Load Sharing in Tungsten Continuous Fiber Reinforced Kanthal MMC's

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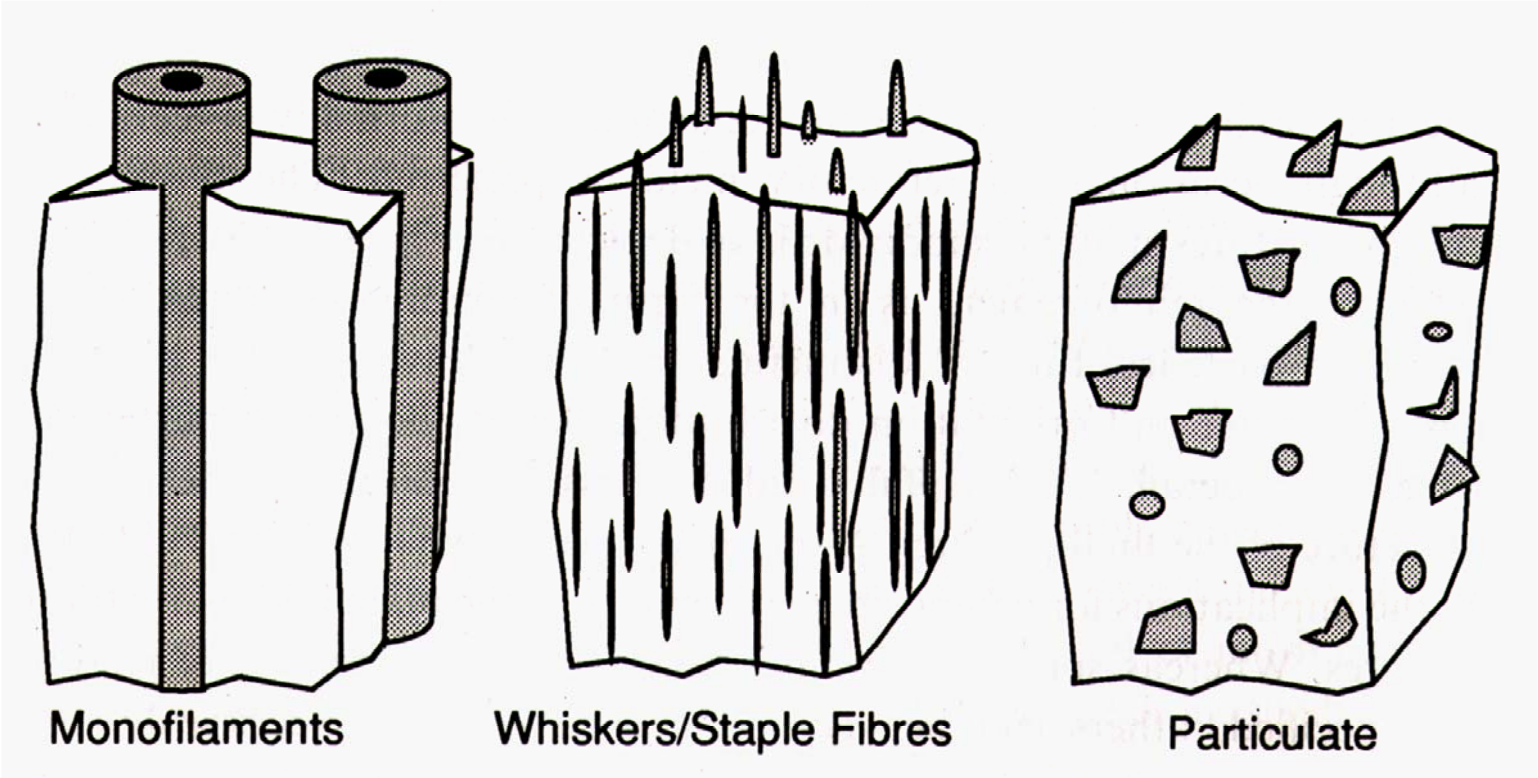
Outline

- Tungsten Continuous Fiber Reinforced Kanthal Metal Matrix Composites
- Neutron Diffraction
- Finite Element Modeling
- Self-consistent Modeling
- Conclusions

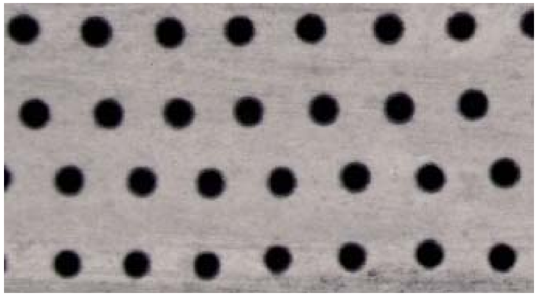
Metal Matrix Composites (MMC)



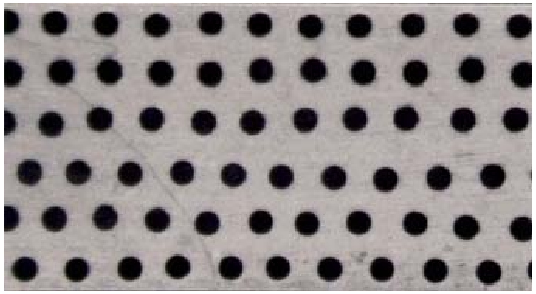
- Thermal Residual Stresses (TRS)
  - Influence mechanical behavior

