Some Thoughts on Flow Localization in Irradiated Alloys - What Are the Consequences?

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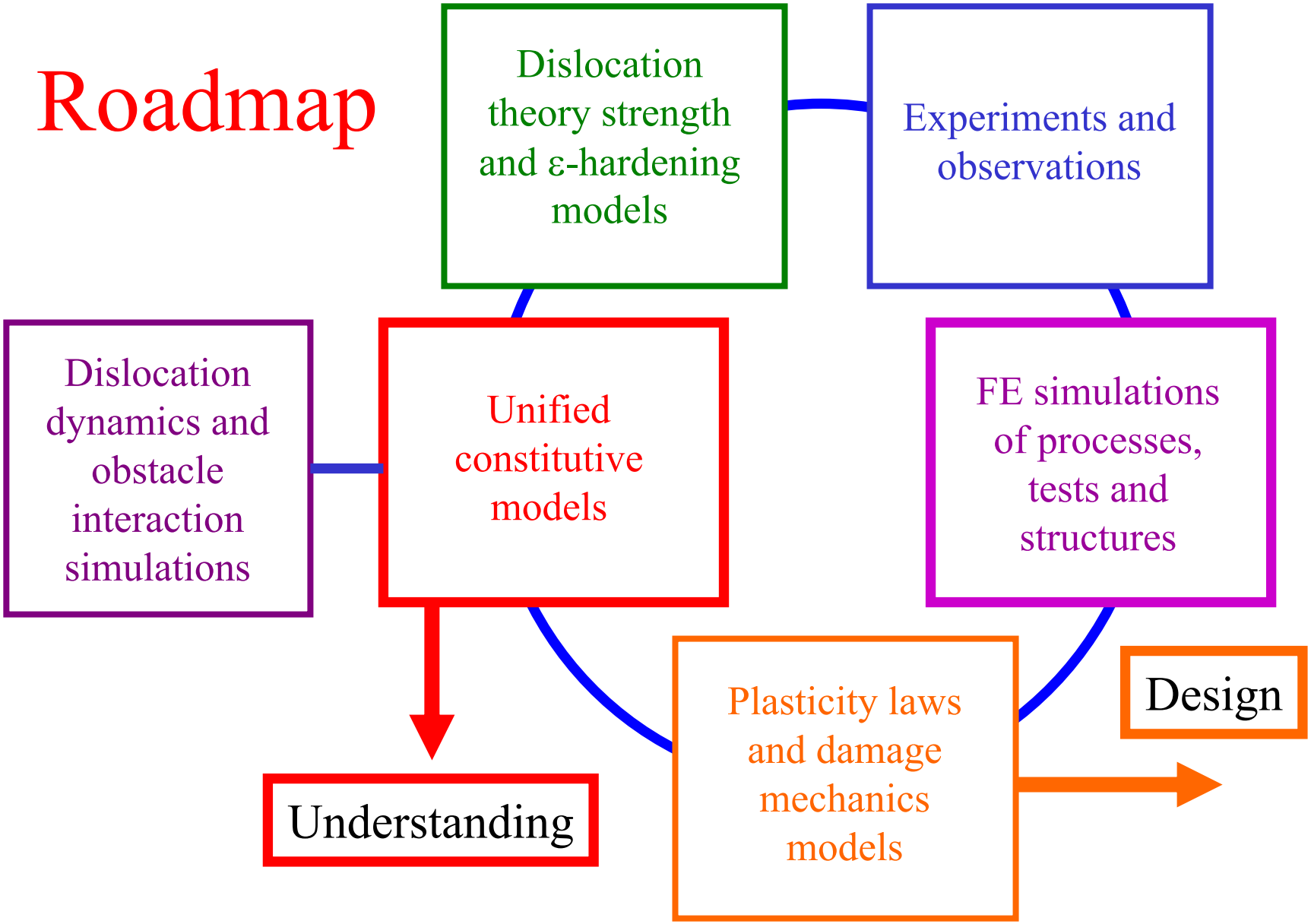
Roadmap

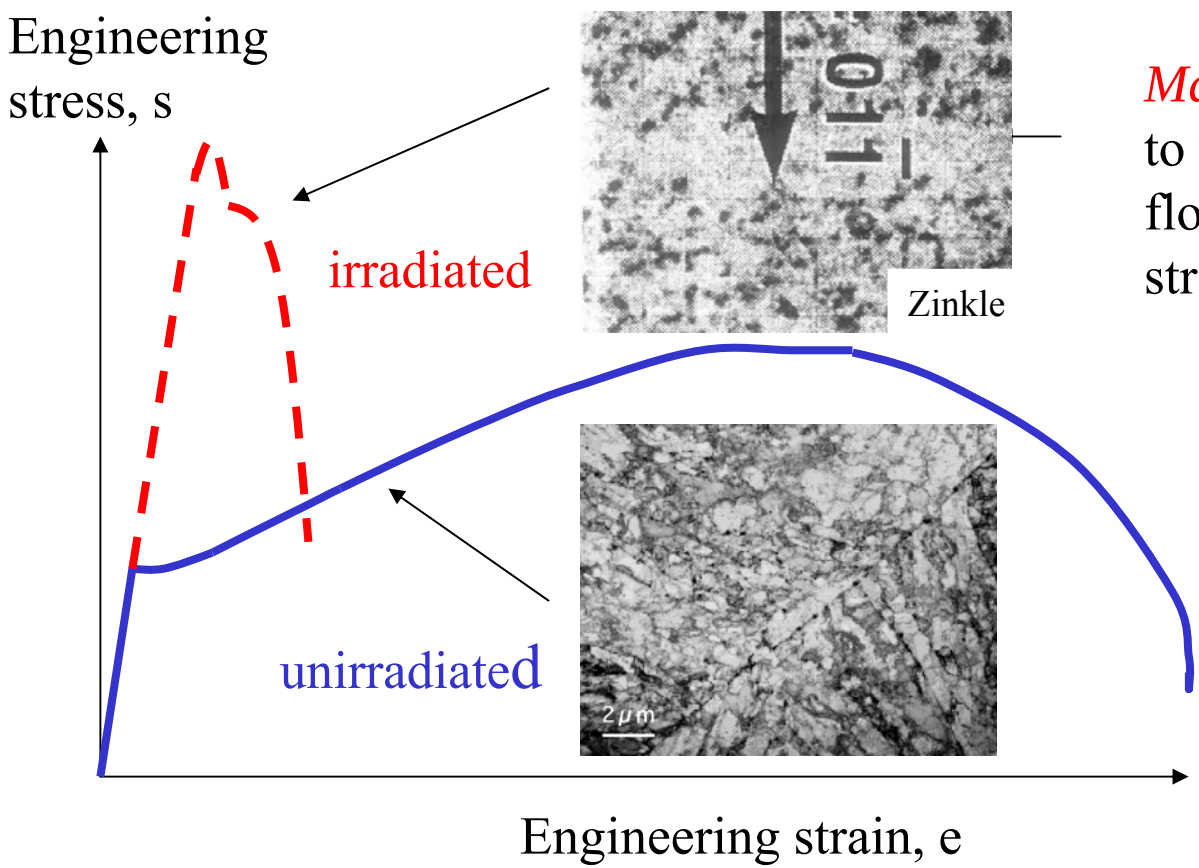

Dislocation theory strength and ε-hardening models
Experiments and observations
Dislocation dynamics and obstacle interaction simulations
Unified constitutive models
FE simulations of processes, tests and structures
Plasticity laws and damage mechanics models
Design
Understanding

Outline

- Brief overview of multiscale deformation phenomena in irradiated bcc alloys with flow localization and severe uniform strain loss
- A continuum model for uniform strain loss and connection to true-stress strain behavior
- A continuum model of meso-scale localization mechanics
- Some ‘fundamental’ implications to experiment

Objective

- Understand, model the multiscale physics of deformation of bcc alloys and effects of irradiation-flow localization.



