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Understanding The Role Of Microstructure in Microplasticity

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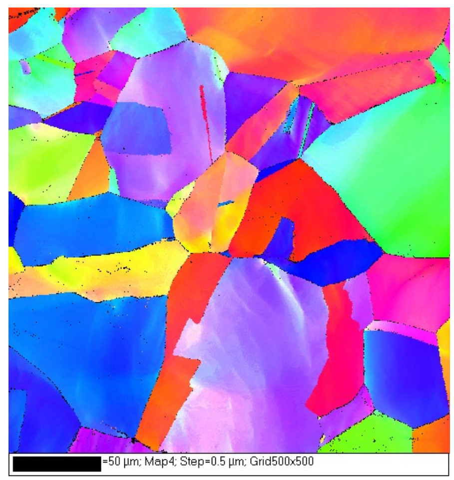

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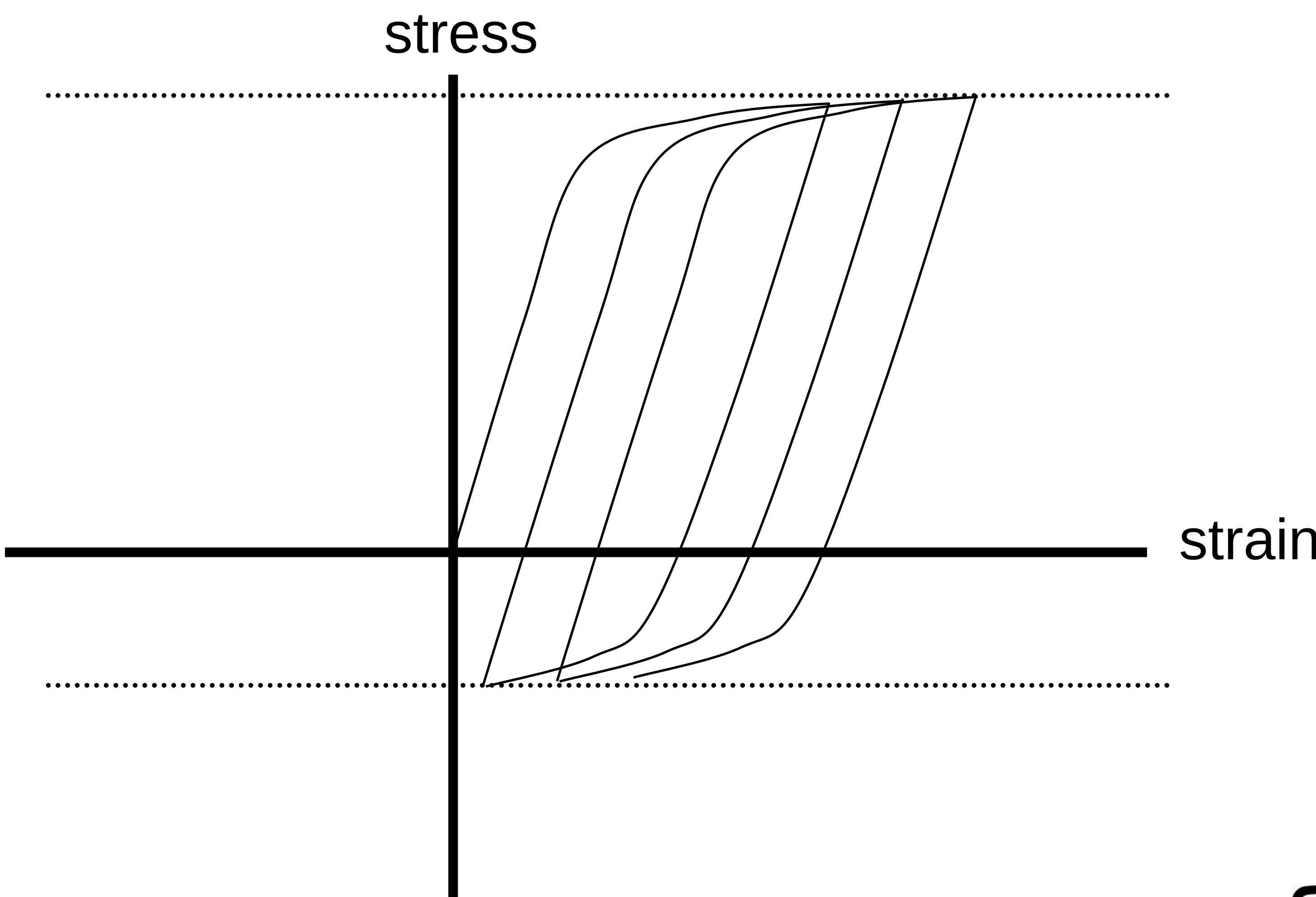
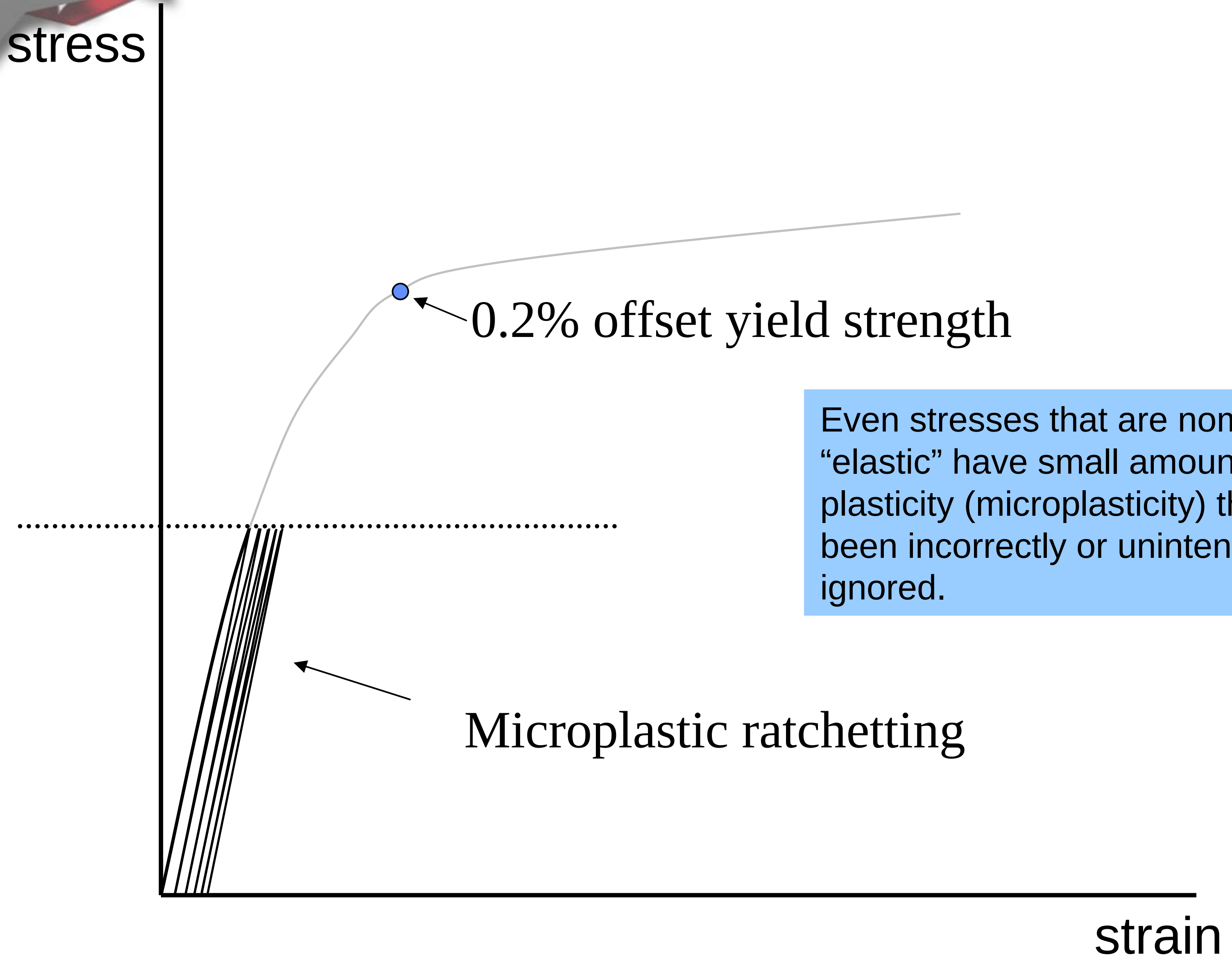
Conventional (Macroplastic) "Ratcheting" or "Cyclic Creep"