Tungsten Continuous Fiber Reinforced Kanthal MMC

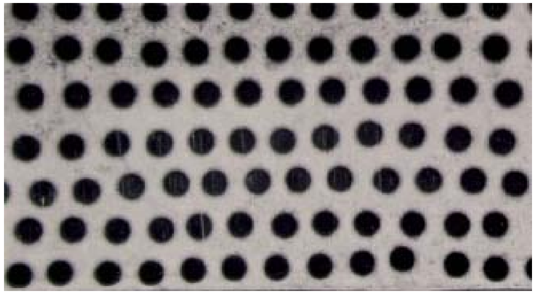
10%



20%



30%

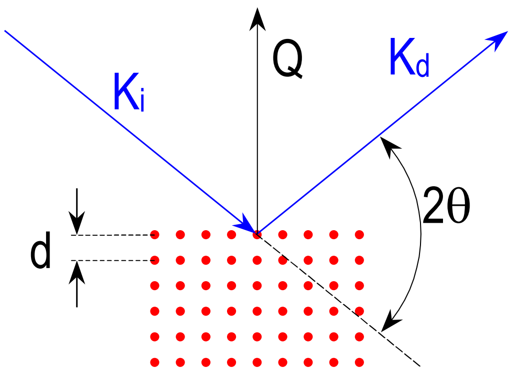


- Kanthal has good high temperature properties
  - Inherent corrosion/oxidization protection by forming an alumina case
  - 73.2% Fe, 21.0% Cr, 5.8% Al and 0.04%C
- Tungsten fibers increase creep resistance
- Samples
  - Monolithic Kanthal.
    - Reference sample. No TRS.
  - 10, 20 and 30 volume percent Tungsten fibers
    - Various levels of TRS due to the differences in CTE
    - Different yield points in tension due to the TRS
- Manufacture technique
  - Arc-sprayed, NASA Lewis, Tufts University
  - Mixed cubic and hexagonal stacking observed

Neutron Diffraction (ND)

$$\lambda = 2d\sin\theta$$

- TOF technique: Measure diffracted intensity as function of time-of-flight

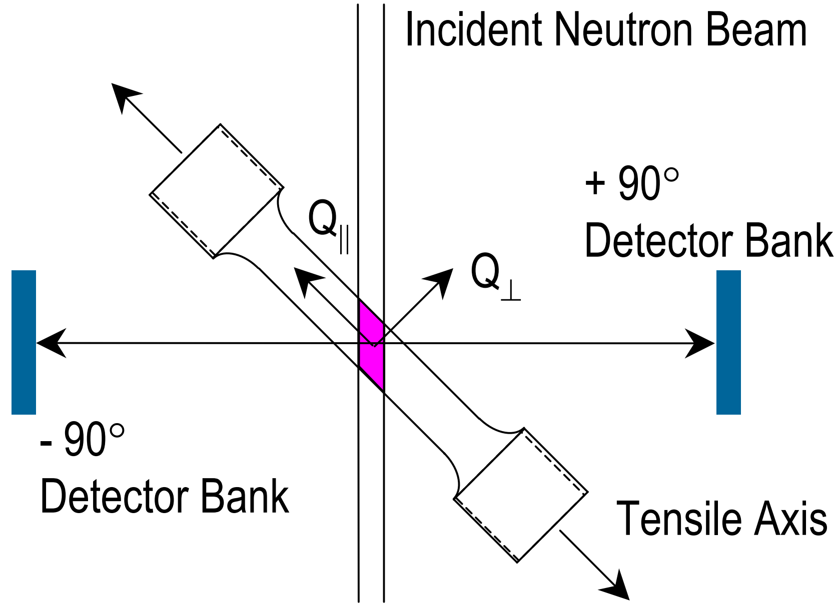


$$\varepsilon_{hkl}^{el} = \frac{d_{hkl} - d_{hkl}^{0}}{d_{hkl}^{0}} = \frac{d_{hkl}}{d_{hkl}^{0}} - 1$$

- Differences in lattice spacing => Elastic Lattice Strain

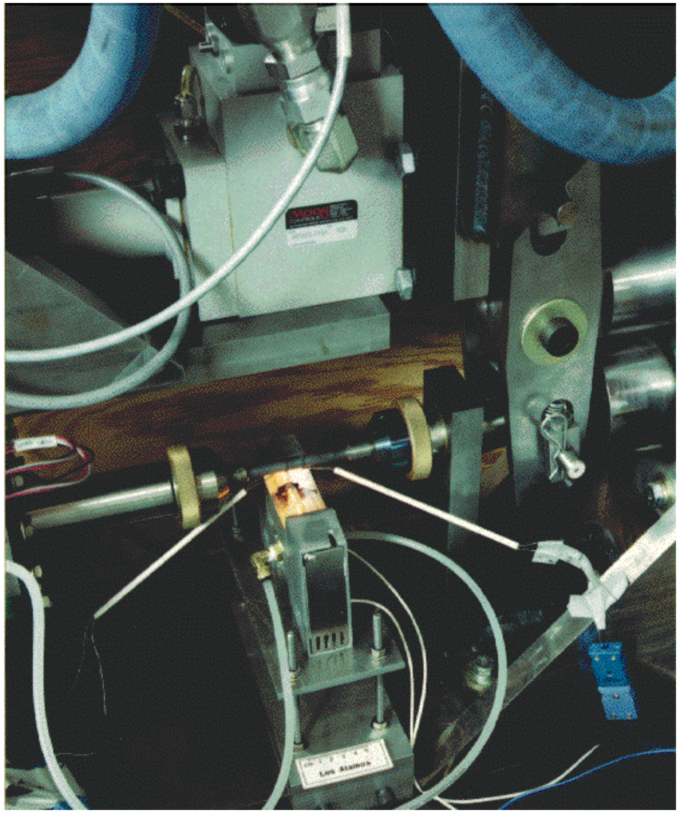
- Unique method to non-destructively determine internal strains in bulk samples
- Phase specific measurements - ideal for composites

Neutron Diffraction



- Neutron Powder Diffractometer (NPD) at LANSCE
- Schematic set-up for *in-situ* loading measurements
- Measurement time is about 2-4 hours per load level
- Measure elastic strains in two directions simultaneously

