INL/CON-24-76723-Revision-0

Temperature-Dependent Mechanical Anisotropy in Textured Zircaloy Cladding

March 2024

Changing the World's Energy Future

Malachi Michael Nelson, David W Kamerman

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Idaho National Laboratory

Research Team

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  - Idaho National Laboratory Graduate Fellow
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  - David Kamerman – Idaho National Laboratory
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  - Shmuel Samuha – UC Berkeley, NCRN
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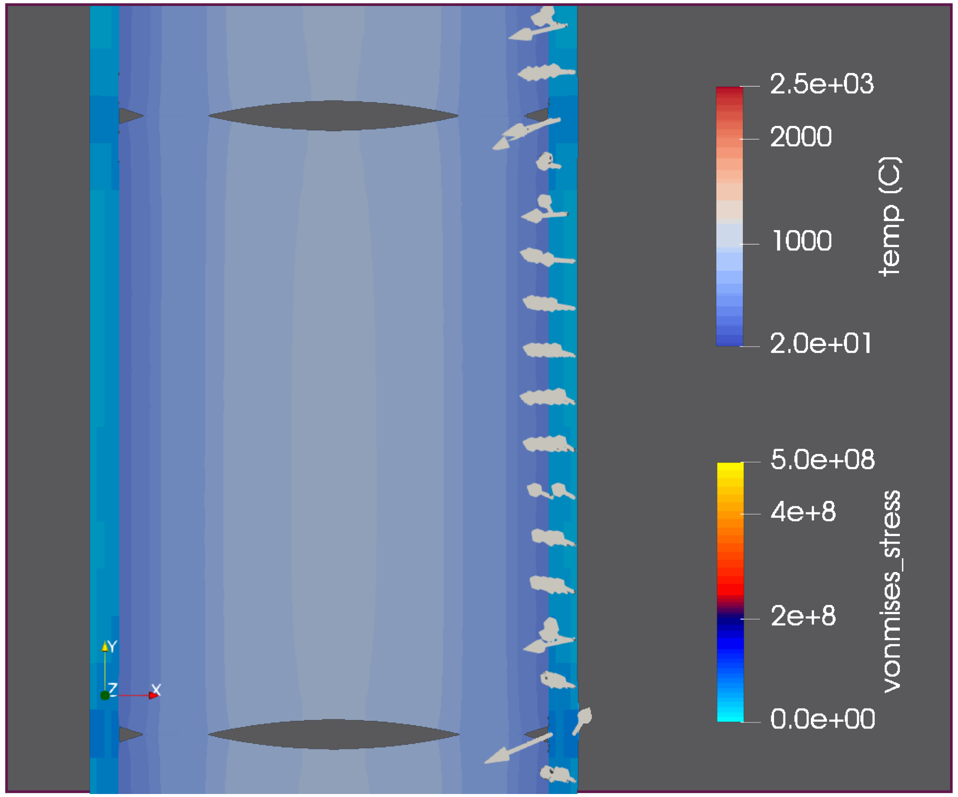
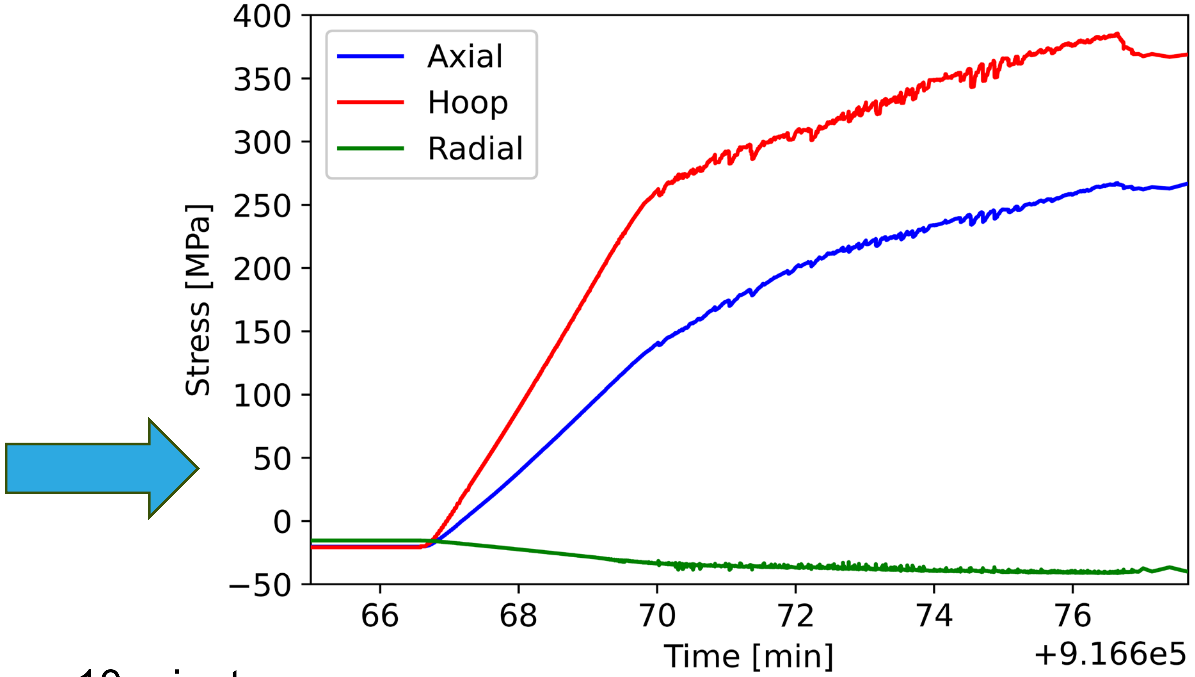
Pellet-Cladding Mechanical Interactions

- **Reactor power increases cause fuel pellet expansion**
- **Can generate stress in cladding, especially at burnup above ~20 GW/MTU**
- **Stress is near biaxial*:** $(\sigma_z, \sigma_\theta, \sigma_r) \cong (0.75, 1, 0)$

*(Udagawa, et al., 2013), (Suzuki et al., 2006)