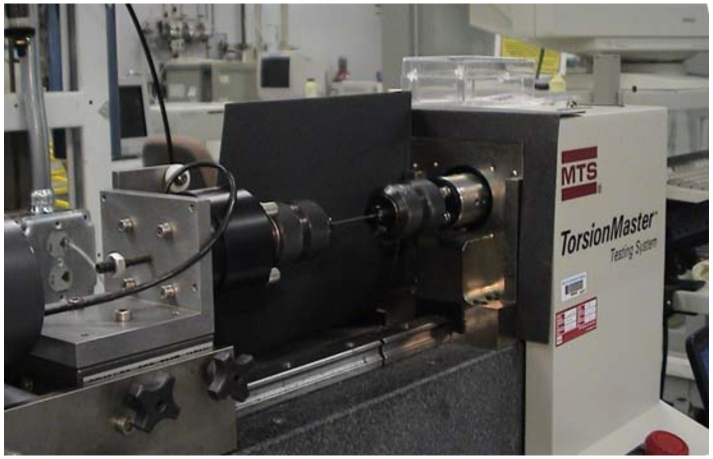
Microplasticity + Ratcheting

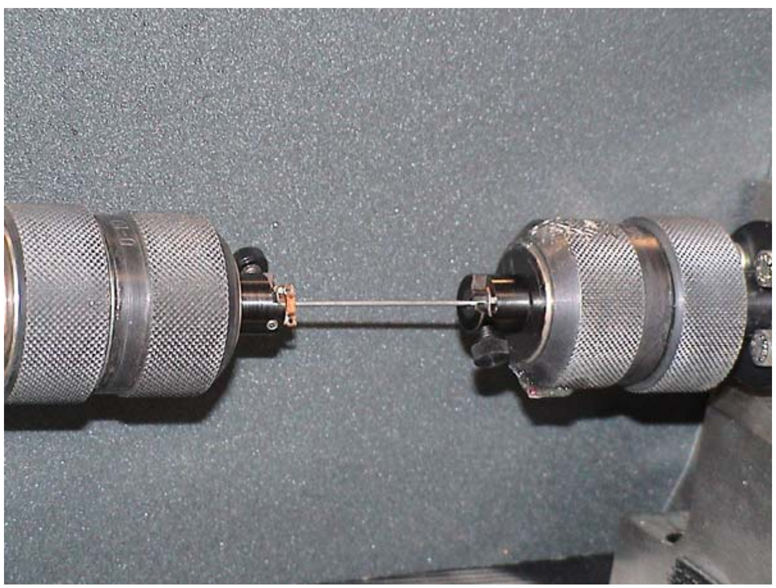


Even stresses that are nominally "elastic" have small amounts of plasticity (microplasticity) that has been incorrectly or unintentionally ignored.

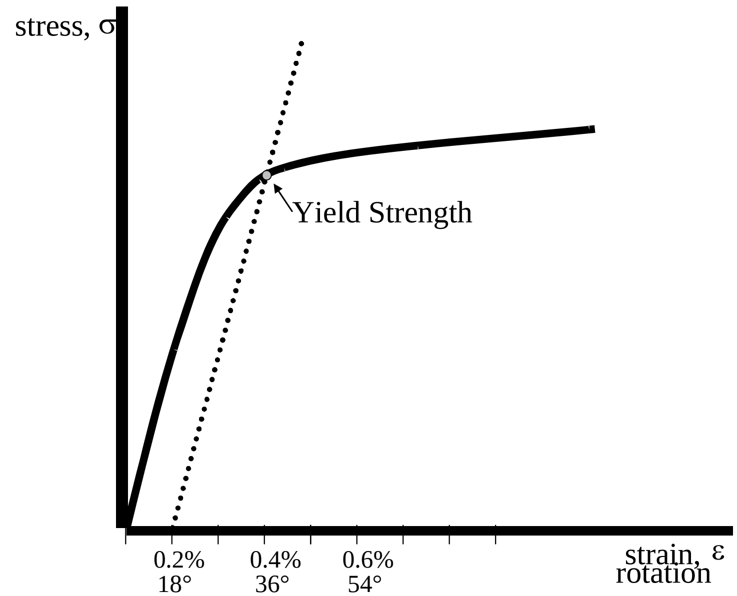
A similar effect is observed when residual stresses are relieved during cycling, leading to a phenomena known as "elastic shakedown"

