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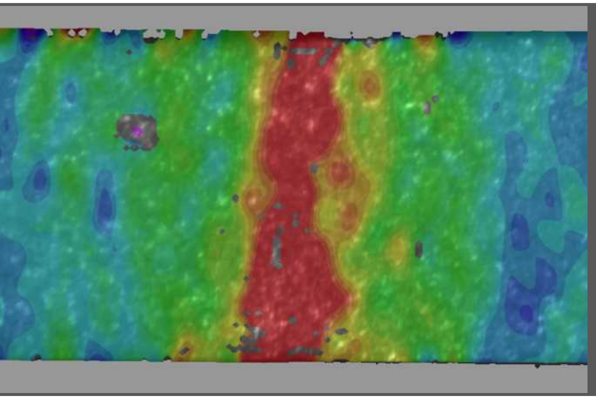

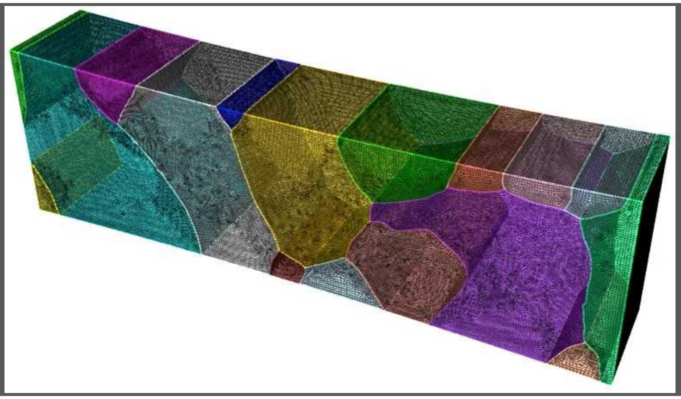

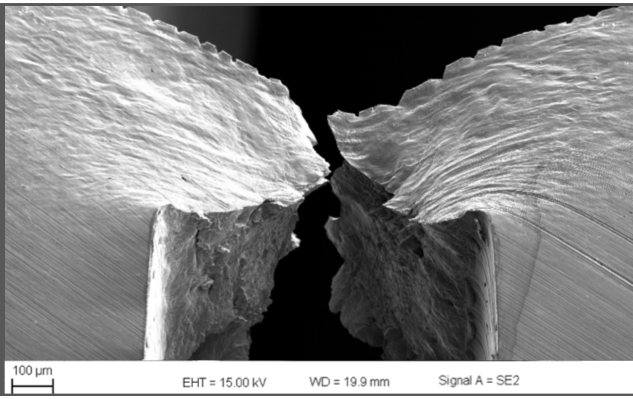

Task 2 Highlight: Damage Nucleation in Ta

Blythe G. Clark, Hojun Lim, Jay Carroll, Corbett Battaile

December 8th, 2014 • PPM Summit • Albuquerque, NM

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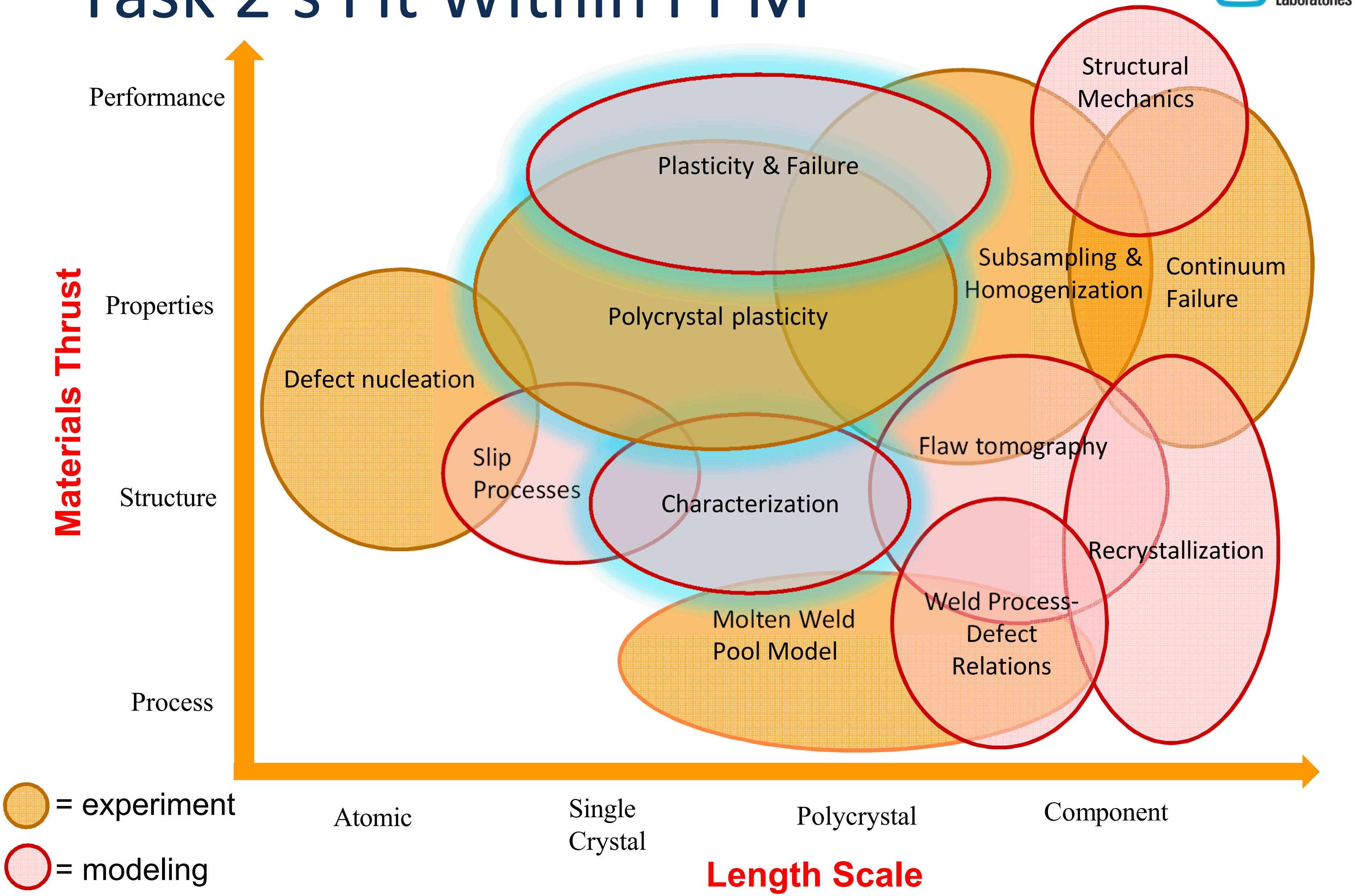
Task 2's Fit Within PPM



