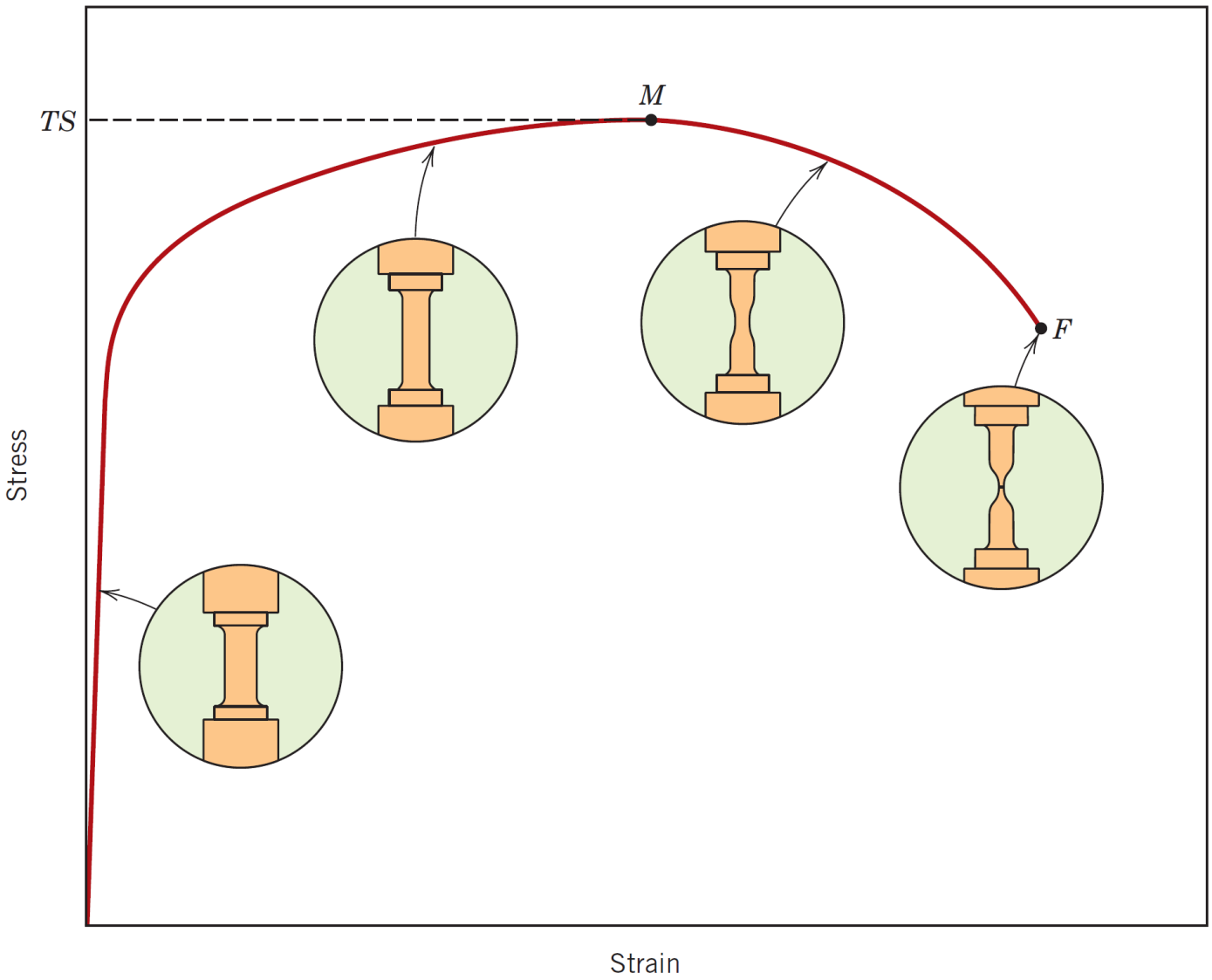
Mechanical Properties of Metals at the Micrometre Length Scale

Can Ayas

Tensile Test



Material Properties

Table: Mechanical properties of several metals and alloys in an annealed state.

Metal Alloy	σ_y (MPa)	σ_{UTS} (MPa)
Aluminium	35	90
Copper	69	200
Brass (70Zn-30Cu)	75	300
Iron	130	262
Steel (1020)	180	380
Titanium	450	520
Molybdenum	562	655

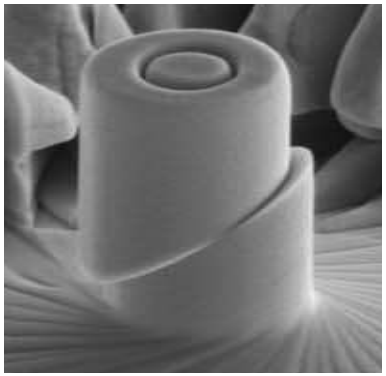
These properties are sensitive to:

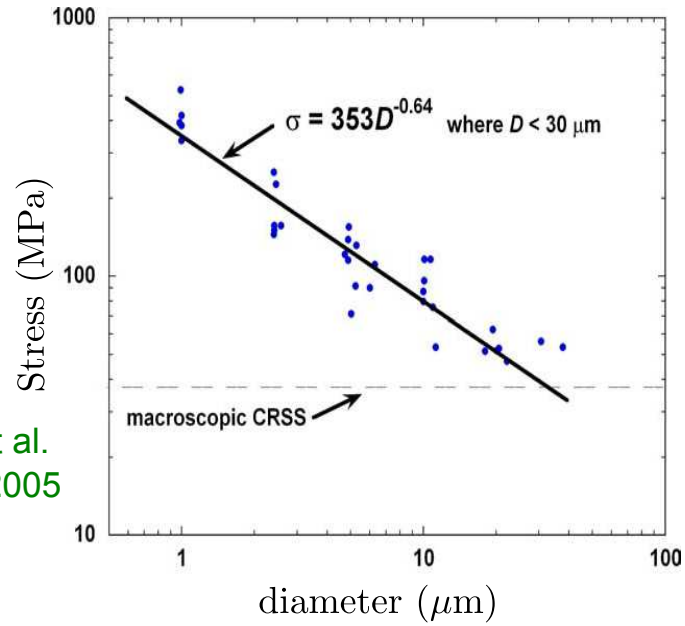
- Microstructure
- Environment
- Rate of loading

