Microstructural Stress/Strain Inhomogeneity in MMCs

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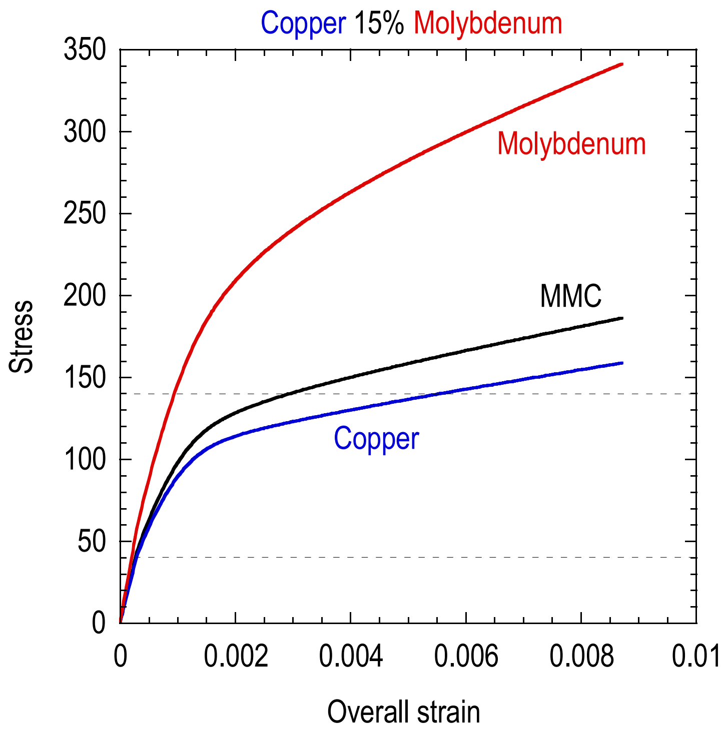
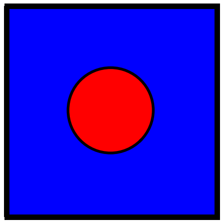
Outline

- Loading of a MMC
  - Elastic and plastic anisotropy
- Neutron Diffraction Measurements
  - Molybdenum Particulate Reinforced Copper (Cu/Mo)
- Model Predictions
  - Self-Consistent Model
- Conclusion

Loading of a MMC





- Soft and ductile matrix (Cu); Stiff reinforcement (Mo)
- Load sharing between phases
- Elastic-plastic FEM (Isotropic), mean phase stresses and strains

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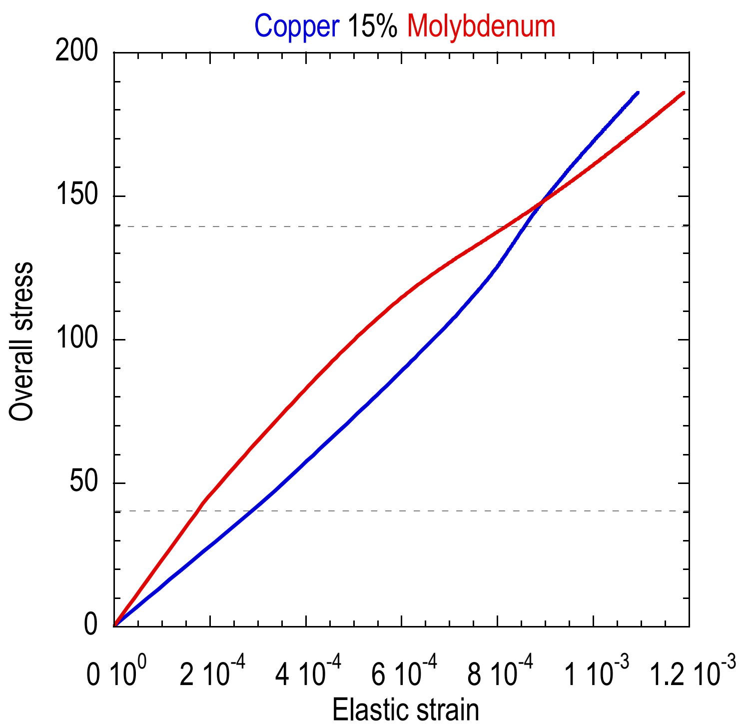
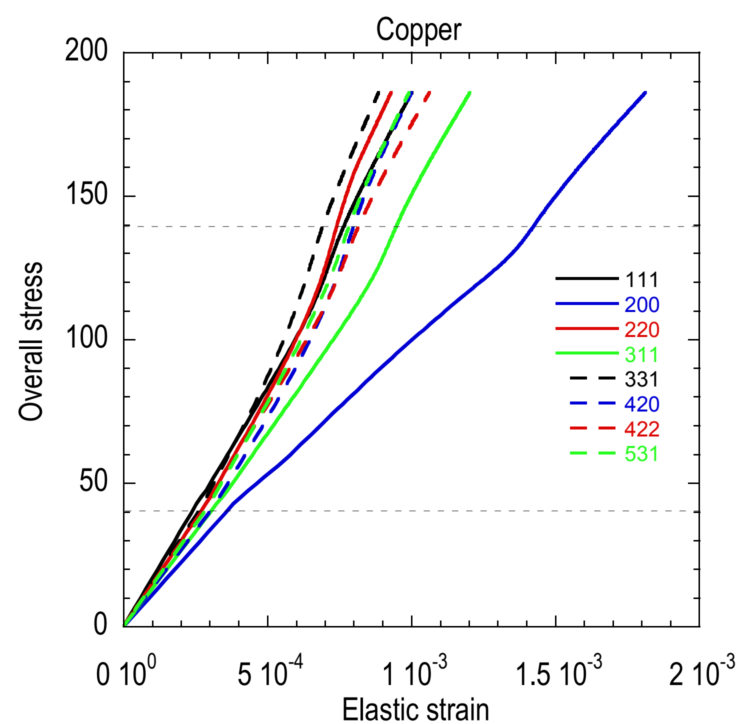
Loading of a MMC





