



# **Strain Amplitude Volume Fraction Method for Evaluation of Nitinol Fatigue Durability**

**SMST 2014 Asilomar**

Craig Bonsignore (presenter)

Payman Saffari

Payam Saffari

We are Nitinol.<sup>TM</sup>

---

## **Introduction**

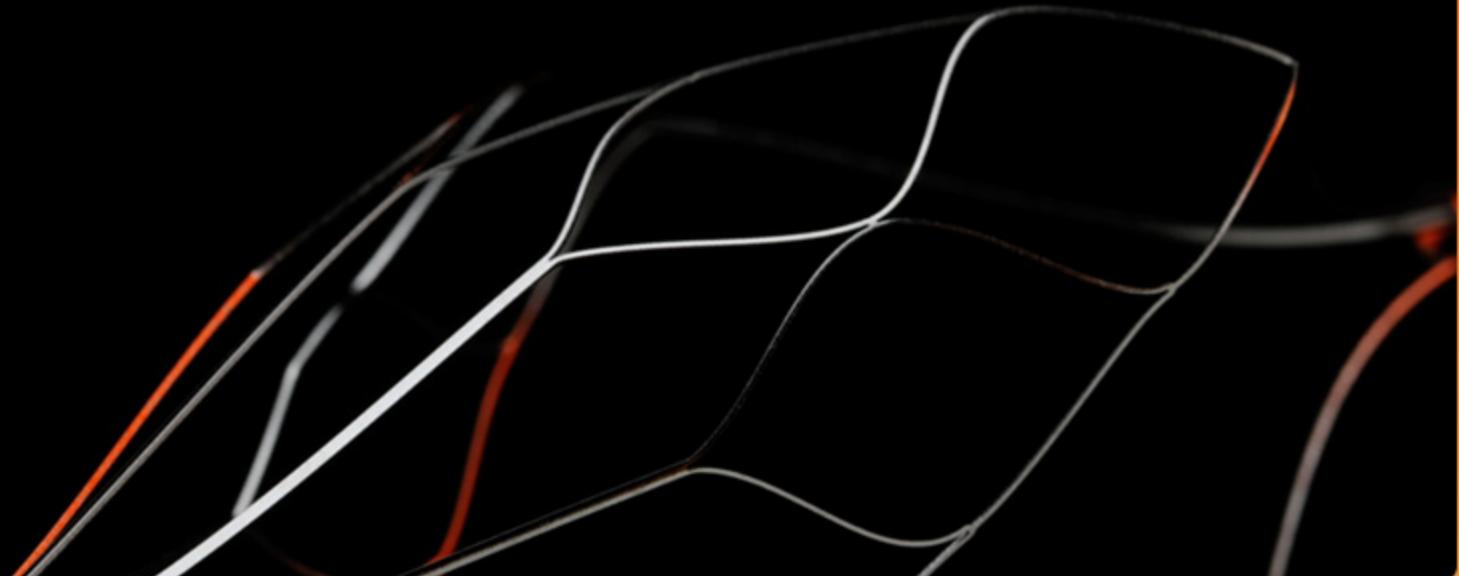
### **Hazard Probability**

### **Volume fraction of inclusions**

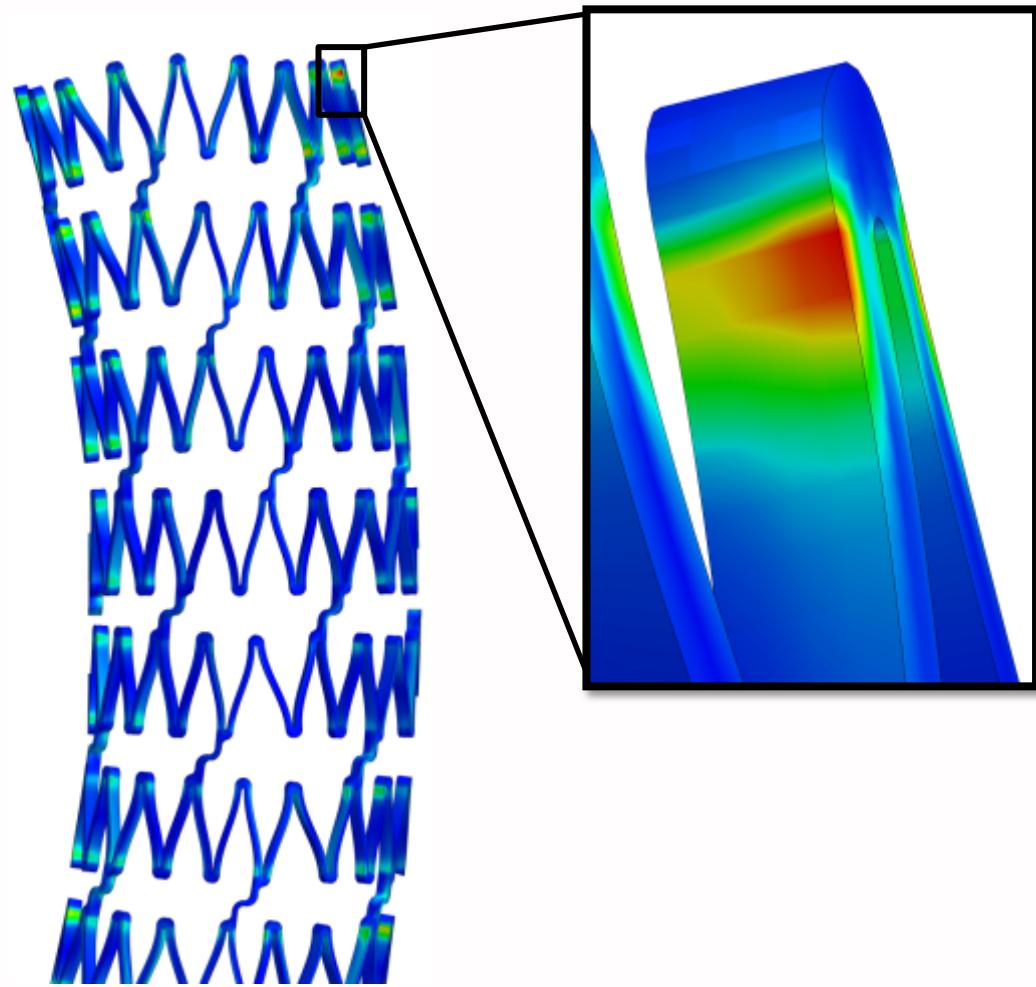
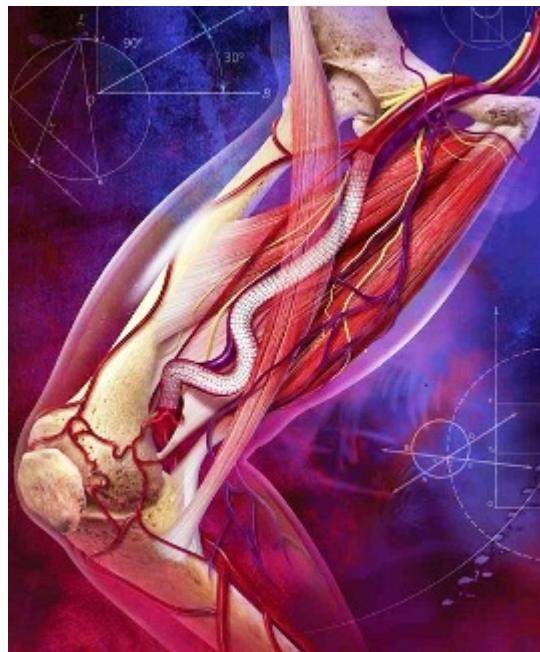
### **Critical strain region probability**