What about size of the specimen

Nickel Pillar

at room temperature $\frac{T}{T_m} = 0.17$



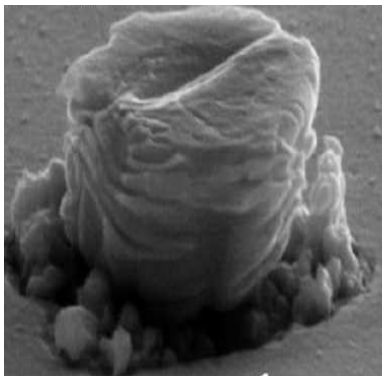


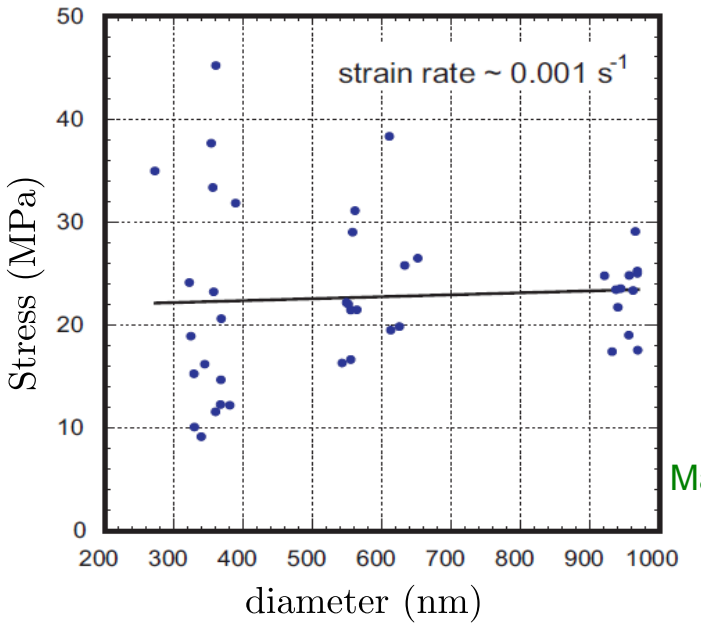
Dimiduk et al.
Acta Mat. 2005

Smaller is stronger

Indium Pillar

at room temperature $\frac{T}{T_m} = 0.70$

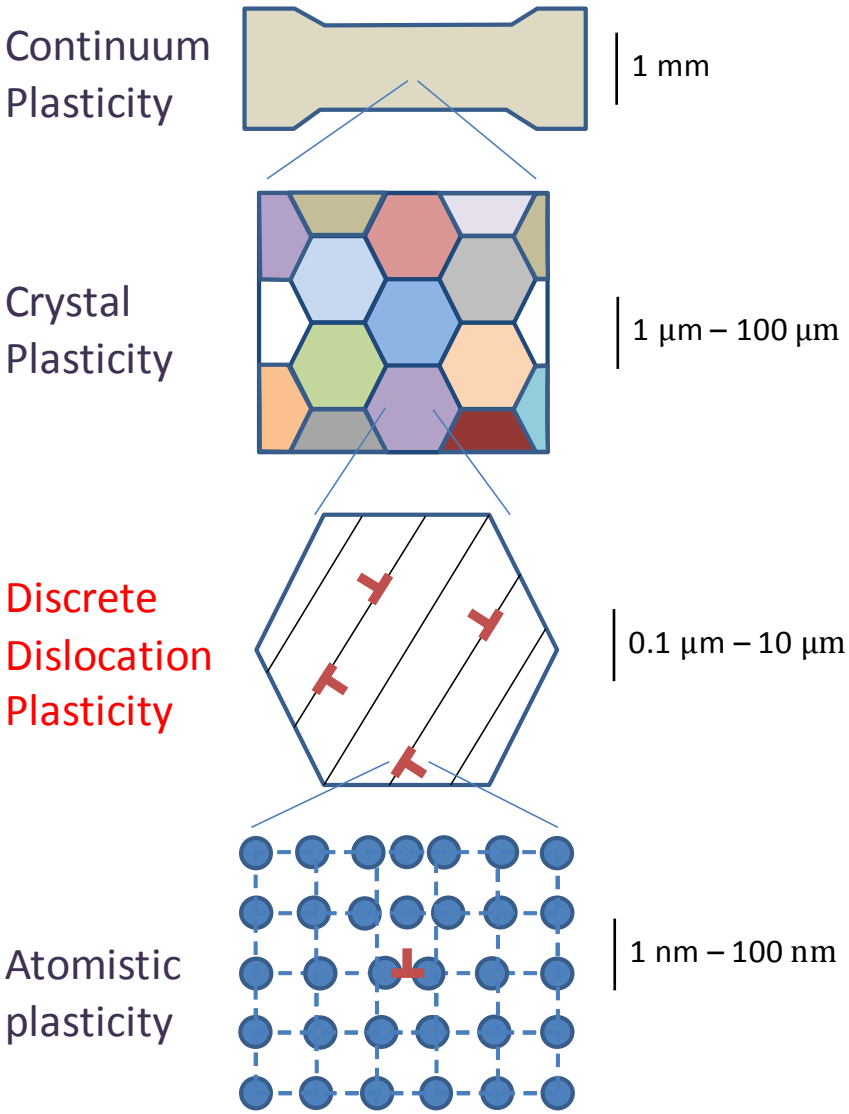




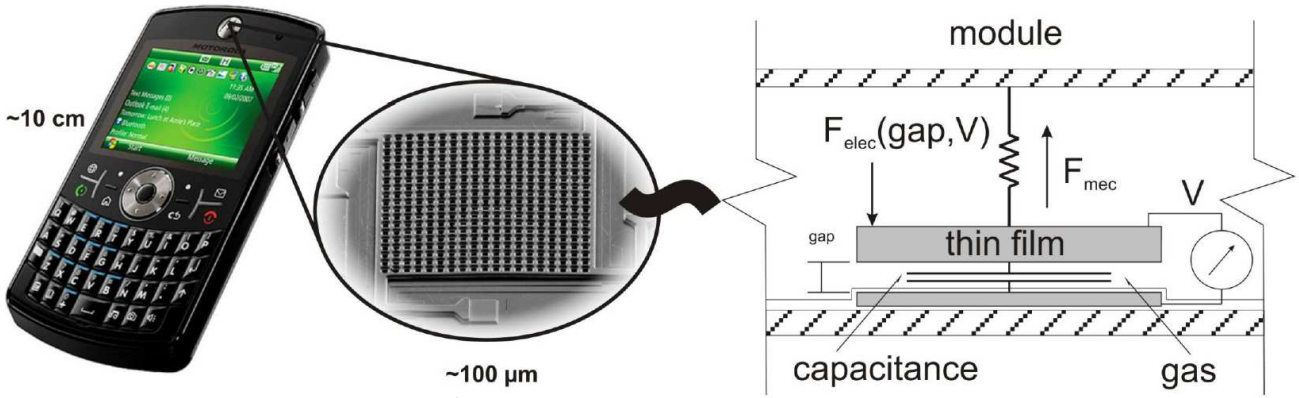
Greer et al.
Mat. Sci. Eng. A 2011

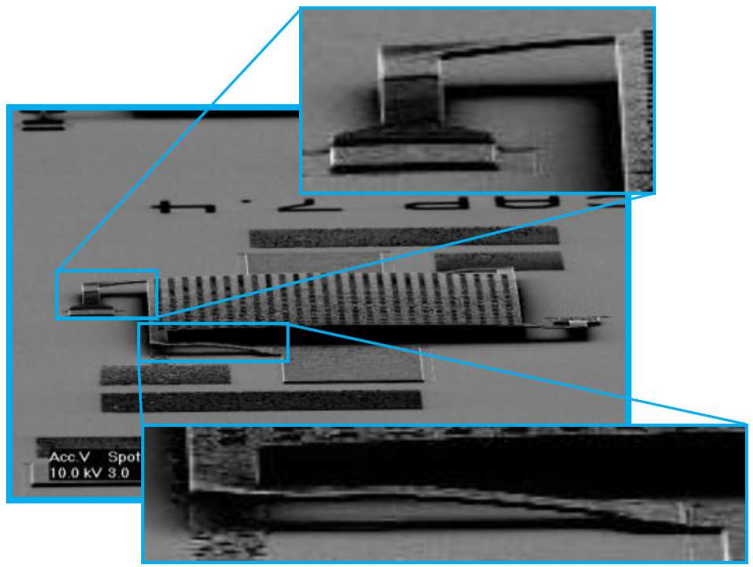
Size effects are absent/less pronounced

Multi Scale Nature of Plasticity



Motivation


~10 cm
~100 µm
module
F_{elec}(gap,V)
F_{mec}
V
gap
thin film
capacitance
gas


Acc.V Spot
10.0 kV 3.0

Motivation

Trent 900 fan set (Rolls Royce)

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- Nickel based single crystal creep resistant superalloys: gas turbines, electricity generation, jet propulsion.
- Complicated chemistry: Ni, Cr, Co, Al, Ti, Ta, Mo, W, Re, Ro.

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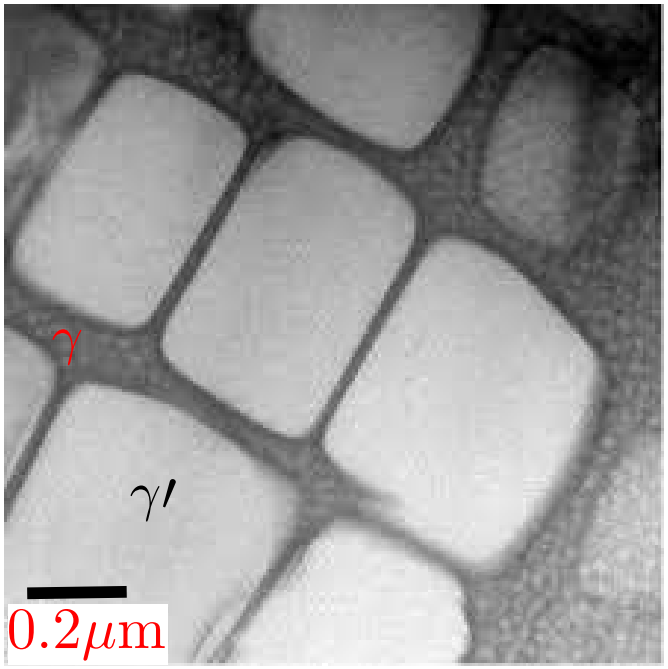

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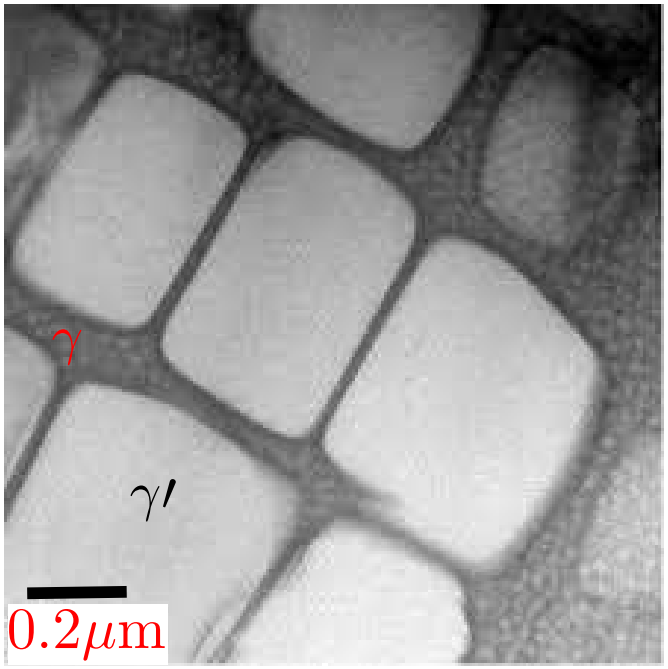

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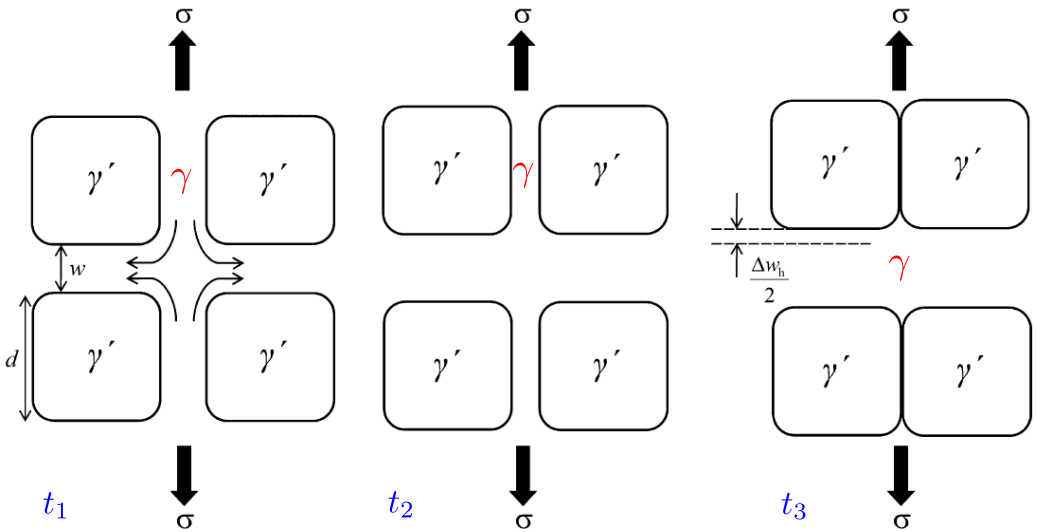

Reed at al. Acta Materialia 60 (2012)