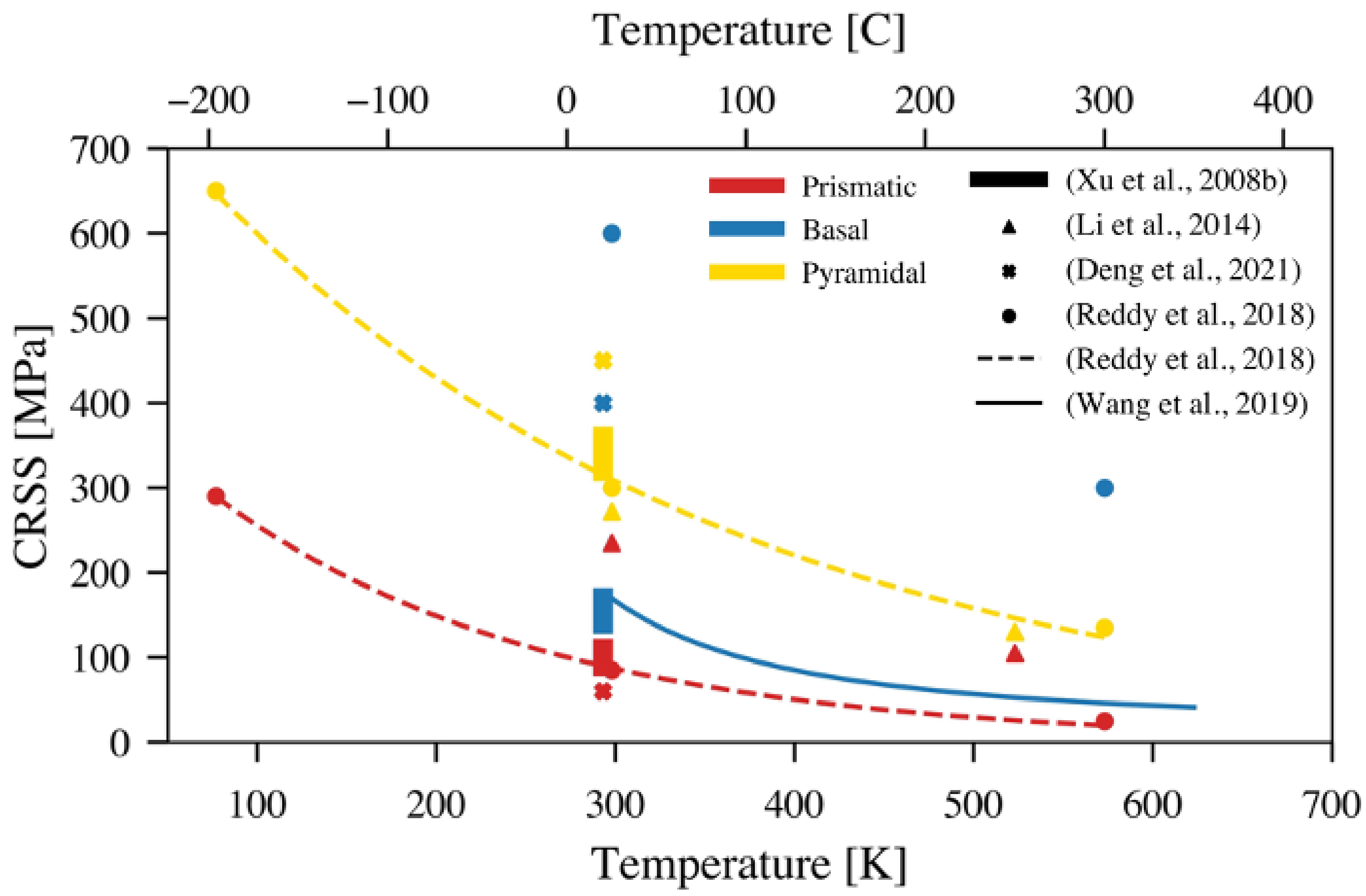


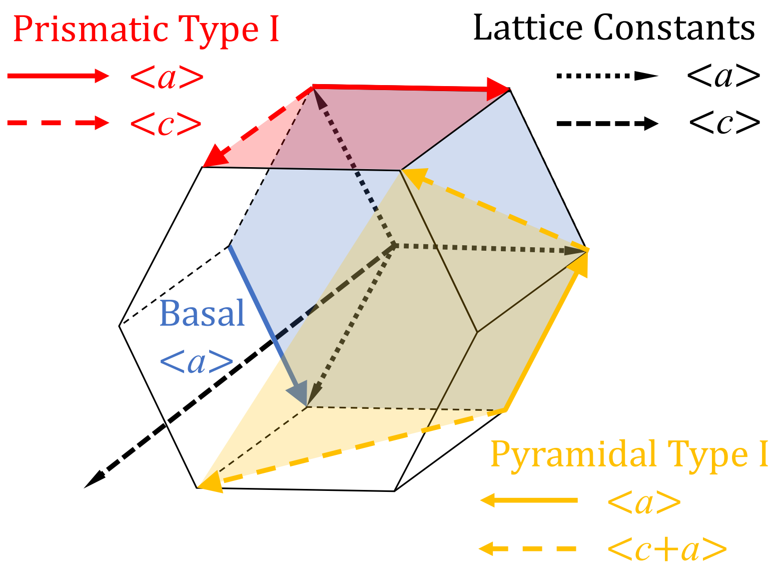


10-minute power ramp simulated using BISON fuel performance code.

Textured Zircaloy-4 Cladding

- **Hexagonal close-packed (HCP) structure**





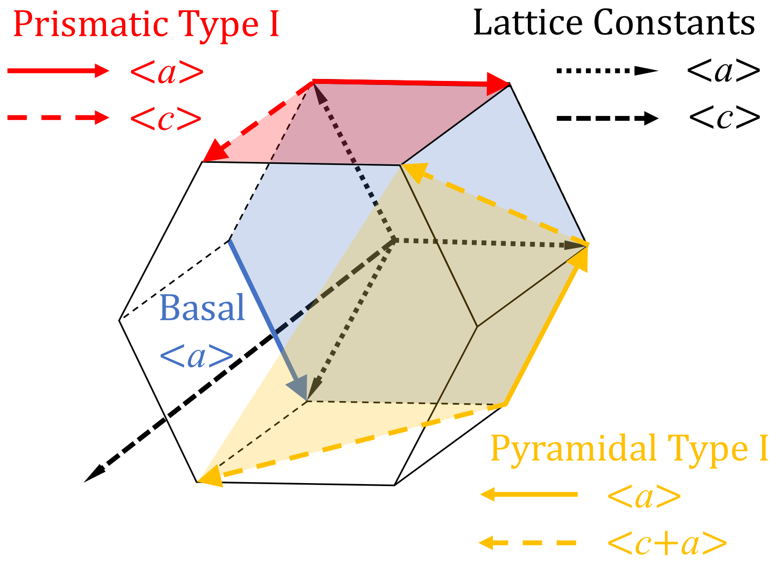
$$CRSS_{prismatic\,<a>} = 439 \cdot exp\left(-\frac{T}{185}\right)$$

$$CRSS_{basal\,<a>} = 11.3 \cdot exp\left(\frac{807.7}{T}\right)$$

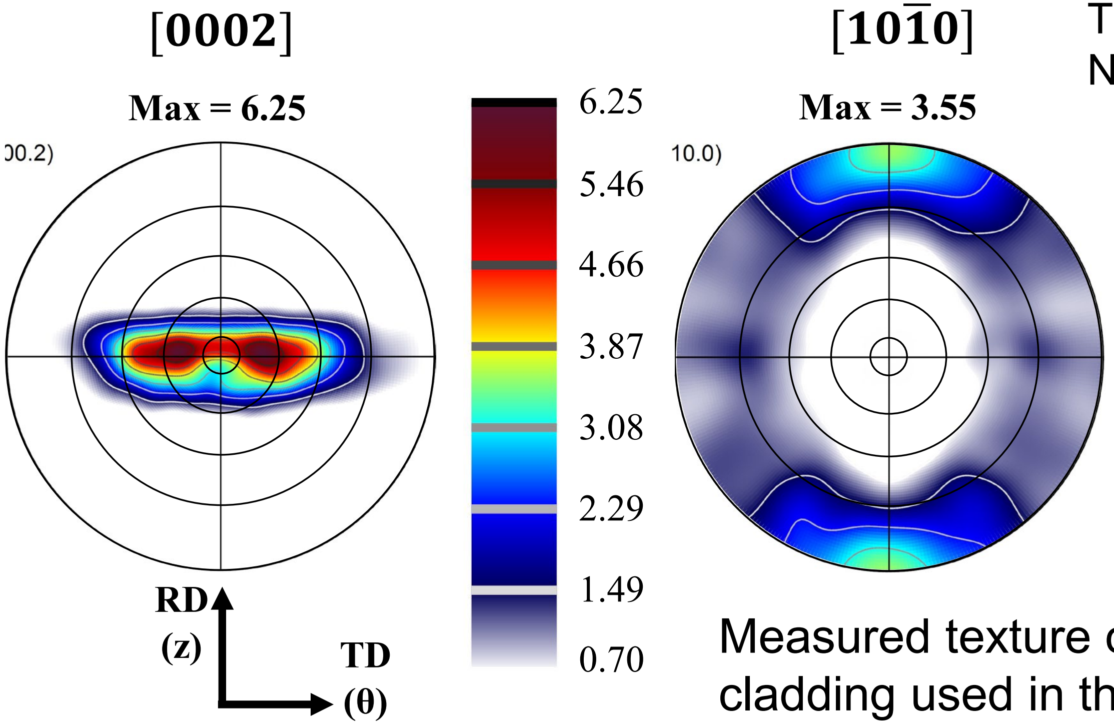
$$CRSS_{pyramidal\,<c+a>} = 837 \cdot exp\left(-\frac{T}{300}\right)$$

Textured Zircaloy-4 Cladding

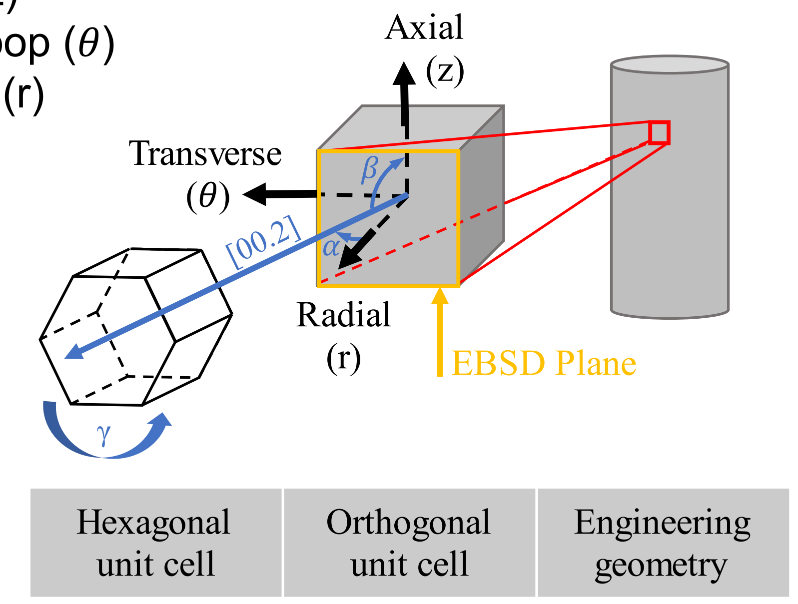
- Hexagonal close-packed (HCP) structure
- Pilgering and rolling results in similar texture
- Texture retained to resist cladding thinning
- Multiscale anisotropy



Rolled direction (RD) = axial (z)
Transverse direction (TD) = hoop (θ)
Normal direction (ND) = radial (r)