A thin rod in torsion is very sensitive to small strains





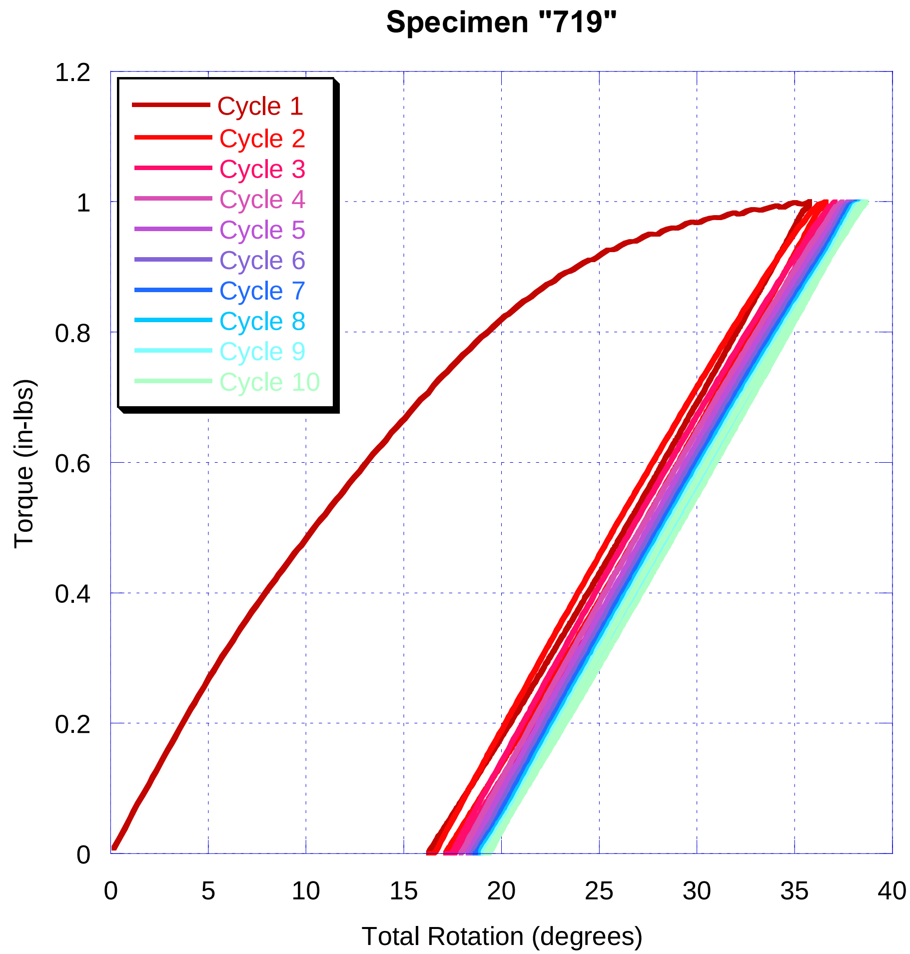
Consider a torsional rod 50 mm long and 1 mm in diameter



$$\varepsilon = 0.2\% = 0.002 \Rightarrow \gamma = 0.004 = \frac{r\phi}{L}$$

$$\Rightarrow \phi = \frac{\gamma L}{r} = \frac{(2.0)(0.004)}{0.025} = 0.32 radians = 18.3°$$

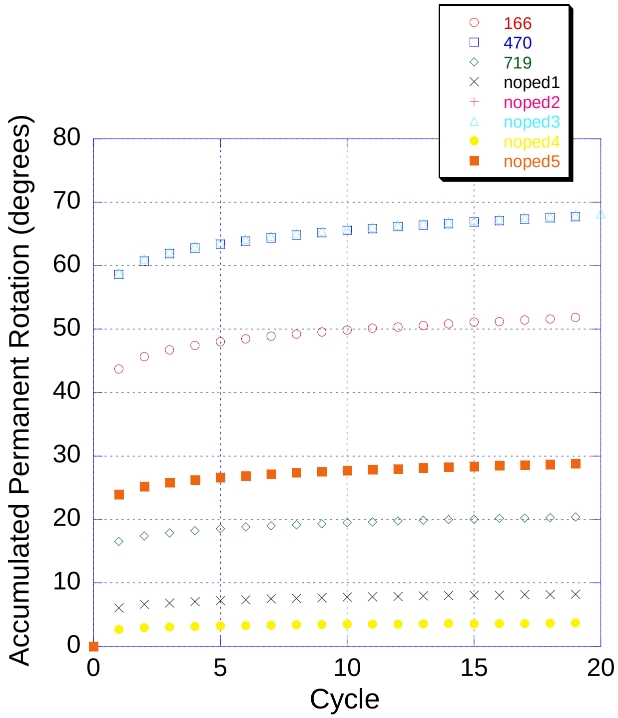
An Example of Microplastic Ratcheting in a Torsional Rod of 304L Stainless Steel



