Small Specimen Fracture and Deformation Testing

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Background

- Numerous small specimen techniques have been developed in the international fusion materials program -- need dictated by:
  - » Small volume irradiation facilities (accelerators, fission reactors, IFMIF)
  - » Enables test matrices with requisite variable combinations and redundancy
- Hence, a host of specimen geometries have been developed -- combination of scaled down mechanical test specimen and development of new tests for small specimens (e.g., TEM discs)

Recent Progress

- Recent (UCSB-ORNL….) efforts directed at combining specimen miniaturization with *understanding* of basic flow and fracture processes and modeling to:
  - » Extract basic properties and insights
  - » Optimize specimens for controlled, single-variable test matrices
  - » Develop multipurpose specimens
  - » Tie to structural integrity assessment

SSTT -- Fracture

- SSTT specimens can be used to develop elements of micromechanics-based approach to fracture
  - » Constitutive equations for use in Finite Element calculations of crack tip stress/strain fields
  - » Local fracture parameters -- e.g., critical stress (σ^*) critical area (A^*) descriptions of cleavage fracture

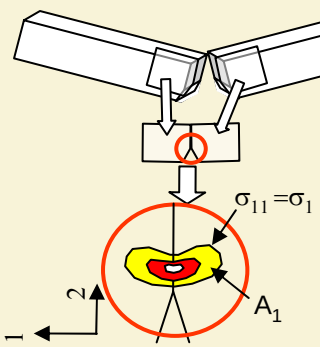
- Application of Confocal Microscopy and Fracture Reconstruction methods a requisite component

Criteria for Cleavage Initiation obtained from MCVN tests

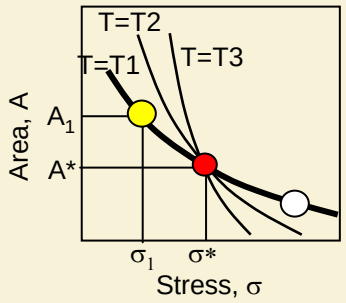
Tensile tests $\sigma = \sigma(T, \varepsilon, d\varepsilon/dt)$

FEM analyses **(high strain rate)**

Criteria to **initiate cleavage**

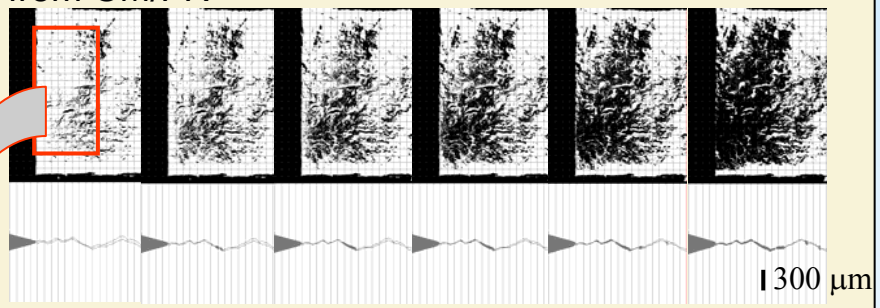


Stressed Area **A** as a function of σ_{11} to initiate Cleavage is determined using FEM.

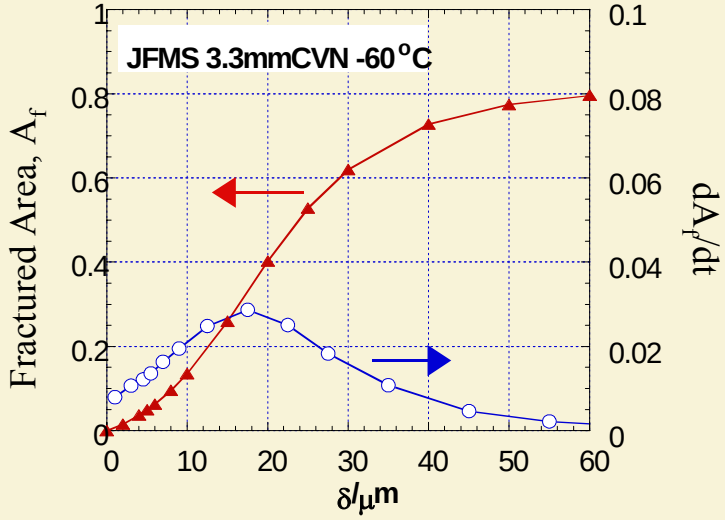


Miniature Impact tests

- Critical displacement for cleavage initiation
  - from Load-Disp. Curve
  - from CM/FR



