CONFLUENT

Volume weighted probabilistic methods for nitinol lifetime prediction

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SMST2017

SHAPE MEMORY AND SUPERELASTIC TECHNOLOGIES CONFERENCE AND EXPOSITION

> **Introduction**

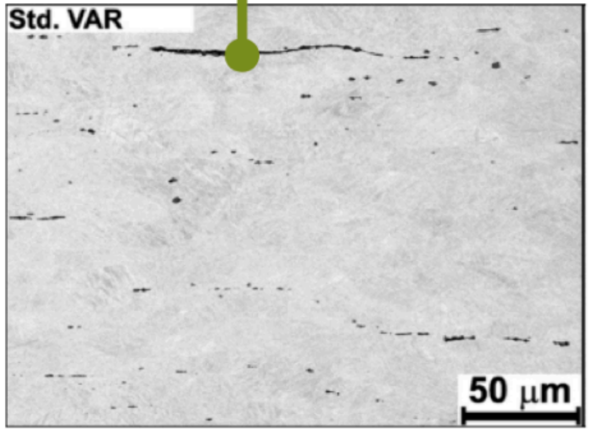
Volumetric FEA methods

Sub-µm x-ray computed tomography

Monte-Carlo risk assessment

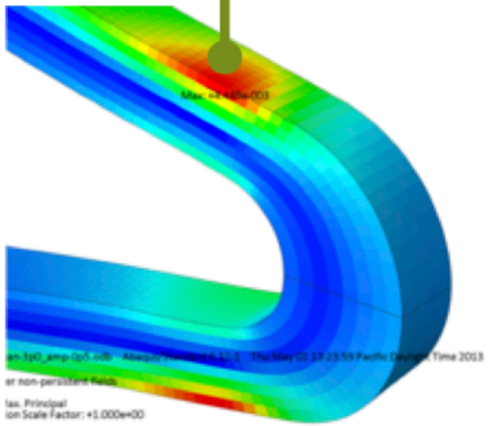
Resources

Motivation

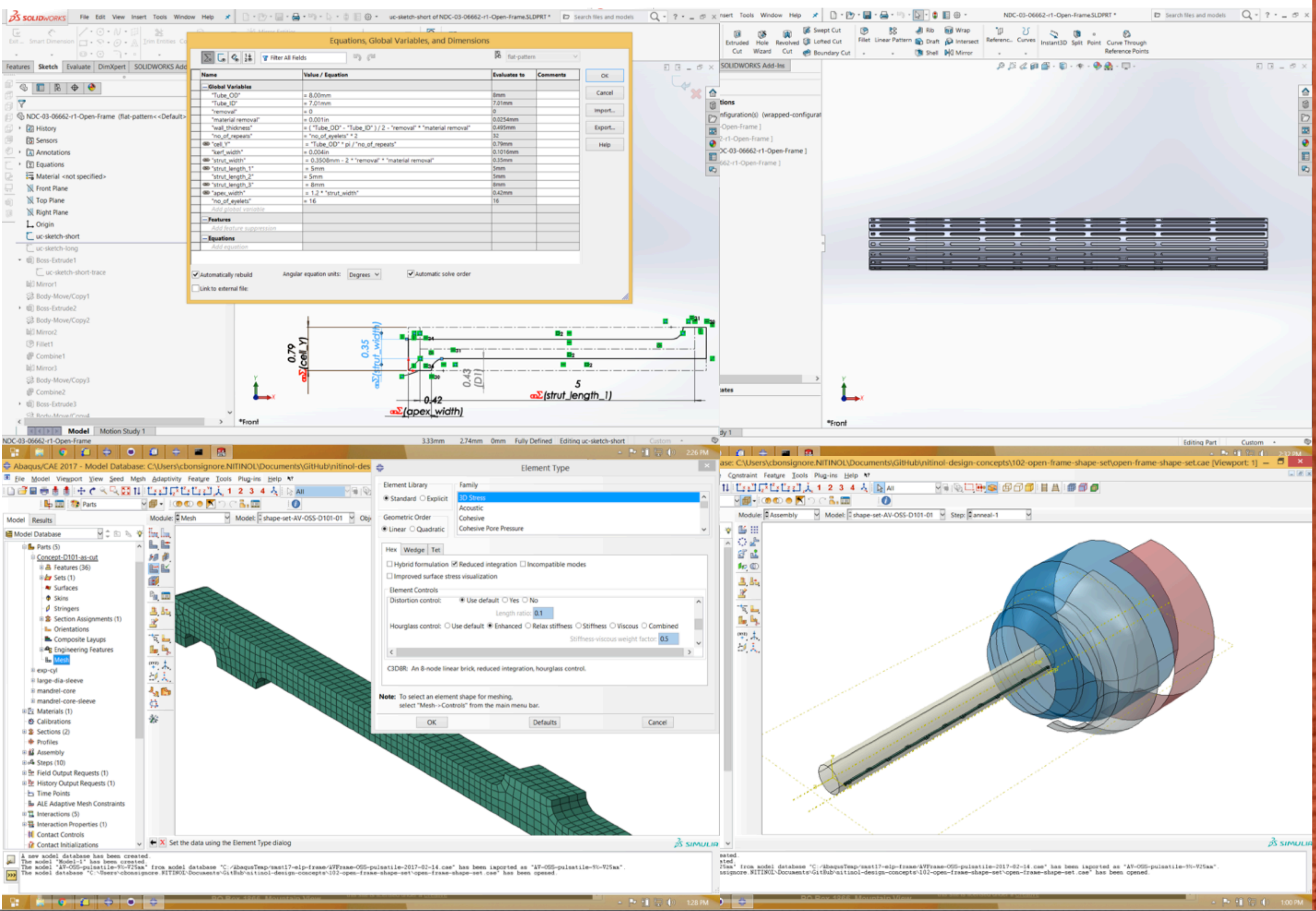


volumetric distribution of material impurities

volumetric distribution of critical regions

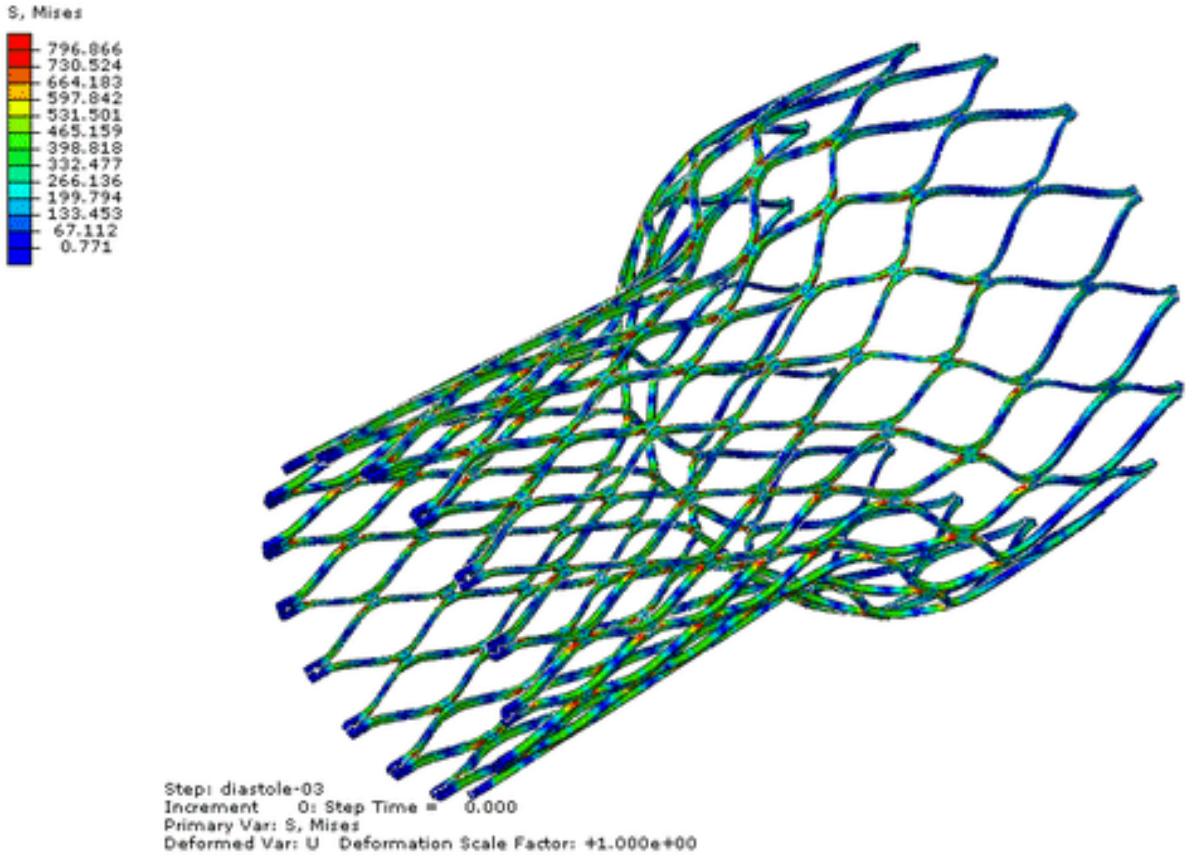


volumetric hazard probability


Equations, Global Variables, and Dimensions
Element Type
C3D8R: An 8-node linear brick, reduced integration, hourglass control.