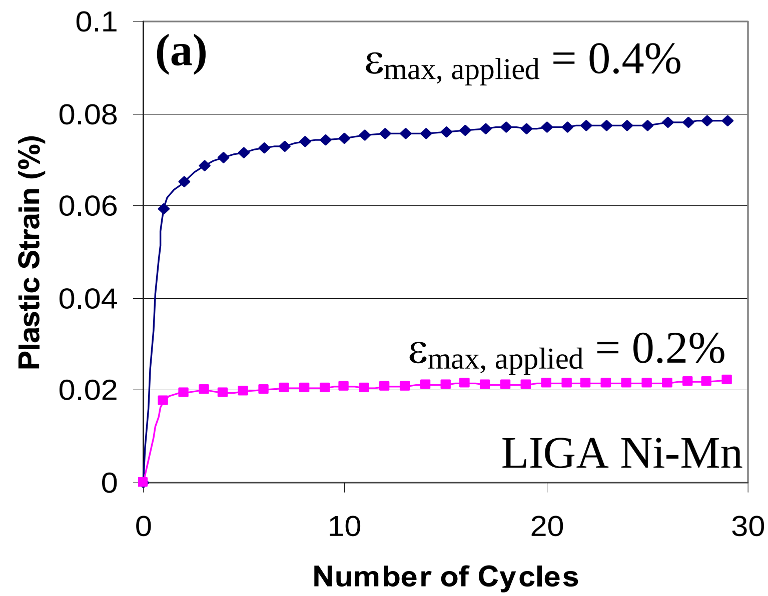
These stresses were below the material's nominal 0.2% offset yield strength, yet extensive microplasticity and cycle-induced ratcheting are observed, resulting in large amounts of unpredicted deformation (twist in this case).

Experimentally Observed Ratcheting Trajectories

304L Stainless Steel



Electroplated Ni-Mn Alloy



While conventional ratcheting phenomena are thought to be related to macro plasticity and Bauschinger effects, the origins of microplastic ratcheting are unknown. Neither can be captured well in existing continuum material models.

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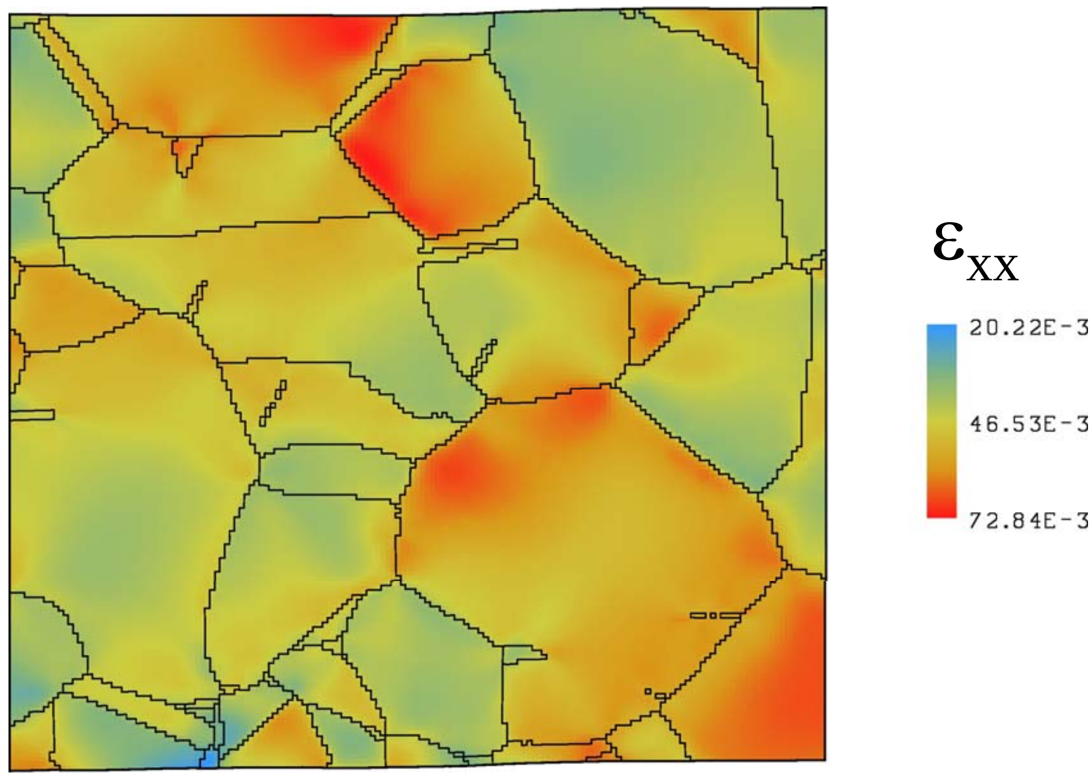
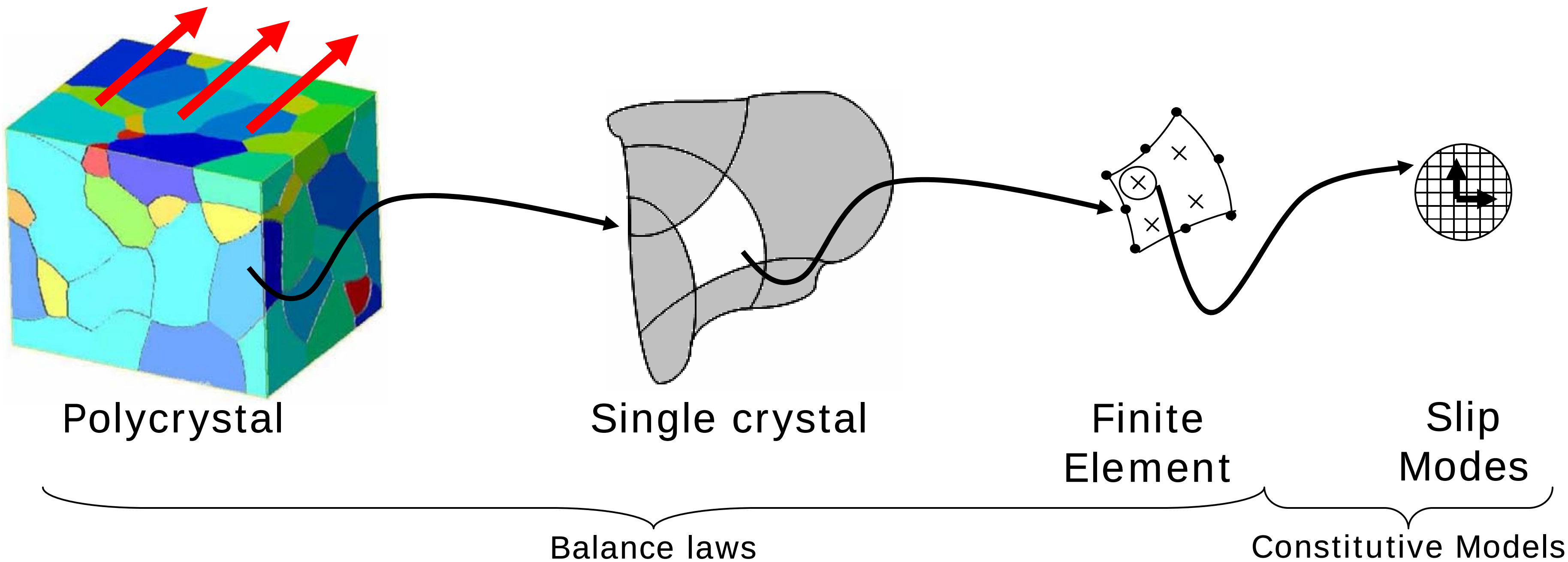
Microstructural Origins