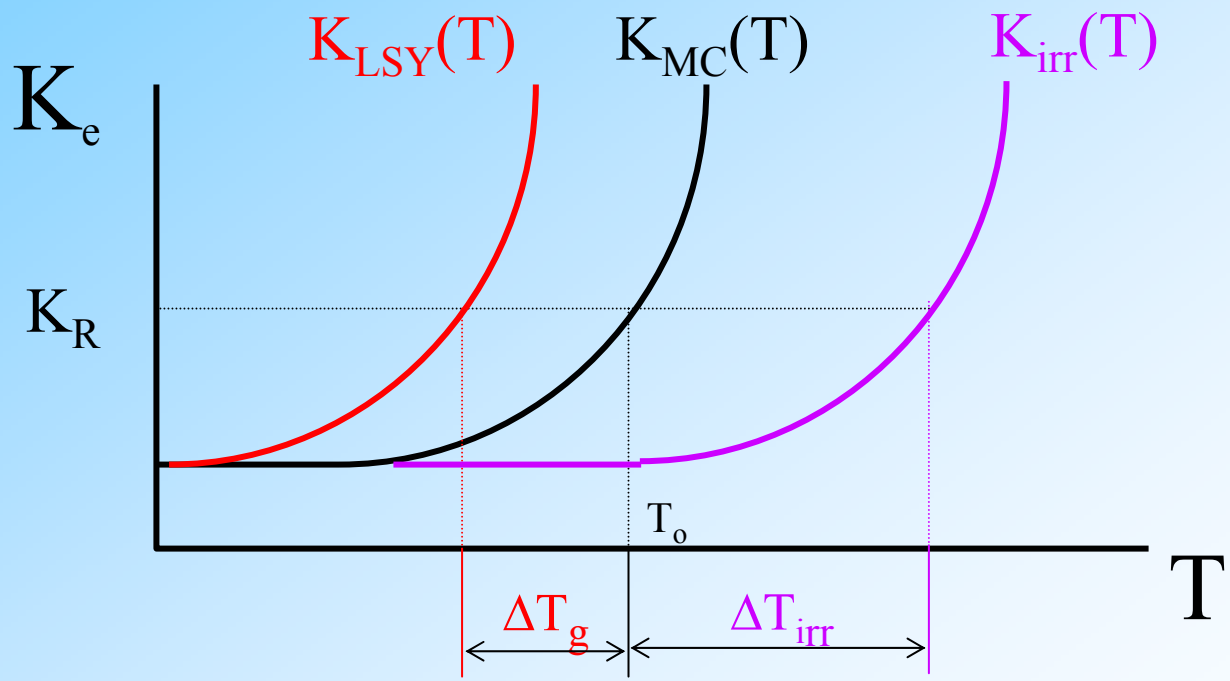
δ = 0μm 10μm 15μm 20μm 25μm 35μm



Edsinger et al, JNM, 1996
Yamamoto et al, ASTM-STP-1418,2002

Fracture

- Much of the recent work addresses use of Master Curve-Shift (MC-ΔT) method for fracture toughness



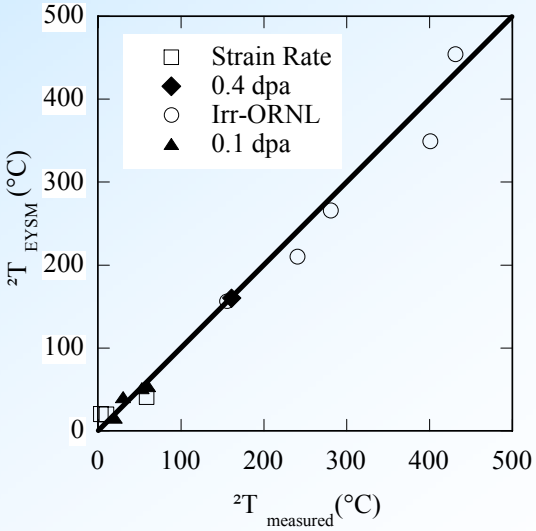
$K_e(T) = K_{MC}(T-[T_o + \Delta T])$ $\Delta T = \Delta T_i + \Delta T_g + \Delta T_{sr} + \Delta T_m$

Odette, JNM, 1994

Equivalent Yield Stress Model

Estimate ΔT_i from temperatures corresponding to yield stress at a reference temperature corresponding to a reference toughness (~100MPa√m)