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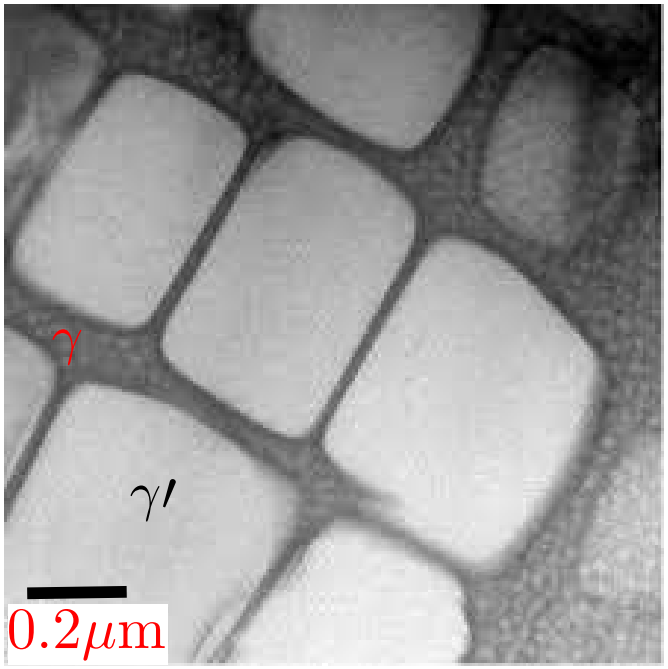

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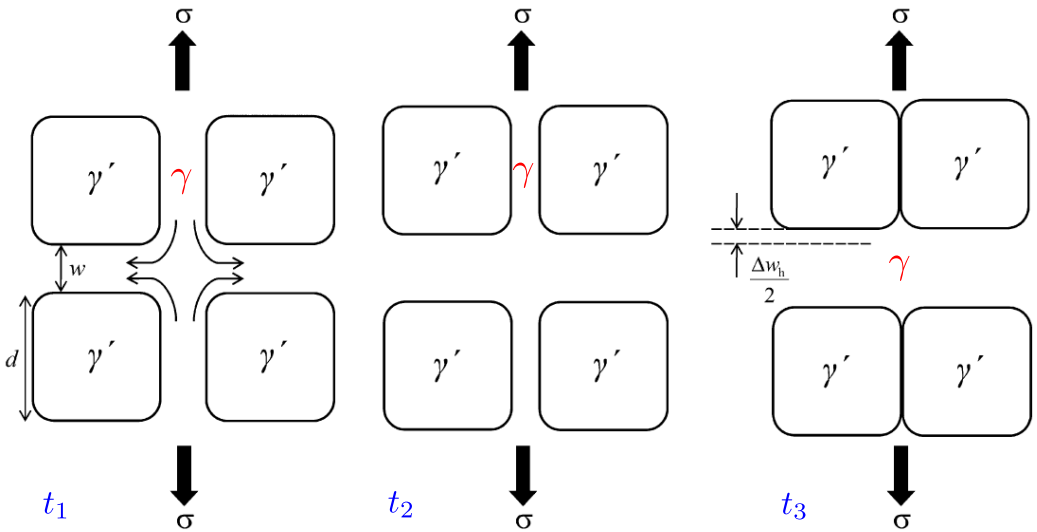
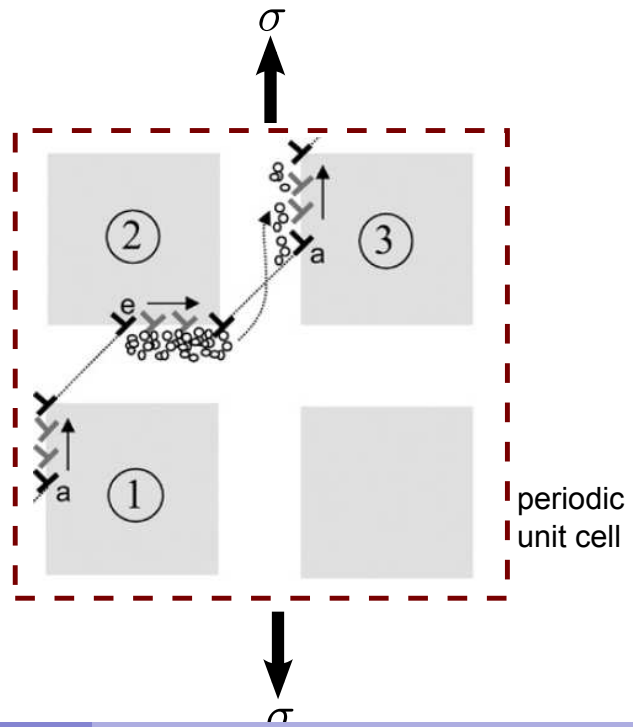
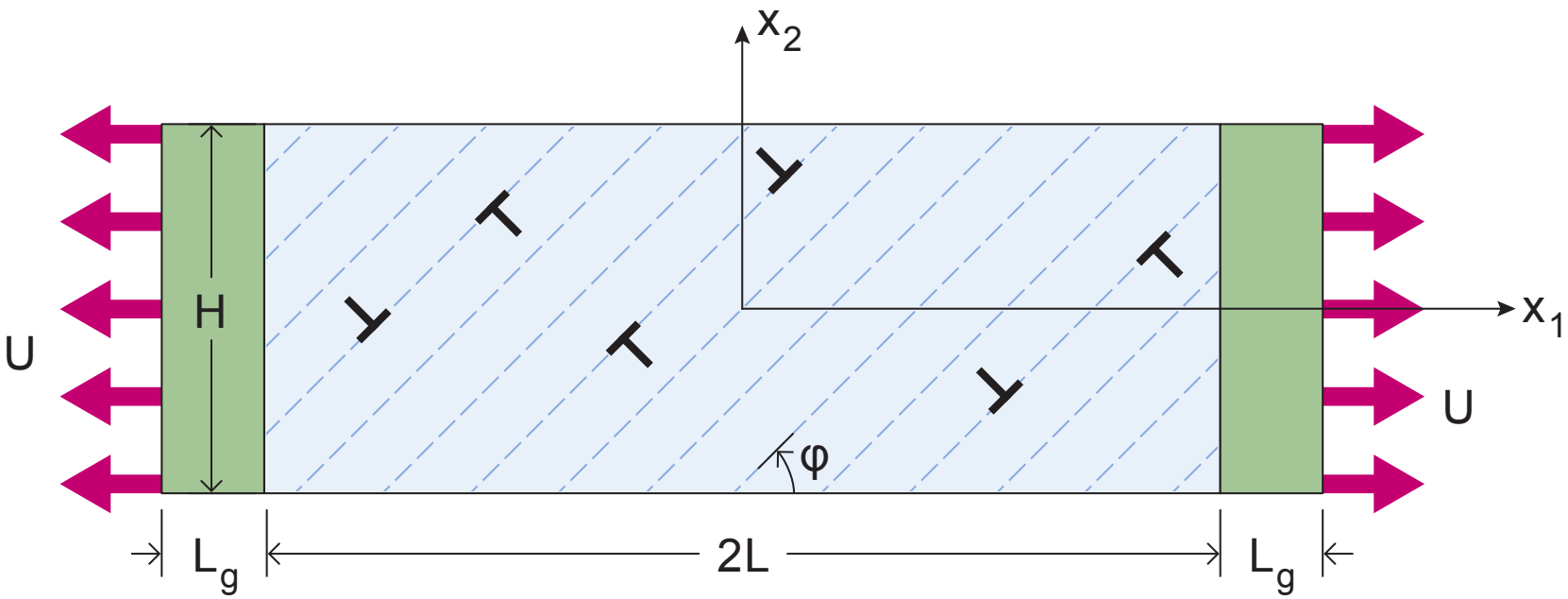




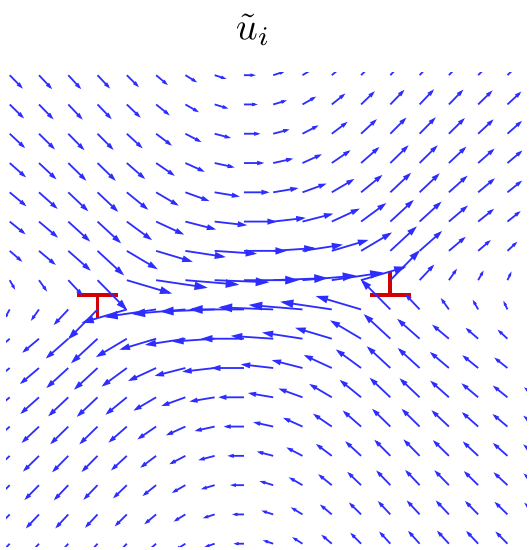
Reed at al. Acta Materialia 60 (2012)

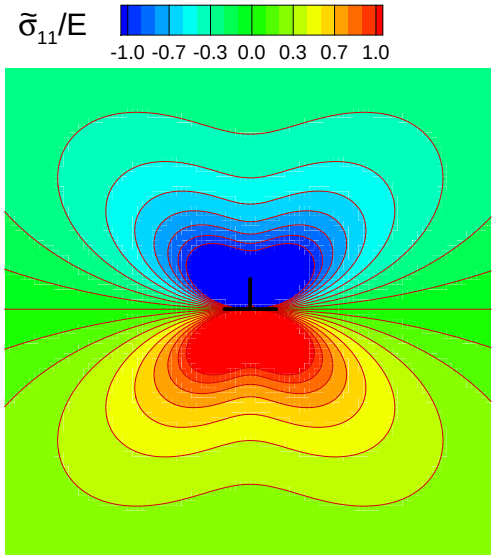
Uniaxial tension of a single crystal

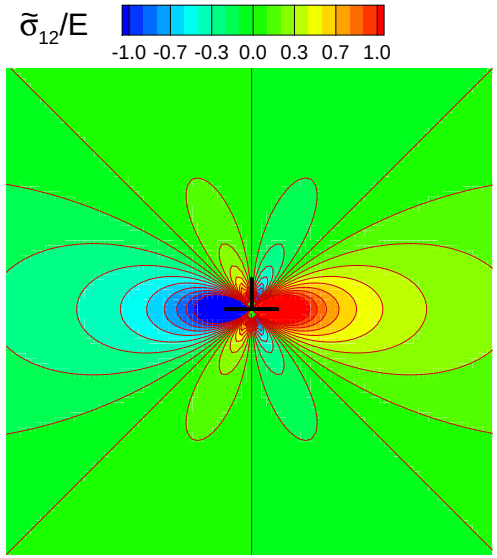


Elastic fields

- Represent singular fields analytically.
- Elastic fields are known in closed-form for an infinite medium.