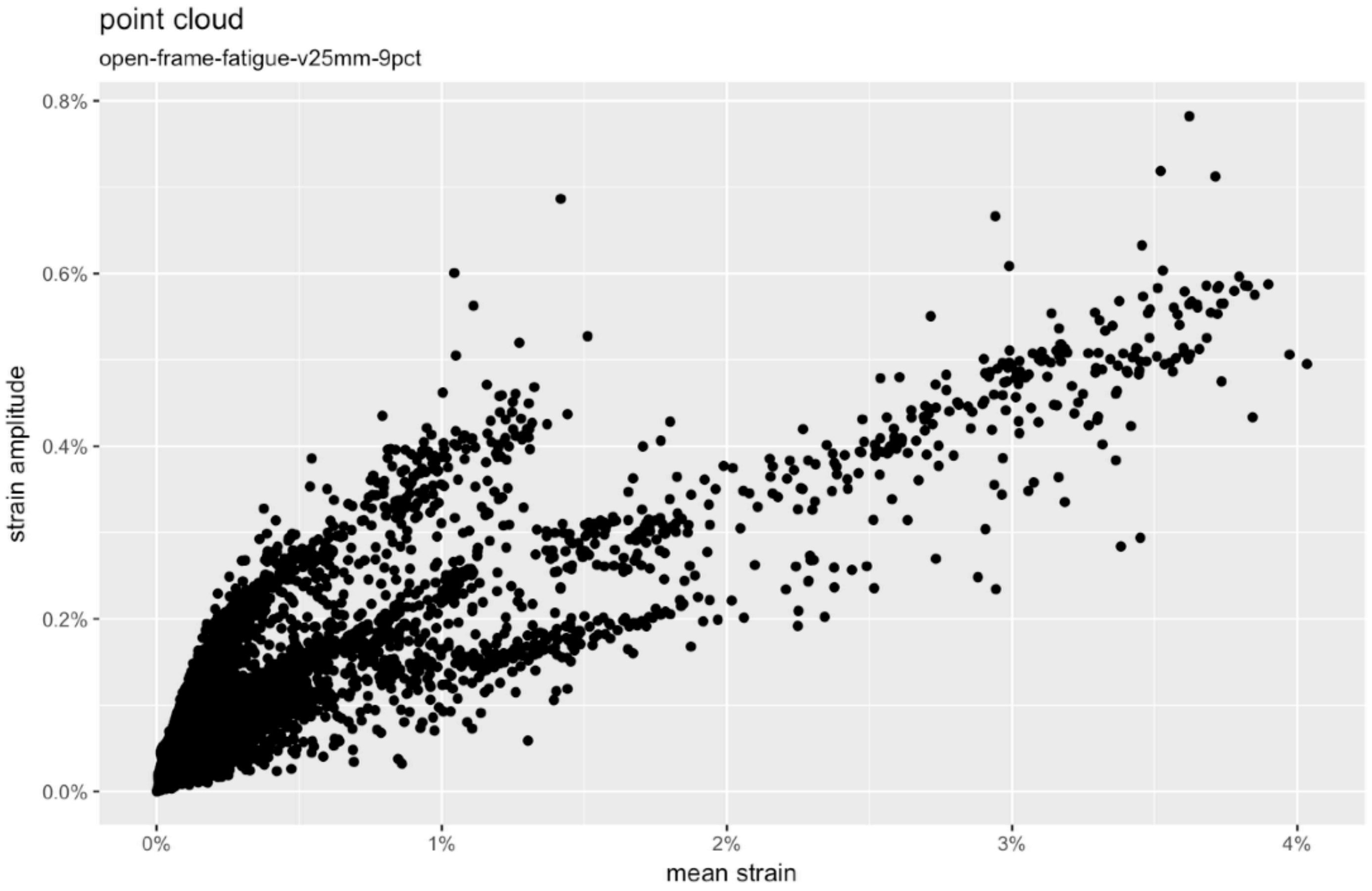
cyclic fatigue condition

9% cyclic change in diameter



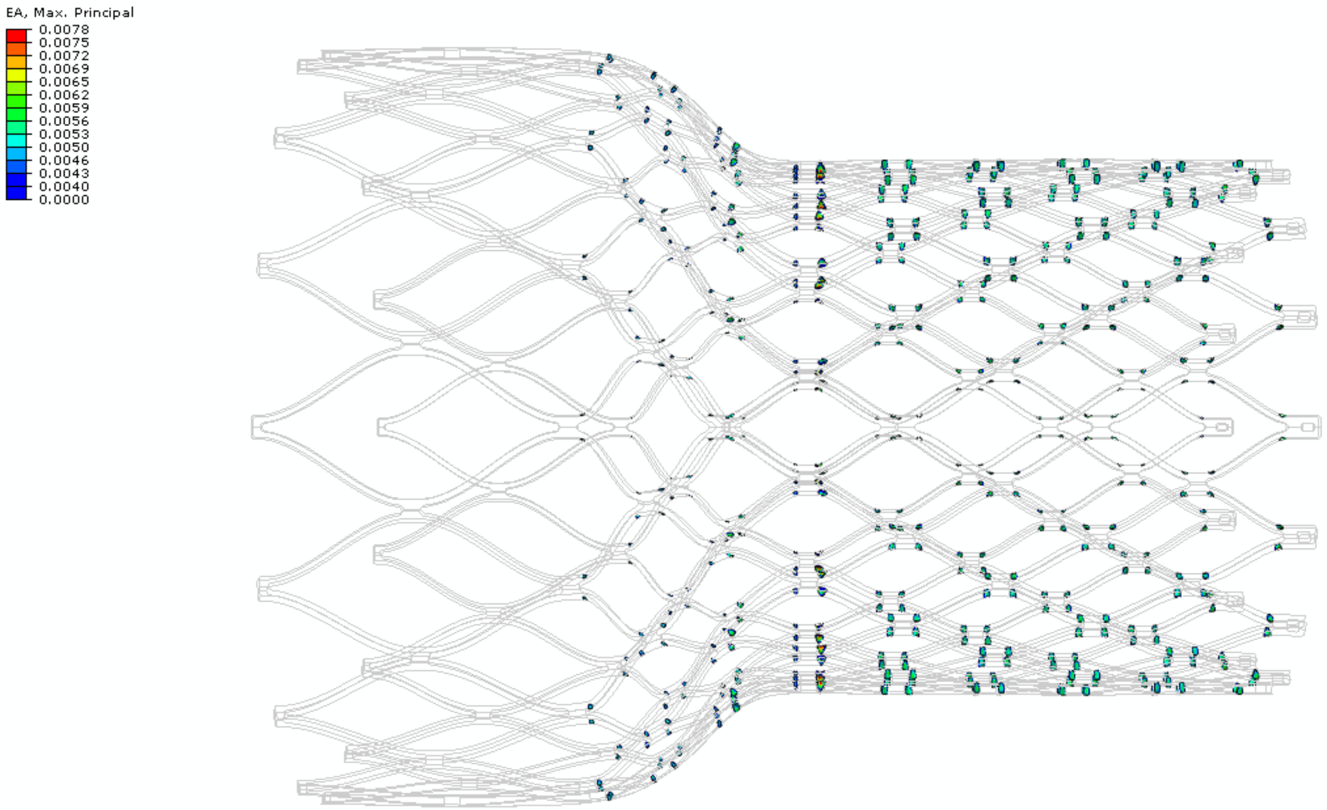
typical point cloud

9% cyclic change in diameter



critical volumes

a small proportion of the volume exceeds a critical limit of strain amplitude.



Tools to extract volume data and more

- integration point volume
- strain, stress at crimping step (pre-strain)
- hydrostatic pressure (tension vs. compression)
- volume fraction of martensite
- mean stress/strain
- stress/strain amplitude
- stress and strain components

ivolResults.004.py

OPEN FILES

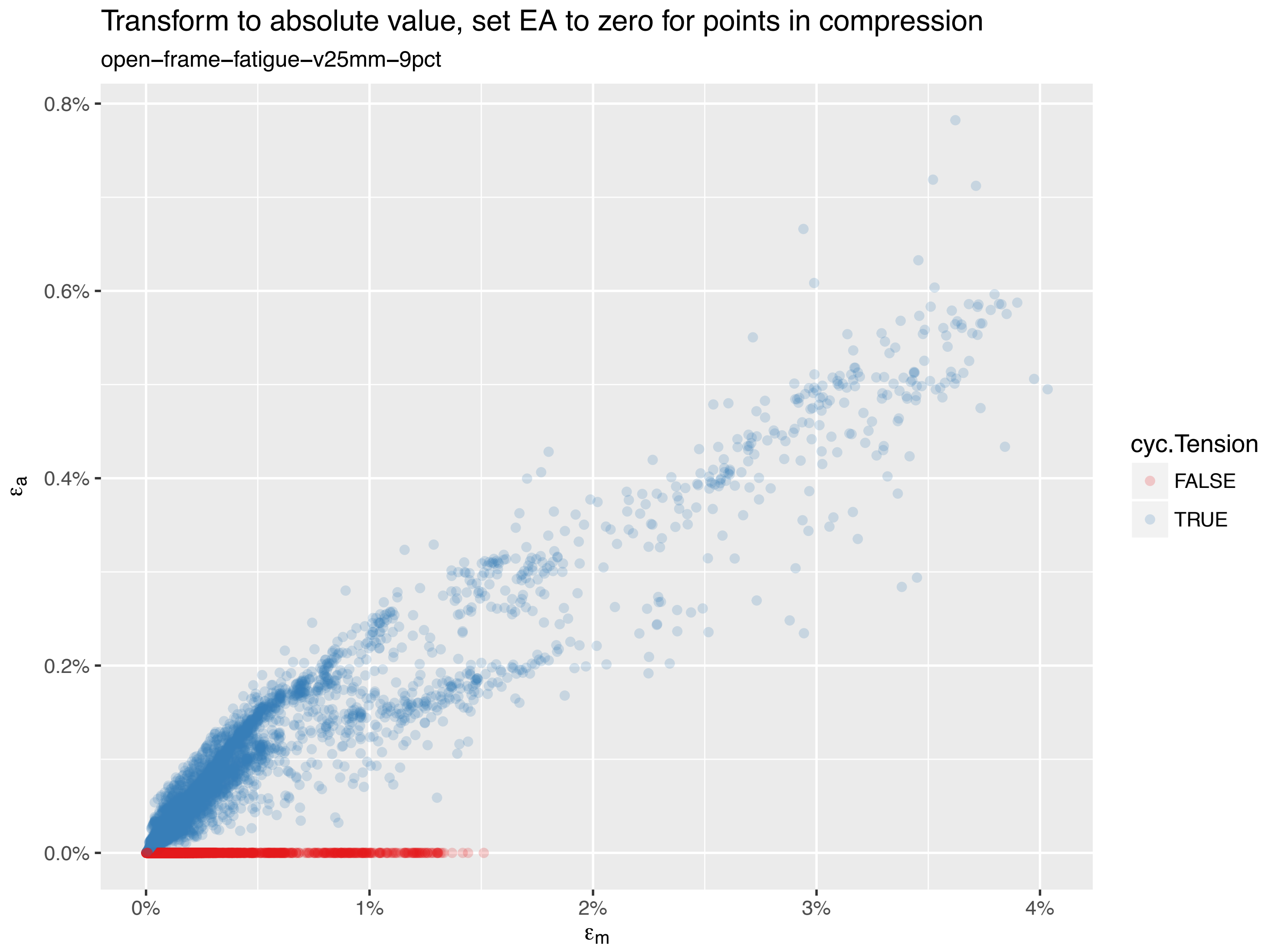
ivolResults.004.py

```
'''
ivolResults.004.py
==================

A Python script to extract volumetric strain and stress results from Abaqus
output database(s). Calculates mean stress and strain, stress and strain amplitude,
prestrain and prestress, and associated volume at each integration point.
Exports data to a CSV file with one row per integration point.

Usage: abaqus python ivolResults.py
        -odbName odbName
        [-oldOdb crimpOdbName]
        -partInstance partInstanceName (name of part instance)
        -crimpStepName crimpStepName  (name of crimping/prestrain step)
        -lastStepName lastStepName  (name of final unloading cycle step)
        [-overwrite yes]

oldOdb is optional, and may be used if crimping (prestrain) results are in a
different ODB from cyclic results.  The script creates a CSV file with the same
job name as odbName, ending in .ivol.csv. If this file exists, script prompts
for a new file name. The "-overwrite yes" option will override this protection.
All other parameters are mandatory.

Field output requests must include strain, stress, state dependant variables,
and integration point volume:
LE, S, SDV, IVOL

See header of CSV file for a definition of all columns:

Example with all results in a single ODB:
abaqus python ivolResults.py -od Job-2 -pa PART-1-1 -cr crimp-1 -la unolad-3 -ov yes

Example with crimping and cyclic results in separate ODBs:
abaqus python ivolResults.py -od Job-2 -ol Job-1 -pa PART-1-1 -cr crimp-1 -la unolad-3 -ov yes
'''


'''
Column details
el     = element number
ip     = integration point
cycEM  = maximum principal cyclic mean strain
cycEA  = absolute maximum principal cyclic strain amplitude
cycTau = absolute maximum principal cyclic strain amplitude
cycSM  = maximum principal cyclic mean stress
cycSA  = absolute maximum principal cyclic stress amplitude
preE   = pre-strain (strain conditioning, e.g. strain during crimping)
preS   = pre-stress (stress conditioning, e.g. stress during crimping)
preP   = hydrostatic pressure during pre-conditioning (compression positive, tension negative)
preM   = volume fraction martensite during pre-conditioning
preV   = integration point volume during pre-conditioning
ldE    = maximum principal strain during loading frame of fatigue cycle
ldTau  = maximum shear strain during loading frame of fatigue cycle
```