- Elastic and plastic anisotropy
  - Intergranular stresses and strains.
  - Effects on design limits for materials and component lifetime.

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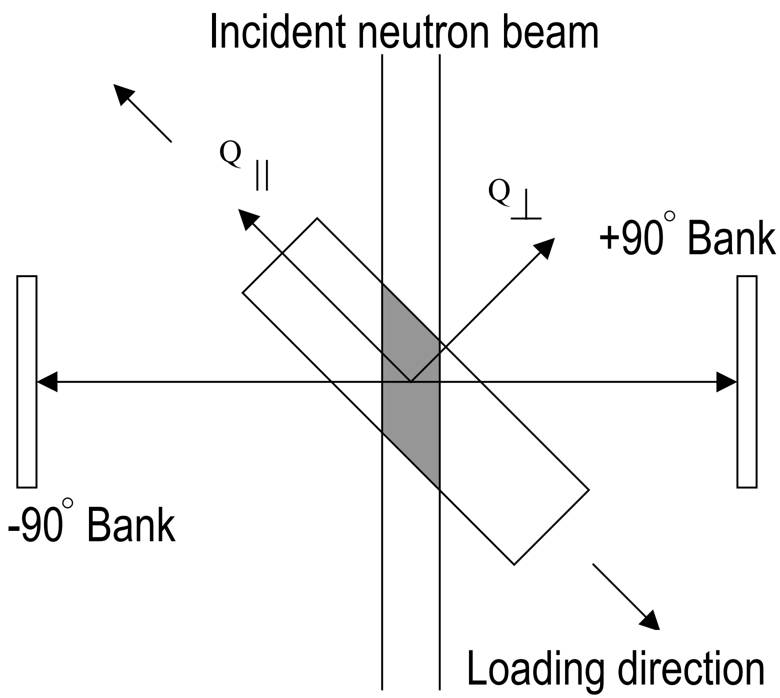
Neutron Diffraction Measurements



Neutron Powder Diffractometer (NPD):

Strain resolution for an *in-situ* loading measurement: 50×10^{-6}

11,000 Pounds, 400 °C

SMARTS:
Strain resolution: 50×10^{-6}
40,000 Pounds, 1500 °C, 1x1x1mm

- Lattice plane response in two directions simultaneously.
- In-situ bulk measurements, penetration dept on the order of cm.
- Typical count time is 1-3 hours.

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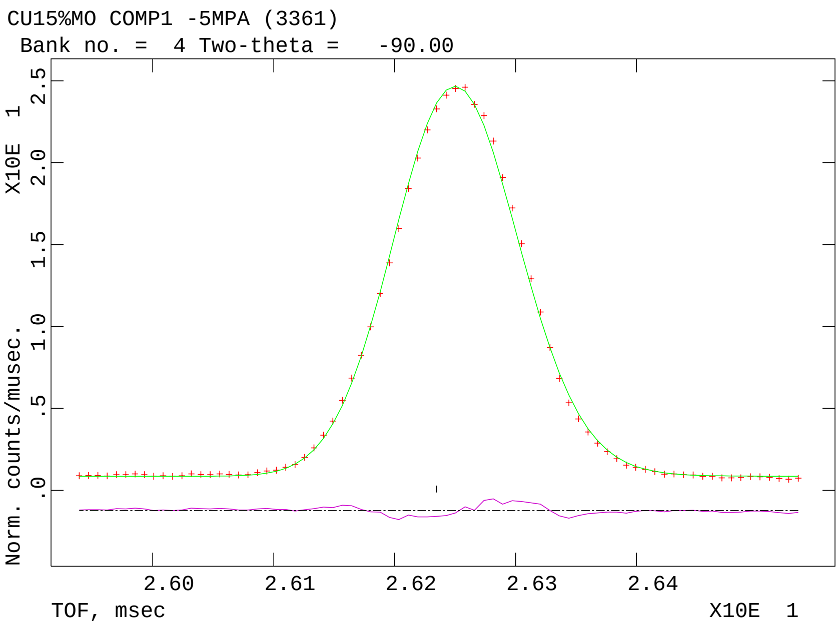
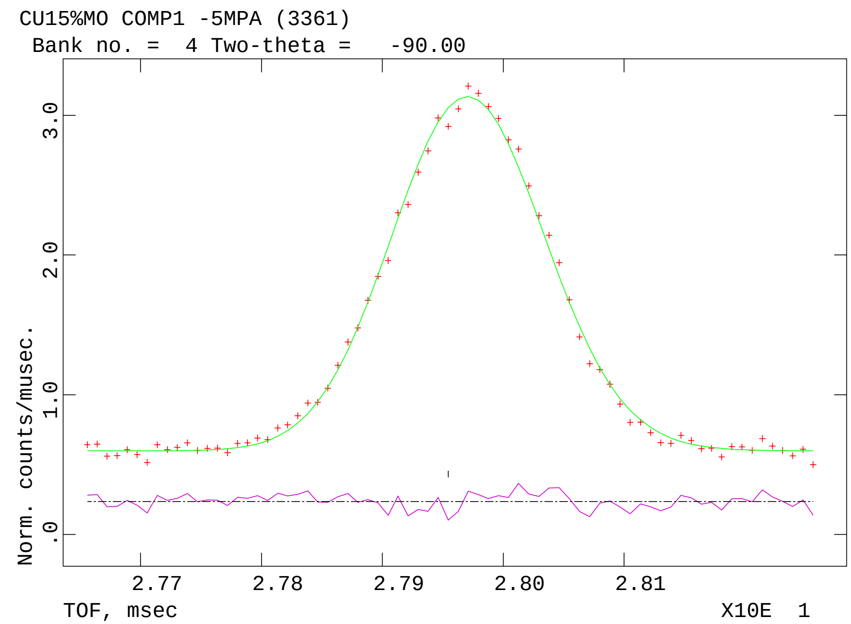
Neutron Diffraction Measurements