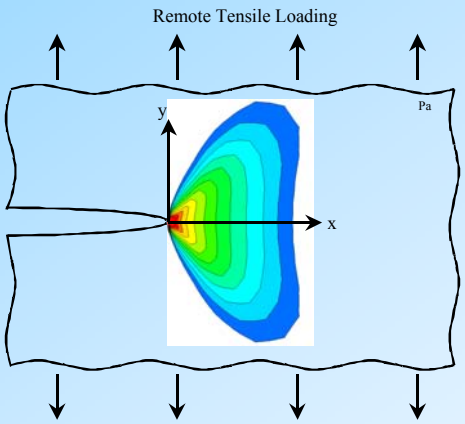
$$\Delta T_r = T_{ri} - T_{ru}, \text{ where } \sigma_{yi}(T_{ri}) = \sigma_{yu}(T_{ru}) + \Delta\sigma_i$$

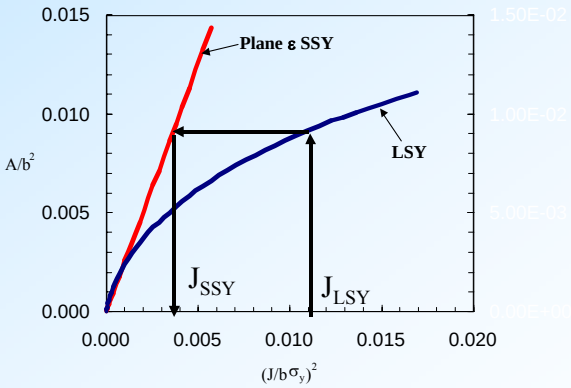


Donahue, Odette, Lucas

Constraint Adjustment

Constraint corrections (ΔT_g) can be made on the basis of equivalent stressed area determined from finite element analysis (FEA) -- necessitates constitutive equation and micromechanics parameters





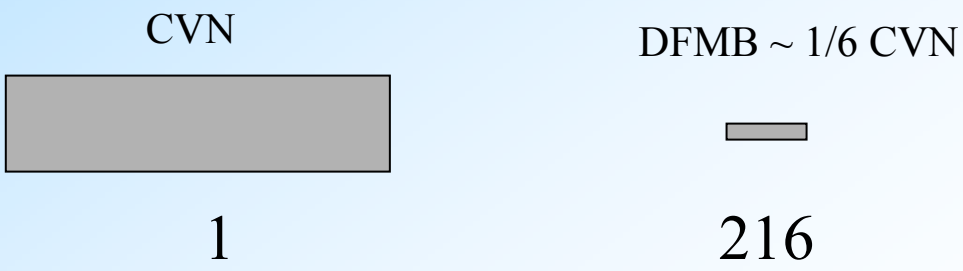
Rathbun, Odette, Lucas

SSTT -- MC-ΔT

- Various specimen sizes and geometries in irradiation experiments provide empirical evaluation of ΔT_g and ΔT_i
  - » Basis of MAster Curve Experiment (MACE)
    - UCSB-PSI-Petten
    - 0.4-2 dpa
    - 0.1-0.5T CT/BB
    - F82H, Eurofer
    - 80-350˚C
    - $0.1 < a/W < 0.5$
  - » Limitations
    - Largest specimens not all that large
    - Limited range of specimen size, a/W