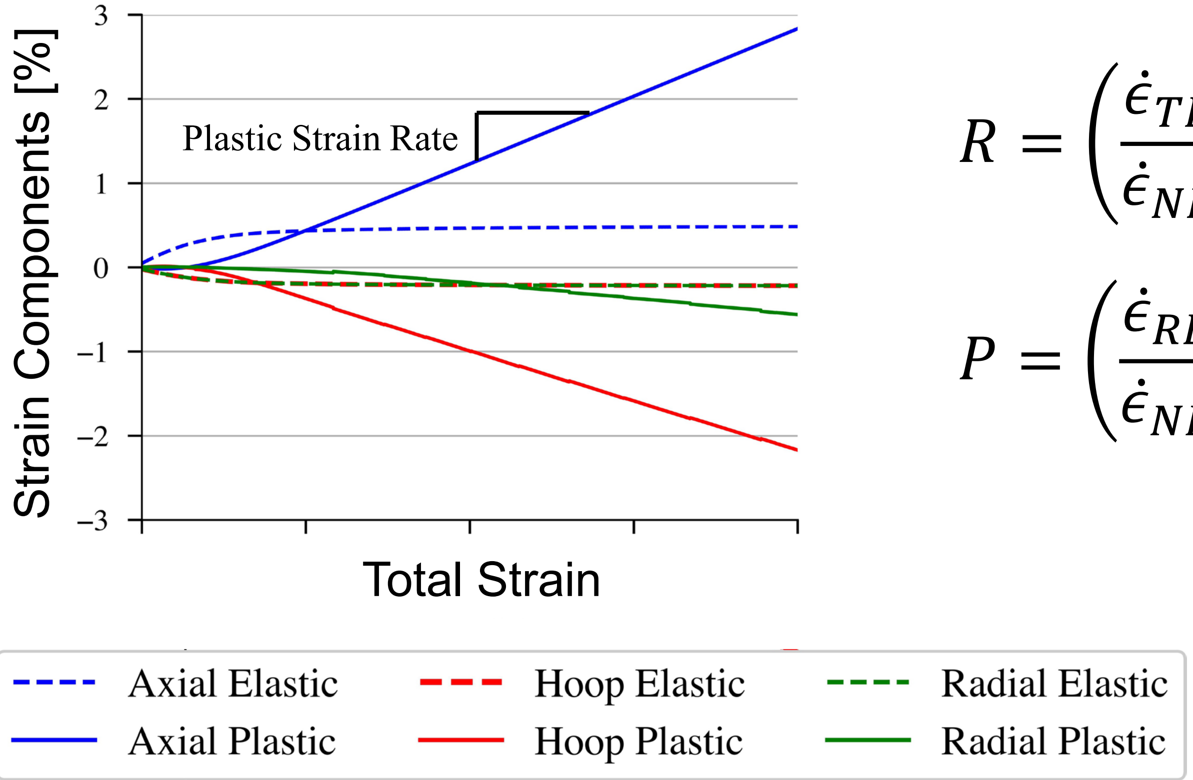


Measured texture of Zry-4 cladding used in this study



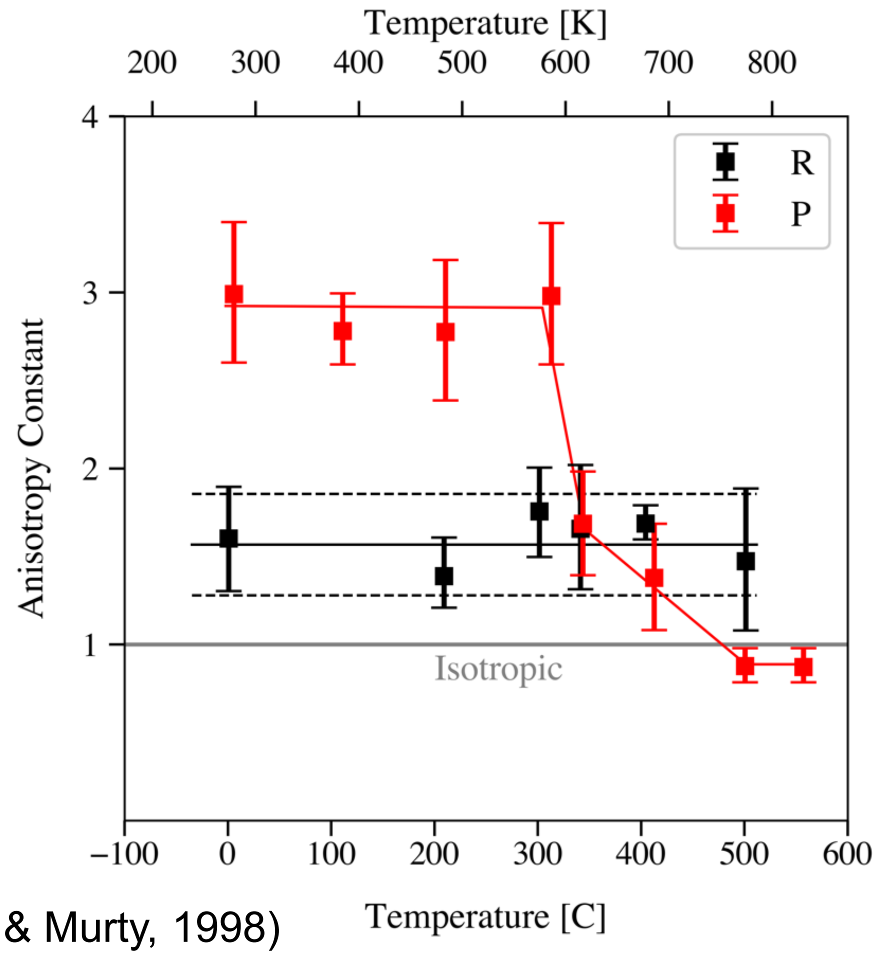
Mechanical Anisotropy in Textured Zircaloy-4

- **Anisotropy defined by plastic strain ratios**
- **Unloaded plastic strains equal for isotropic**
- **Temperature <u>independent</u> anisotropy for RD**
- **Temperature <u>dependent</u> anisotropy for TD**



$$R = \left(\frac{\dot{\epsilon}_{TD}}{\dot{\epsilon}_{ND}}\right)_{\sigma_{RD}}$$

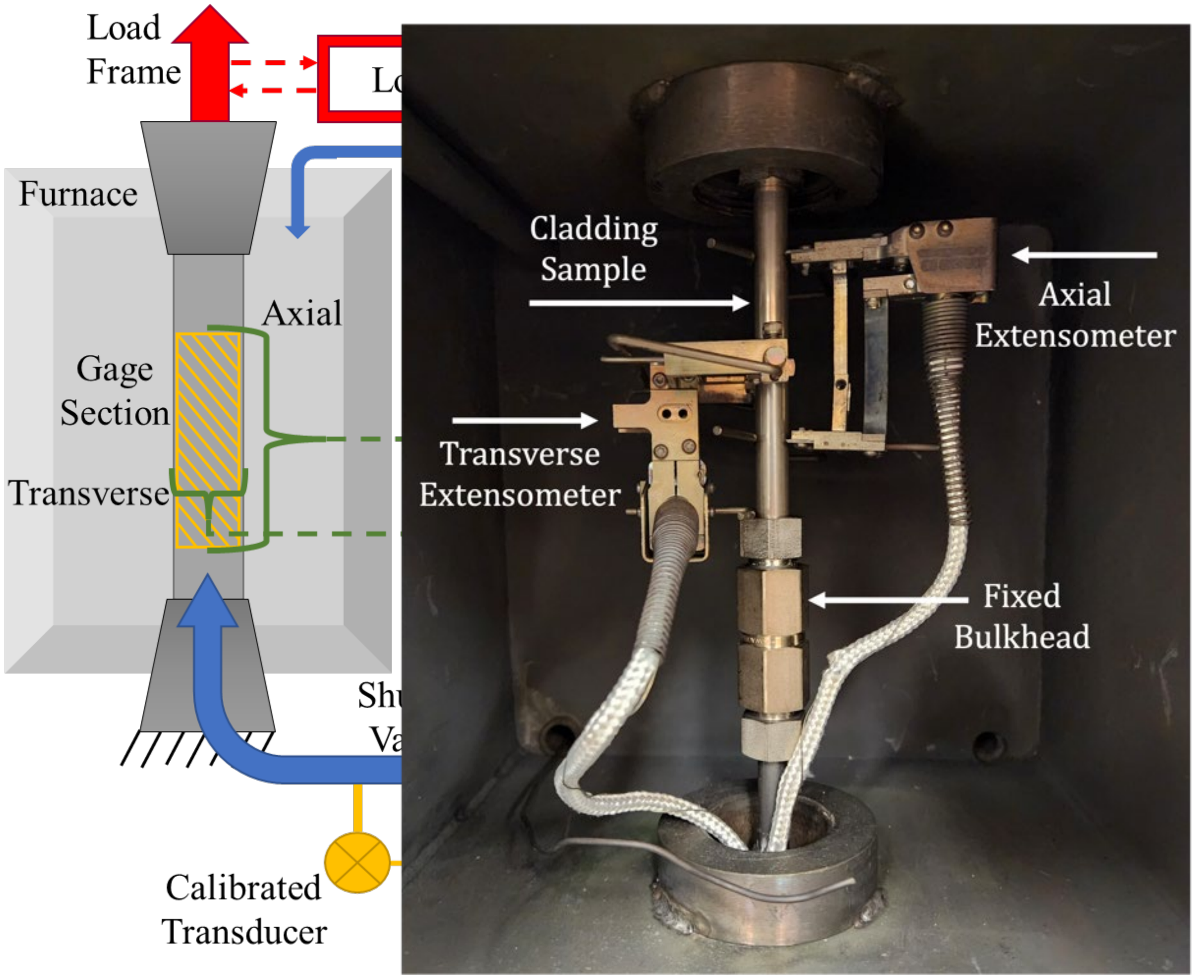
$$P = \left(\frac{\dot{\epsilon}_{RD}}{\dot{\epsilon}_{ND}}\right)_{\sigma_{TD}}$$