Copper 111



Molybdenum 110

- Single peak fitting allows us to determine lattice strains for specific reflections.
- Some peaks have rather poor intensity.

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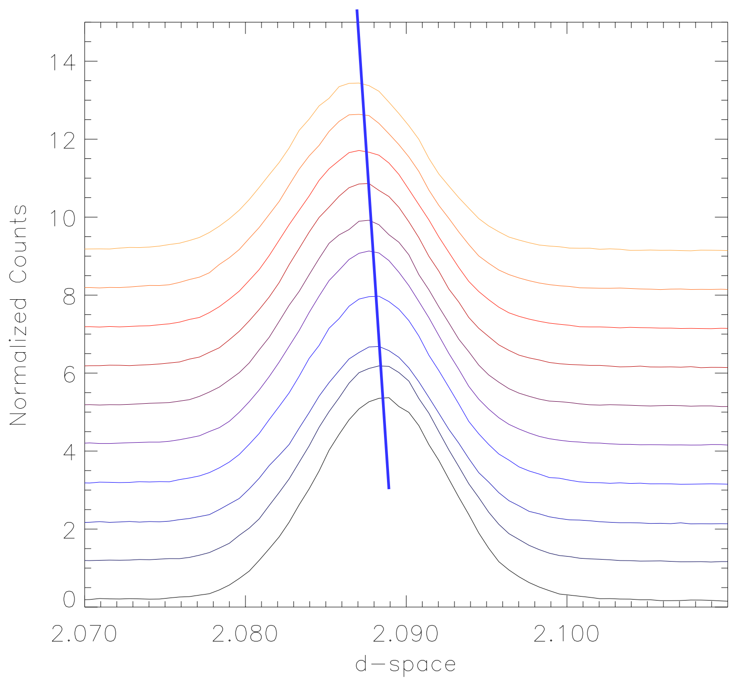
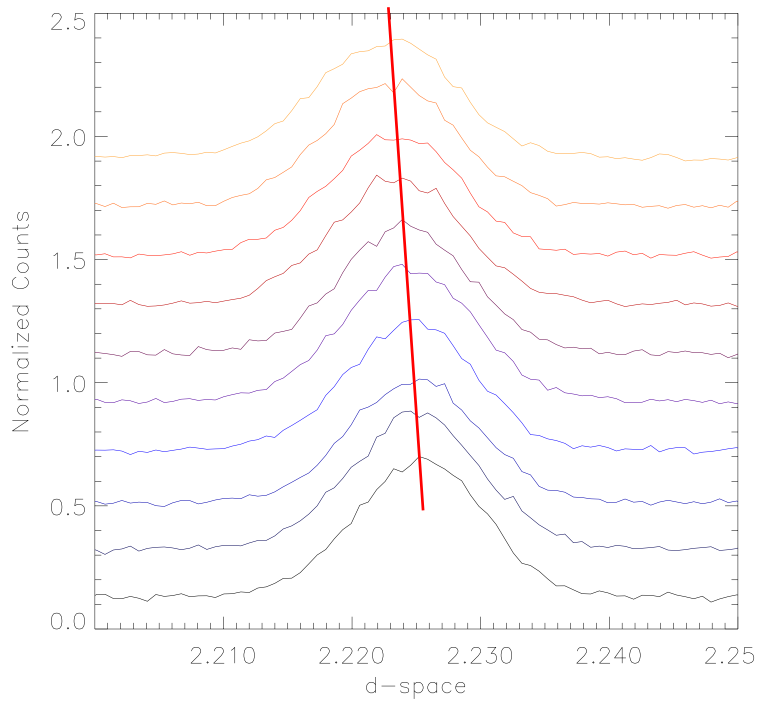
Neutron Diffraction Measurements



Copper 111



Molybdenum 110

- Movement of peaks due to the applied stress.