### **Putting everything together**

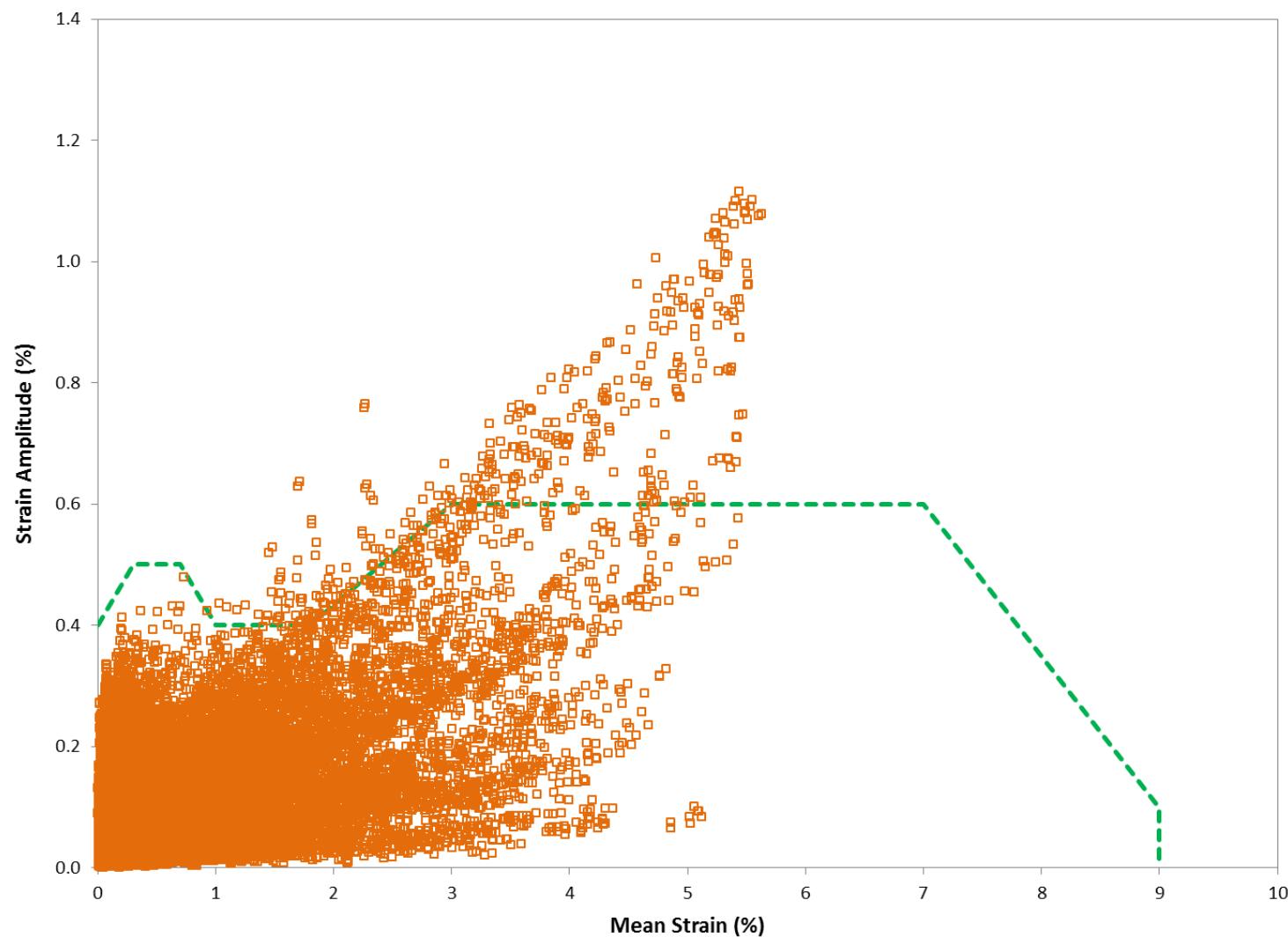
### **Online resources**



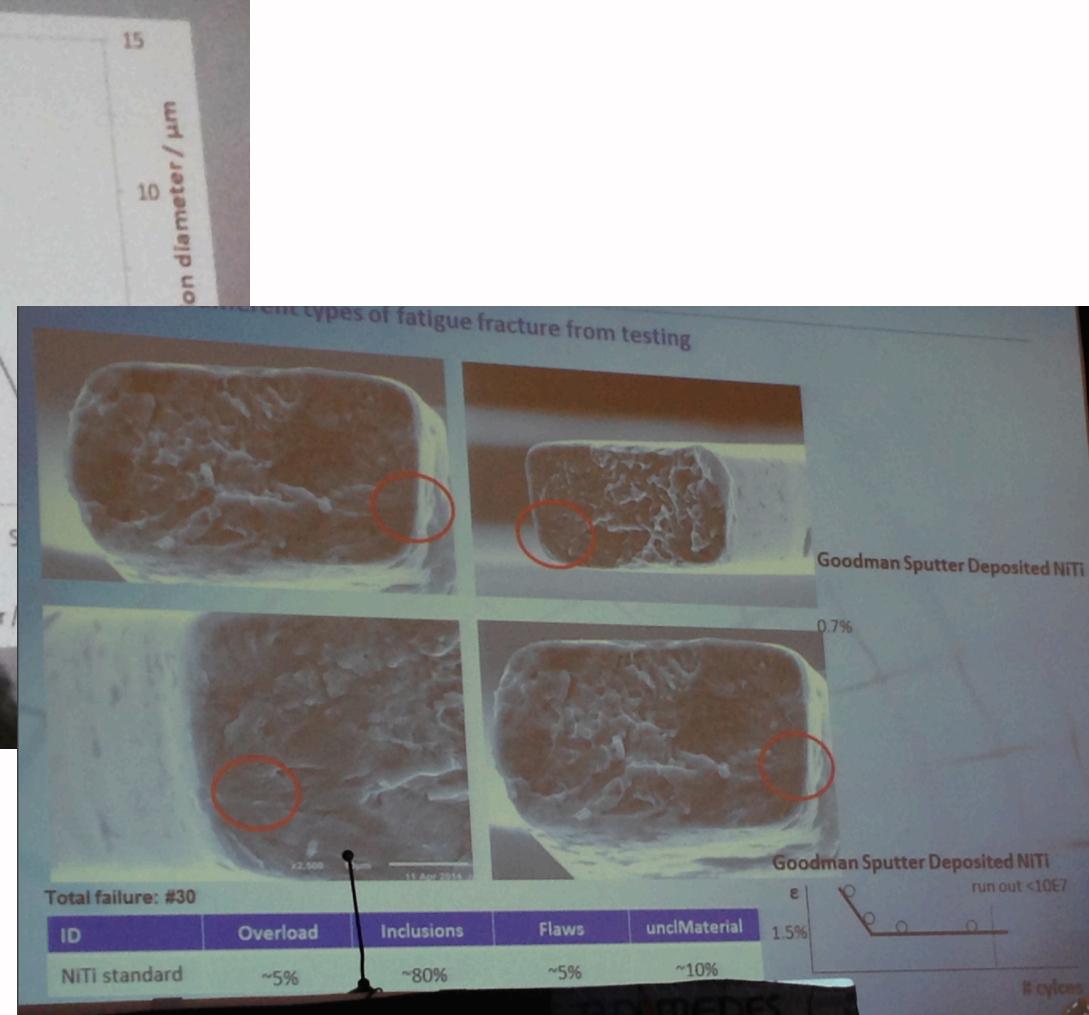
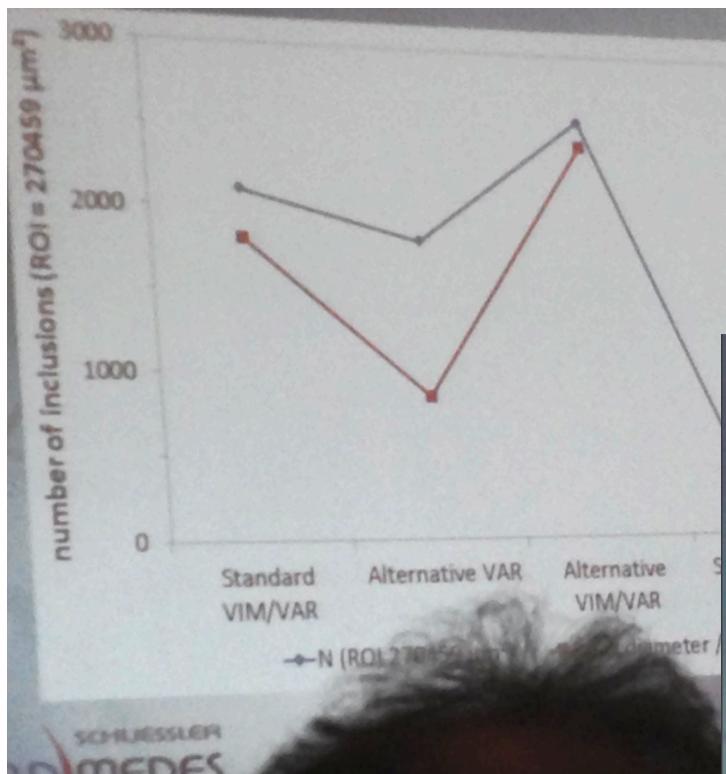
# Stress/Strain Field



# Will the device represented here fail in fatigue?



# Alloy purity and relationship to durability



We are Nitinol.<sup>TM</sup>

---

**Introduction**

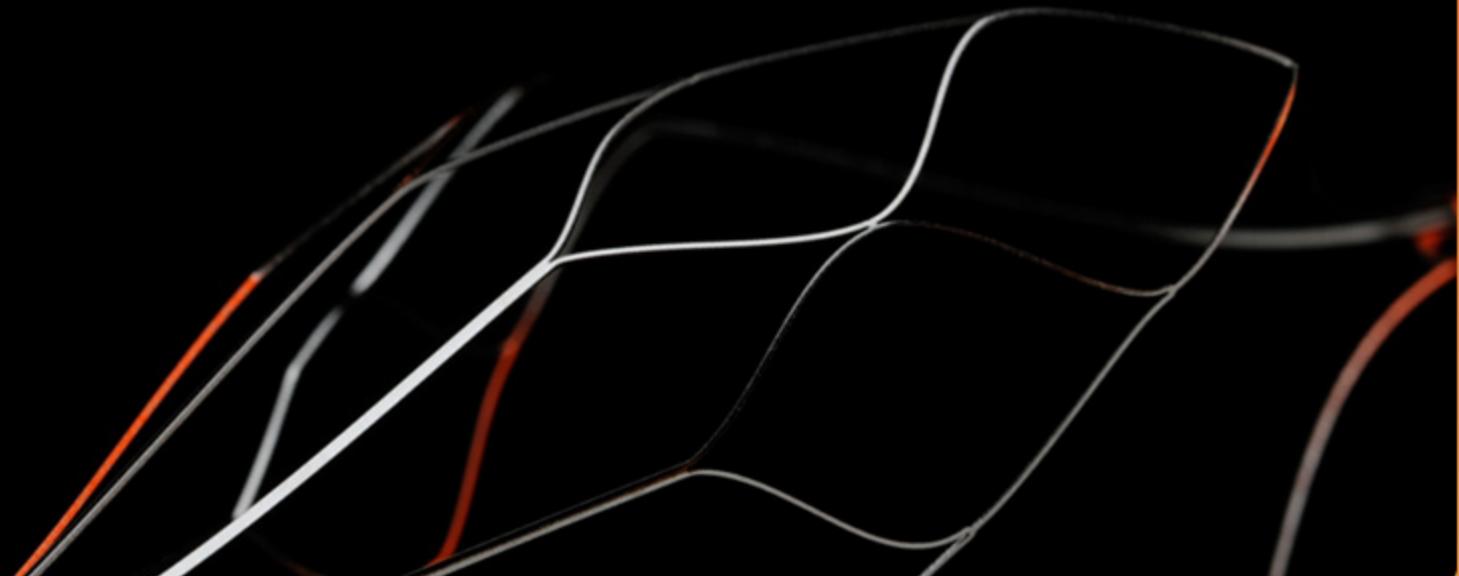
**Hazard Probability**

**Volume fraction of inclusions**

**Critical strain region probability**

**Putting everything together**

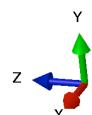
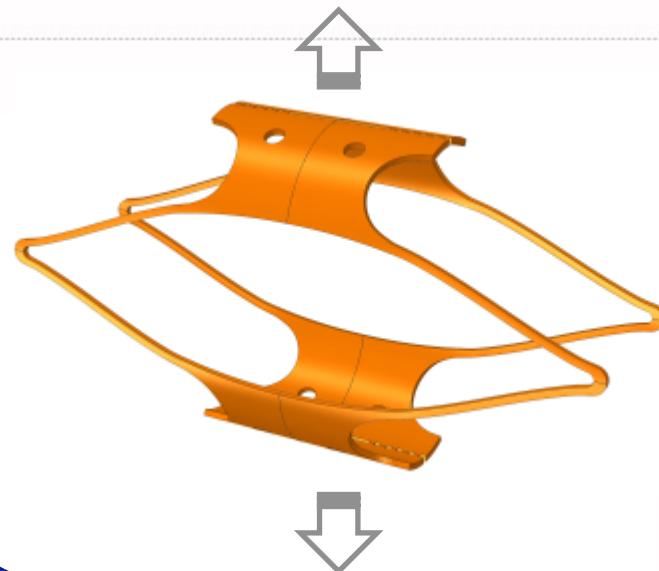
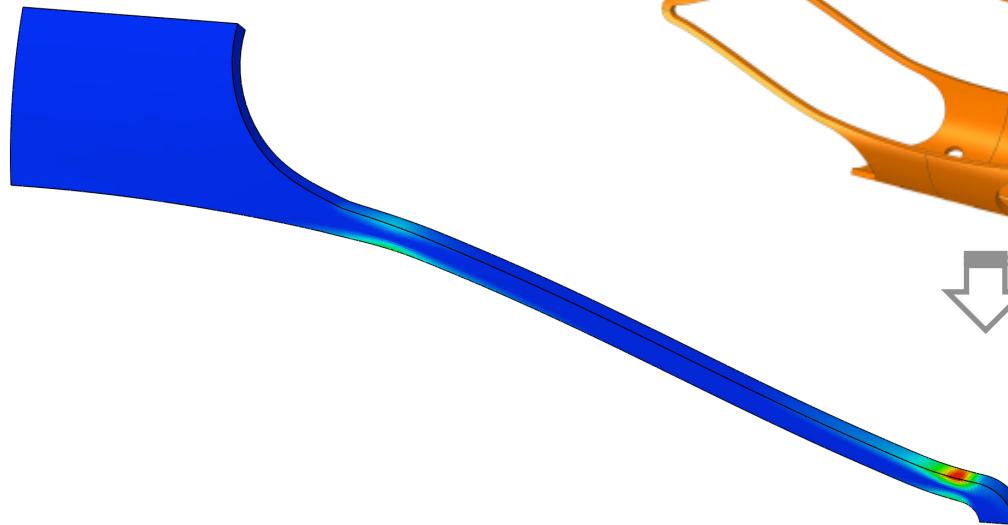
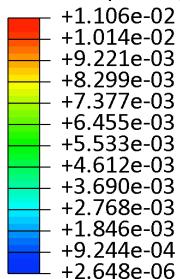
**Online resources**



# Example Case: Diamond Specimen



Strain Amplitude, Max. Principal



ODB: SE508-fatigue-m3\_20-a1\_10.odb Abaqus/Standard 6.12-1 Wed May 08 01:13:18 Pacific Daylight Time 2013