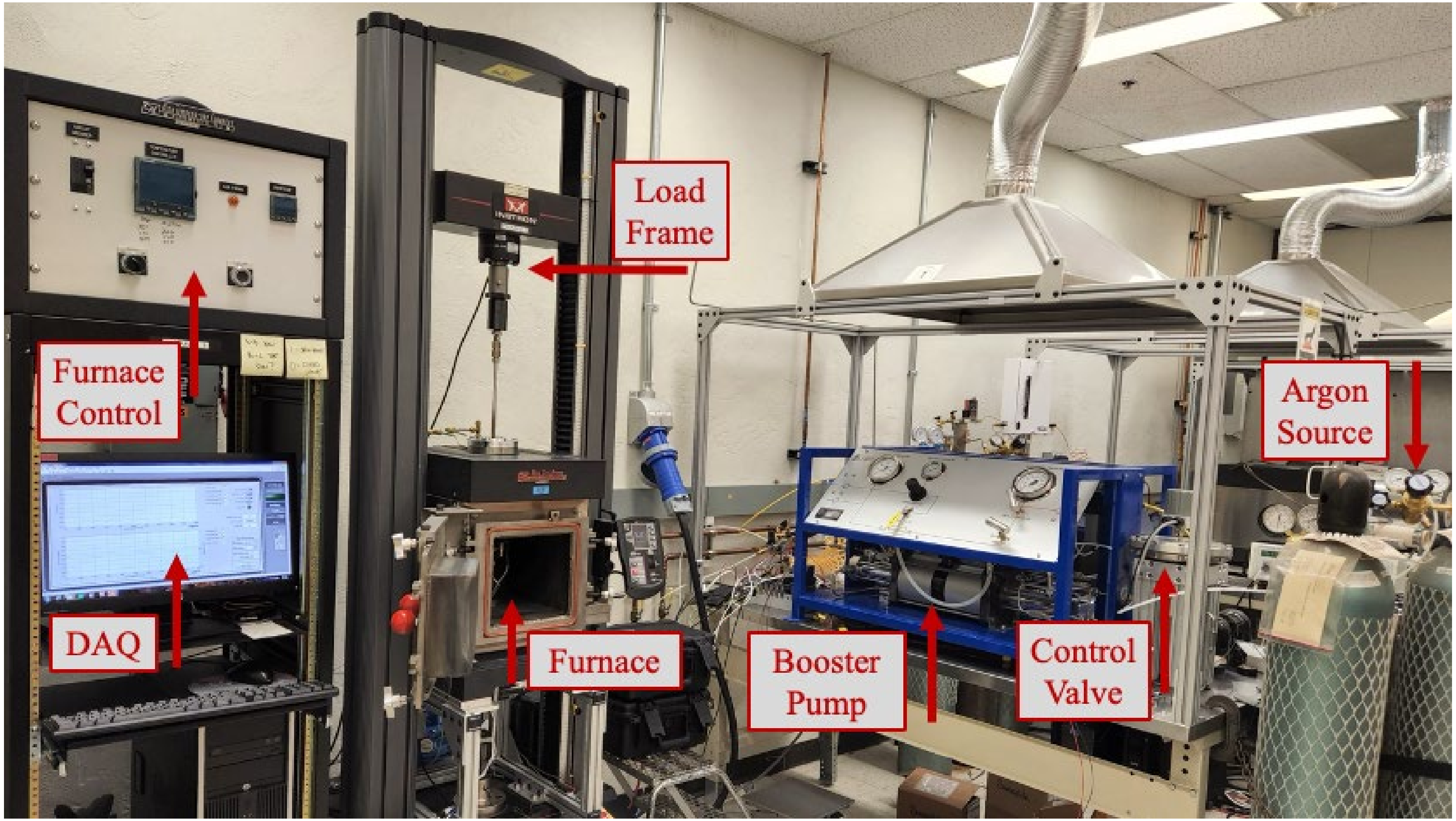
(Wang & Murty, 1998)

Mechanical Testing

- **Loading system**
  - Full tube axial tension
  - Internal pressure
- **Strain decomposition**
  - Axial and transverse extensometers
  - Plastic flow volume conservation

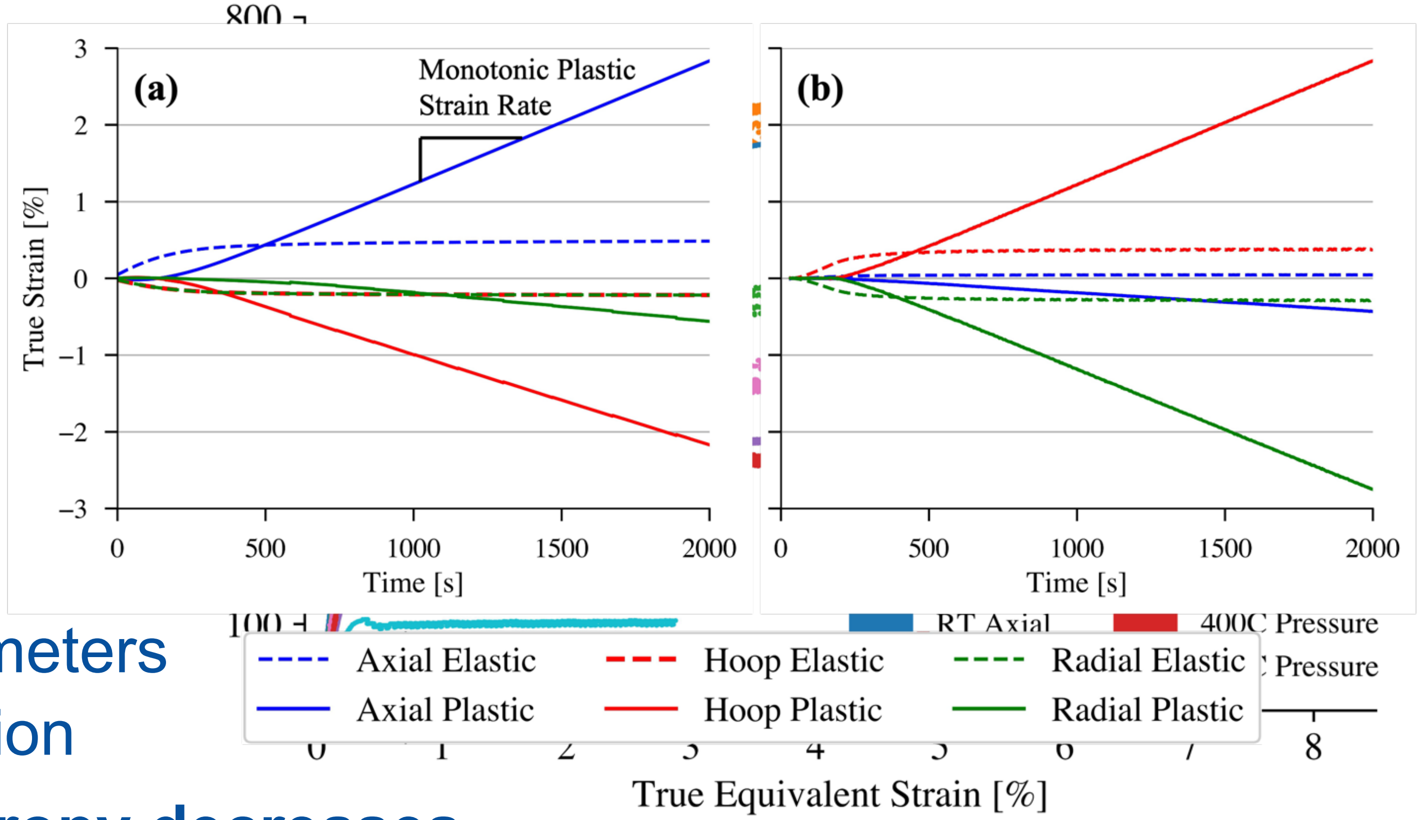


Mechanical Testing



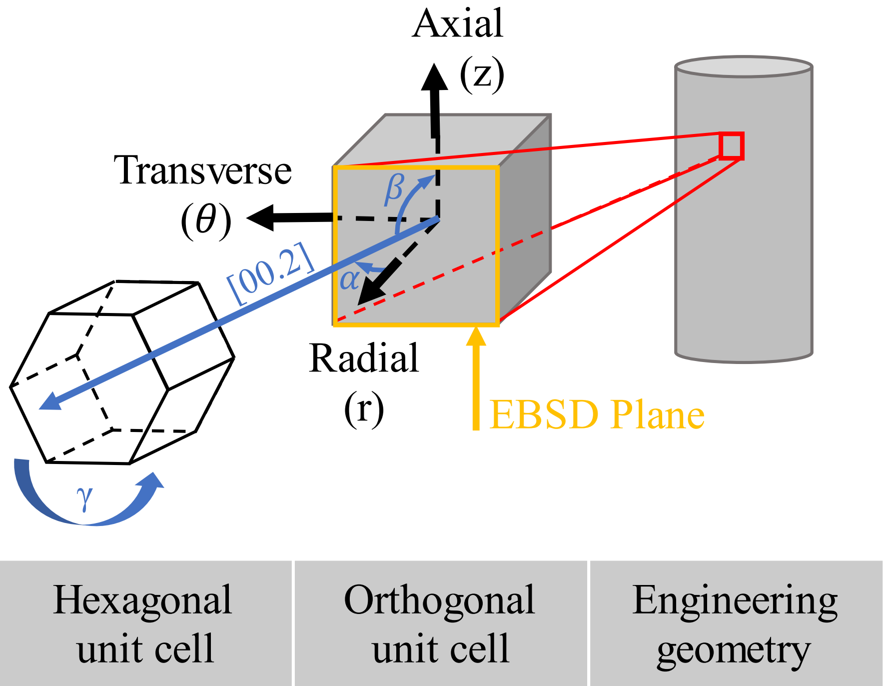
Mechanical Testing

- **Loading system**
  - Full tube axial tension
  - Internal pressure
- **Strain decomposition**
  - Axial and transverse extensometers
  - Plastic flow volume conservation
- **Found internal pressure anisotropy decreases significantly between 275 and 400 °C**



