

Vieillissement et corrélations spatiales

Aspects directionnels du vieillissement

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Motivations: yield point and Bauschinger overshoot



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Absence of yield points in iron on strain reversal after aging, and the Bauschinger overshoot [☆]

Robert A. Elliot ¹, Egon Orowan ², Teruyoshi Udoguchi ³, Ali S. Argon ^{*}

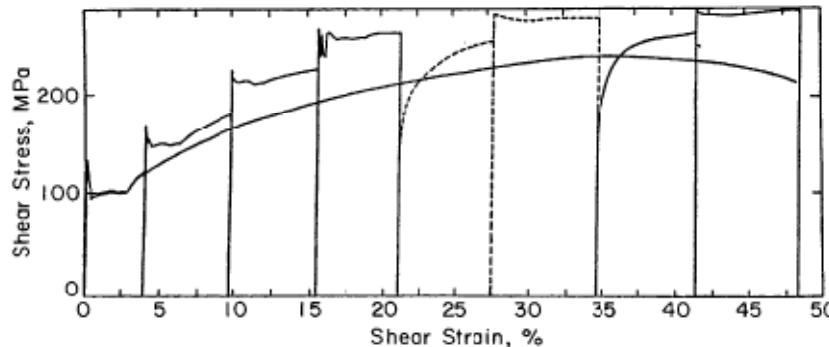


Fig. 4. As Fig. 2 but the sign of straining was opposite to that of the initial straining where the line is dashed. No yield phenomenon after aging whenever the straining is reversed with respect to the straining just before aging.

Outline

- 1. Directionality of yield point

- ✓ Yield point phenomenon, Lüders band
 - ✓ Directionality of yield point

- 2. Field Dislocation Mechanics

- ✓ Governing equations of FDM
 - ✓ Phenomenological Mesoscale FDM
 - ✓ Heuristic 1D-model in torsion

- 3. Modeling strain aging

- 4. Results

- ✓ 3D simulations
 - ✓ Interplay between strain aging and polar dislocation microstructure