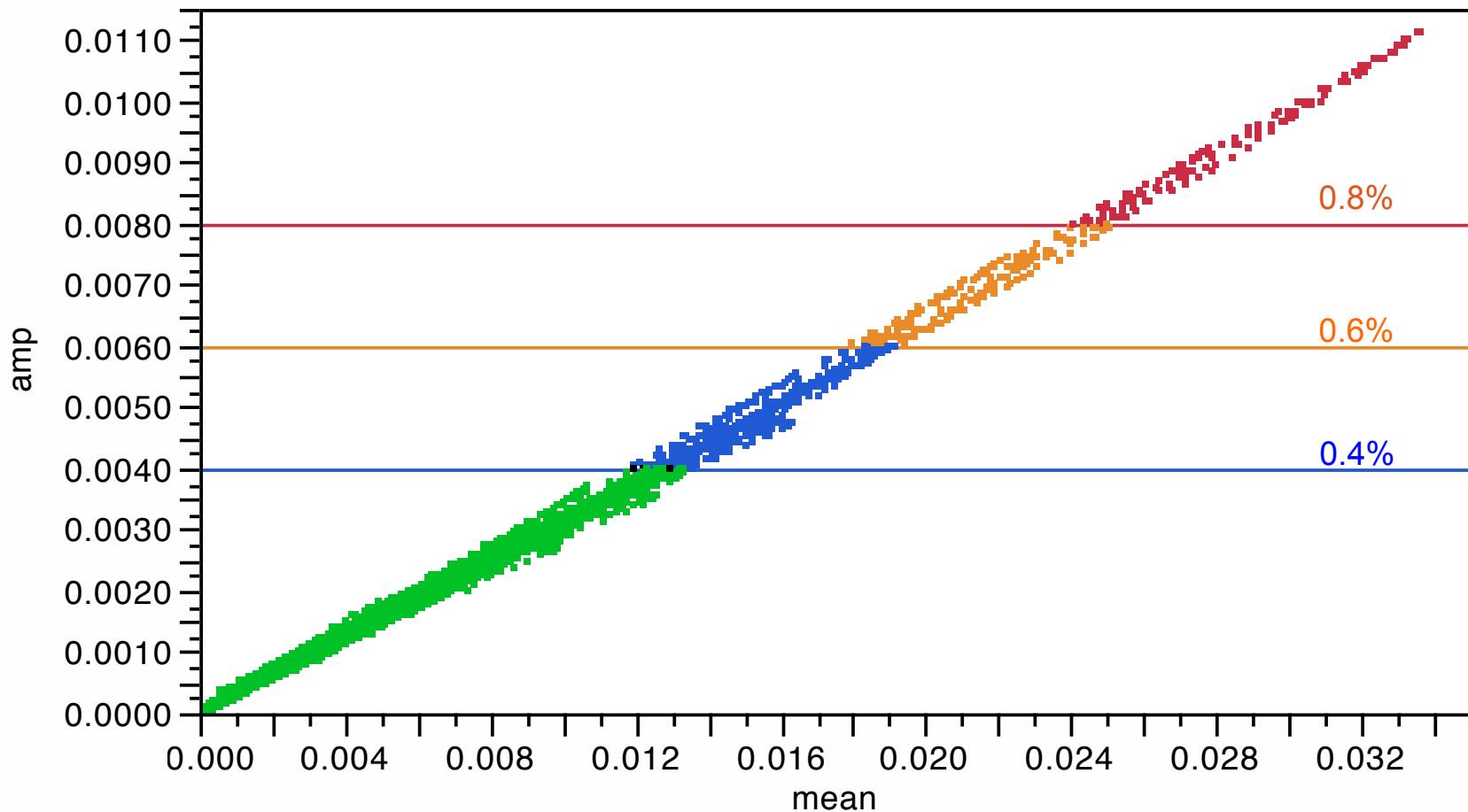
Step: Session Step, Step for Viewer non-persistent fields

Session Frame

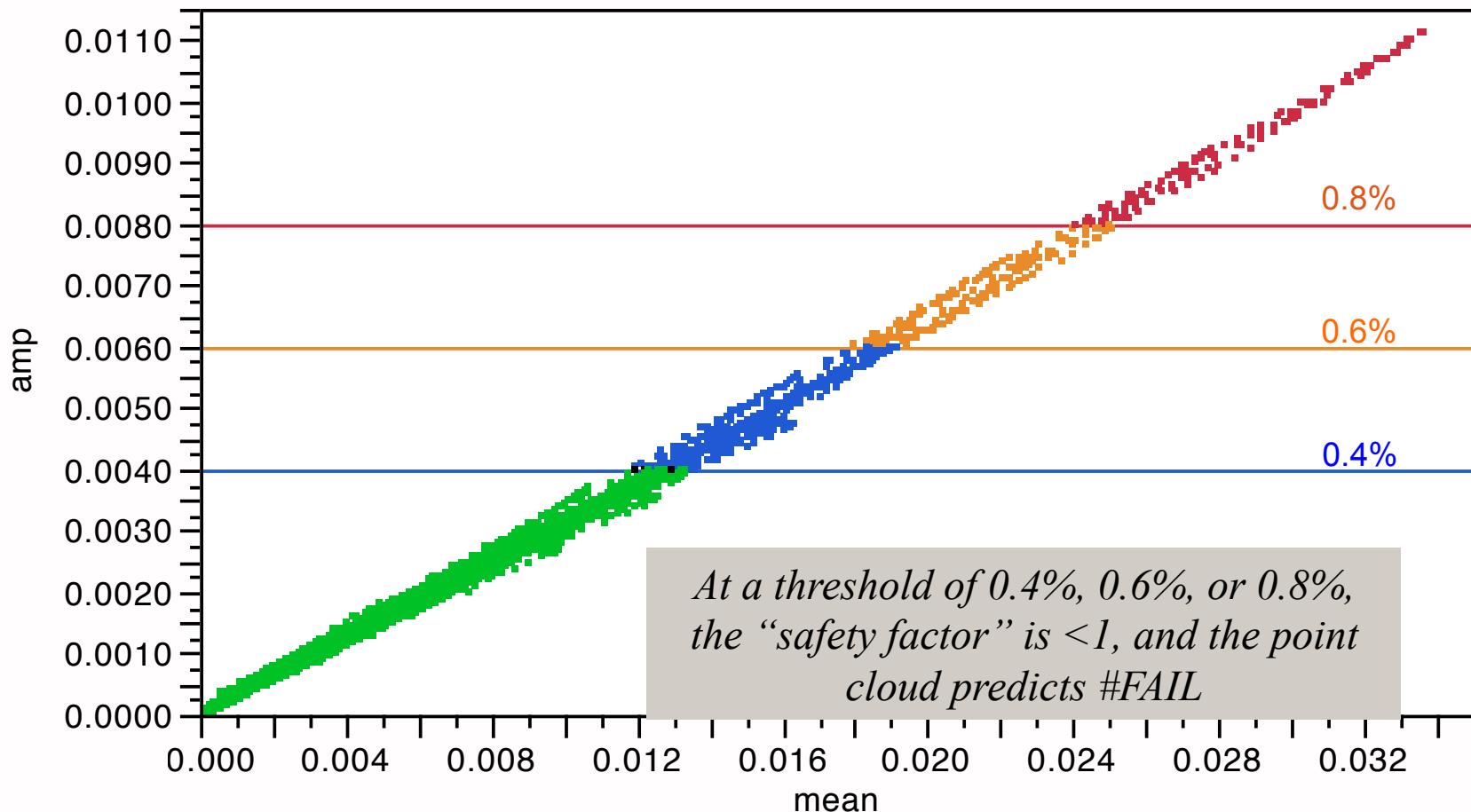
Primary Var: Strain Amplitude, Max. Principal

Deformed Var: not set Deformation Scale Factor: not set

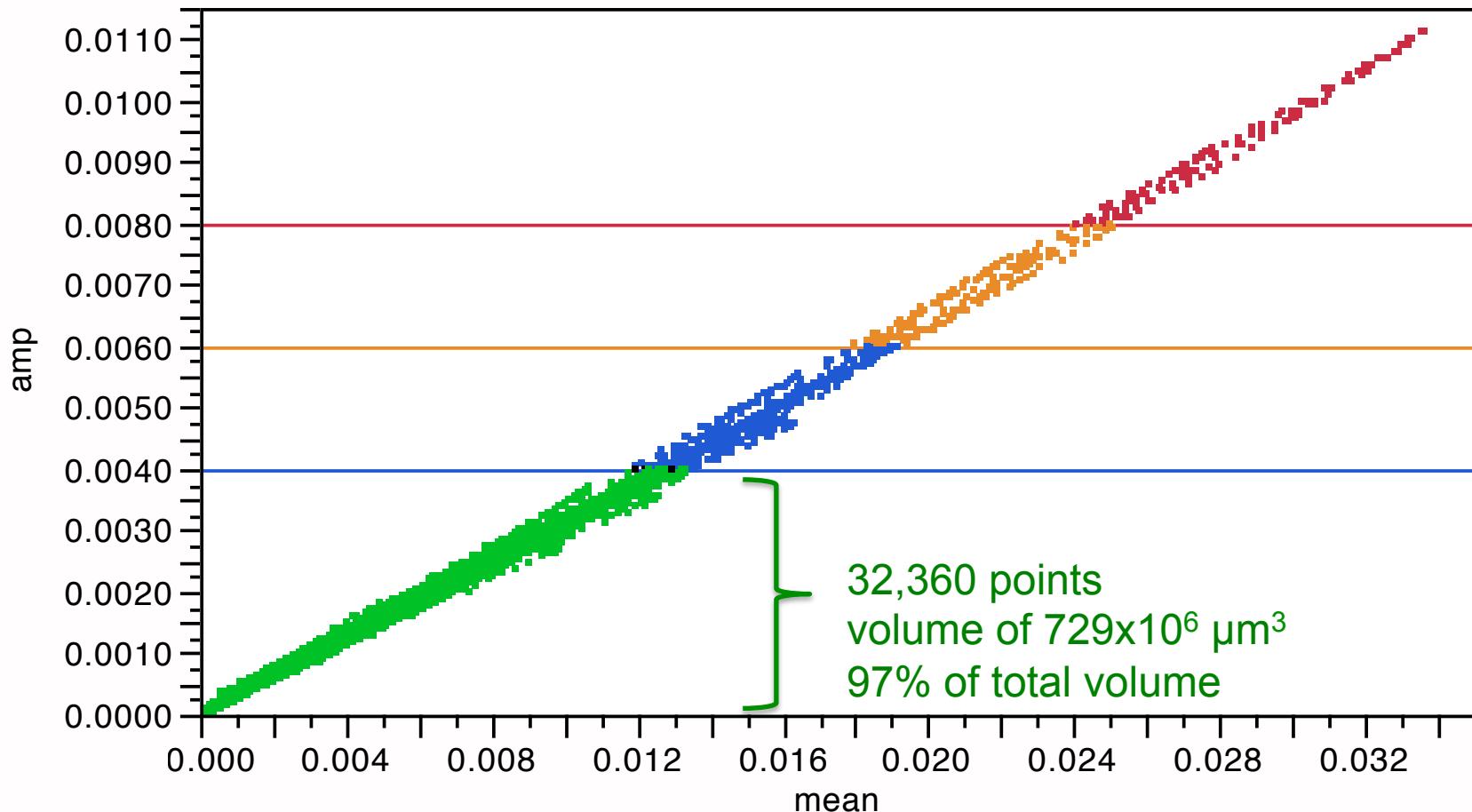
# Point Cloud



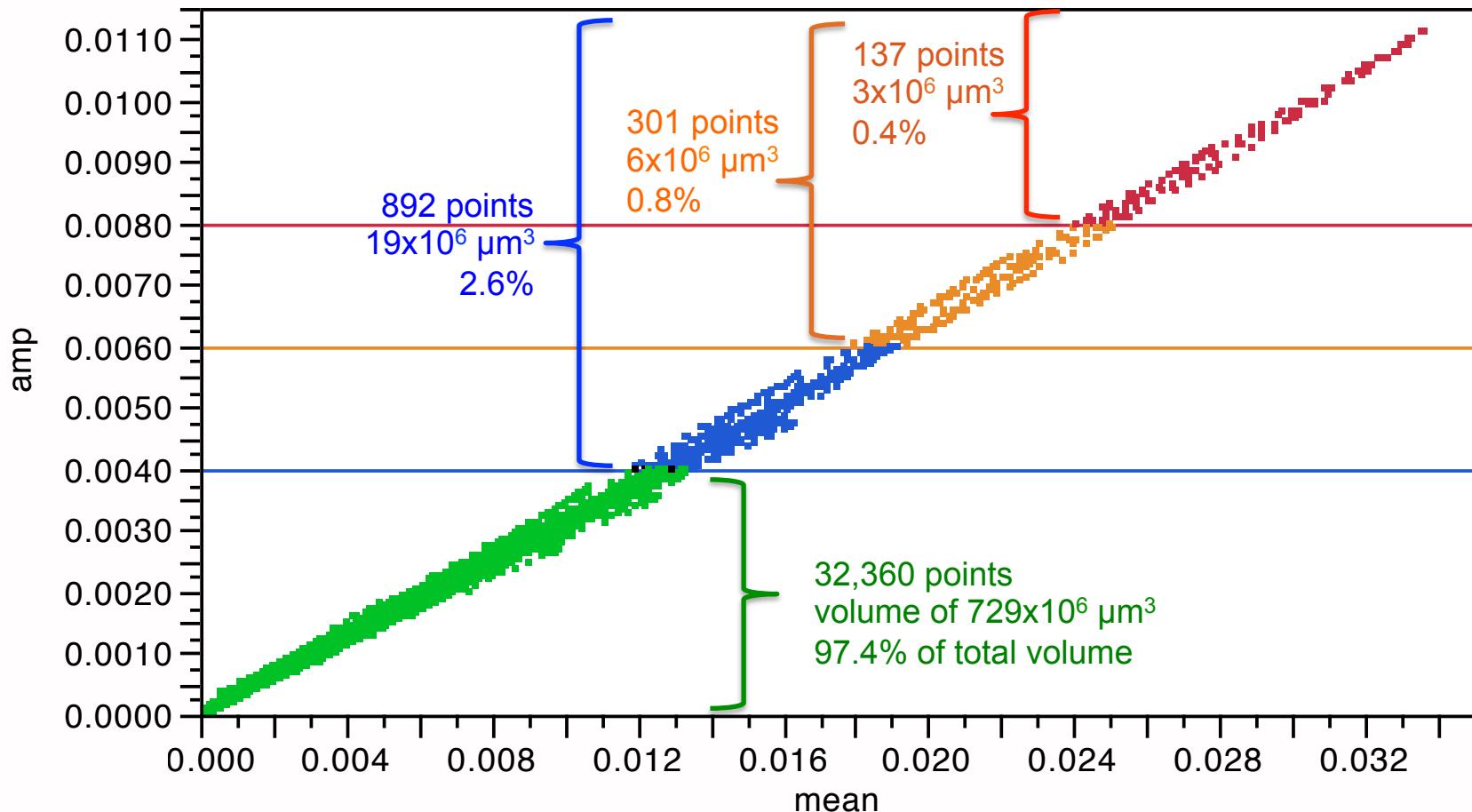
# Point Cloud and Safety Factor: Binary result “PASS” or “FAIL”