Line 1, Column 1 Spaces: 4 Python

Typical point cloud

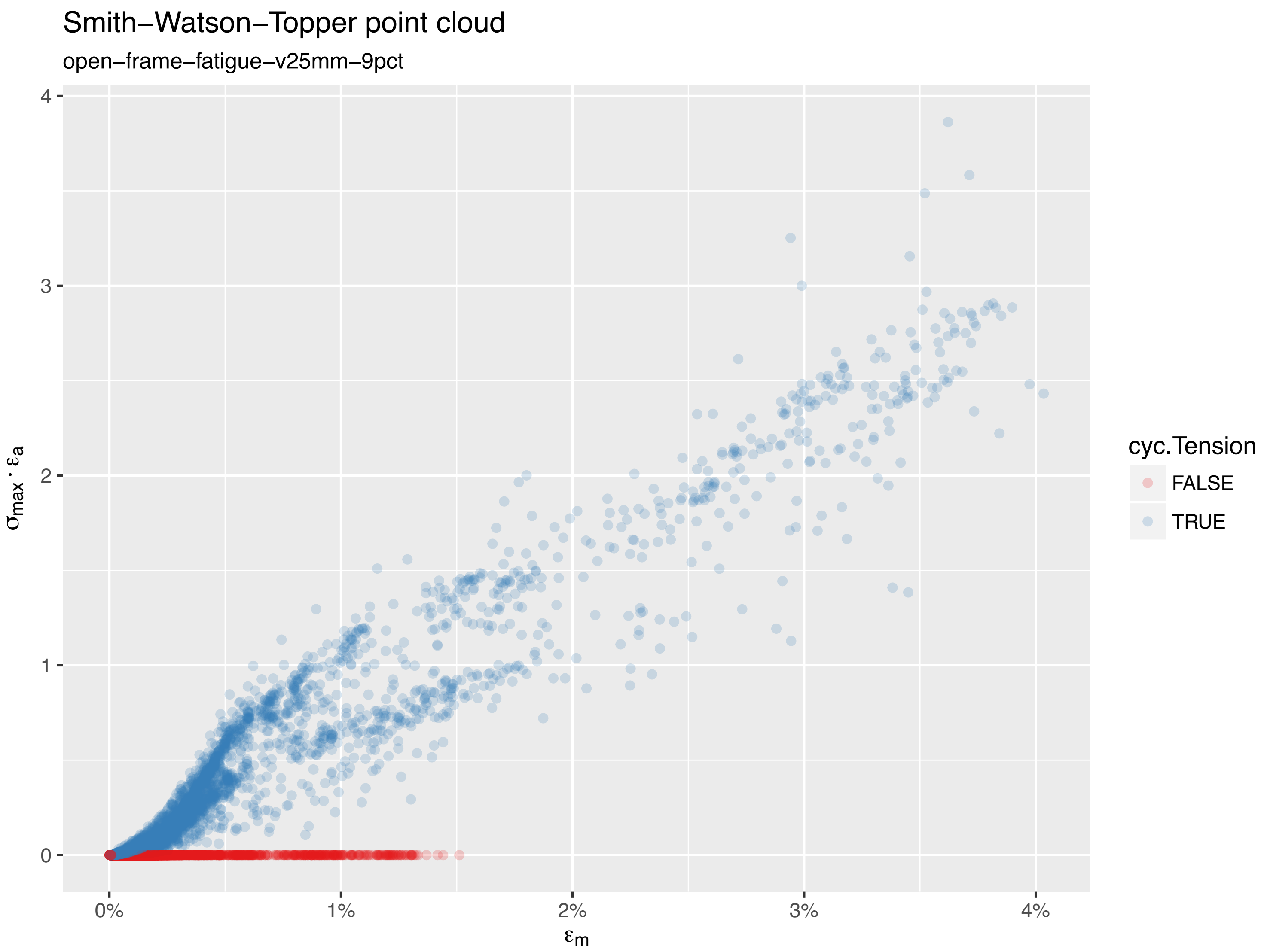
strain amplitude vs. mean strain



SWT point cloud

Smith-Watson-Topper

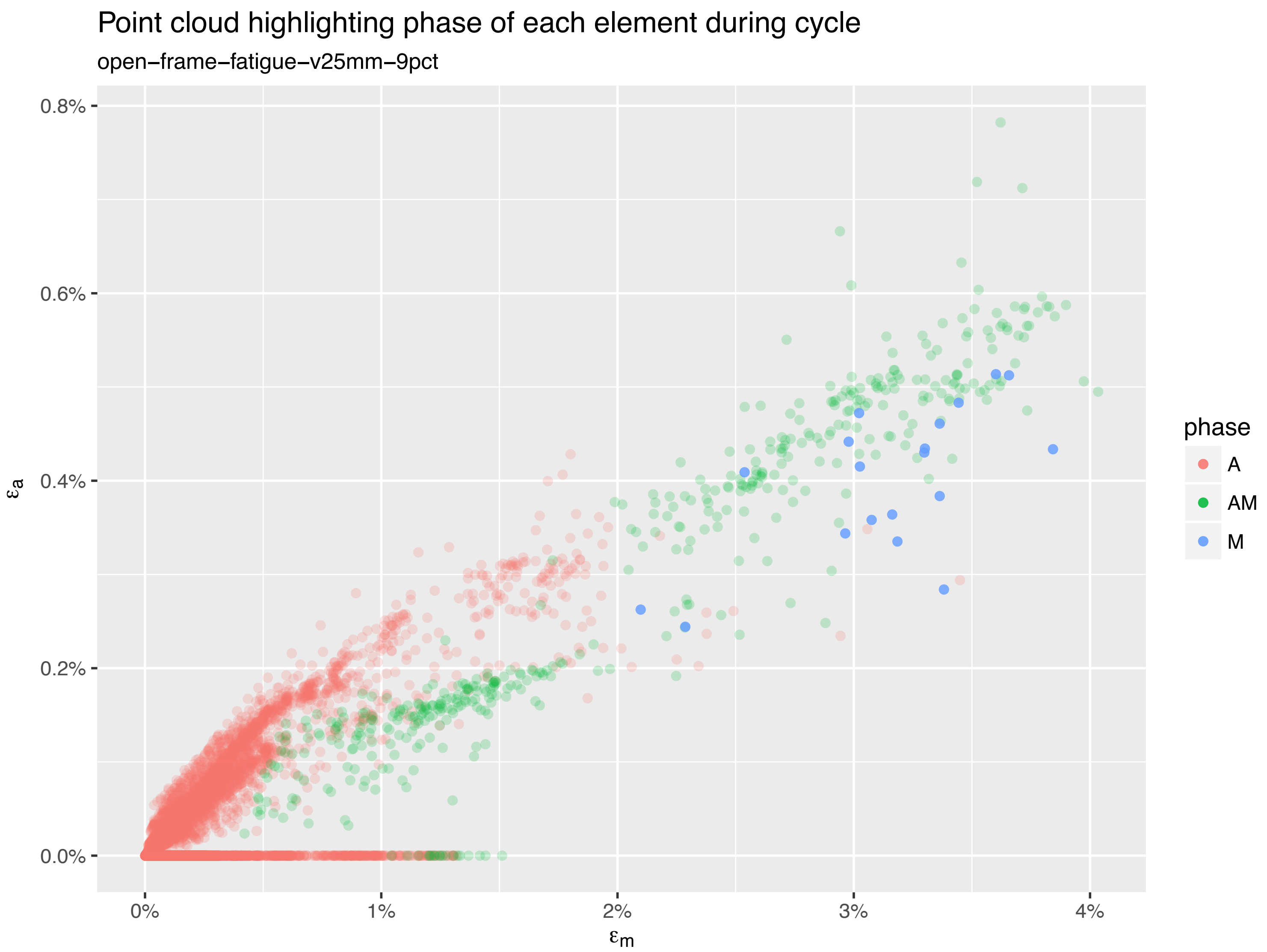
(maximum stress)·(strain amplitude)



Phase map

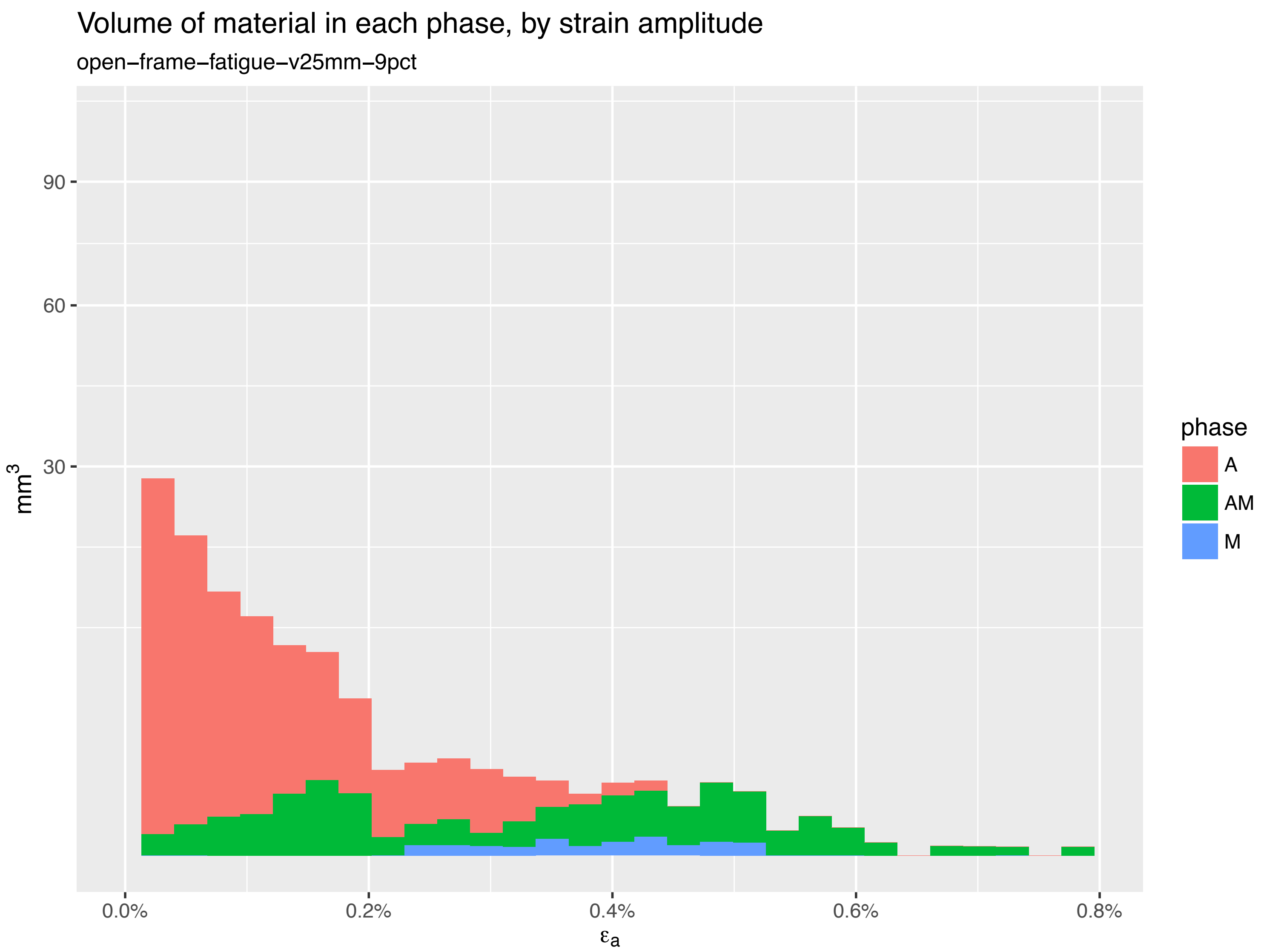
During the fatigue cycle, elements may:

- Remain austenite throughout
- Remain martensite throughout
- Alternate A/M during cycle



Volumetric histogram

Measure the total volume of material in each phase, according to strain amplitude (or SWT, or any other criterion)



Standard VAR
(SE508)

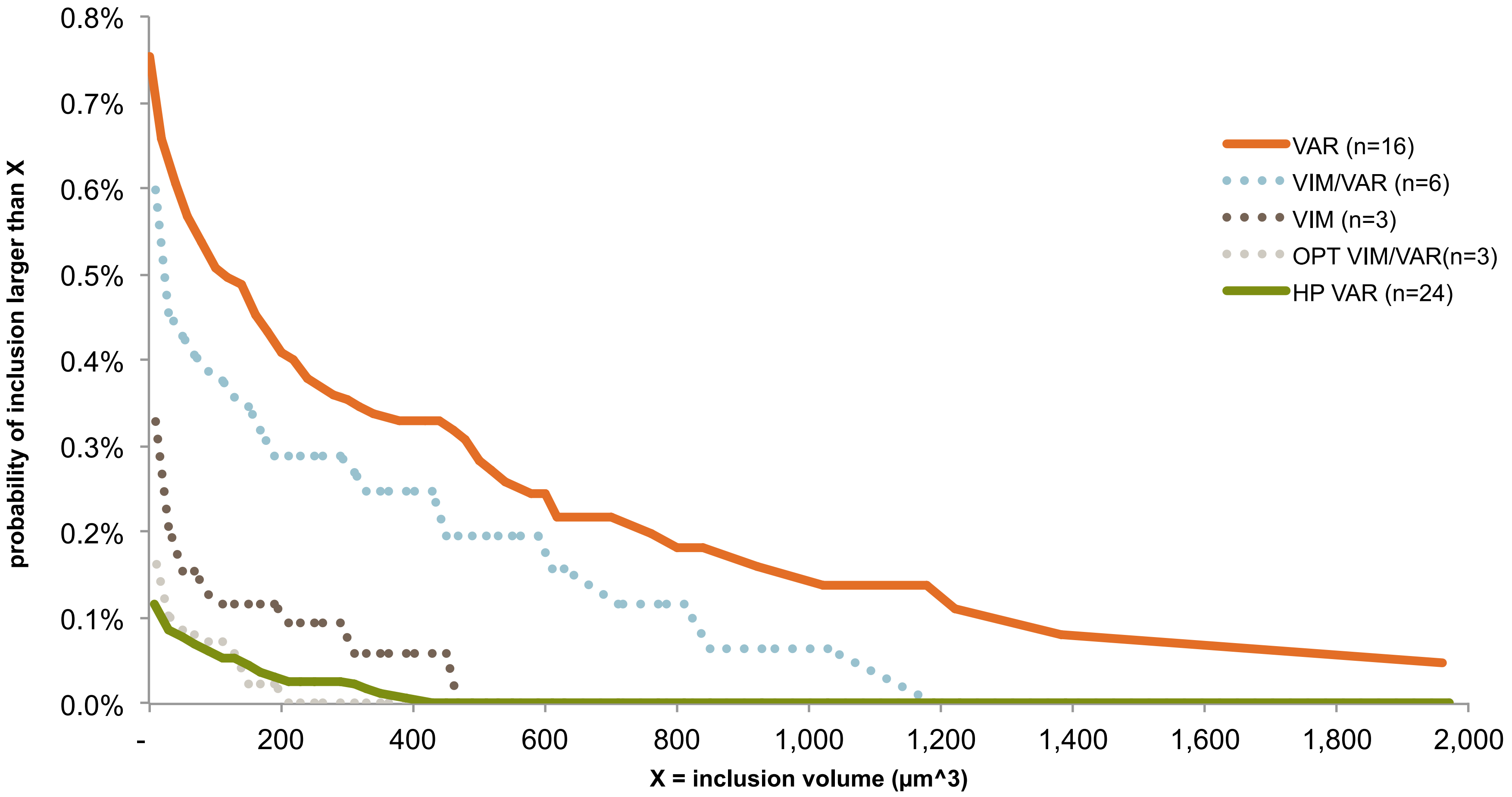
264.46x198.35 µm (1280x960); 8-bit; 1.2MB

High Purity VAR
(SE508-ELI)

264.46x198.35 µm (1280x960); 8-bit; 1.2MB

SMST 2014: Strain Amplitude Volume Fraction Method for Evaluation of Nitinol Fatigue Durability

Approximation of inclusion volumetric probability



SMST 2013: Strain Amplitude Volume Fraction Method for Evaluation of Nitinol Fatigue Durability

Durability performance benefit of high purity material

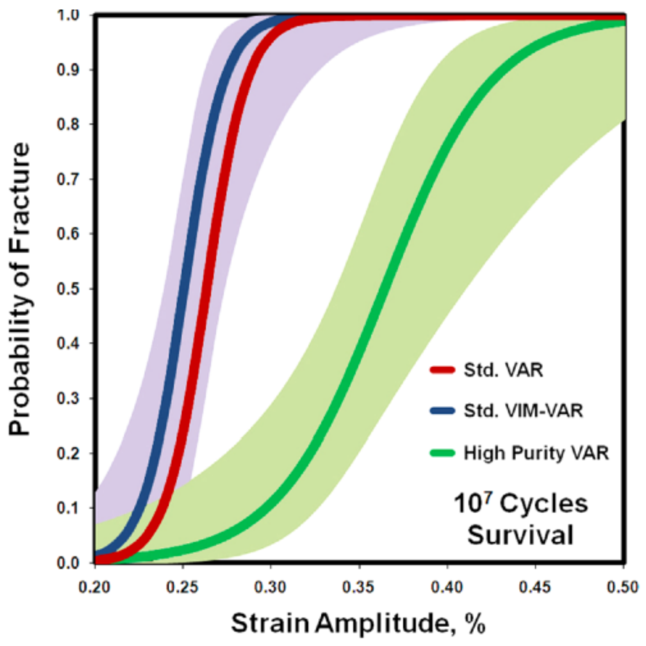


Fig. 8 – Probability of Nitinol wire fracture versus strain amplitude plots with the curve fit line shown bracketed by the 95th percentile upper and lower confidence interval bands.

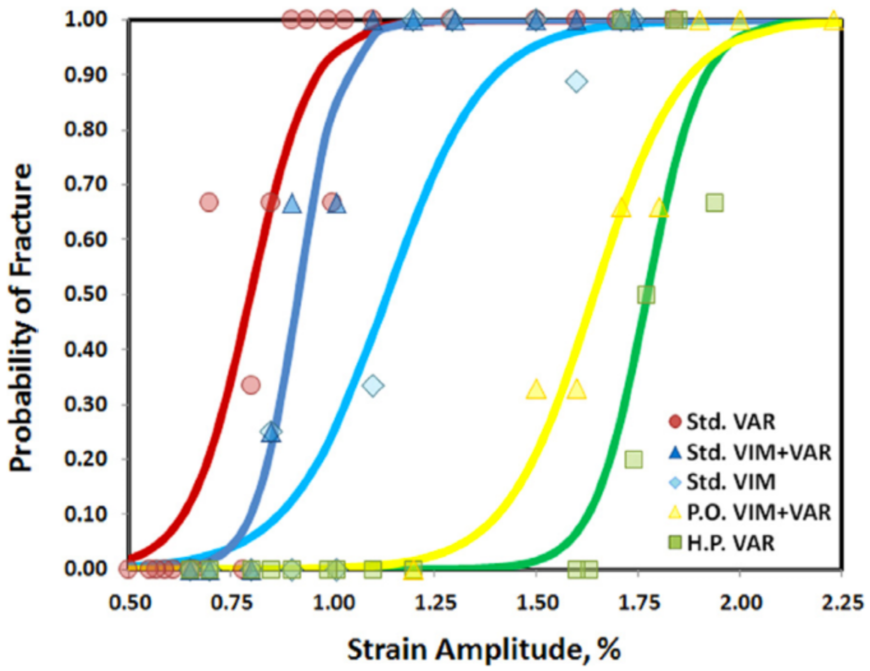


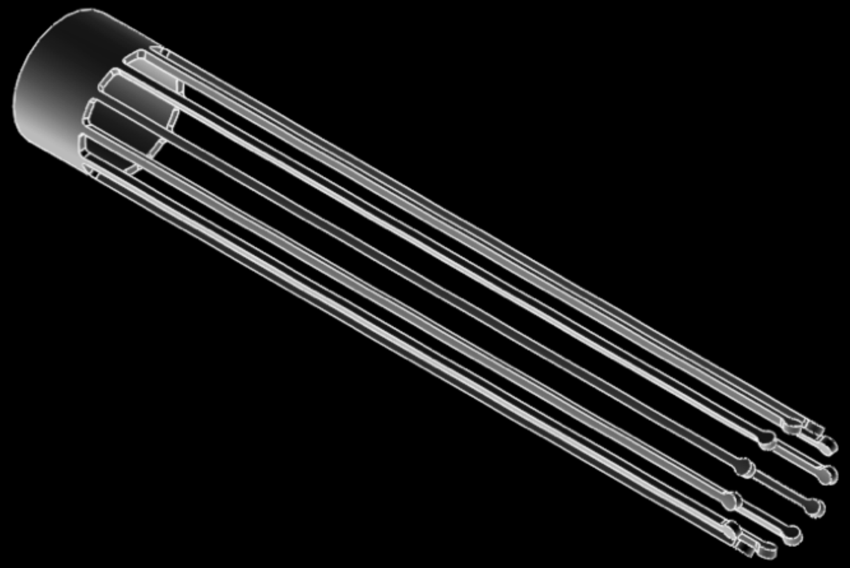
Fig. 9 – Probability of Nitinol diamond fracture at 10^7 cycles versus strain amplitude plots with a logit sigmoidal curve fit line for each data set.