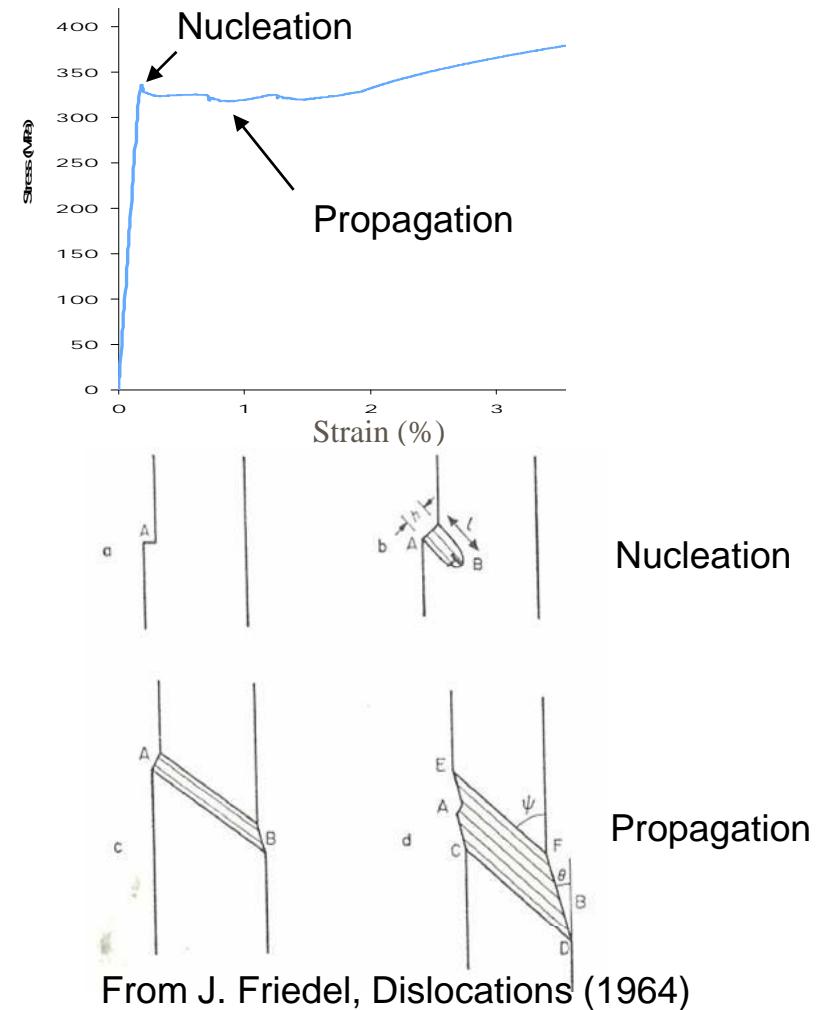
- 4. Conclusions

Directionality of yield point

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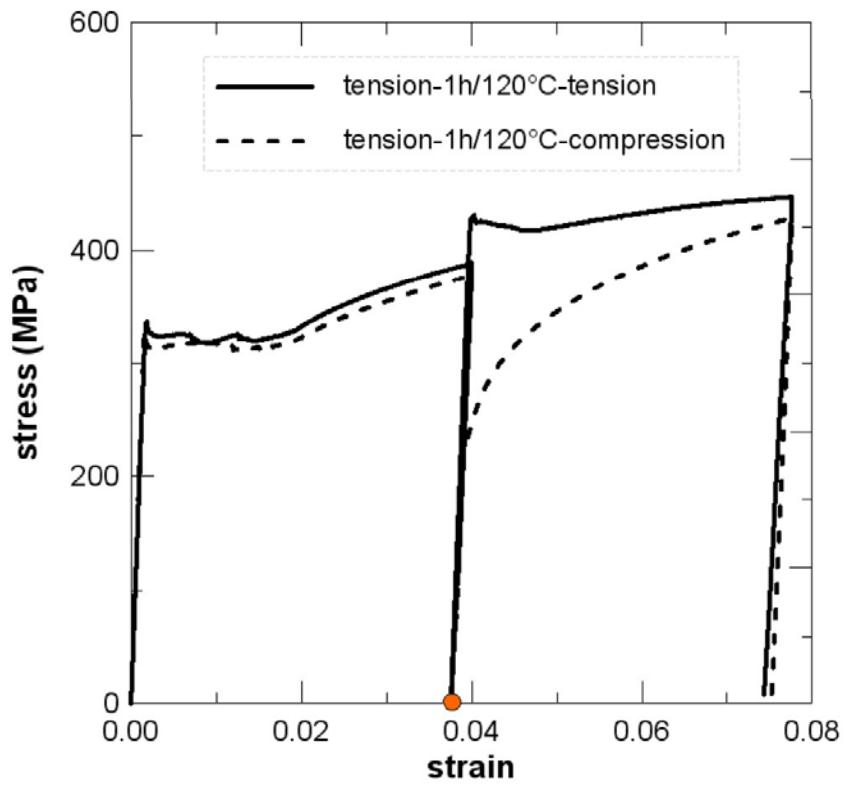
The yield point phenomenon

- Drop in stress from upper yield point (UYP) to lower yield point (LYP), corresponding to band nucleation and propagation
- Band of localized plastic activity propagating at constant stress (LYP)
- Strain aging is responsible: solute atoms diffuse to arrested dislocations, increasing unpinning stress up to UYP
- Strain incompatibility induces internal stress development in the vicinity of the band



Modeling scheme

- Forward straining
 - ✓ Unpinning of dislocations needs UYP
- Reverse straining
 - ✓ Bauschinger effect
 - ✓ Unpinning of dislocations is favored
- Modeling directions
 - ✓ The model should couple strain aging and internal stress development



