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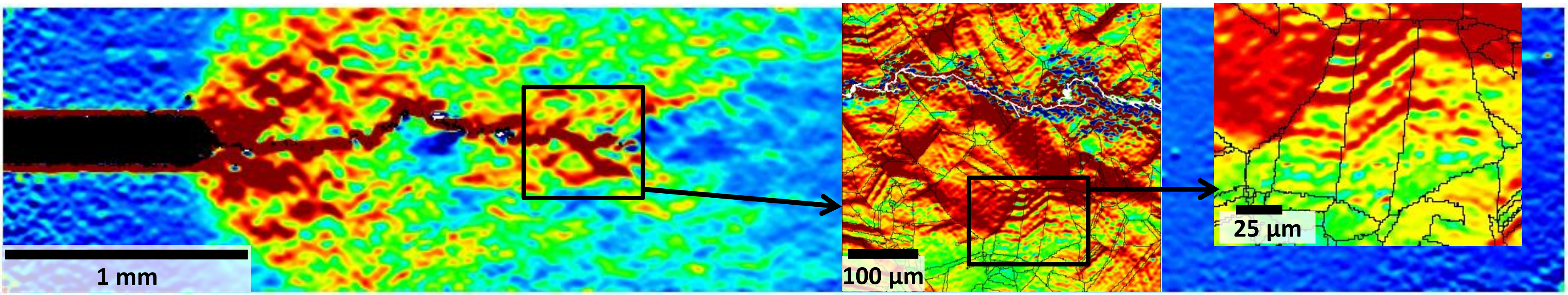

Multiscale Digital Image Correlation for Validation of Multiscale Stochastic Models

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Richard Field Jr., Joseph Bishop

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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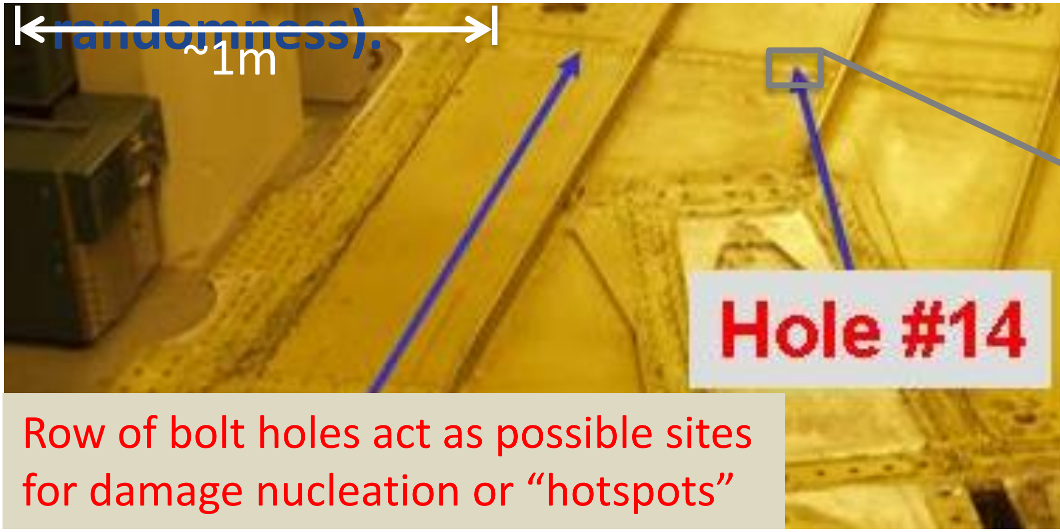
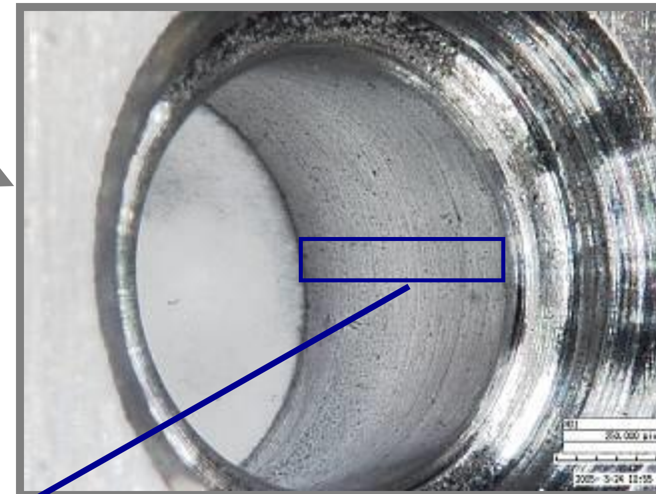
Why do multiscale? Because structural reliability is influenced by *random* microstructure (among other sources of randomness).



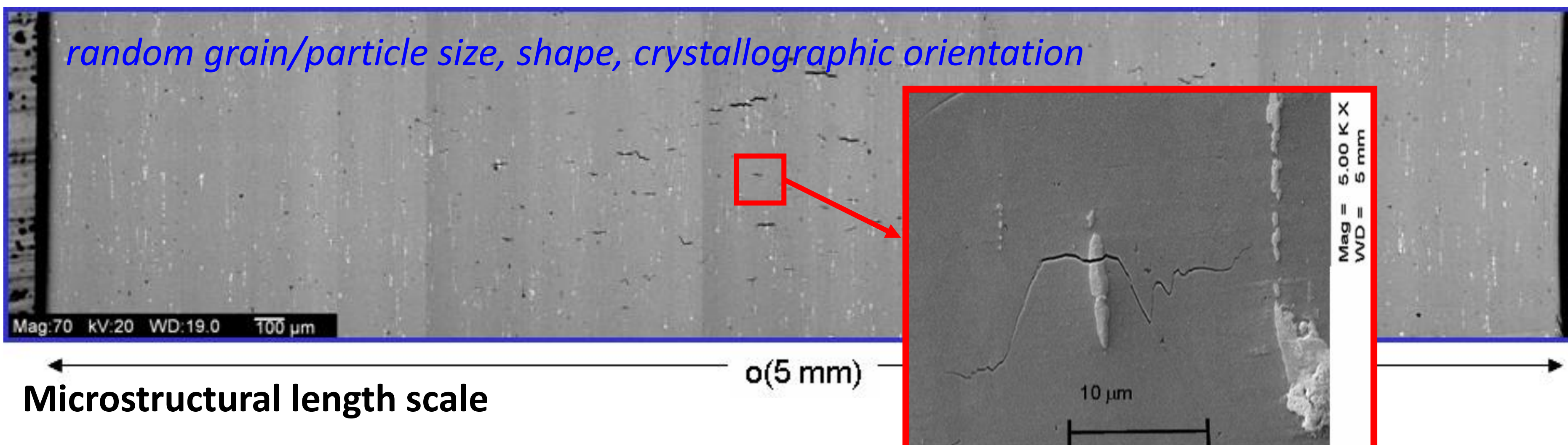
Row of bolt holes act as possible sites for damage nucleation or "hotspots"

Engineering length scale



Structural feature – stress concentration or "hotspot"

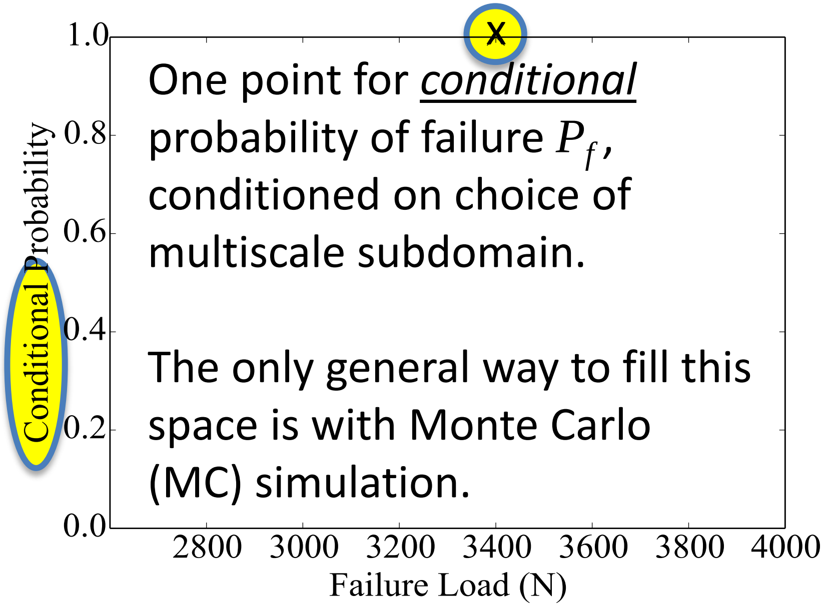
random grain/particle size, shape, crystallographic orientation



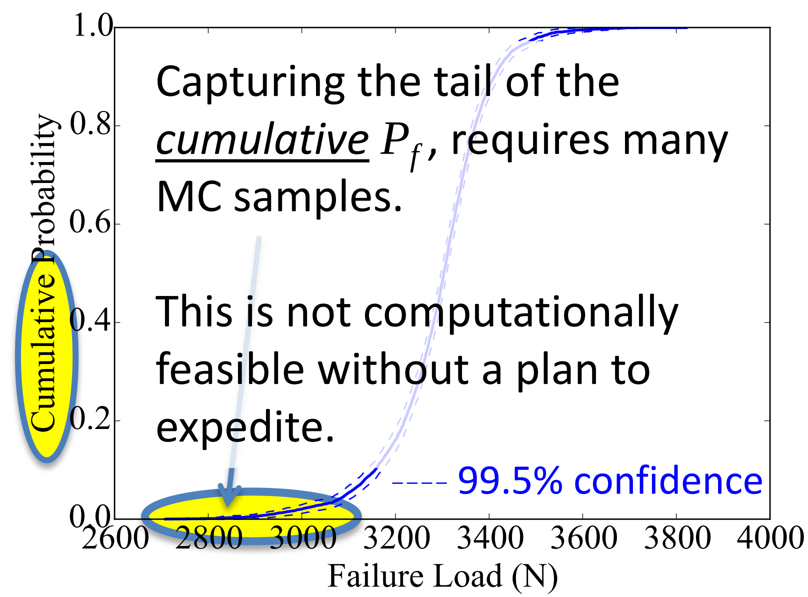
Microstructural length scale

One multiscale calculation is necessary but not sufficient

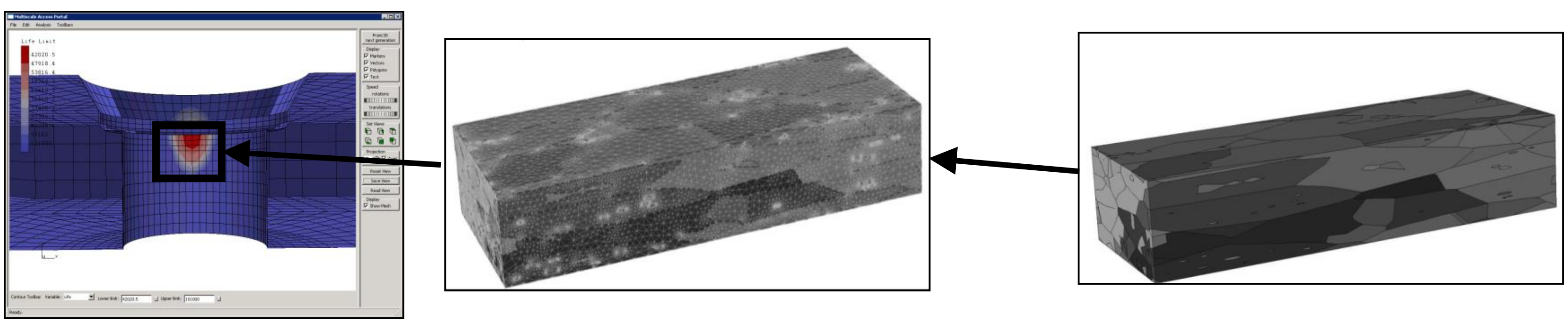
One multiscale calculation gives you this:



But you set out to compute this:



- Multiscale models involve enormous calculations:
- 1e6 DOF (structure) + 100e6 DOF (mstructure) + lagrange multipliers= One Enormous & Cumbersome Calculation!