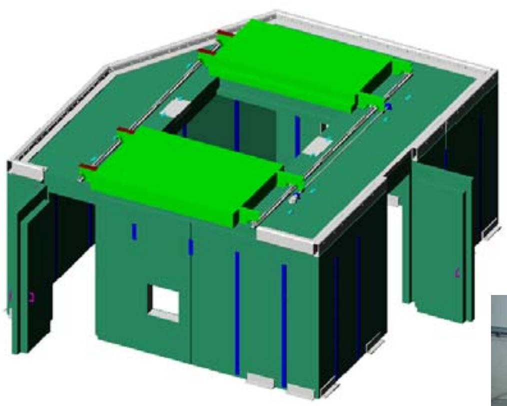
Neutron Diffraction

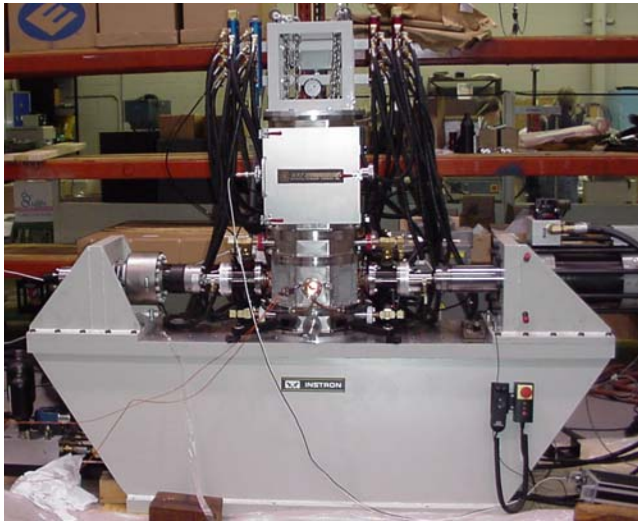


- The NPD load frame
  - 48 kN maximum load in tension or compression
  - Mirror furnace, 350°C maximum temperature

Neutron Diffraction

SMARTS: Spectrometer for Materials Research at Temperature and Stress





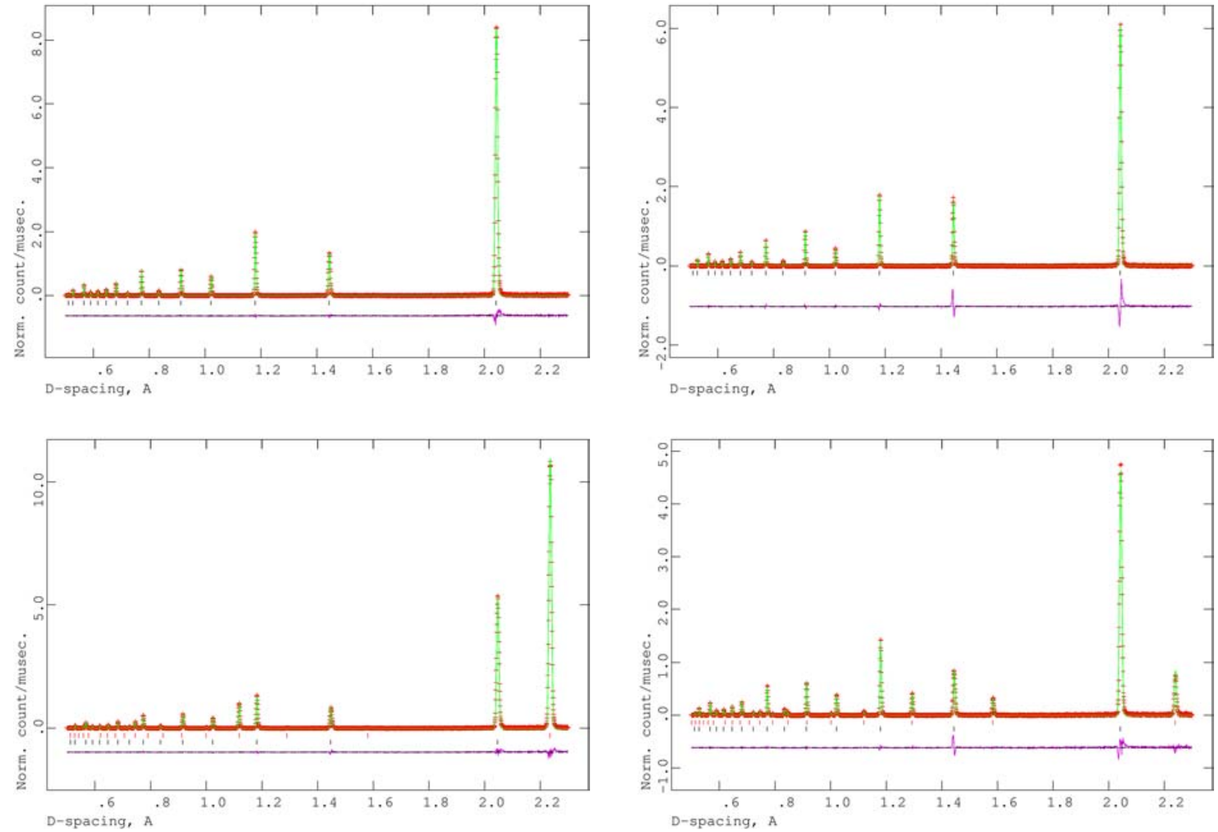
- SMARTS; First neutrons by May 2001
  - Order of magnitude lower count times than NPD (10-20 min)
  - 1 cubic millimeter gauge volume
  - **Combined** ±250kN, 1500°C and translation/rotation

Neutron Diffraction

- Monolithic Kanthal
  - Random (texture index is 1.04)
- 30% Tungsten fibers
  - Kanthal matrix is still random (1.05)
  - The fibers are highly textured (5.87)