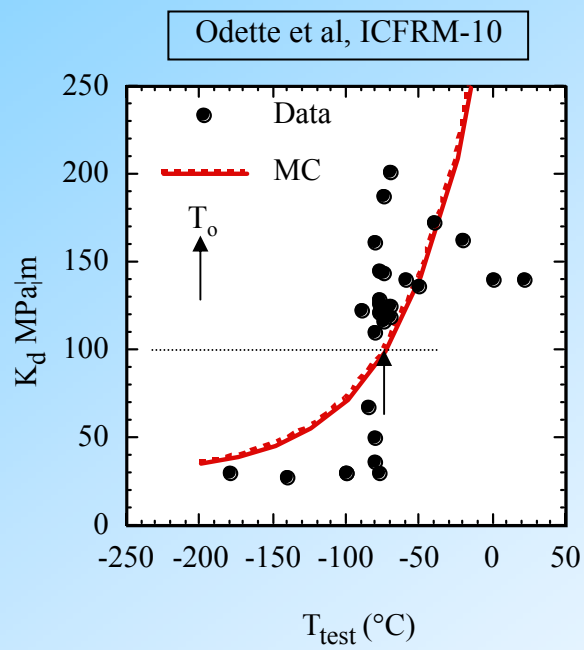
DFMB's

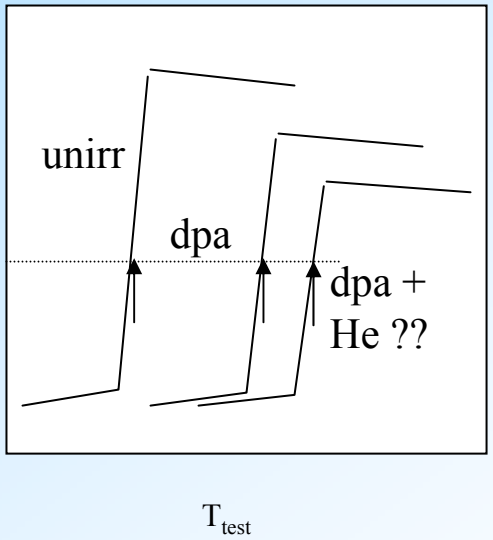
- Reliance on miniature specimens to empirically test MC-ΔT at high dpa -- development of the Deformation and Fracture Mini Bend (DFMB) specimen
  - » Single variable experiments for alloy design
  - » Mechanism studies
  - » Ion beam irradiations

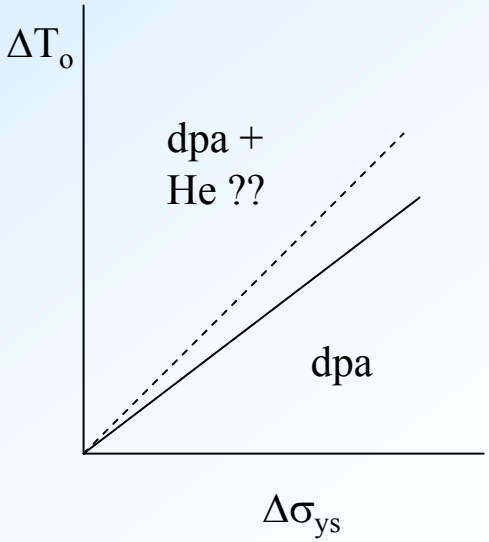


DFMB's

- Dynamic (impact) fracture toughness from 1.6x1.6x10 mm bend bars - the ultra-sharp transition facilitates comparative T_o assessments in single variable effects studies (e.g. He effects).

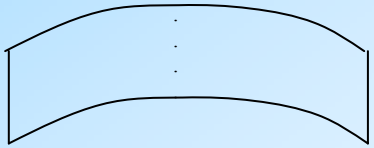






DFMB's

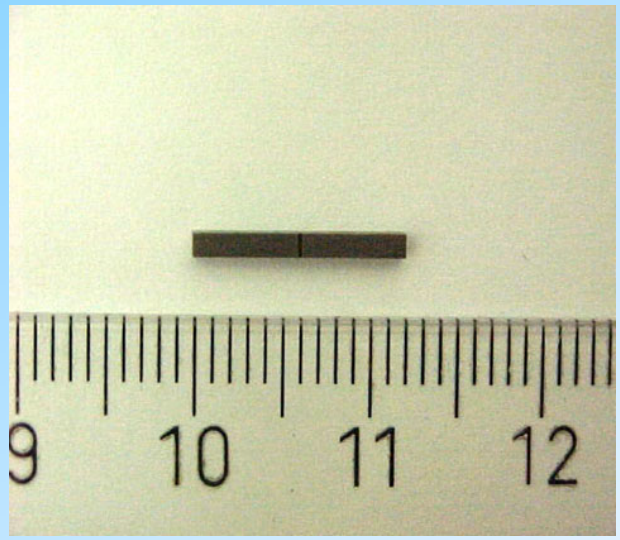
- DFMB's can be used as multipurpose specimens
  - » Deformation studies
    - Microhardness
    - Bent beam plasticity



  - » Microstructural characterization (SANS, TEP, SC…)

Subminiaturized Bend Bars

- Similar 1mm x 1mm bend bars have been readied for irradiation in PIREX
  - » He effects studies in a 590 MeV proton spectrum
  - » Small mass reduces beam heating