Macroscopic connection to to *microscale* localized flow - coarse slip to high strain flow channels?

<u>Mechanisms</u>

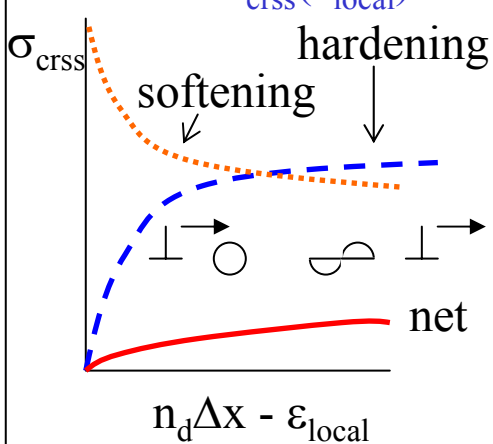
- source hardening
- defect free channels
- twinning
- retarded cross slip.

Decoupling Localization Effects

- Isolate and properly integrate *multiscale* parts - what controls the *observables*?

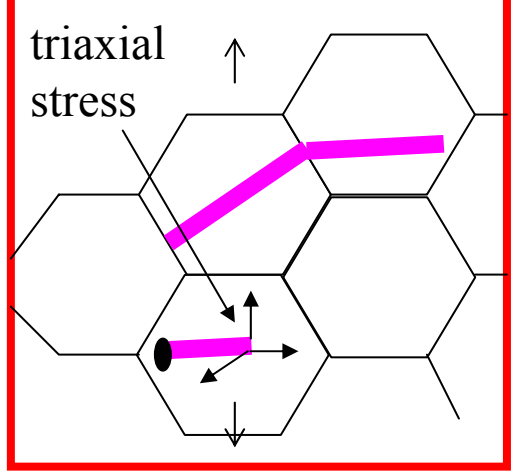
Microconstitutive

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 and load-instability-necking

Flow Localization

- Flow localization is common - occurs in various alloy systems and may arise from a very wide variety reasons (adiabatic heating, precipitate cutting, ordering super-dislocations, ...) and in a number of different forms
- Key issue metalworking & some alloys like Al-Li
- The various manifestations of localization are often very sensitive to a number of extrinsic factors related to size and shape, loading conditions, load-train compliance and displacement constraints,….
- Low uniform strains occur without micro-localization (channels) and vice versa

Tensile Necking Instability

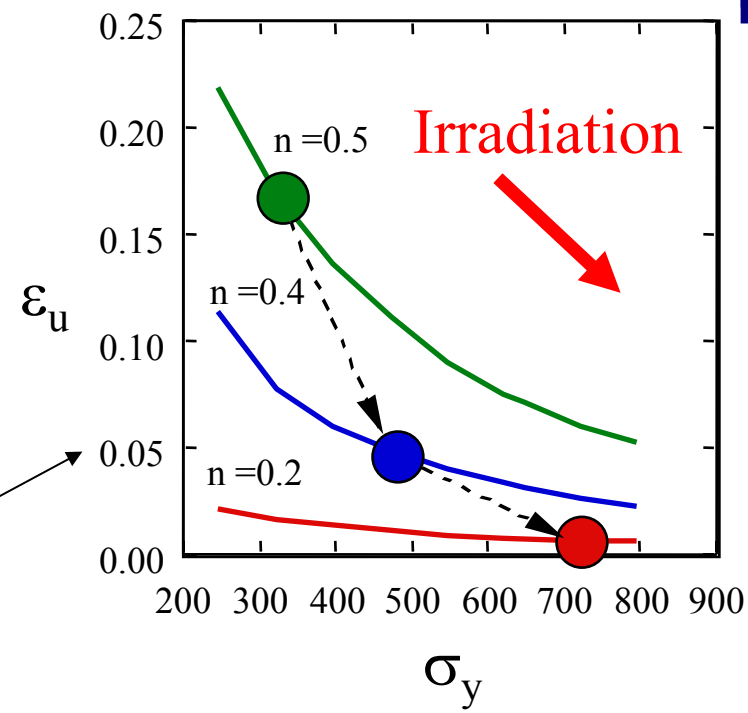
- Necking controls ε_u in tensile engineering s(e) curves - strongly influenced by *extrinsic* geometric factors as well as by the *intrinsic* true stress strain $\sigma(\varepsilon)$

Analytic Model

$$\sigma(\varepsilon) = \sigma_y + \kappa(\varepsilon/\varepsilon_y)^n$$

$$\varepsilon_u^{n-1} - [\varepsilon_y^n \sigma_y/\kappa + \varepsilon_u^n]/n = 0$$

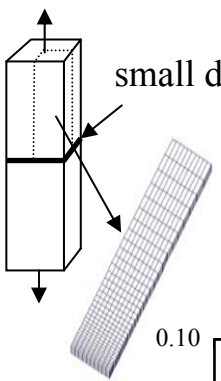
Increased σ_y and decreased n *both* lead to reduced ε_u