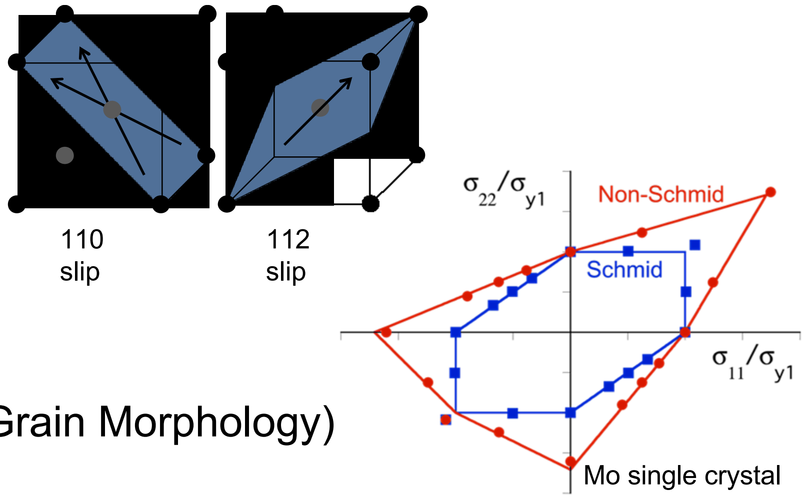
FY14 Focus Areas and Successes

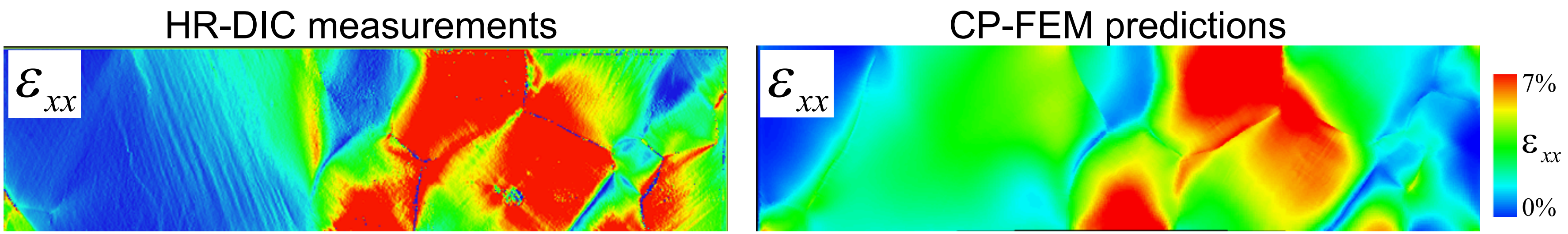
- Microstructural Variability
- Multiscale Simulation Arc in BCC Metals
- Single and Oligo Crystal Experiments
- Quantitative Model via Experimental Comparisons
- Grain Rotation Measurements
- Temperature and Strain Rate Dependence
- **Damage in Ta**

