Low-to-Intermediate Temperature Deformation and Fracture

presented by

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Fusion Program Review

Santa Barbara, CA

August 27-28, 2001

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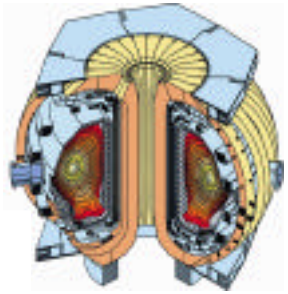
A Concurrent Strategy



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

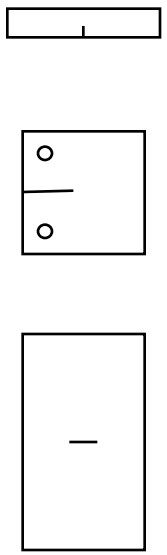
Performance maps

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

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

Objective - Structural Integrity Assessment

Test-Analysis



mostly small specimens

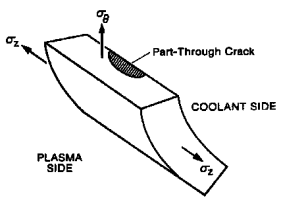
$K_e(T,\dot{K},\varphi t)$

$\downarrow$

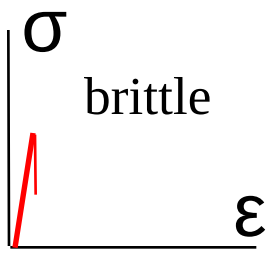
$K_{Jc}(T,\dot{K},\varphi t)$

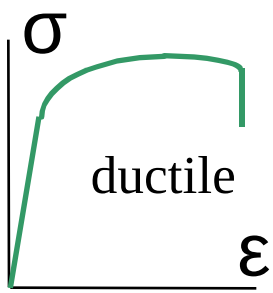
Structural-Analysis

t = 250 mm

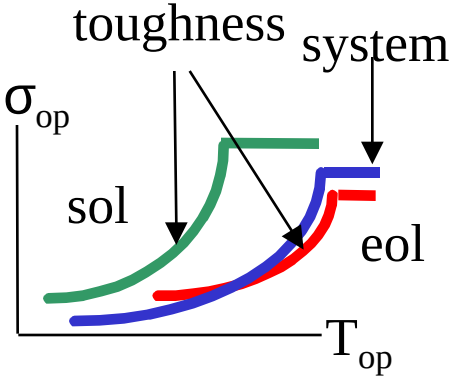


t = 3 mm





Operating-Limits



Key Cross-Cutting Issues

- Fracture toughness for defect tolerant assessments of fast fracture: irradiation embrittlement, role of He (if any), compositional, microstructural, impurity effects?

  - Master Curve (MC)-Shifts (ΔT)Method
  - experimental-computational macro-micromechanics, size effects, basic fracture mechanisms and models

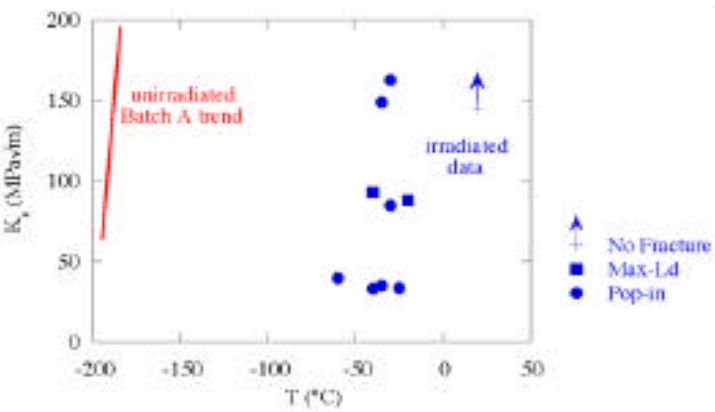
- Constitutive-plasticity laws including irradiation hardening and loss of uniform strain capacity.

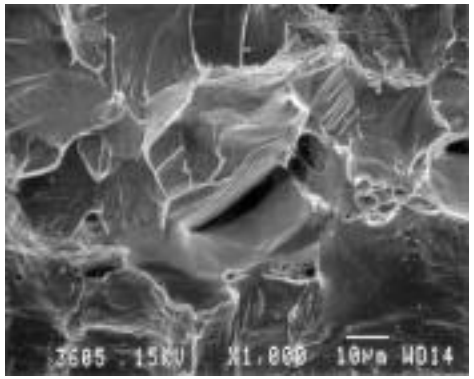
  - unified dislocation-based constitutive laws for bcc alloys
  - multiscale nature of flow ‘localization’

- Implications to structural integrity and alloy development.