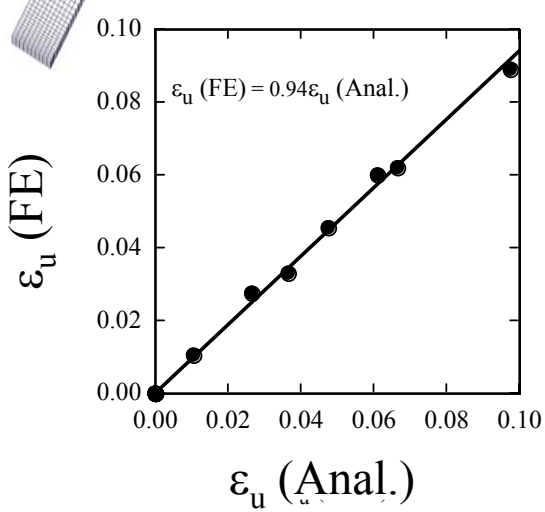
FE Modeling Tensile Test

- Model pre and post necking s(e) - σ(ε) relation

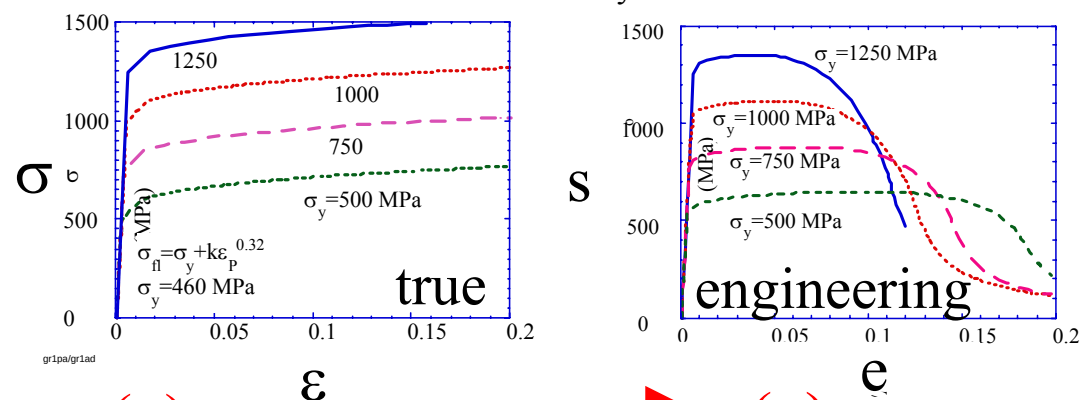
ABAQUS - 1320 8-noded brick elements



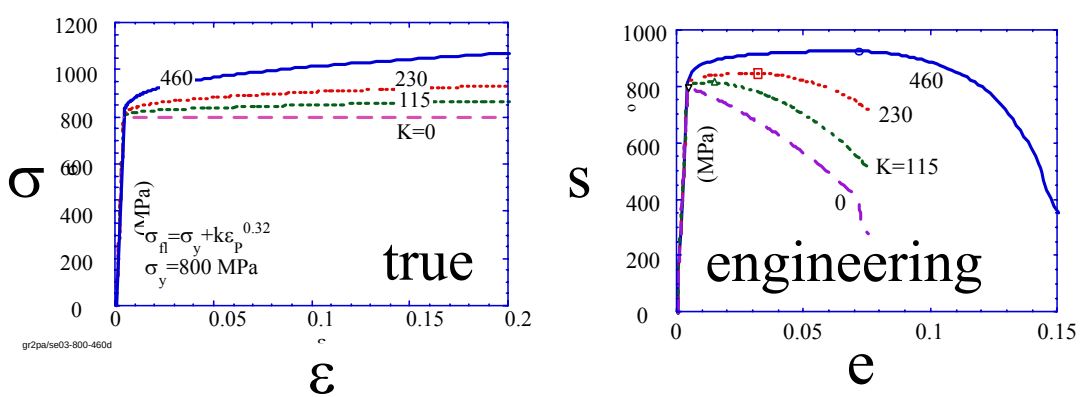
small defect - insensitive to detail



Increasing σ_y - constant n



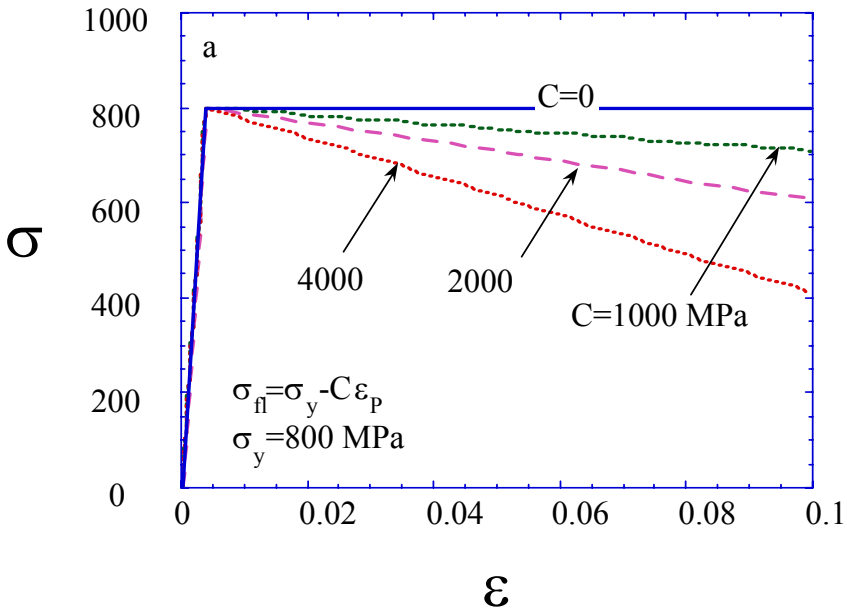
σ(ε) → s(e)

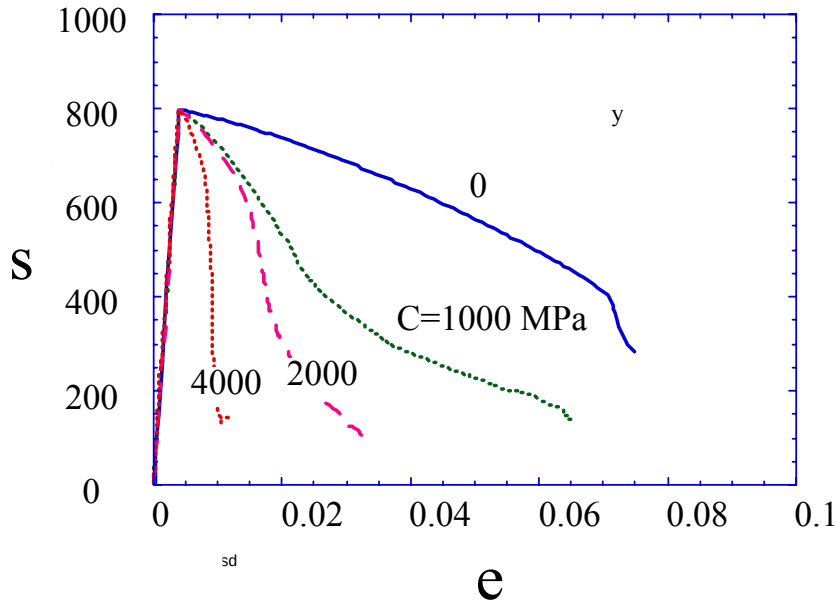


Decreasing n - constant σ_y

Strain Softening

- Modest true strain softening greatly reduces engineering necking strain: $\sigma = \sigma_y - C\varepsilon$ (C =1000 to 4000)



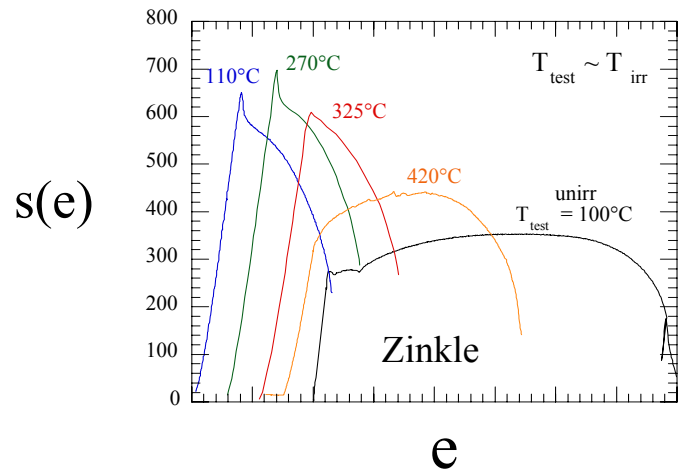


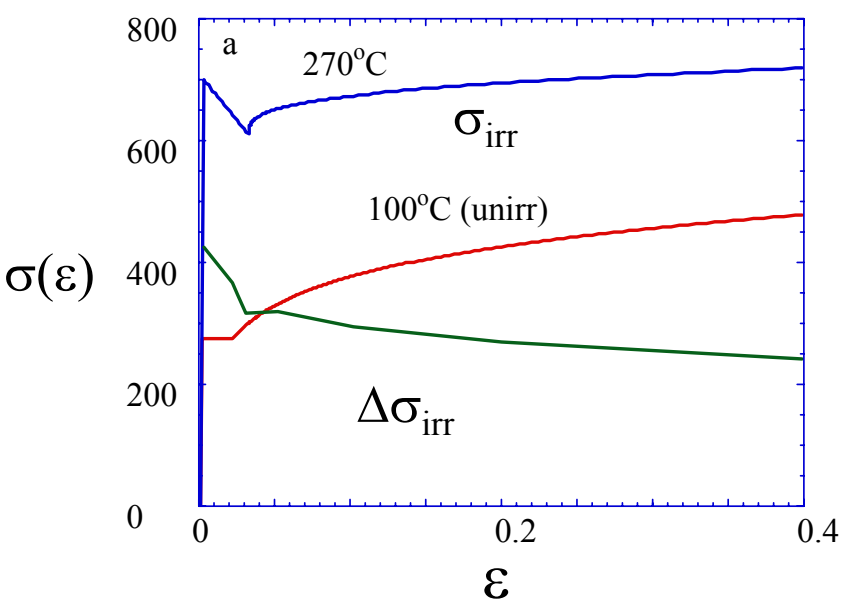
Irradiated σ(ε)