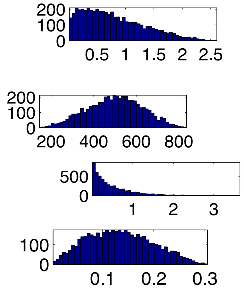


Schematic of the hierarchy

SROM = Statistical Reduced Order Model

Level I

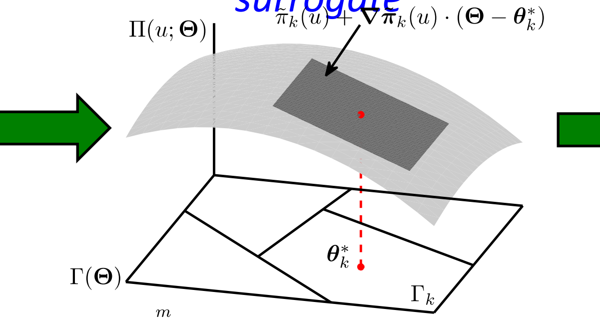
uncertain data



*SROM

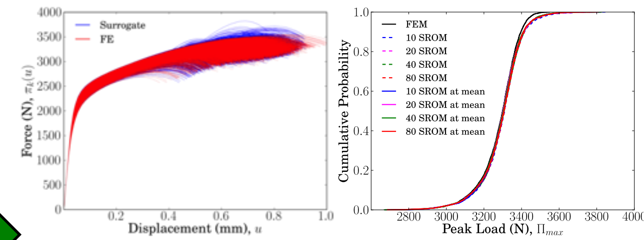
prior distribution

MCS of engineering-scale response via SROM-surrogate

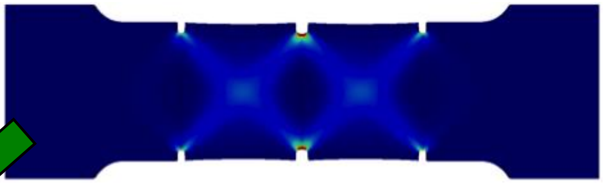


$$\tilde{\Pi}_L(u;\boldsymbol{\Theta}) = \sum_{k=1}^{m} 1(\boldsymbol{\Theta}\in\Gamma_k)\ [\tilde{\pi}_k(u) + \nabla\tilde{\pi}_k(u)\cdot(\boldsymbol{\Theta}-\boldsymbol{\theta}_k^*)]$$

Low-fidelity Probability of Failure



Hotspot selection & prioritization

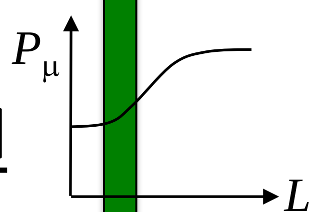


Bayesian update

Level II

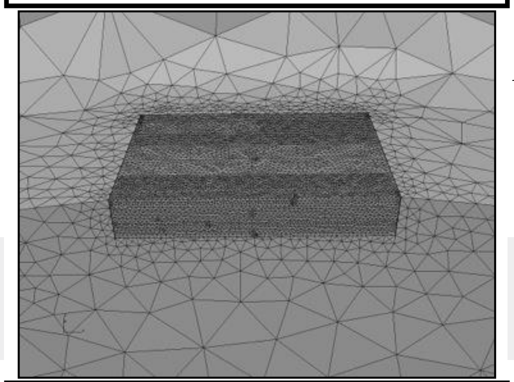
For hotspot i, iterate.
Repeat for all hotspots.

i++

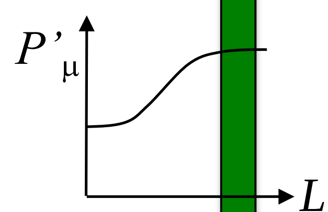


prior distribution of conditional failure

$P_m(L \mid a_i)$



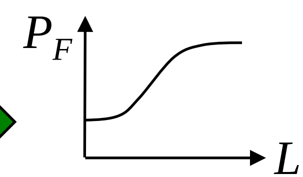
Multiscale calculation



a posteriori distribution of conditional failure

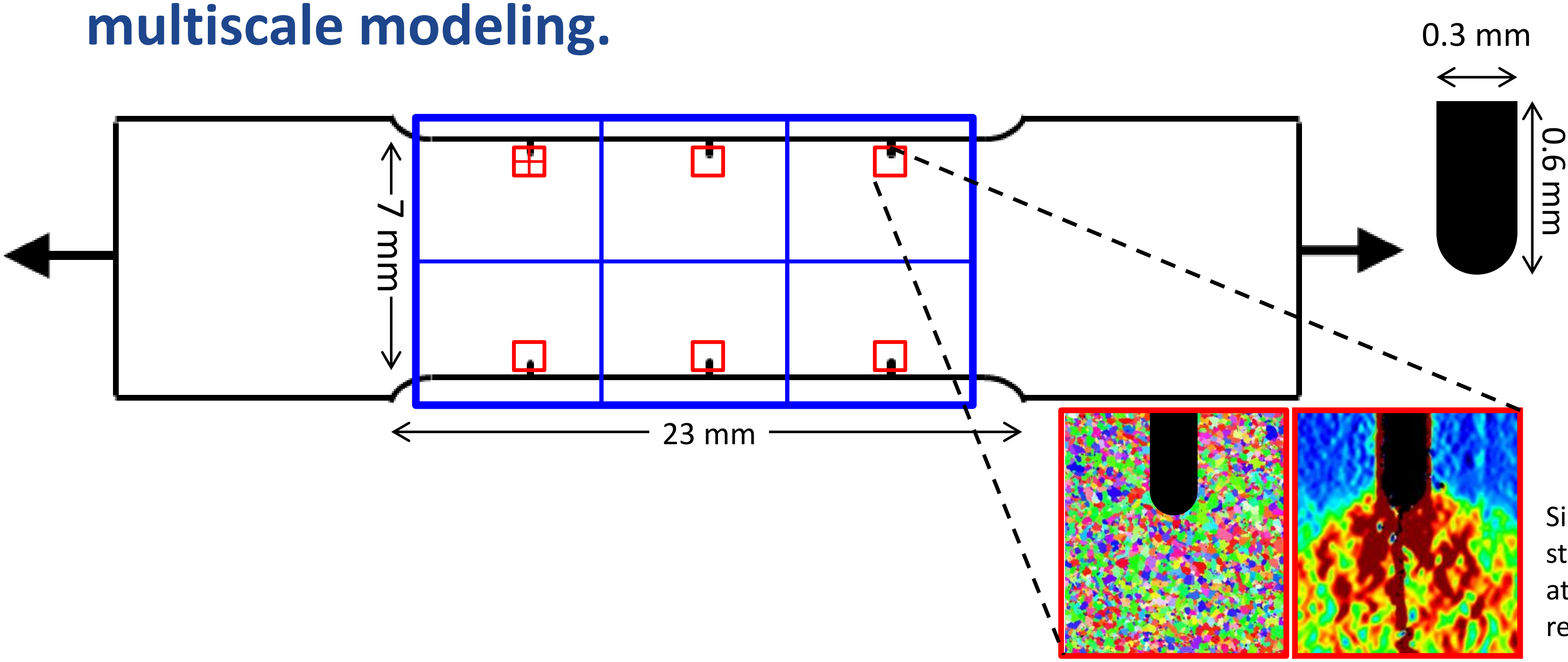
$P'_m(L \mid a_i)$

$$P_F(L) = \sum_{i}^{hotspots} P(L \mid a_i) P(a_i)$$



Higher fidelity prediction

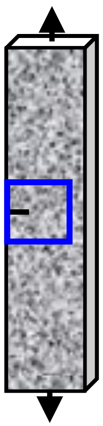
Multiscale experimental validation is necessary for multiscale modeling.

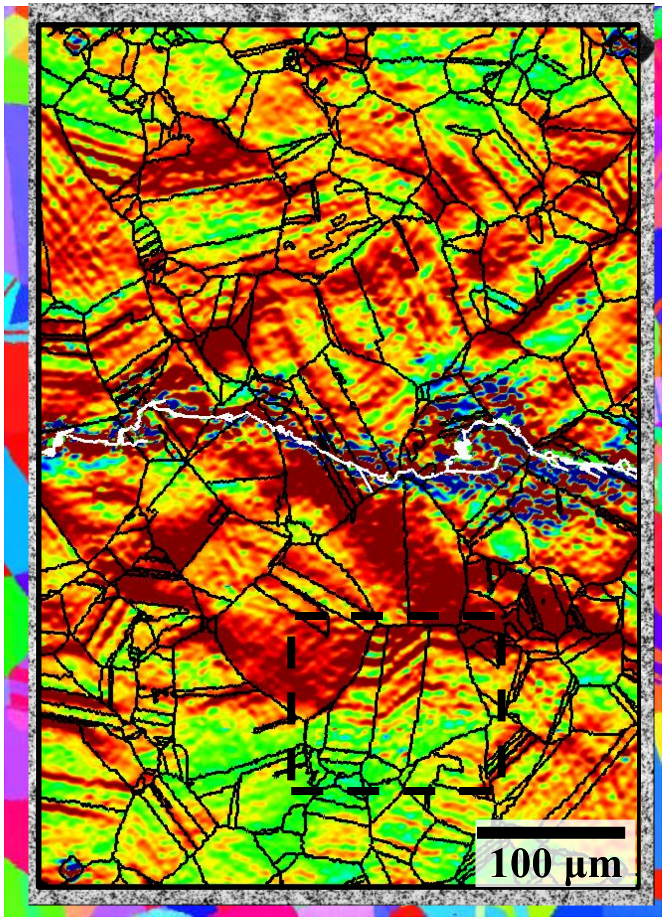


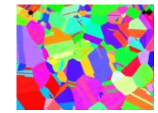
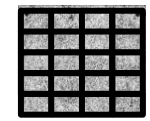
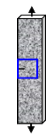
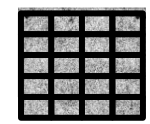
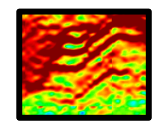
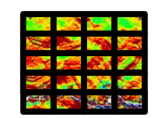
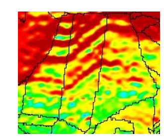
Similar to this strain field, but at much higher resolution.