Resolved Shear Stress (RSS) Analysis

- **Use generalized Schmid factor (GSF)**
  - Normalized for any stress magnitude
  - Generalized to multiaxial stresses
- **Calculate SF on primary glide planes**
- **Evaluate SF for different orientations**
- **Project using basal <*a*> pole figures**



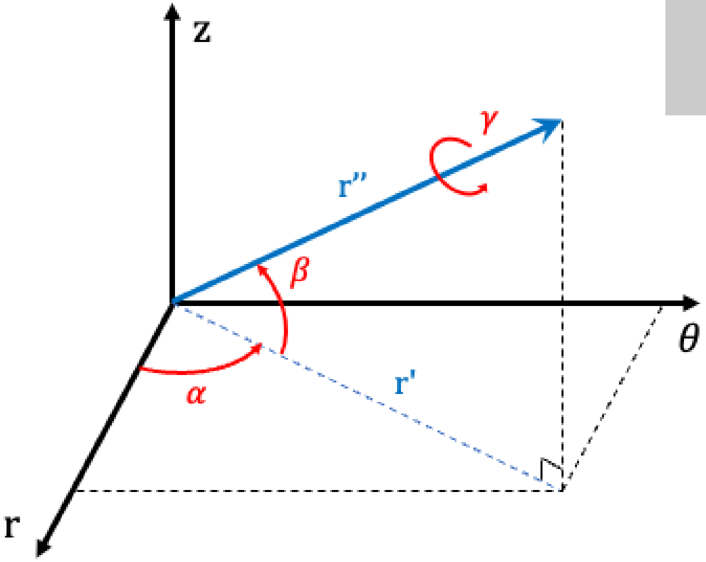
Rotation matrix

$$GSF = \hat{b} \cdot \mathbf{g} \cdot \boldsymbol{\sigma} \cdot \mathbf{g}^{T} \cdot \hat{n}$$

