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Geometrically Explicit Simulation of Microstructurally Small Fatigue Crack Formation and Propagation

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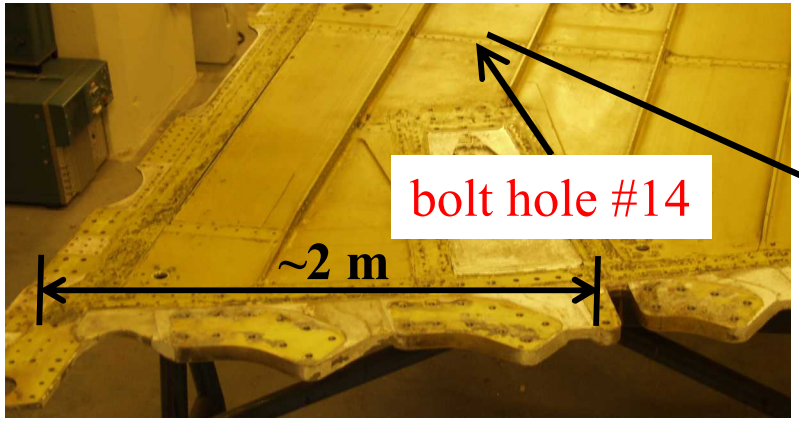
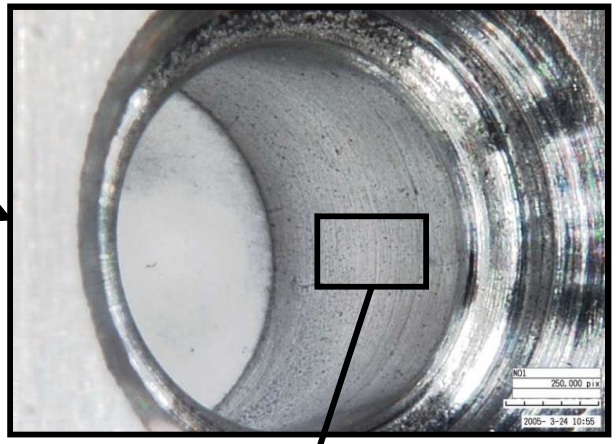
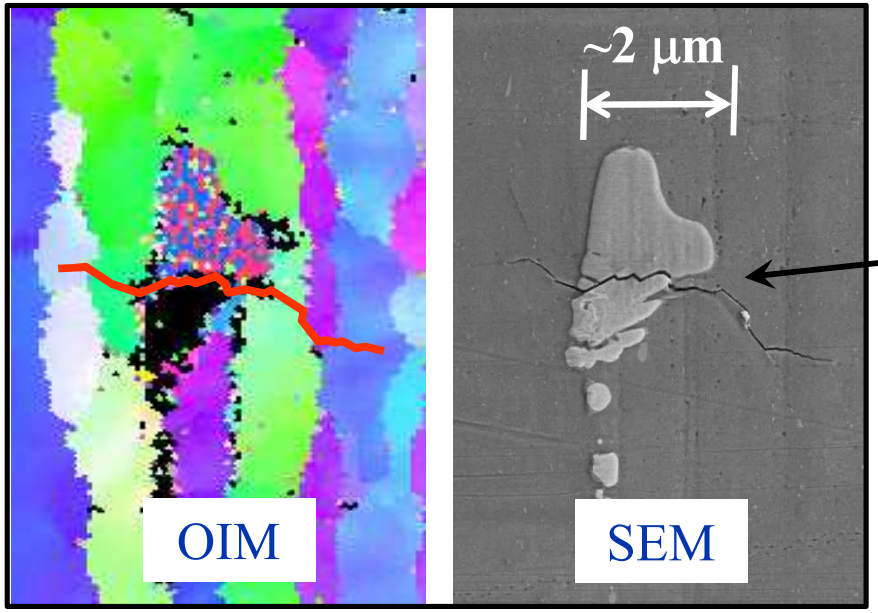
Presentation Outline