Preliminary polycrystal plasticity modeling suggests that elasto-plastic anisotropy in the polycrystalline microstructure could cause local yielding and subsequent ratchetting well below the macroscopic yield strength.

Can Crystal Plasticity Modeling Explain the Microplastic Ratcheting Phenomenon?

- **Crystal plasticity =** Grain-level (mesoscale) approach **to materials modeling using multiscale strategies**
- **Explicitly model** discrete **grains and slip systems (anisotropy, texture evolution,…)**



Conventional Crystal Plasticity Formulation

Kinematics $\mathbf{L}^p = \dot{\mathbf{F}}^p \mathbf{F}^{p^{-1}} = \sum_{a=1}^{N_{sys}} \dot{\gamma}^a \left(\bar{\mathbf{s}}^a \otimes \bar{\mathbf{m}}^a \right)$

Elasticity $\sigma^{PK2} = \mathbf{C}^e : \tilde{\mathbf{E}}^e$

Slip evolution $\dot{\gamma}^\alpha = \dot{\gamma}_0 \left| \frac{\tau^a}{\tau^\alpha_{CRSS}} \right|^{1/m} \mathrm{sgn}\left(\tau^a\right)$

(Power law viscoplastic flow rule)

Hardening law $\tau^a_{CRSS} = C\mu b\sqrt{\rho^a}$

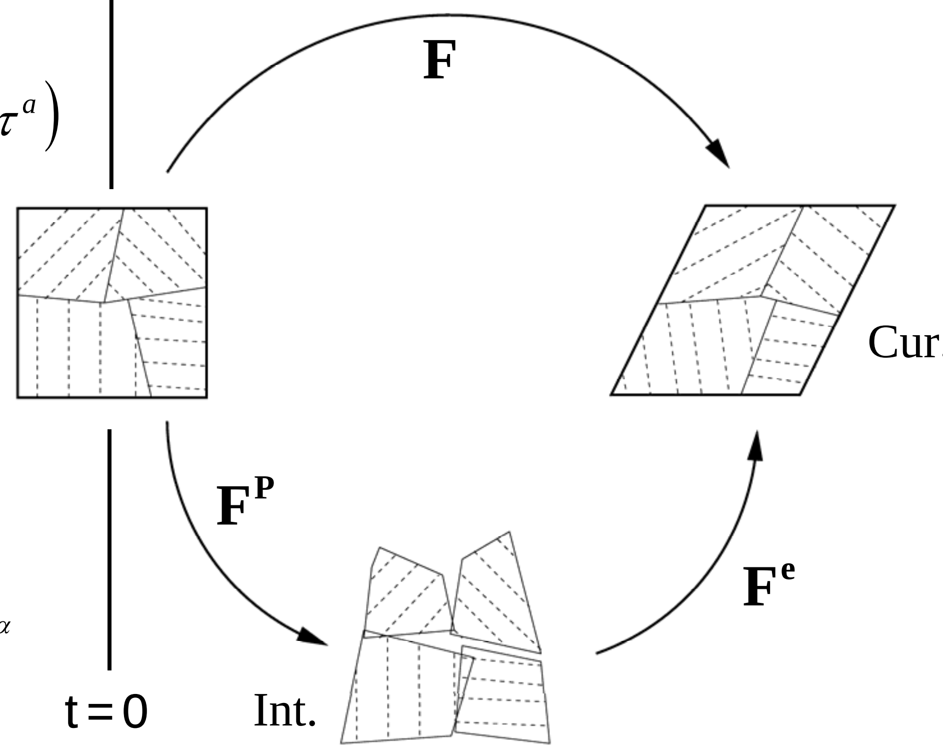
(Anisotropic Taylor hardening)

Dislocation density evolution

(Static and dynamic recovery)

$$\frac{\mathrm{d}\rho^\alpha}{\mathrm{d}\gamma^\alpha} = \mathrm{c}_1\sqrt{\rho^\alpha} - \mathrm{c}_2\, \rho^\alpha$$

Conventional kinematics describe the deformation, starting from a reference polycrystal



[J.W. Hutchinson, (1970) "Elastic-plastic behaviour of polycrystalline metals and composites", Proc. Roy. Soc. Lon., 319 p.247]
[Estrin and Mecking, *Acta Met.* 32 (1984) p.57]

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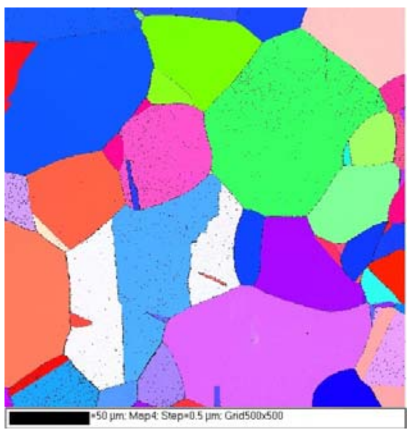
Direct Coupling Between Experiments and Models to Assess Validity