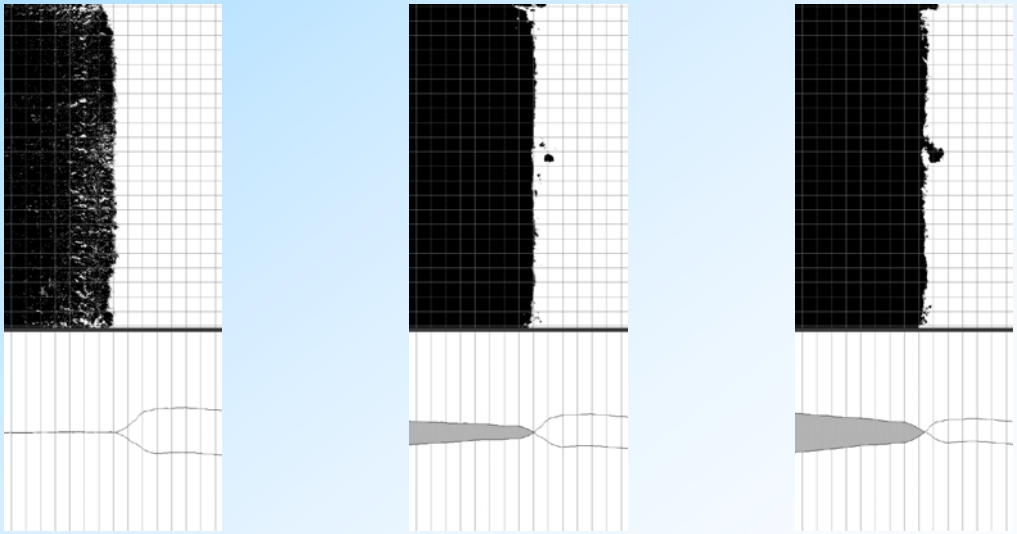


Courtesy, PSI

Ductile Fracture

- Work on irradiated V-4Cr-4Ti shows evidence of ductile tearing -- shear band decohesion
- Requires more extensive investigation using SSTT, CMFR, modeling

$\delta = 0\ \mu m$ 60 μm 150 μm



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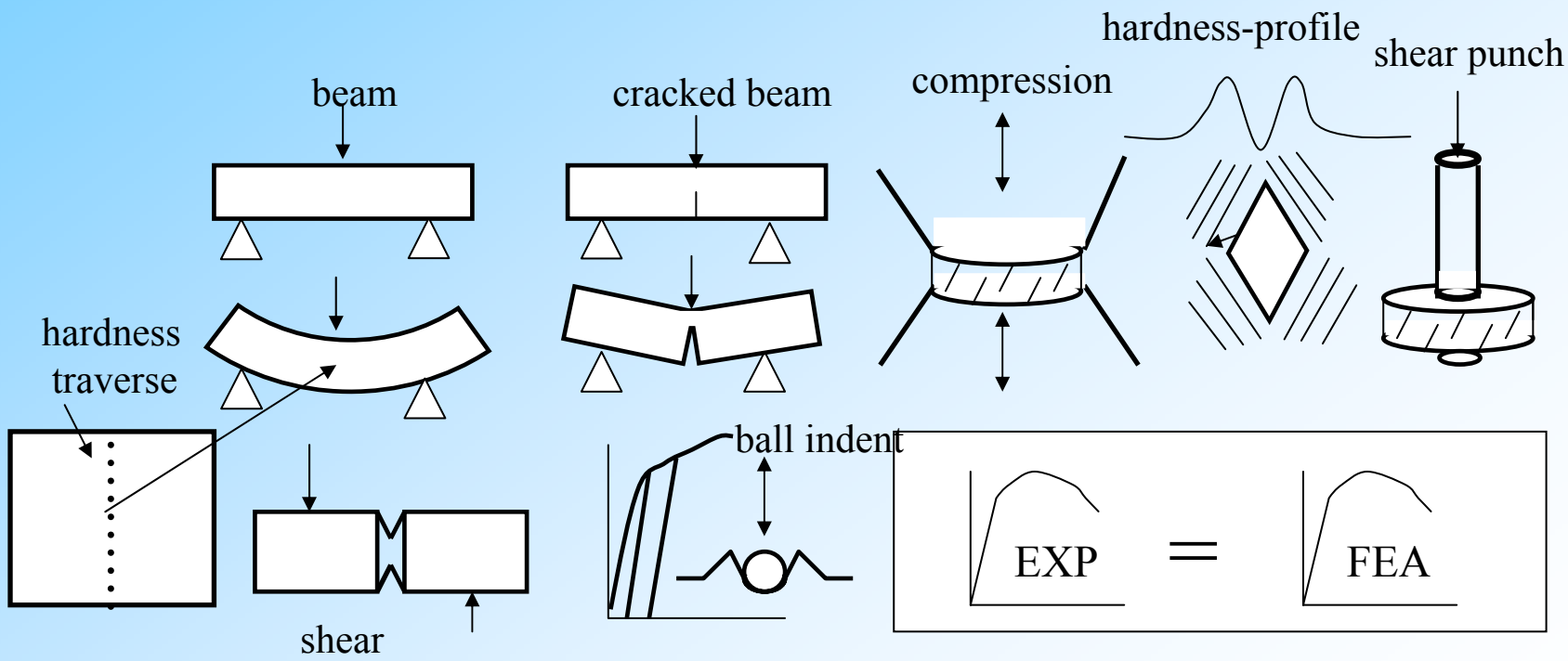
Deformation