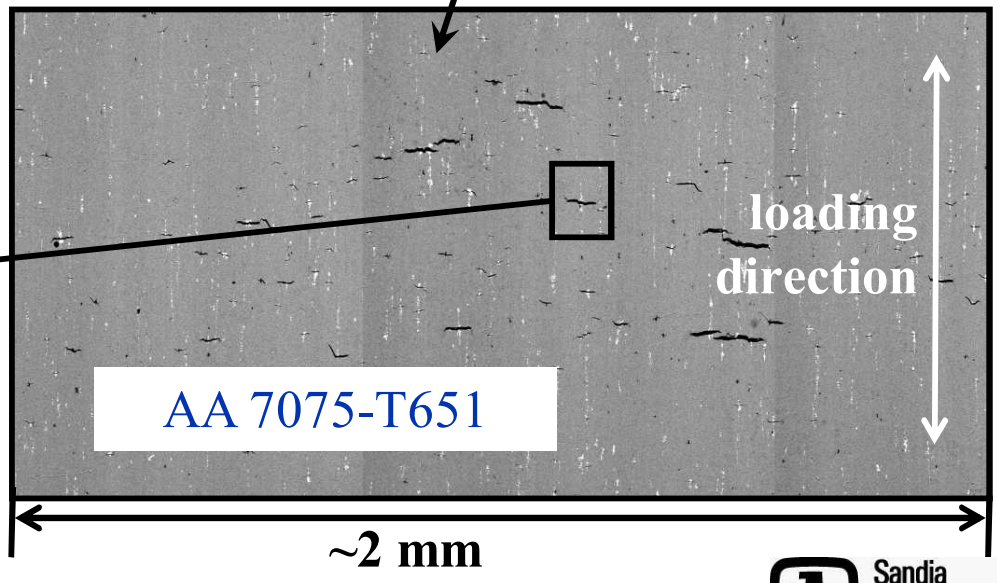
- **Motivation**
  - large-scale impacts driven by microstructural scale phenomena
- **Modeling approach**
  - high-fidelity, stochastic replication of microstructural geometry & physics
- **Crack growth simulation**
  - determination of microstructurally small fatigue crack (MSFC) growth rate & direction criteria

Why Model the Microstructure?









*images courtesy of Northrop Grumman Corp.

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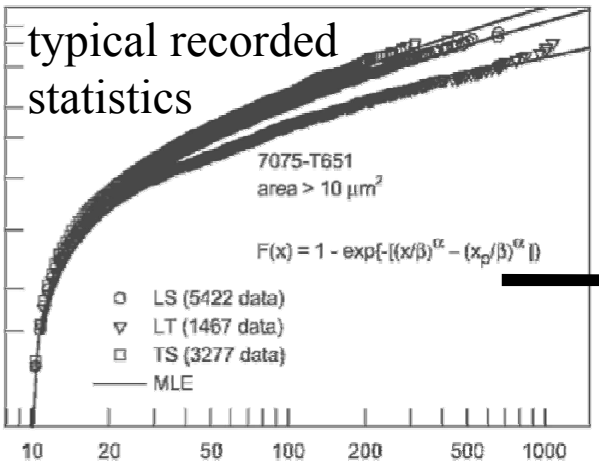
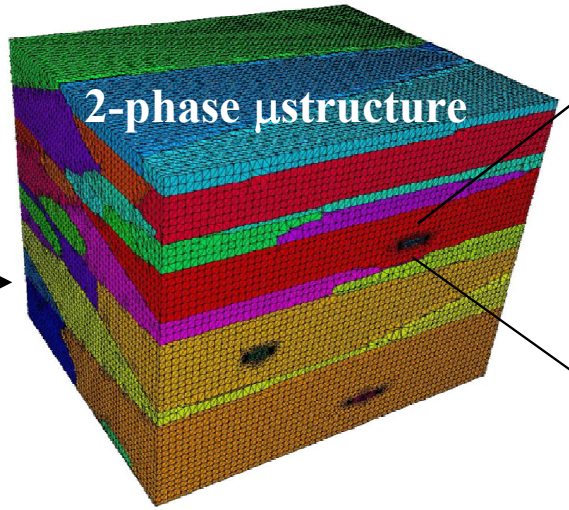
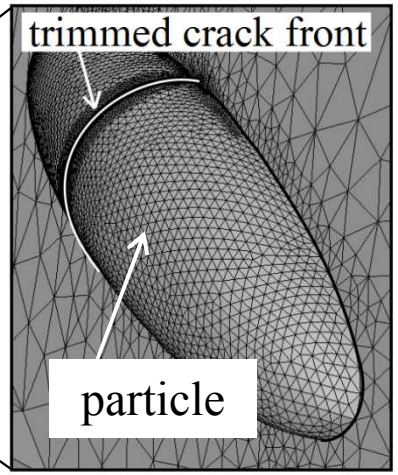
Stochastic Microstructure Replication