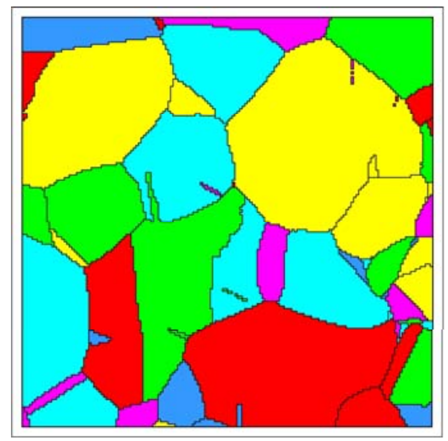
Experimental

- Annealed Ni (99.9%) polycrystal
- Interrupted tensile tests
  0%, 1%, 5%, 10% strain
- EBSD* data @ same location
  - Zeiss Supra 55VP-FEG SEM
  - 20keV, 0.5μm steps, 500x500
  - 3 areas on 3 tensile samples



Numerical simulation

- Initial microstructure meshed from EBSD map
- Local / Non-local models to 10% strain
- Periodic boundary conditions
  : columnar structure



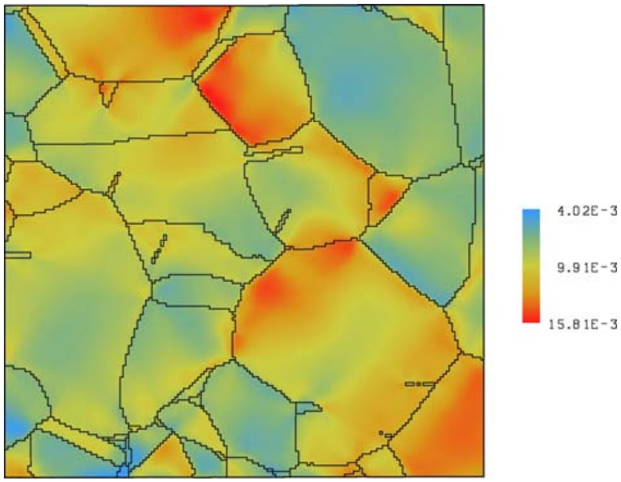
Directly compare the sub-microstructural grain rotations and the sub-microstructural strain tensor.

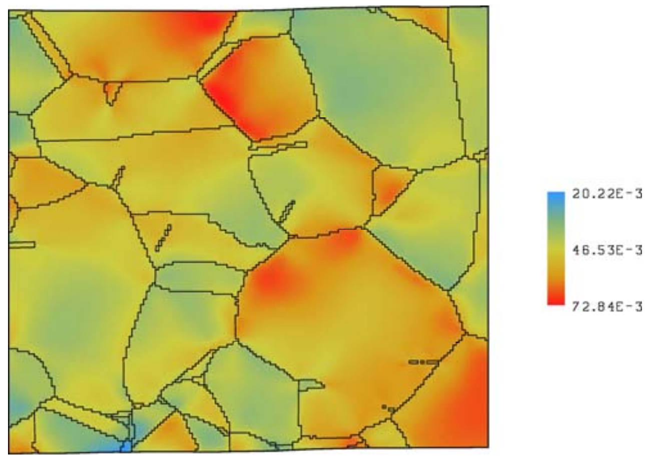
***Electron backscattered diffraction**

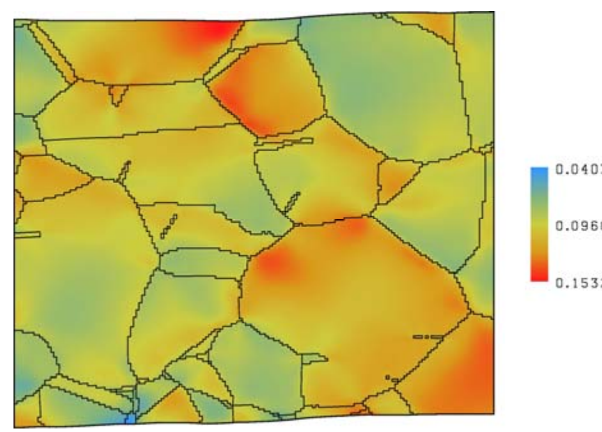
Simulation Results: Strain (Local Model-ε_{xx})

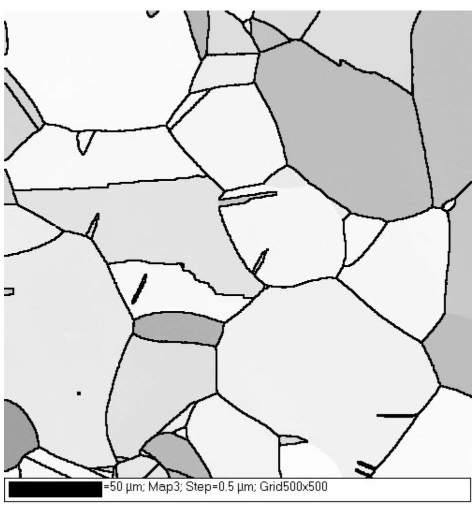
Average value is very close to applied strain.

Note the range of values from one grain orientation to another.









