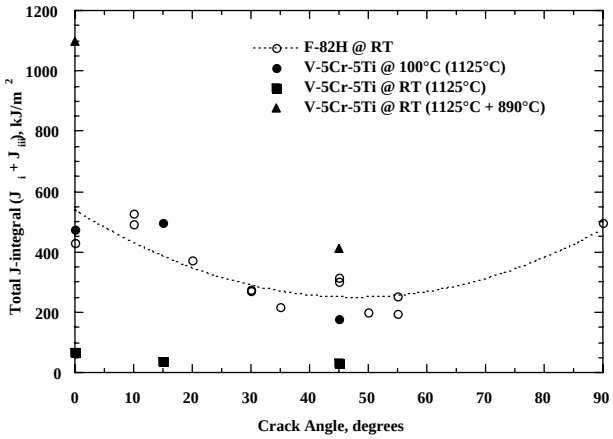


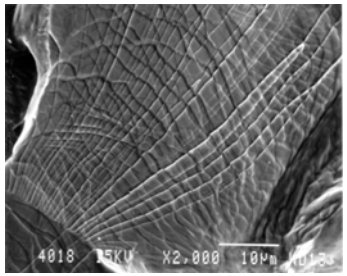
Other Fracture Issues

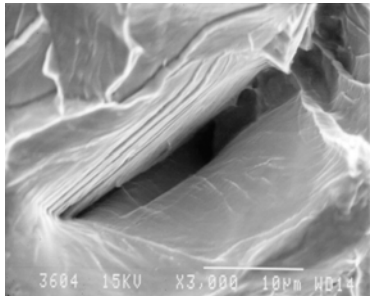
- Low ductile tearing intitiation and resistance, shear band decohesion.
- Interstitial impurity effects (NIFS heat of 4CR-4Ti).
- Toughness-strength optimization in advanced alloys such as higher strength-multiphase V alloys.
- Non-hardening embrittlement mechanisms in V and IG fracture (impurity-solute segregation, phase/structural instabilities, H, damage).
- Subcritical crack growth (fatigue, envonmentally assisted).
- Realities of actual service: warm pre-stressing, shallow surface flaws, multiaxial/mixed mode loading, dynamic strain aging, creep relaxation.

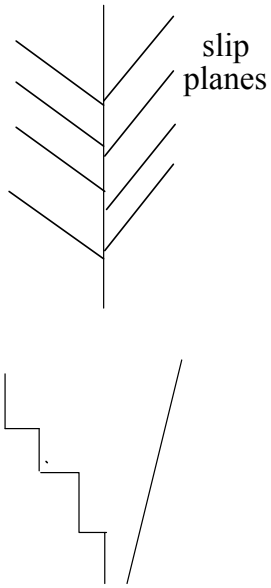
Flow Localization - Fracture Interaction

- Lower mixed mode ductile fracture toughness - lead to shear band decohesion in irradiated materials?
- Enhanced formation of microcracks (cleavage and IG)) by coarse slip bands - reduce σ*?









Implications to Fusion Structures

- Structural 'strength and ductility' depends on both intrinsic material and extrinsic factors related to size and geometry.