Statistics from experiment

- *Grain* dimensions, orientations, & misorientations*
- *Particle* dimensions, aspect ratios, & nearest neighor distances**

Microstructure Model

- Statistical realizations generated by *mbuilder**
- Geometry-conforming surface meshing***
- Tetrahedral volume meshing

Crack Representation

- w/ FRANC3D
- Geometry & mesh adaptation
- Material state remapping

*In collaboration with: *A.D. Rollett et al., CMU; **G. Harlow, Lehigh Univ.; ***Y. Zhang et al., CMU*

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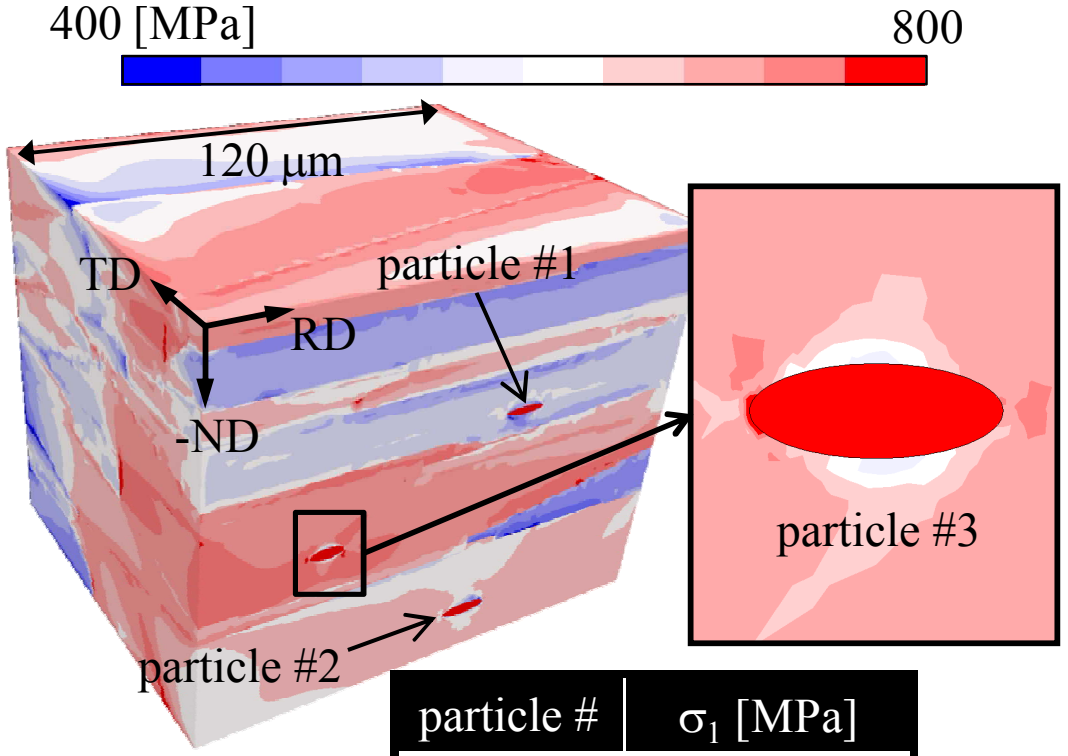
Example Microstructural Simulation Results

