



Modeling size effects on void growth and coalescence in single crystals

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Modeling Size Effects on Void Growth and Coalescence in Single Crystals

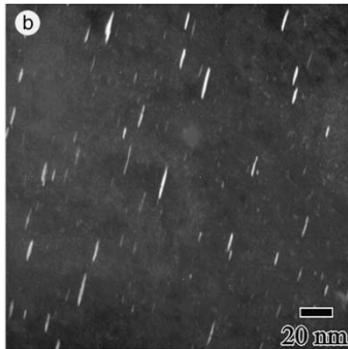
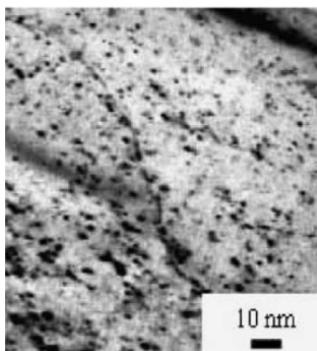
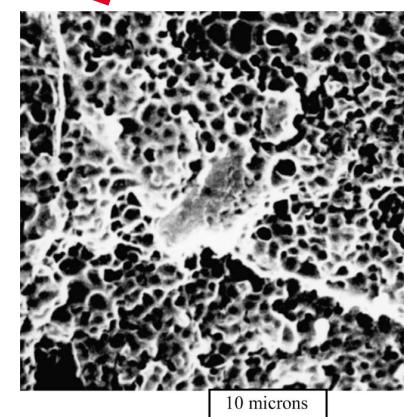
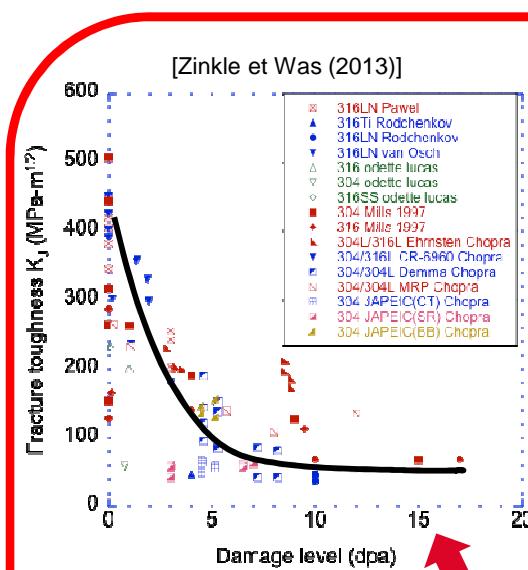
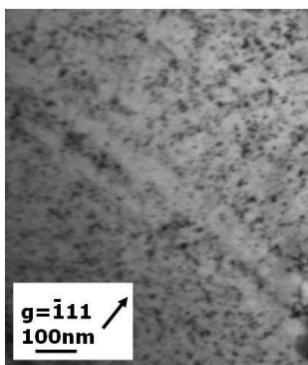
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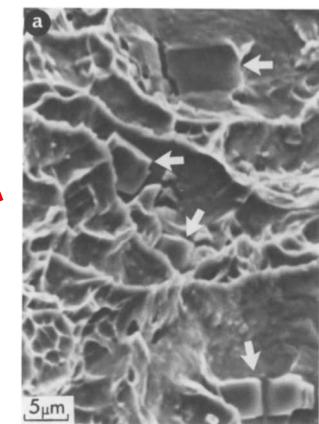
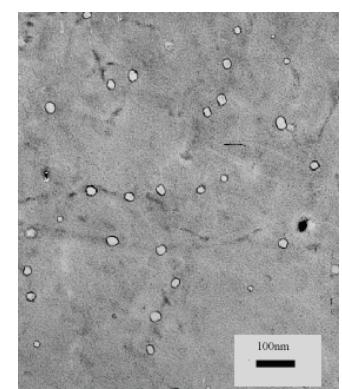
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BACKGROUND AND MOTIVATION

Frank loops**Black dots****Clear bands**

Fracture surface in the Fe-18Cr-10Ni-Ti stainless steel irradiated in BOR-60
[Neustroev and Garner (2009)]

[Little (1986), Garner et al. (2005)]

Micro-sized precipitate**Nano-size voids**

OUTLINE

- Gradient enhanced single crystal plasticity
- Localization analysis
- Size dependent void growth
- Conclusion

GRADIENT ENHANCED SINGLE CRYSTAL PLASTICITY

Assumption:

Stress state of a material point depends on plastic strain gradient.