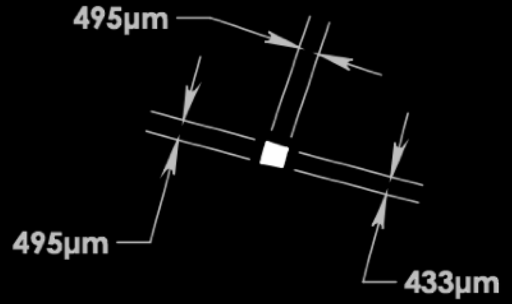
Robertson, S. W. et al. A statistical approach to understand the role of inclusions on the fatigue resistance of superelastic Nitinol wire and tubing. J. Mech. Behav. Biomed. Mater. 51, 119–131 (2015).

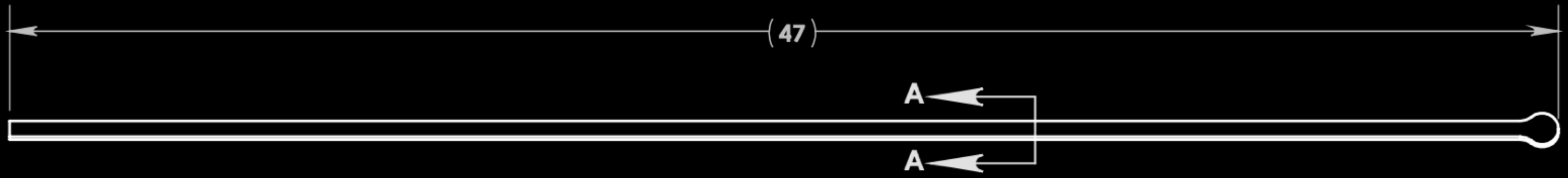
X-ray computed tomography (XCT) test specimens

8.00x7.01 superelastic nitinol tubing
0.5mm x 0.5mm x 50mm laser cut “matchstick” samples

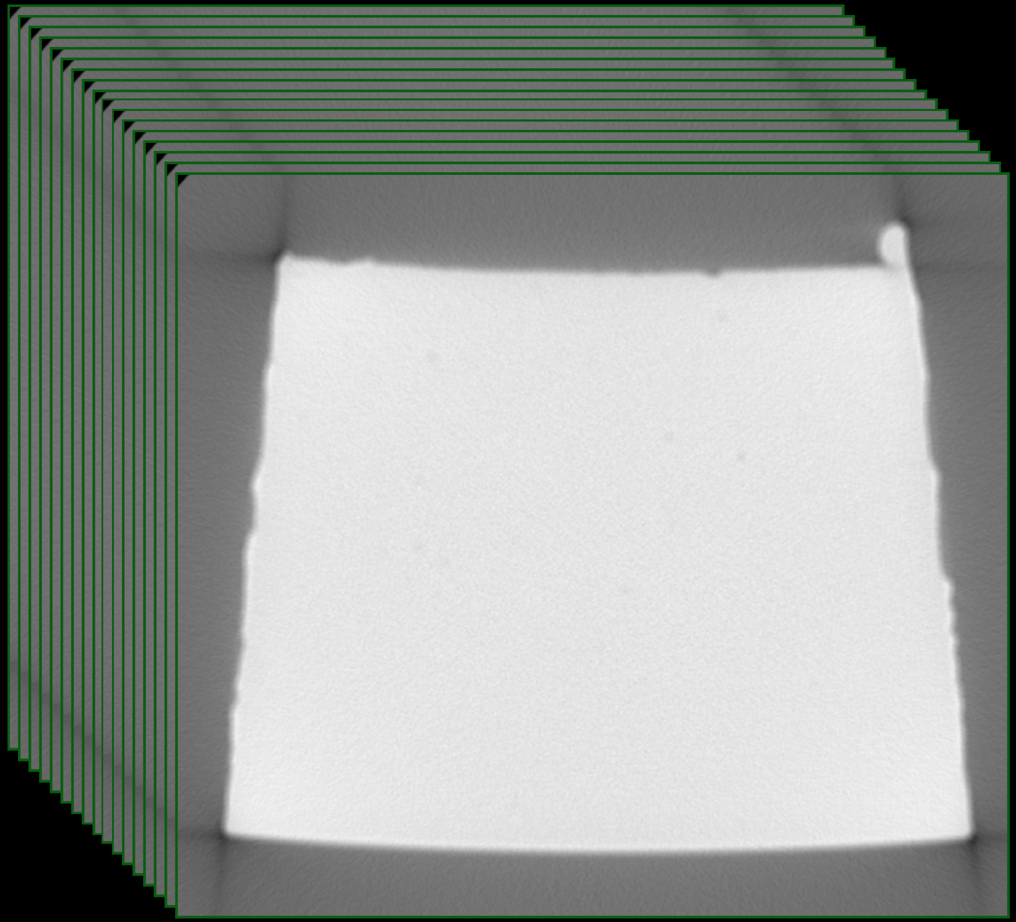
scan01: SE508
scan02: SE508ELI
scan03: SE508ELI







XCT scan output: 1,994 16-bit images (0.50μm^3 voxel)



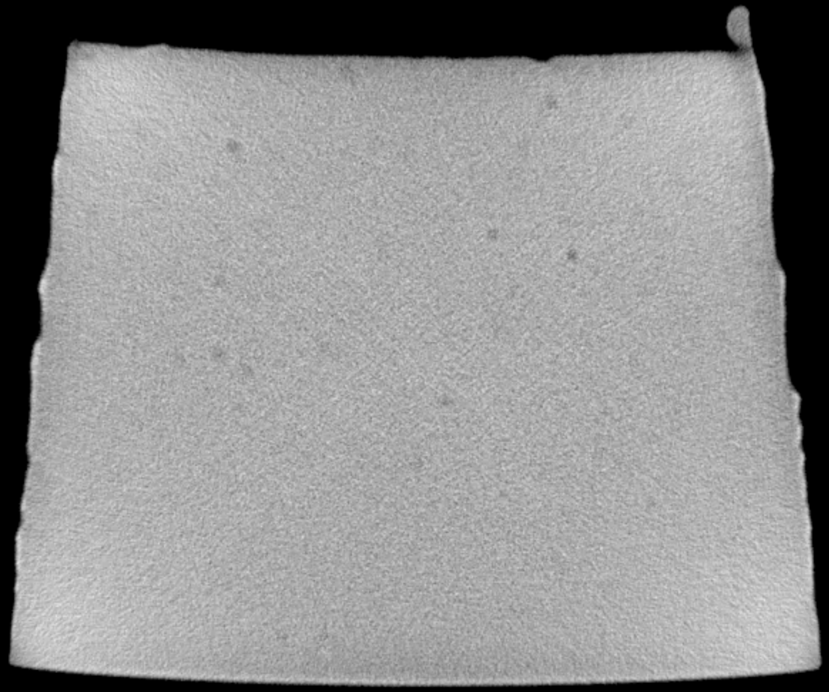
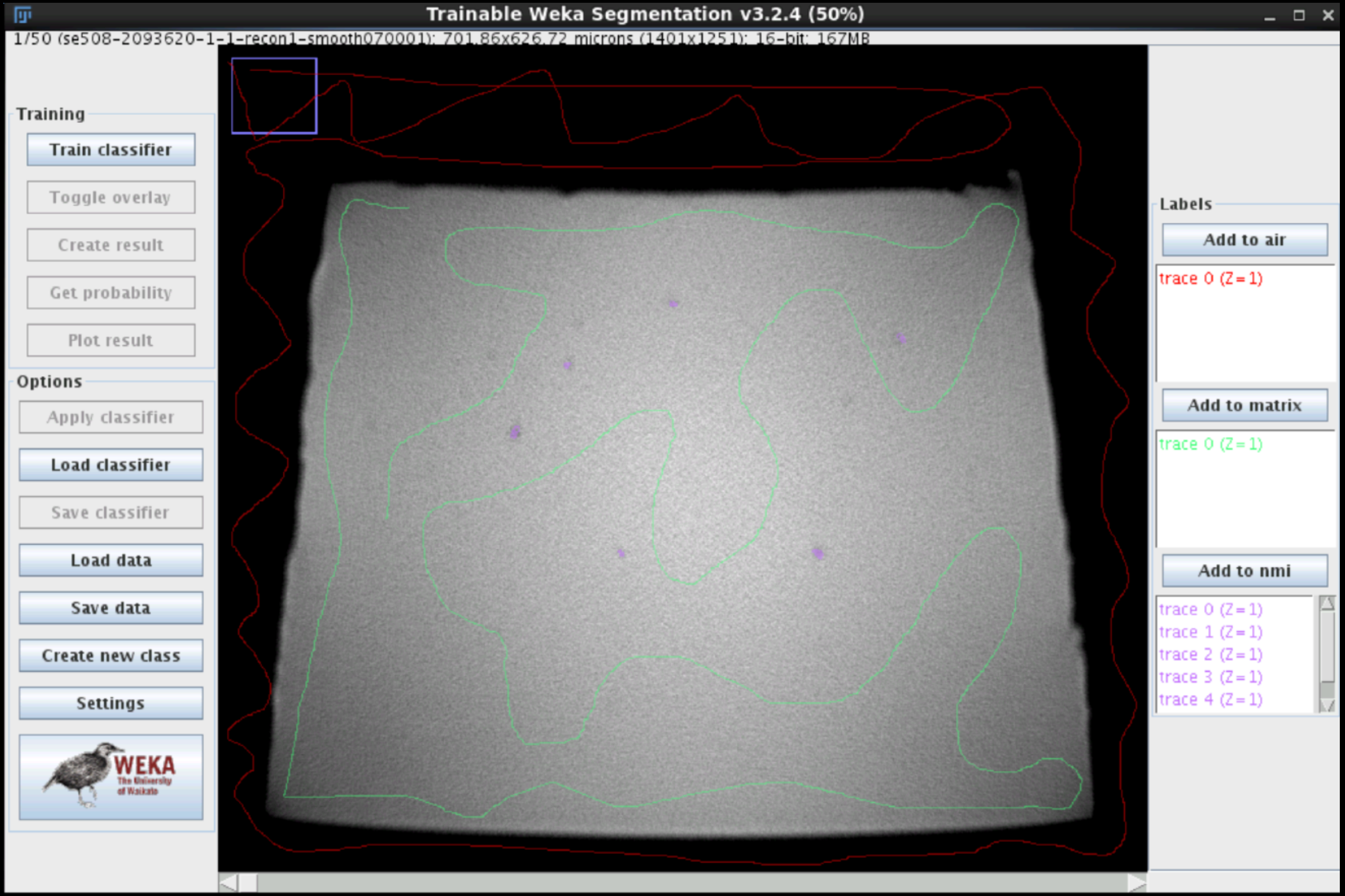


Image segmentation by machine learning

Fiji [1] is just ImageJ [2]

Trainable Weka Segmentation [3]