Schmid factor

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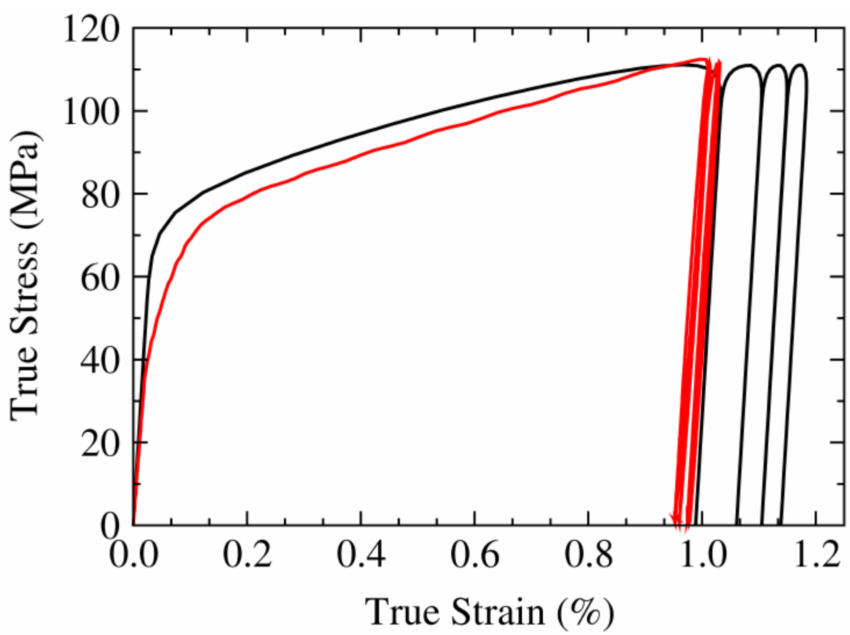
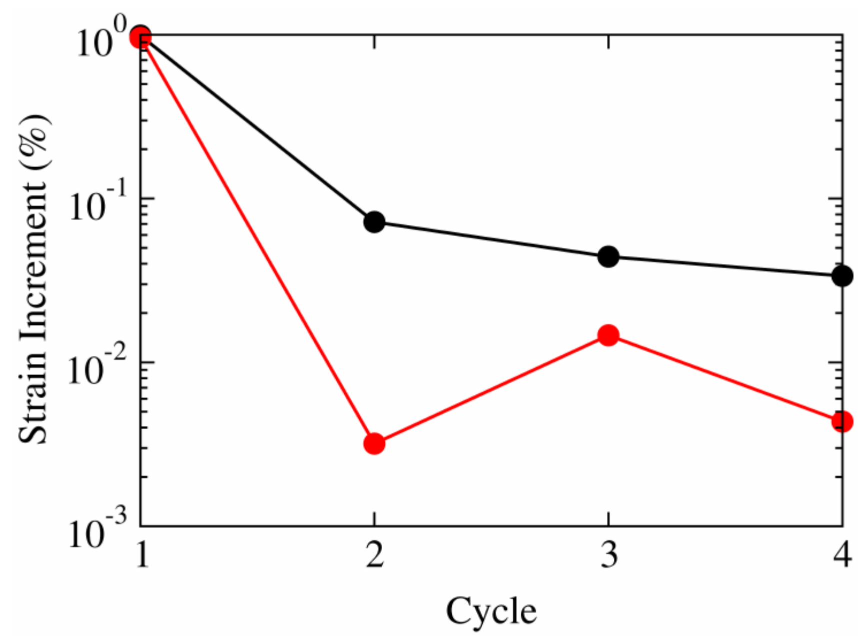
Ratcheting is predicted, but not quantitatively accurate





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We would like to compare the model to reality at the microstructural scale, where the "action" is…

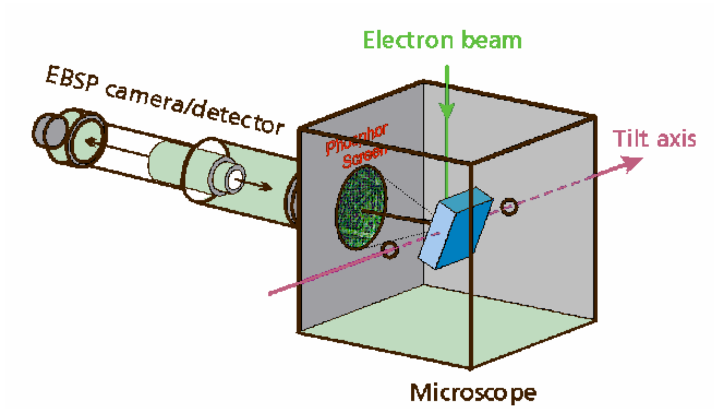
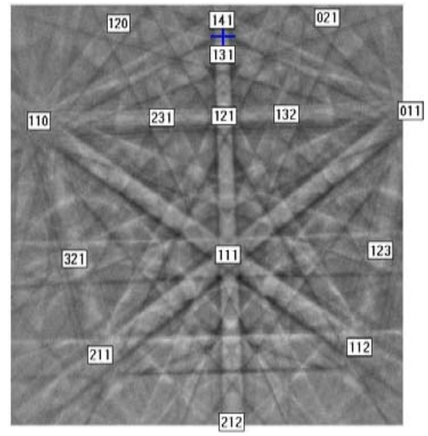
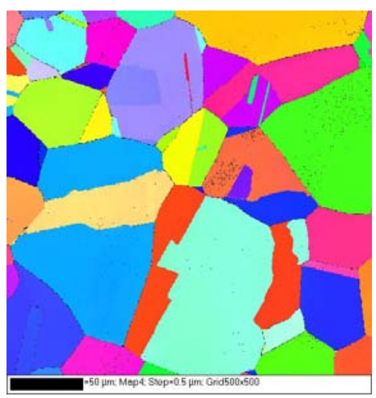