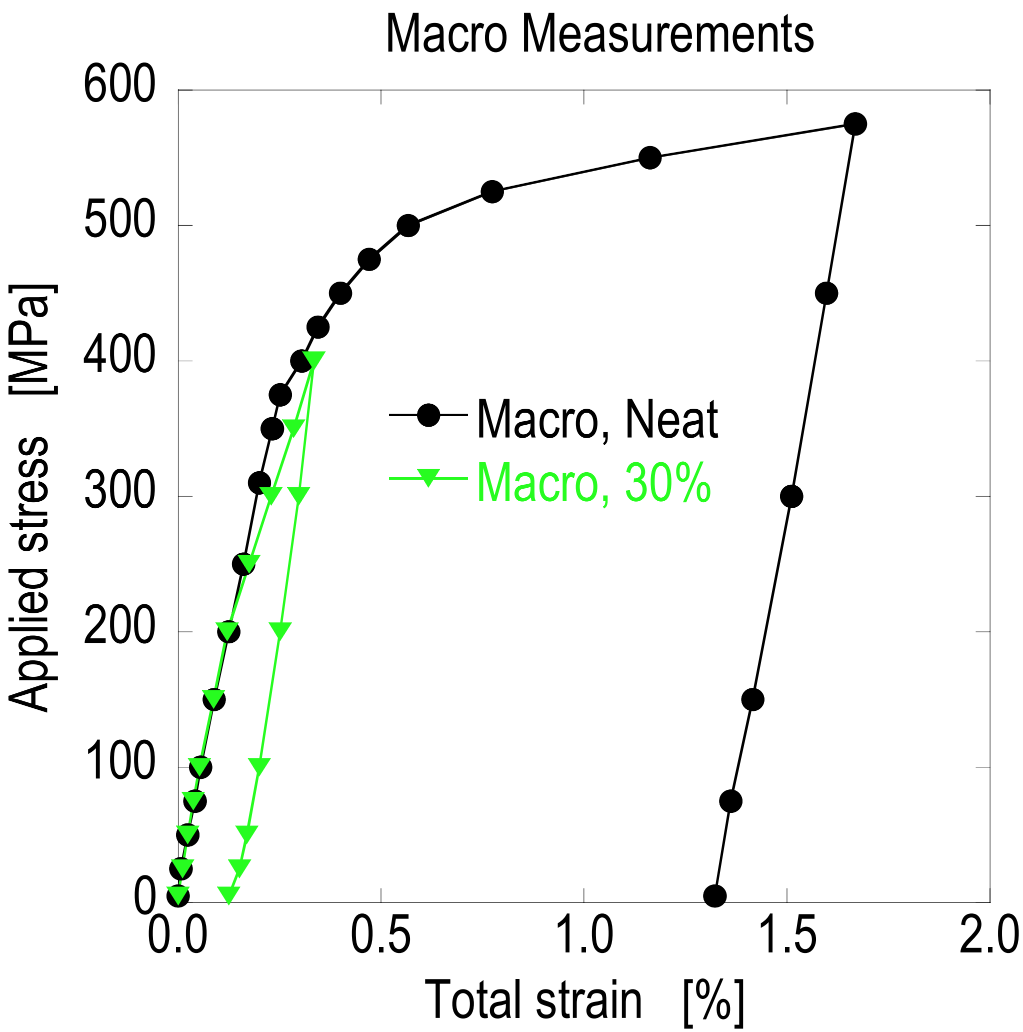
Parallel

Perpendicular



- Rietveld refinement provides an empirical lattice elastic mean phase (LEMP) strain

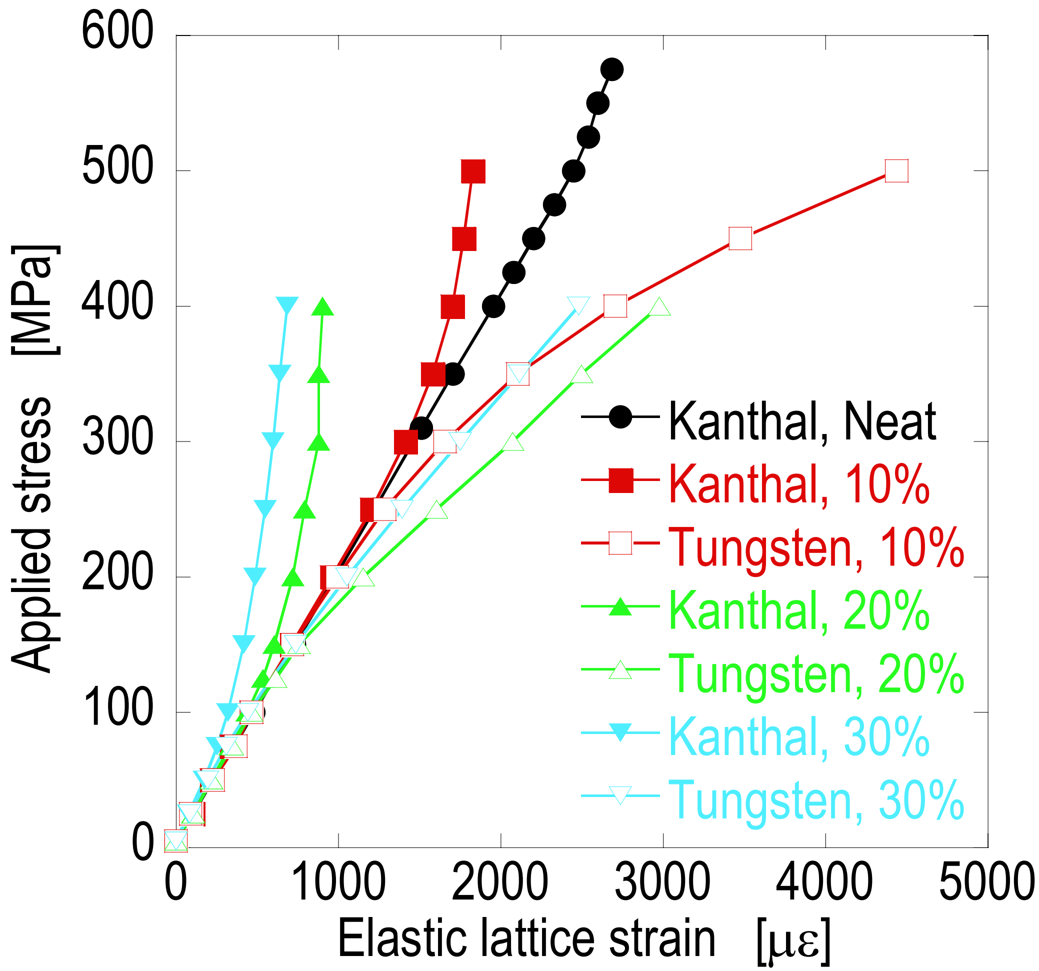
Neutron Diffraction



- Measured macroscopic stress/strain curves
- 10 and 20% N/A due to extensometer problems