Field Dislocation Mechanics

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Field Dislocation Mechanics

- ✓ Lattice incompatibility

$$\operatorname{curl} \mathbf{U}_p^\perp = -\operatorname{curl} \mathbf{U}_e^\perp = -\boldsymbol{\alpha}$$

- ✓ Elasto-viscoplasticity

$$\mathbf{T} = \mathbf{C} : \{\mathbf{U}_e\} = \mathbf{C} : \{\mathbf{U}_e^\perp + \mathbf{U}_e^{/\!/}\} = \mathbf{C} : \{\mathbf{U}_e^\perp + \operatorname{grad} \mathbf{u} - \mathbf{U}_p^{/\!/}\}$$

$$\mathbf{T} = \mathbf{C} : \{\operatorname{grad} \mathbf{u} - \mathbf{U}_p^\perp - \mathbf{U}_p^{/\!/}\} = \mathbf{C} : \{\operatorname{grad} \mathbf{u} - \mathbf{U}_p\}$$

- ✓ Compatible plastic distortion rate

$$\dot{\mathbf{U}}_p^{/\!/} = (\boldsymbol{\alpha} \times \mathbf{V} + \mathbf{L}_p)^{/\!/}$$

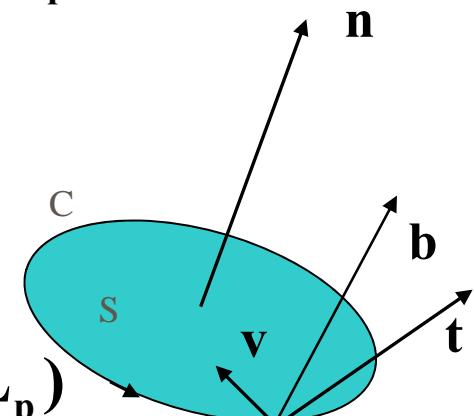
- ✓ Equilibrium + B.C.

$$\operatorname{div} \mathbf{T} = \mathbf{0}$$

- ✓ Dislocation transport

$$\dot{\boldsymbol{\alpha}} = -\operatorname{curl} \dot{\mathbf{U}}_p = -\operatorname{curl} (\boldsymbol{\alpha} \times \mathbf{V} + \mathbf{L}_p)$$

- ✓ Constitutive behavior specified through \mathbf{V} and \mathbf{L}_p



Acharya, JMPS **49**, 761 (2001), Acharya & Roy, JMPS **54**, 1687 (2006)

Nonlocal character of FDM

- 3D balance of momentum
- Long-range correlations due to incompatible lattice distortion
- Short-range interactions due to dislocation transport
- Not implemented in the present investigation:
 - Continuous modeling of interfaces → relations on limiting values of elastic/plastic distortion from both sides of the interface
 - Nonlocal elasticity at nanoscale

→ **nonlocal character** of the framework

Finite Element implementation

- Rate form of equilibrium

$$\operatorname{div} \dot{\mathbf{T}} = \operatorname{div} \mathbf{C} : \{ \operatorname{grad} \mathbf{v} - \dot{\mathbf{U}}_P \} = \mathbf{0}$$

$$\mathbf{T} \quad \curvearrowleft \quad \curvearrowright \quad \mathbf{a}, \dot{\mathbf{U}}_P = \mathbf{a} \times \mathbf{V} + \mathbf{L}_P$$

- Transport

$$\dot{\mathbf{a}} = -\operatorname{curl} \dot{\mathbf{U}}_P$$

- Numerical implementation

- ✓ Equilibrium problem solved using ABAQUS
- ✓ UMAT for transport problem solving
- ✓ Galerkin-Least Squares FEM scheme for UMAT

S.N. Varadhan, A.J. Beaudoin, A. Acharya and C. Fressengeas, MSMSE **14**, 1245 (2006)