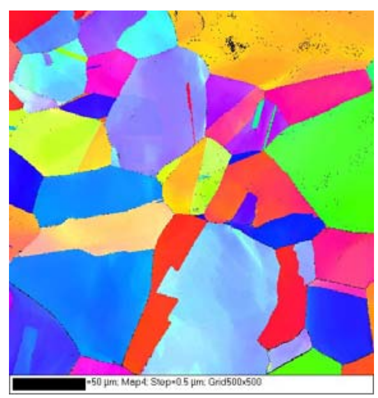
Figure courtesy of J. Sutliff



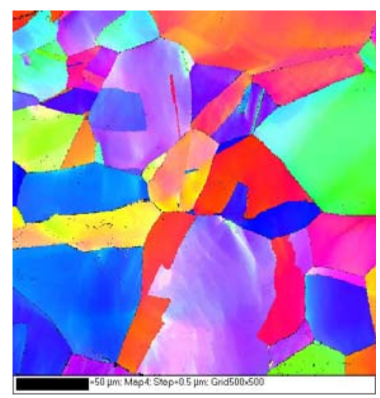
1% strain



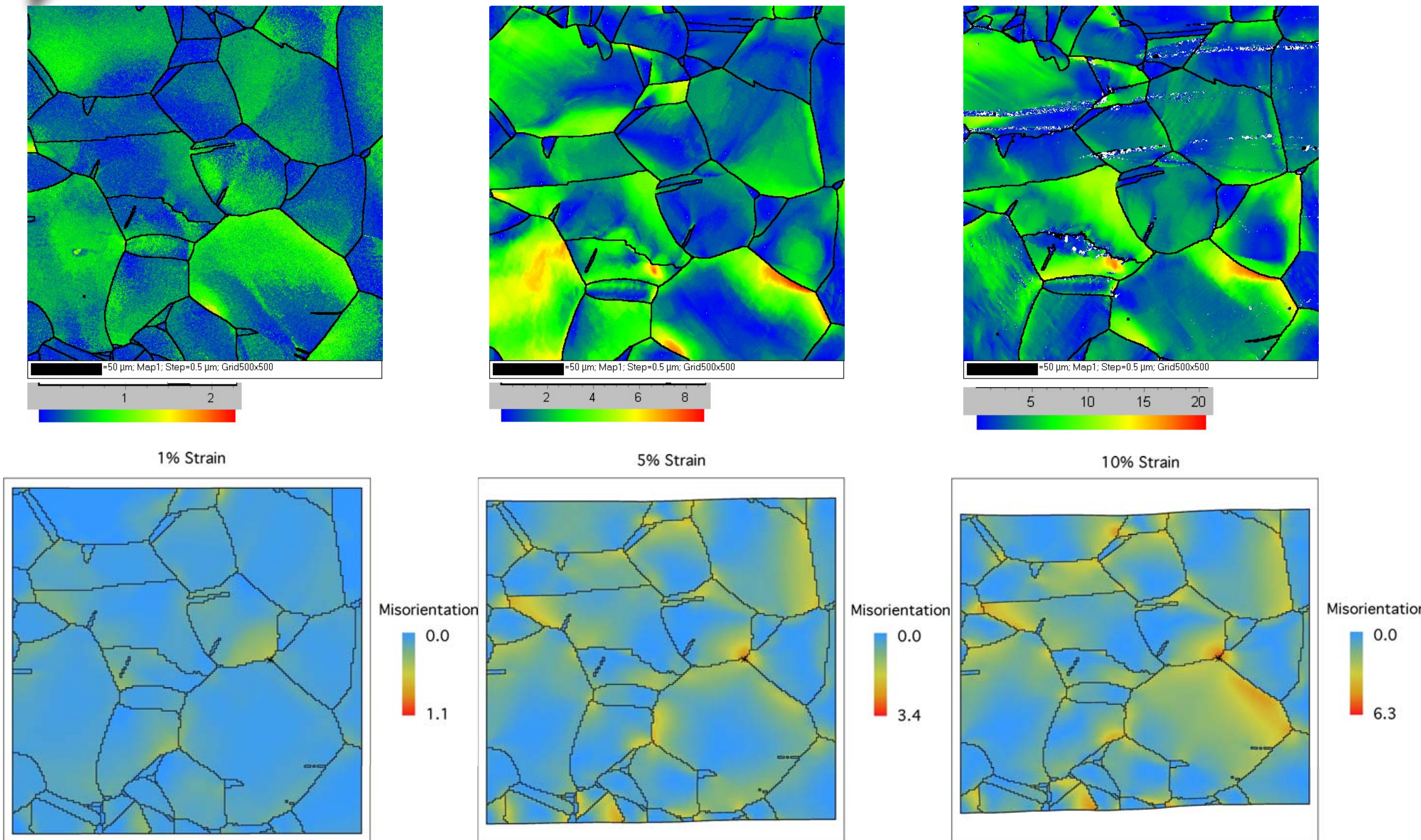
5% strain



10% strain



Comparison of Local Model and EBSD: Misorientation Distributions



Intragranuary Misorientation Parameter Described in: L.N. Brewer et al., Microscopy and Microanalysis, 2006

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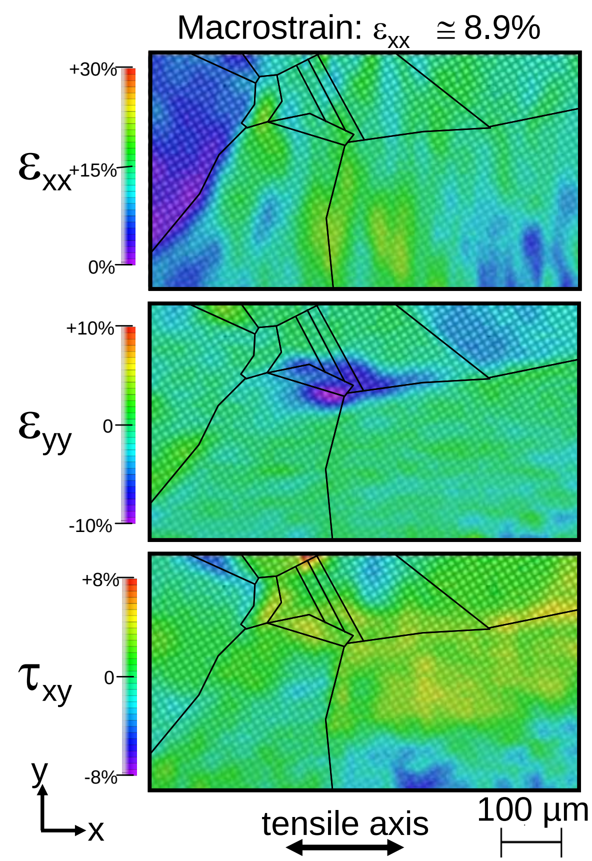
Potential Problems With This Conventional Polycrystal Plasticity Formulation…

1. **Aspects of the crystal plasticity formulation are not physically realistic or adequate.**
2. **Simplified isostrain or isoforce boundary condition on the edge of the region of interest. Model's volume is self-contained with free surfaces, where as experimental ROI is embedded in a deforming matrix.**
3. **Comparing a 3D experiment to a model based on 2D information.**



Conclusions

- Ratcheting can occur at the microplastic scale, where small strains are accumulated at stresses well below the yield strength.
- Microplastic ratcheting would not be observed in any continuum model.
- The origin of microplastic ratcheting is thought to be inhomogeneous microstructural stresses.
- A local polycrystal plasticity model produces cyclic strain accumulation, but severely overestimates the magnitude.

Where Do We Go From Here?

- A non-local polycrystal plasticity models are being developed and validated through direct comparison with experiments at the sub-microstructural scale.

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