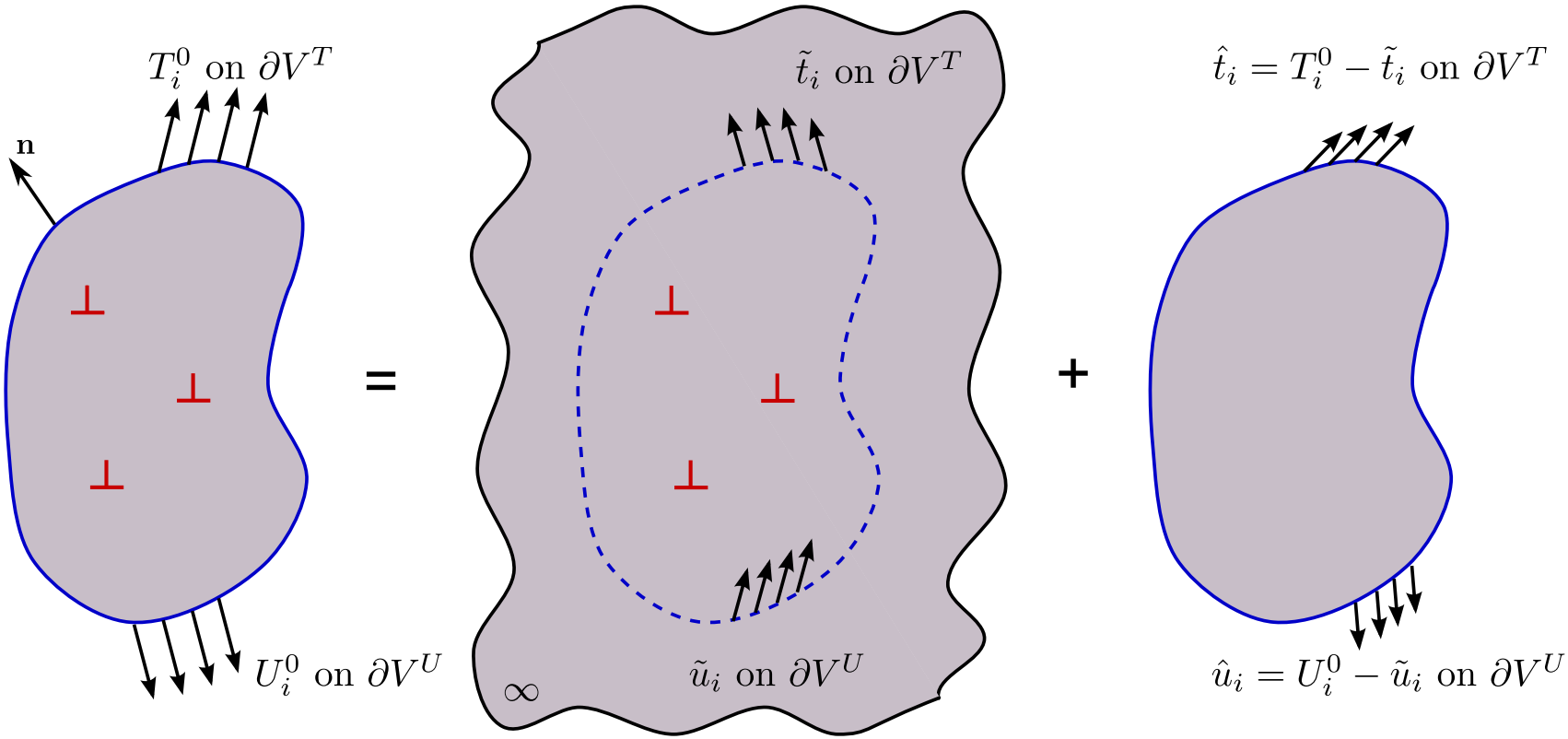






$$\begin{aligned} \tilde{u}_i &= (x_i, E, \nu) \\ \tilde{\varepsilon}_{ij} &= (x_i, E, \nu) \\ \tilde{\sigma}_{ij} &= (x_i, E, \nu) \end{aligned}$$

Boundary Value Problems

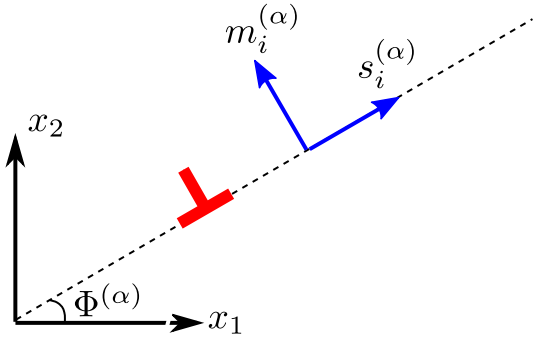


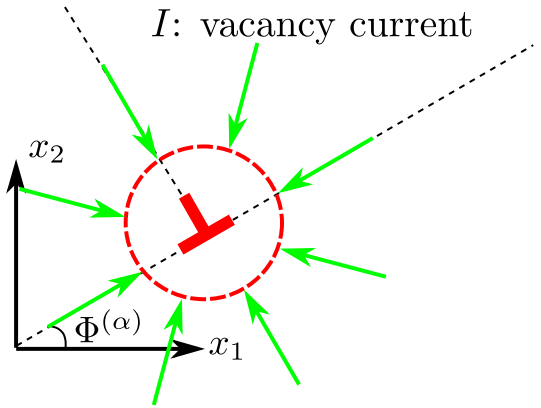
$$u_i = \sum_{I=1}^{N} \tilde{u}_i^{(\mathrm{I})} + \hat{u}_i$$

$$\sigma_{ij} = \sum_{I=1}^{N} \tilde{\sigma}_{ij}^{(\mathrm{I})} + \hat{\sigma}_{ij}$$

van der Giessen & Needleman MSMSE (1995)

Constitutive Rules



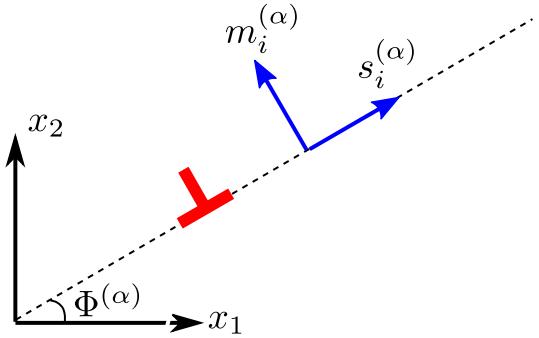


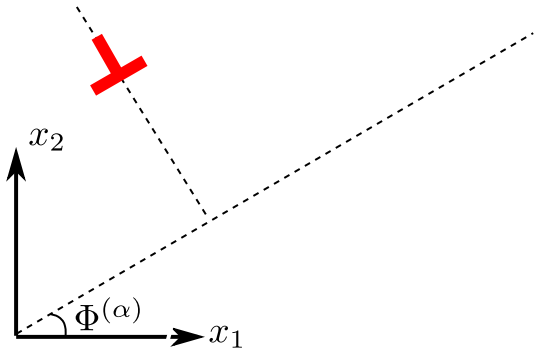
Peach-Kohler force:

Drag controlled mobility:

- glide: $f_{\mathrm{g}}^{(\mathrm{I})}(\sigma_{ij})$ $\qquad V_{\mathrm{g}}^{(\mathrm{I})} = \dfrac{f_{\mathrm{g}}^{(\mathrm{I})}}{B_{\mathrm{g}}}$
- climb: $f_{\mathrm{c}}^{(\mathrm{I})}(\sigma_{ij})$ $\qquad V_{\mathrm{c}}^{(\mathrm{I})} = \dfrac{f_{\mathrm{c}}^{(\mathrm{I})}}{B_{\mathrm{c}}}$ $\qquad$ uncoupled