Slip direction

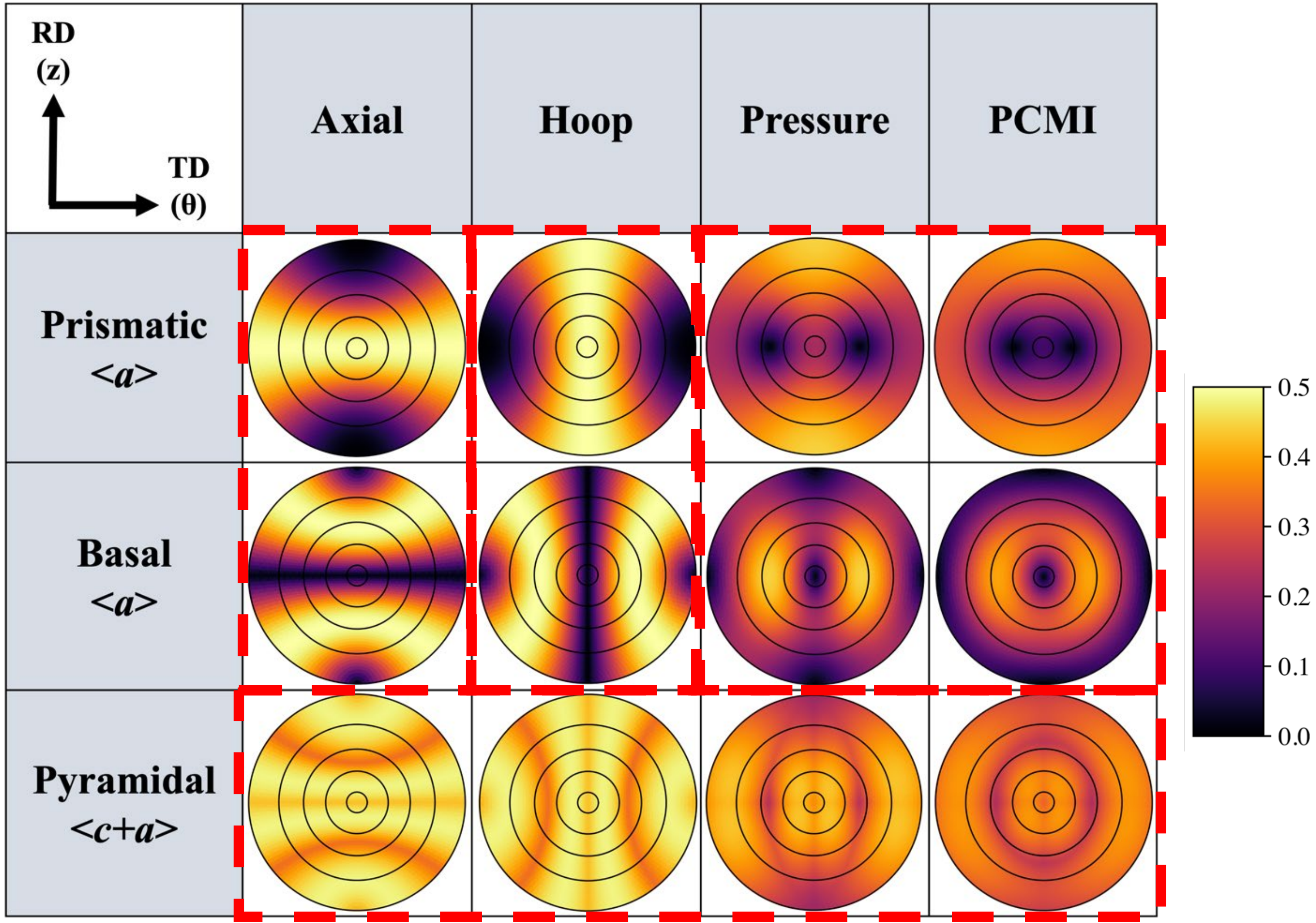
Glide plane normal

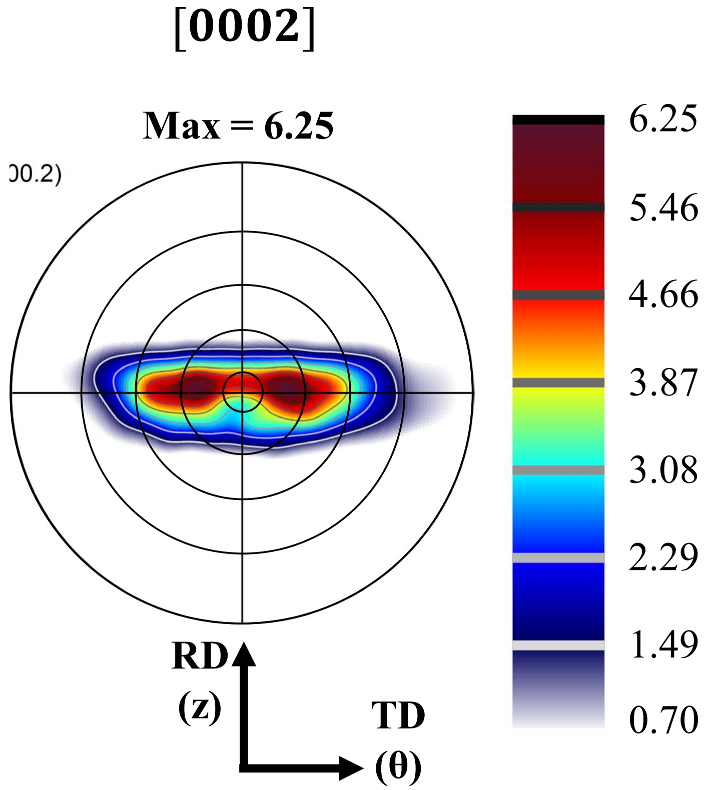
Applied stress



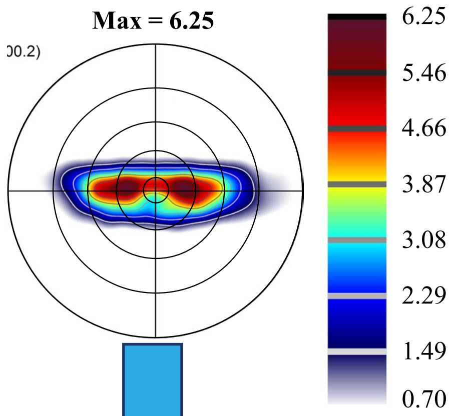
RSS Analysis Results

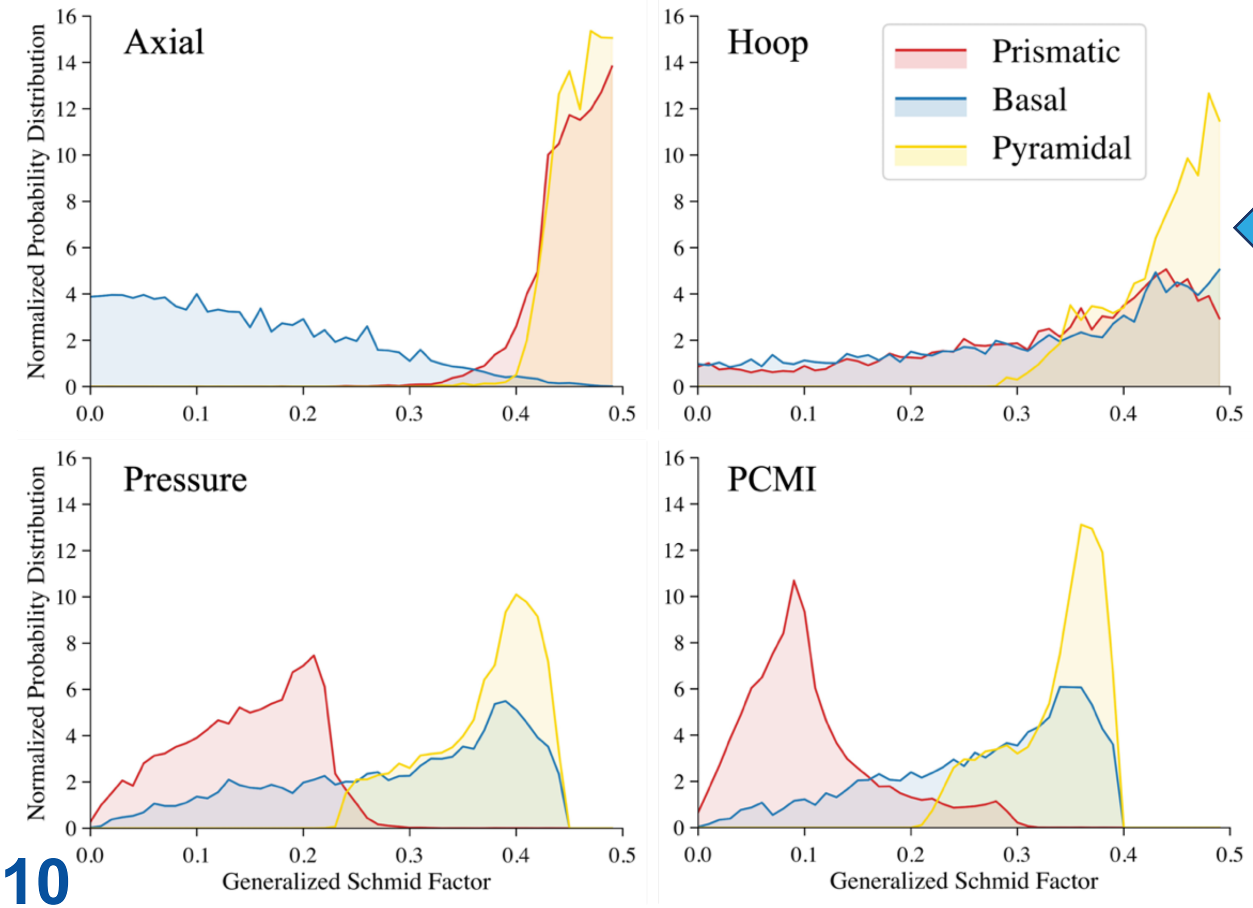
- **Max RSS for slip directions displayed**