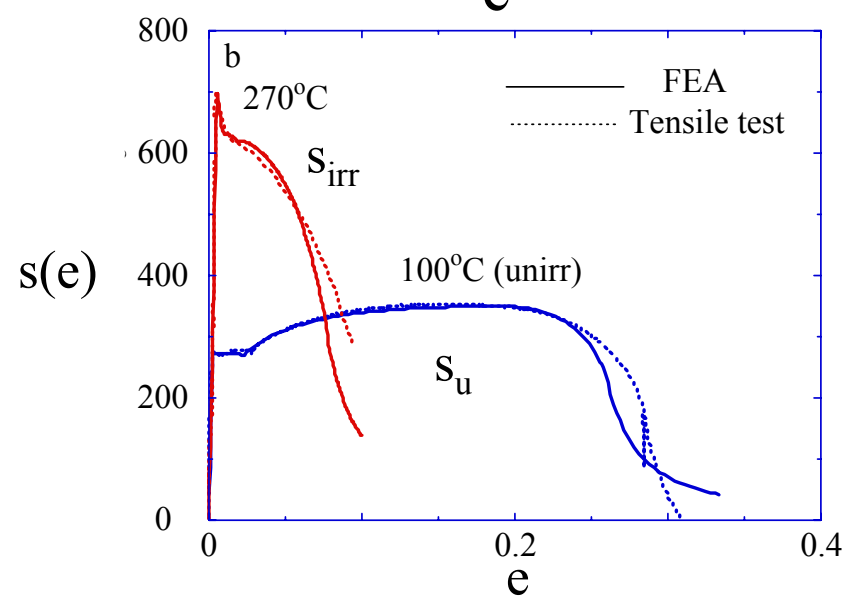
V-4Cr-4Ti
at 0.4dpa

- The σ(ε) 'fit' to typical s(e) curve shows irradiation hardening persists to high ε

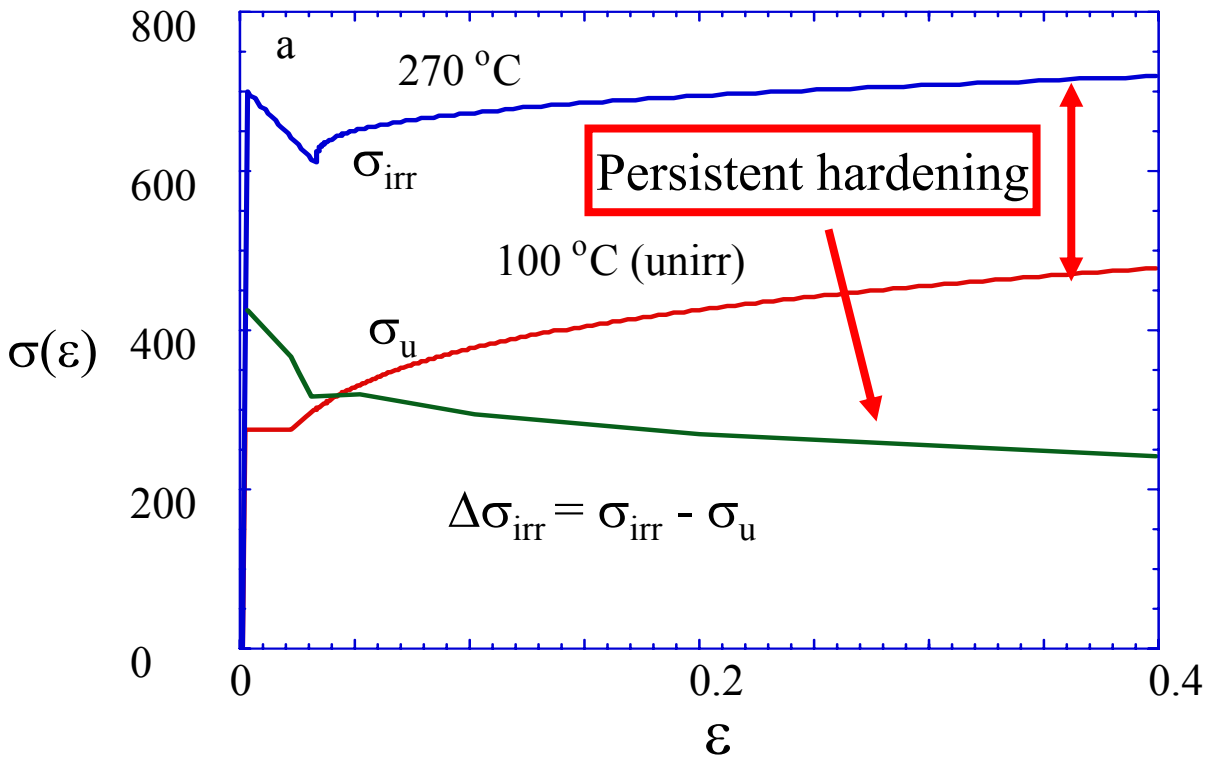
σ(ε) ⟷ self-consistent ⟷ s(e)





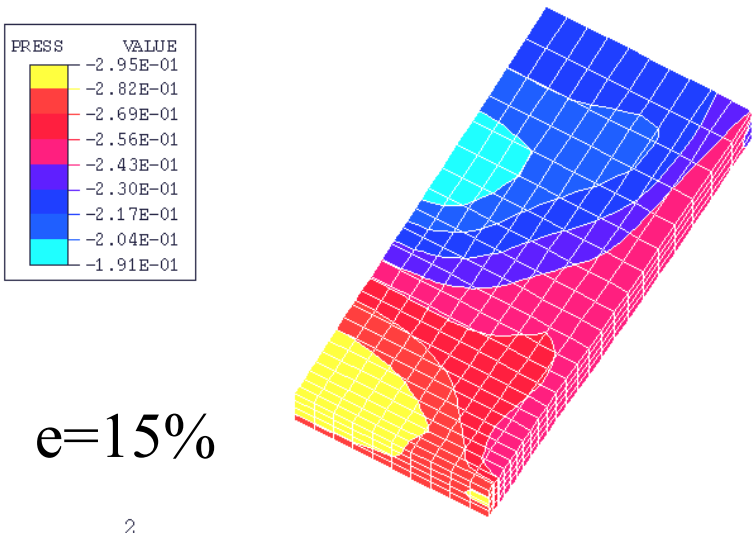


Irradiated $\sigma(\varepsilon)$ - Persistent $\Delta\sigma_{irr}(\varepsilon)$



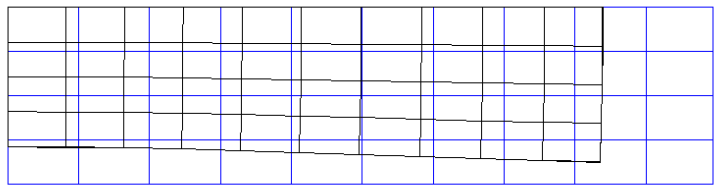
Modeling Tensile Test

- A great deal of other detailed information is available from FE simulations -- large geometry change, stress, stress-state, strain distributions -- compare to experiment.