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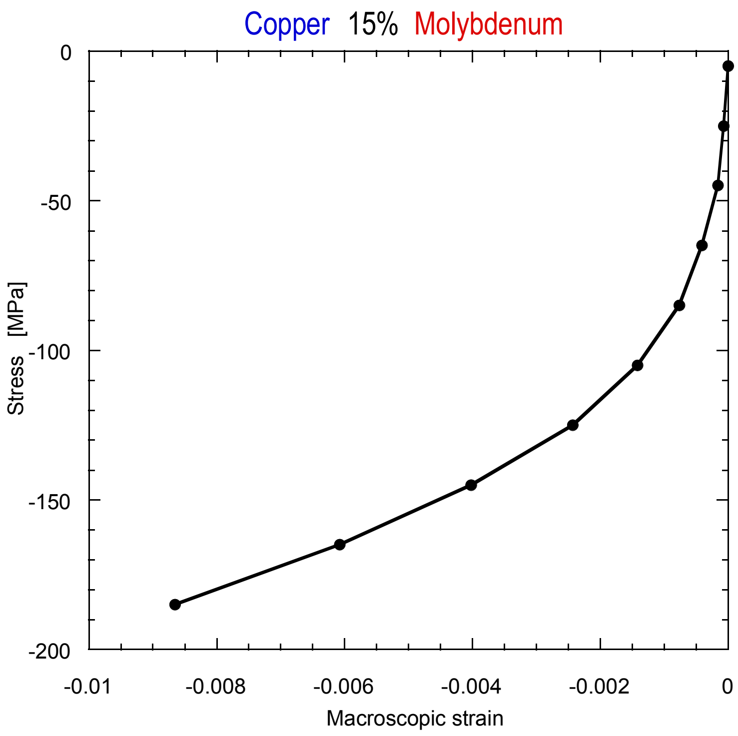
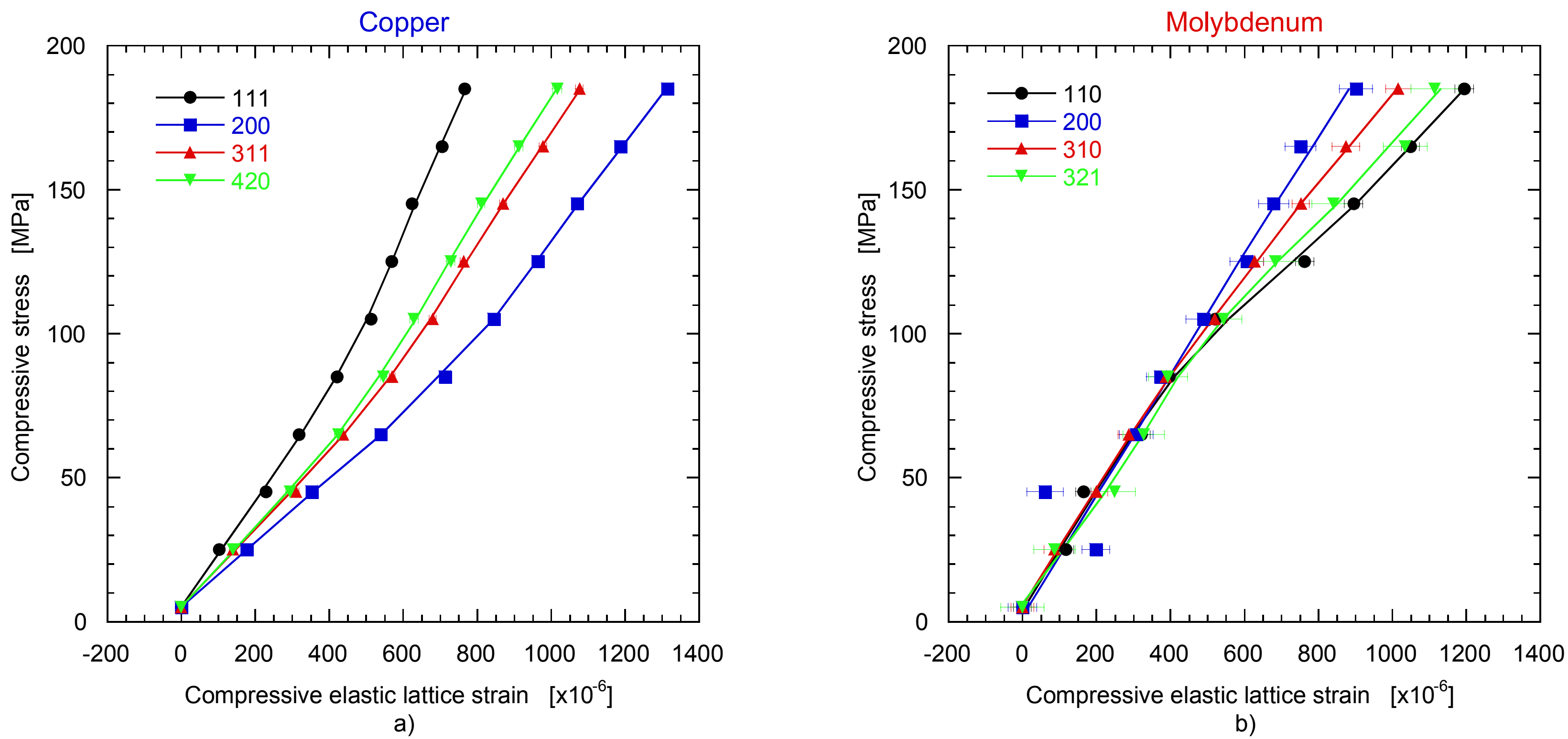
Neutron Diffraction Measurements