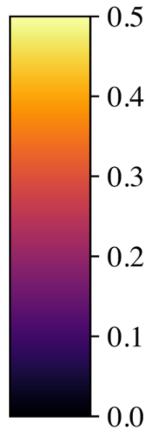


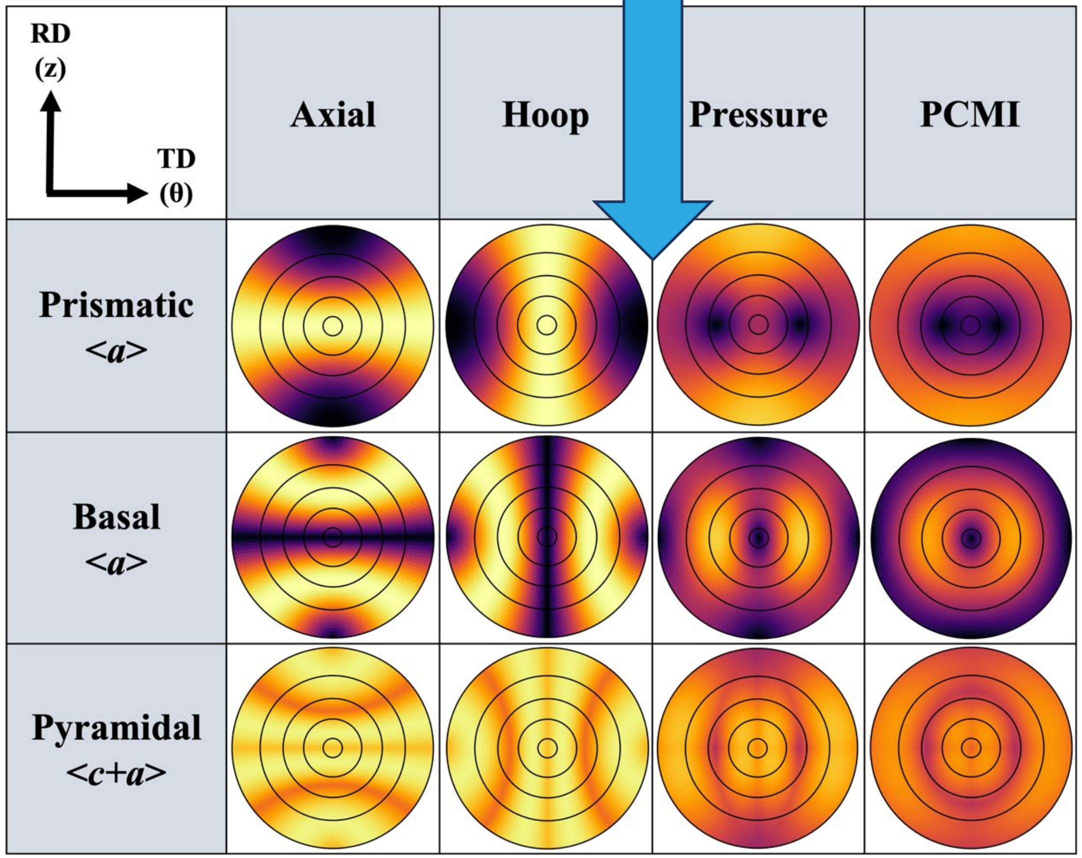


Microstructure RSS Distributions



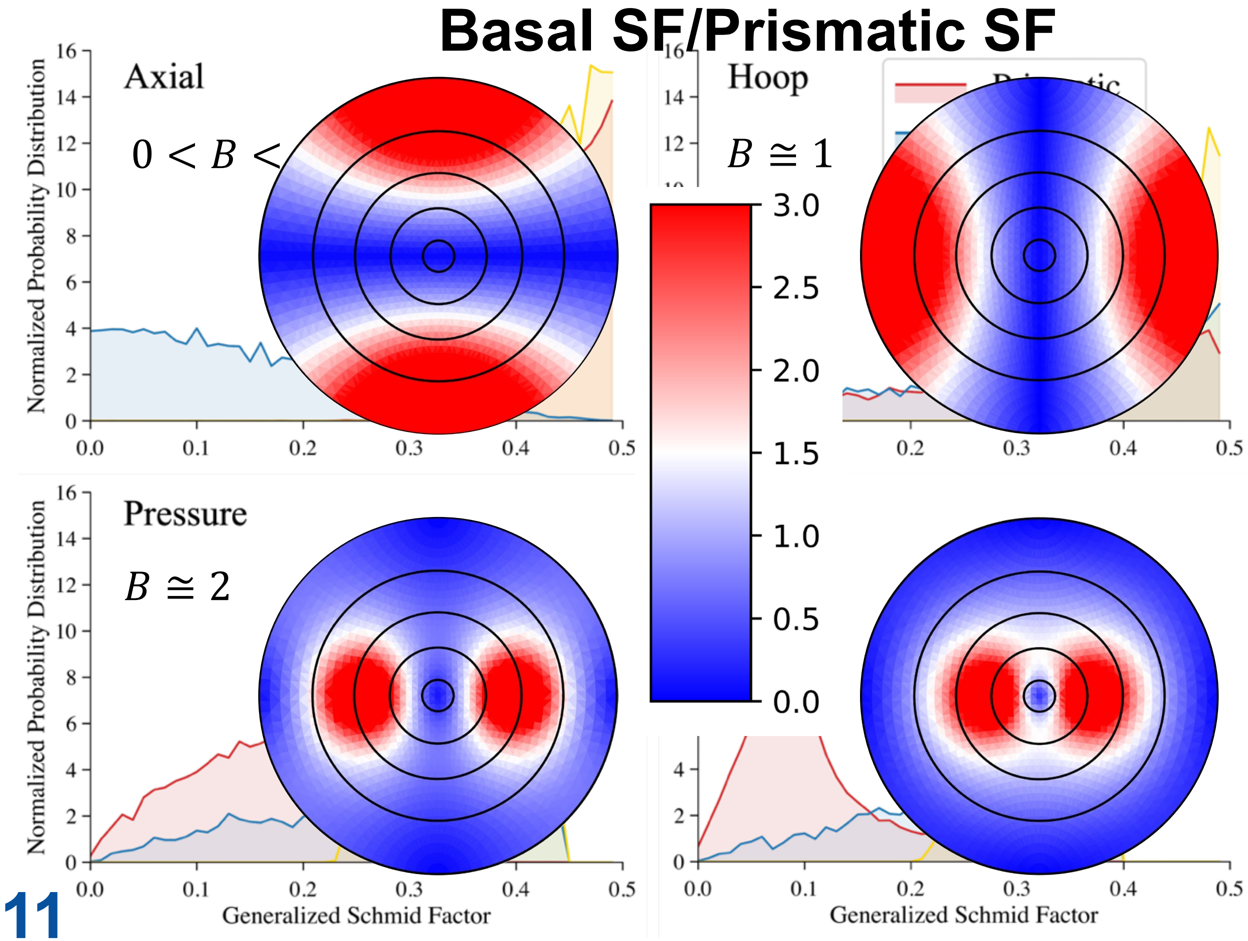




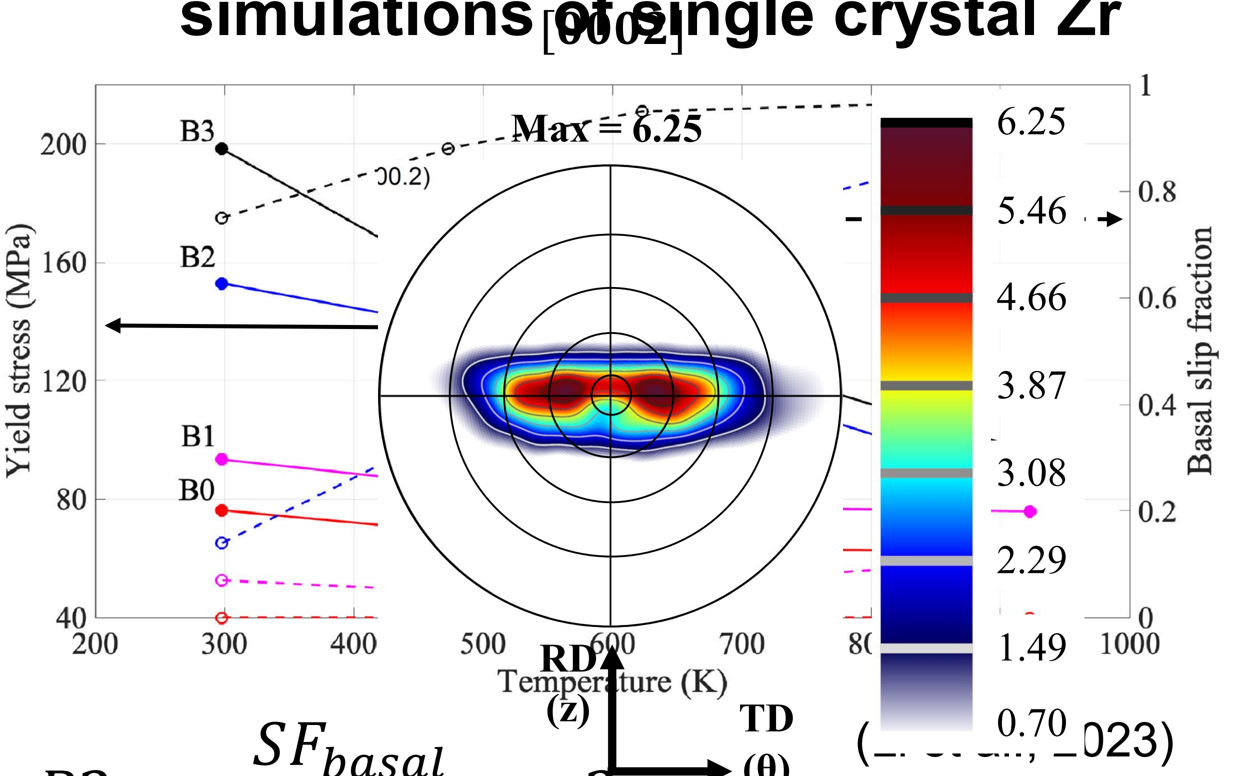


Schmid Factor Ratios

- **Basal <a> activity increases temperature dependence**



Discrete dislocation dynamics simulations of single crystal Zr



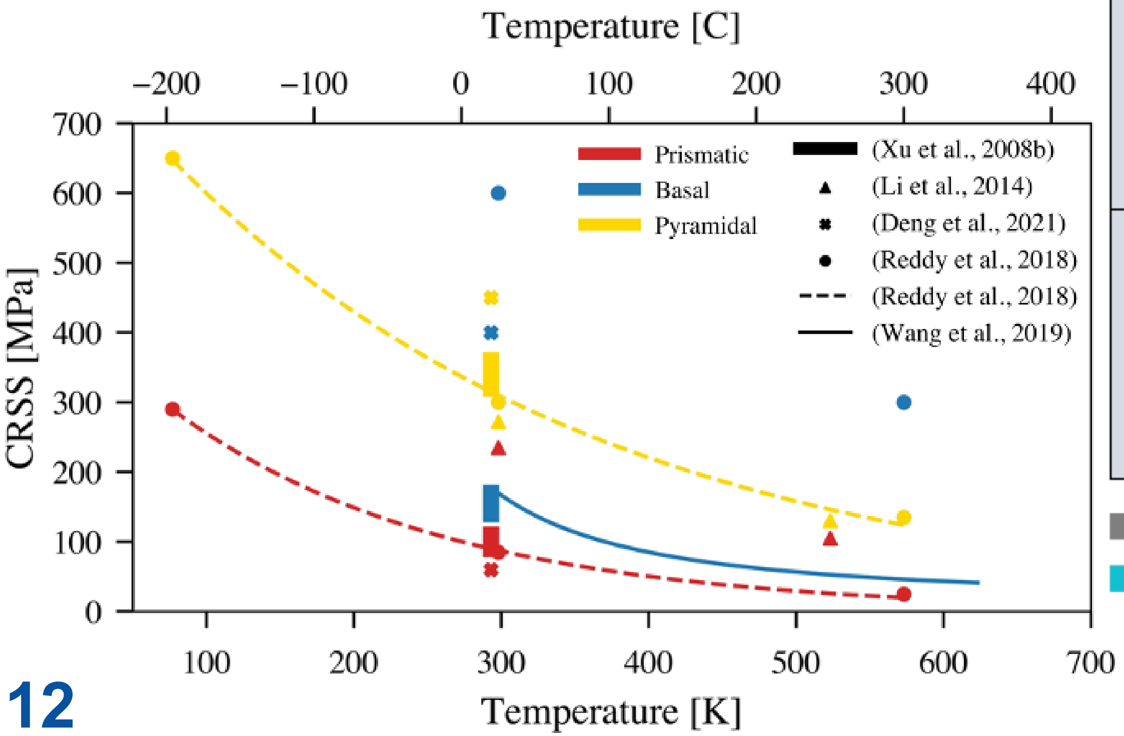
$$B2 \rightarrow \frac{SF_{basal}}{SF_{prismatic}} = 2$$

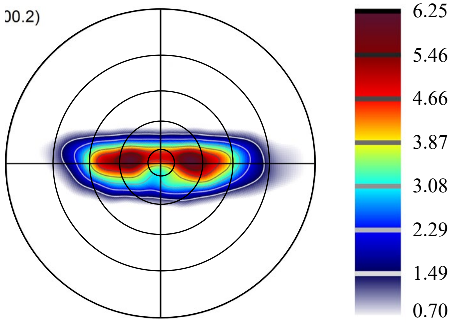
(... 2023)