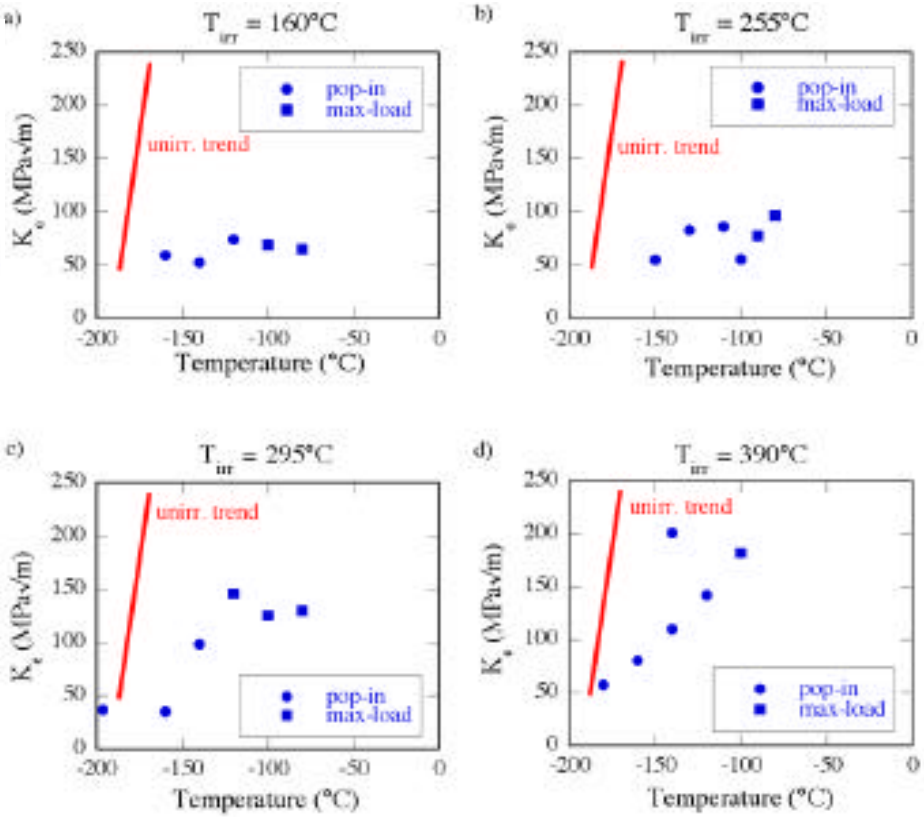
Irradiation Effects of V-4Cr-4Ti

T_{irr} = 200°C, 0.4 dpa



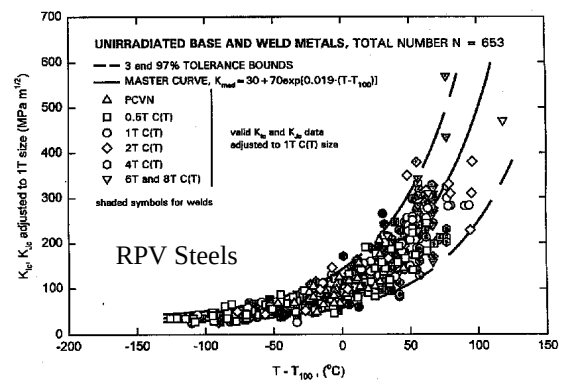


0.1 dpa



The MC-ΔT Method

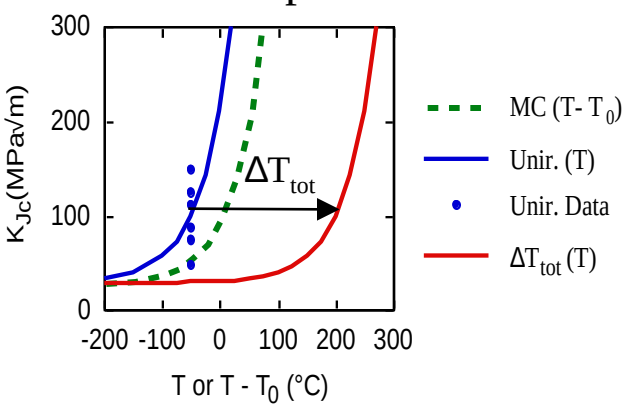
- Combinations of many variables control embrittlement - it is prohibitive to 'measure' a huge number of toughness-temperature K(T) curves - must use (very) small specimens.
- MC-ΔT method measures a *reference-temperature* (T_o) with a small number of small specimens for small family of fixed $K_{eff}(T-T_o)$ 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).



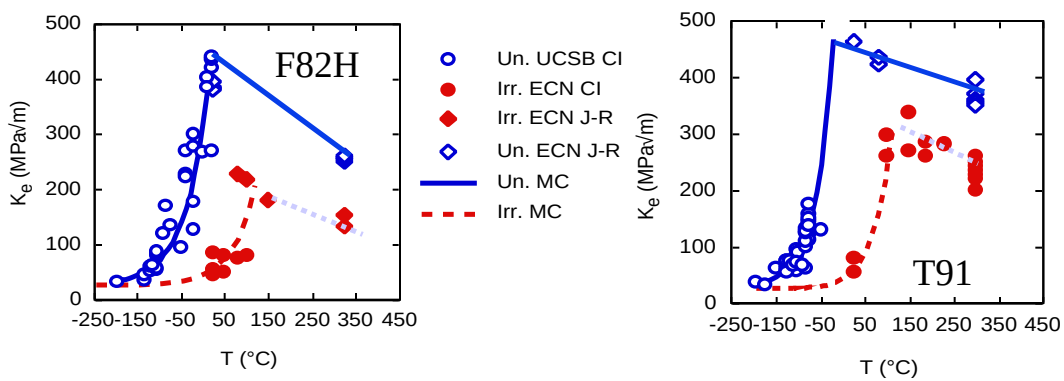
MC-ΔT Method

- $K(T-T_o)$ 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-Europe, US-JAERI, US-MEXT)

Concept

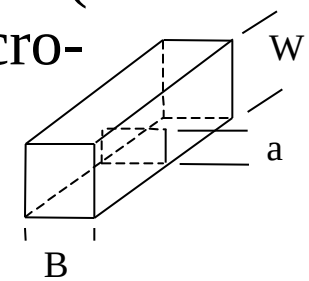


US- Europe Collaboration



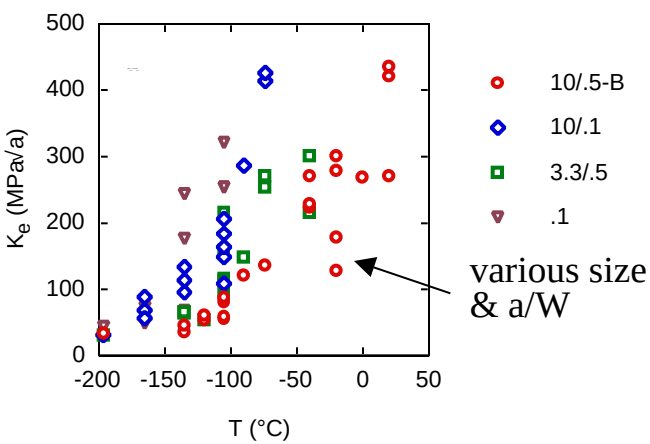
Micromechanical Models

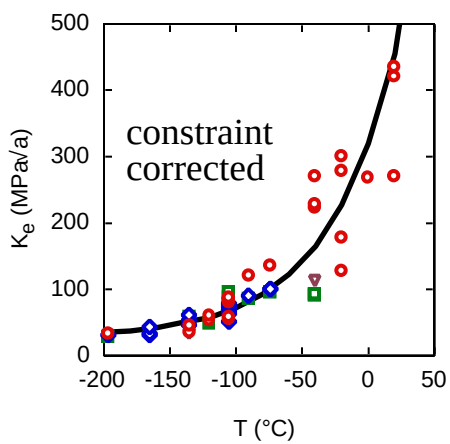
- Models of cleavage combine $\sigma(\varepsilon, \varepsilon', T)$ in FE simulations of crack tip σ-ε fields with local fracture properties (σ^*-A^*/V^* or σ_w, m) mediated by trigger particle micro-structures & intrinsic ferrite toughness to treat:

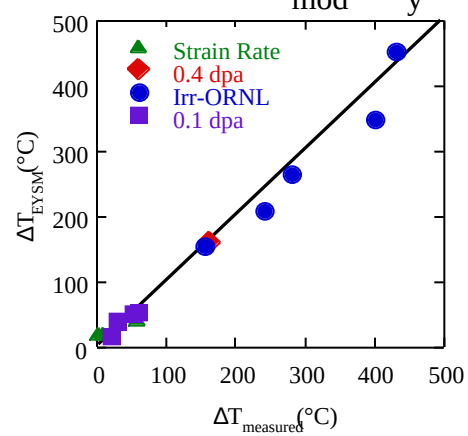


  - constraint-statistical (W, a/W, B) size effects (small specimens to structures) on K(T) and T_o
  - loading rate and irradiation on ΔT_o [$\Delta\sigma(\varepsilon)$ and $\Delta\sigma^*$]
  - invariance of $K_{ssy}(T)$ for small scale yielding

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





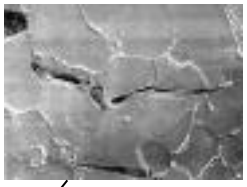


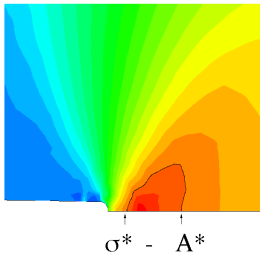
FE σ(ε)-σ*(A*) Model

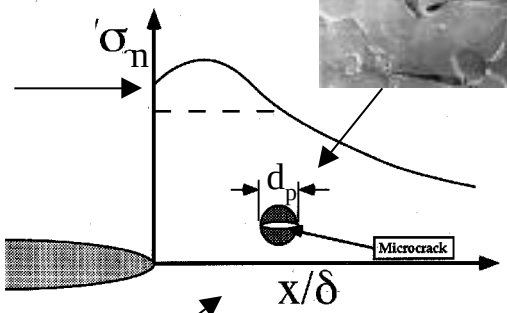
Cracked Body Geometry

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

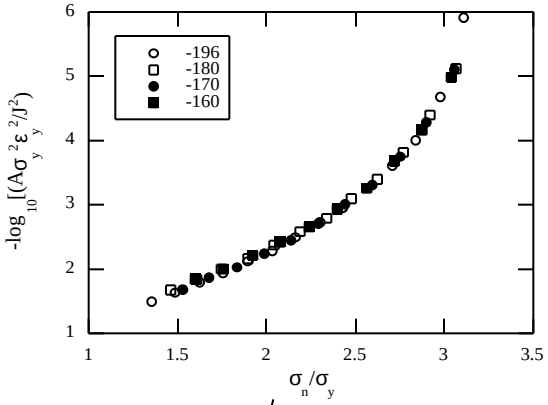
$\sigma(\varepsilon, \varepsilon', T)$ model