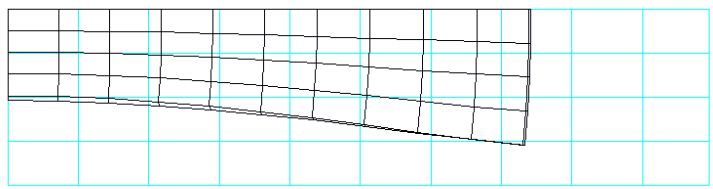


e=15%

ε=15%

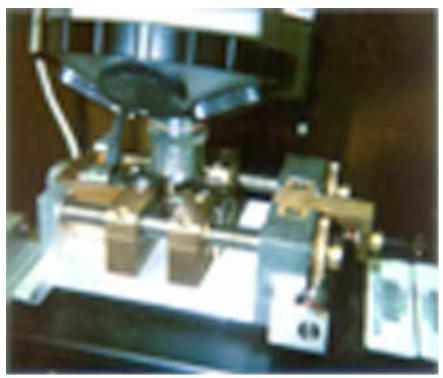


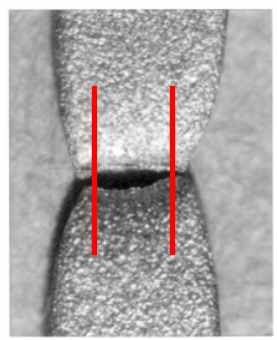
ε=17%

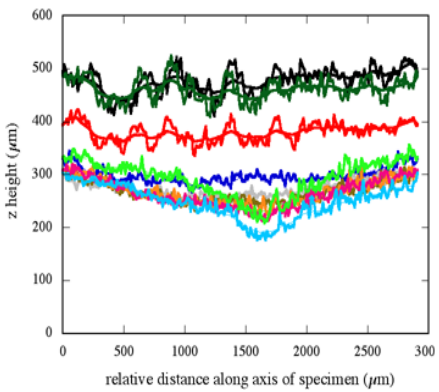


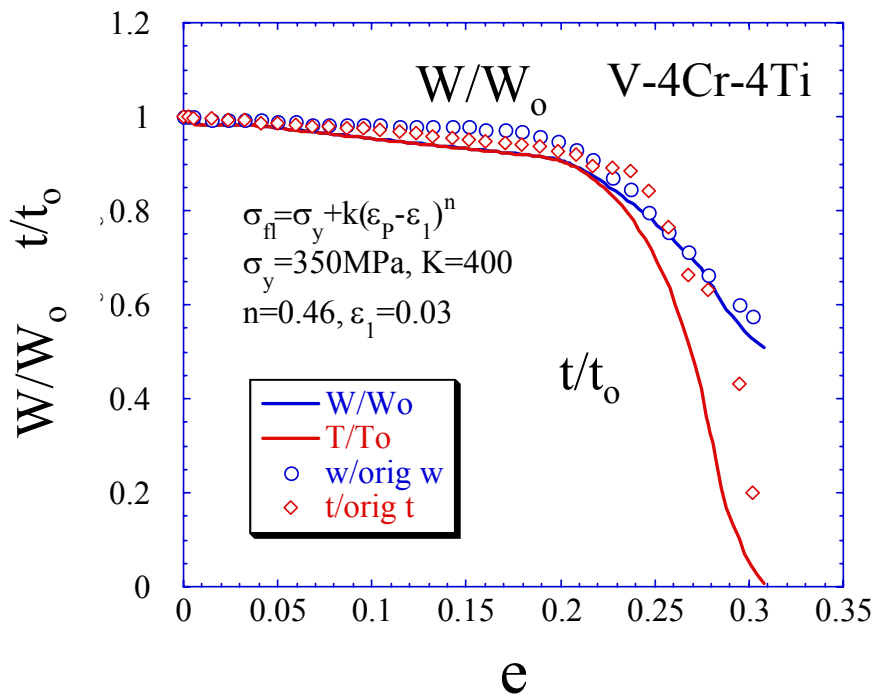
3-D Tensile Neck Evolution

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



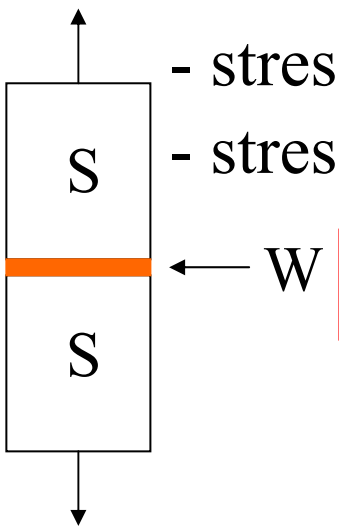






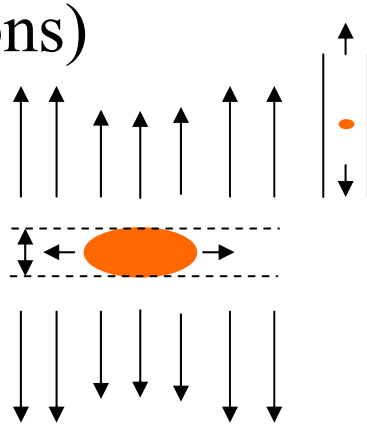
Summary - FE Tensile Test Modeling

- The FEM + J_2 flow theory appears adequate modeling macroscopic deformation in alloys that flow localize
- Even with severe loss of ε_u and micro-localization global irradiation and some strain hardening persist
- Understand the continuum solid micromechanics of *heterogeneous deformation* - obey equilibrium/ compatibility and basic plasticity laws -- internal redistribution of



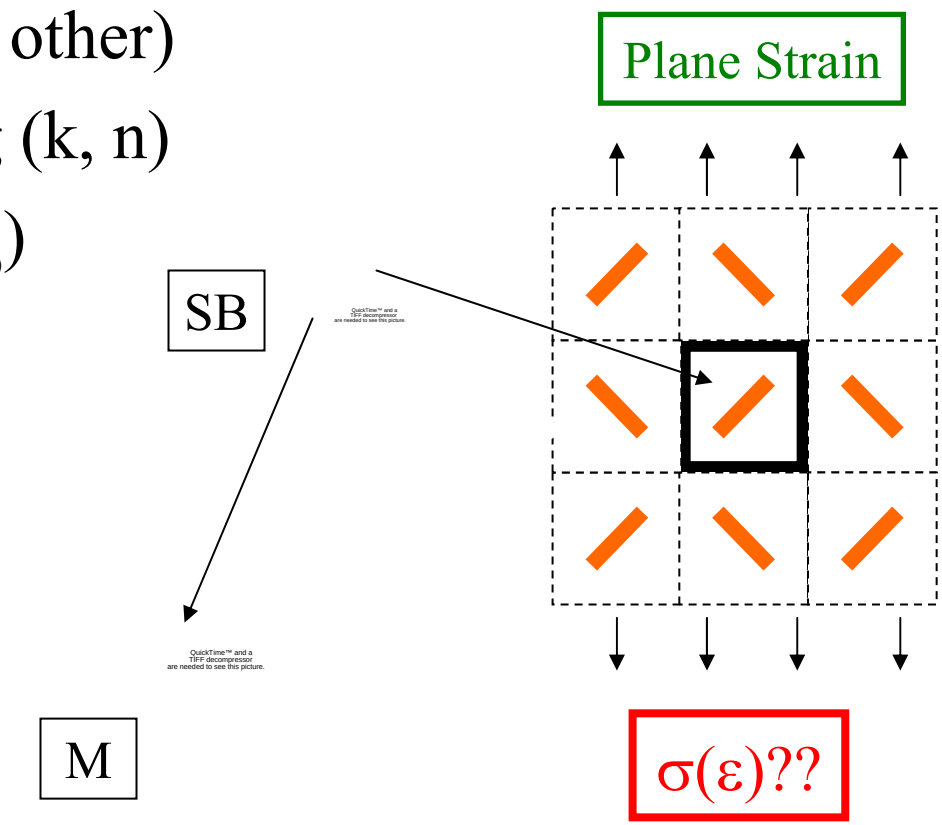
- stress (from 'weak' to 'strong'regions)
- stress-state (uniaxial to triaxial)