- Macroscopic stress strain curve for Cu/Mo particulate MMCs.
- The symbols indicate a neutron diffraction measurement.
- Plasticity starts at about 50 MPa and $\sigma_{0.2\%}$ is at about 140 MPa.

Molybdenum Particulate Reinforced Copper



- Showing compressive stresses and strains.
- Lines are smooth fits to the data.
- Elastic anisotropy is very different in Copper and Molybdenum (3.21 and 0.87)

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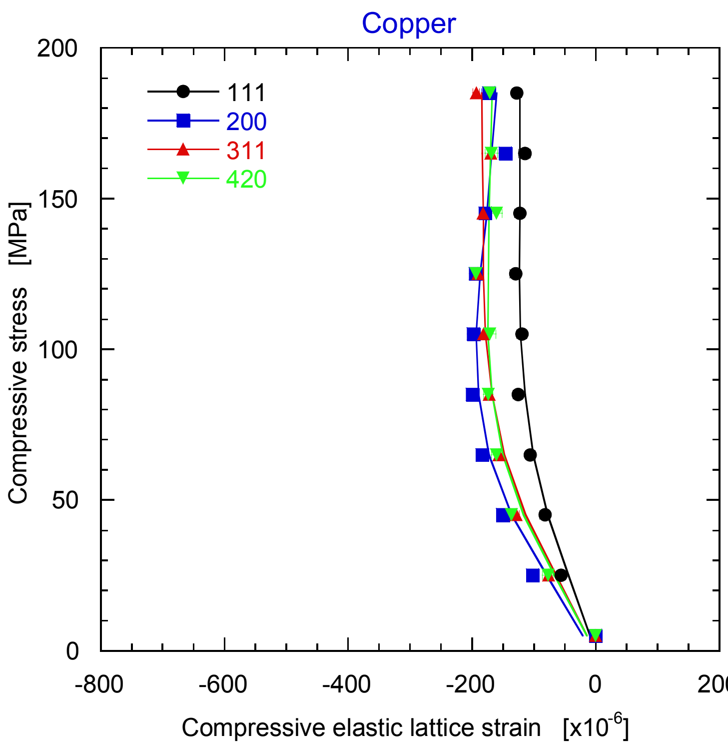
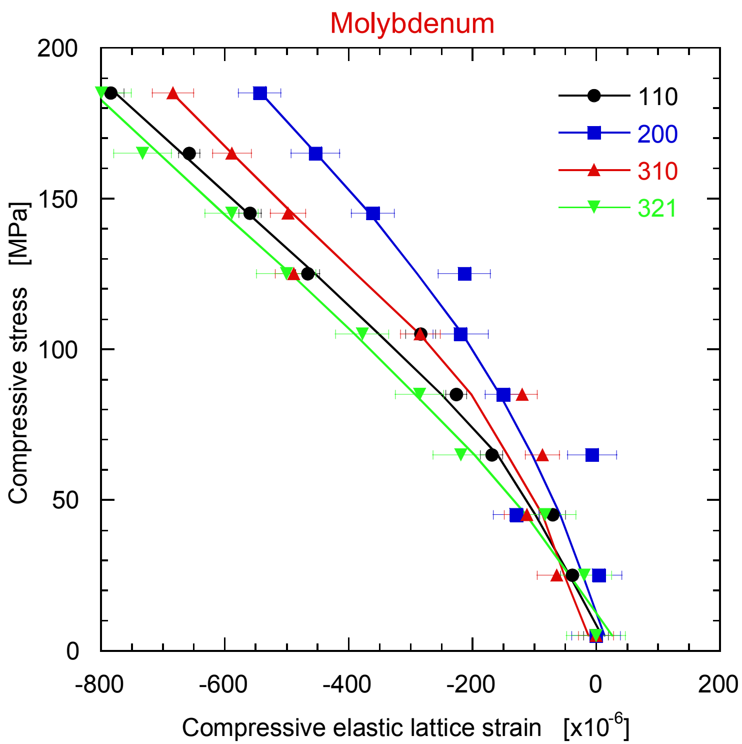
Molybdenum Particulate Reinforced Copper