Internal forces power [Germain, 1973]

$$P^i = \int_D \tilde{\sigma} : (\text{grad } \underline{v}) + s \dot{\gamma}_\chi + \underline{m} \cdot \text{grad } \dot{\gamma}_\chi dV, \quad \forall D \subset \Omega$$

Principle of virtual power → *Equilibrium equations and boundary conditions*

$$\begin{cases} \text{div } \tilde{\sigma} = 0 & \forall \underline{x} \in V \\ \text{div } \underline{m} - s = 0 & \end{cases} \quad \begin{cases} \underline{t} = \tilde{\sigma} \cdot \underline{n} \\ m = \underline{m} \cdot \underline{n} \end{cases} \quad \forall \underline{x} \in \partial V$$

Free energy potential

$$\rho \psi = \frac{1}{2} \frac{\rho}{\rho_i} \tilde{E}_{GL}^e : \tilde{\Lambda} : \tilde{E}_{GL}^e + \frac{1}{2} \frac{\rho}{\rho_0} \text{Grad } \gamma_\chi \cdot \tilde{A} \cdot \text{Grad } \gamma_\chi + \frac{1}{2} \frac{\rho}{\rho_0} H_\chi (\gamma_\chi - \gamma_{cum})^2$$

Positive dissipation density $D := p^i - \rho \dot{\psi} \geq 0 \rightarrow$ *Yield function and flow rule*

$$f^s = |\tau^s| - (\tau_c^s - S) \geq 0, \quad \text{with} \quad S = J_s = H_\chi (\gamma_\chi - \gamma_{cum})$$

GRADIENT ENHANCED SINGLE CRYSTAL PLASTICITY

Multiplicative decomposition of the deformation gradient:

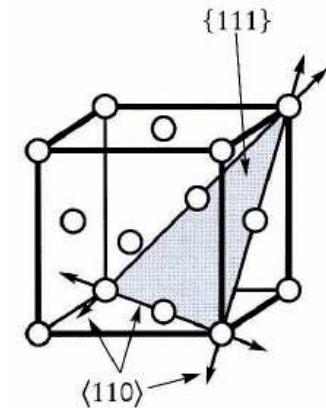
$$\tilde{\mathbf{F}} = \tilde{\mathbf{E}} \cdot \tilde{\mathbf{P}}$$

Plastic strain rate:

$$\dot{\tilde{\mathbf{P}}} \cdot \tilde{\mathbf{P}}^{-1} = \sum_{s=1}^{12} \dot{\gamma}^s \underline{\mathbf{l}}^s \otimes \underline{\mathbf{n}}^s$$

Total cumulative slip

$$\gamma_{cum} = \int_0^t \sum_{s=1}^{12} |\dot{\gamma}^s| dt$$



Yield functions for the slip system s :

$$f^s = |\tau^s| - (\tau_c^s - S) \geqslant 0 \quad \text{with} \quad S = J_s = H_\chi(\gamma_\chi - \gamma_{cum})$$

Plastic slip rate:

$$\dot{\gamma}^s = \left\langle \frac{|\tau^s| - (\tau_c^s - S)}{K} \right\rangle^n \operatorname{sign}(\tau^s)$$

SIMPLE SHEAR ON A DEFECTED PLATE

- Plane strain
- Periodic boundary condition

$$\underline{u} = \overline{\underline{F}} \cdot \underline{X} + \underline{v}$$

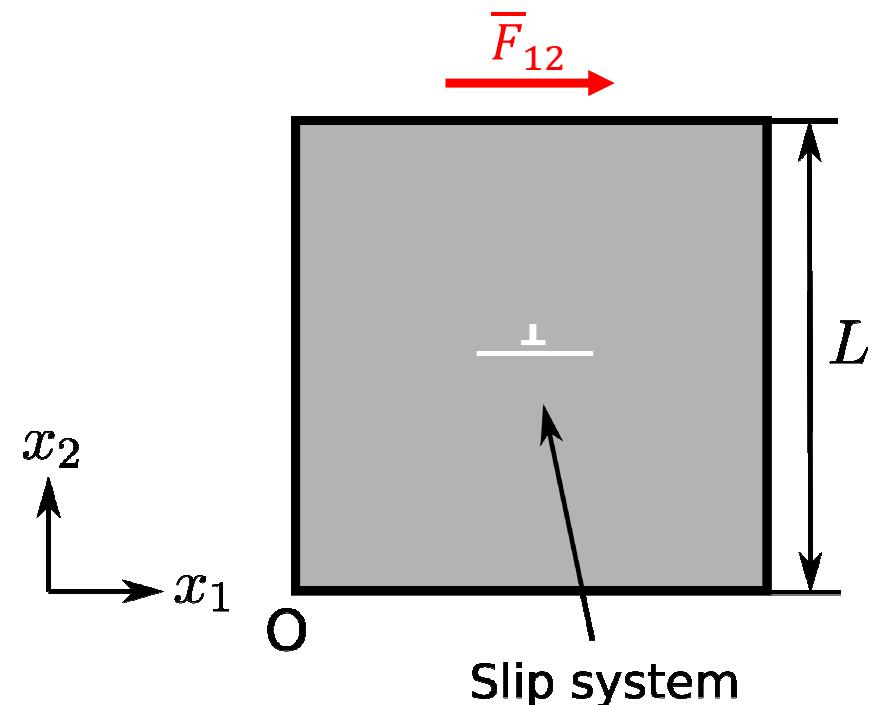
- Point O fixed
- \overline{F}_{12} imposed