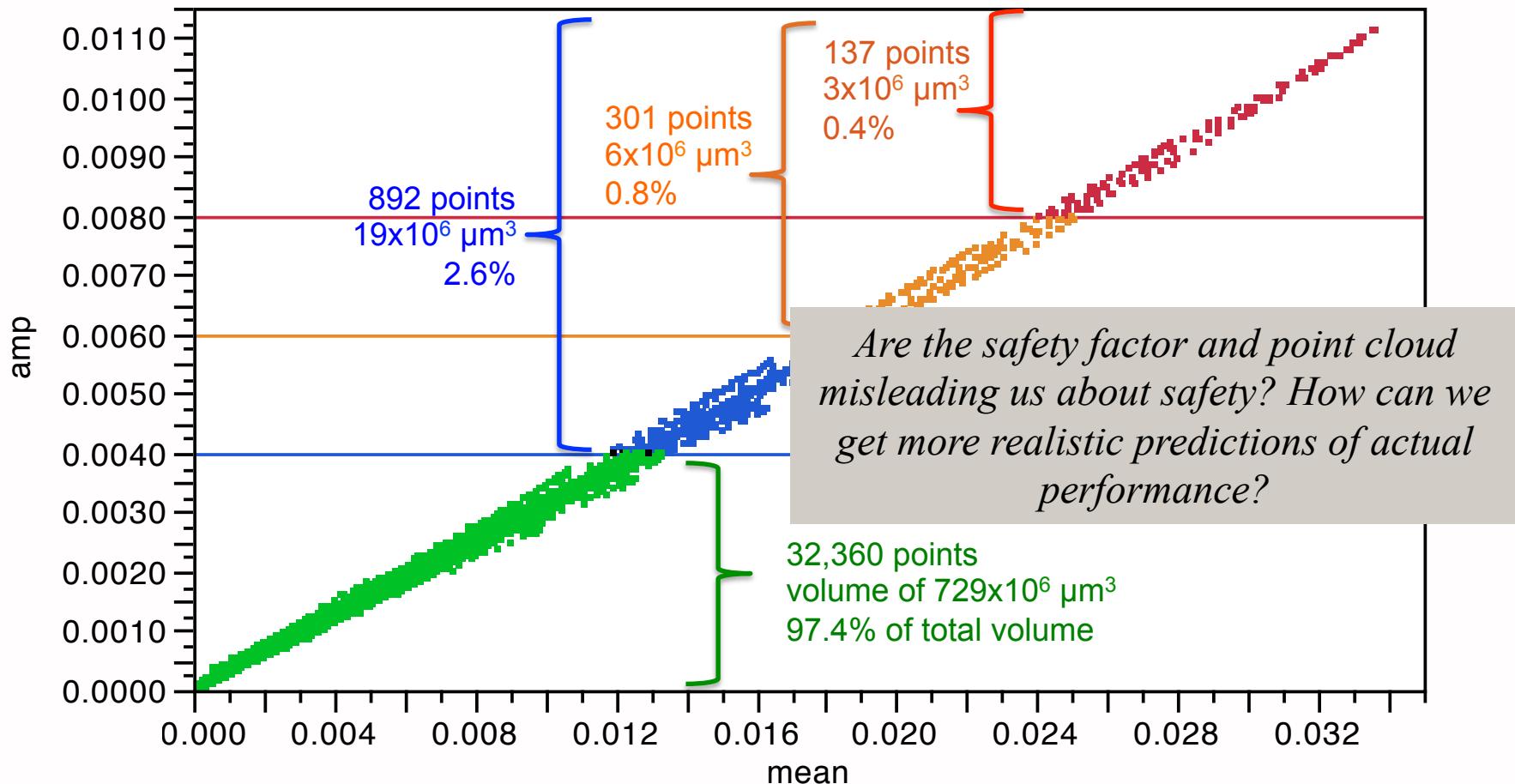
# Point Cloud Limitations



# Point Cloud Limitations



# Point Cloud Limitations



# Strain Amplitude Volume Fraction



- Define a relevant strain amplitude threshold:  $\varepsilon_{\text{limit}}$
- Calculate strain amplitude for all integration points
- Calculate the volume of material for all element having a strain amplitude exceeding the threshold:  $\sum V \varepsilon_{\text{limit}}$
- Calculate the total volume of material in the model:  $V_{\text{total}}$
- The Strain Amplitude Volume Fraction:  $\text{SAVF} = \frac{\sum V \varepsilon_{\text{limit}}}{V_{\text{total}}}$

# Hypothesis 1

Fatigue fractures commonly originate at the location of an inclusion, void, or related material impurity.

Let's define the hazard associated with this condition:

$$P_{\text{hazard}_i}$$

Fatigue fractures may also occur at a location unrelated to a material impurity. Let's define that hazard as:

$$P_{\text{hazard}_m}$$

The total hazard is then the sum:

$$P_{\text{hazard}} = P_{\text{hazard}_i} + P_{\text{hazard}_m}$$

## Hypothesis 2

Impurity hazard probability at any location depends on coincidence of

$(\varepsilon_{amp} > \text{threshold}) \text{ AND } (\text{presence of an impurity})$

$$P_{\text{hazard}_i} = P(A \cap B) = P(A) \cdot P(B)$$

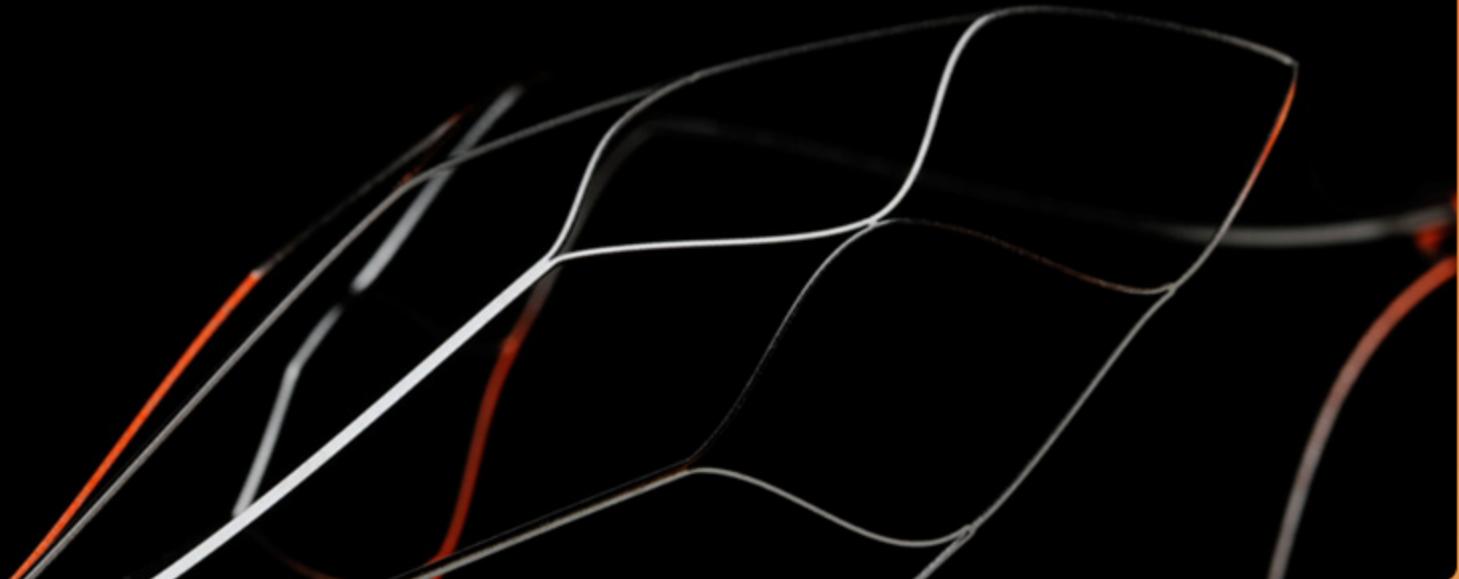
**P(A)** = Probability of an impurity at a location = Volume fraction of impurities detected in the material

**P(B)** = Probability of strain amplitude exceeding threshold at the same location = Volume fraction of elements exceeding threshold in a finite element analysis model (SAVF)

We are Nitinol.<sup>TM</sup>

---

**Hazard Probability**  
**Volume fraction of inclusions**  
**Critical strain region probability**  
**Putting everything together**  
**Online resources**



# Volume fraction of inclusions: Considerations



- ASTM F-2063 requires:
  - Voids and nonmetallics  $\leq$  2.8% area fraction at 500X
  - Oxide and Carbide particles  $\leq$  39.0  $\mu\text{m}$
  - Oxide and Carbide  $\leq$  500 PPM (by mass)
- None of these provide meaningful information about the volume percent of inclusions in typical materials
- So let's try to figure this out using some new methods...