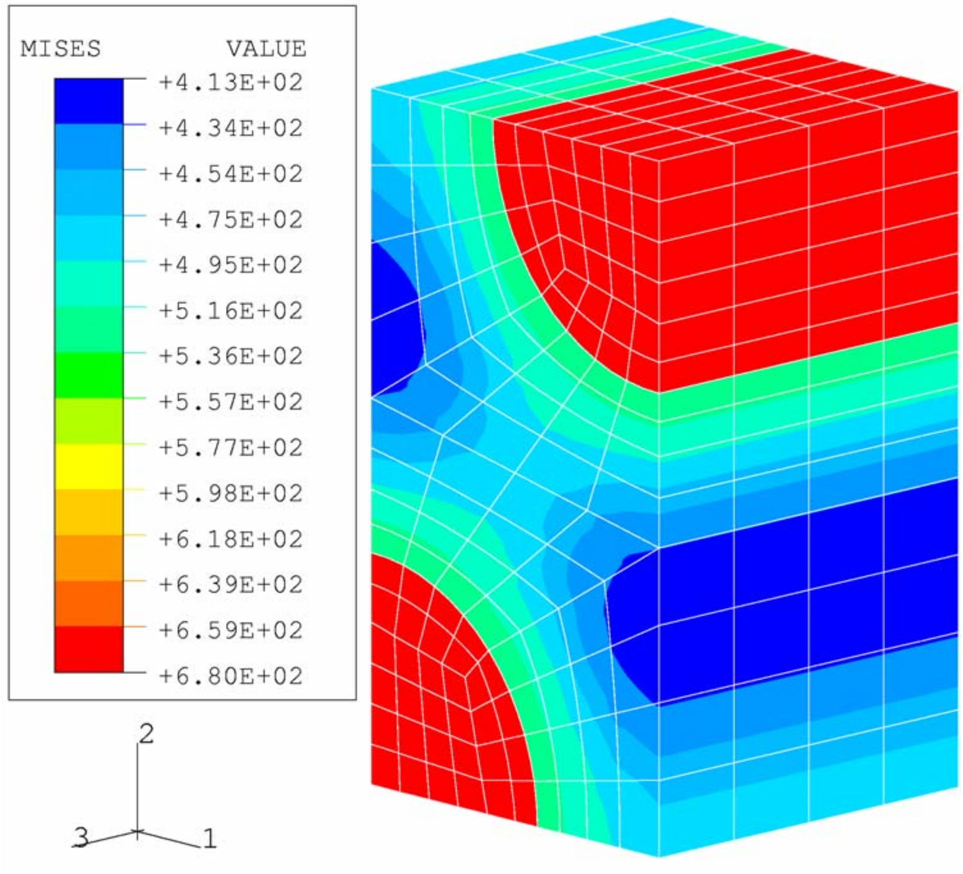
- Difference in curves?
- Young's modulus?
- Yield point?

Neutron Diffraction



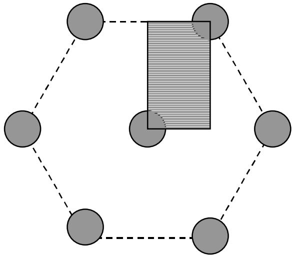
- Measured LEMP strains
  - Monolithic Kanthal. The LEMP strain is not linear in the plastic region due to build-up of intergranular strains.
  - 10%. Co-deformation until 200 MPa. Load sharing as Kanthal becomes plastic.
  - 20%. Co-deformation until 100 MPa.
  - 30%. Region with co-deformation is very limited (about 50 MPa).
- Initial stiffness; Appears to be the same in all samples
  - Elastic region ?
- Neutron diffraction is the only tool that can provide us with this type of data

Finite Element Modeling (FEM)

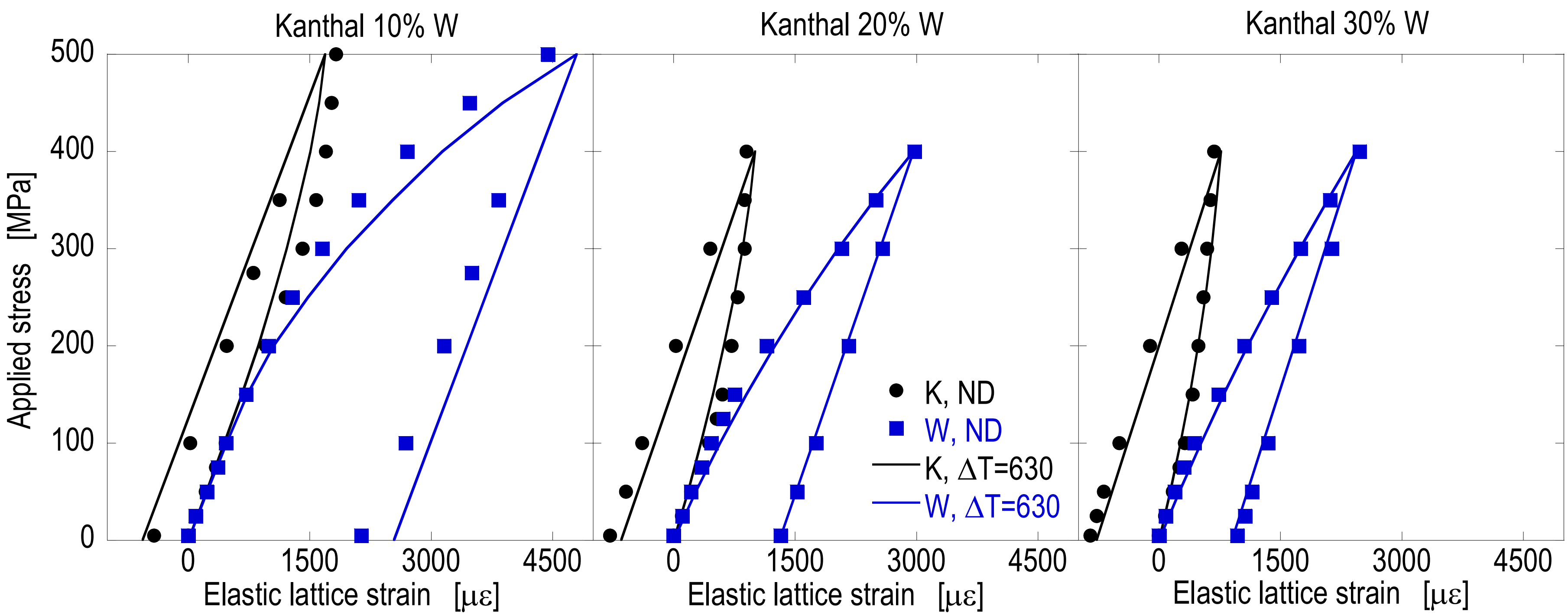


FE Model for 30 volume percent Tungsten fibers

- 3D model to accommodate the “out-of-plane” loading
- Unit-cell assumptions
  - Outer surfaces with x=constant or y=constant are kept as planes with x=constant or y=constant, respectively
- Plane strain assumption
  - Outer surfaces with z=constant are kept as planes with z=constant.