Constitutive Rules





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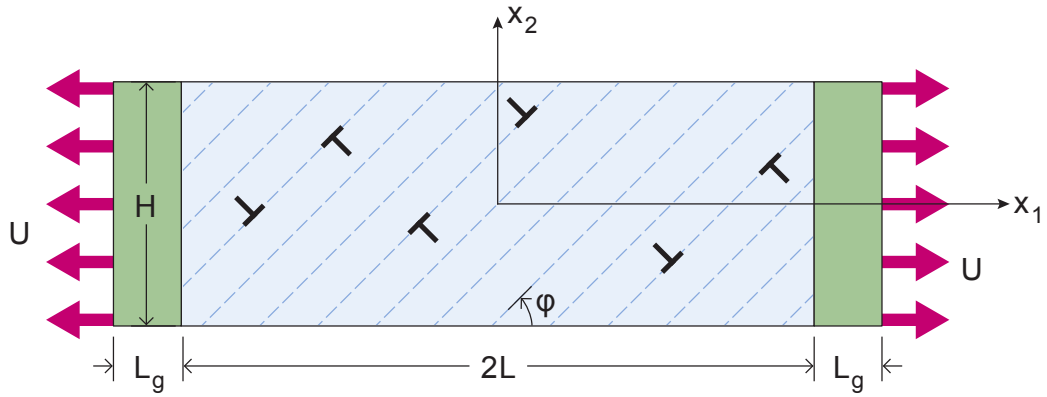
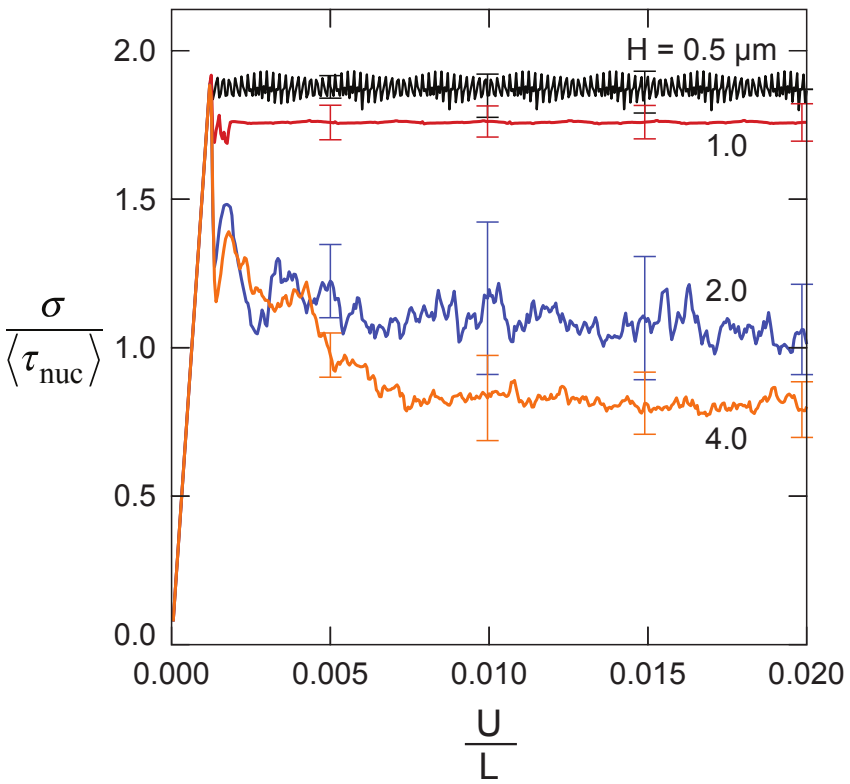
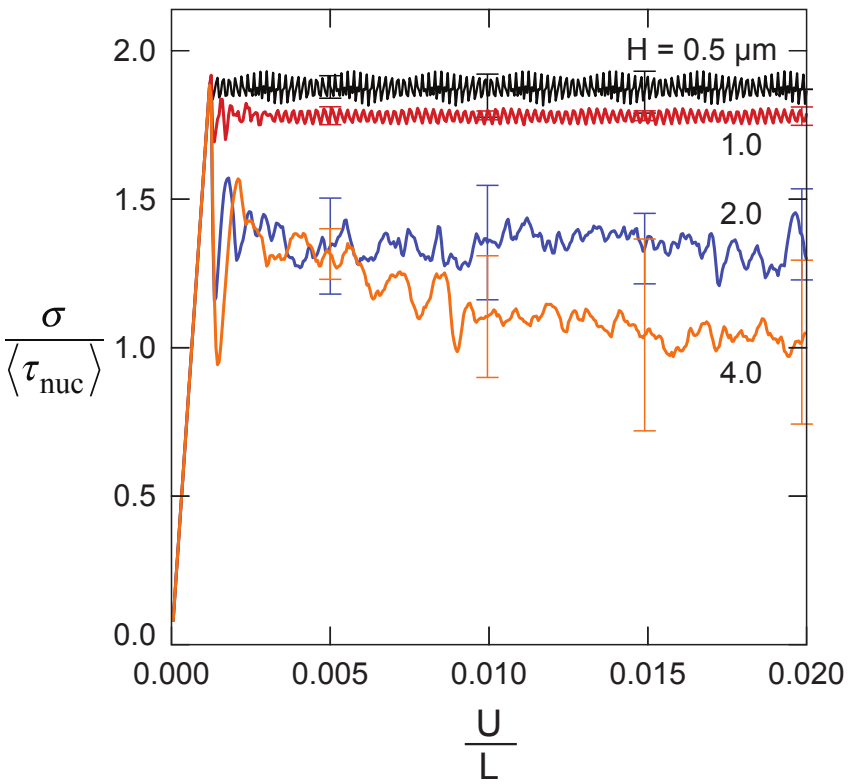
Uniaxial tension of a single crystal



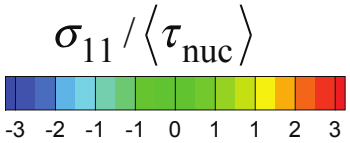
Glide only

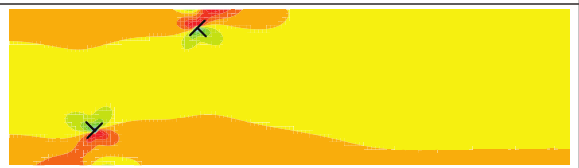
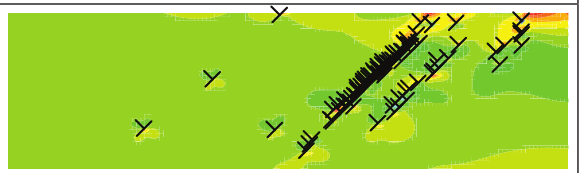
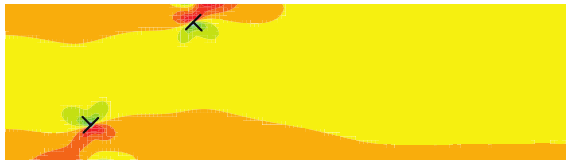
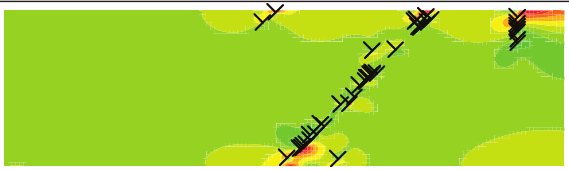