# Volume fraction of inclusions: Methodology

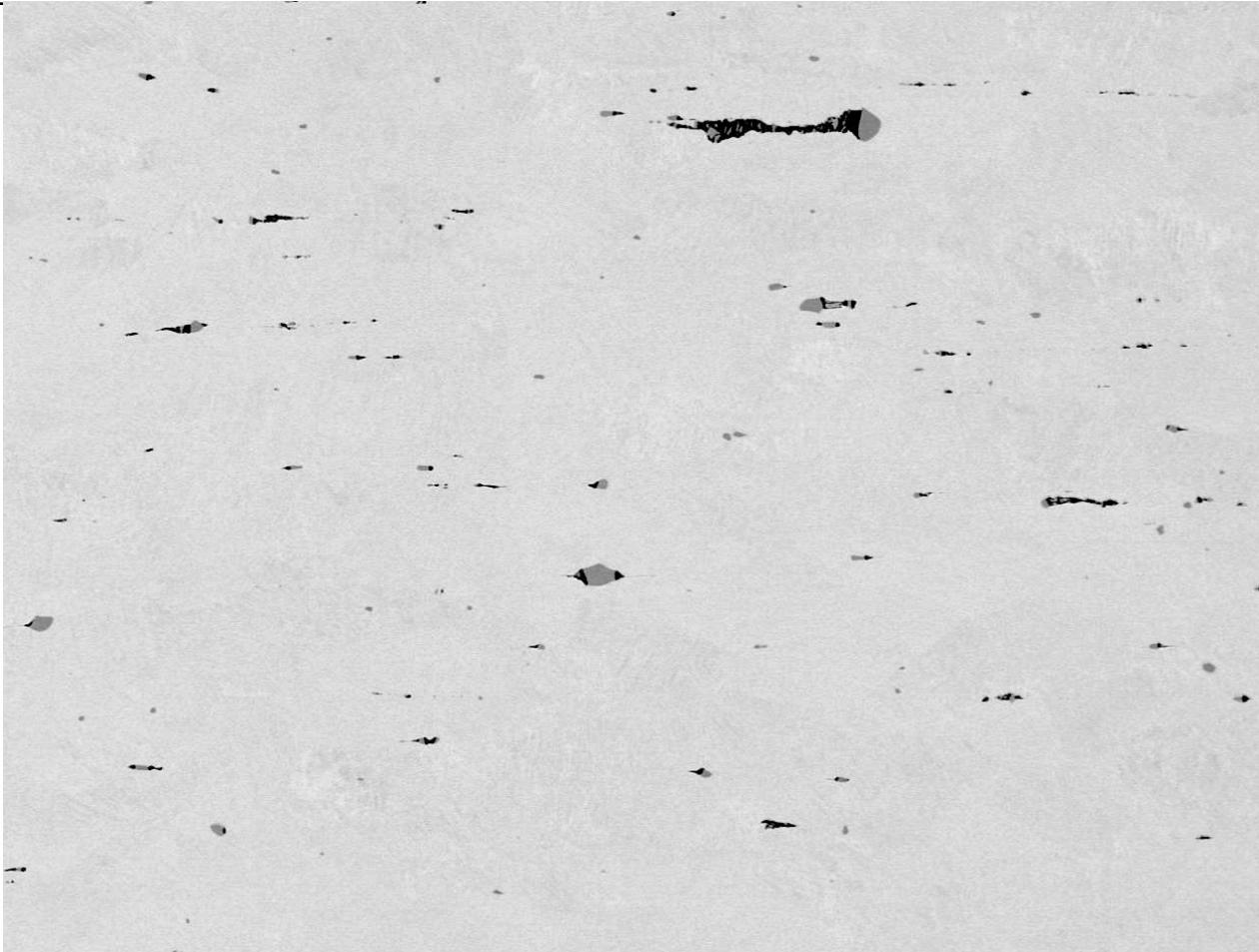


- SEM micrographs, tubing transverse sections, 500X
  - n=16 micrographs for typical VAR material
  - n=24 micrographs for typical high-purity VAR material
  - n=6 micrographs for standard VIM/VAR material
  - n=3 micrographs for process optimized VIM/VAR material
  - n=3 micrographs for standard VIM material
- An image processing algorithm was used to isolate particles in each image, and quantify their size in  $\mu\text{m}^2$
- The volume of each particle was estimated as follows:
  - if particle area  $\leq 25 \mu\text{m}^2$ , depth =  $(\text{particle area})^{1/2}$
  - if particle area  $> 25 \mu\text{m}^2$ , depth = 5  $\mu\text{m}$
- The volume fraction of particles was calculated assuming each cross section accounts for 5  $\mu\text{m}$  depth

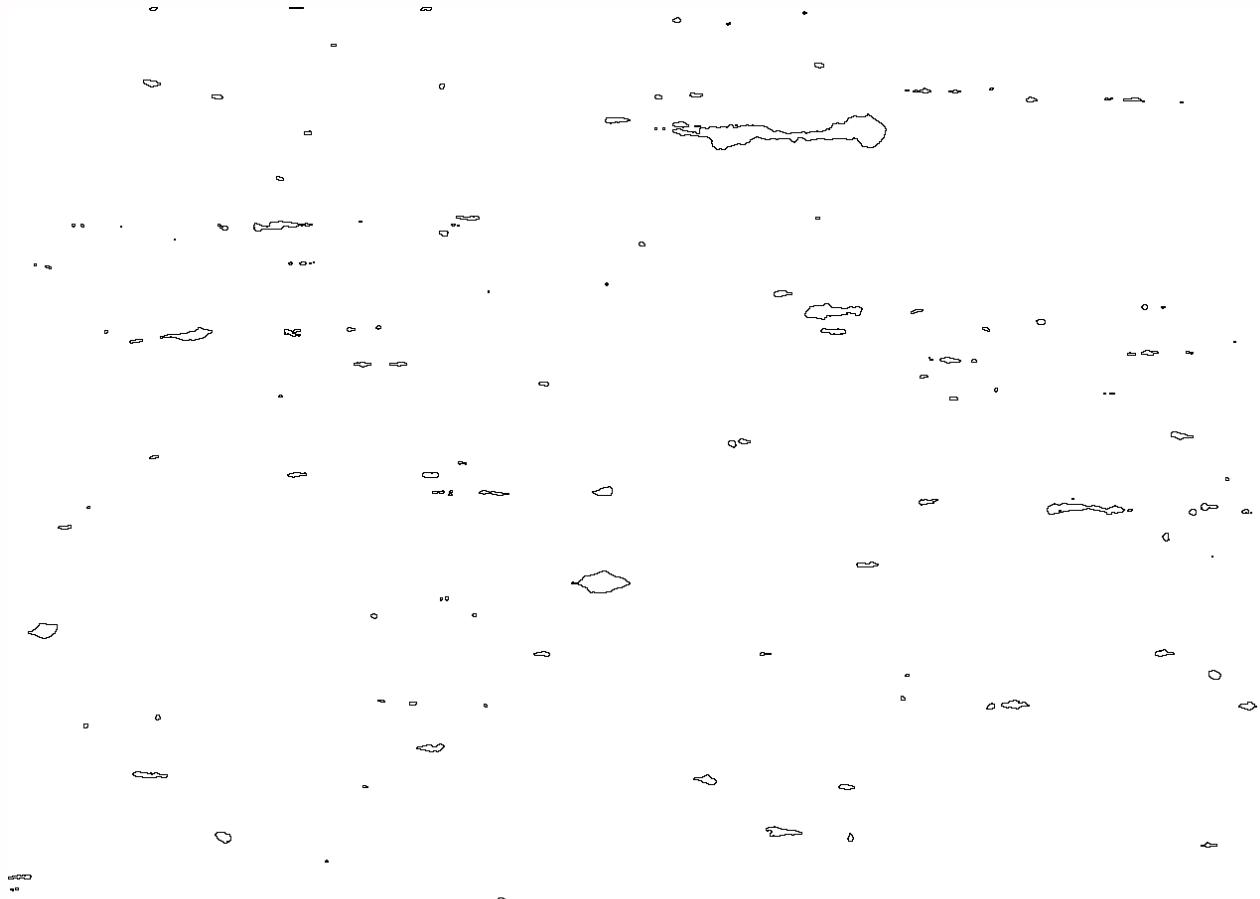
# Typical raw image – VAR material



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



# Typical particle detection – VAR material

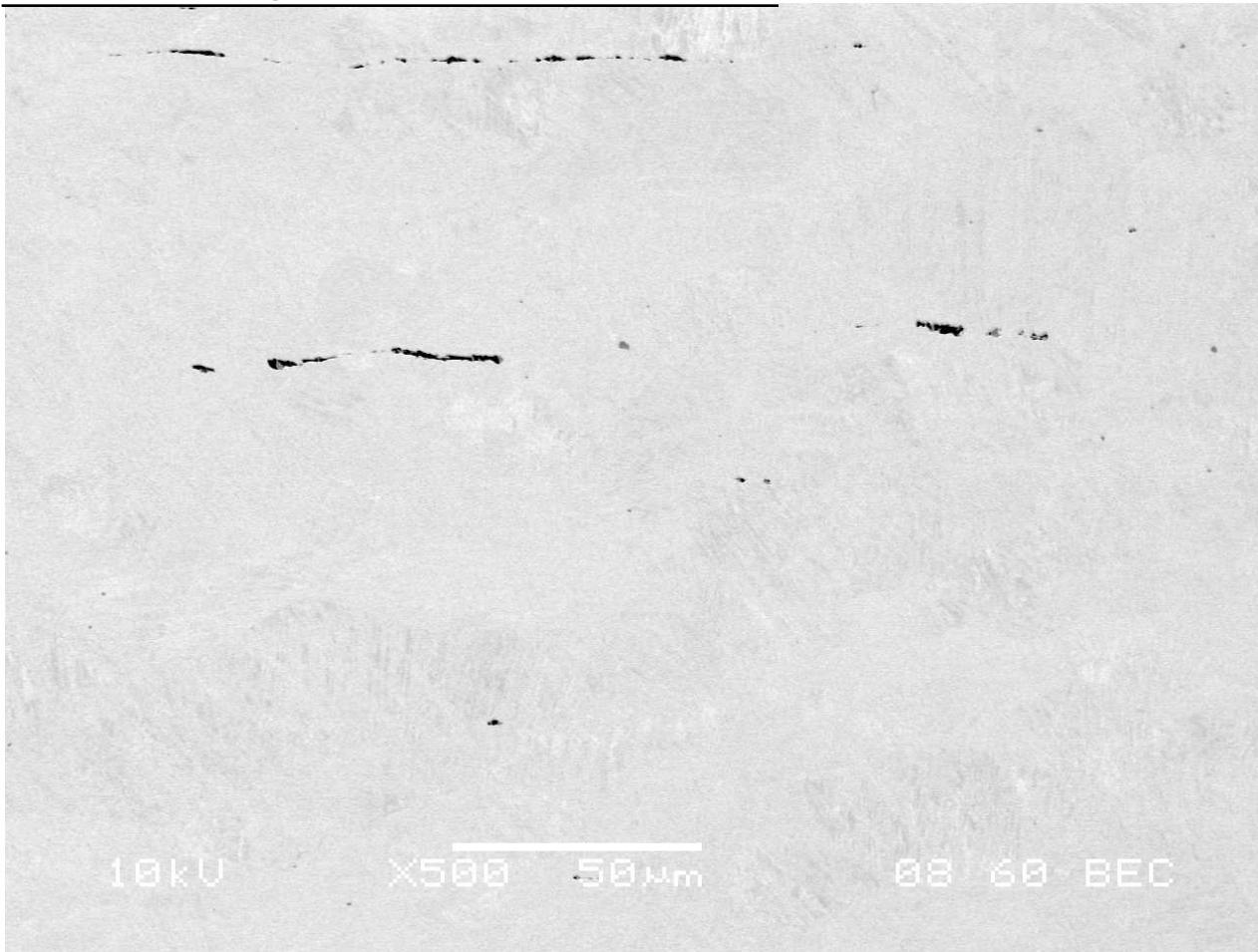


151 “particles” (inclusions) detected

# Typical raw image – high purity VAR



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

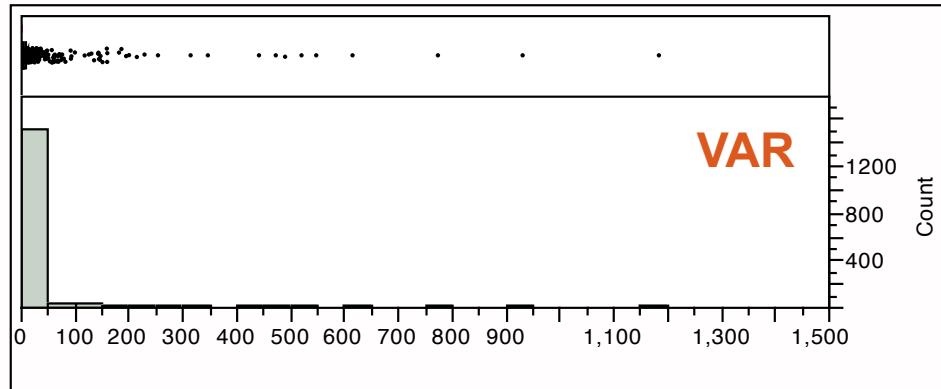


# Typical particle detection - ELI



55 “particles” (inclusions) detected

# Volume Histograms for VAR, High Purity VAR



## Quantiles

100.0%	maximum	1185.67
99.5%		477.427
97.5%		77.238
90.0%		12.326
75.0%	quartile	3.697
50.0%	median	0.730
25.0%	quartile	0.130
10.0%		0.025
2.5%		0.009
0.5%		0.009
0.0%	minimum	0.009