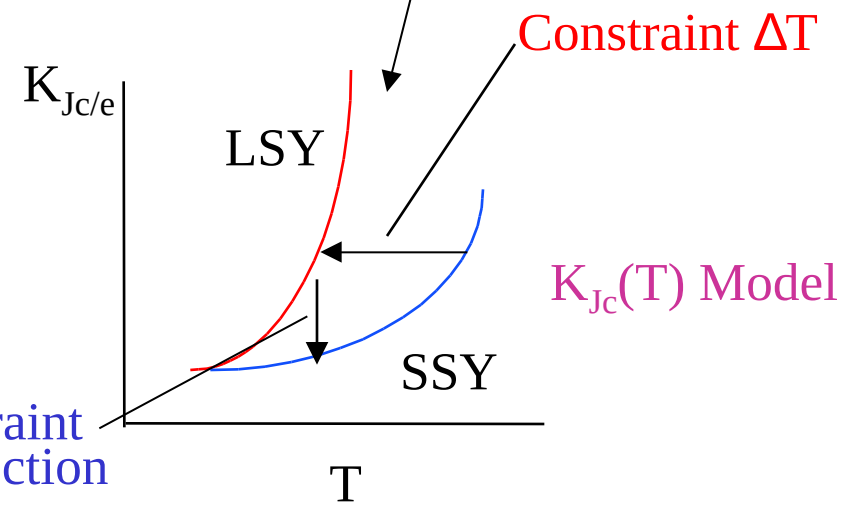


$A=f[K_J,\sigma_n, \sigma(\varepsilon)]$



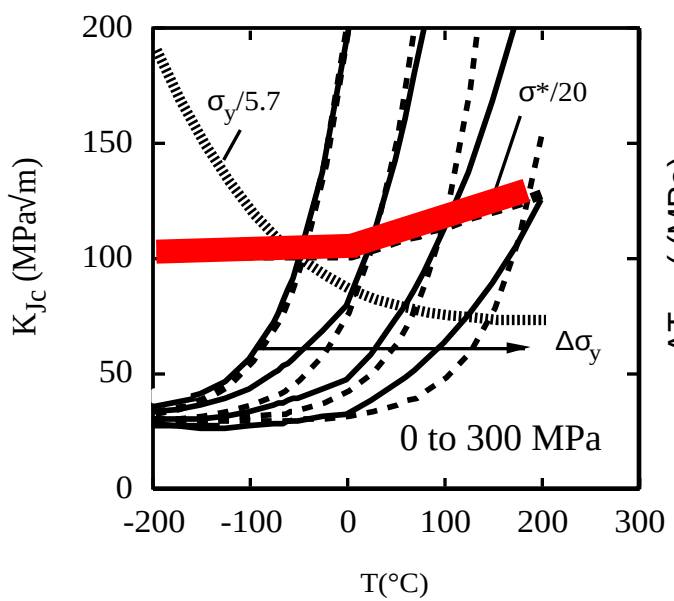
Micromechanics

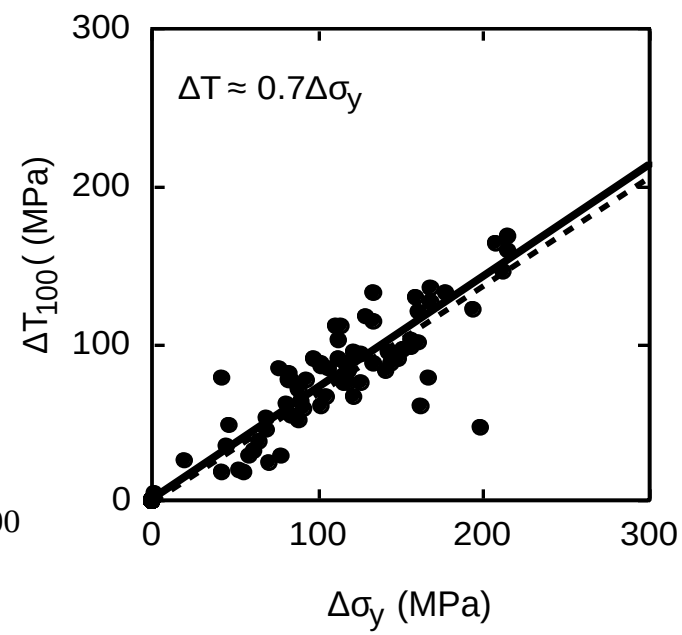
$A(\sigma_n = \sigma^*, K_{Jc/e}) = A^*$



MC Shape and Shift Model

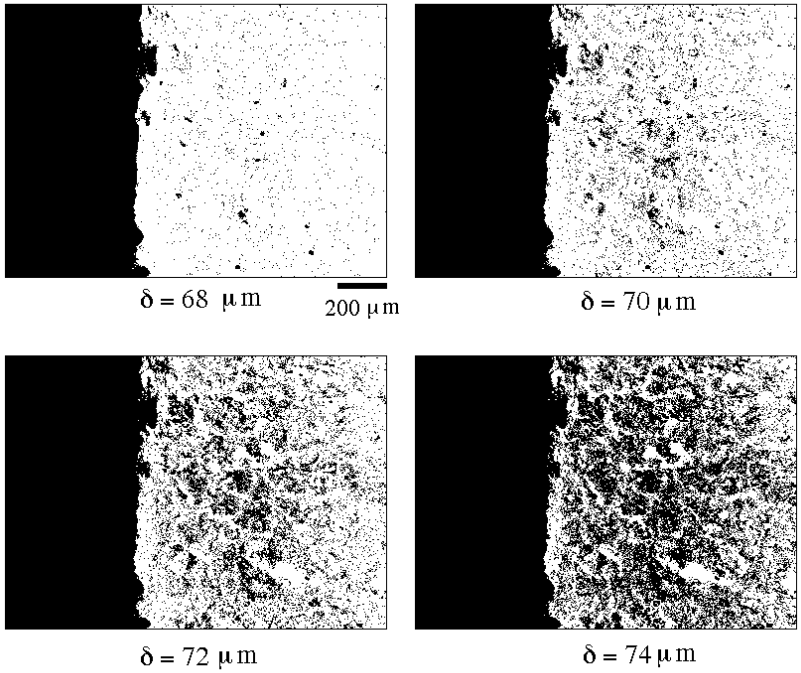
- Shape $K_{ssy}(T-T_o) \approx$ invariant and irradiation hardening $\Delta\sigma_y$ induced ΔT consistent with if $\sigma^*(T)$ [prior assume $\neq f(T)$].
- Magnitude of σ^* depends on extrinsic trigger particle (carbide) microstructure but macro T-dependence metered by inherent ferrite (bcc lattice) micro-arrest toughness $K_{ma}(T)$.





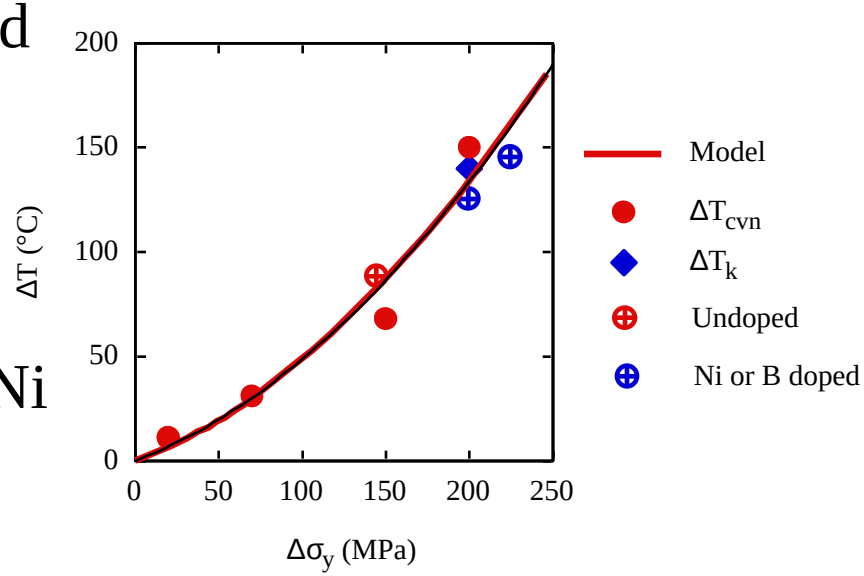
CM-FR

- Confocal-Microscopy Fracture-Reconstruction (CM-FR) first proposed by Kobiashi refined and extended. Permits the tomographic imaging of damage development leading to fracture or rupture. CM gives 3-D maps of deformed conjugate fracture surfaces. FR overlaps and separates surfaces to show the sequence of local material separation-damage events. CM-FR provides detailed information on damage development (e.g., cleavage-trigger or microvoid nucleating particles), damage development failure instability and ductile crack tearing. Crack opening and angle are direct measures of toughness.