- A variety of techniques have been developed and applied to determine various flow properties of irradiated materials:
  - » Miniaturized tensile specimens (useful for $\sigma(\varepsilon,\varepsilon',T)$)
  - » Spherical Punch tests (complex deformation history)
  - » Shear Punch tests (complex fields)
  - » Microhardness, instrumented microhardness,…

- Ongoing work to extend and automate techniques

Alternate Deformation Geometry

- Real opportunities to develop specimens for multi-axial stress and alternate flow geometry -- combine with FE modeling



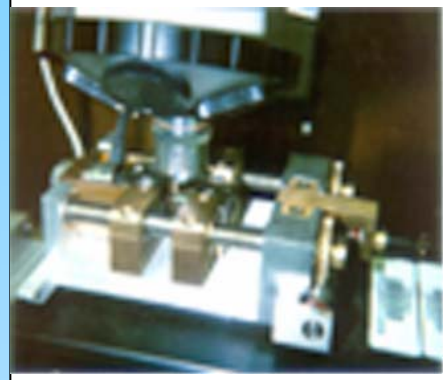
Odette et. all

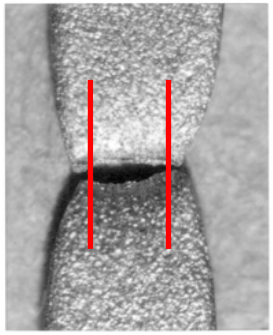
Examples of Combining FEA with Deformation Experiments

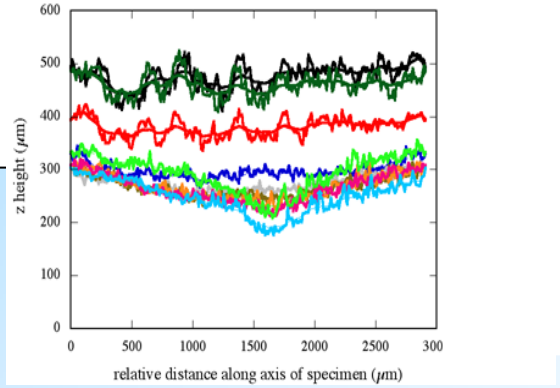
- Minitensile strain history
  - » Track multiaxial strain with CM
  - » Compare to FEA simulations (see Odette later)
- FEA of cone and ball hardness tests
  - » Combine pile up geometry with P-Δ to obtain yield stress
  - » Examine yield/flow stress -- hardness relation
  - » Need to develop capabilities for
    - A range of temperatures and loading rates
    - Semi-automated procedures