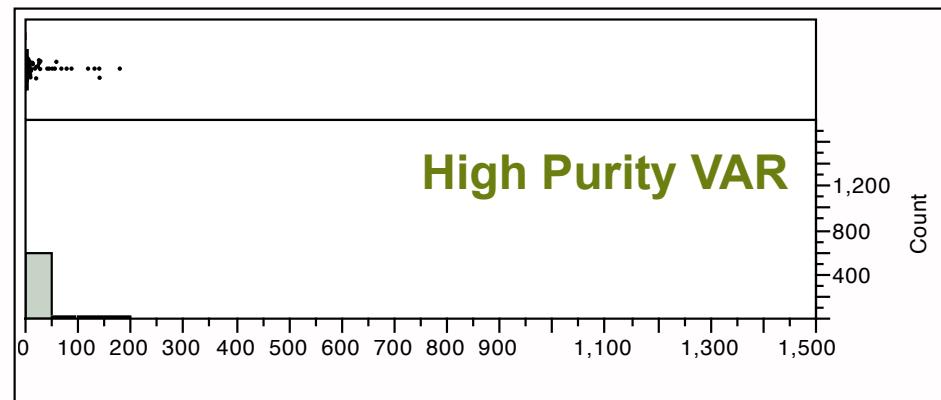
## Summary Statistics

Mean	10.793
Std Dev	58.644
Std Err Mean	1.485
Upper 95% Mean	13.706
Lower 95% Mean	7.881
N	1560.000

**N=1,560**

**$\mu=10.8$**

**$\sigma=59$**



## Quantiles

100.0%	maximum	181.000
99.5%		142.010
97.5%		29.986
90.0%		4.772
75.0%	quartile	1.342
50.0%	median	0.200
25.0%	quartile	0.046
10.0%		0.009
2.5%		0.009
0.5%		0.009
0.0%	minimum	0.009

## Summary Statistics

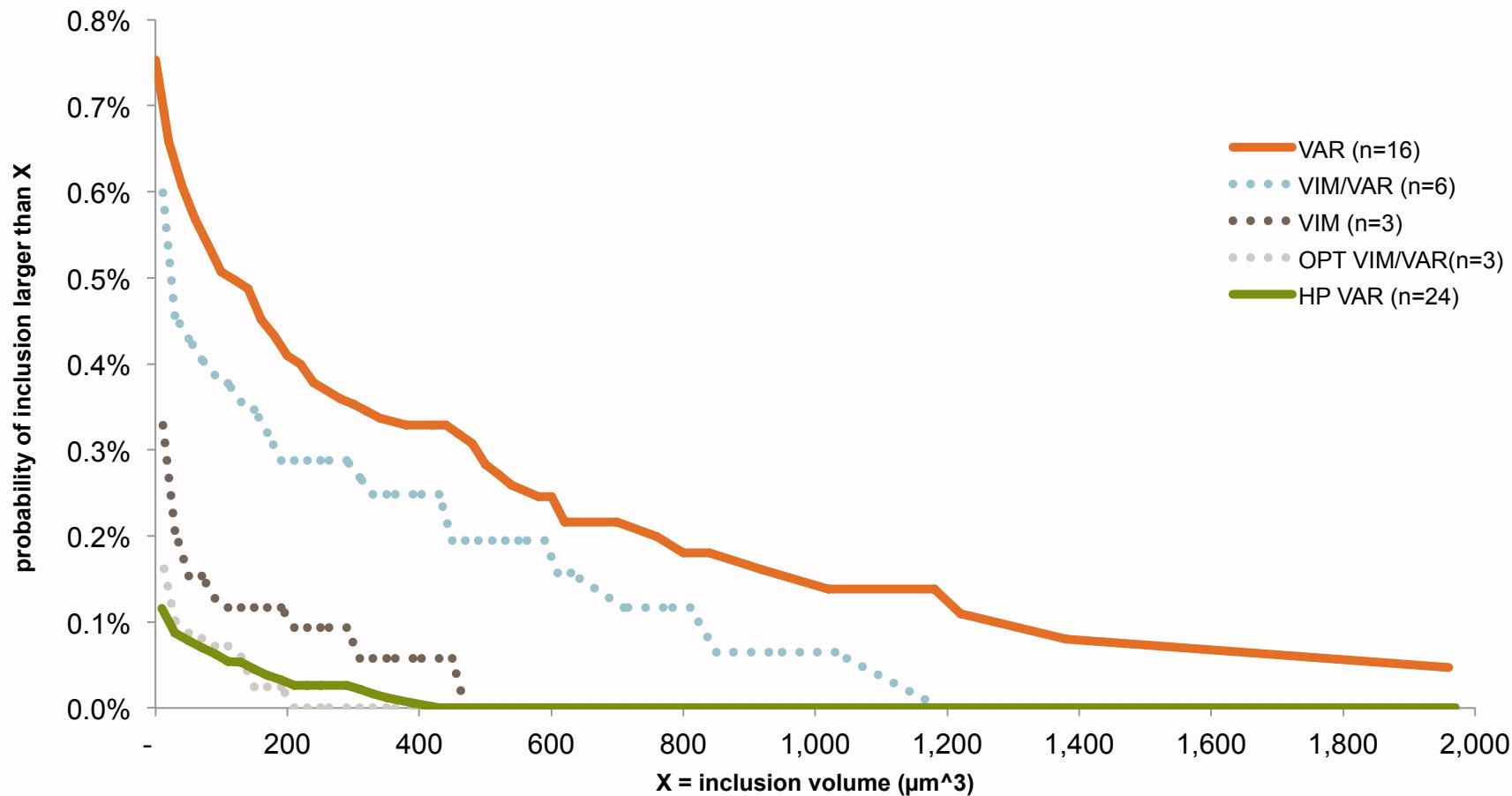
Mean	3.562
Std Dev	15.616
Std Err Mean	0.650
Upper 95% Mean	4.839
Lower 95% Mean	2.286
N	577.000

**N=577**

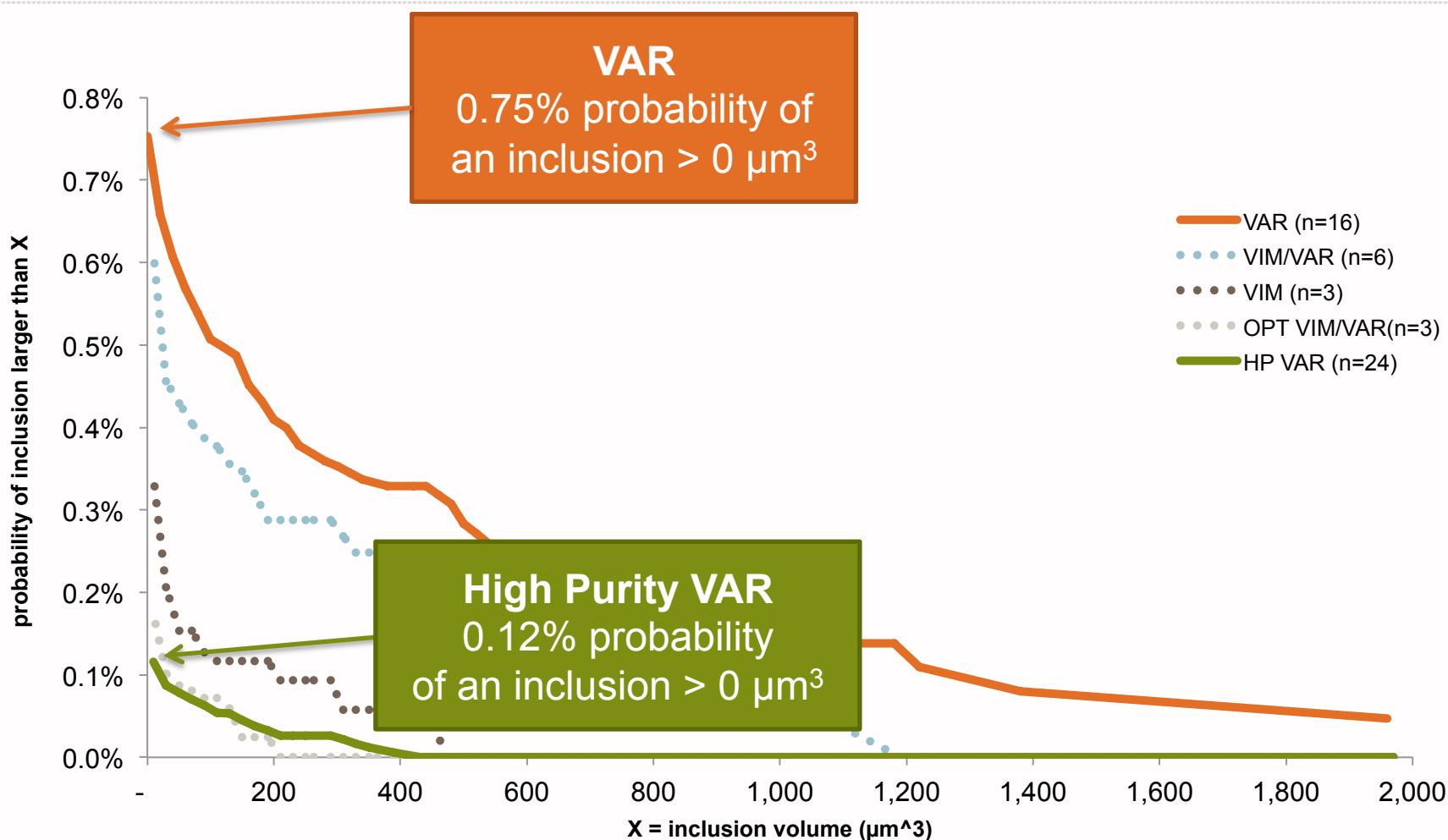
**$\mu=3.6$**

**$\sigma=16$**

# Cumulative probability for inclusions by volume



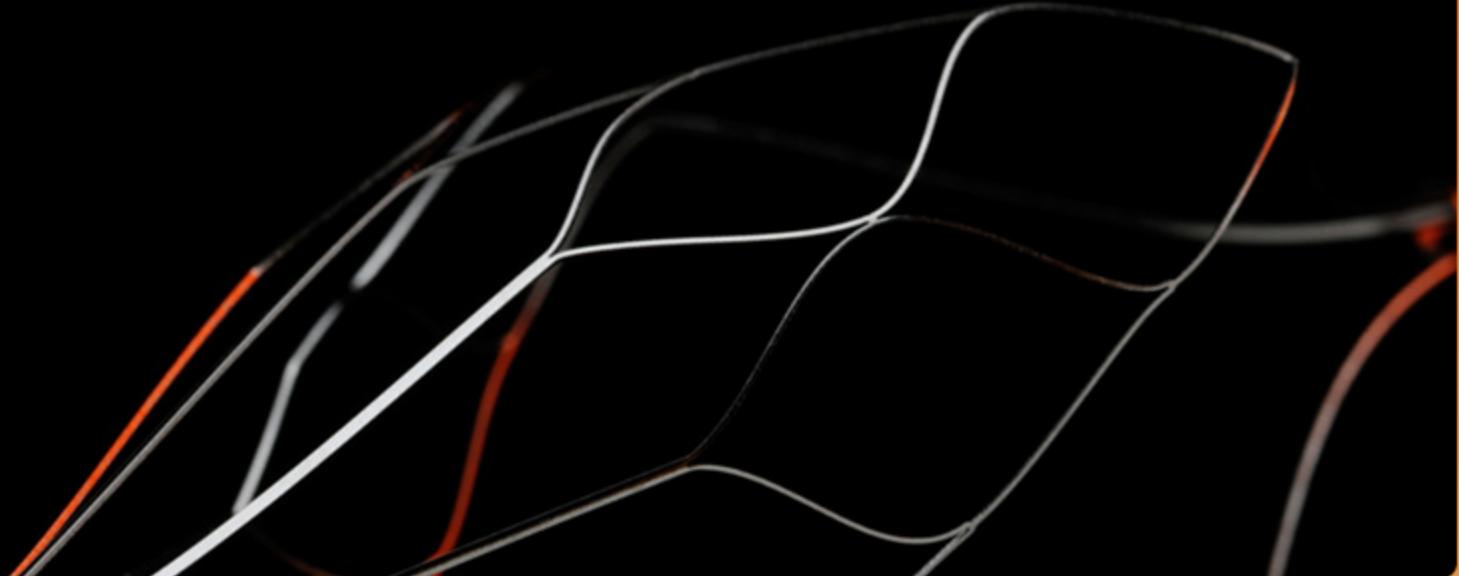
# Cumulative probability for inclusions by volume