He Effects on Fast Fracture

- Substantial controversy regarding possible effect of He on fast fracture other than generally modest effect (at He levels experienced) on $\Delta\sigma_y$. Does high helium reduce σ^*? Available data indicating *yes*, *no and possibly* is all confounded and/or too uncertain-limited to reach a real conclusion. No known mechanism.
  A systematic approach designed for the US-JAERI experiment, based on deviations from expected ΔT-$\Delta\sigma_y$ relation
- Example, subset of F82H-type steels showing little effects of Ni and B doping to produce high He on the ΔT- $\Delta\sigma_y$ relation



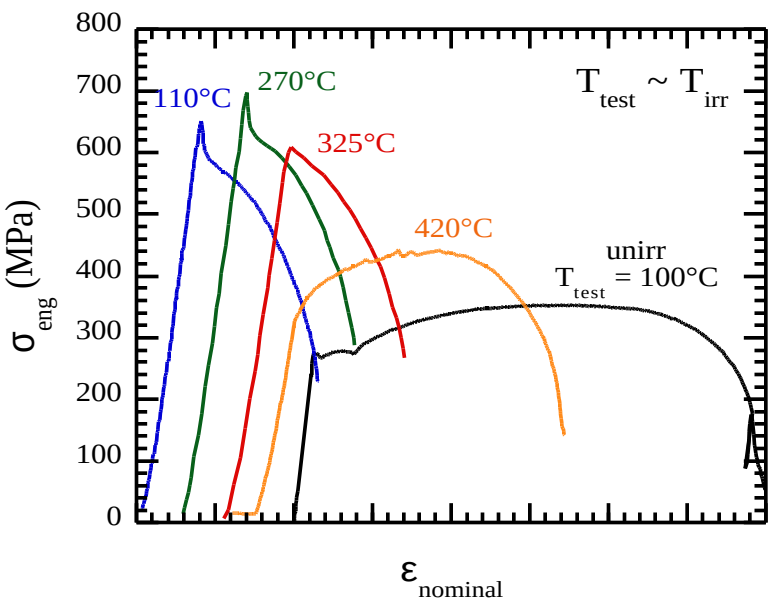
Other Fracture Issues

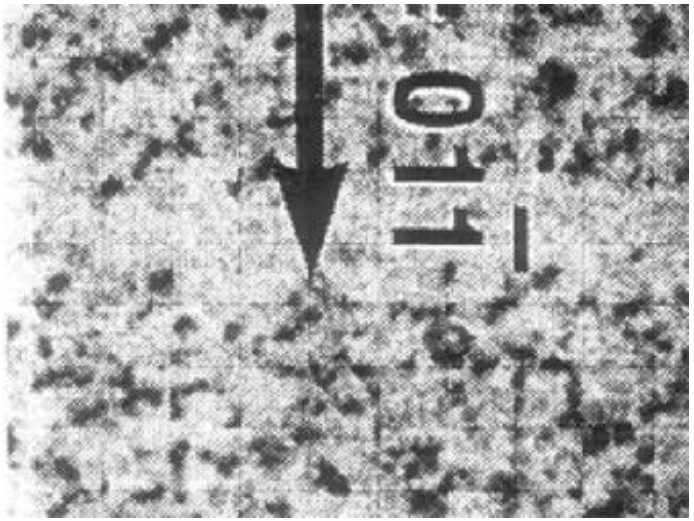
- Low ductile tearing intitiation and resistance, shear band decohesion.
- Interstitial impurity effects (NIFS heat of 4Cr-4Ti).
- Toughness-strength optimization in advanced alloys such as nanocomposited ferritics and higher strength-multiphase V alloys.
- Non-hardening embrittlement mechanisms in both V and Fe-based alloys 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.

Deformation

- Low-to-intermediate T 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

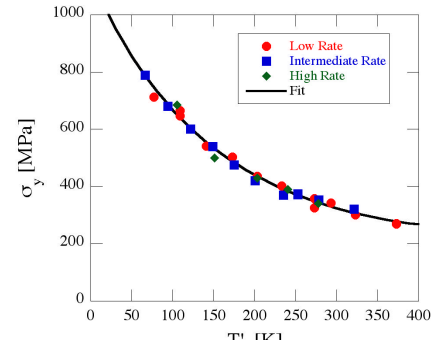
Effect of 0.4 dpa irradiation on σ(ε) curves

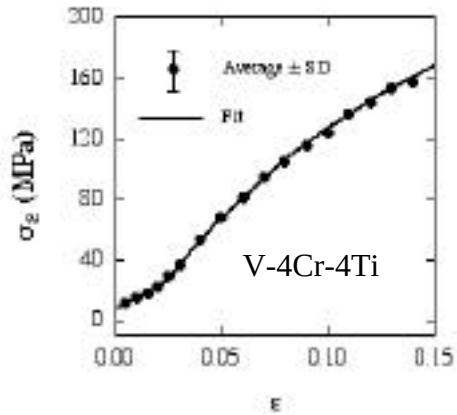




Constitutive Models

- 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 FMS & 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.

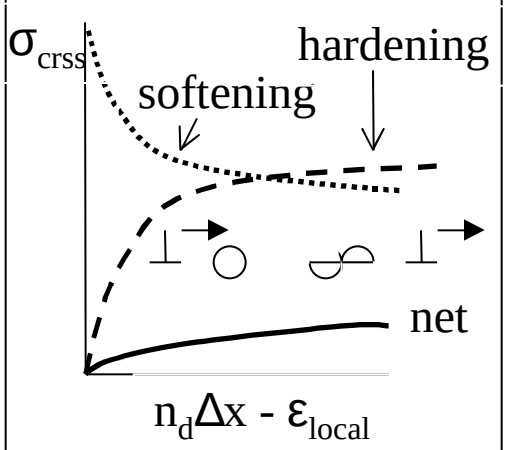




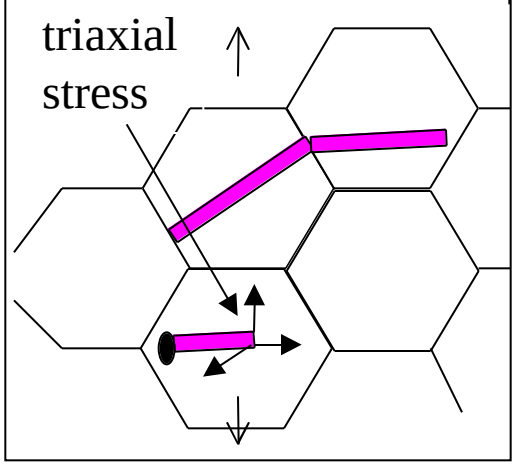
Deconvoluting Localization Effects

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

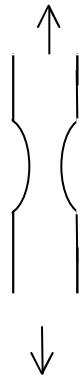
Microconstitutive
dislocation-obstacle interactions and processes controlling local $\sigma_{crss}(\varepsilon_{local})$