- Low magnification, (HR-DIC) strain field over entire specimen.
- High magnification, (HR-DIC) strain field near notches.
- Microscale resolution and microstructure only near hot spots
  - Analogous to our multiscale modeling approach.
- Both large and small speckles needed for multiresolution DIC.
  - "100x difference in scale".

High resolution digital image correlation (HR-DIC) improves spatial resolution over region of interest.

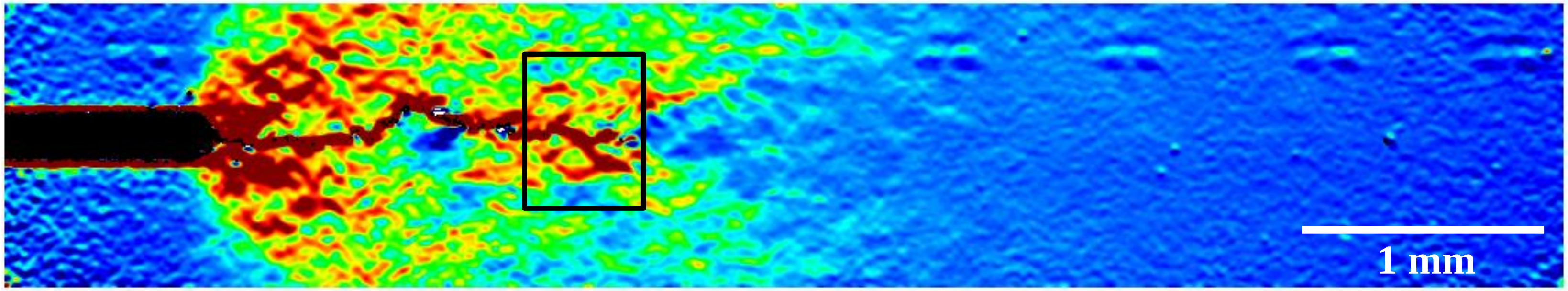


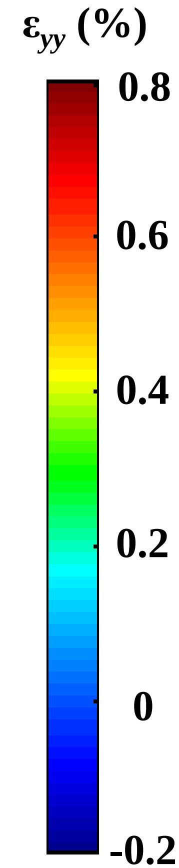


1. **EBSD: microstructure** 
2. **Capture reference images** 
3. **Load specimen** 
4. **Capture deformed images** 
5. **DIC on each image location.** 
6. **Stitch DIC results into large field of view** 
7. **Overlay Microstructure** 

- **Carroll et al., *Rev. Sci Inst.*, v. 81 (2010).**
- Carroll et al., *Int J. Fracture*, v. 180 (2012).
- Carroll et al., *Int. J. Fatigue*, (2013).

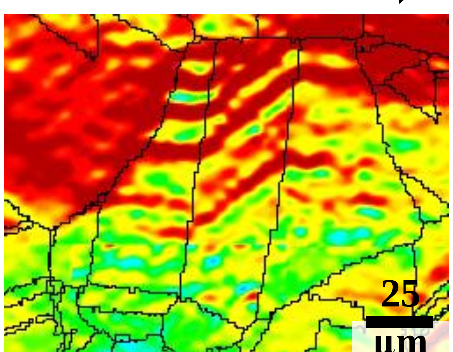
High Resolution DIC (HR-DIC)

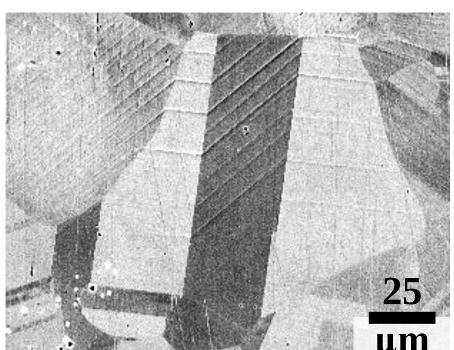


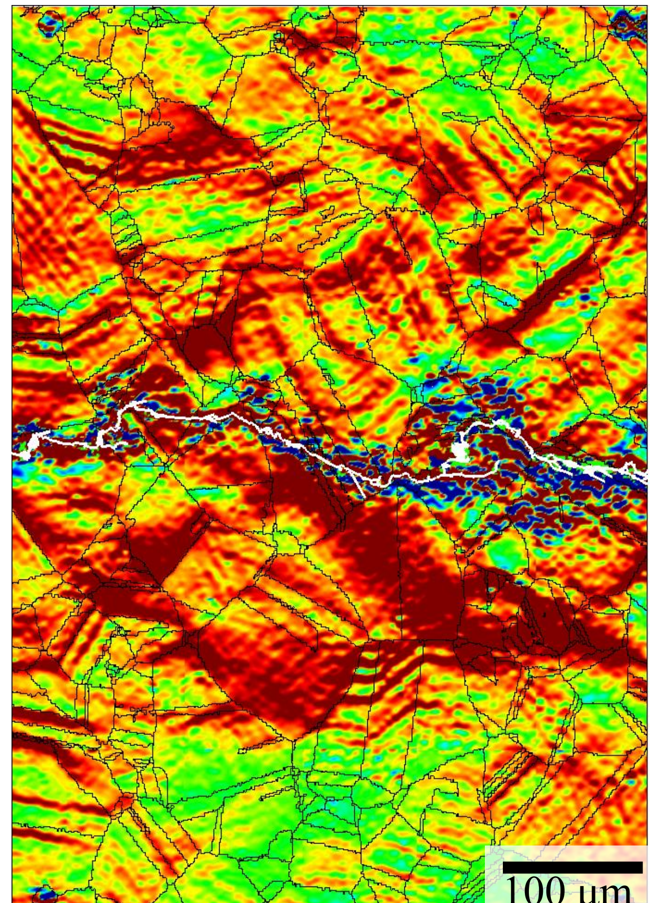


Entire width of specimen

- **HR-DIC gives good mesoscale resolution over large regions (centimeters).**
- **HR-DIC gives sub-grain level resolution over hundreds of microns.**

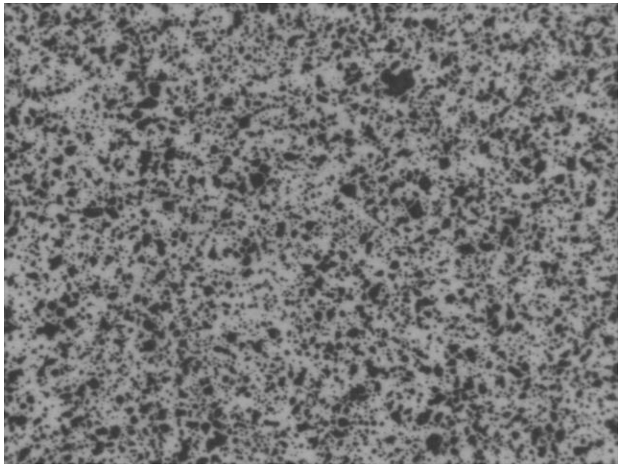




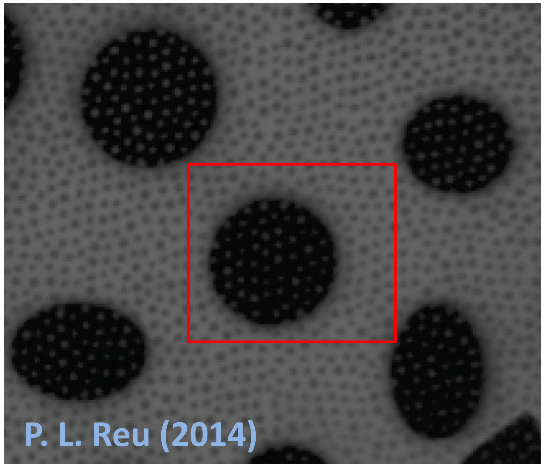


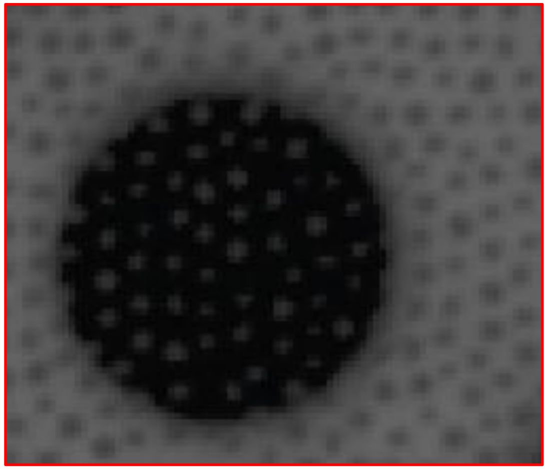
Multiscale speckle patterns required for multiscale DIC.

Conventional speckle pattern: All speckles are equal size.

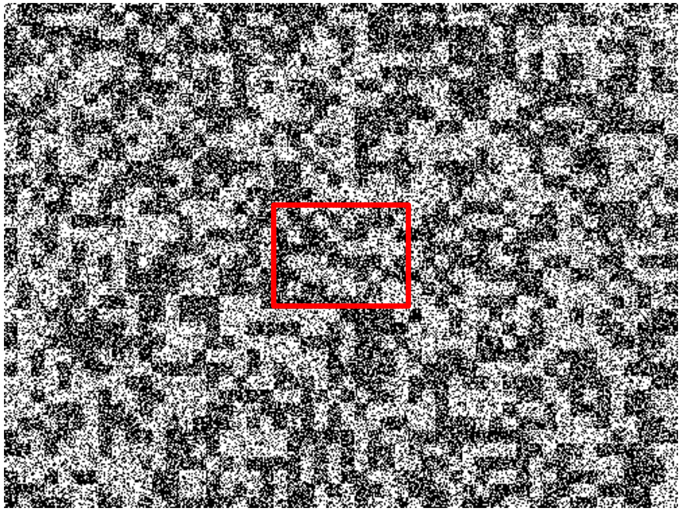


Dual scale speckle pattern: Large and small speckle patterns are overlaid.