Goal: To understand the nucleation and accumulation of damage in Ta to optimize the inclusion of damage in our CP-FEM model

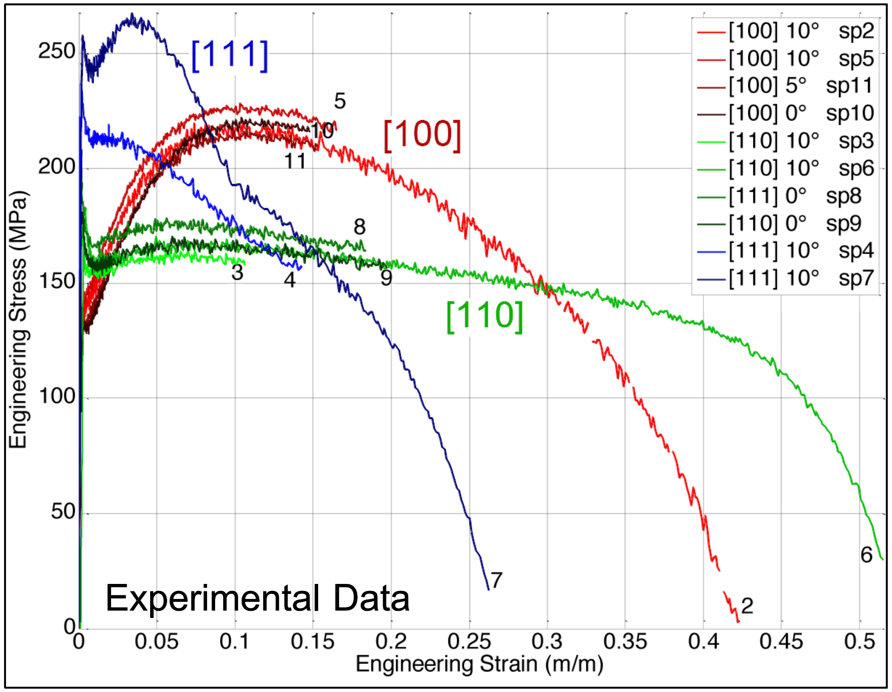
CP-FEM for BCC Metals

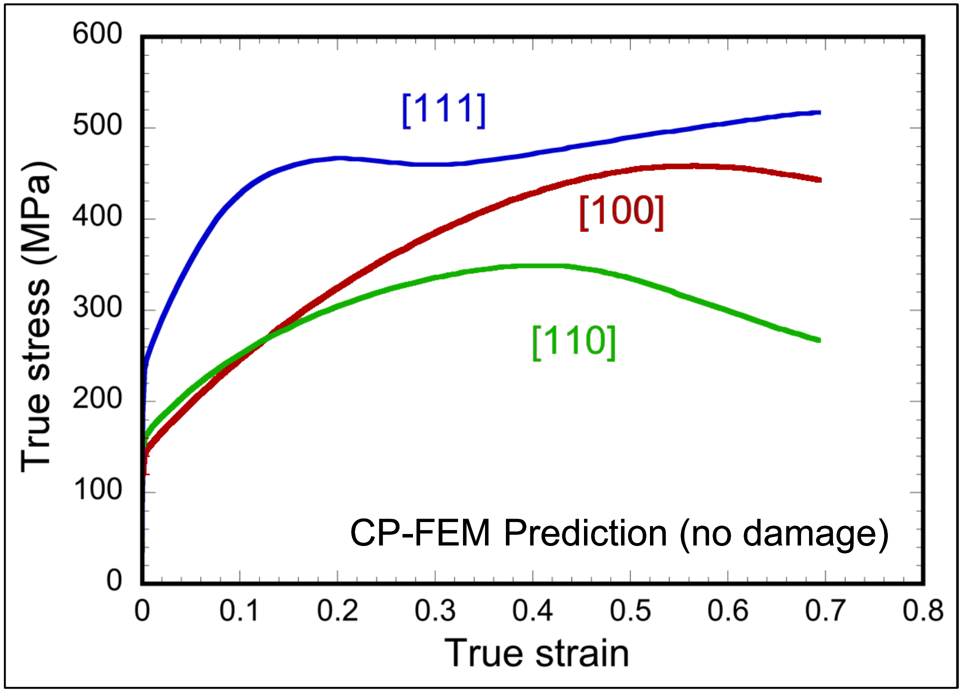
- Crystal Plasticity Finite Element Modeling
- FEM code developed at Sandia (JAS-3D)
- For BCC: 24 {110}<111> slip systems
- Advantages:
  - Realistic Length and Time Scales
  - Considers Microstructural Variability (e.g. Grain Morphology)
- Predicts:
  - Macroscopic Stress-Strain Response
  - Localized Stress/Strain Field Distributions
  - Texture Evolution