- Linear softening

$$f = |\tau| - (\tau_0 + H\gamma + H_x(\gamma_x - \gamma)) \leq 0$$

with $H < 0$

- $L = 1 \text{ mm}$ and element width = 0.02 mm
- Localization band. Its width ?



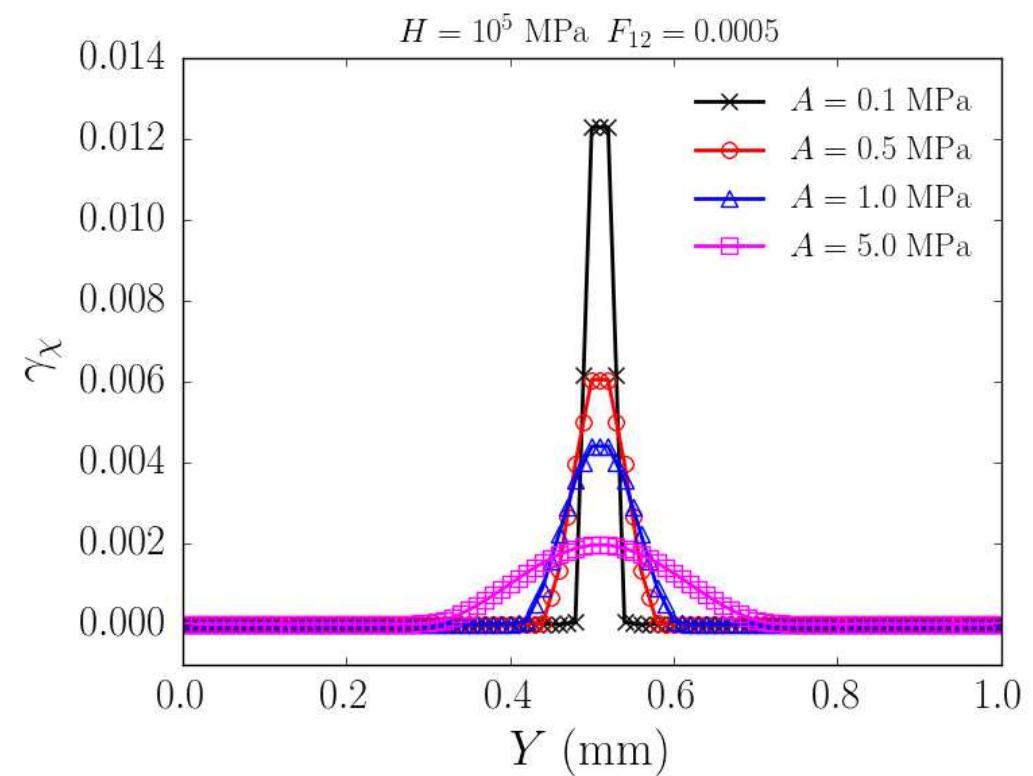
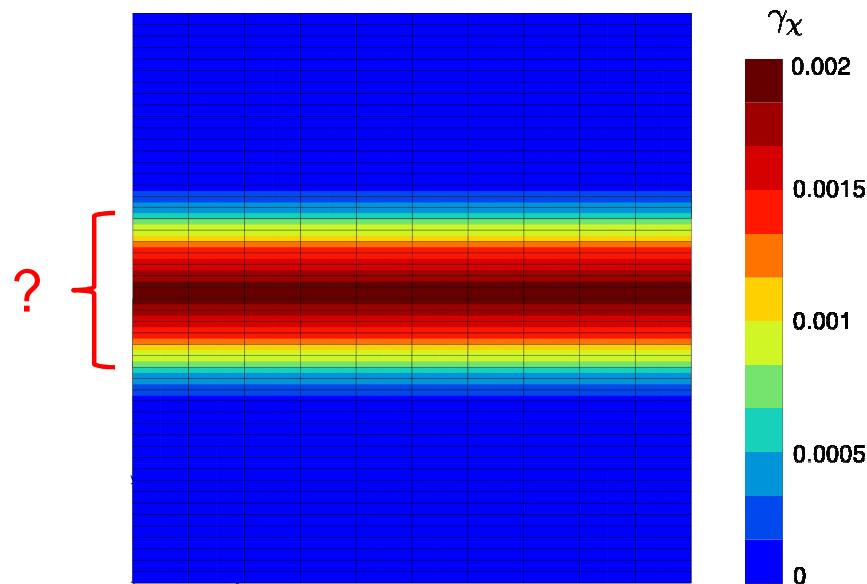
$$\tau_0 = 10$$