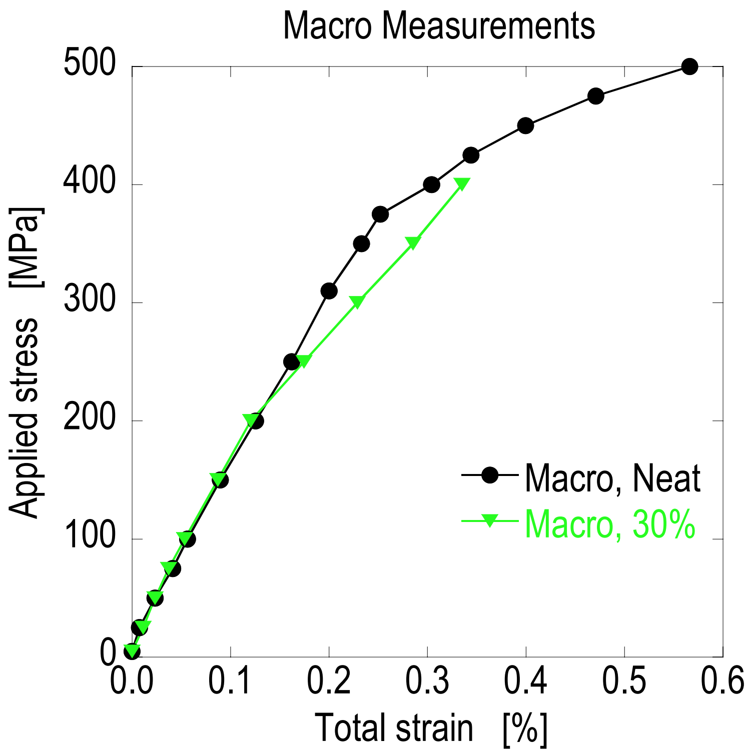


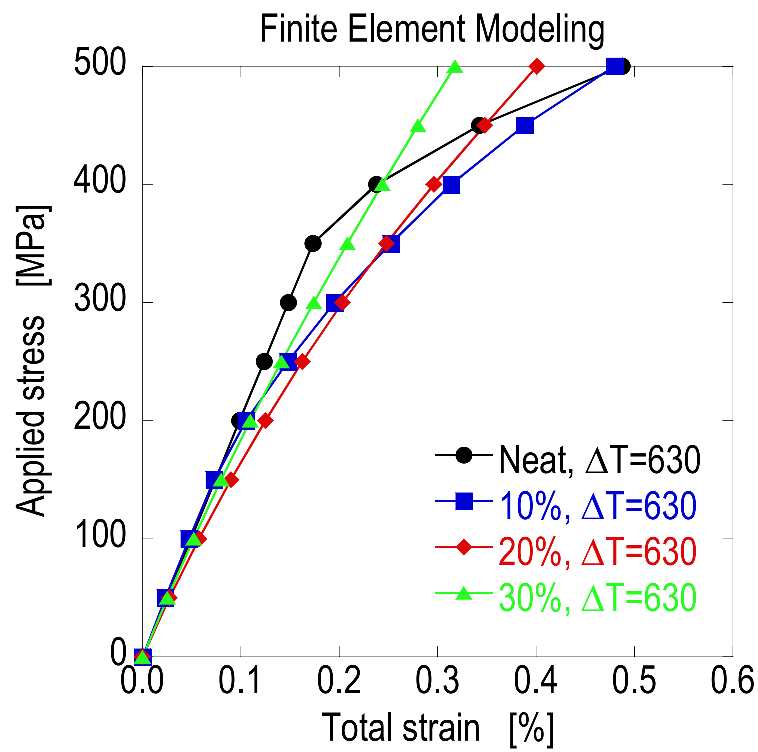
FEM Compared to ND



- Previous residual stress measurements indicate a “stress-free” temperature of 650°C
- Material behavior of Kanthal from tensile test; Tungsten fibers assumed fully elastic
- Qualitative Agreement:
  - Residual strains, Yield point (region of co-deformation), Same ΔT for all volume fractions

FEM Compared to Macro Measurements

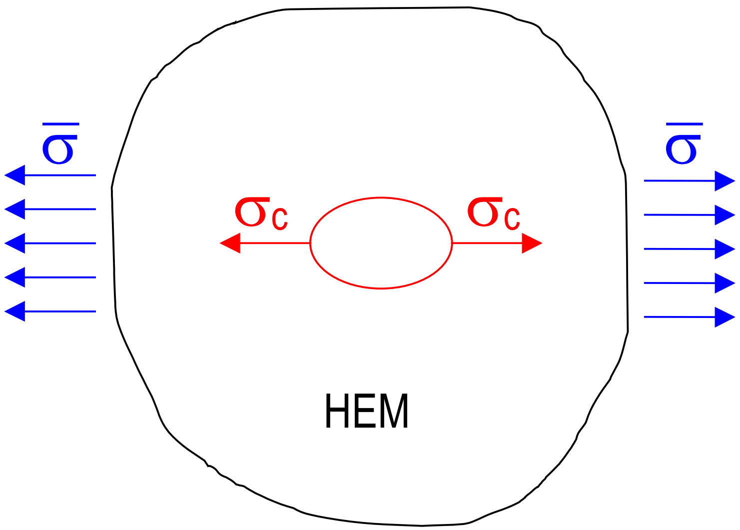




- Initial slope is similar for all
  - TRS induces micro-yielding that reduces apparent stiffness
  - At least measured neat and 30% behavior agrees with FEM
  - Waiting for independent tensile measurements on all volume fractions