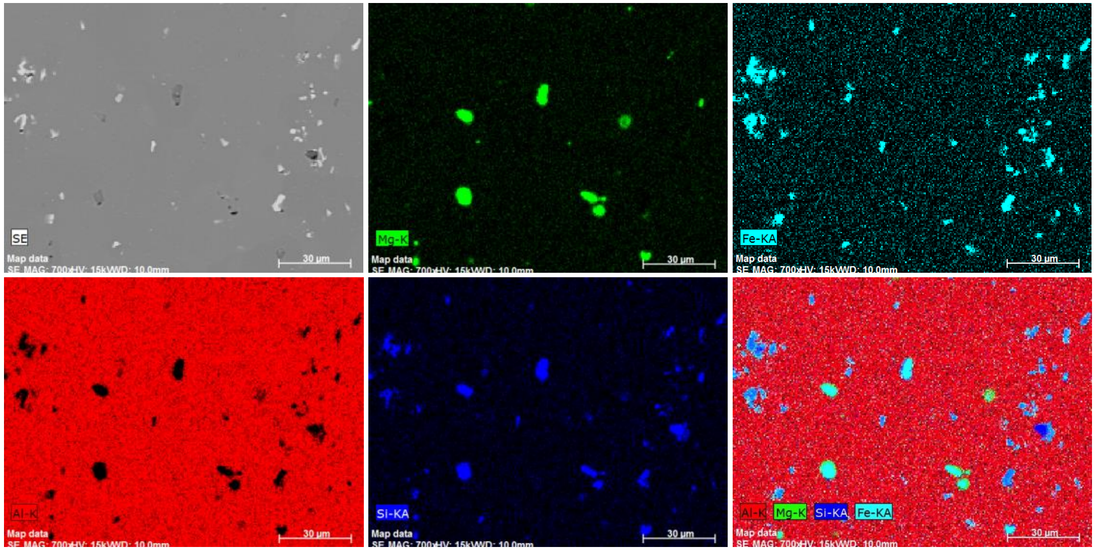




Fractal speckle pattern: Large speckles consist of clumps of smaller speckles.



Inherent multiscale speckle pattern in Al 6061-T6.

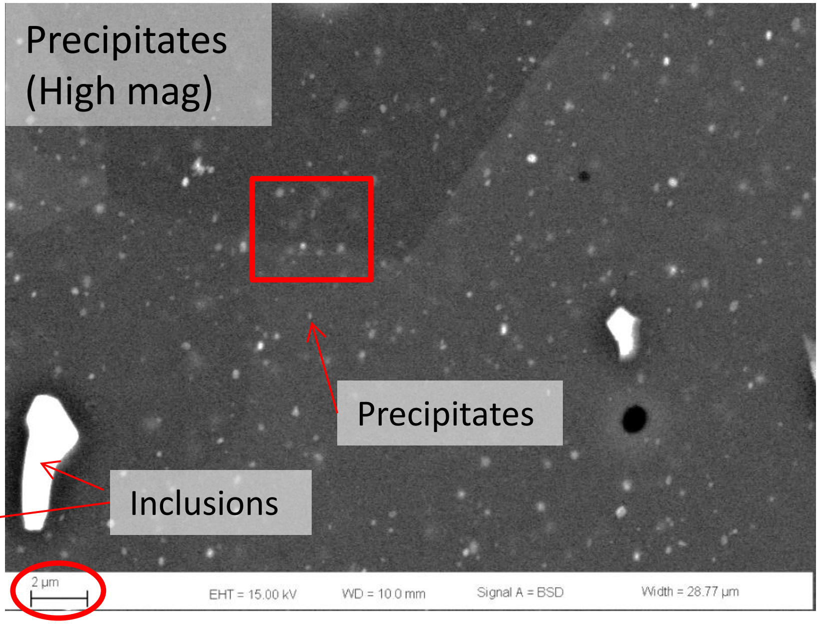


EDS Chemical Composition shows unexpected very fine precipitates in addition to large particles

- Very fine precipitates of Fe (~1um) throughout specimen.
- Larger inclusions of Mg_2Si and of Fe on the scale of 10 um

Also see A. Ghahremaninezhad, K. Ravi-Chandar, Int. J. Fract., 174 (2012) 177-202.

Resolution down to ~150 um

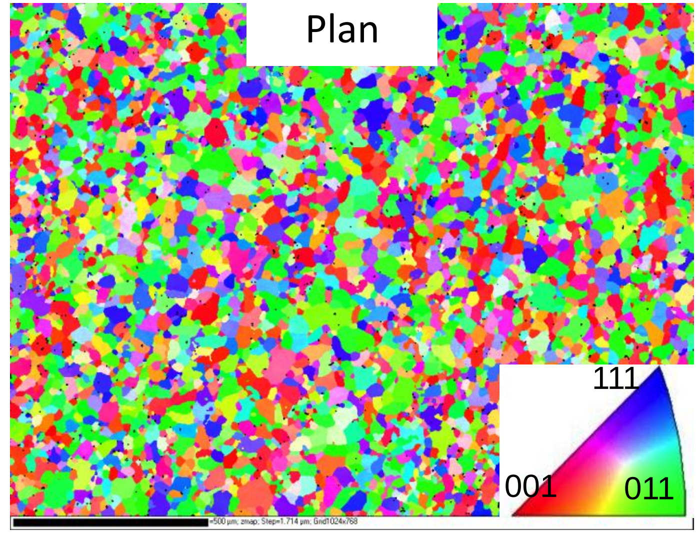


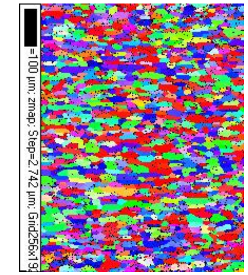
Resolution down to ~4 um

Aluminum 6061-T6

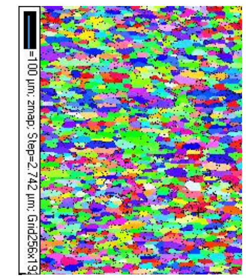
EBSD measurements for calibration

- 6020 grains in plan view
- 2027 grains in transverse view
- 1965 grains in longitudinal view
- Grain size = 33 µm in plane, 18 µm through thickness (90 percentile).
- Slight 100 texture in the rolling direction.
  - Using 5 deg critical misorientation with 1 deg GB completion.
  - Black points (unindexed pixels) are most likely intermetallic particles

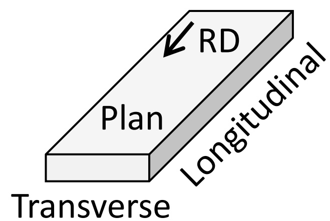




Transverse



Longitudinal



	Alloying Elements					Impurities				
	Al	Mg	Si	Cu	Cr	Fe	Zn	Mn	Ti	Other
Min	95.8	0.8	0.4	0.15	0.04	0	0	0	0	0
Max	98.6	1.2	0.8	0.4	0.35	0.7	0.25	0.15	0.15	0.15
Nominal	**97.2**	**1**	**0.6**	**0.275**	**0.195**	**0.35**	**0.125**	**0.075**	**0.075**	**0.075**

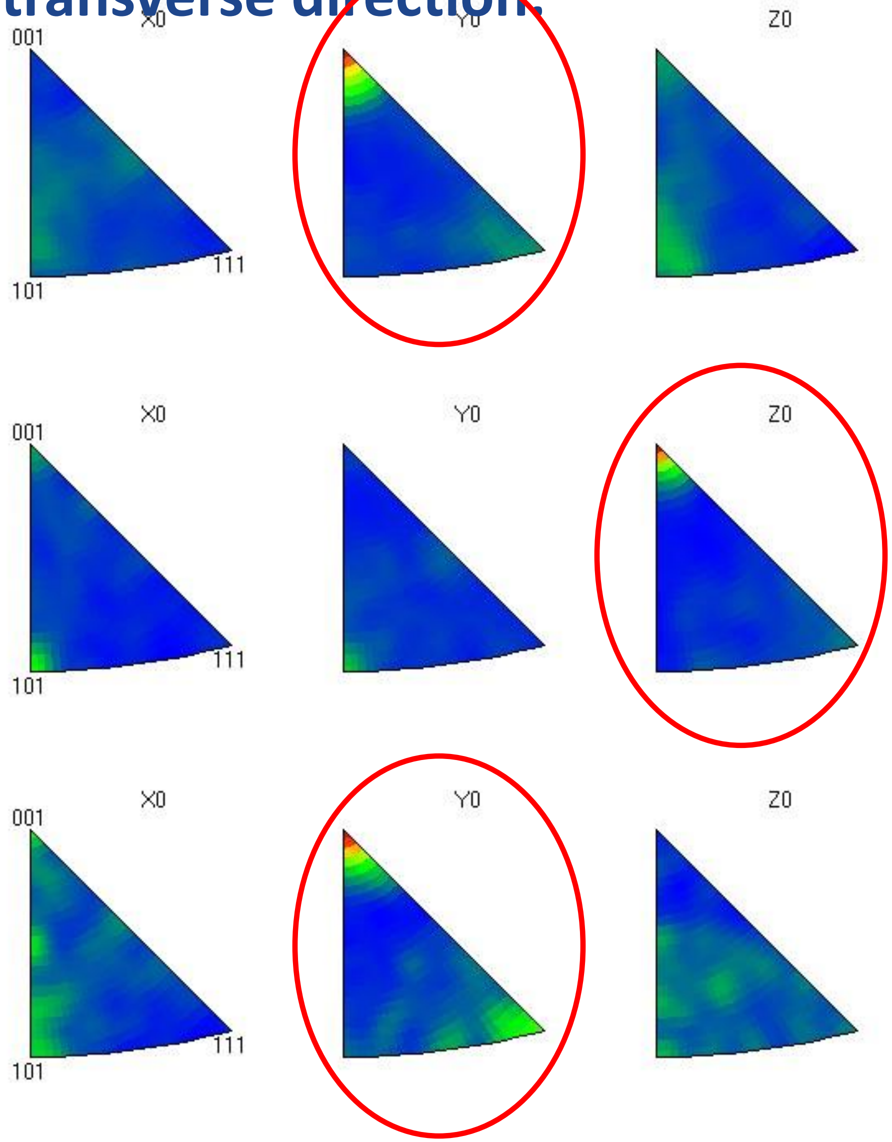
http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

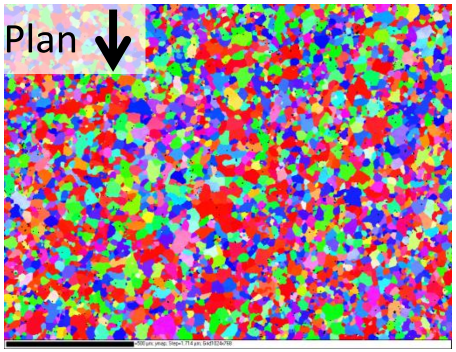
Mild texture present. <100> directions tend to be aligned with transverse direction.