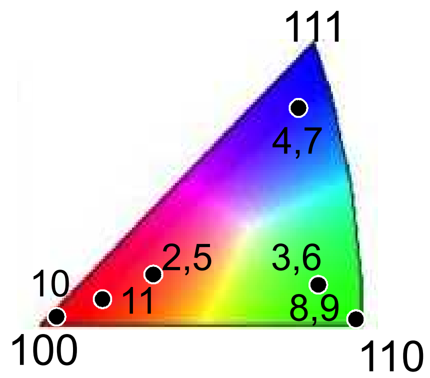




Including Damage in CP-FEM







Without including damage:

- No softening occurs other than necking
- The material does not "degrade" (e.g. voids, crack, tearing)
- Stress-strain response does not match experiments

Getting the Damage “Right”

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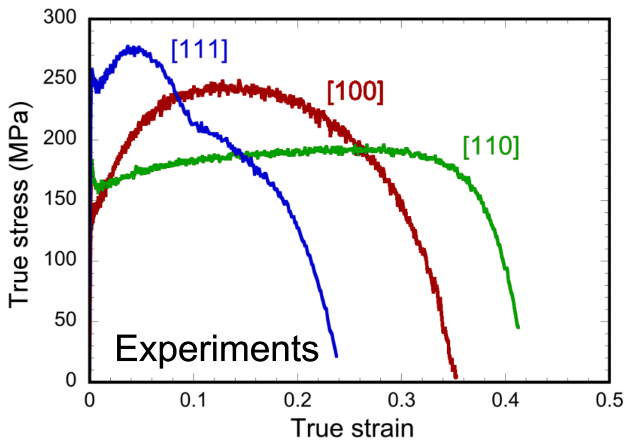


*Metrics for Microstructurally Small Fatigue Crack (MSFC)**

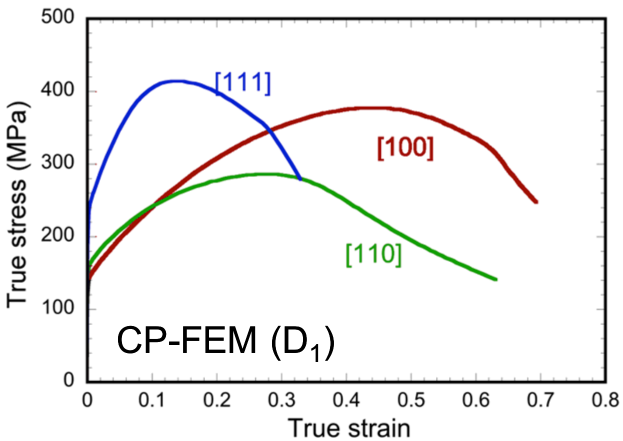
$$D_1 = \max_{\alpha} \int_0^t \left|\dot{\gamma}^{\alpha}\right| dt$$ (Max. accumulated slip over each slip system)

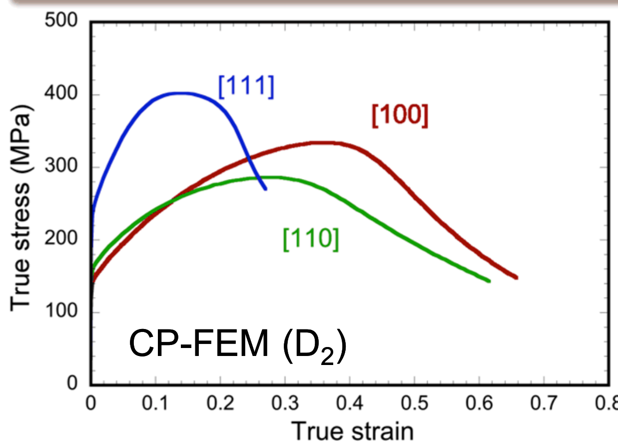
$$D_2 = \max_{p} \int_0^t \left|\dot{\gamma}^{p}\right| dt$$ (Max. accumulated slip over each slip plane)

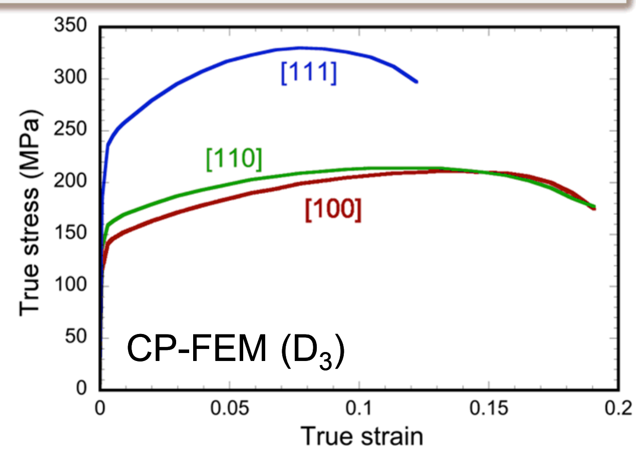
$$D_3 = \sum_{\alpha=0}^{N} \int_0^t \left|\dot{\gamma}^{\alpha}\right| dt$$ (Total accumulated slip over each slip system)