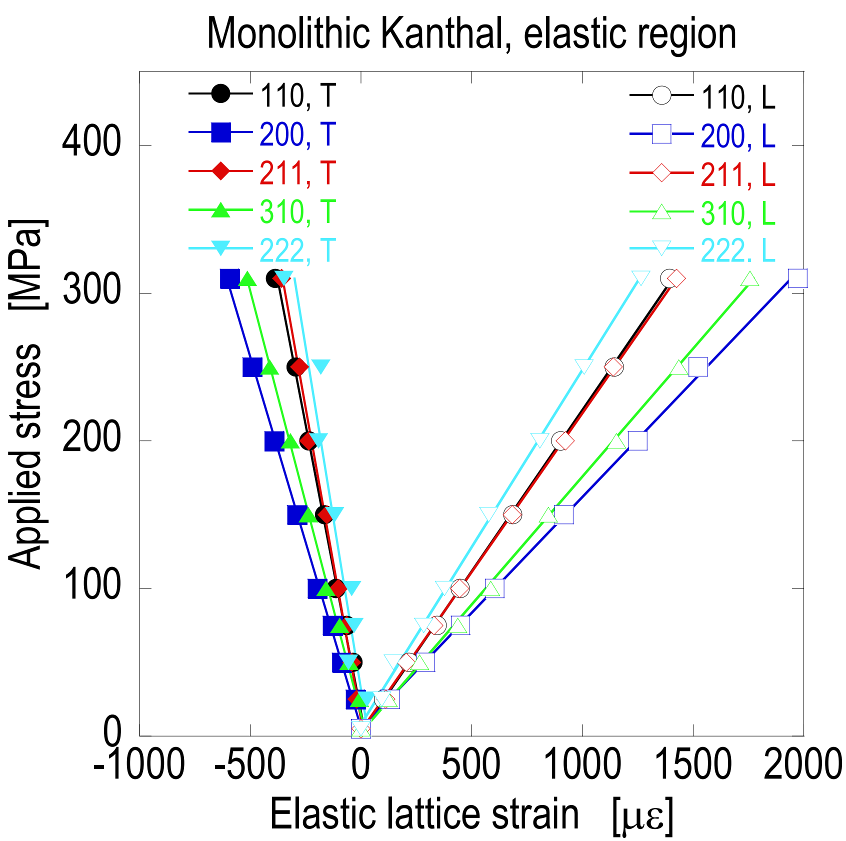
Self-consistent model (SCM)

- Material parameters
  - Single crystal stiffnesses and coefficients of thermal expansion
  - Description of texture with discrete set of grain orientations
  - Crystal structure, slip (and twinning) systems
  - CRSS and hardening law
- Model Assumptions
  - Eshelby inclusion theory
  - HEM properties equal to weighted average of the grains



- Output
  - Direct comparison with neutron diffraction measurements
  - Averages over grains sets representing reflections