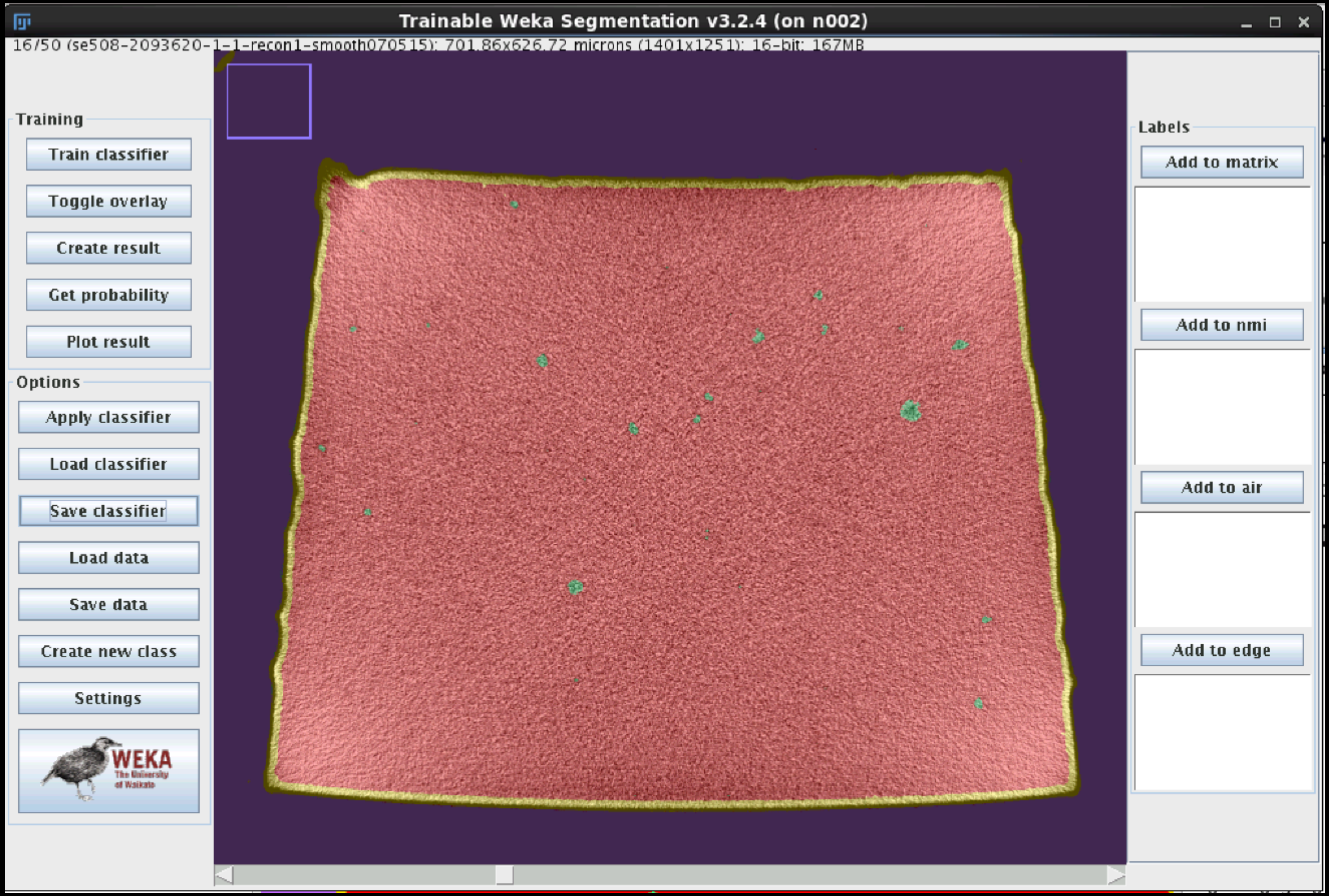


[1] J. Schindelin, I. Arganda-Carreras, E. Frise, V. Kaynig, M. Longair, T. Pietzsch, S. Preibisch, C. Rueden, S. Saalfeld, B. Schmid, J.-Y. Tinevez, D.J. White, V. Hartenstein, K. Eliceiri, P. Tomancak, A. Cardona, Fiji: an open-source platform for biological-image analysis., Nat. Methods. 9 (2012) 676–82. doi:10.1038/nmeth.2019.
[2] M.D. Abràmoff, P.J. Magalhães, S.J. Ram, Image processing with imageJ, Biophotonics Int. 11 (2004) 36–41. doi:10.1117/1.3589100.

Voxel Classification

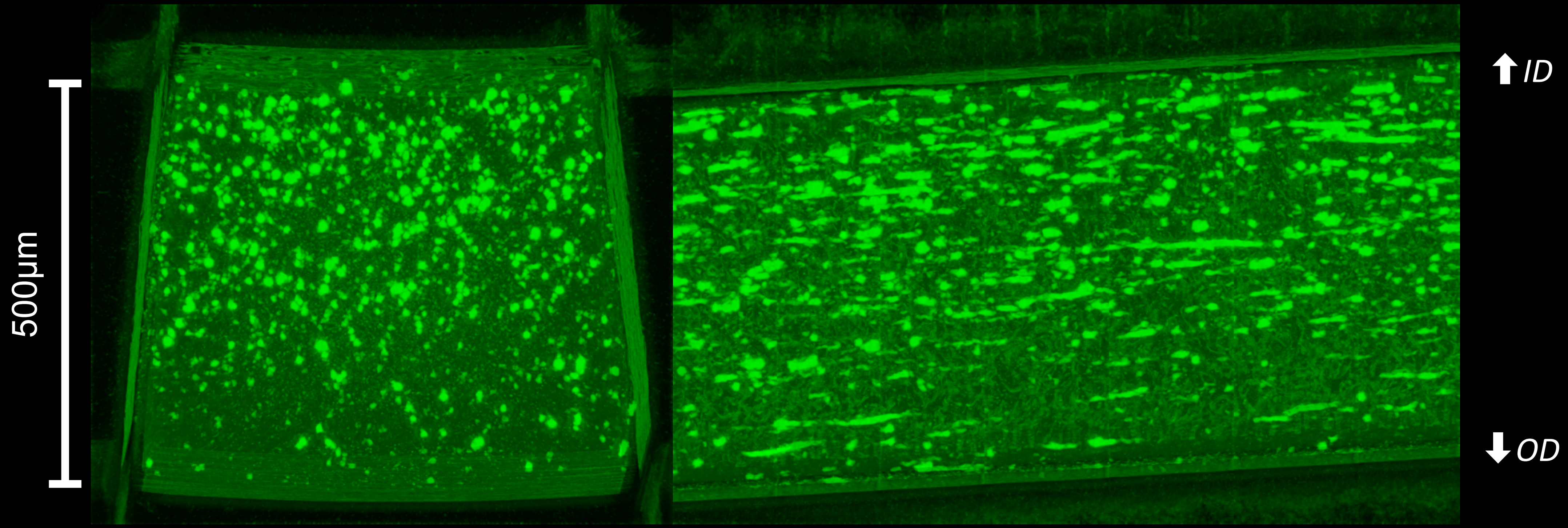
Train classifier to identify probability of each voxel as:

- matrix
- nmi (inclusion/void)
- air
- edge



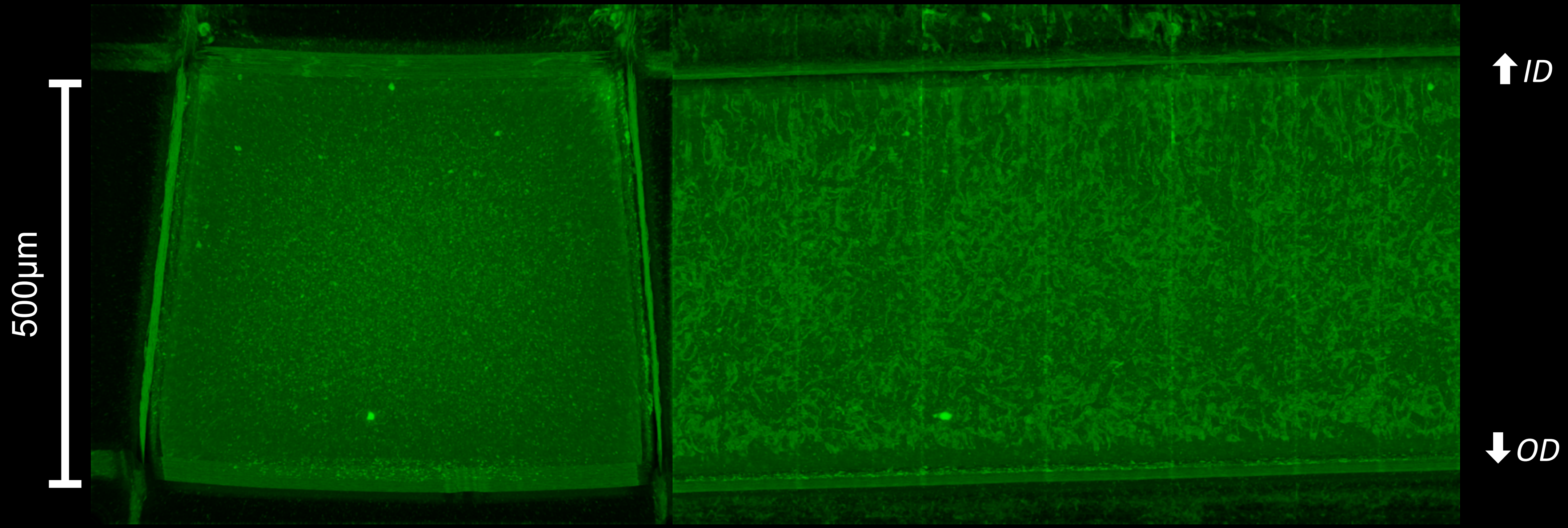
[3] I. Arganda-Carreras, V. Kaynig, J. Schindelin, A. Cardona, H.S. Seung, Trainable Weka Segmentation: A Machine Learning Tool for Microscopy Image Segmentation, Neurosci. 2014 Short Course 2 - Adv. Brain-Scale, Autom. Anat. Tech. Neuronal Reconstr. Tract Tracing, Atlasing. (2014) 73--80.

SE508 maximum intensity projection of inclusion probability



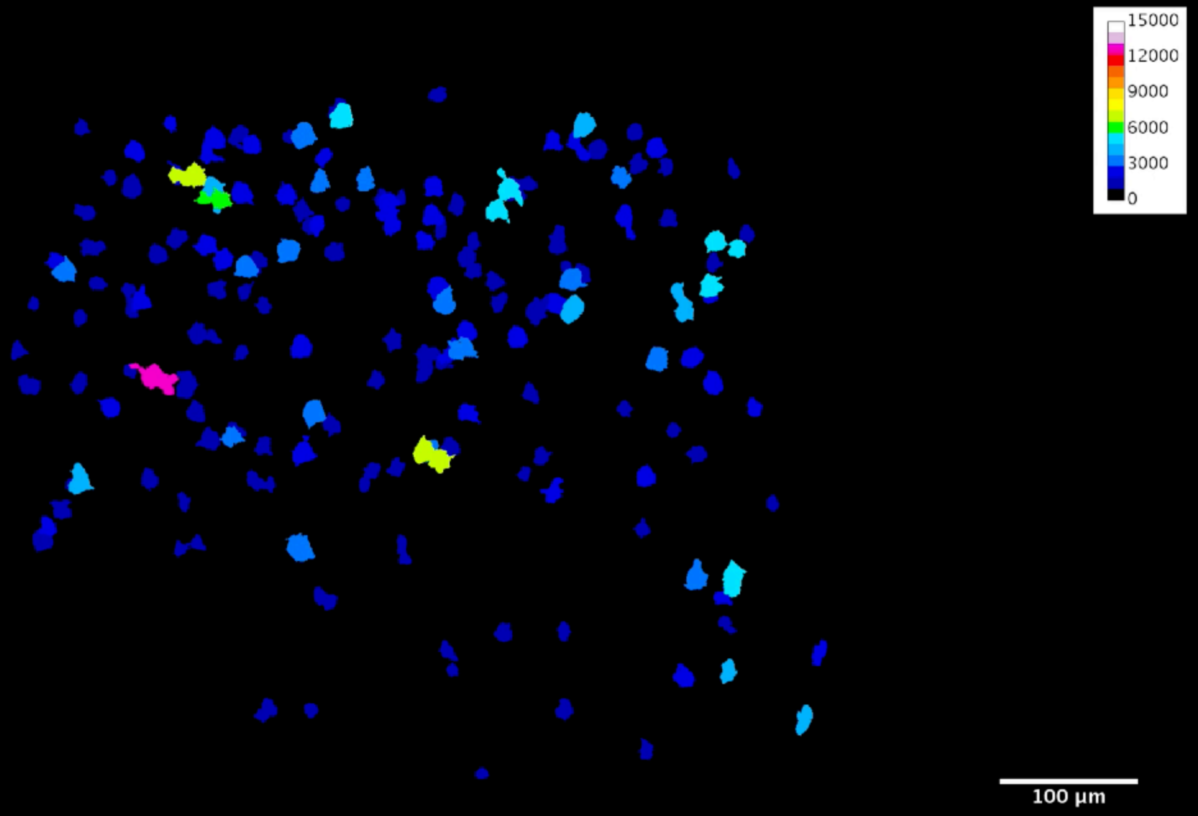
visualization superimposes all inclusions through 500µm thickness