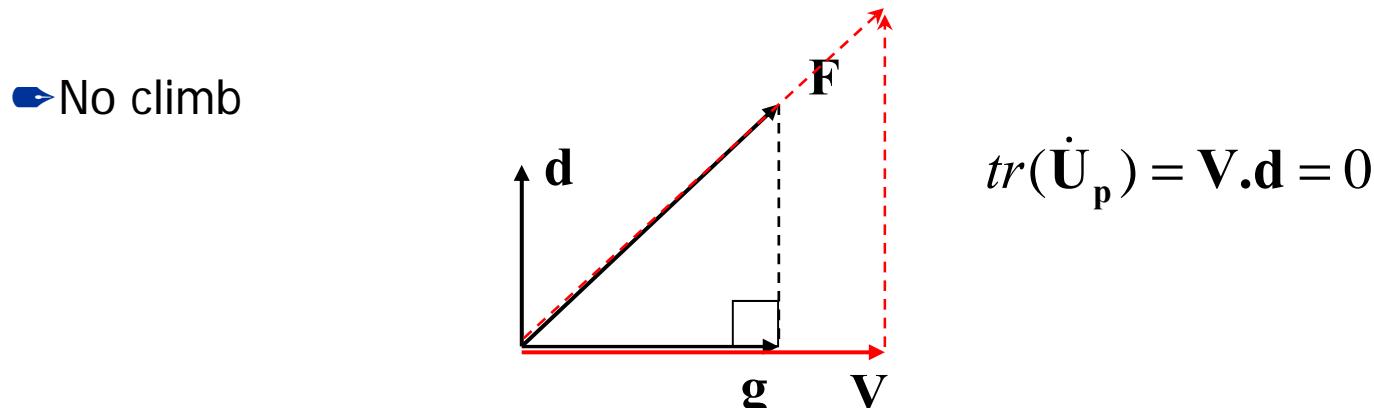
Material behavior

- Dislocation velocity

- ✓ Positive dissipation : $D = \mathbf{T} : \dot{\mathbf{U}}_p = \mathbf{V} \cdot \mathbf{F} \geq 0$
 - ✓ \mathbf{F} : "Peach-Köhler" driving force conjugate to dislocation velocity

$$\mathbf{F} = \mathbf{T}^t \cdot \mathbf{b} \times \mathbf{t}; \quad \mathbf{a} = \mathbf{b} \otimes \mathbf{t}$$

- ✓ Pressure independence ("associative plasticity")



$$\mathbf{g} = \mathbf{F} - (\mathbf{F} \cdot \frac{\mathbf{d}}{|\mathbf{d}|}) \frac{\mathbf{d}}{|\mathbf{d}|}; \quad \mathbf{V} = V \frac{\mathbf{g}}{|\mathbf{g}|}; \quad \mathbf{V} \cdot \mathbf{F} = \mathbf{V} \cdot \mathbf{g} = V > 0$$

Crystal plasticity

- ✓ Schmid tensor, resolved shear stress

$$\mathbf{P}_s = \mathbf{m}_s \otimes \mathbf{n}_s, \quad \boldsymbol{\tau}_s = \mathbf{T} : \mathbf{P}_s$$

- ✓ Gradient velocity tensor, slip system shear rate

$$\mathbf{L}_p = \mathbf{grad} \dot{\mathbf{u}}_p = \left(\frac{\partial \dot{u}_i^p}{\partial x_j} \right) = \sum_s \dot{\gamma}_s \mathbf{P}_s ; \dot{\gamma}_s = \dot{\gamma}_s(\boldsymbol{\tau}_s, T \dots)$$

- ✓ Orowan equation

$$\dot{\gamma}_s = \rho_m b V_s$$

- ✓ Dislocation velocity through strain aging model

Modeling strain aging

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Strain aging model

- Dislocation velocity

$$V = V_s = v_0 \rho_f^{-1/2} \operatorname{sgn}(\tau_s) \exp\left(\frac{V^*}{kT} \sigma^*\right)$$

- Waiting time

$$V_s = \frac{\rho_f^{-1/2}}{t_w + t_f} \approx \frac{\rho_f^{-1/2}}{t_w} \longrightarrow t_w^{-1} = v_0 \exp\left(\frac{V^*}{kT} \sigma^*\right)$$