Glide + Climb

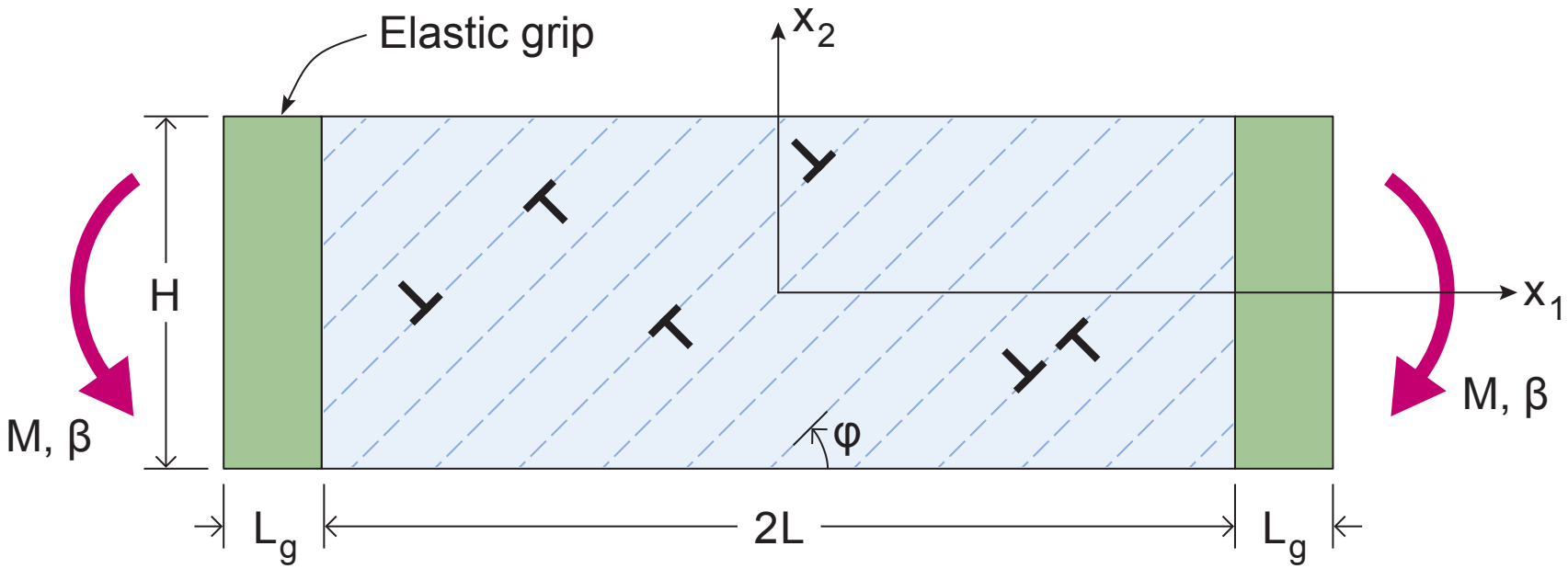


Tension response



	$H = 0.5\ \mu$m	$H = 2\ \mu$m
glide-only		
$\overline{\tau} = 3.2 \times 10^5$		

Bending of a single crystal



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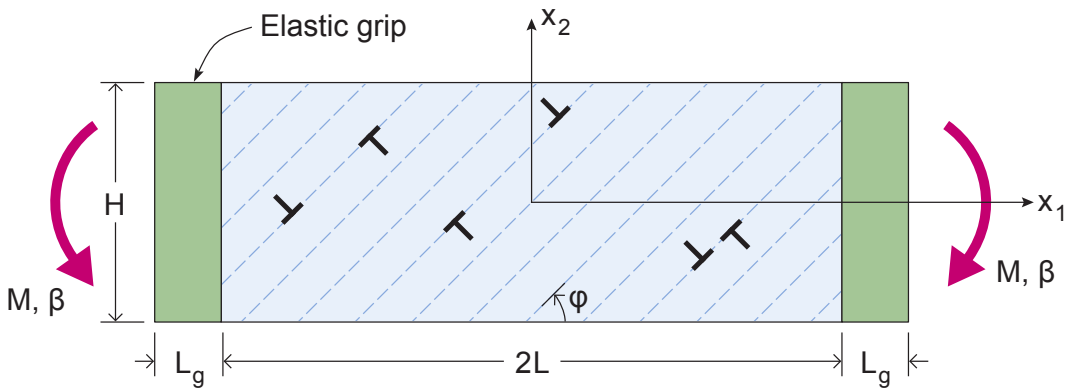
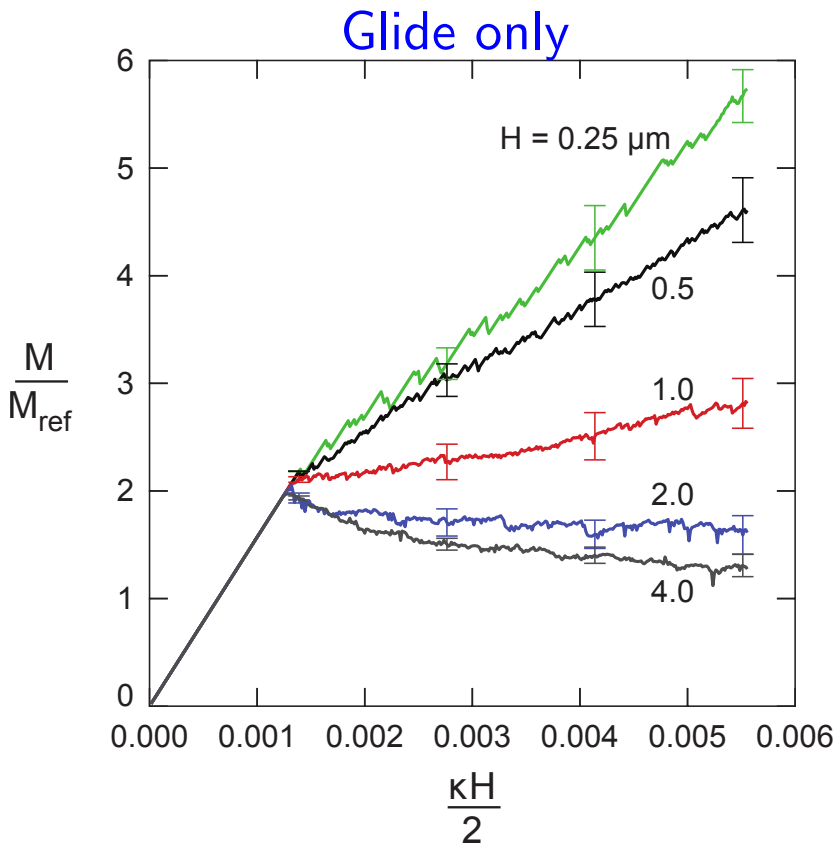
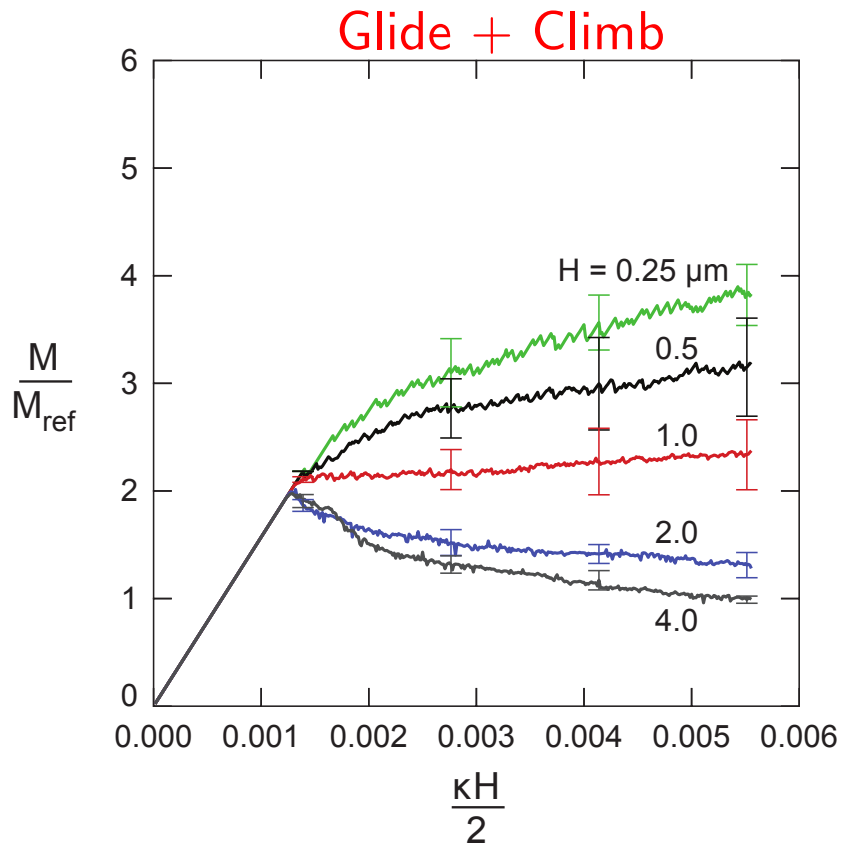
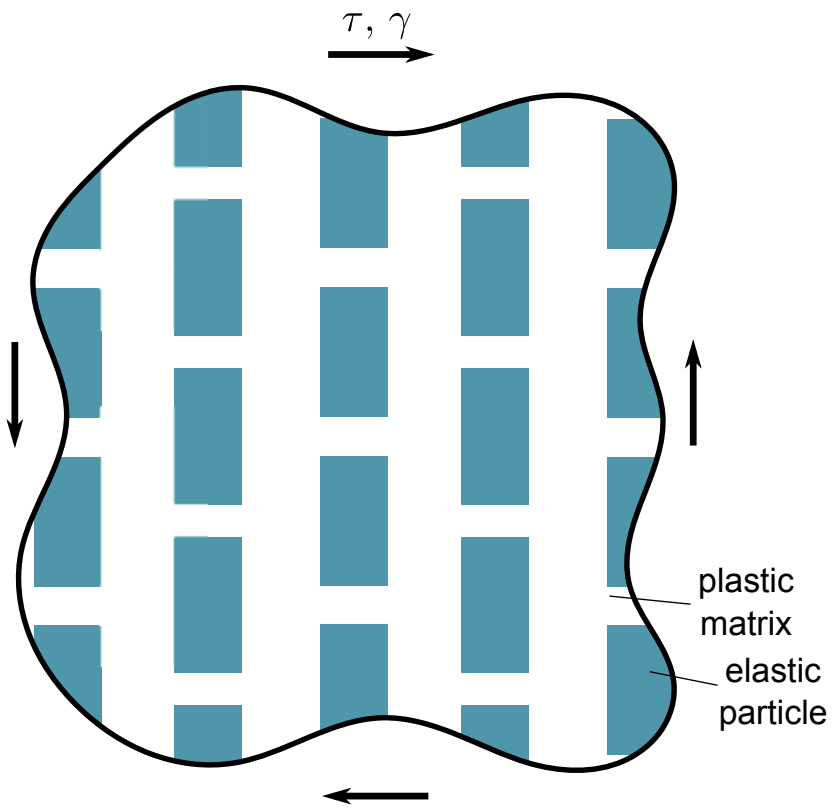






Composite microstructure

- Infinitely large composite under shear.
- Doubly periodic unit cell.
- matrix: plastic
- particles: elastic & impenetrable to dislocation motion.



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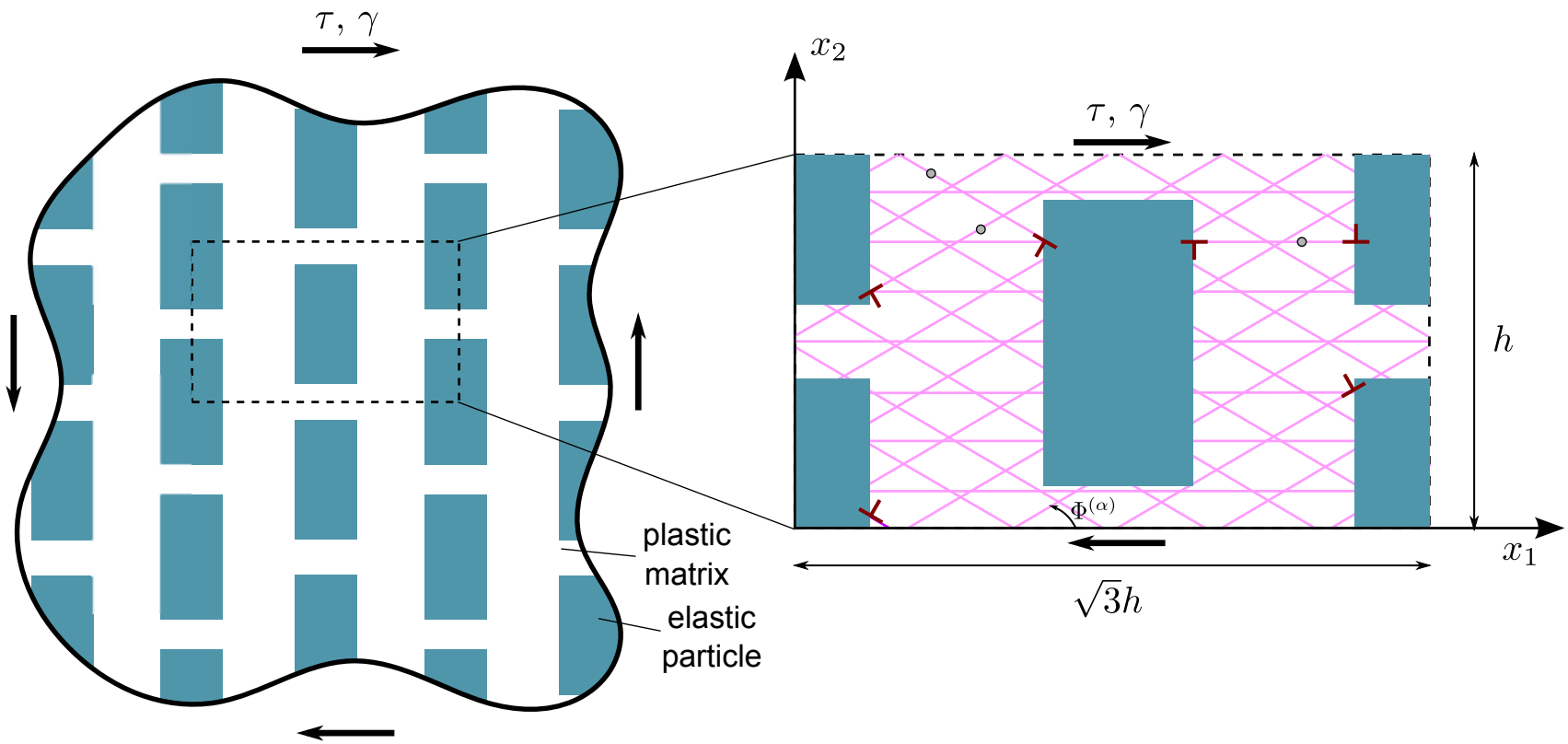