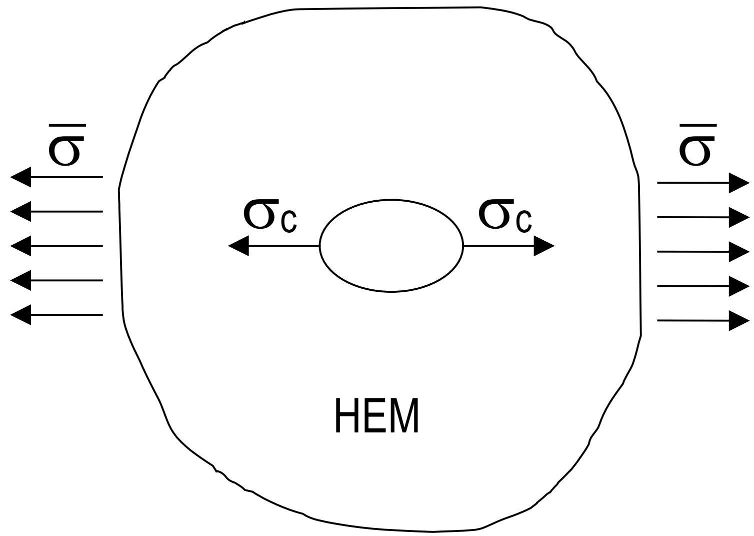
a)



b)

- No increase in elastic strain for copper in the plastic region.
- Larger scatter in the molybdenum.

Self-Consistent Model



- Hill-Hutchinson self-consistent model. Eshelby type calculation.
- Overall material parameters are found as average over all grains.
- Do not include grain-to-grain interactions.
- Iteratively solve for the overall material parameters.
- Set of grains to represent texture of sample.
- Same level of detail as neutron diffraction. Average over many grains with different neighbors is similar to average over some grains in a HEM .

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Self-Consistent Model

$$\dot{\boldsymbol{\varepsilon}}^P_c = \sum_i \dot{\gamma}^i \boldsymbol{\mu}^i$$

$$\boldsymbol{\sigma}_c \boldsymbol{\mu}^i = \tau^i \quad \text{and} \quad \dot{\boldsymbol{\sigma}}_c \boldsymbol{\mu}^i = \dot{\tau}^i$$

$$\dot{\boldsymbol{\varepsilon}}_c = \boldsymbol{\mathcal{M}}_c \dot{\boldsymbol{\sigma}}_c + \dot{\boldsymbol{\varepsilon}}^P_c \quad \text{or} \quad \dot{\boldsymbol{\sigma}}_c = \boldsymbol{\mathcal{L}}_c \left(\dot{\boldsymbol{\varepsilon}}_c - \dot{\boldsymbol{\varepsilon}}^P_c \right)$$

$$\sum_j \dot{\gamma}^j X^{ij} = \boldsymbol{\mu}^i \boldsymbol{\mathcal{L}}_c \dot{\boldsymbol{\varepsilon}}_c \,, \qquad X^{ij} = h^{ij} + \boldsymbol{\mu}^i \boldsymbol{\mathcal{L}}_c \boldsymbol{\mu}^j$$

$$\dot{\tau}^i = \sum_j h^{ij} \dot{\gamma}^j \quad \text{where} \quad h^{ij} = h_\gamma \left(q + (1 - q)\delta^{ij} \right)$$

$$\dot{\gamma}^i = \boldsymbol{f}^i \dot{\boldsymbol{\varepsilon}} \,, \qquad \boldsymbol{f}^i = \sum_k Y^{ik} \boldsymbol{\mathcal{L}}_c \boldsymbol{\mu}^k$$

$$h_\gamma = h_{initial} \left(1 + \left(h_{ratio} - 1 \right) e^{\left(-h_{exp} \gamma^{acc} \right)} \right)$$

$$\boldsymbol{L}_c = \boldsymbol{\mathcal{L}}_c \left(\boldsymbol{I} - \sum_m \boldsymbol{\mu}^m \boldsymbol{f}^m \right)$$

Self-Consistent Model

$$\dot{\boldsymbol{\varepsilon}}_c = \boldsymbol{A}_c \dot{\bar{\boldsymbol{\varepsilon}}} \ , \qquad \boldsymbol{A}_c = (\boldsymbol{L}^* + \boldsymbol{L}_c)^{-1}(\boldsymbol{L}^* + \boldsymbol{L})$$

$$\boldsymbol{L}^* \boldsymbol{S} = \boldsymbol{L}(\boldsymbol{I} - \boldsymbol{S})$$

$$\boldsymbol{L}^* = \boldsymbol{\Lambda}^{-1} - \boldsymbol{L}$$

$$\Lambda_{ijmn} = \frac{1}{16\pi} \int_{\theta=0}^{\pi} \int_{\phi=0}^{2\pi} \left(\hat{U}_{im} k_n k_j + \hat{U}_{jm} k_n k_i + \hat{U}_{in} k_m k_j + \hat{U}_{jn} k_m k_i \right) \sin\theta \mathrm{d}\theta \mathrm{d}\phi$$

$$L_{ijkl} \hat{U}_{km} k_j k_l = \delta_{im} \quad k_1 = \sin\theta\cos\phi \quad k_2 = \sin\theta\sin\phi \quad k_3 = \cos\theta$$

$$\{\dot{\boldsymbol{\sigma}}_c\} = \dot{\bar{\boldsymbol{\sigma}}} \ \Rightarrow \ \boldsymbol{L} = \{\boldsymbol{L}_c \boldsymbol{A}_c\}$$