- Effective stress for obstacle overcoming $\sigma^* = |\tau_s| - \sigma_s - \sigma_0 - \sigma_h$

- Forest (Taylor) hardening

$$\sigma_h = \bar{\alpha} \mu b \sqrt{\rho_f}$$

- Solute stress (Louat)

$$\sigma_s = f(1 - \exp(-(t_a/\tau)^{2/3}))$$

- McCormick kinetics for static aging

$$\dot{t}_a = 1 - t_a/t_w$$

Strain aging model

- Statistical dislocation densities evolved using modified Kubin-Estrin model

$$\begin{aligned}\dot{\rho}_m &= \left(\frac{C_1}{b^2} - \frac{C_3}{b} \sqrt{\rho_f} \right) \dot{\Gamma} \\ \dot{\rho}_f &= \left(\frac{C_0}{b} |\alpha| + \frac{C_3}{b} \sqrt{\rho_f} - C_4 \rho_f \right) \dot{\Gamma} \\ \dot{\Gamma} &= |\mathbf{a} \times \mathbf{V}| + |\mathbf{L}_P|\end{aligned}$$

- C_o reflects the contribution of GNDs to forest hardening

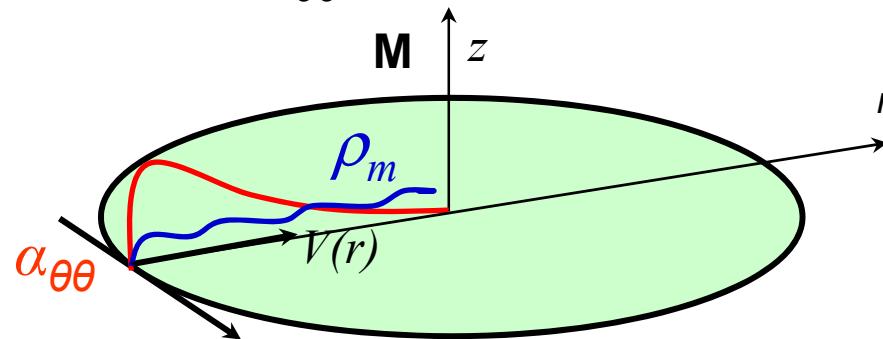
A. Acharya, A.J. Beaudoin, JMPS **48**, 2213 2000

V. Taupin et al, Acta Mater. **56**, 3002 (2008)

S. Varadhan et al, JMPS **57**, 1733 (2009)

Heuristic 1-D model at slip plane level in pure torsion

- Tangential screw density $\alpha_{\theta\theta}$, plastic distortion rate $\dot{\varepsilon}_{\theta z} = \alpha_{\theta\theta} V_r + \rho_m b V$



- Transport $\dot{\alpha}_{\theta\theta} + \dot{\varepsilon}_{\theta z, r} = 0$
- Dislocation velocity