“Accumulated slip”

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0^{\alpha} \left(\frac{\tau^{\alpha}}{(1 - D_i) g^{\alpha}} \right)^{1/m}$$







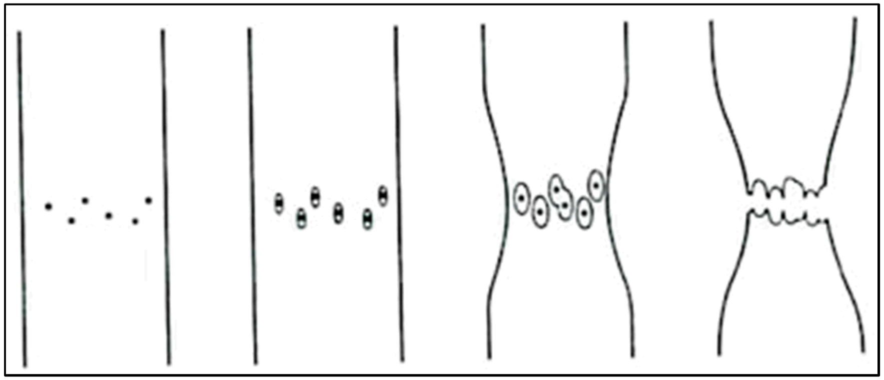
What controls the initiation of damage in Ta?
How can we better understand how damage nucleates and accumulates?

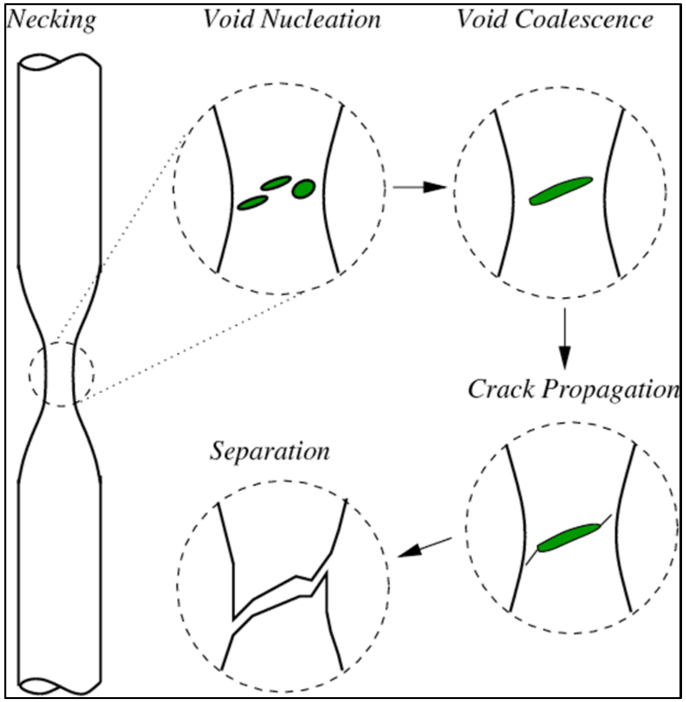
*J. D. Hochhalter et al., *Modelling Simul. Mater. Sci. Eng.*, 2010. v.18, 045004

Void-Dominated Ductile Fracture

- Initiation of voids through decohesion at second-phase particles or inclusions
- Voids continue to grow in response to high stresses
- Eventual coalescence of voids, leading to failure
- *In this study, 99.9% Ta used showed no evidence of second-phases or inclusions via SEM or TEM*

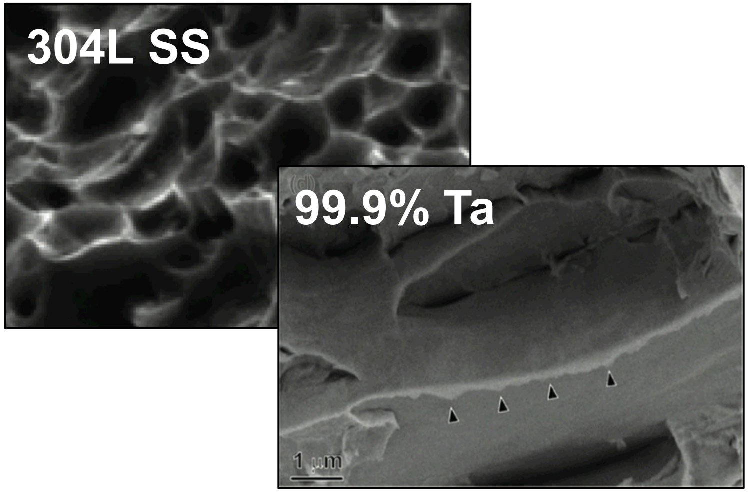
How do voids initiate in a pure metal?