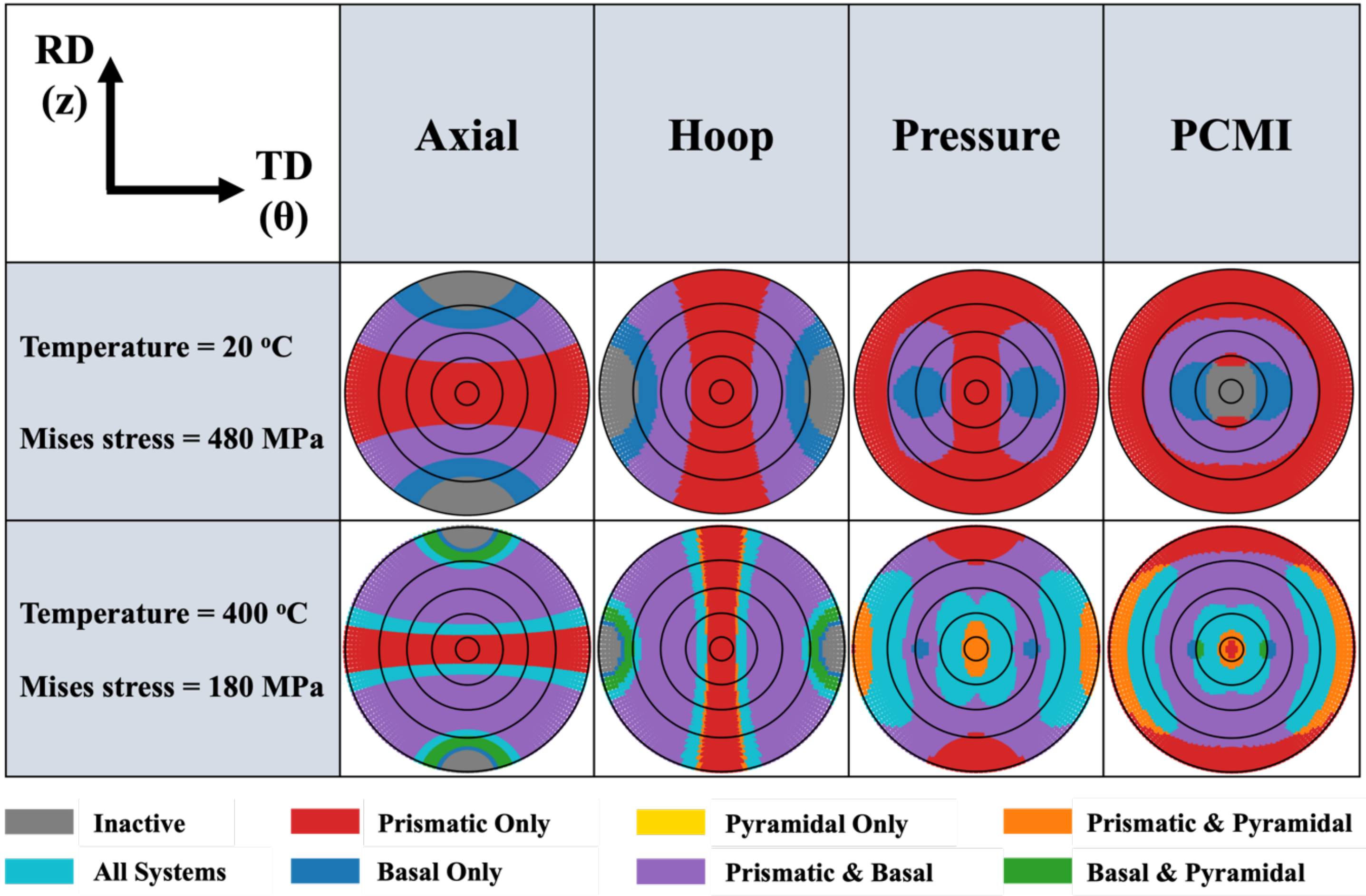
Temperature Dependent Activation

- **Critical-RSS (CRSS) ratio decreases with temperature**

$$RSS - CRSS(T) = \begin{cases} +\ \text{active} \\ -\ \text{inactive} \end{cases}$$

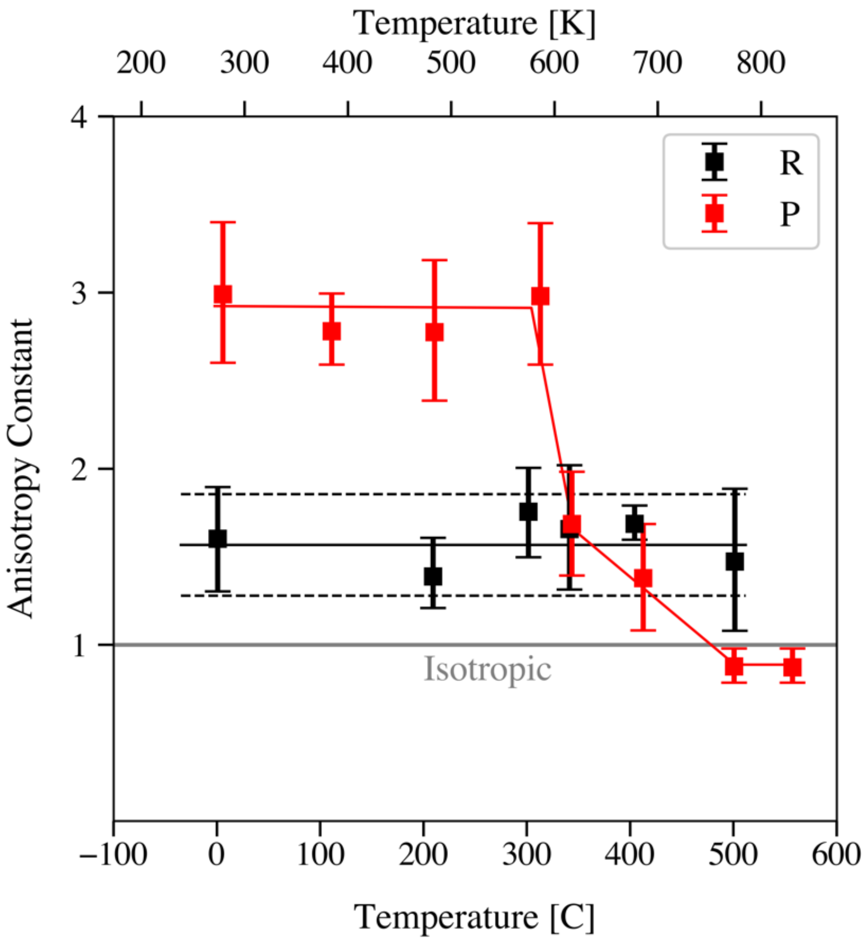






Conclusions

- **Axial stress produces:**
  - High SF on prismatic <a> systems
  - Low SF on basal <a> systems
  - Dominant prismatic <a> slip activity
  - Temperature independent mechanical anisotropy
- **Hoop stress produces:**
  - Mixed SF on prismatic <a> systems
  - Mixed SF on basal <a> systems
  - Competitive basal <a> and prismatic <a> slip activity
  - Temperature dependent mechanical anisotropy
- **Biaxial stress states produce:**
  - Low SF on prismatic <a> systems
  - High SF on basal <a> systems
  - Competitive basal <a> and prismatic <a> slip activity
  - Temperature dependent mechanical anisotropy



(Wang & Murty, 1998)

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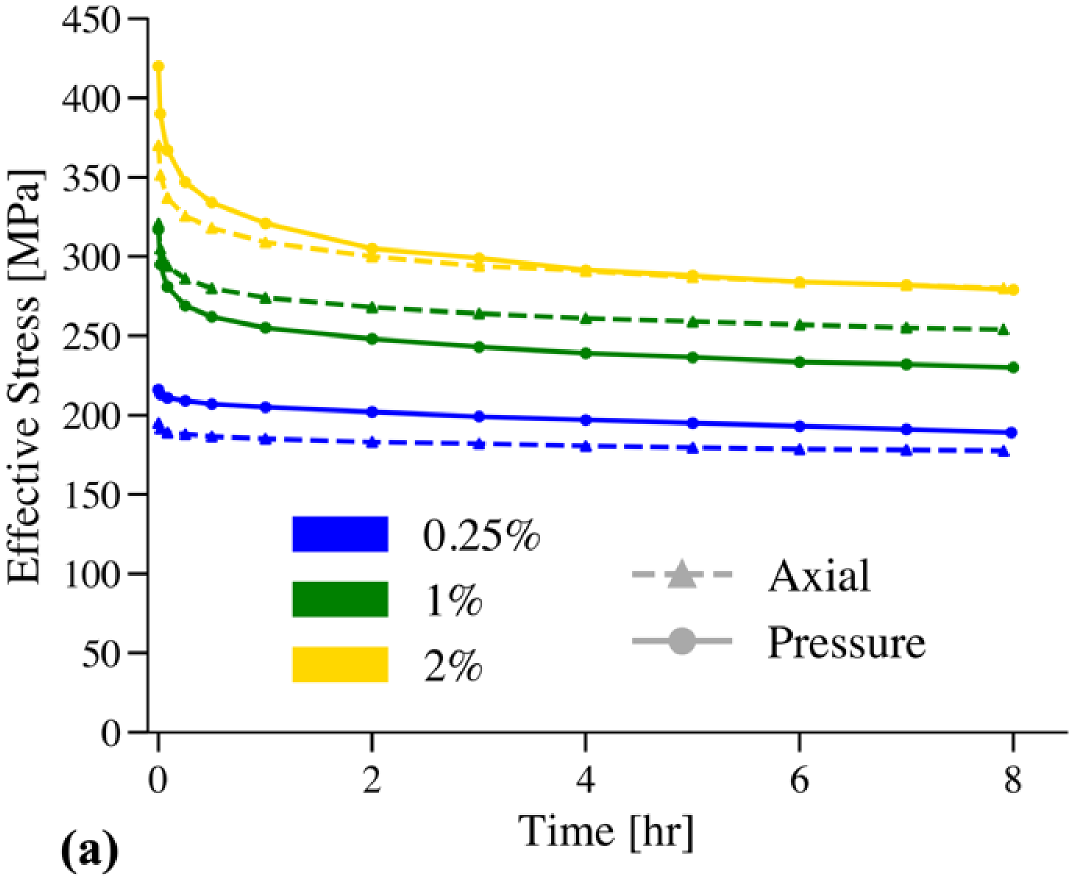
Future Work – Effect on Stress Relaxation



Activation Volume Analysis
Preliminary Results