$$\sigma_{effw} = 3\sigma_{yw}$$

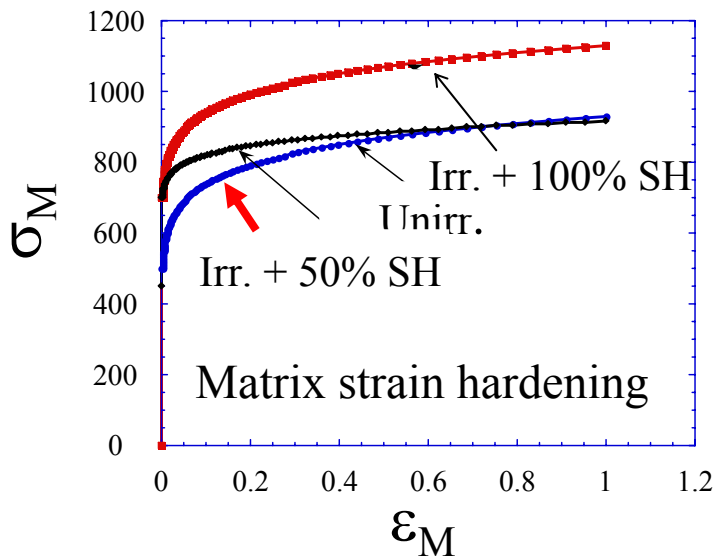


FE σ(ε) Model With Localization

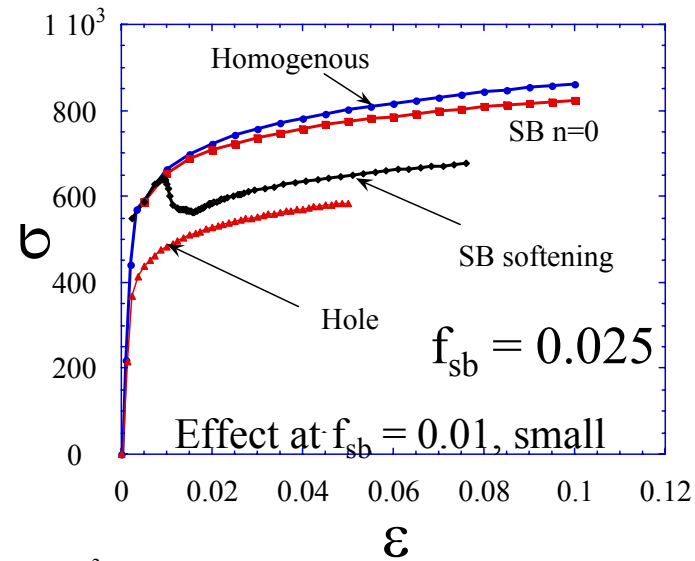
- Embed localized strain *softening shear* band (SB) regions in *strain hardening* matrix (M) - many variables:
  - SB strain softening (C, other)
  - matrix strain hardening (k, n)
  - SB volume fraction (f_{sb})
  - SB geometry (θ)
  - plasticity laws
  - damage
  - mirror or periodic unit cell boundary condition