- Quasi-static loading
  - 1% max. RD strain
  - Load ratio = 0.1
  - Second load peak shown
- No cracks
- Approx. 6 million dof's
  - ~25,000 CPU hours per load cycle on NERSC's Franklin HPC cluster
- Microstructure causes large stress variations
  - *Grain orientation* ***(~2X variability)***
  - *Particles* ***(~2X rise)***



Max. Principal Stress (σ_1) Plot

particle #	σ_1 [MPa]
1	1120
2	1160
3	1180

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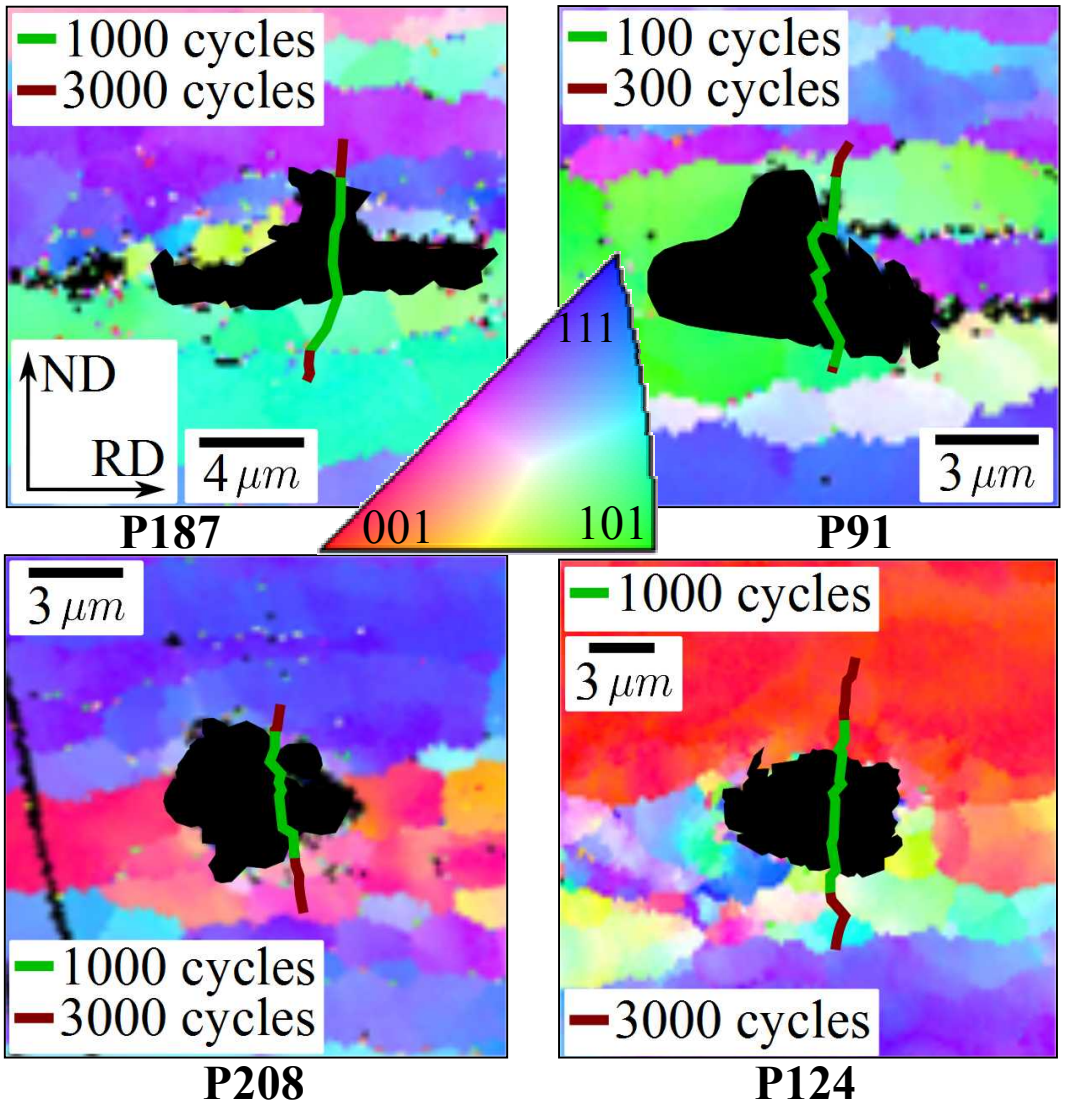
Observations of Early Crack Propagation