$$\tau_0 = 9.9$$



EFFECTS OF PARAMETER A

$H = -10^3$ MPa, $H_\chi = 10^5$ MPa and $A = 5$ N

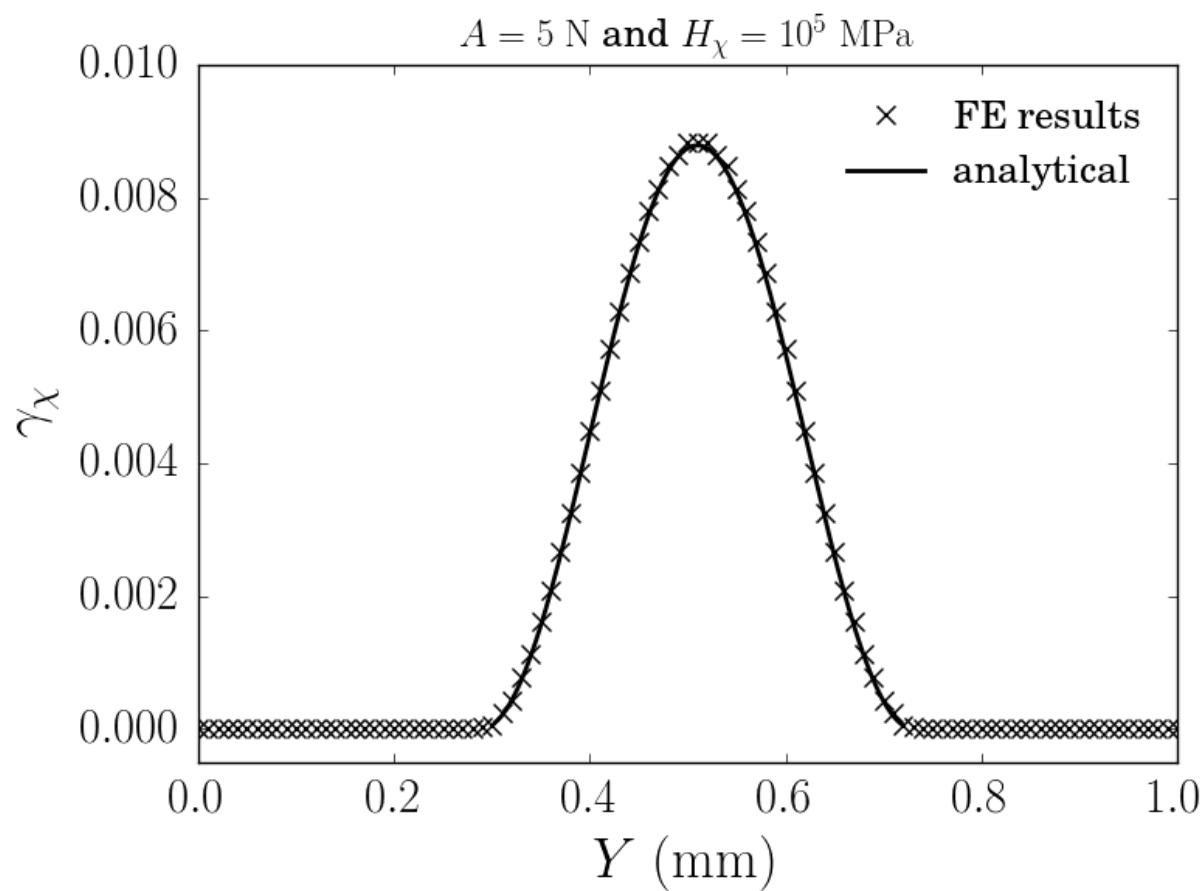


- Band width varies with A .