Plan
Max MUD
= 6.48

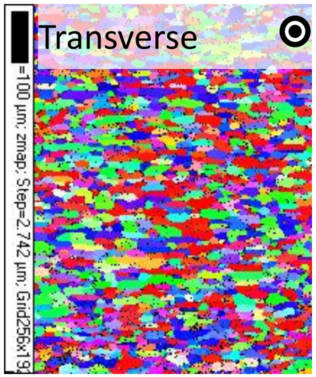
Transverse
Max MUD
=9.07

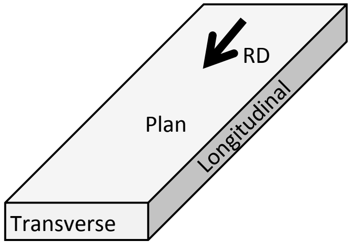
Longitudinal
Max MUD =
5.26

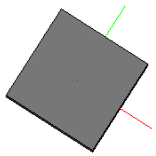


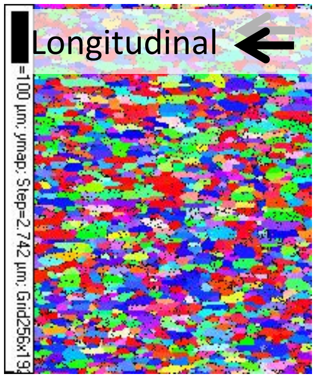


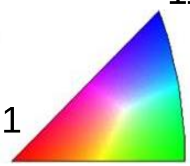
RD shown
by arrows





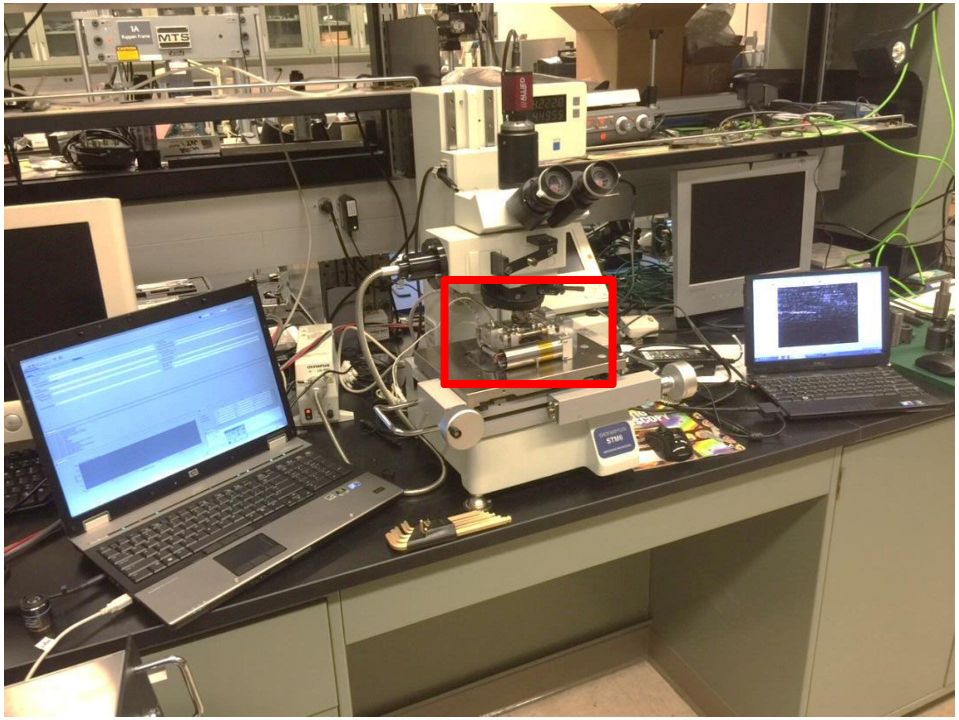


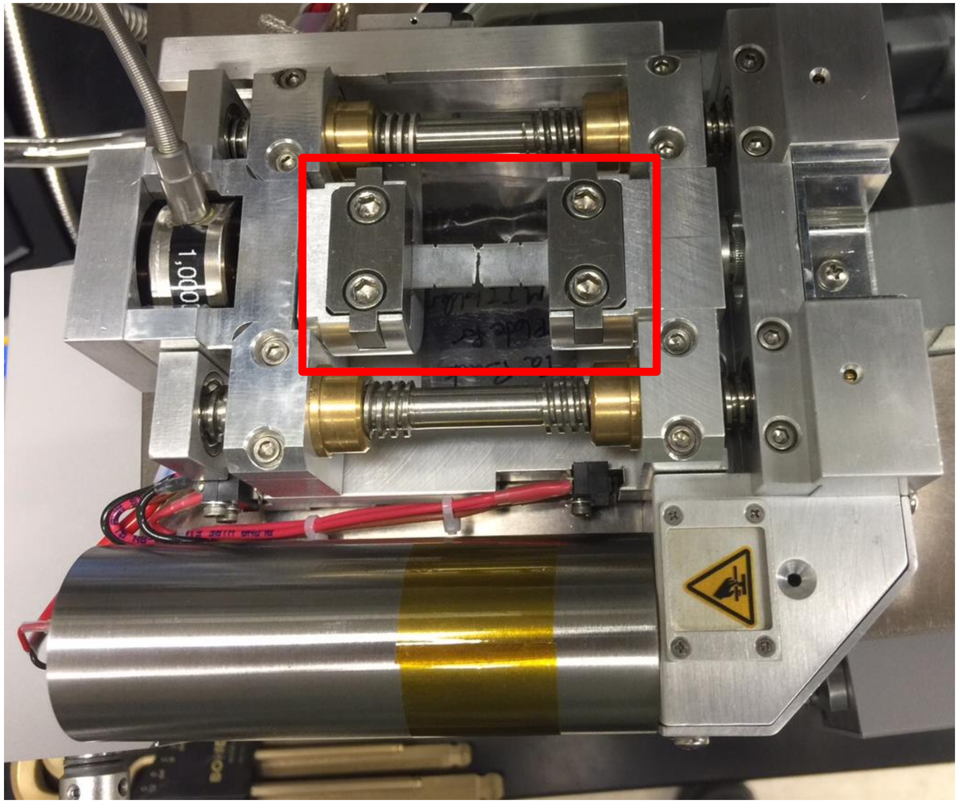


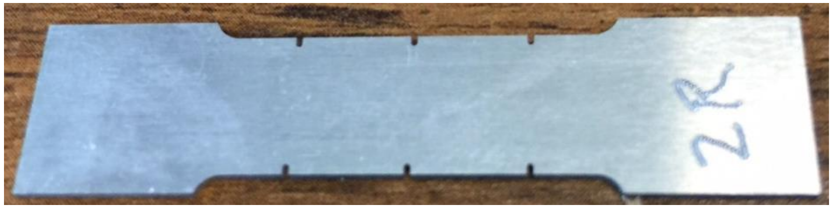