SE508-ELI maximum intensity projection of inclusion probability



visualization superimposes all inclusions through 500µm thickness

SE508 inclusion segmentation colored by volume

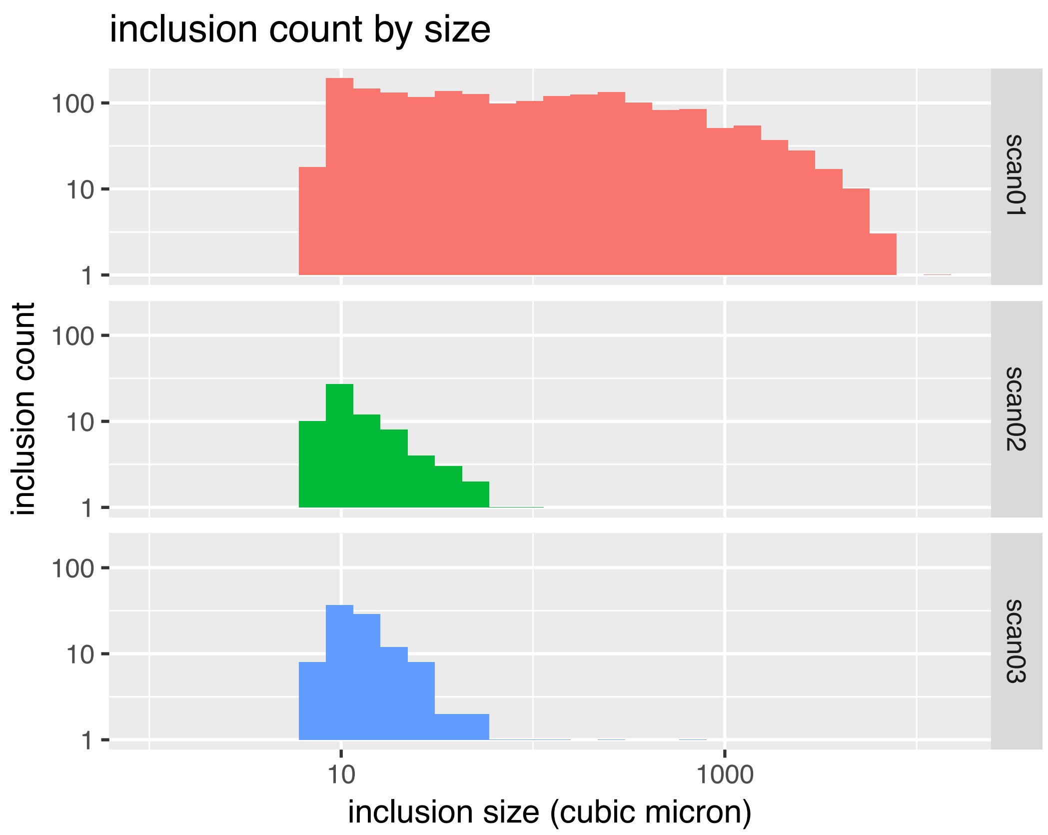


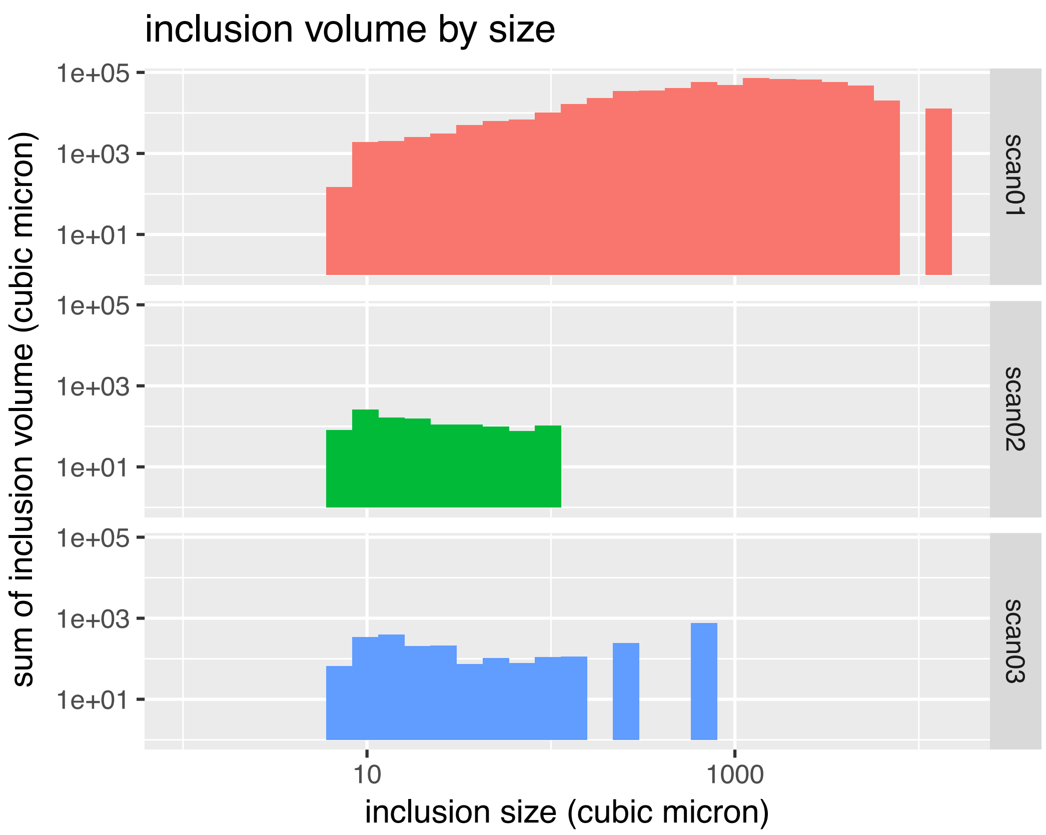
[1] D. Legland, I. Arganda-Carreras, P. Andrey, MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, Bioinformatics. (2016) btw413. doi:10.1093/bioinformatics/btw413.

SE508-ELI inclusion segmentation colored by volume

[1] D. Legland, I. Arganda-Carreras, P. Andrey, MorphoLibJ: integrated library and plugins for mathematical morphology with ImageJ, Bioinformatics. (2016) btw413. doi:10.1093/bioinformatics/btw413.

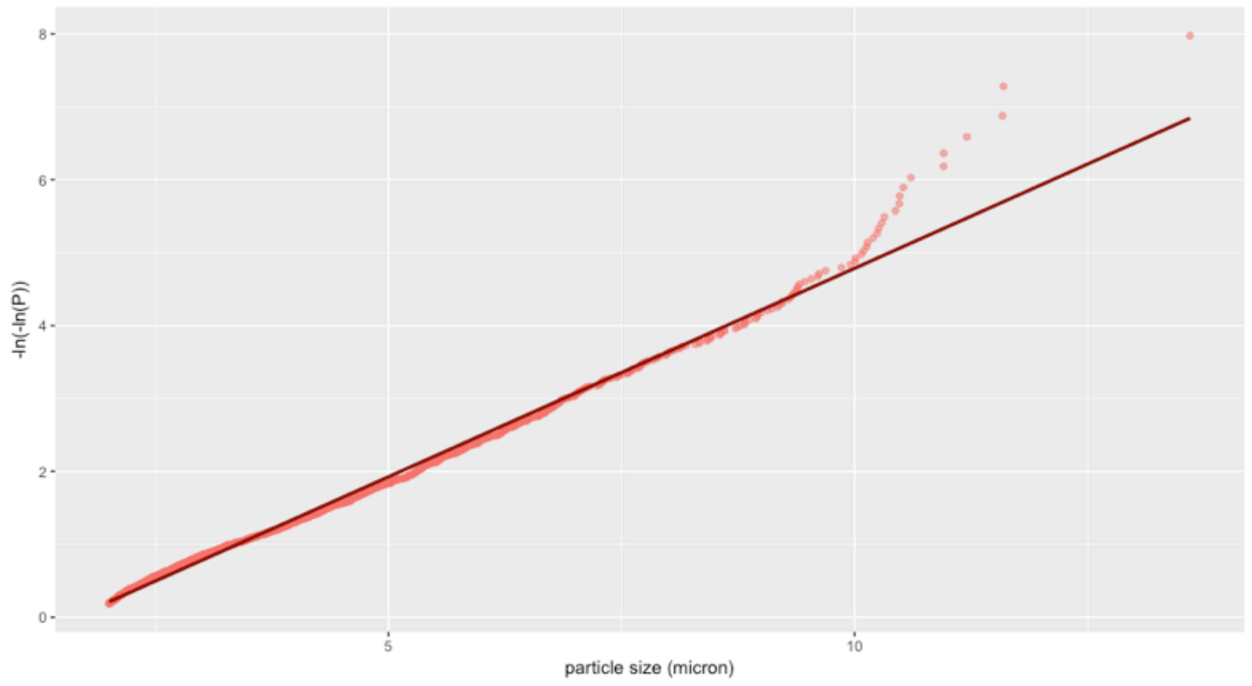
Volumetric distribution of inclusions

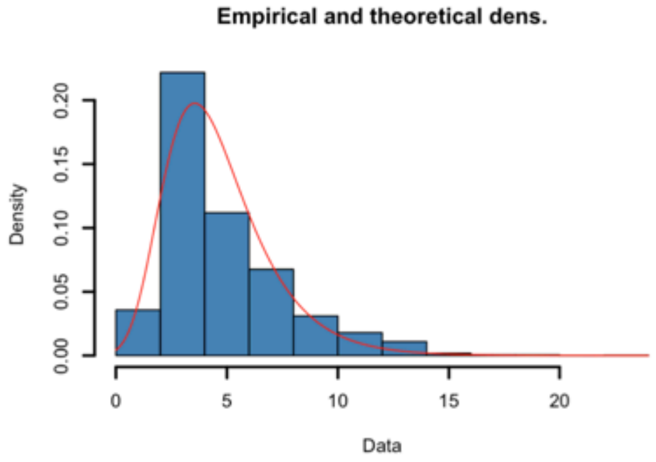


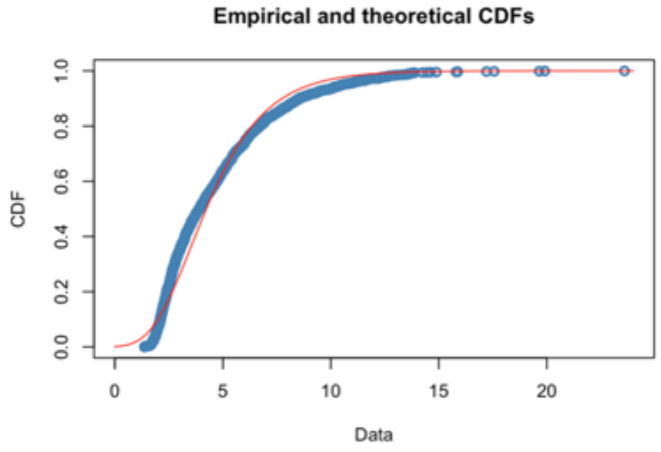


* *note log-log scales*

√Area fit to Extreme Value Distribution per Urbano[1]







[1] M.F. Urbano, A. Cadelli, F. Sczerzenie, P. Luccarelli, S. Beretta, A. Coda, Inclusions Size-based Fatigue Life Prediction Model of NiTi Alloy for Biomedical Applications, Shape Mem. Superelasticity. 1 (2015) 1–12.

Inclusion density, Gumbel location and scaling parameters

SE508 Inclusion Distribution Parameters

plane	cutoff (μm^3)	inclusion density ($1/mm^3$)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	7,475	2.84	1.36
yz (longitudinal)	8	7,475	3.59	1.96
xz (longitudinal)	8	7,475	3.55	1.86

ELI Inclusion Distribution Parameters

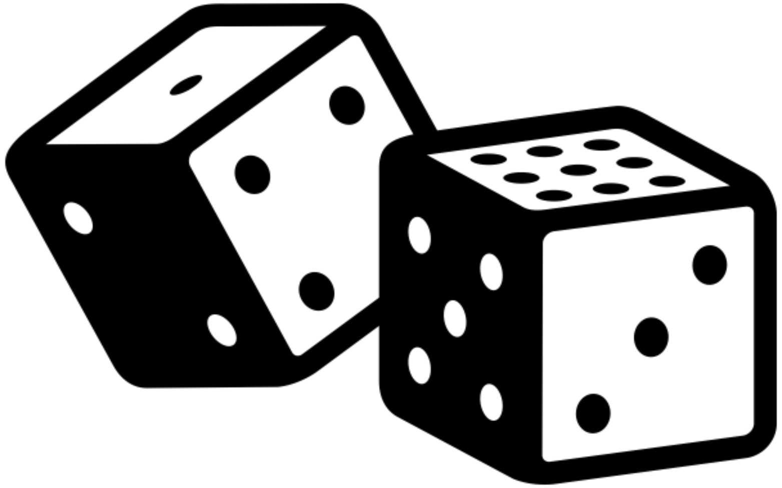
plane	cutoff (μm^3)	inclusion density ($1/mm^3$)	Gumbel μ (μm)	Gumbel σ (μm)
xy (transverse)	8	340	1.77	0.40
yz (longitudinal)	8	340	2.06	0.40
xz (longitudinal)	8	340	2.27	0.45

Fingerprint by Mitchell Eva, from the Noun Project

Quantile function: *calculate random defects with sizes following the Gumbel distribution for each material*

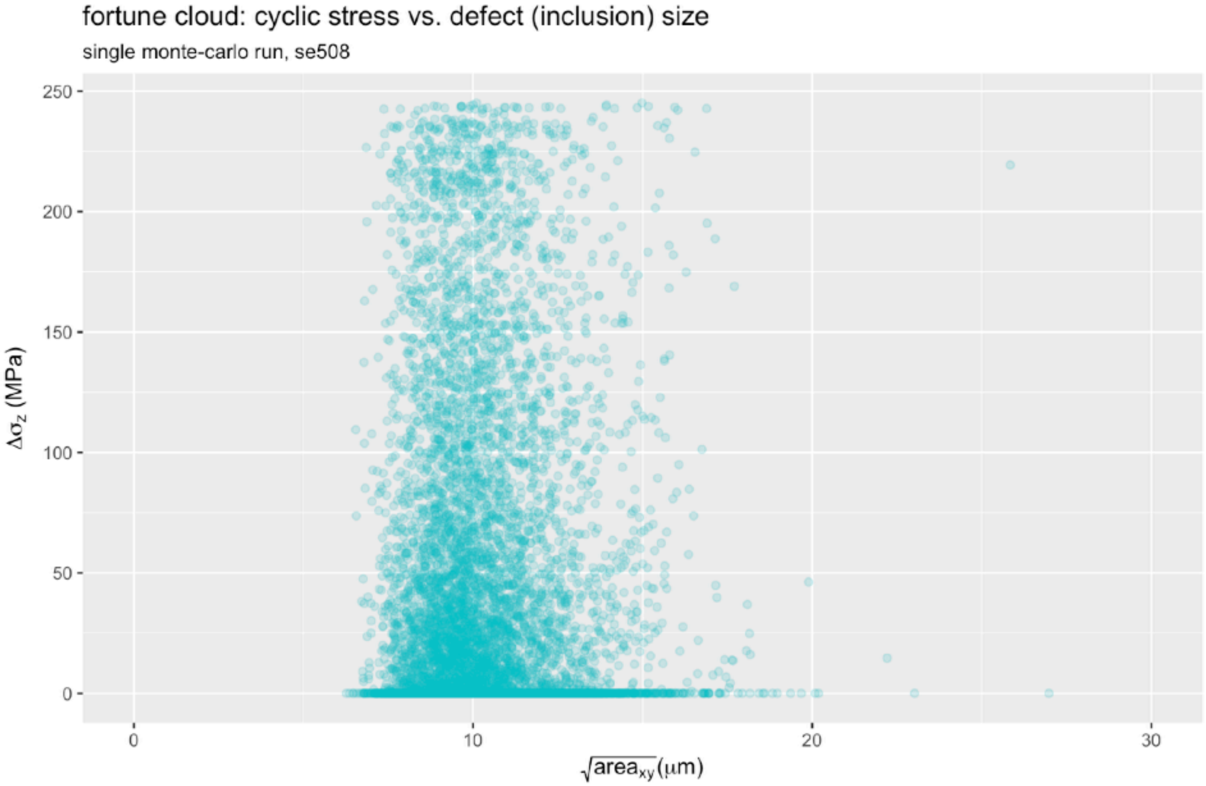
$$Q(p) = \mu - \sigma \ln[-\ln(p)]$$

$Q(U)$ has a Gumbel distribution
for random values of U drawn from
a uniform distribution on the interval (0,1)



Dice by b farias, from the Noun Project

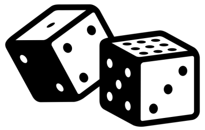
“Fortune cloud”: Δσ vs. √area (single run SE508, ELI)