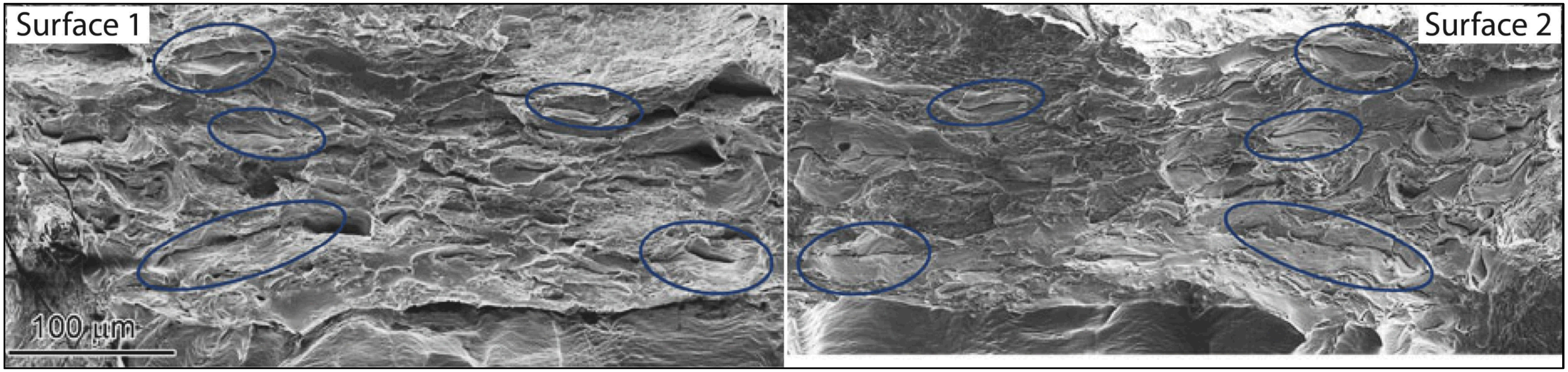




Void Formation in 99.9%Ta

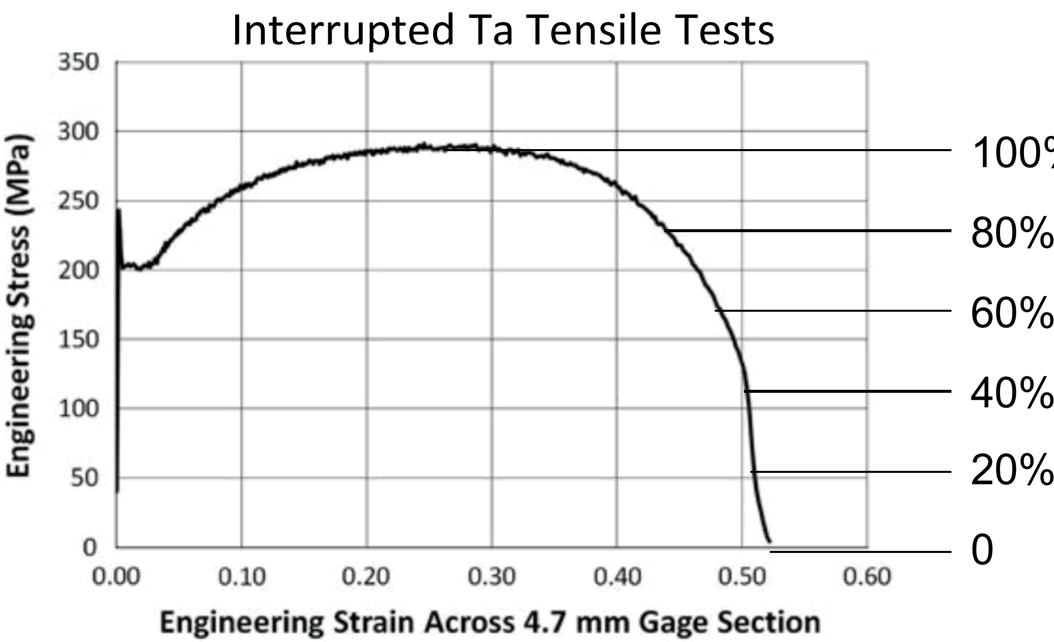
- Ta exhibits significant ductility, but with valley/ridge fracture surface
  → no 'classic' hemispherical dimpling
- Mating surfaces are mirrored
  → with no evidence of cup-cone