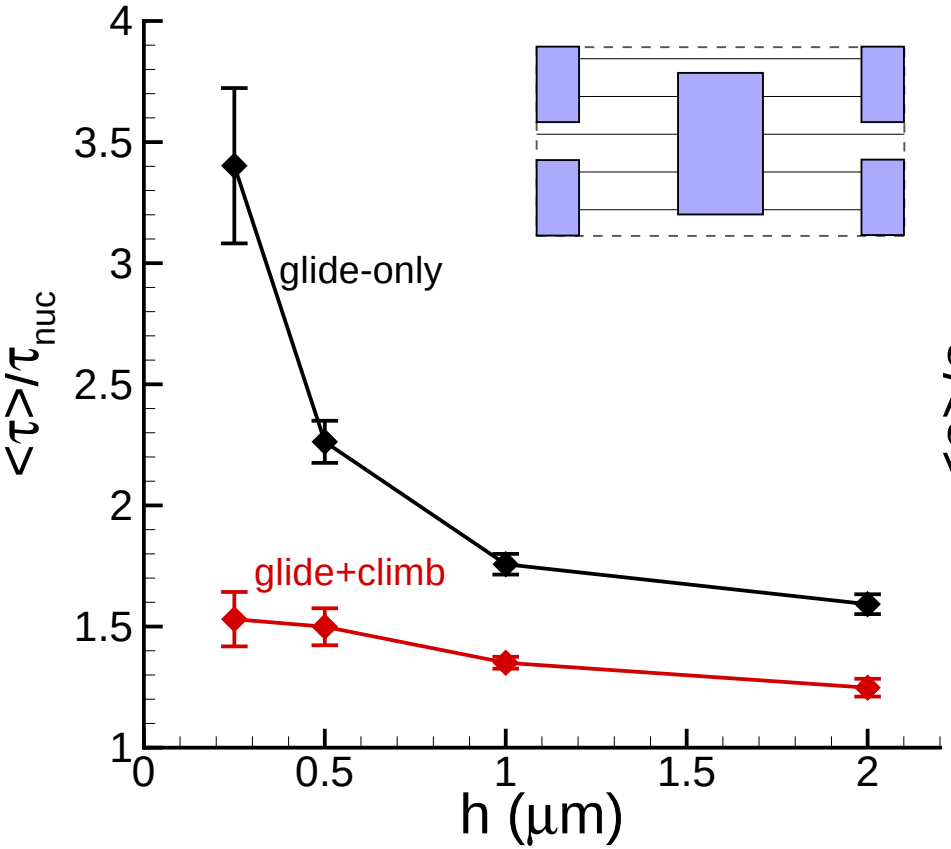
Size Effects

$$\langle \tau \rangle = \tau \ @\gamma = 0.02$$

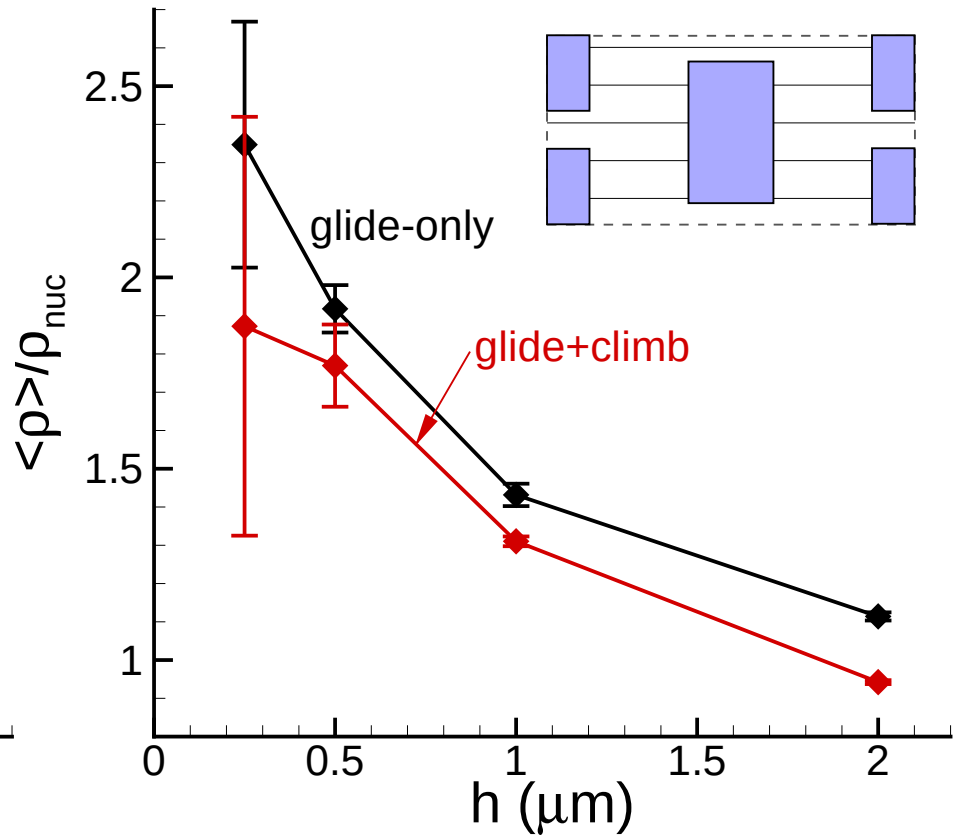
$$\langle \rho \rangle = \rho \ @\gamma = 0.02$$

Single slip

$\Phi = 0^\circ$



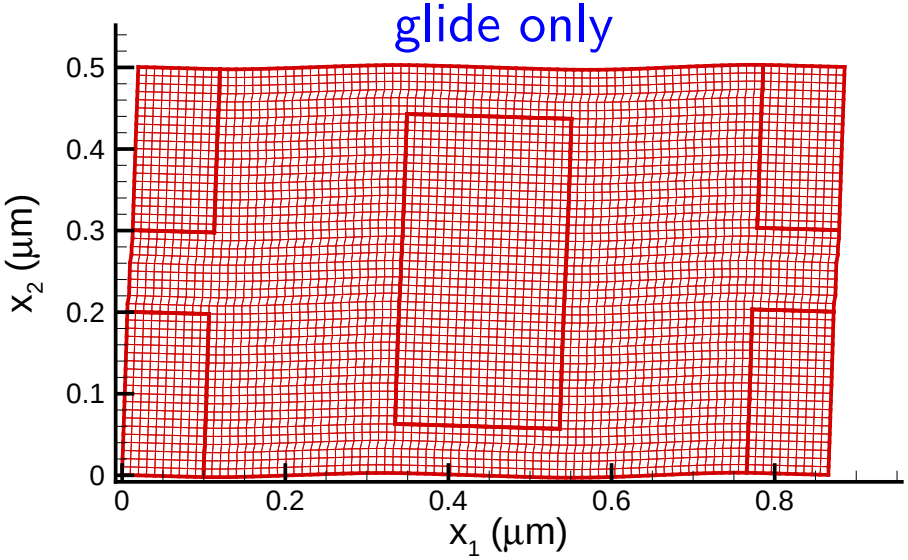
Dislocation density



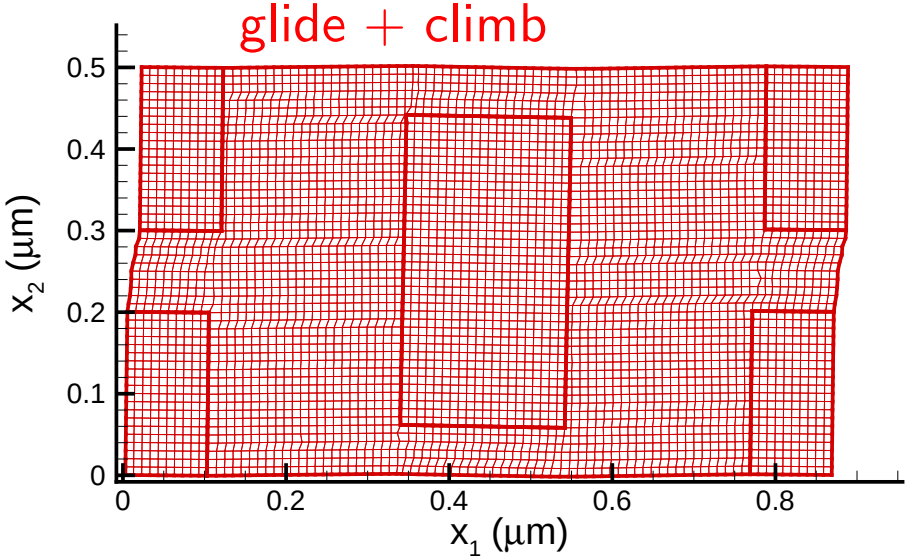
Lattice rotations

$$\omega_{12} = \tilde{\omega}_{12} + \hat{\omega}_{12} = \left(\tilde{u}_{1,2} - \tilde{u}_{2,1}\right) + \left(\hat{u}_{1,2} - \hat{u}_{2,1}\right)$$

glide only



glide + climb



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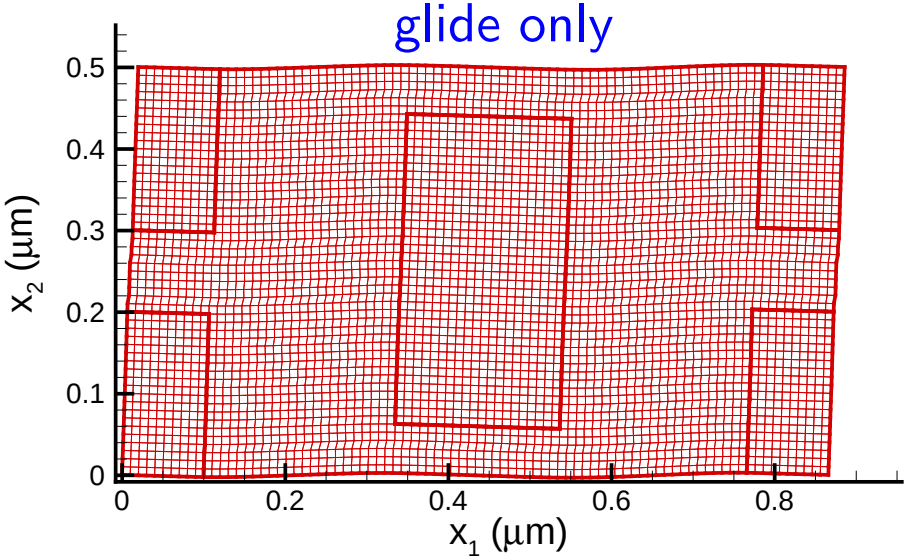