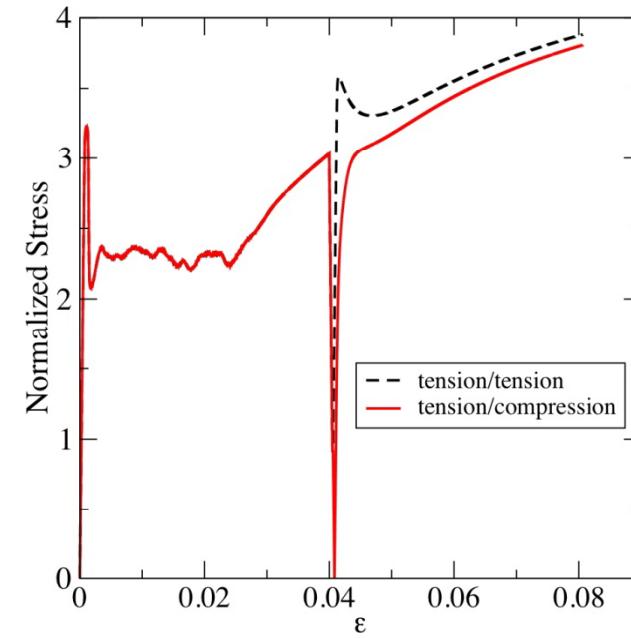
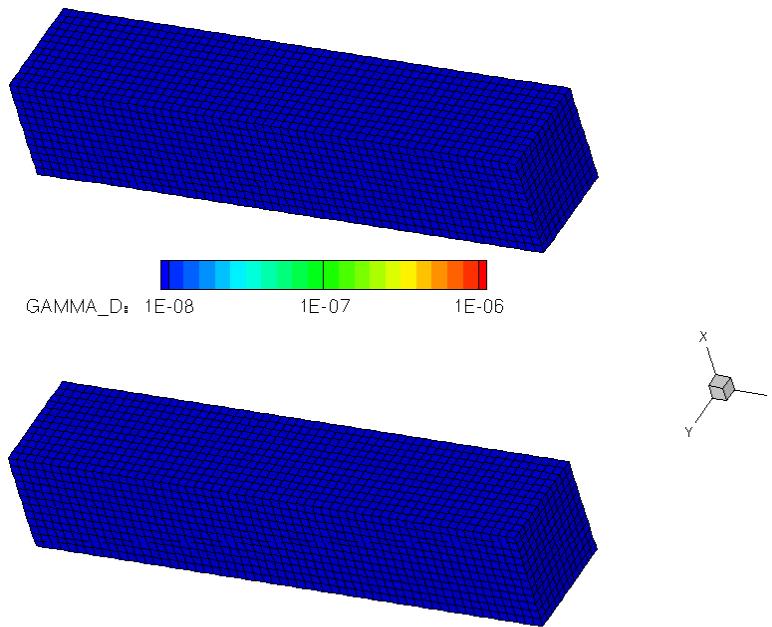
$$V_r = V = v_0 \rho_f^{-1/2} \operatorname{sgn}(\sigma_{\theta z} - \sigma_\mu) \exp \left(\frac{V^*}{kT} (|\sigma_{\theta z}| - \sigma_\mu \operatorname{sgn}(\sigma_{\theta z}) - \sigma_s - \sigma_h) \right)$$

- Back-stress evolution, kinematic-hardening-style $\dot{\sigma}_\mu = \tilde{\alpha} \mu \alpha_{\theta\theta} V_r - \frac{\sigma_\mu}{\tau_R}$, $\tau_R = \frac{\hat{a}b}{|V_r|}$