- 1% max. RD strain, R = 0.1
- Avg. crack dir. normal to RD
  - Local deviations along GB's

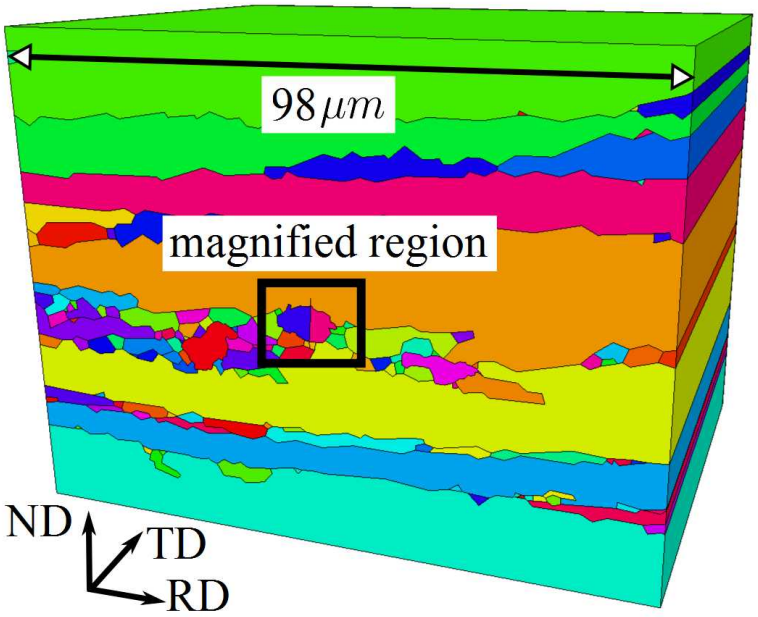
observed growth rates

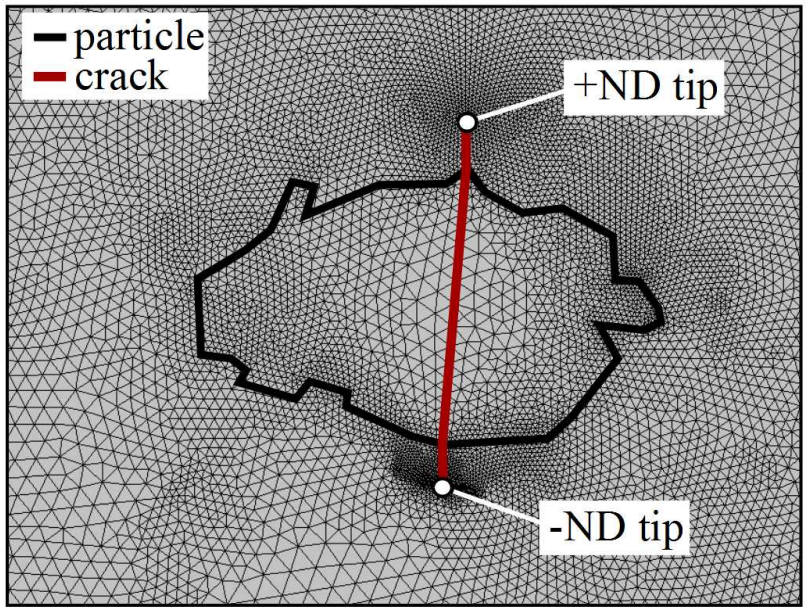
ID	cycle range	$\Delta a / \Delta N$ **
P187	1000-3000	0.50
P91	30-100	14.29
	1000-3000	1.31
P208	1000-3000	1.38
P124	300-1000	0.53
	1000-3000	1.75