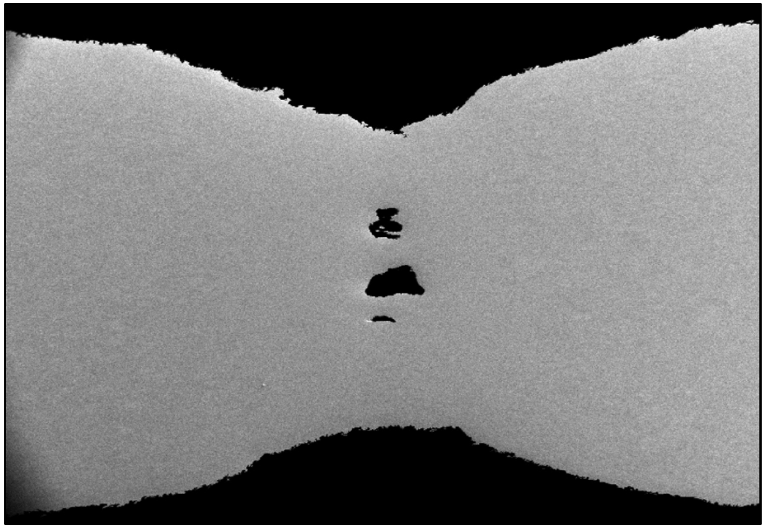


What role does local microstructure play in void initiation and growth?

Void Formation in 99.9%Ta

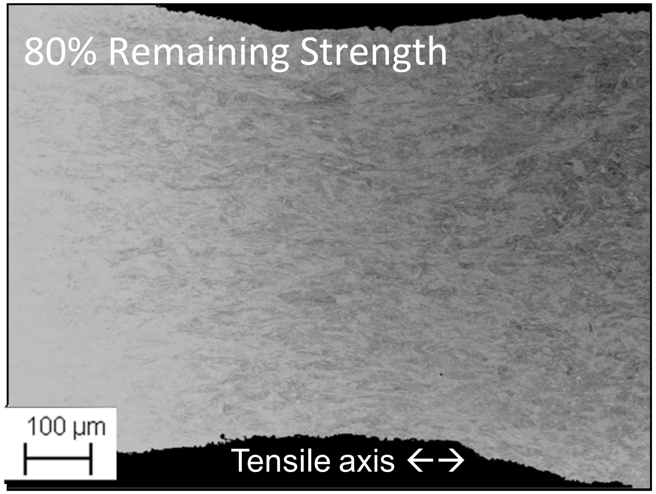


Deformed Ta samples polished to mid-plane to investigate local microstructure in voided regions

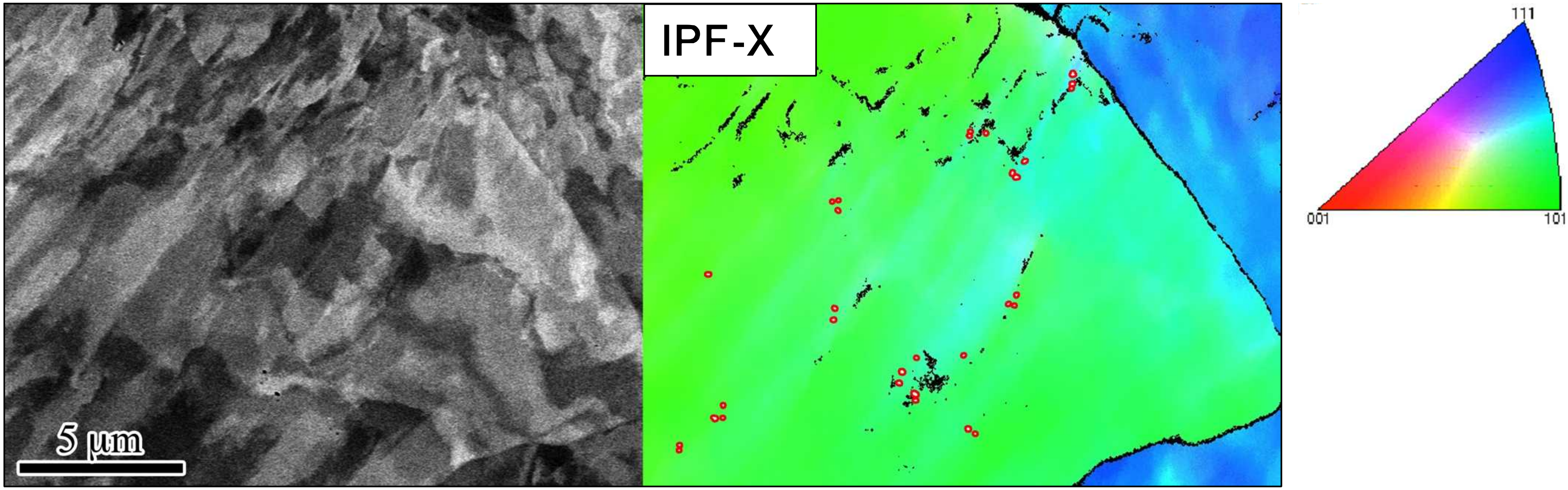


Ta tensile bar deformed at $5x10^{-3}$ to 40% remaining strength and polished to mid-plane for void analysis