We are Nitinol.<sup>TM</sup>

---

**Hazard Probability**  
**Volume fraction of inclusions**  
**Critical strain region probability**  
**Putting everything together**  
**Online resources**



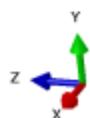
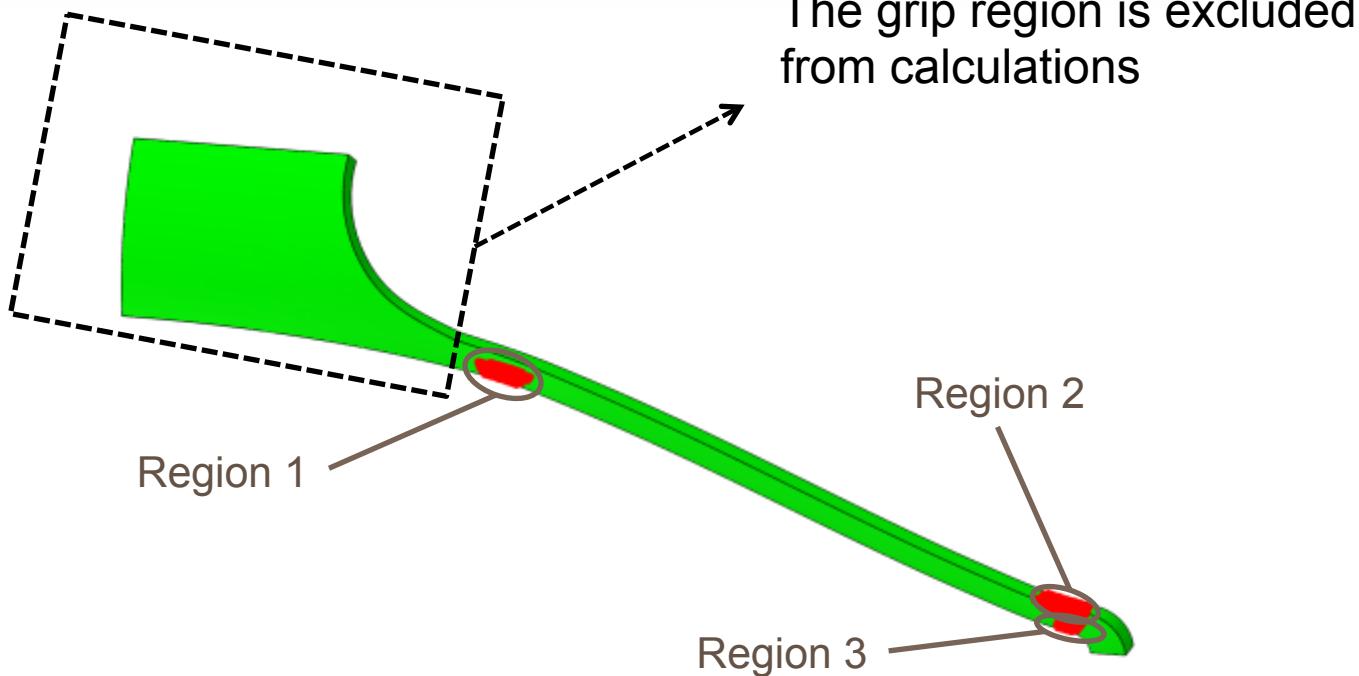
# Critical strain region volume



- An algorithm was developed
  - to identify contiguous regions of elements with a strain amplitude exceeding a defined threshold...
  - and measure the volume of each of these regions
- The algorithm has been implemented as an Abaqus Python script
- The critical strain regions are illustrated on the following slides

# Critical strain region volumes:

Case 1, strain threshold = 0.4%



ODB: SE508-fatigue-m3\_20-a1\_10.odb Abaqus/Standard 6.12-1 Wed May 08 01:13:18 Pacific Daylight Time 2013

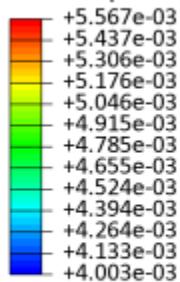
Step: Session Step, Step for Viewer non-persistent fields  
Session Frame

Deformed Var: not set Deformation Scale Factor: not set

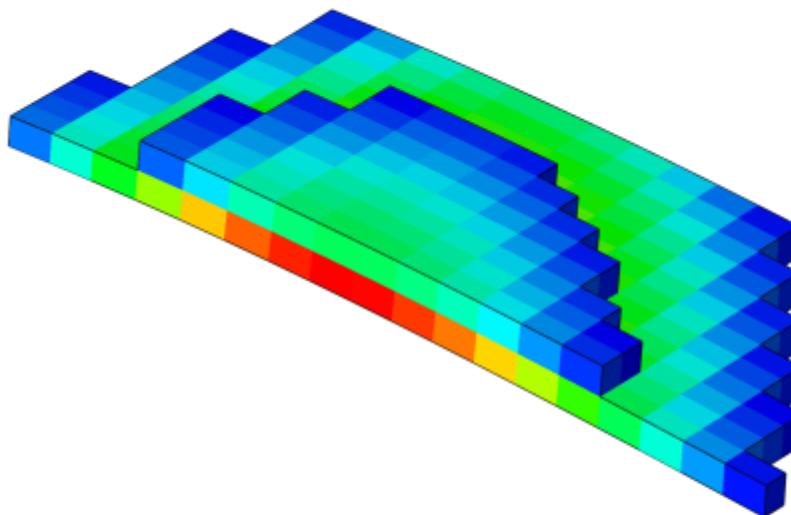
# Critical strain region volume 1: Case 1, strain threshold = 0.4%



Strain Amplitude, Max. Principal



For region 1,  $V_{\varepsilon} = 5,671,500 \mu\text{m}^3$



Batch 1



ODB: SE508-fatigue-m3\_20-a1\_10.odb Abaqus/Standard 6.12-1 Wed May 08 01:13:18 Pacific Daylight Time 2013

Step: Session Step, Step for Viewer non-persistent fields

Session Frame

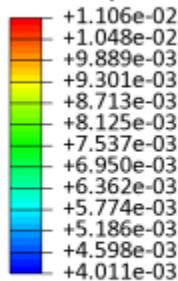
Primary Var: Strain Amplitude, Max. Principal

Deformed Var: not set Deformation Scale Factor: not set

# Critical strain region volume 2:

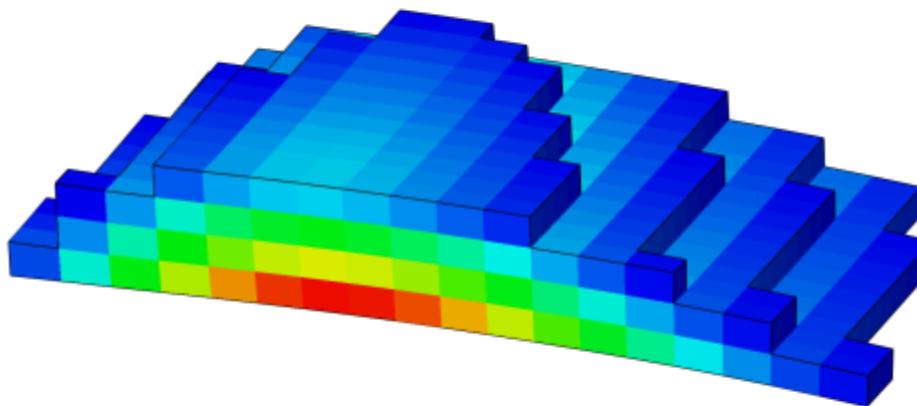
## Case 1, strain threshold = 0.4%

Strain Amplitude, Max. Principal



For region 2,  $V_\varepsilon = 11,702,000 \mu\text{m}^3$

Batch 2



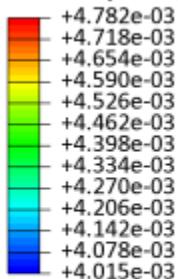
ODB: SE508-fatigue-m3\_20-a1\_10.odb Abaqus/Standard 6.12-1 Wed May 08 01:13:18 Pacific Daylight Time 2013



Step: Session Step, Step for Viewer non-persistent fields  
Session Frame  
Primary Var: Strain Amplitude, Max. Principal  
Deformed Var: not set Deformation Scale Factor: not set

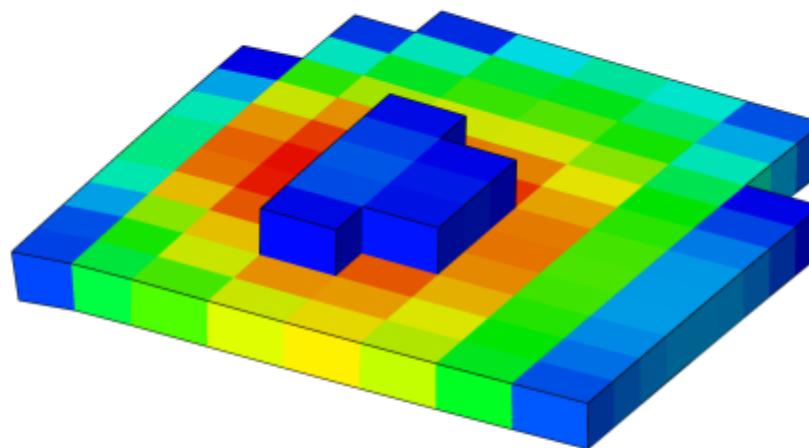
# Critical strain region volume 3: Case 1, strain threshold = 0.4%