MUD = Multiples of Uniform Density

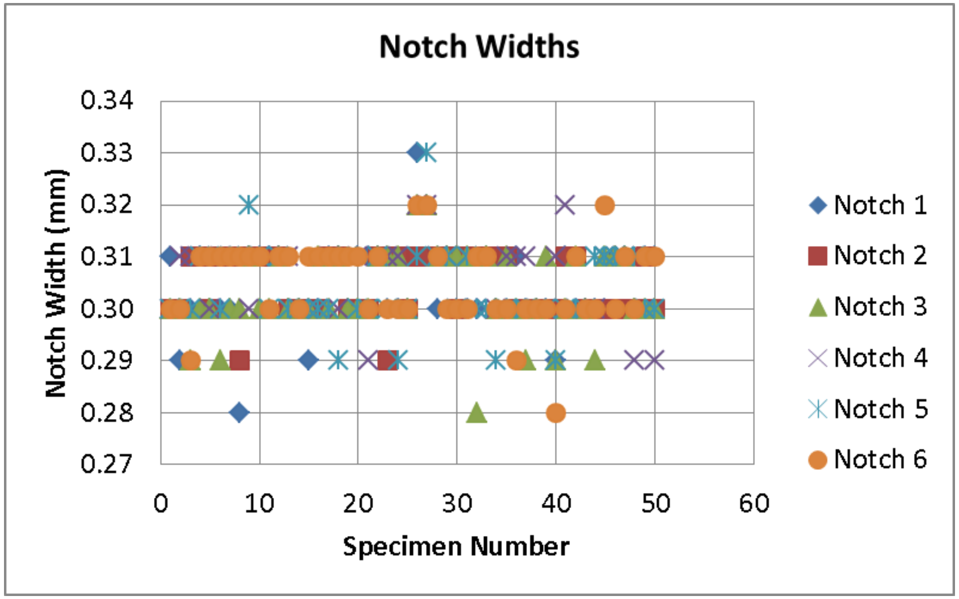
Loaded test sample of 6-notch specimen

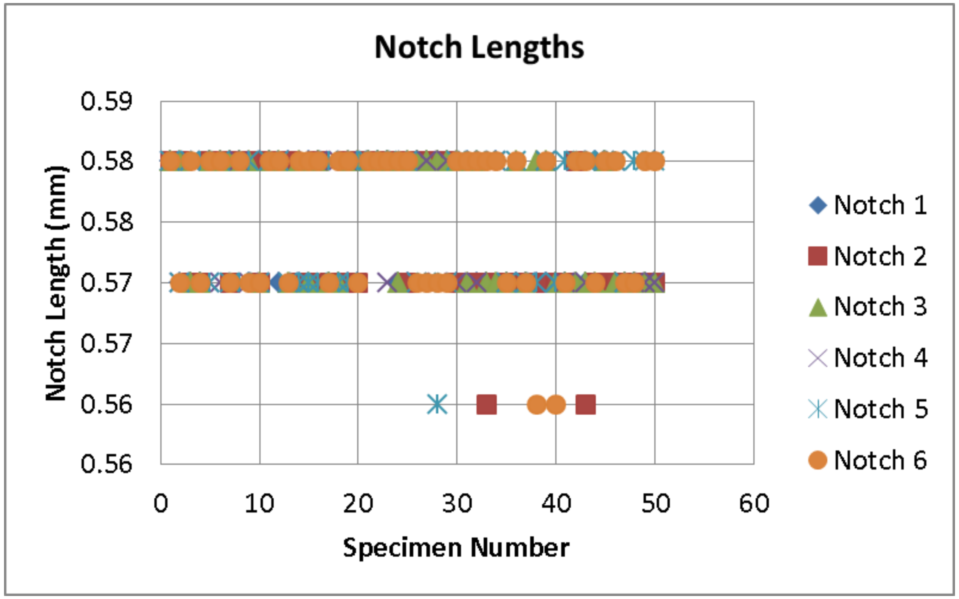


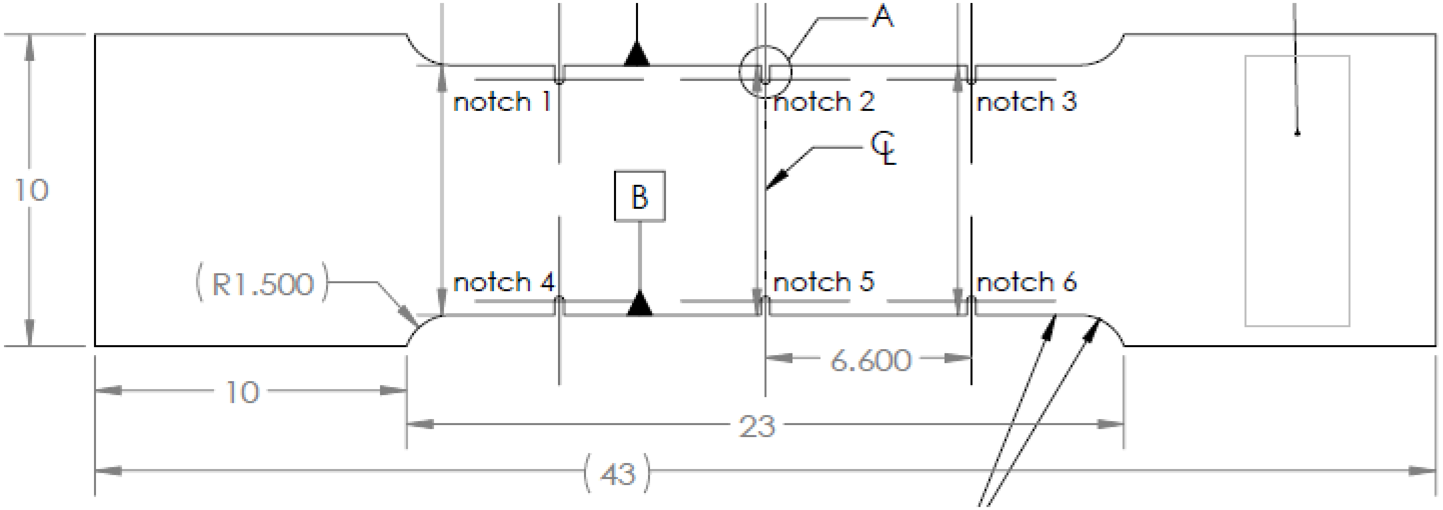




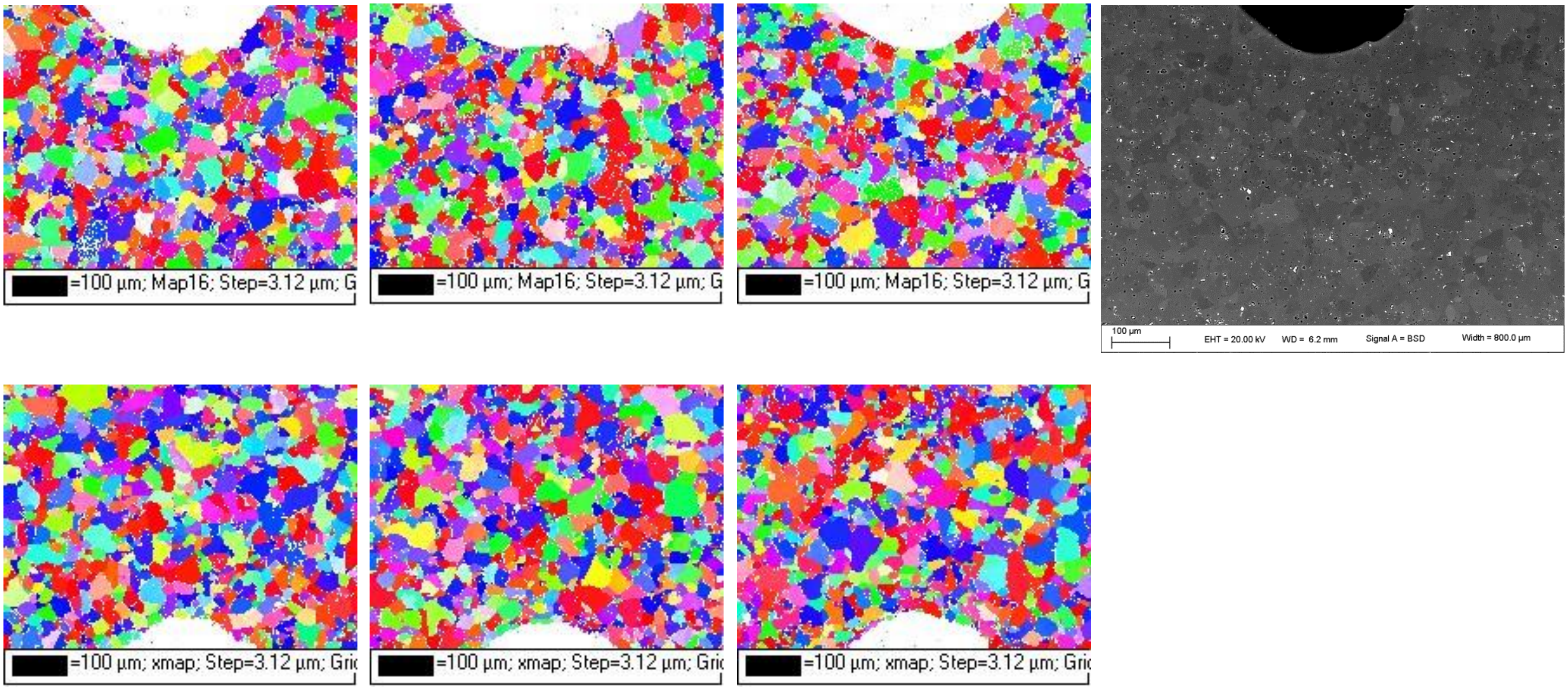
Geometry measured for each specimen to investigate the effects of tolerances on deformation behavior.





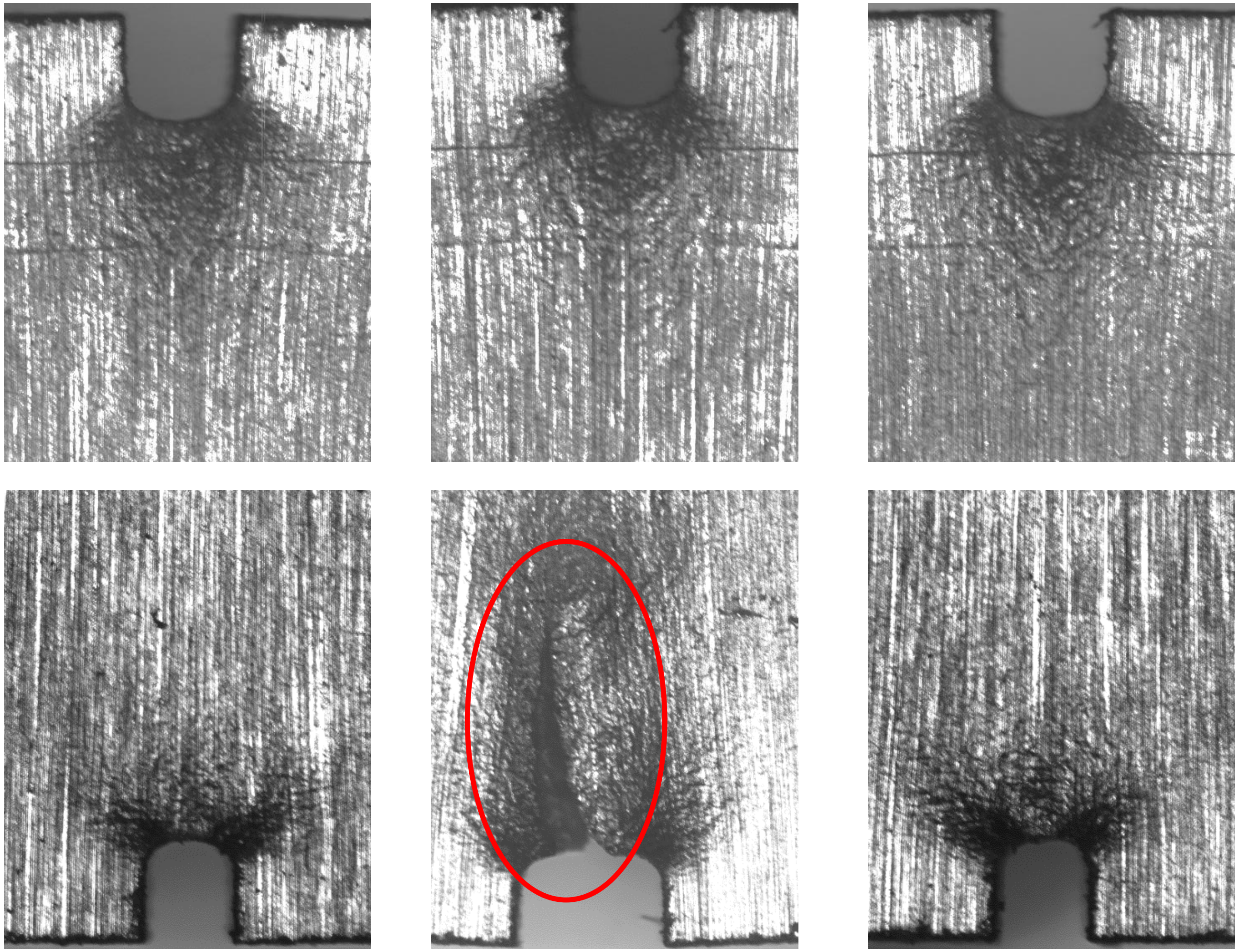


EBSD at each of 6 notches gives some insight into microstructure.