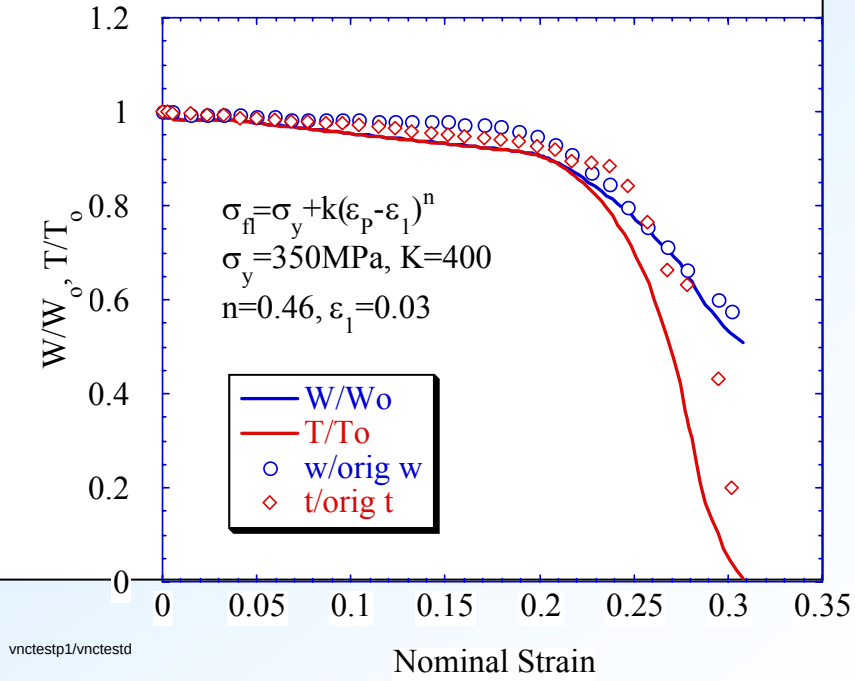
Characterization of Necking Strains

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





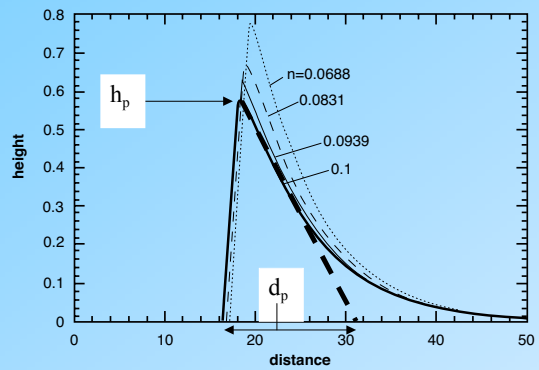




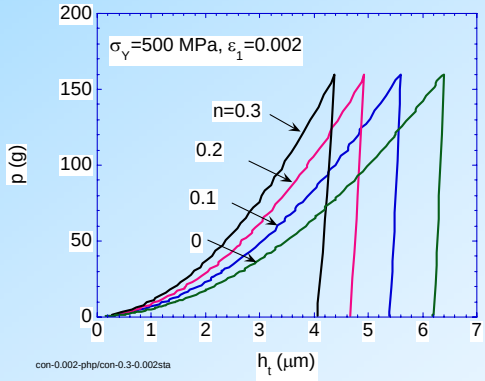
vnctestp1/vnctestd

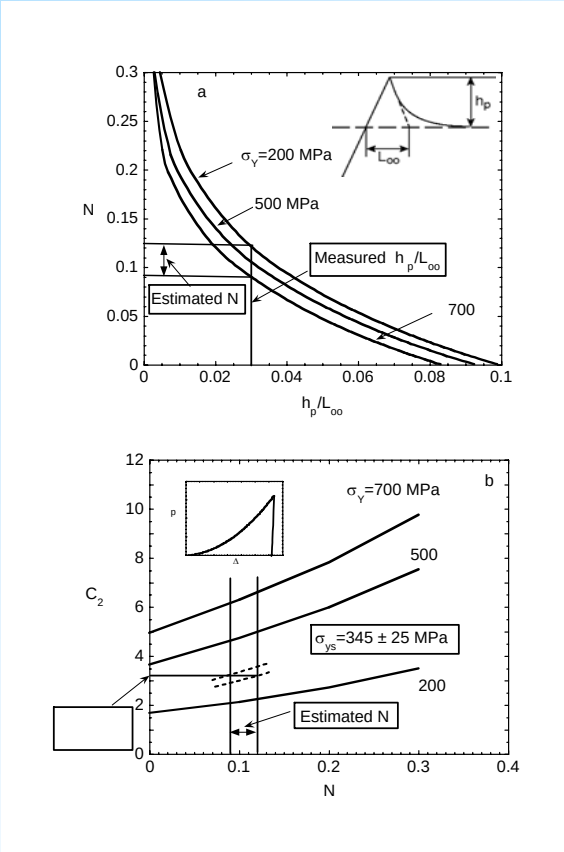
Combined h_p/d_p - P-h_t Method

- New iterative procedure to evaluate σ_{ys} [and $\sigma(\varepsilon)$] from combination of pile-up geometry <u>and</u> P-d_t