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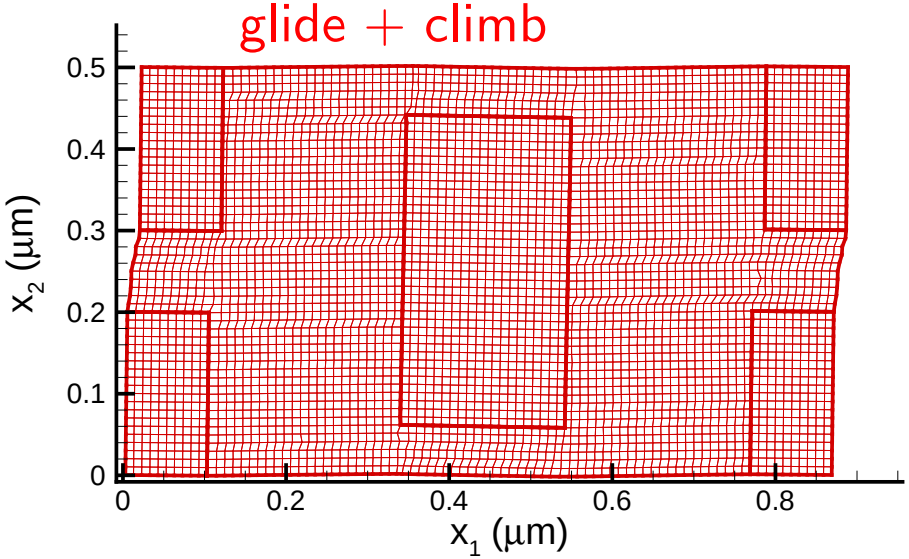
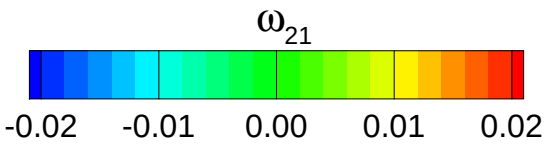
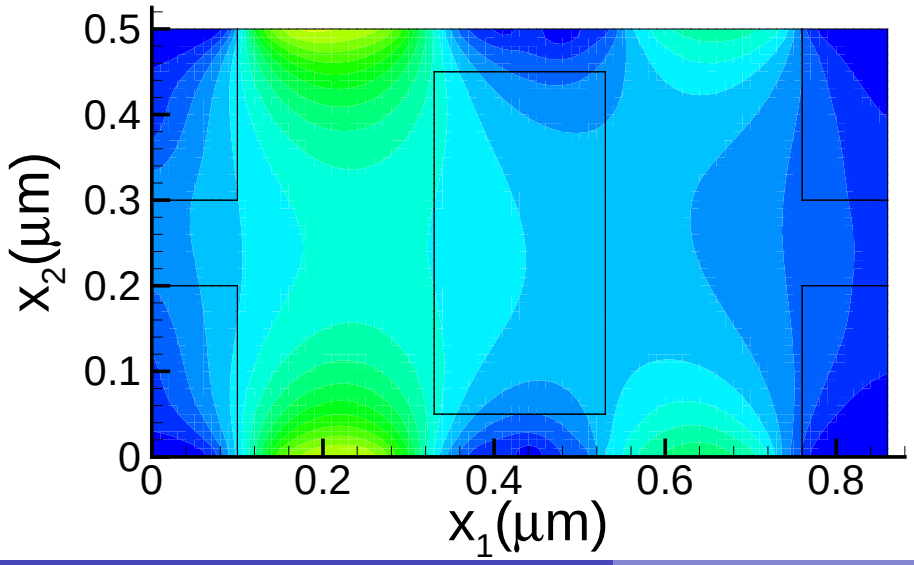
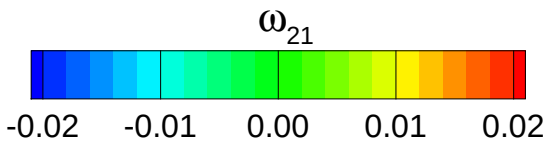
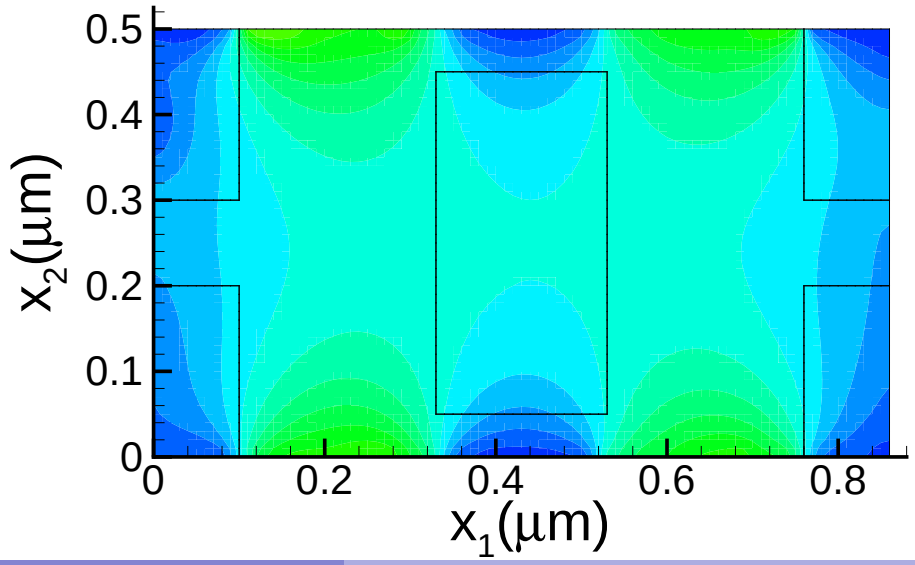






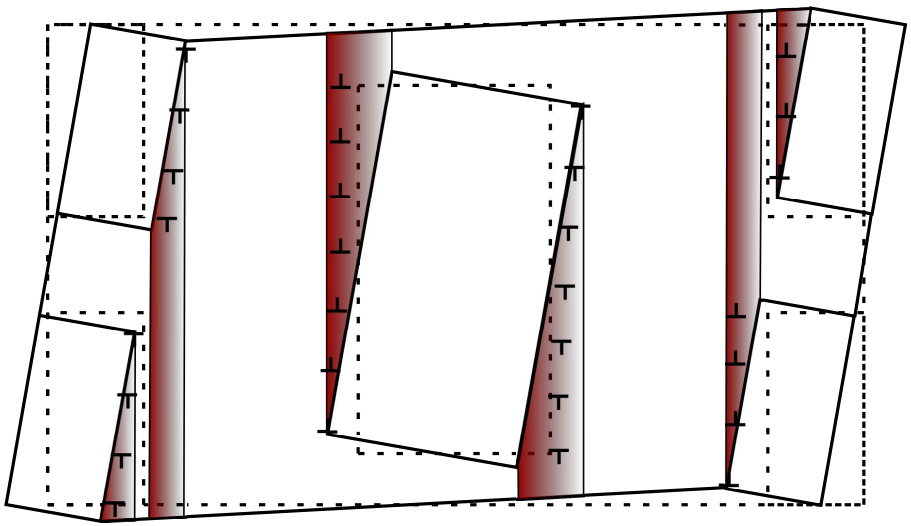




Mass transport mechanism

glide only

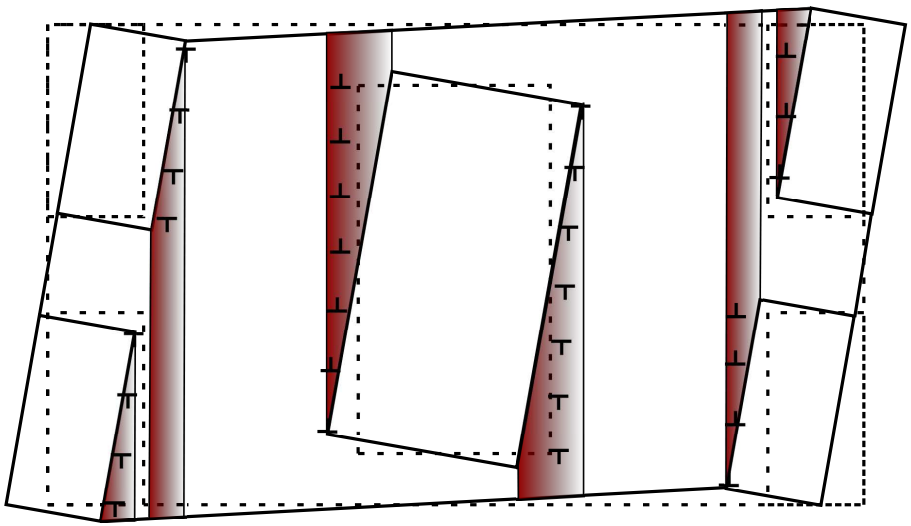
GND induces rotations



Mass transport mechanism

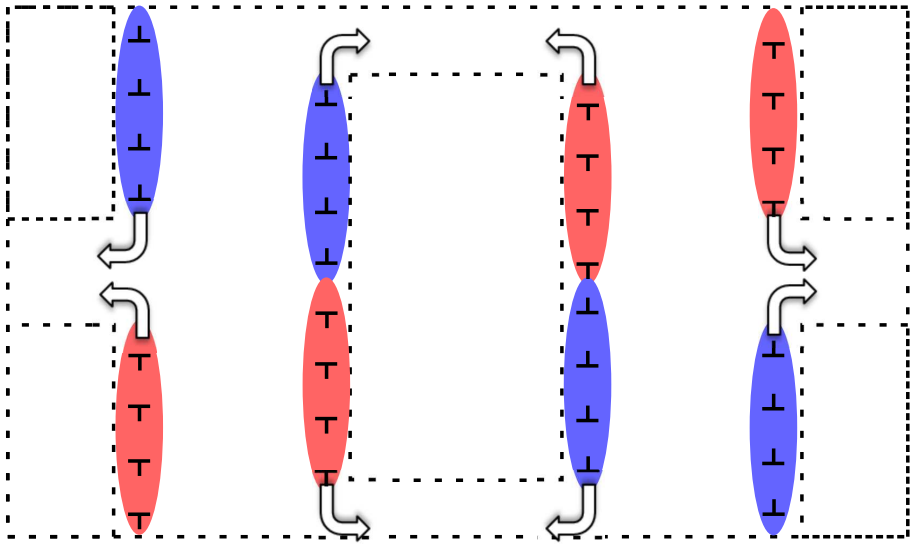
glide only

GND induces rotations



glide + climb

GND is reduced due to annihilations



Conclusions

- Discrete dislocation plasticity is a powerful simulation tool which is capable of capturing plasticity size effects and provide insight about the origin of these size effects.
- Dislocation climb can significantly reduce the size effects.