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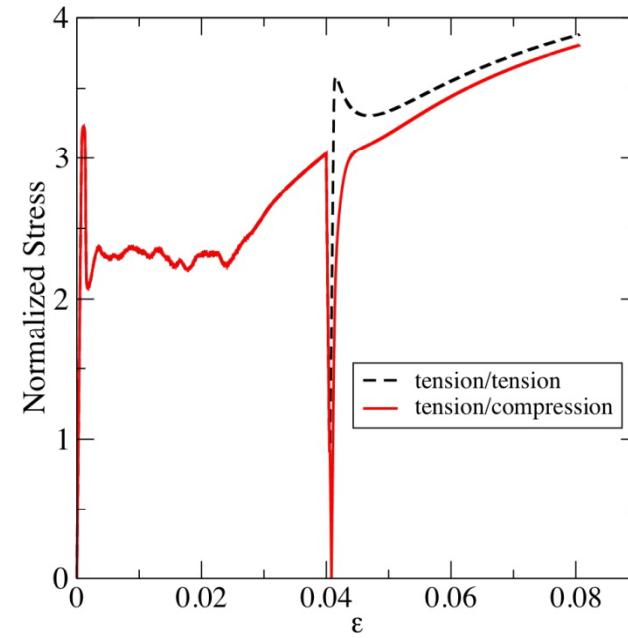
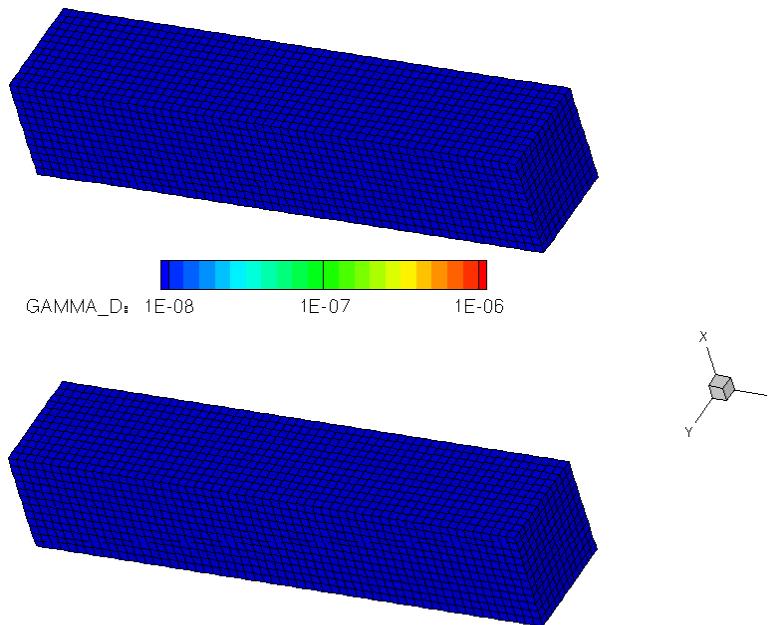
Results



- Polycrystal, each element is assigned a single crystallographic orientation
- $12 \times 12 \times 60 = 8640$ elements
- Galerkin FEM method for equilibrium equation
- Galerkin – Least Squares FEM method for transport equation

V. Taupin et al, Acta Mater. **56**, 3002 (2008)

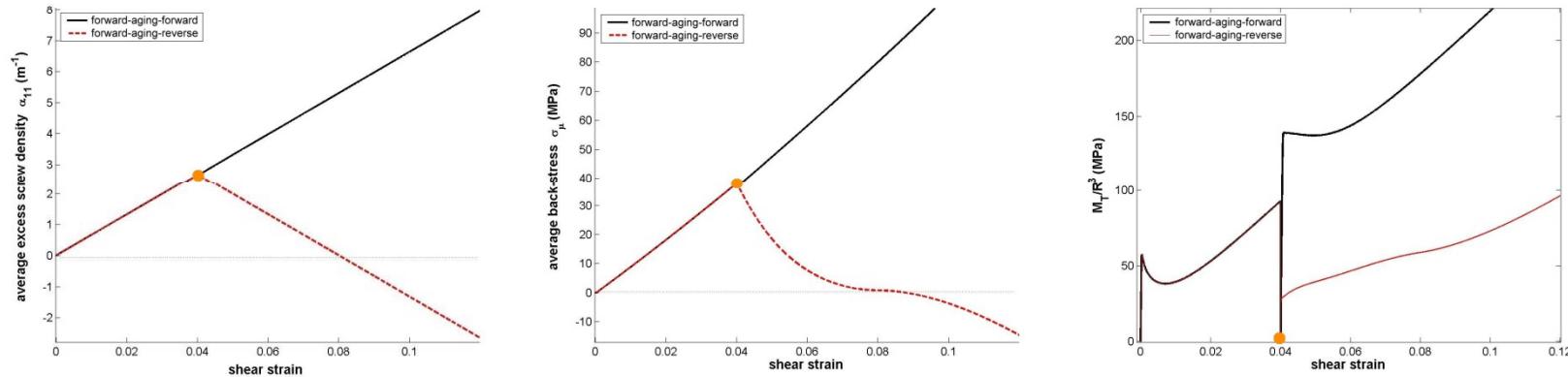
Results



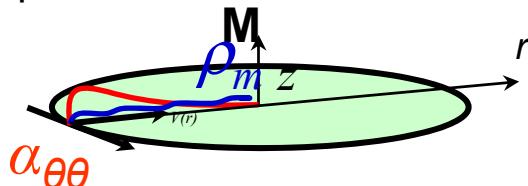
- Band at angle with axial and transverse directions (see Neuhäuser, ASME 95)
- Residual strain rate behind the band
- Bauschinger effect predicted
- UYP removed when straining is reversed
- Transient inflexion of strain hardening after path reversal