Estimating stress intensity factor K by Murakami's √area

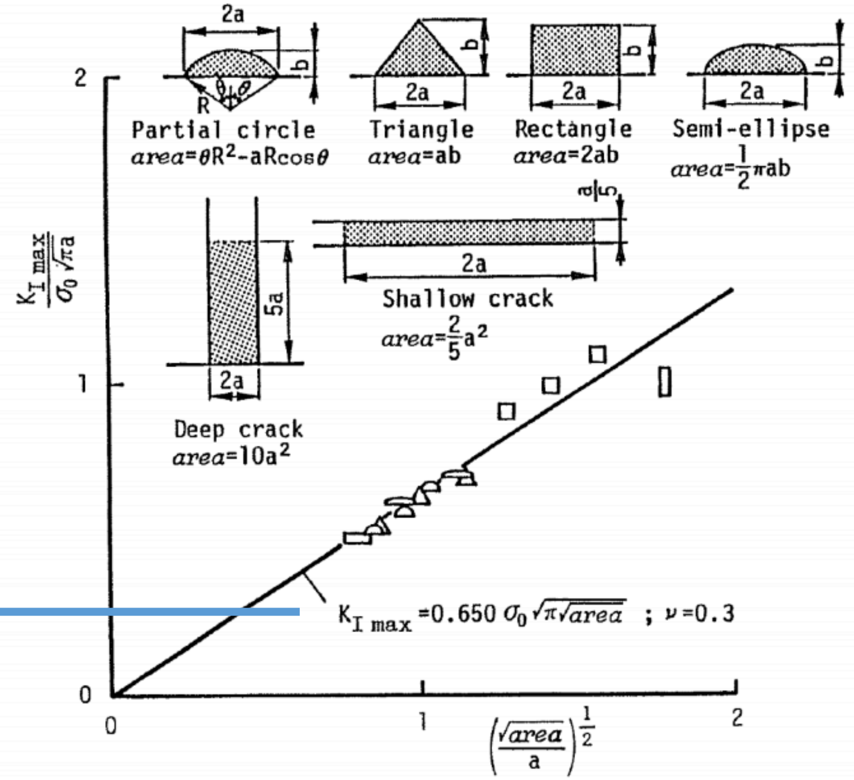
FEA

XCT, Gumbel Parameters



$$K\left(\sigma, \sqrt{area}\right) = 0.65 \cdot \sigma\sqrt{\pi \cdot \sqrt{area}}$$

Figure 7 shows the relationship between the maximum stress intensity factor K_{Imax} and $\sqrt{area}$ for surface cracks (elastic analysis) (24)(25). (See also (20)(66).)



Murakami Y, Endo M (1986) Effect of hardness and crack geometries on ΔK_{th} of small cracks emanating from small defects, In: The Behavior of Short Fatigue Cracks, EGF Pub. 1, pp 275–293

K and ΔK in each plane, at each integration point

$$K_x = 0.65 \cdot \sqrt{\sigma_x \cdot \sqrt{area_{yz}}}$$

$$K_y = 0.65 \cdot \sqrt{\sigma_y \cdot \sqrt{area_{xz}}}$$

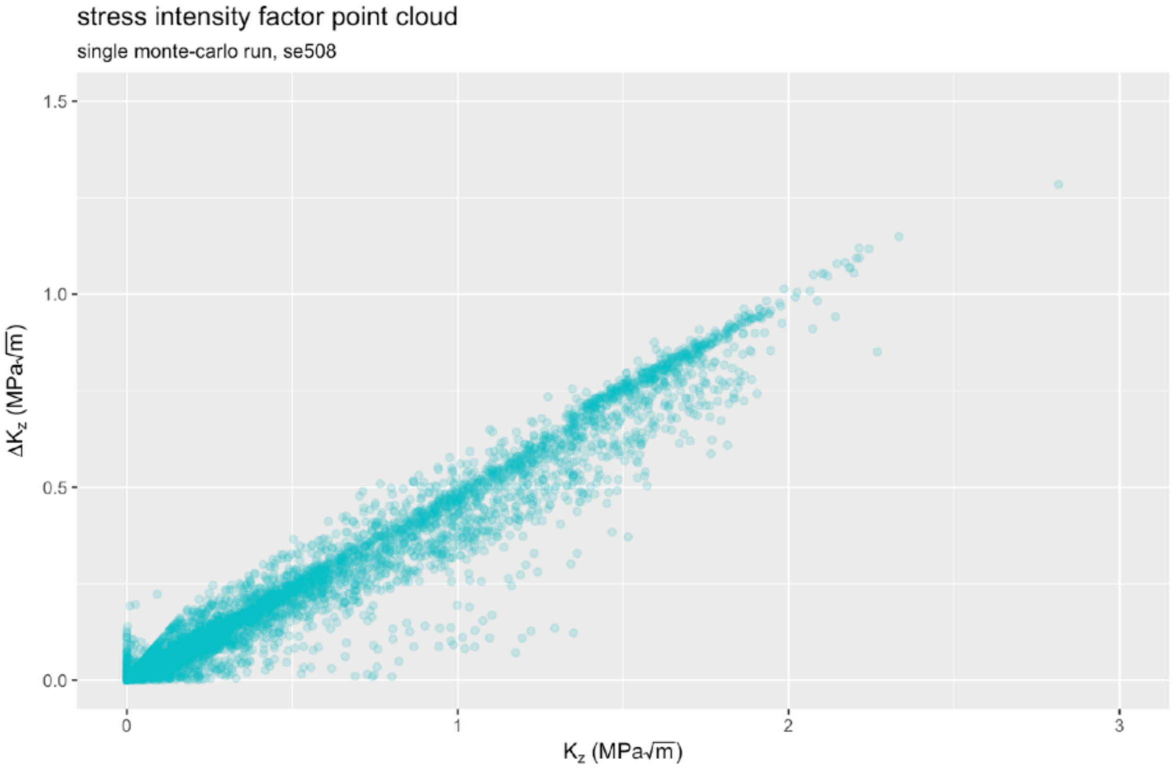
$$K_z = 0.65 \cdot \sqrt{\sigma_z \cdot \sqrt{area_{xy}}}$$

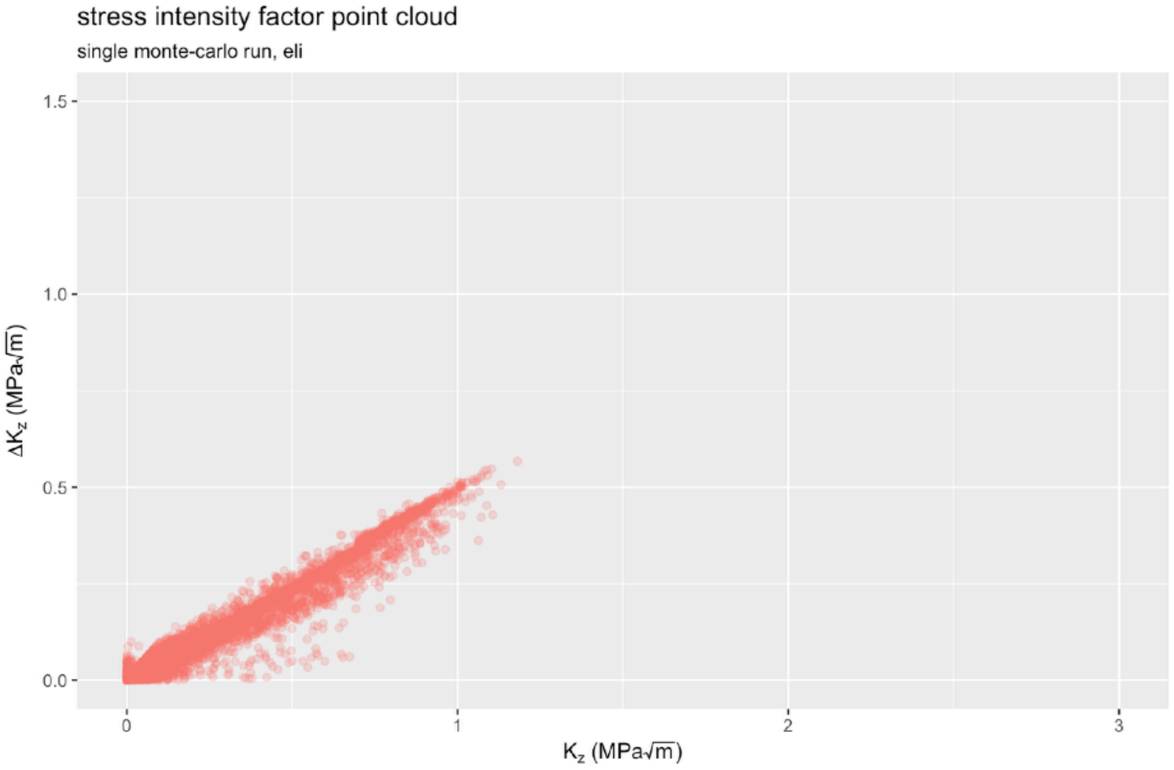
$$\Delta K_x = 0.65 \cdot \sqrt{\Delta\sigma_x \cdot \sqrt{area_{yz}}}$$

$$\Delta K_y = 0.65 \cdot \sqrt{\Delta\sigma_y \cdot \sqrt{area_{xz}}}$$

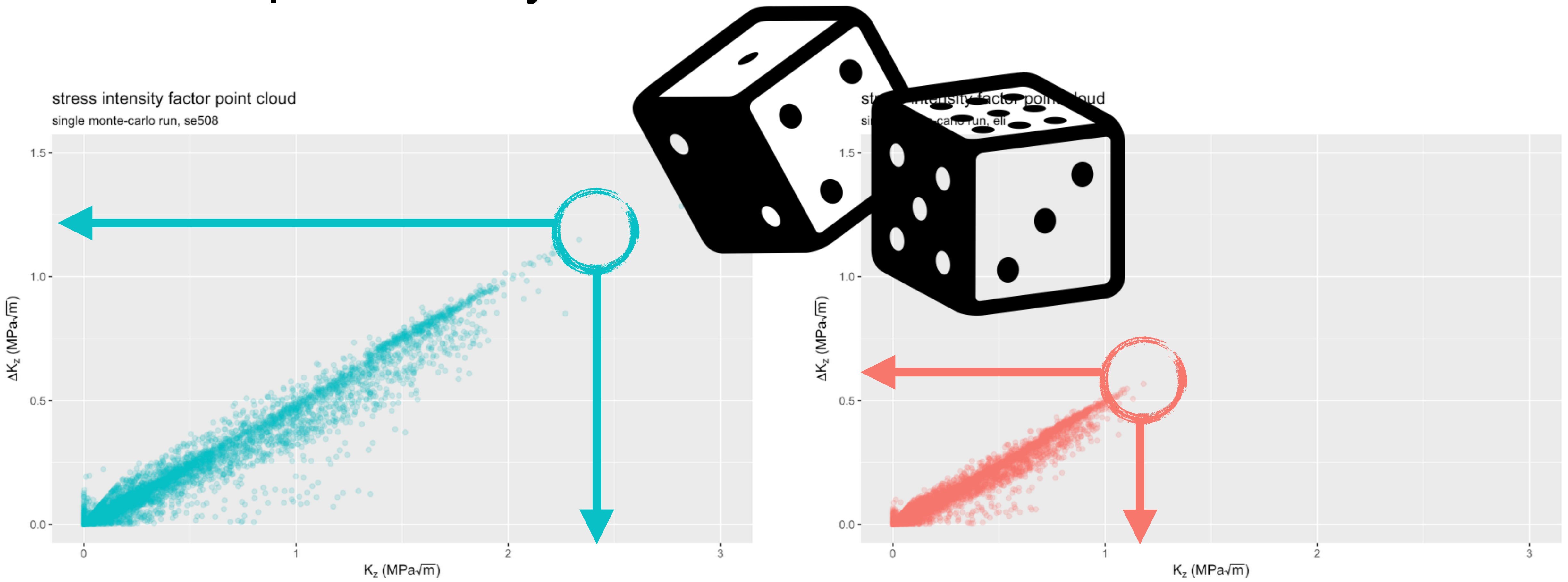
$$\Delta K_z = 0.65 \cdot \sqrt{\Delta\sigma_z \cdot \sqrt{area_{xy}}}$$

“K point cloud” (single run SE508, ELI)