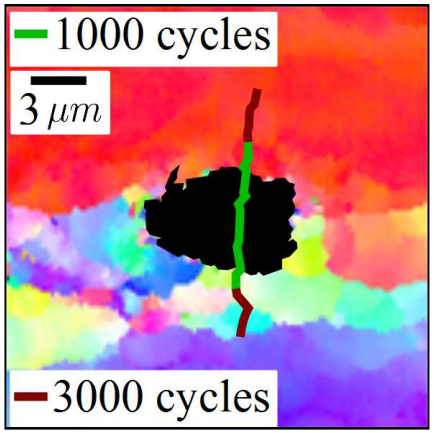
***$\Delta a / \Delta N$ in 10^{-3} μm/cycle*

** EBSD images courtesy of Northrop Grumman Corp.*

FEM Replications of Observations







- Replication of MSFC in P124
  - Crack extends ~1μm beyond particle
  - Approx. crack shape @ 1000th cycle
- '+ND tip' is transgranular
- '-ND tip' is intergranular

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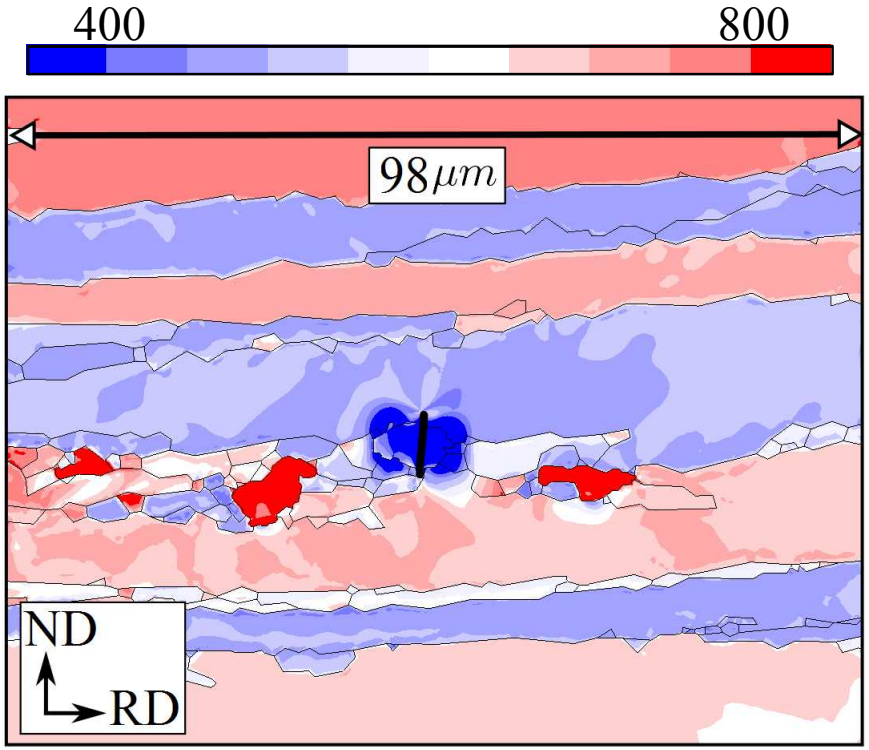
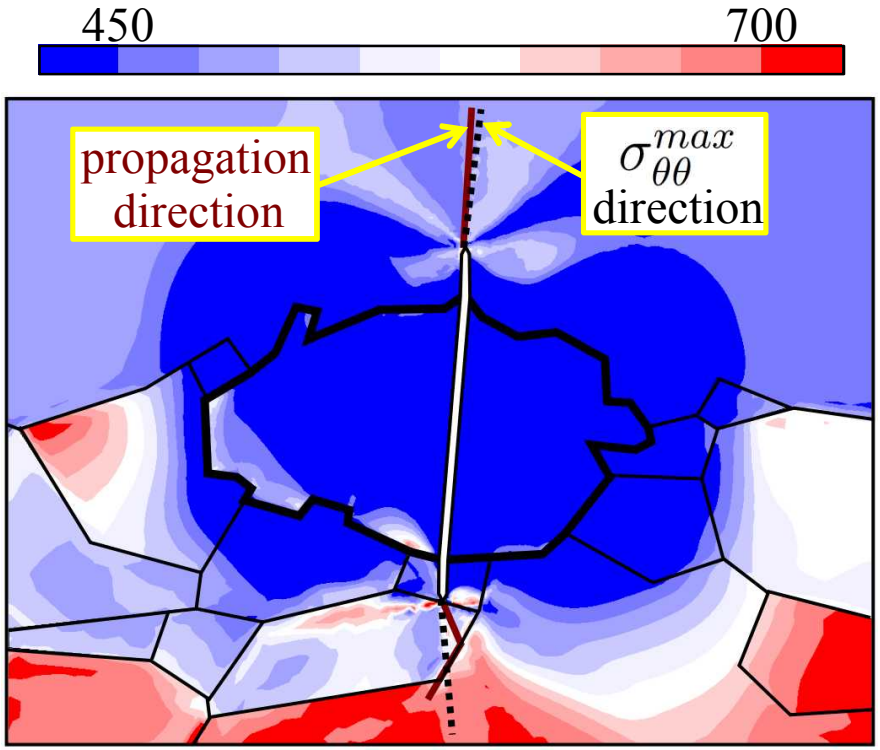
Replication Simulation Results: Growth Direction