Micromechanics
deformation patterns and localization- depend on σ, σ-state redistribution



Continuum Mechanics
large geometry-change deformation & load- instability-necking



Effect of σ_{ys} and n on ε_u

- Robust and physically-based $\sigma(\varepsilon, \varepsilon', T)$

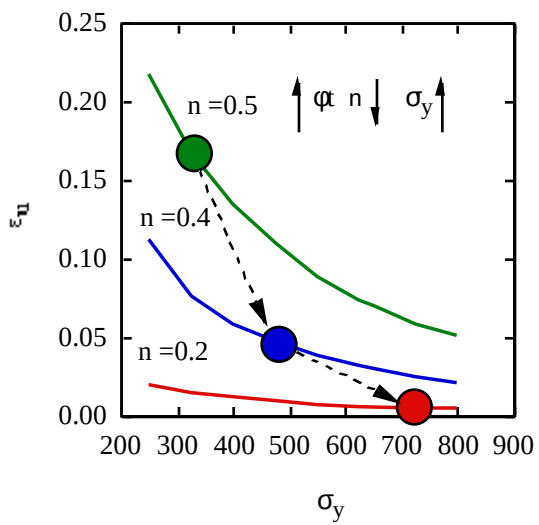
$$\sigma(\varepsilon, \varepsilon',T) = [\sigma_{ys}(\varepsilon',T) + \sigma_{ysa}] + \sigma_{sh}(\varepsilon,T) + \text{H.O.T.}$$

  of great practical importance in FE studies and has provided fundamental insight on processes leading to irradiation effects on ε_u.

- Simple analytical model rationalizes combined effect of lower n <u>and</u> higher σ_{ys} on ε_u.

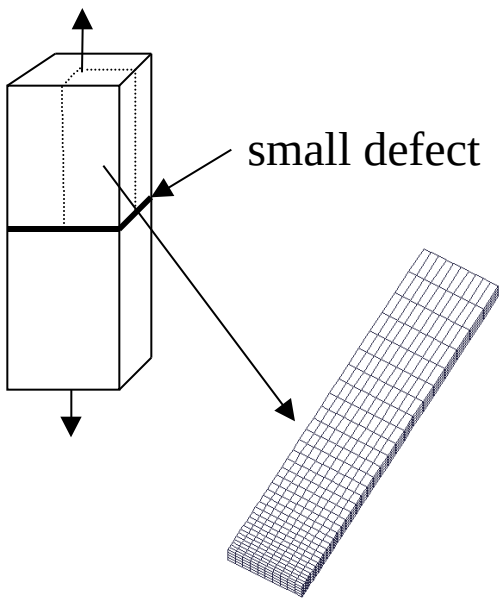
$$\sigma_{fl}(\varepsilon) = \sigma_{ys} + \kappa_{sh}(\varepsilon/\varepsilon_{ys})^n$$

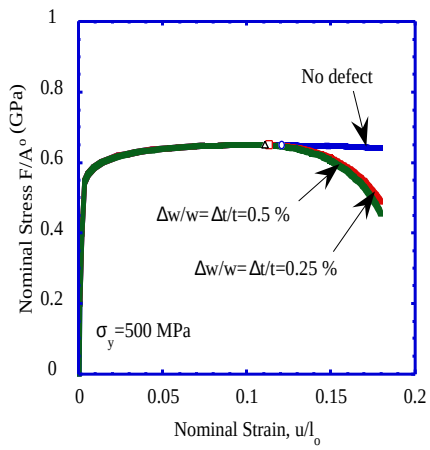
$$\varepsilon_u^{n-1} = [(\sigma_{ys}\,\varepsilon_{ys}^{n})/\kappa_{sh} + \varepsilon_u^{n}]/n = 0$$