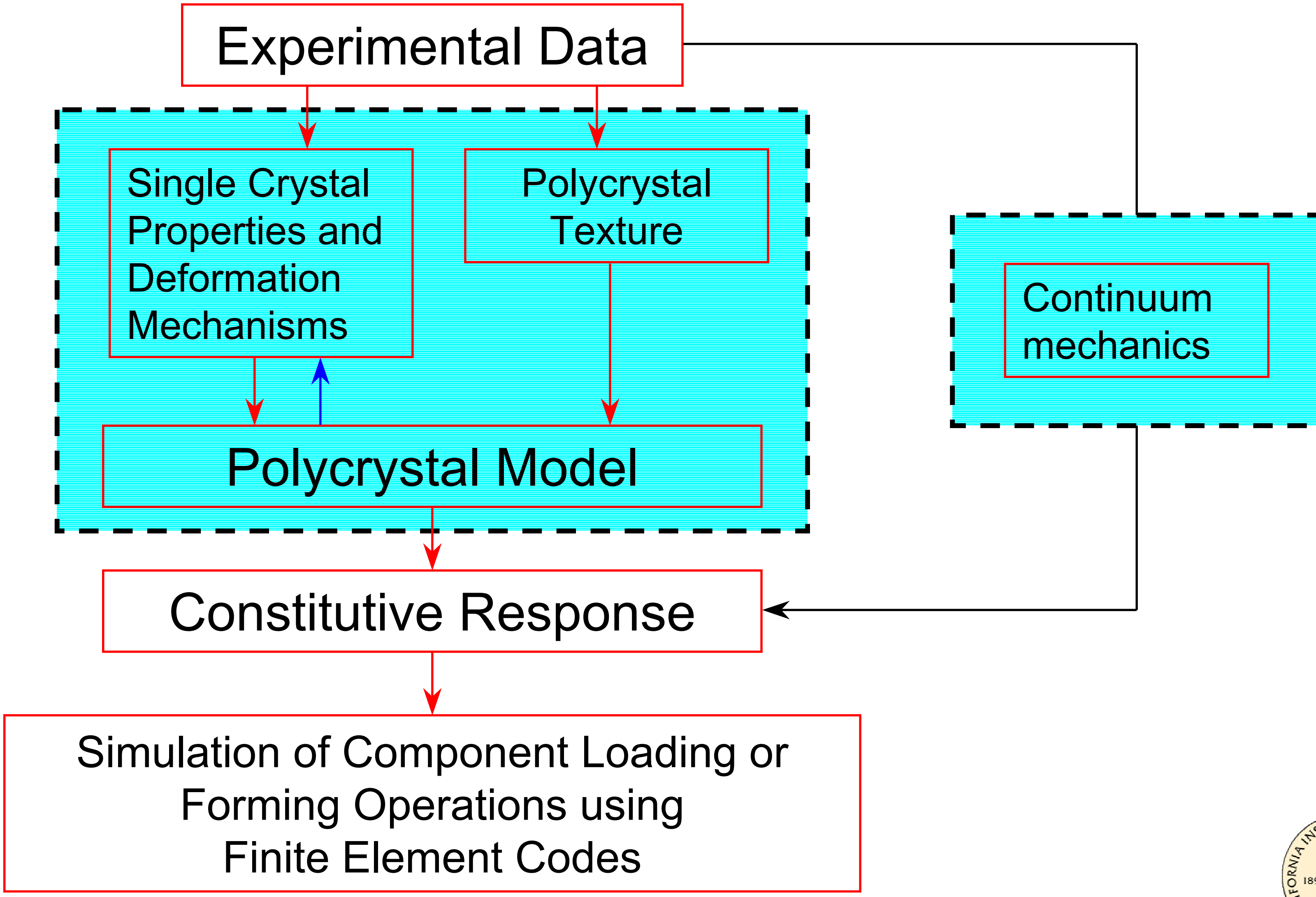
Single Crystal Elastic Constants



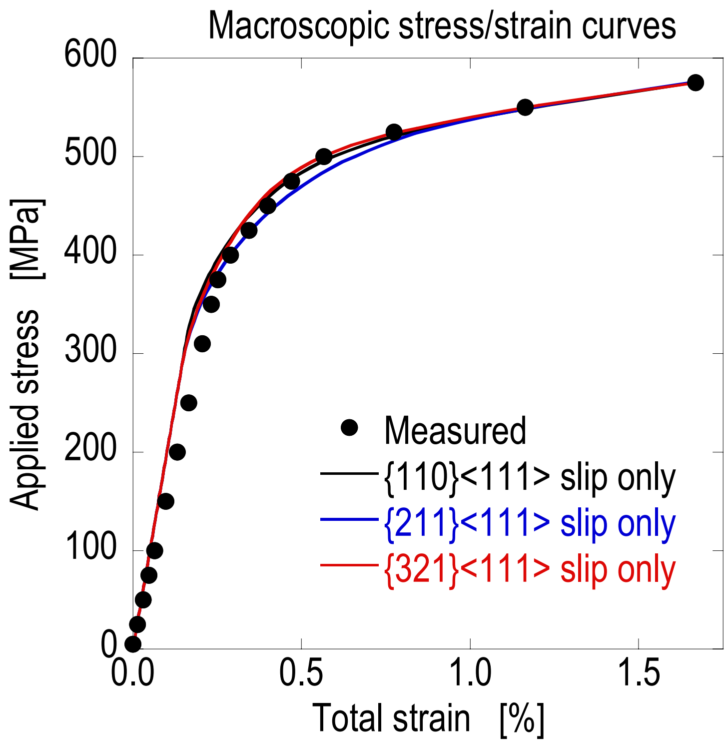
- Assumption of calculation of macroscopic moduli from single crystal values
  - Reuss-Voigt
  - Bollerath, Hauk & Müller
  - de Wit (based on Eshelby theory)
- Crystal symmetry
- Slopes gives diffraction elastic constants
  - E_{hkl} and ν_{hkl}

- Single crystal elastic stiffnesses from neutron diffraction data
  - T. Gnäupel-Herold, P.C. Brand and H.J. Prask, J. Appl. Cryst., 1998, vol. 31, pp. 929-935

Polycrystal versus Continuum Constitutive Description

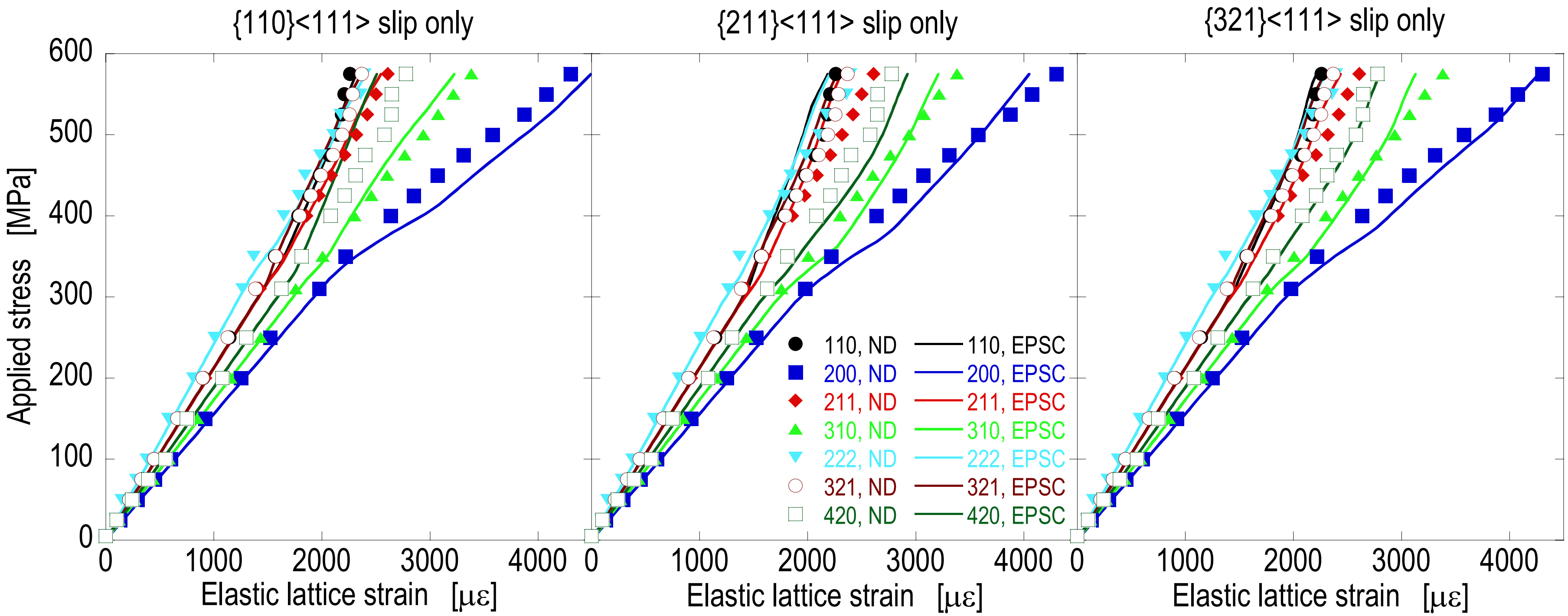


SCM Compared to ND



- Macroscopic stress/strain curve for monolithic Kanthal
  - Used to fit the macro result of the model to the measurements
  - Enables direct comparison on the micro level
- Different sets of active slip systems

SCM Compared to ND



- Variation of plastic anisotropy depending on active slip systems
- Best agreement with only one set of active systems is {321}<111>
- Parameter study
  - Could indicate relative level of activity on different slip systems

Conclusions

- Neutron diffraction measurements
  - Unique ability to measure *in-situ* phase strains in MMC's during loading
  - Directly applicable for model validation on a microstructural level
- FEM predictions show qualitative agreement with the measurements
  - Micro yielding in composites; residual strains
  - Model development
    - Unit cell assumptions; hexagonal, cubic, coaxial, multi fiber, …
- SCM predictions show qualitative agreement with the measurements
  - Monolithic Kanthal only
    - Quantitative agreement in the elastic region
    - Plastic anisotropy depends on set(s) of active slip systems