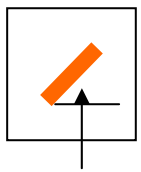


Examples of Results - f_{sb}

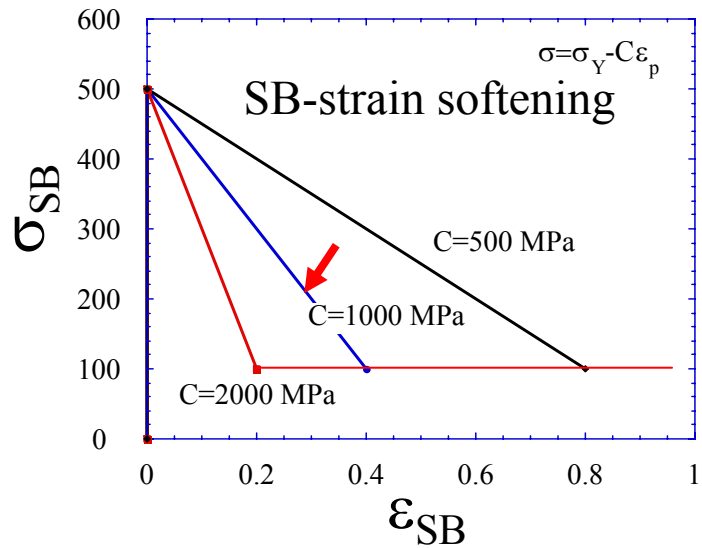


Unirr.
$\sigma_y = 500$
$C = 1000$
$\theta = 45$
Mirror

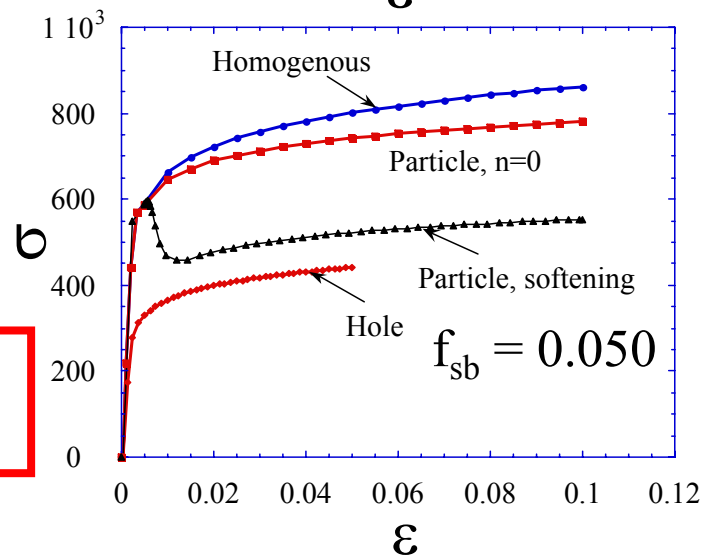




θ

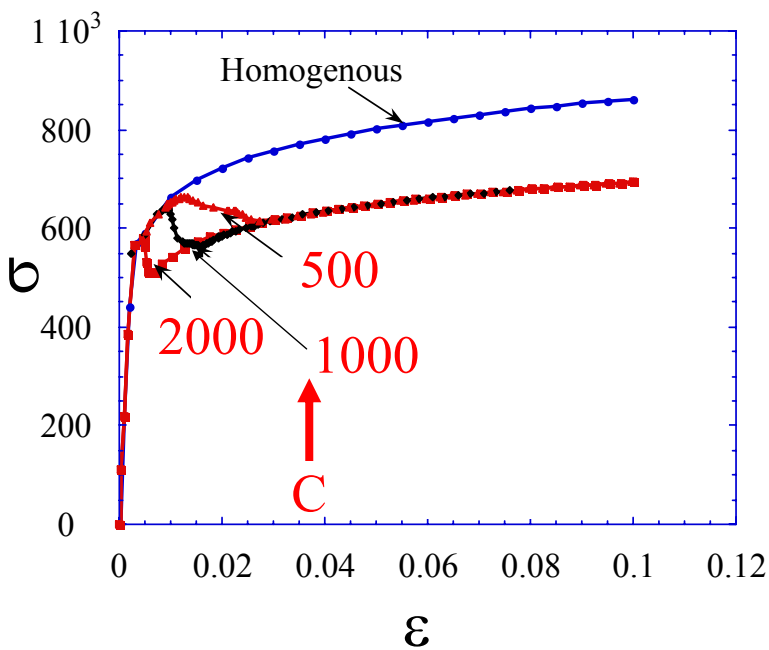


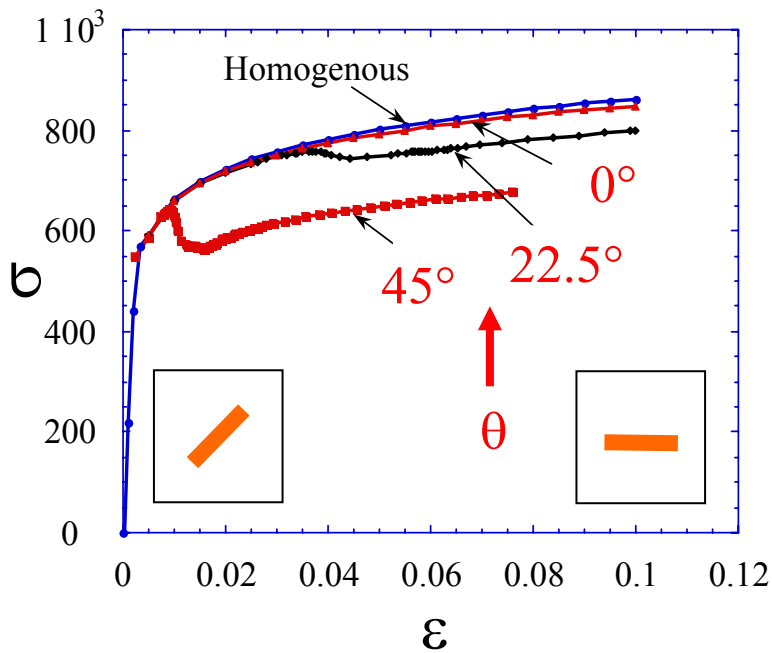
Periodic b. c.
similar



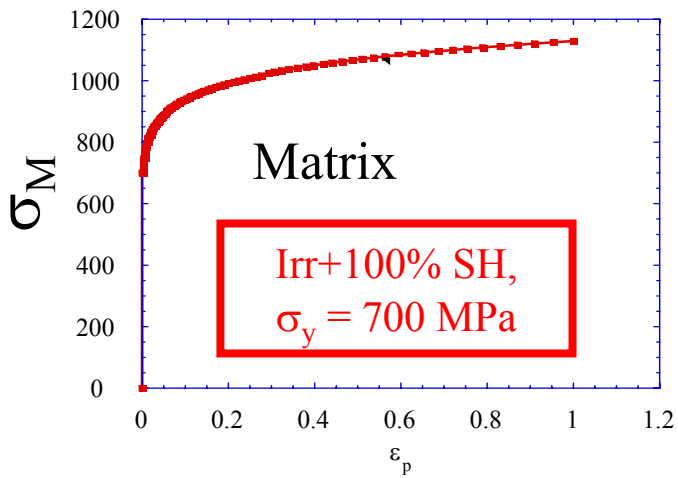
Examples of Results - C and θ

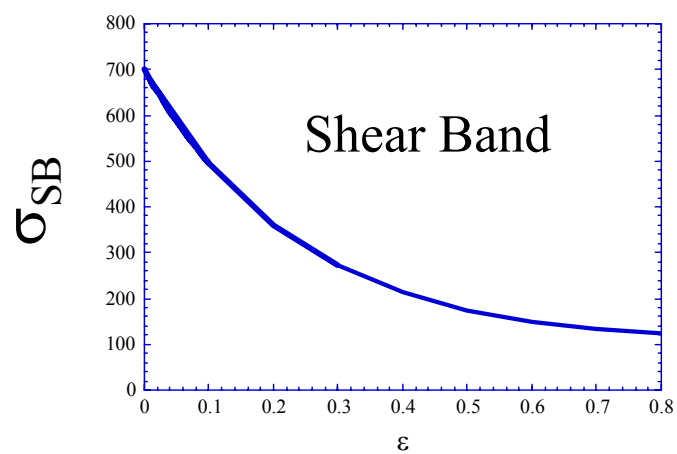
Unirr, f_{sb} - 0.025, σ_y = 500 MPa

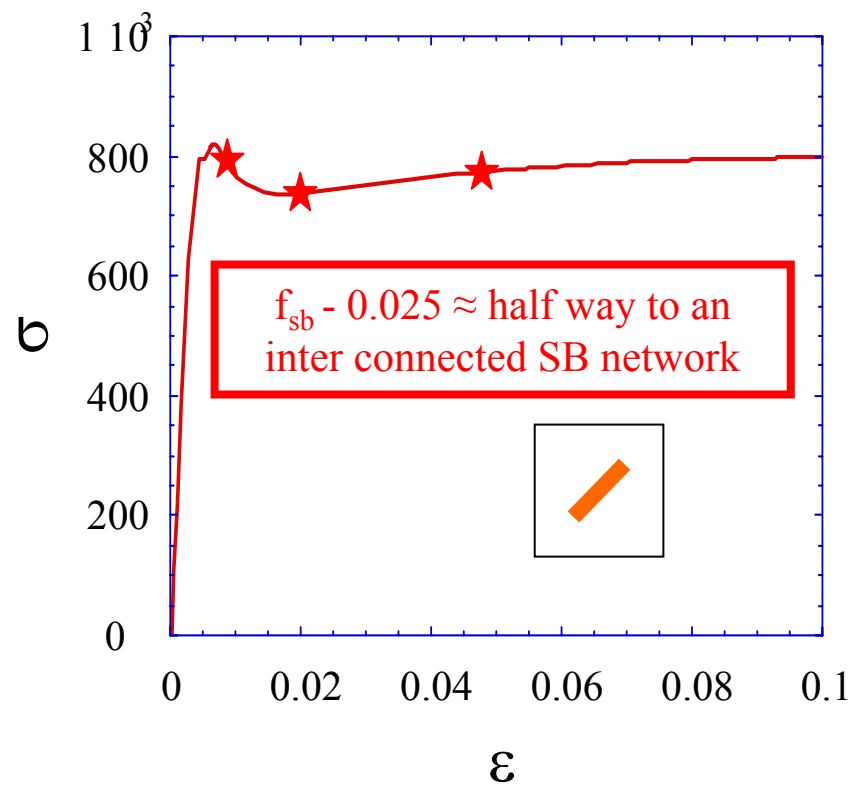




Irradiated σ(ε)