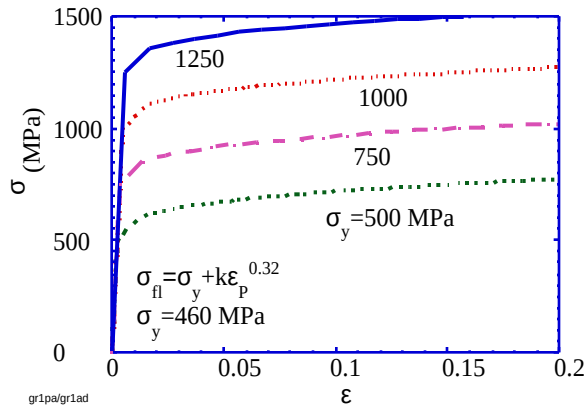


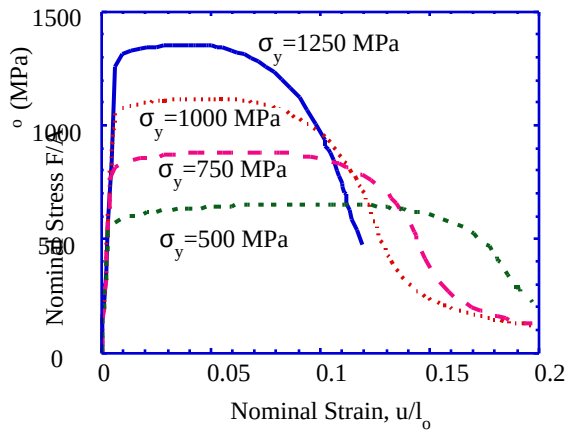
Modeling the Tensile Test

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



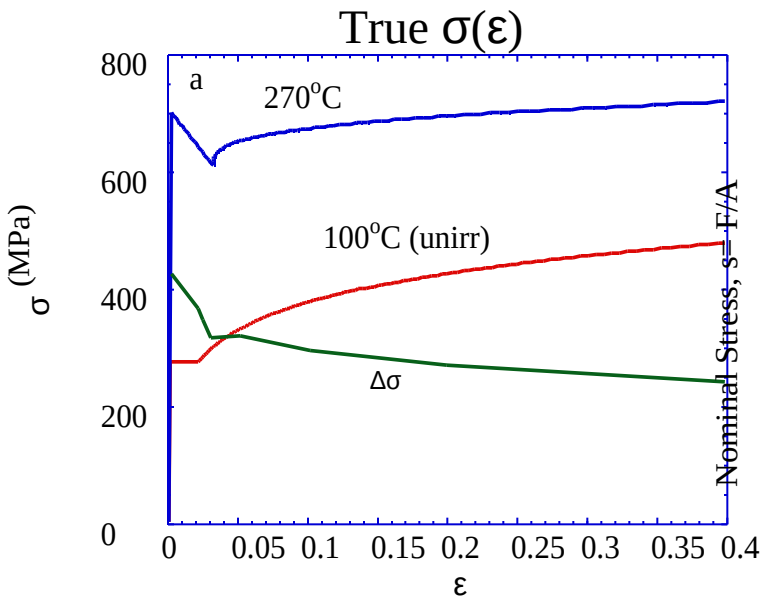


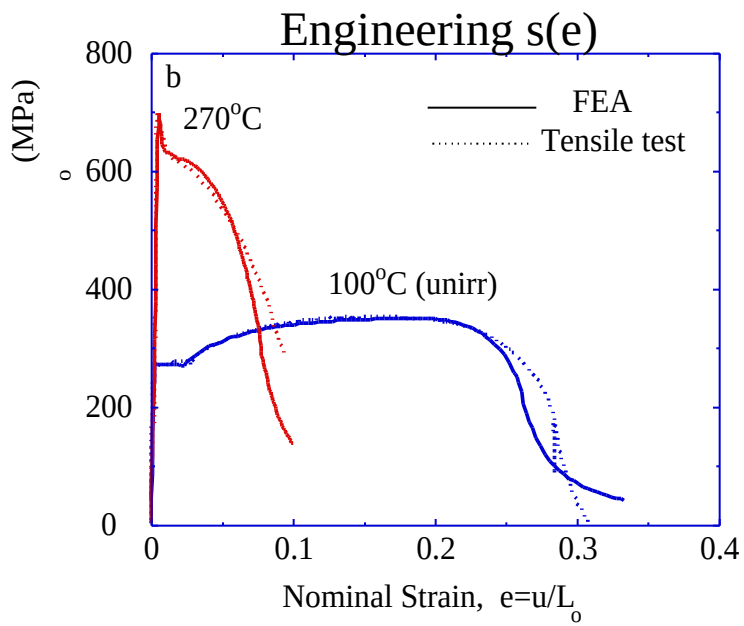




Strain Softening-Hardening

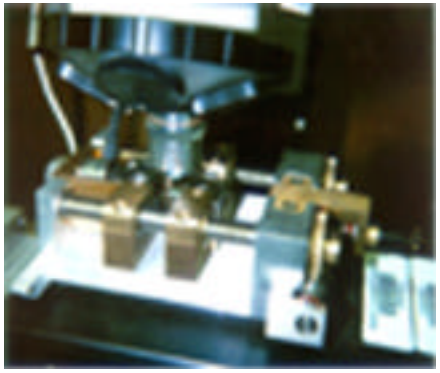
- Engineering s(e) data fit by $\sigma_{fl}(\varepsilon)$ with a gradual yield drop softening followed by hardening. Estimate of the minimum $\Delta\sigma_{fl}$ shows a persistence of irradiation hardening to high ε.