σ_1 contour plots at 2nd load peak

- '+ND tip' propagates normal to $\sigma_{\theta\theta}^{\max}$ (stage II)
- '-ND tip' propagates along favorably oriented GB's

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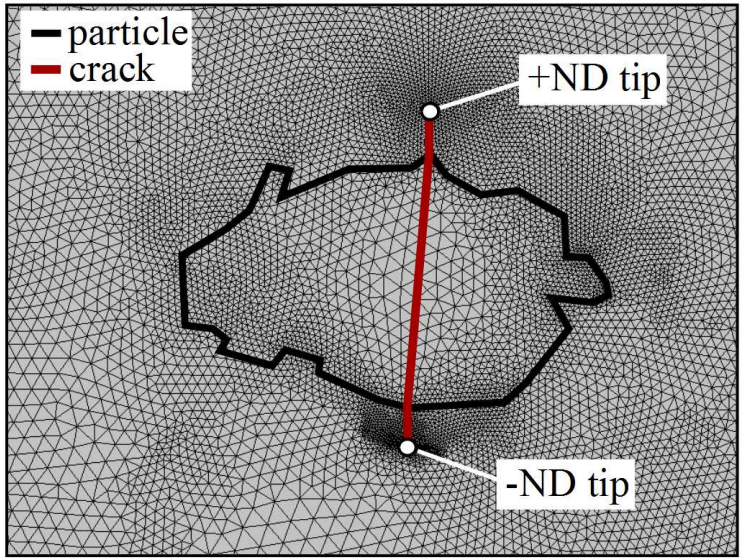
Replication Simulation Results: Growth Rate

ID	crack tip	*ΔCTD**	*Δa /ΔN **	*G*
P187	+ND	9.1	0.5	0.005
	-ND	9.3	0.5	0.005
P208	+ND	8.5	1.4	0.016
	-ND	8.4	1.4	0.017
P124	+ND	9.4	1.8	0.019
	-ND	8.8	1.8	0.020



*ΔCTD = "Change in Crack Tip Displacement /Cycle" in 10^{-2} μm **$\Delta a / \Delta N$ in 10^{-3} μm/cycle

- *G* calculated from***:

$$\frac{da}{dN} = G(\Delta CTD - \Delta CTD_{TH})$$

where:
$$\frac{da}{dN} = \frac{\Delta a}{\Delta N}$$
$$\Delta CTD_{TH} \Rightarrow O(10^{-4}) \approx 0$$

- *G* of MSFC's, from McClintock****:
  - Commonly *O*(10^{-1})
  - Varies significantly w/ load & material
  - High strain + high strength not studied