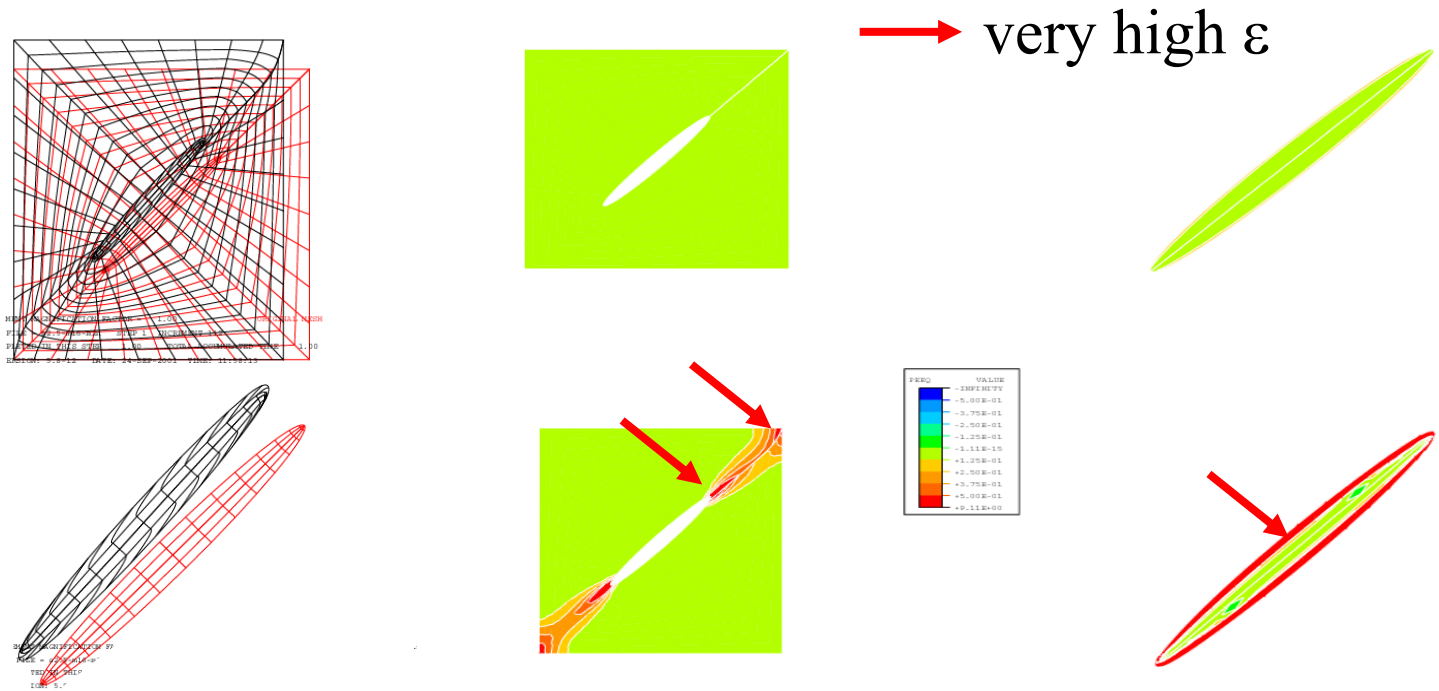






Internal Strain Distributions

- High strains in the SB with maximum softening but SB deformations accommodated by lower matrix strain with strain hardening



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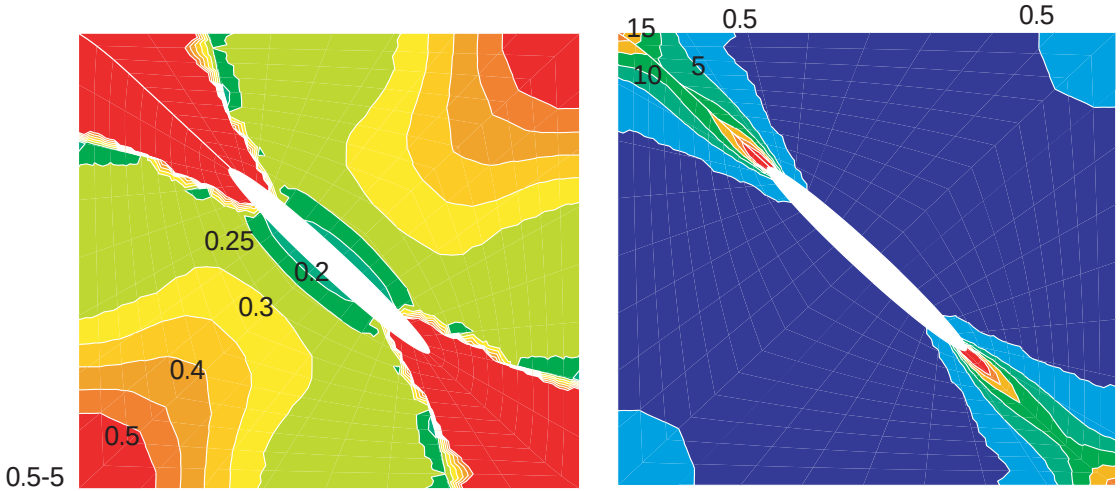
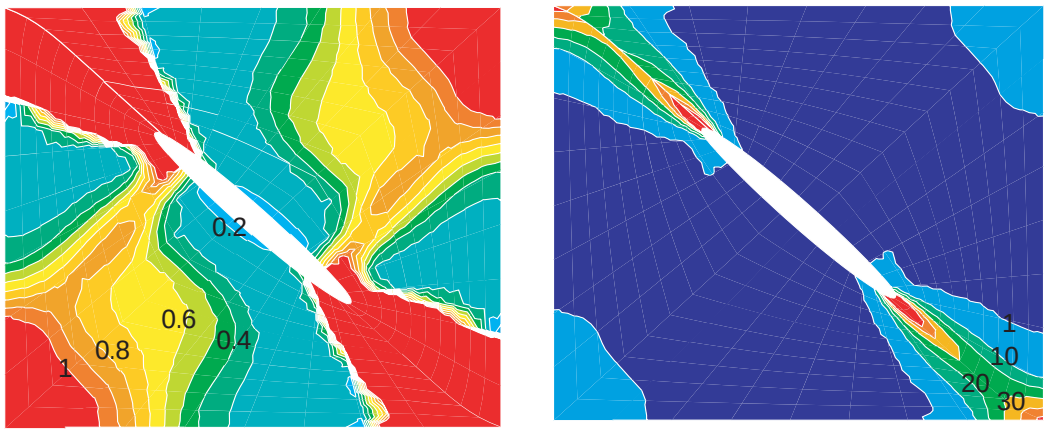


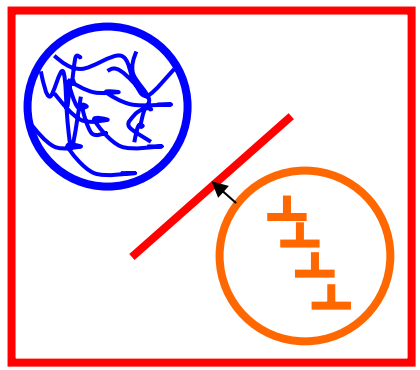
Effective Plastic Strain at 2% Average Strain (%)



Effective Plastic Strain at 5% average Strain (%)

Implications _ What To Look For

- Irradiated σ(ε) consistent with *almost* interconnected high ε-highly softened 45° SB network
- SB deformation accommodated by matrix ε with ≈ normal ε-hardening rate
- Localization high ε between between SB and intersections of these regions
- Key *observables* would result -- deformation patterns, varied dislocation structures - soft and hard regions,….
- Experiment-modeling interplay is critical to fundamental understanding



Summary and Conclusions

- Irradiation induced severe loss of ε_u is an inherently compex multiscale phenomena and not only (or even) related to localization - meso-macroscale deformation mechanics is critical.
- Considerable progress in understanding mechanics has major implications to both fundamental science-based uderstanding and practical applications of consitutive and structural deformation models.