COMPARISON: NUMERICAL AND ANALYTICAL RESULTS

$$\gamma_{\chi,222} - \frac{H_\chi}{A} \tilde{H} \gamma_{\chi,2} = 0 \quad \text{with} \quad \tilde{H} = \frac{H}{H_\chi + H}$$

- ✓ One periodic solution is sinusoidal with wave length:

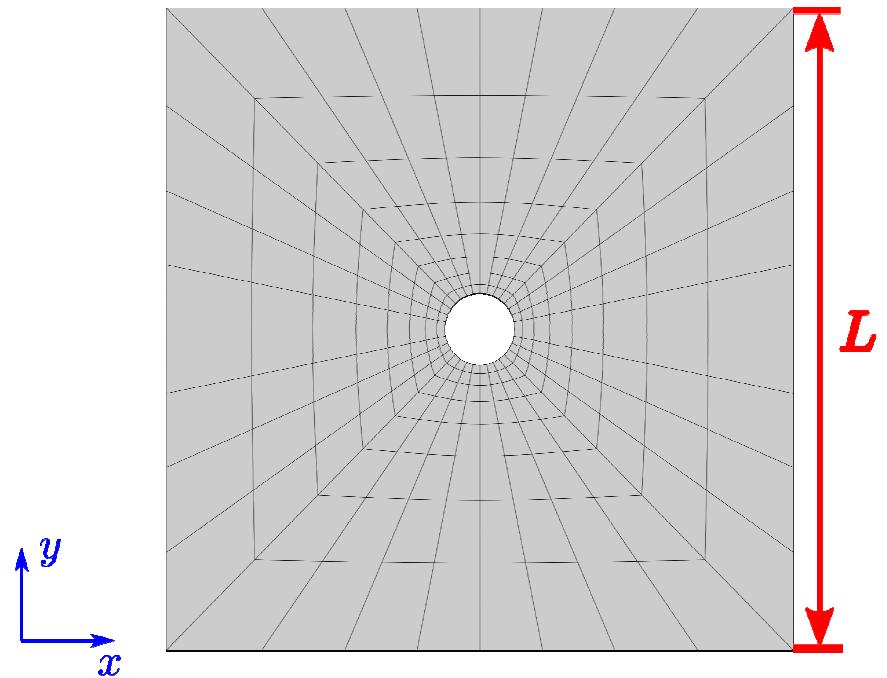


$$\lambda = 2\pi / \sqrt{\frac{H_\chi |H|}{A(H_\chi + H)}}$$

- ✓ $H = -10^3 \text{ MPa}$
- $H_\chi = 10^5 \text{ MPa}$ and $A = 5 \text{ N}$
- $\bar{F}_{12} = 0.002$

SIZE DEPENDENT VOID GROWTH

- Plane strain
- **Biaxial tension:** $a = \bar{\sigma}_{22}/\bar{\sigma}_{11} = 0.625$
- 1% initial void volume fraction
- 3 values for L : 0.1mm, 1mm, 10mm
- $H_\chi = 5 \times 10^4$ MPa and $A = 5$ N
- Hardening law based on the evolution of dislocation density