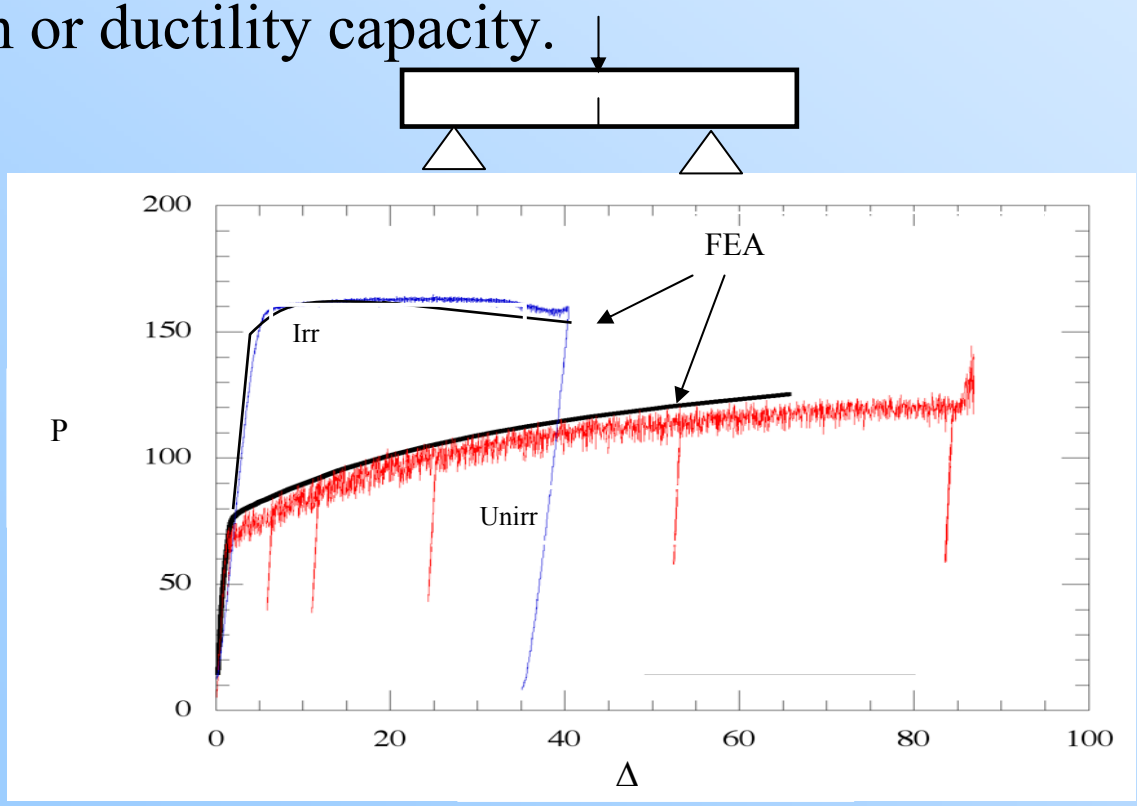
  - large $\Delta\sigma_y$ are beneficial and low e_u are detrimental, but - cases such as simple bending are not sensitive to e_u, while shear dominated processes may be very sensitive.

  - effects of lower K_{eff} by irradiation $\Delta\sigma_y$ depend on size and geometry - a material state that leads to elastic fracture ($\sigma << \sigma_{ys}$) of a heavy-section pressure vessel may have little or no effect on the fracture stress and effective ductility of a thin structure with a small surface crack.

- An irradiated structure can be effectively 'stronger'.

Performance Maps

- Example -FE simulation of V-4Cr-4Ti bend bar.
- Objective - define functional material- structural metrics that can map *detrimental vs. beneficial* changes stress and strain or ductility capacity.



Ongoing Experiments

- Jupiter Irradiation Experiment -- R. Kurtz

What Remains?

- Constitutive laws for irradiated material
  - $\sigma(\varepsilon,\varepsilon',T) = f_p(\phi t, T_i, \text{dpa}, \text{He},...)$
  - Multiscale modeling
  - Flow localization
  - Contributions of DSA

What Remains -- cont'd

- Continued development of MC-ΔT and micromechanics approaches to characterize and predict $K_e(T)$ for irradiated material
  - Incorporation of constitutive laws for irradiated material in FEA simulations
  - Micromechanics in irradiated materials--cleavage and ductile fracture
  - ΔT's for constraint, irradiation, loading rate

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- Low ductile tearing intitiation and resistance, shear band decohesion.
- Interstitial impurity effects (NIFS heat of 4CR-4Ti).
- Toughness-strength optimization in advanced alloys such as higher strength-multiphase V alloys.
- Non-hardening embrittlement mechanisms in V and IG fracture (impurity-solute segregation, phase/structural instabilities, H, damage).
- Subcritical crack growth (fatigue, envonmentally assisted).
- Realities of actual service: warm pre-stressing, shallow surface flaws, multiaxial/mixed mode loading, dynamic strain aging, creep relaxation.