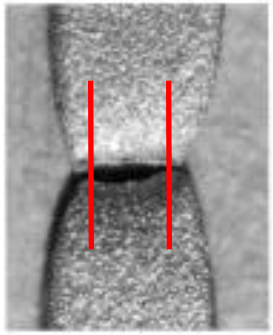


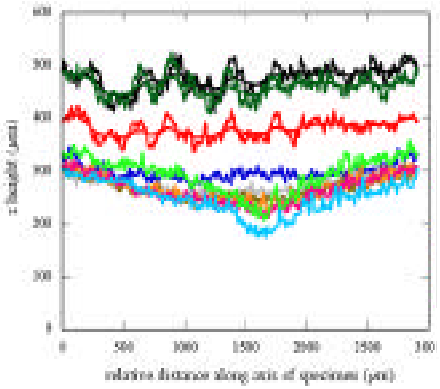


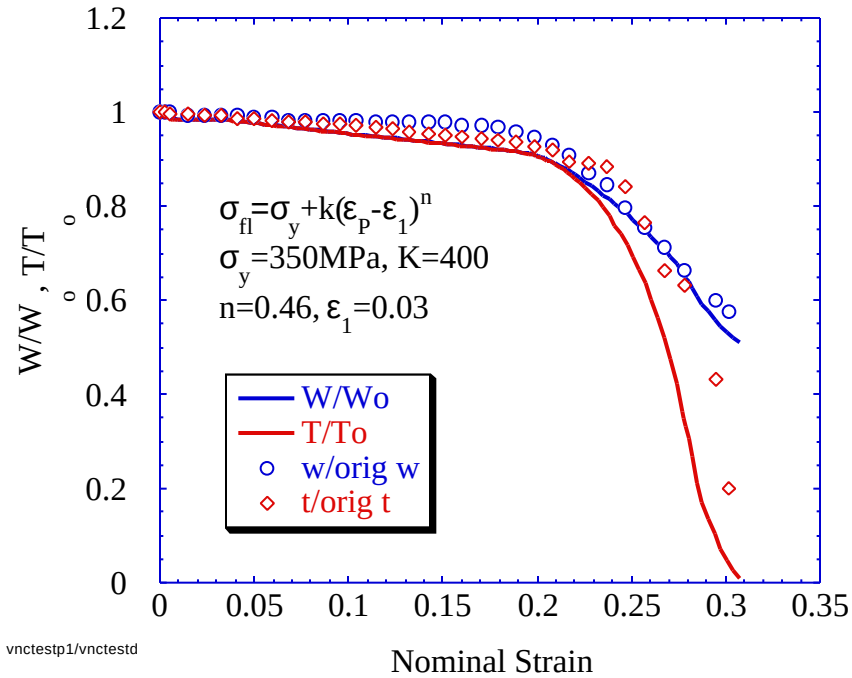
Characterization of Necking Strains

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









Implications of FE $\sigma(\varepsilon)$-s(e) Modeling

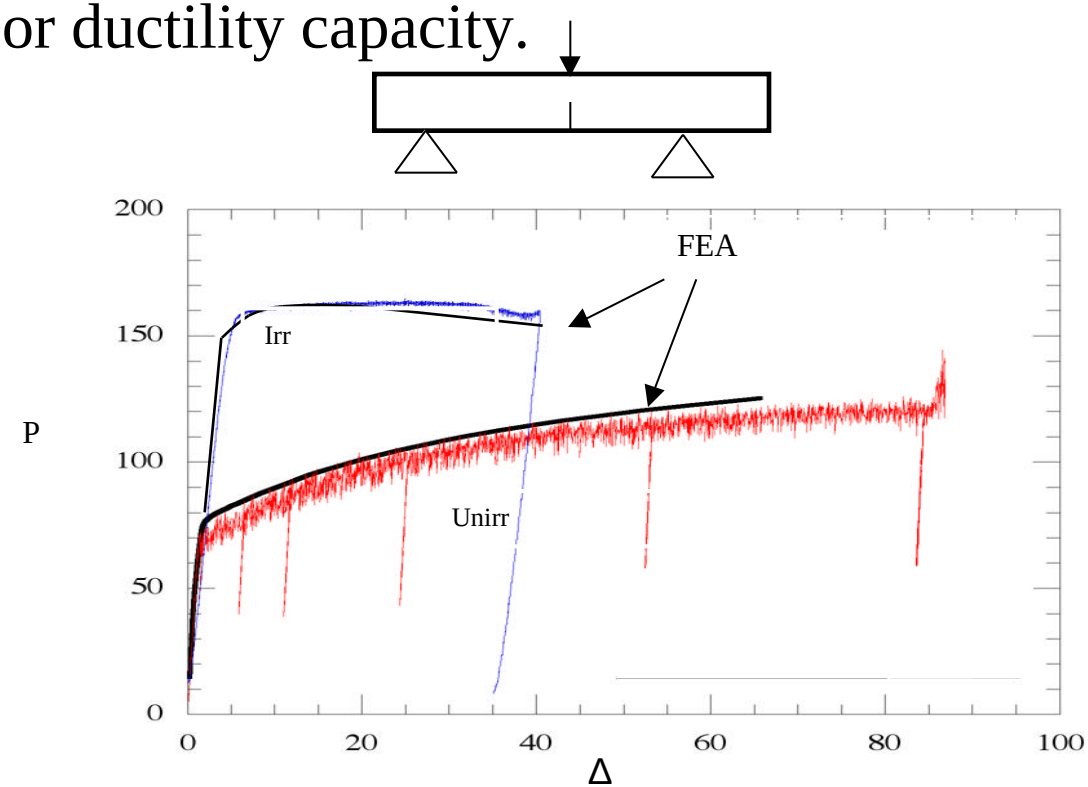
- Effects of irradiation on the s(e) curves can reproduced in FE simulations using continuum, incremental flow (J_2) laws.
- The $\sigma(\varepsilon)$ is controlled by a competition of initial softening followed by modest hardening - significant irradiation hardening persists to high ε.
- Role of micro-localization 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, structure evolution with ε and the local mechanics of defect softening.

Implications to Fusion Structures

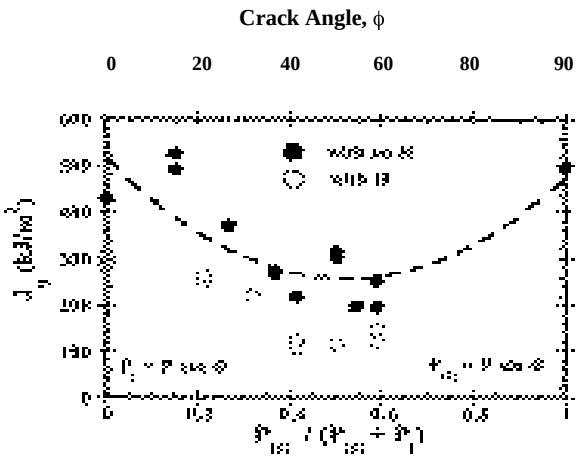
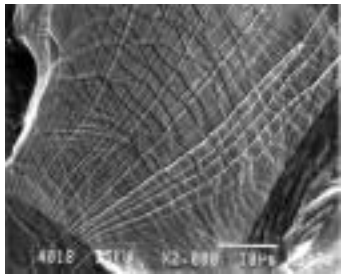
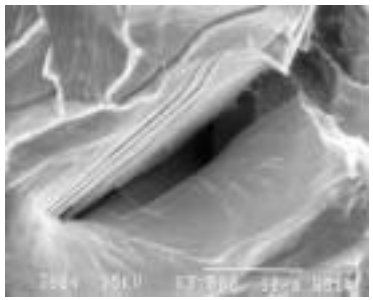
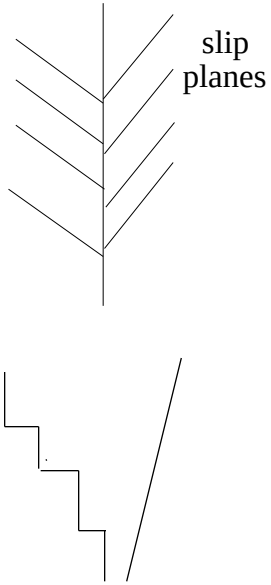
- Structural 'strength and ductility' depends on both intrinsic material and extrinsic factors related to size and geometry.
  - large $\Delta\sigma_y$ are beneficial and low e_u are detrimental, but - cases such as simple bending are not sensitive to e_u, while shear dominated processes may be very 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 shallow 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.



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*?

Unirradiated F82H