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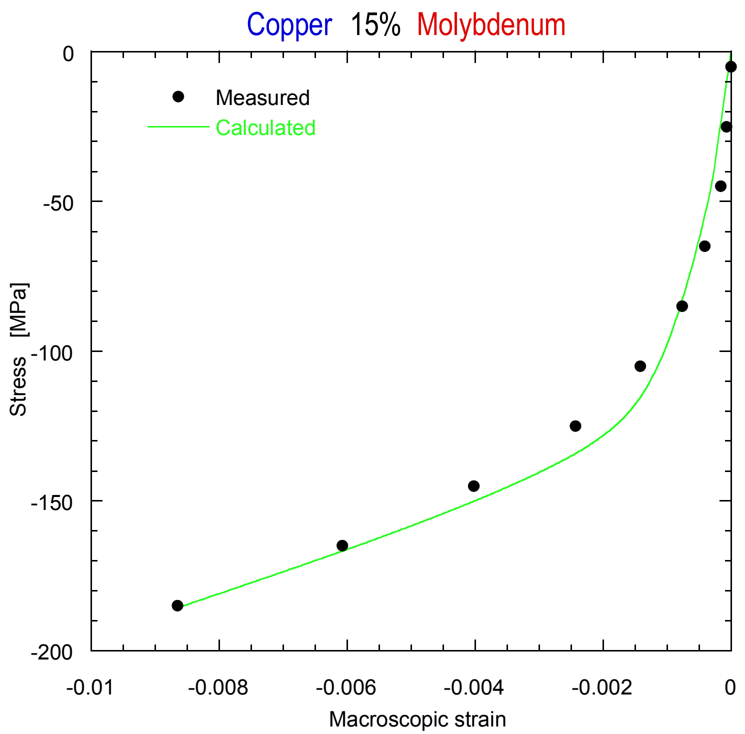
Self-Consistent Model



- Macroscopic response of the SCM fitted to the measured data using initial CRSS and hardening parameters.

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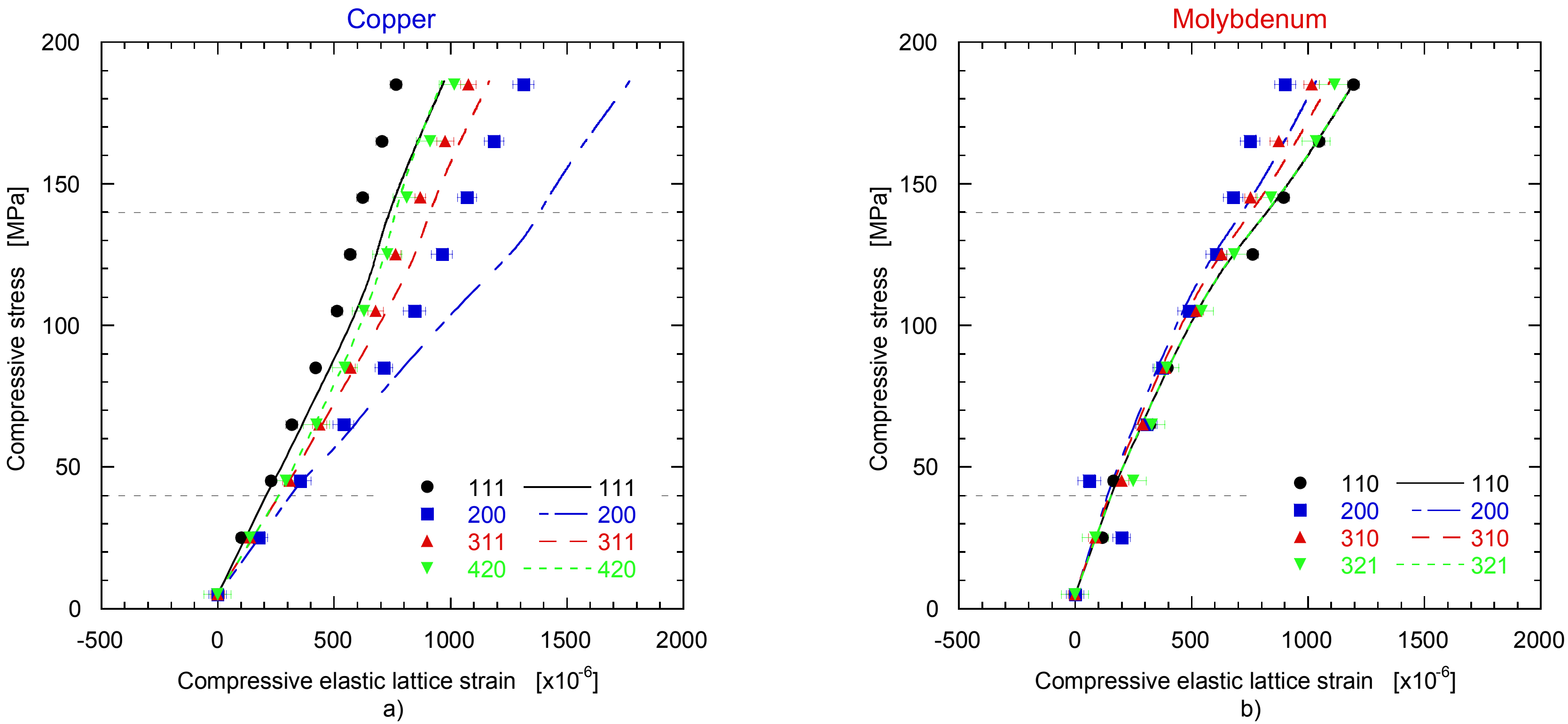
Self-Consistent Model



- Good agreement in the elastic region.
- Plastic anisotropy of copper is slightly overestimated.
- Good agreement in plastic region for molybdenum.