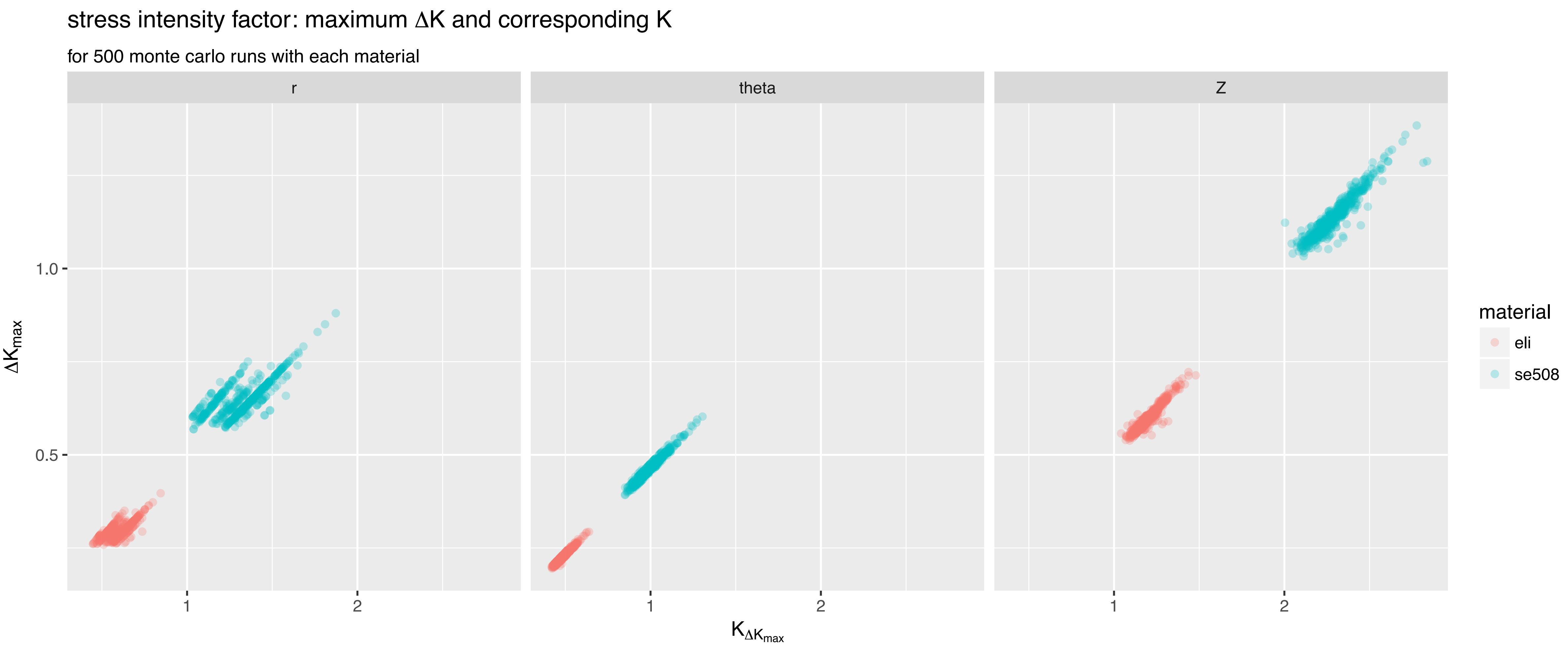




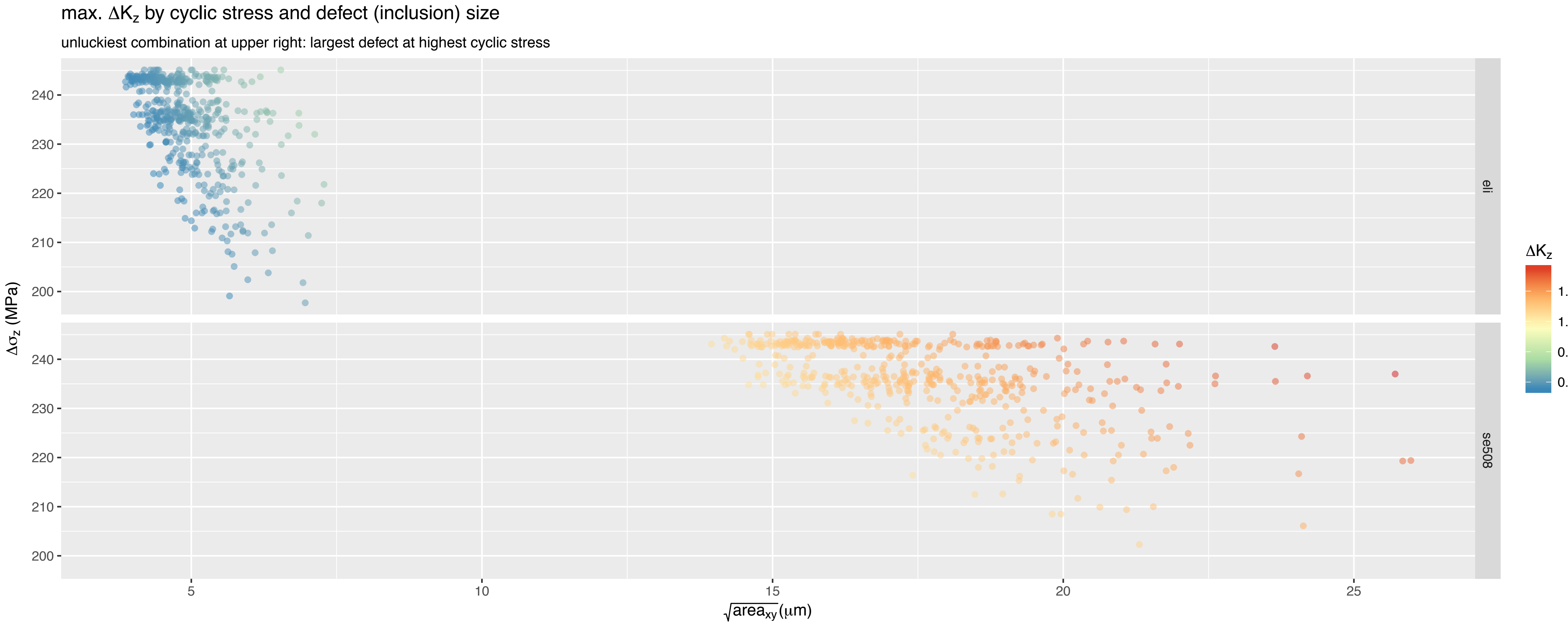
Next: repeat many times, record ΔK_{max} and K



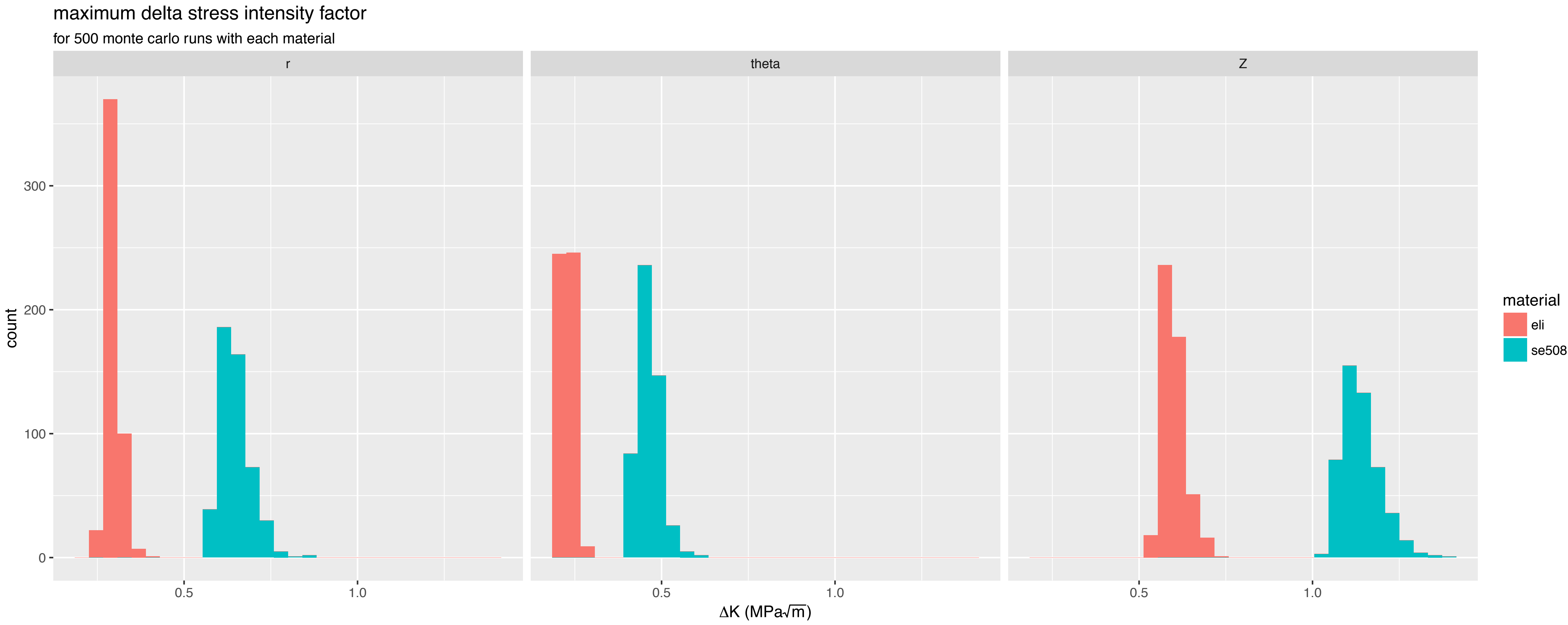
Maximum stress intensity factors for 500+500 runs



“Fortune plot” for 500+500 runs



ΔK_{max} for 500+500 runs



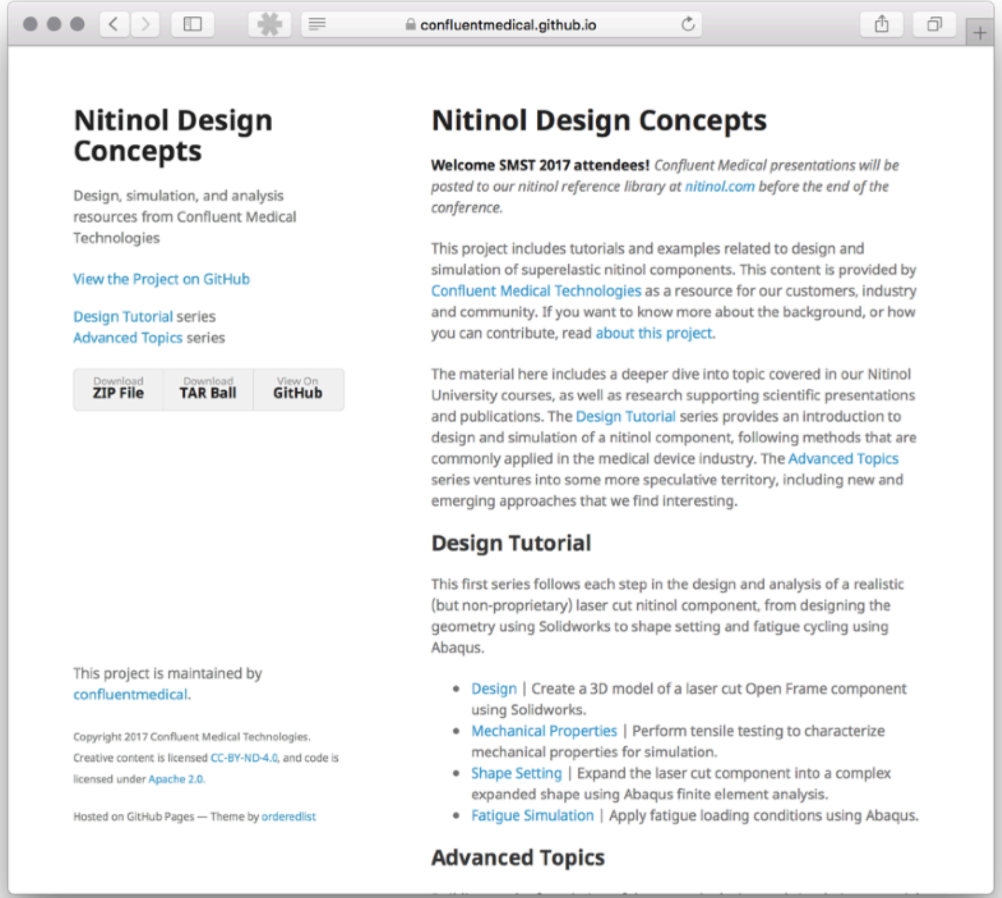
Limitations

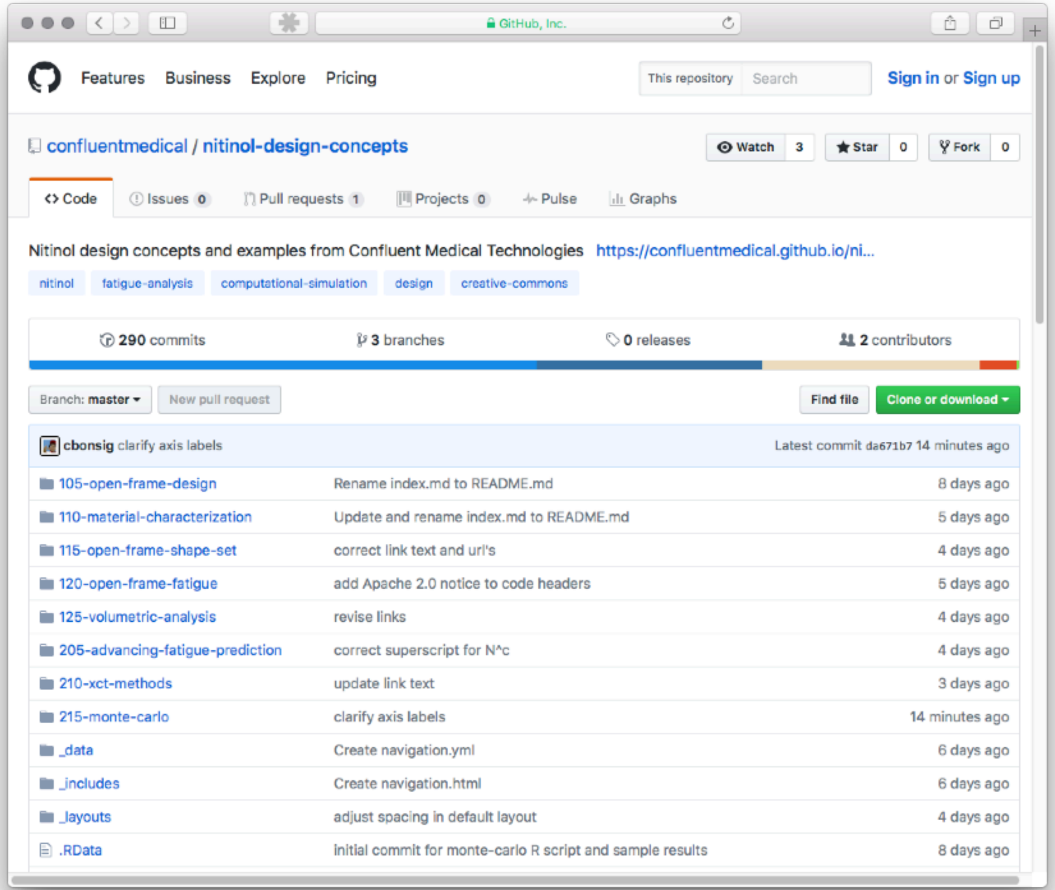
- XCT results are currently limited to a single tubing configuration, and three sample volumes
- Resolution limit for XCT unconfirmed; comparison with conventional 2D analysis TBD
- K, ΔK are based on linear elastic fracture mechanics
- Muramaki 0.65 factor does not account for defect depth from surface
- No experimental confirmation completed (yet)
- Material properties for example FEA are unverified
- Code is all new and probably full of mistakes!

- Critical review and feedback will be greatly appreciated!

Introduction
Volumetric FEA methods
Sub-μm x-ray computed tomography
Monte-Carlo risk assessment
> **Resources**

More resources online: Nitinol Design Concepts





bit.ly/smst17ndc

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