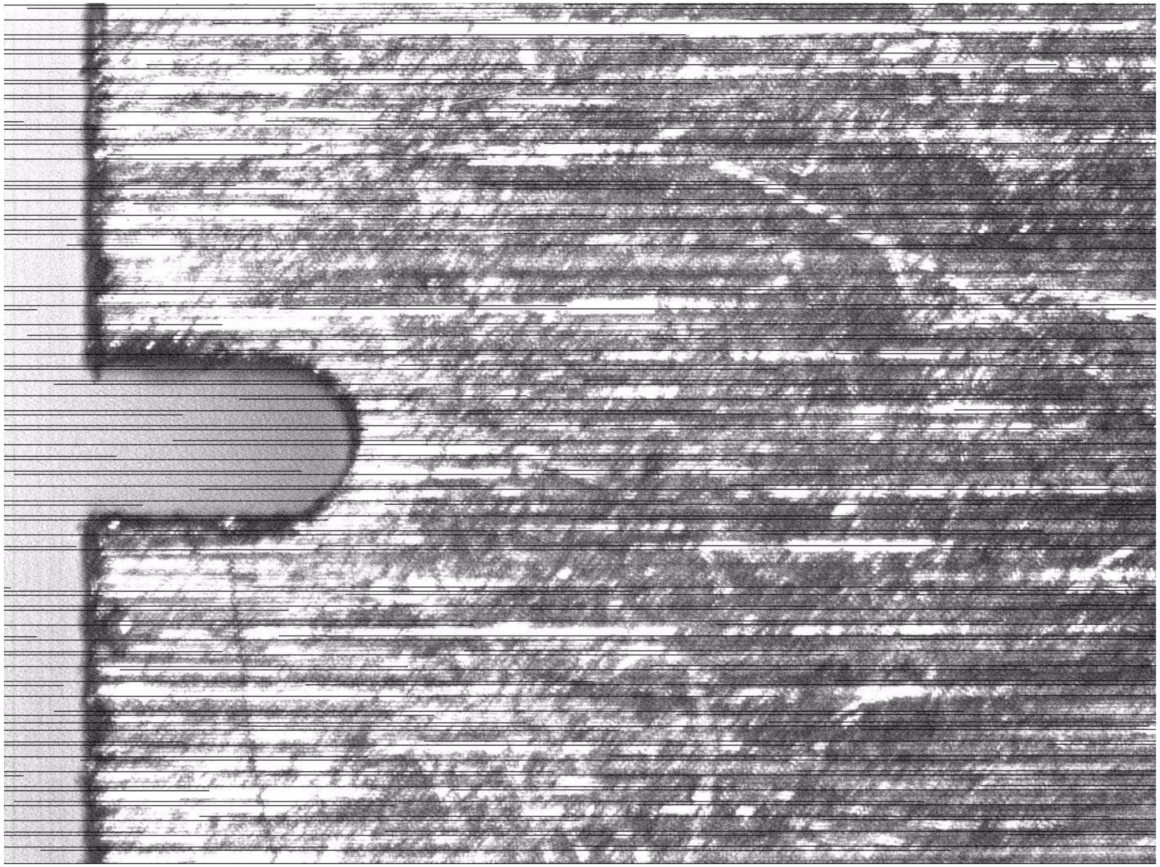
- **Fast EBSD preparation through electropolishing.**
- **EBSD reveals surface microstructure for comparison to surface strain fields.**
- **This particular specimen will be loaded soon.**

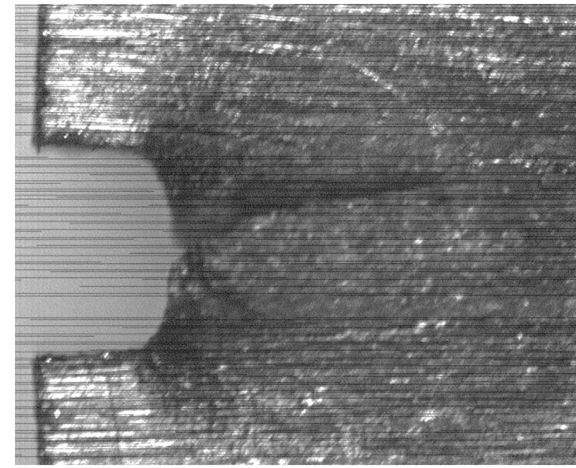
Fracture of first specimen initiated at a center notch with significant plasticity in all notches.



- **Brittle fracture occurred after this substantial crack was observed.**

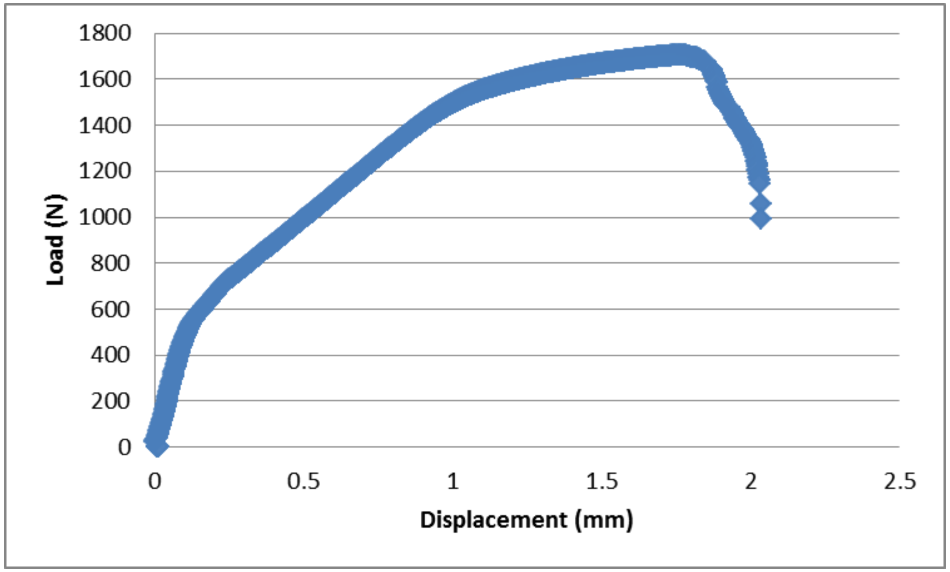
Fracture at center notch in specimen 2 also

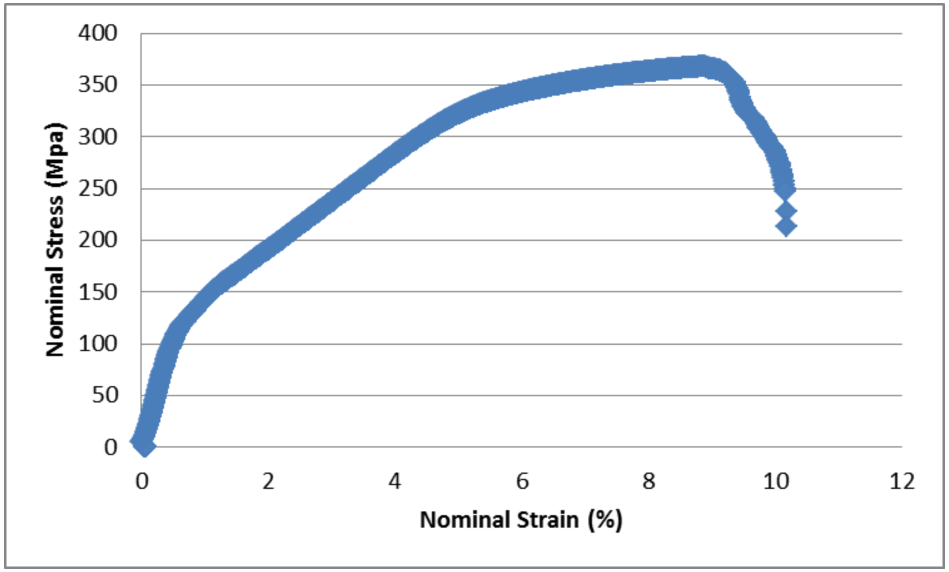




- Crack initiates and grows from center notch before sudden fast fracture.
- X-shaped shear planes at notch root give two possible crack paths at each notch.

Load-displacement curve for 6-notch tests

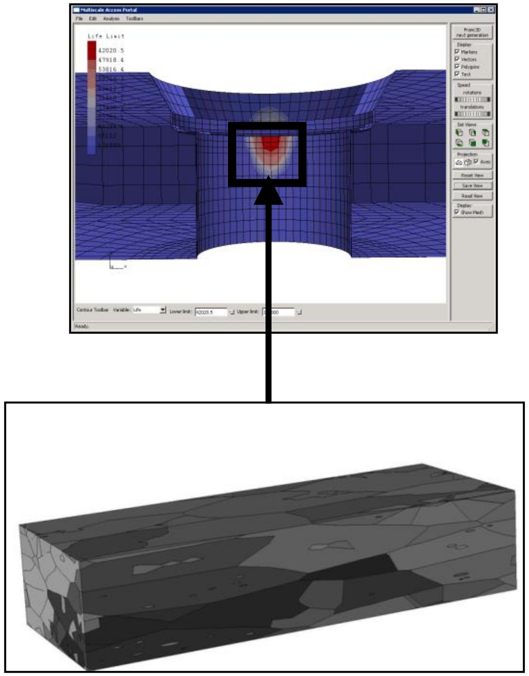


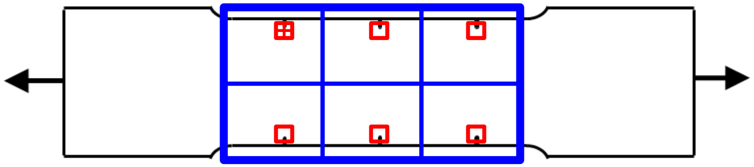


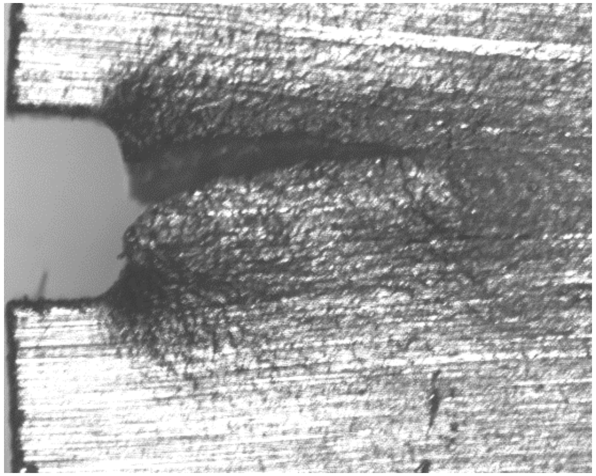
- **Estimates of "Stress" and "strain" calculated from net section measurements and overall gage length.**
  - **Estimates are inline with Ghahremaninezhad et al.,**
    - **UTS ~350 MPa, Ductility ~15%.**

Conclusions

1. **Validating stochastic multiscale modelling.**
2. **Developing multiscale DIC techniques.**
3. **Initial experiments indicate fracture initiates at center notch most of the time. Looking for statistical quantification.**