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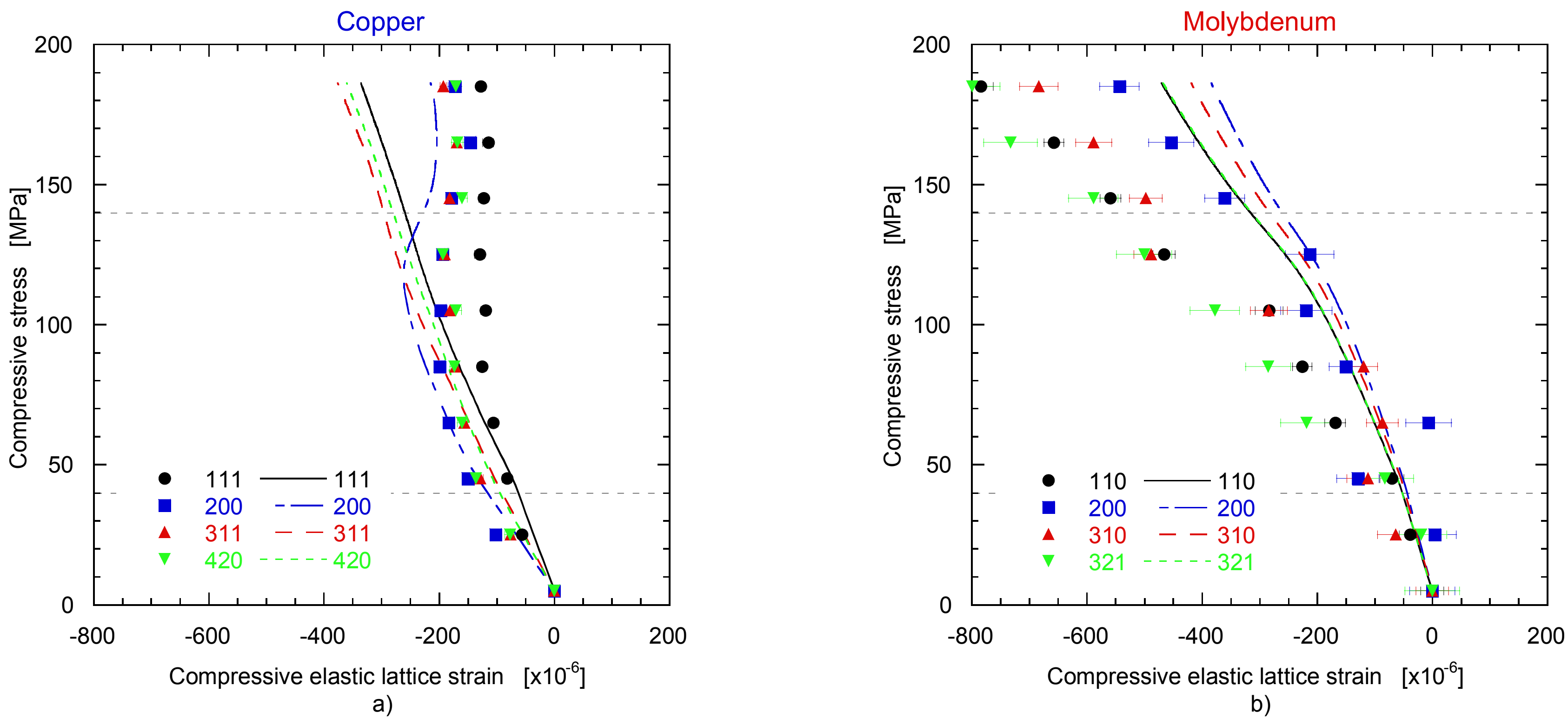
Self-Consistent Model



- Reasonable agreement in the elastic region.
- For copper only the predictions for the 200 reflection follows the measured data.
- For molybdenum all the reflections are predicted softer than shown by the data.

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Conclusion

- Good agreement in the elastic region.
- Poorer agreement in the plastic region
  - Near isotropic hardening law.
  - Dislocation theory.
- Predictions for the reinforcement (Mo) is more accurate than for the matrix (Cu) in the plastic region.
- Best agreement parallel to the compression axis. Well defined stress state.

Further Research

- Prediction of material behavior after production.
  - Intergranular stresses and strains.
  - Thermal Residual Stresses and strains (TRS).
  - Effects on component lifetime, design limits for materials.

- New capabilities:
  - Neutron diffraction:
    - SMARTS
  - Self-consistent Model
    - Two site model, grain-to-grain interaction, twinning, failure.
    - More crystal structures (hcp, tetragonal, etc.)