V. Taupin et al, Acta Mater. **56**, 3002 (2008)

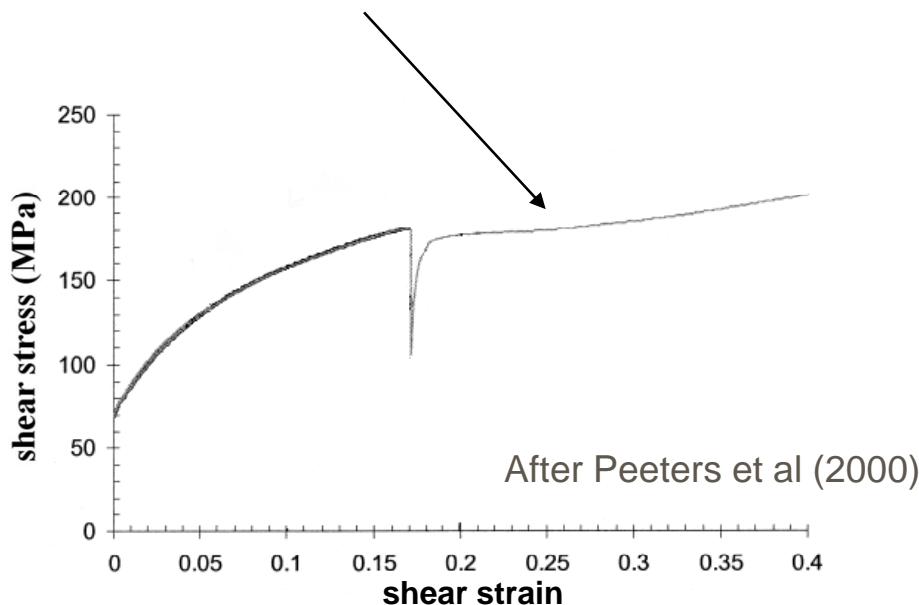
Interplay internal stresses-strain aging



- Radial gradients in plastic strain rate generate polar dislocations
- In **forward torsion**, polar density and back-stress build up
 - ✓ Back-stress opposes dislocation unpinning by lowering effective stress and dislocation velocity, hence favors UYP
- In **reverse torsion**, polar density of opposite sign is generated
 - ✓ Back-stress increases effective stress, favors dislocation unpinning, hence UYP is no more necessary for unpinning
 - ✓ Annihilation of microstructure built in forward torsion and generation of a new polarized microstructure
 - ✓ Subsequent inflection of strain hardening in reverse straining



Experimental evidence for transient behavior in reverse straining



- Polycrystalline aluminum at various temperatures

Hasegawa et al, Mater. Sci. Engng, **20**, 267 (1975)

- Interstitial Free steels

Peeters et al, Acta. Mater. **48**, 2123 (2000)

Conclusions

- FDM + Strain aging model allow reproducing
 - ✓ Bauschinger effect (directionality of strain hardening)
 - ✓ Yield point directionalitythrough history of polar dislocation microstructures:
 - ✓ Microstructure built in forward straining annihilate at reverse straining, and inverse polarization occurs
 - ✓ Microstructure evolution translates into inflexion of strain hardening after strain path reversal
- The theory naturally involves internal length scales and spatial correlations reflecting
 - ✓ Dislocation transport (cross-slip...)
 - ✓ Lattice incompatibility and long-range internal stresses
- The theory is effective in predicting anisotropic hardening in complex strain paths