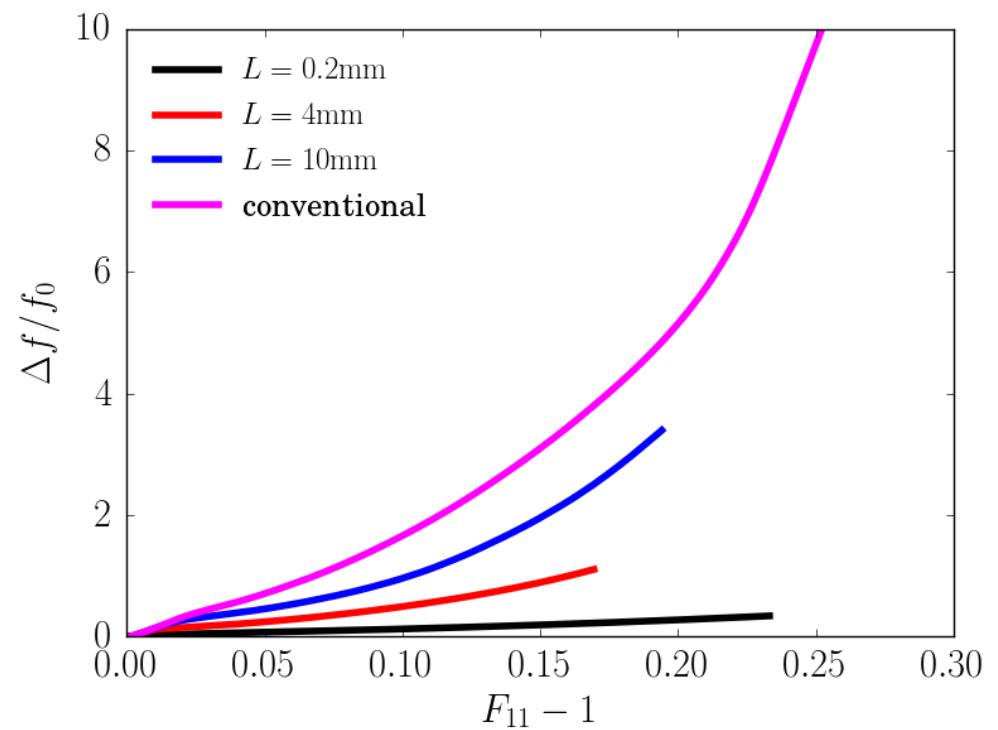
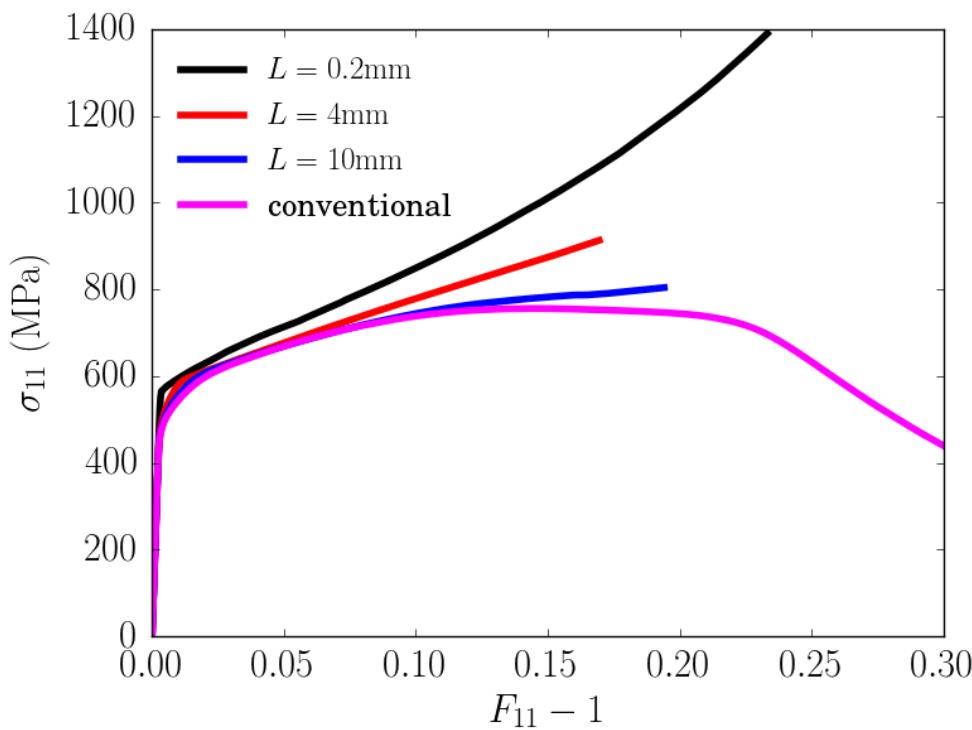


$$\tau_c^s = \tau_0 + \mu b_D \sqrt{\sum_u^{12} a^{su} \rho_D^u}$$

$$\dot{\rho}_D^s = \frac{1}{b_D} \left(\frac{1}{L^s} - g_c \rho_D^s \right) |\dot{\gamma}^s| \quad \text{with} \quad L^s = \kappa \left(\sum_u^{12} b^{su} \rho_D^u \right)^{-\frac{1}{2}}$$

↓ *Multiplication* ↓ *Annihilation*

SIZE DEPENDENT VOID GROWTH



CONCLUSION

- Gradient enhanced single crystal plasticity
- Regularization of plastic strain localization
- Size dependent void growth: big voids grow faster than small ones