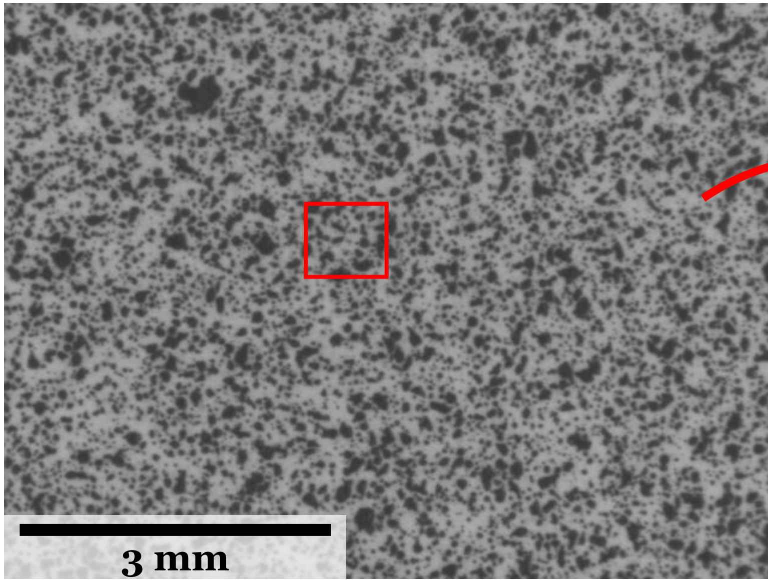




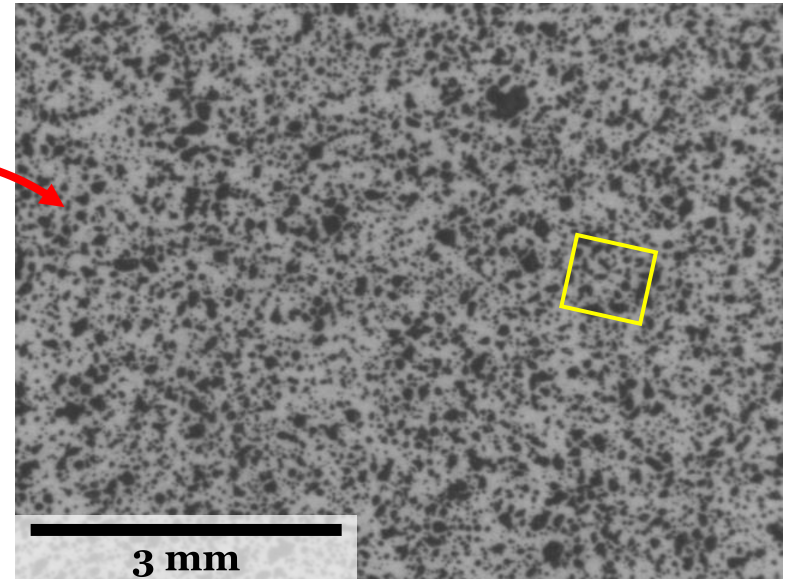
Bonus Slides

Digital image correlation (DIC) measures full field displacements and strains by tracking speckles.

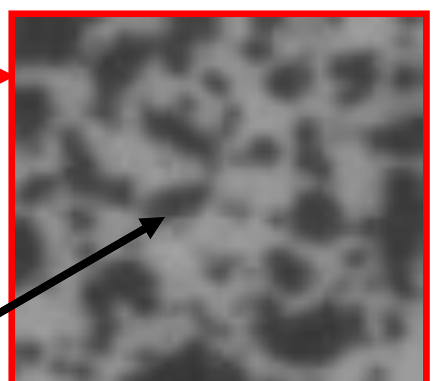
Reference



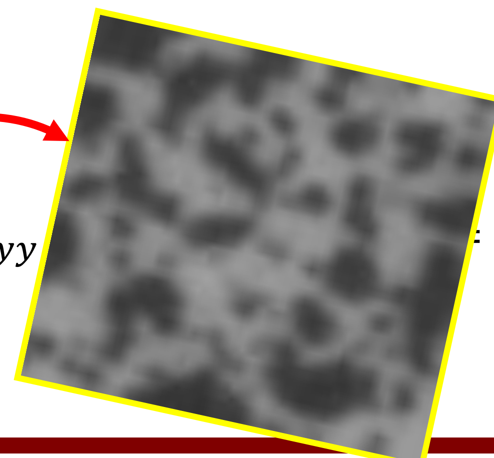
Deformed



Subset



Speckle

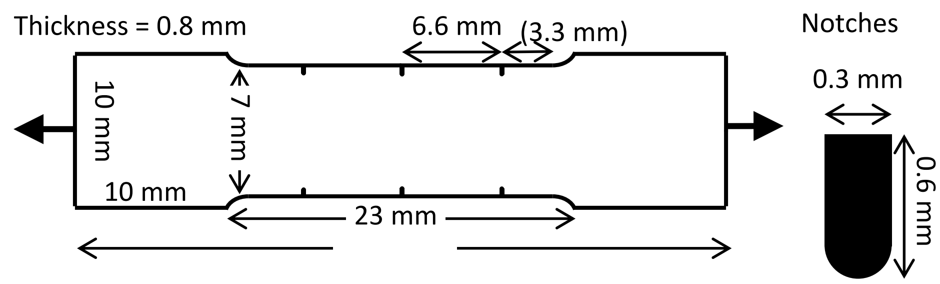


Calculate Strains

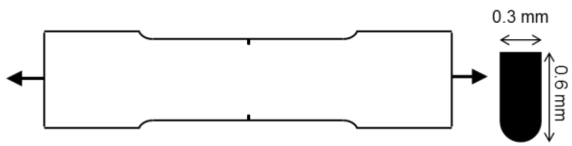
$$\varepsilon_{yy} = \frac{1}{2}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)$$

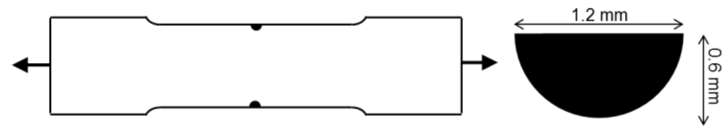
Specimen designs

- **6-notch specimens for microstructure effects and UQ.**

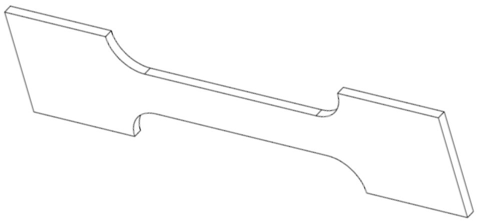


- **2-notch specimens for calibration**





- **Tensile specimens**



- **For much smaller scales, we could do compression of micropillars using our Hysitron in-situ SEM nanoindenter**
- **Quantity of samples: making 60 of 6-notch, 50 tension, 20 of each style of 2-notch specimens. Total = 150 specimens**

Composition

	Alloying Elements					Impurities				
	Al	Mg	Si	Cu	Cr	Fe	Zn	Mn	Ti	Other
Min	95.8	0.8	0.4	0.15	0.04	0	0	0	0	0
Max	98.6	1.2	0.8	0.4	0.35	0.7	0.25	0.15	0.15	0.15
Nominal	**97.2**	**1**	**0.6**	**0.275**	**0.195**	**0.35**	**0.125**	**0.075**	**0.075**	**0.075**

http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=MA6061t6

- **Nominal is the average of max and min.**
- **"Impurities" are defined as elements with 0 min concentrations.**
  - **Note that Fe is potentially at higher concentration than Cr or Cu.**
- **Particles are intermetallic compounds of type Fe-Cr-Mn-Si that do not contribute to hardening.**

Previous studies on Al 6061-T6 give background on stress/strain behavior and on particles/precipitates.

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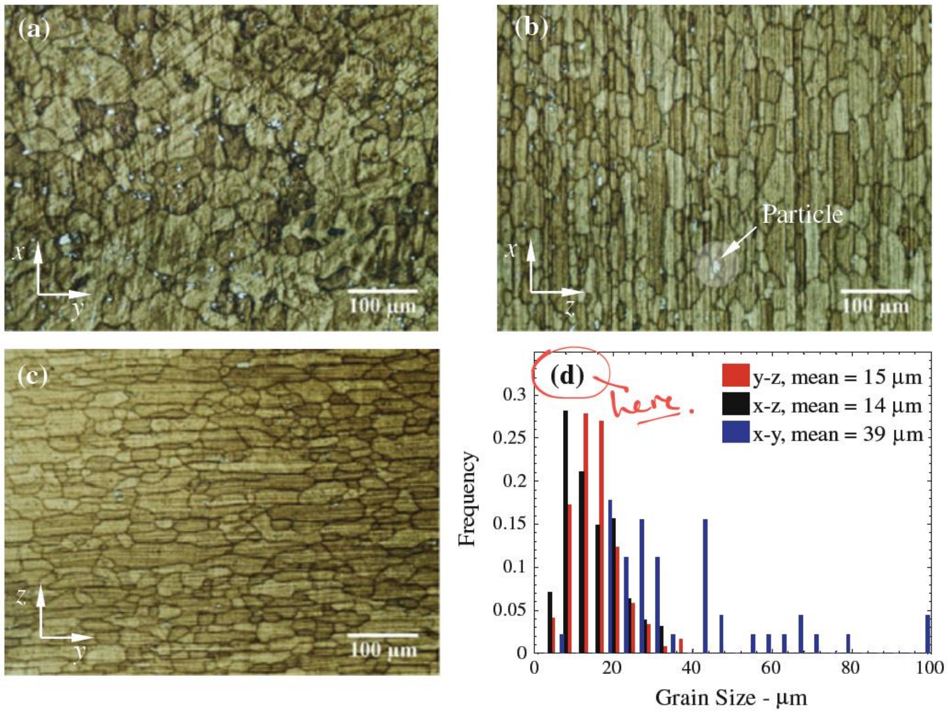
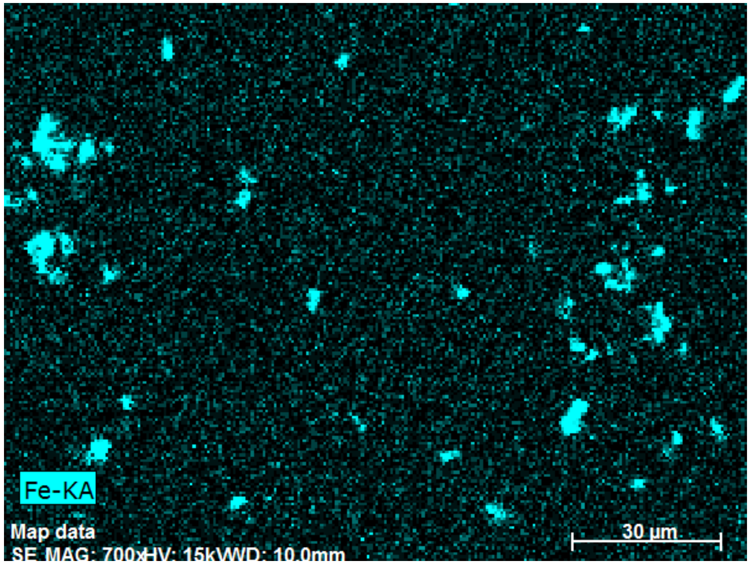


A. Ghahremaninezhad, K. Ravi-Chandar, Int. J. Fract., 174 (2012) 177-202.

"…peak aged with a coherent distribution of fine precipitates of Mg_2Si within the grains…"
This is not what we see in this picture. We see larger particles here.



- These fine precipitates are typical of Al 6061-T6.