***D.L. McDowell et al., EFM(2003); and Y. Xue et al., EFM(2009)

****in ***Engineering Against Fatigue*** (1999)

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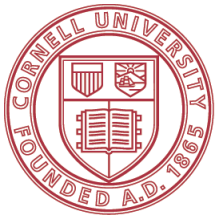
Conclusions

- **Localized deviations in MSFC mechanisms can be accurately, and probabilistically, simulated with microstructural realization models**
  - Significant computational cost
    - Need to pre-determine which realizations will give the most important computational results
- **FE replications of MSFC's utilized to evaluate growth rate and direction metrics**
  - Growth direction either along favorably oriented GB's or perpendicular to max. principal stress
  - Crack tip displacement (one commonly used measure of MSFC growth rate) much larger than anticipated



Acknowledgements

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- **Sandia National Laboratories**

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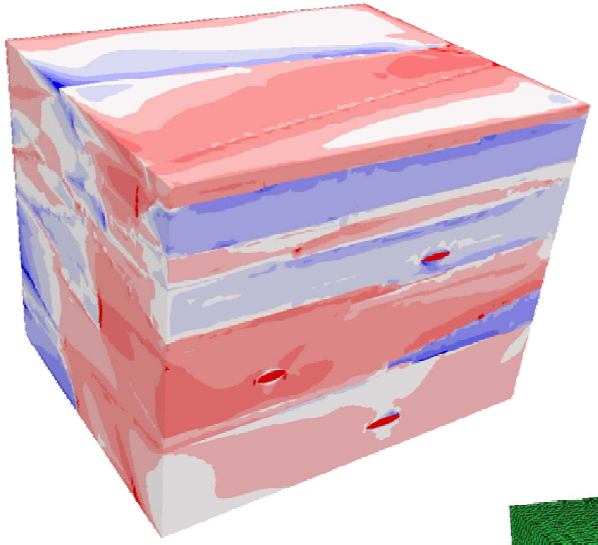
Questions



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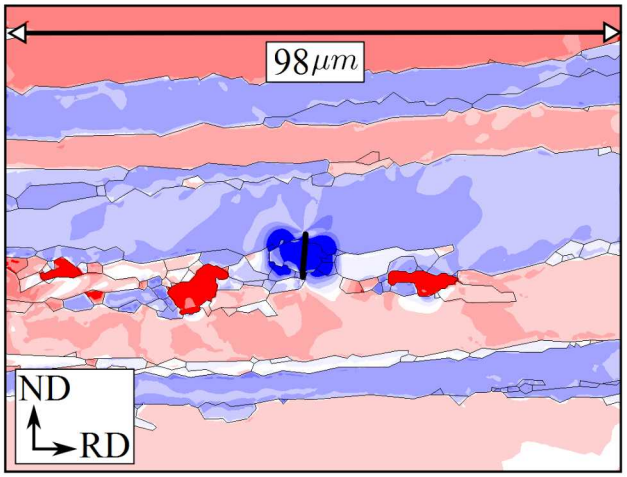

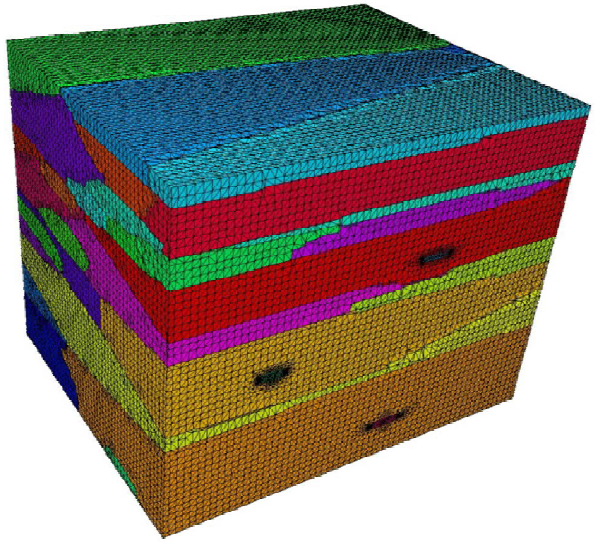

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