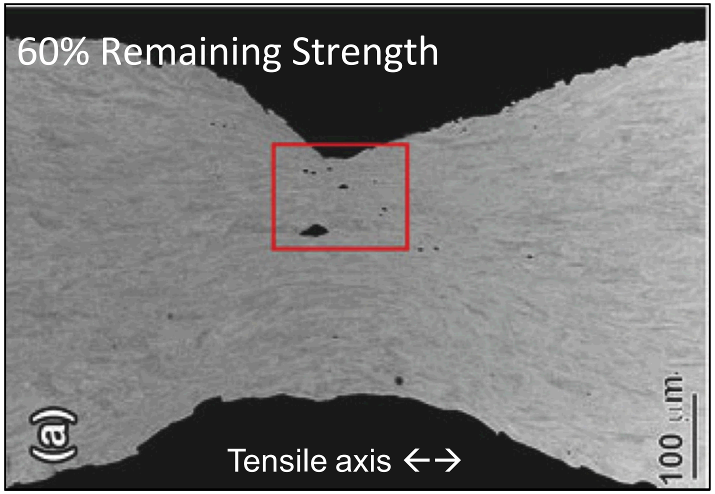
Void Formation in 99.9%Ta



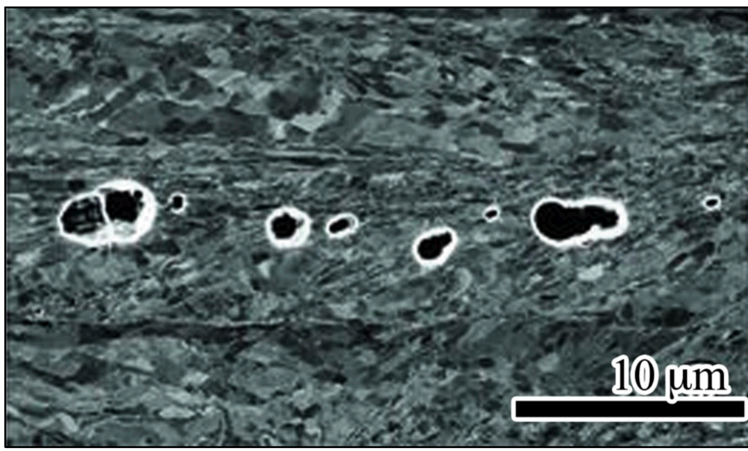
- Sample has begun to neck
- No large voids observed
- EBSD shows scattered small voids (30-100 nm) near bands of [122] / [110] aligned with tensile axis

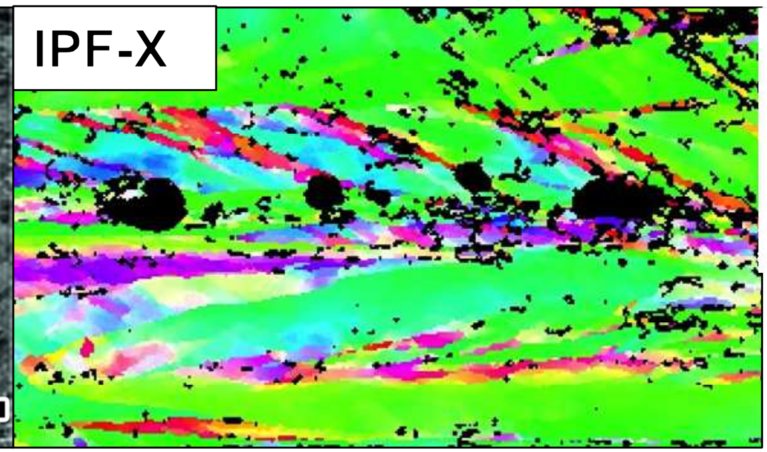


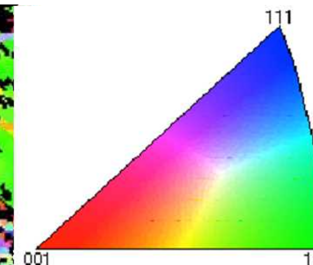
Void Formation in 99.9%Ta



- Arrays of voids aligned along tensile axis
- EBSD shows elongated, inclined [001] subgrains associated with each void
- Alternating regions of [122] indicates high angle GBs







Ta failure is void-driven, with deformation-induced microstructural changes and stress state controlling the initiation/growth of voids

Conclusions

- 99.9% pure Ta is ductile, but does not exhibit a ‘classic’ ductile fracture surface (i.e. hemispherical dimples)
  → but, fracture surface still indicates void-driven failure
- Voids in interrupted tensile test specimens were analyzed by SEM and EBSD
  → voids prevalent in regions of high misorientation
- No inclusions or second-phases observed via SEM or TEM
  → void initiation likely at dislocation junctions / sub-boundaries

Failure mechanism of Ta is void-driven, with deformation-induced microstructural changes and stress state controlling the initiation and growth of voids