$$\sigma(\varepsilon) = \sigma_o(\varepsilon/\varepsilon_o)^n$$

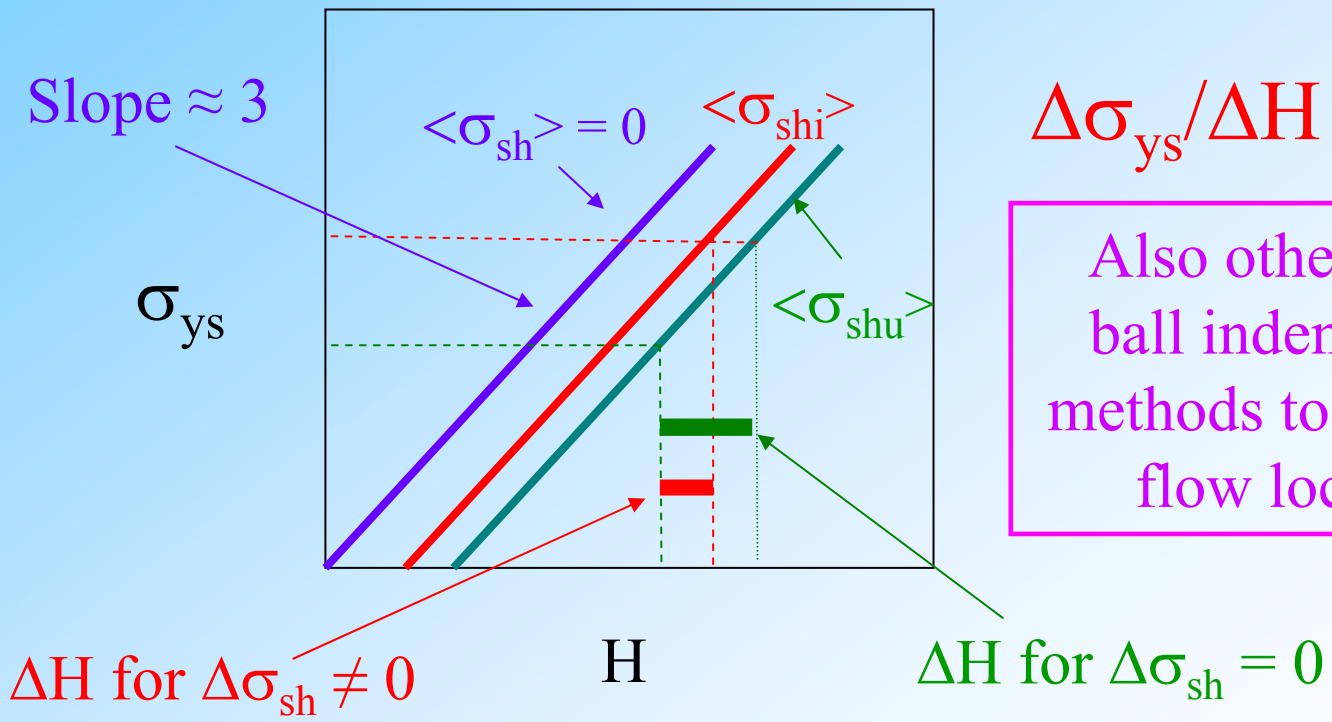




He et alIcFRM 10

Hardness -- Flow Stress Relations

- Enormous opportunity for aggressive development and application of advanced hardness methods



$$\Delta\sigma_{ys}/\Delta H = f(\Delta\sigma_{sh})$$

Also other advanced ball indentation and methods to characterize flow localization

Odette et. al.

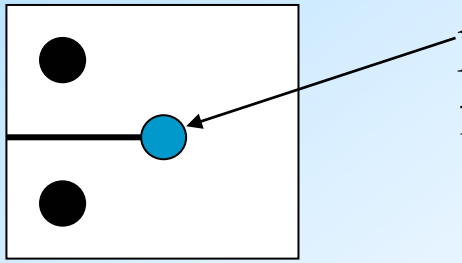
$$\sigma(\varepsilon) = \sigma_{ys} + \sigma_{sh}(\varepsilon) \quad \text{(Zerelli-Armstrong-Voce)}$$

Future Opportunities

- Experimental verification, semi-automated implementation of advanced hardness methods including temperature and rate dependence
- Apply multiple techniques to a given sample geometry -- e.g., SPT, or multipurpose coupons for basic studies (SANS, μH, PIA, TEM,…)
- Use arrays of small specimens in combination with automated testing -- e.g., combinatorial chemistry approach to alloy development
- Apply techniques to examine property evolution during processing

Composite Specimens

- Composite specimens offer approaches to testing limited quantities of materials
- Example -- diffusion bond + Q&T ^{54}Fe TMS alloy wire for studying effects of He on fracture behavior



process zone occupied by wire from few grams of ^{54}Fe

Odette, ICFRM-10d

Other Multipurpose Approaches

- Combine semi -non destructive mechanical property (e.g., hardness) and/or microstructural (e.g., TEP, resistivity…) techniques with post-irradiation annealing
- Successful in RPV research in characterizing defect populations