Strain Amplitude, Max. Principal



For region 3,  $V_{\varepsilon} = 1,791,300 \mu\text{m}^3$

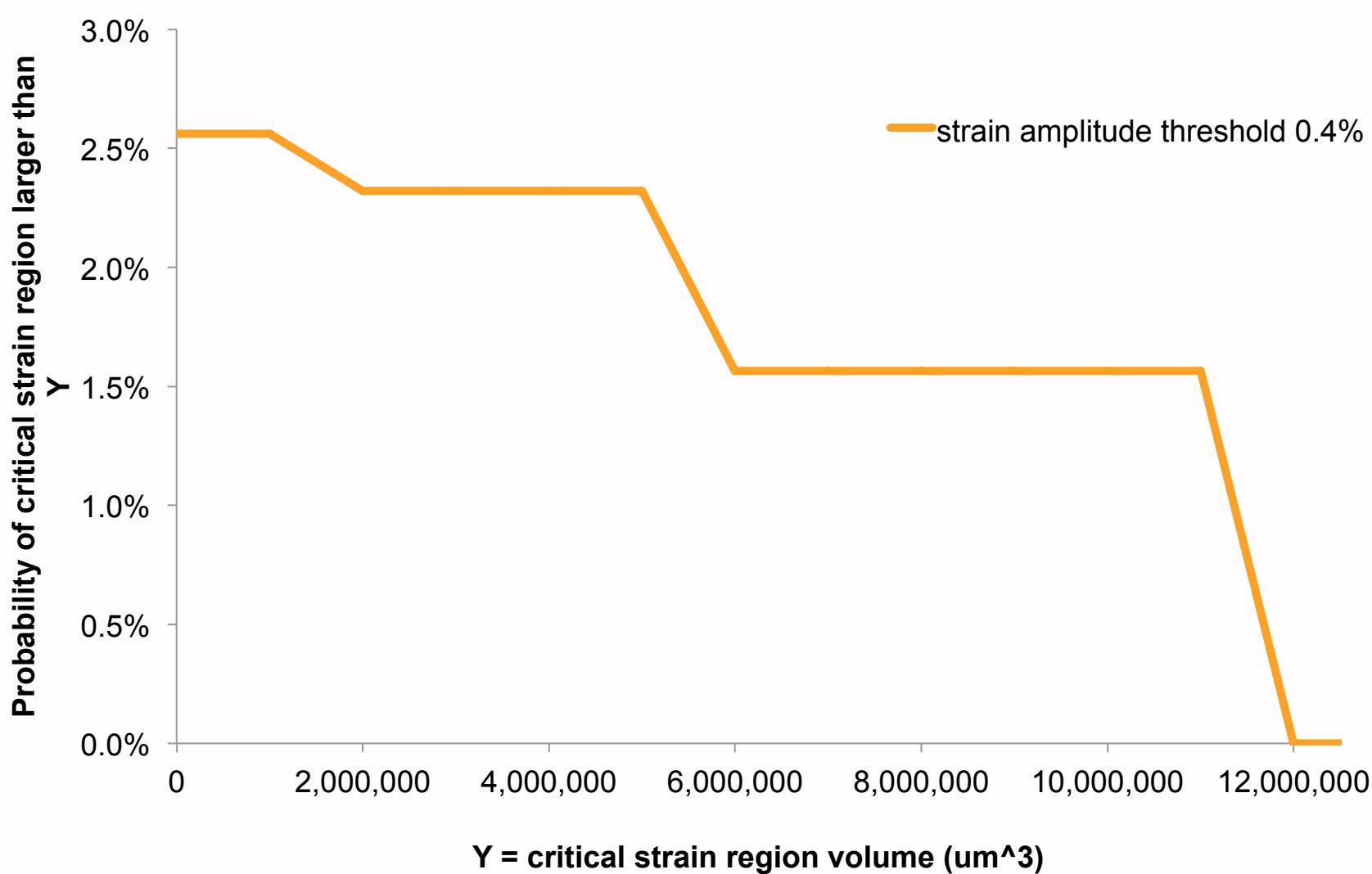
Batch 3



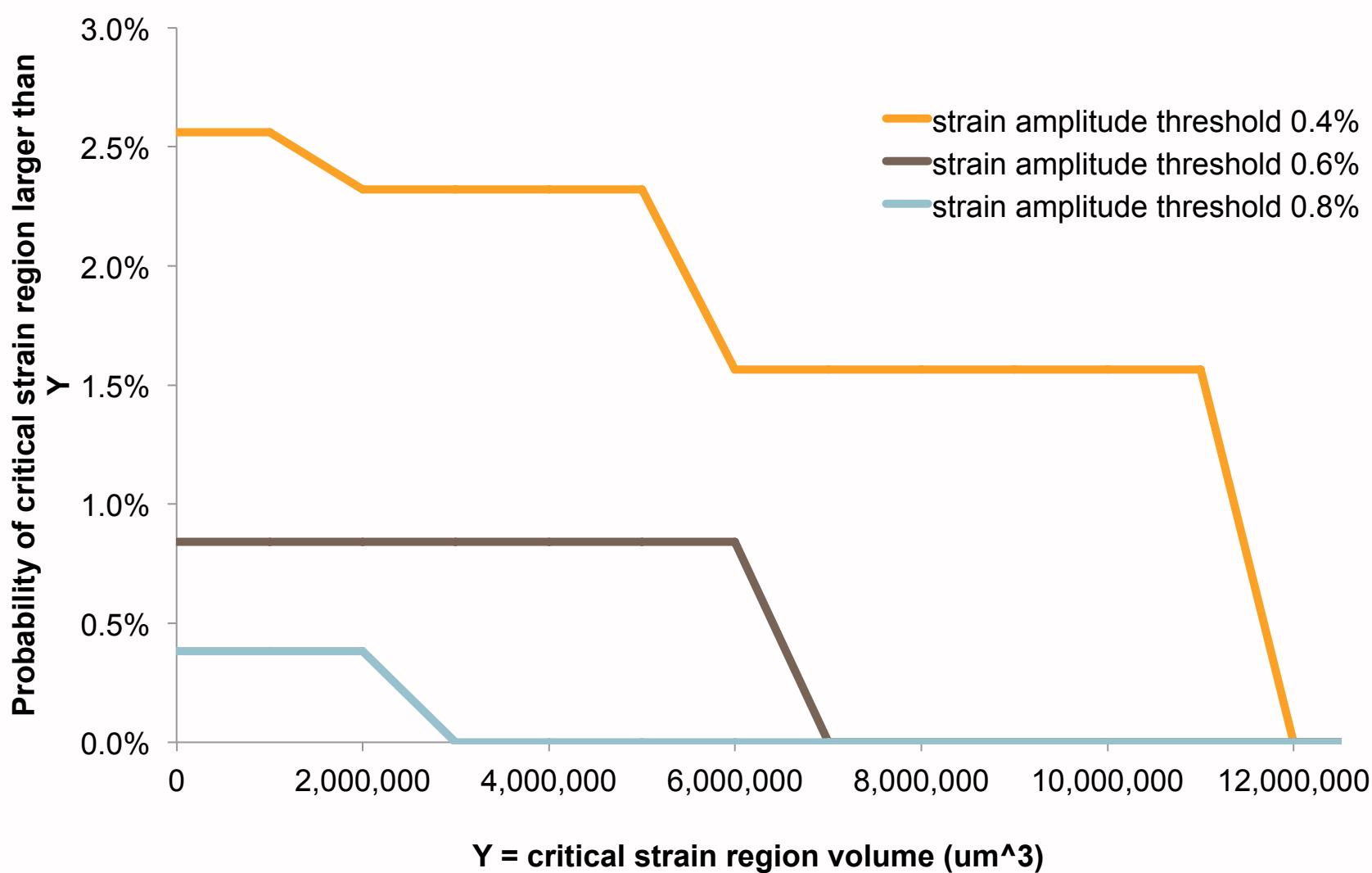
ODB: SE508-fatigue-m3\_20-a1\_10.odb Abaqus/Standard 6.12-1 Wed May 08 01:13:18 Pacific Daylight Time 2013

Step: Session Step, Step for Viewer non-persistent fields  
Session Frame  
Primary Var: Strain Amplitude, Max. Principal  
Deformed Var: not set Deformation Scale Factor: not set

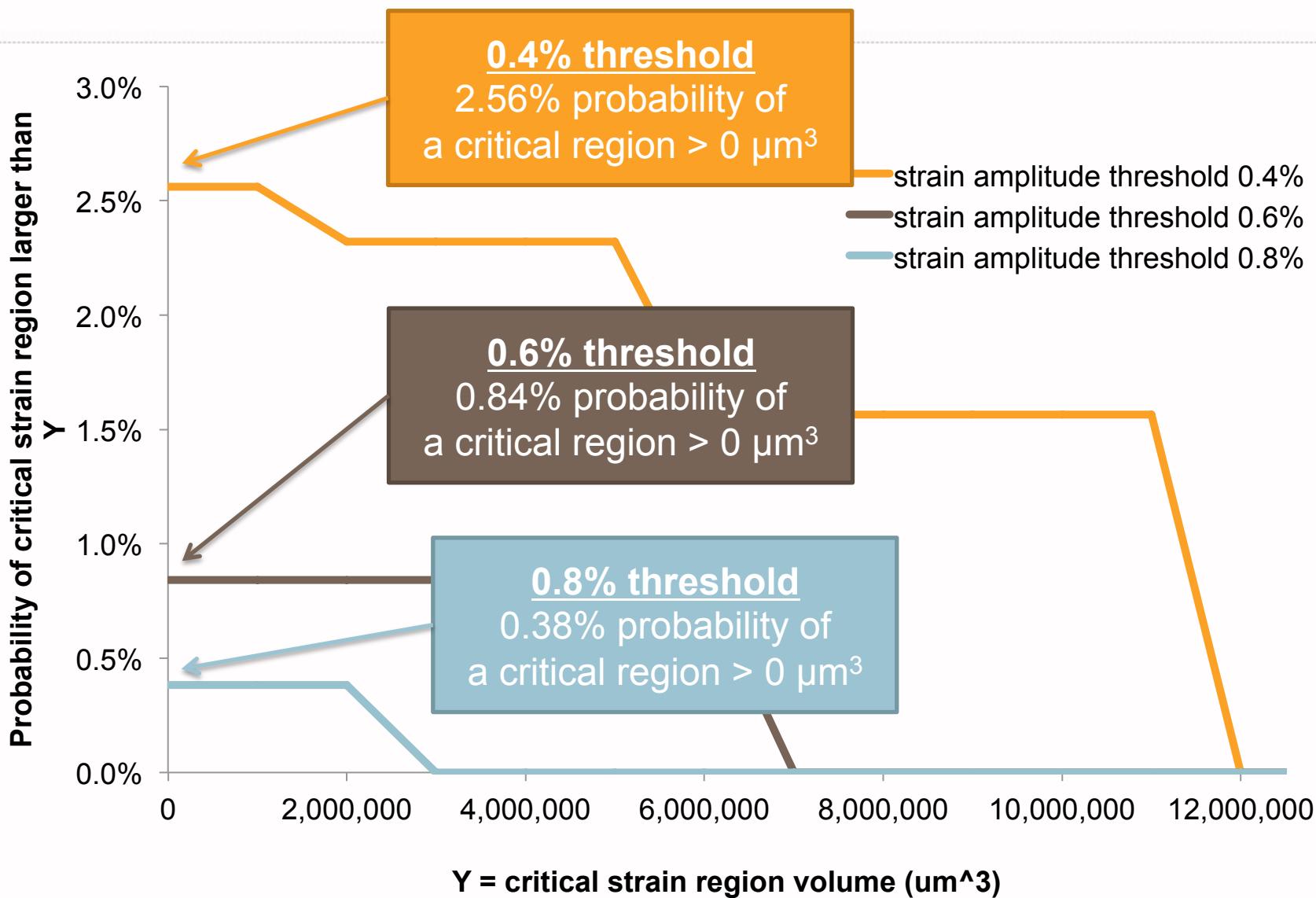
# Probability vs. critical strain region size



# Probability vs. critical strain region size



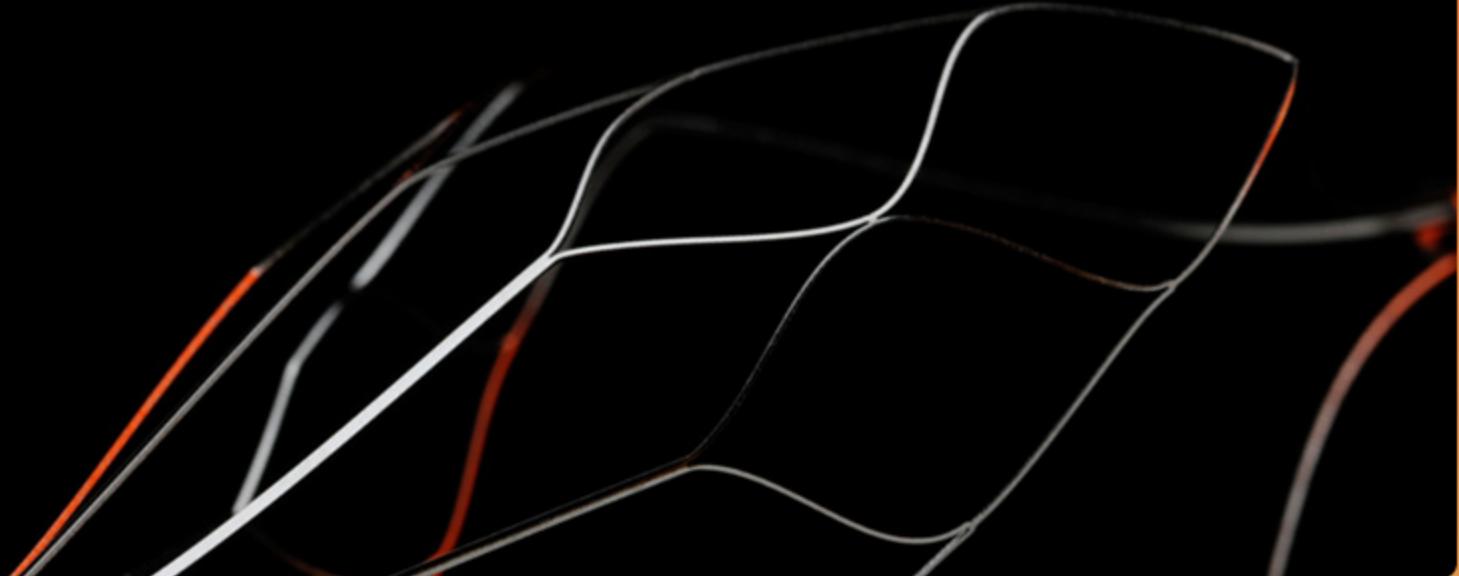
# Probability vs. critical strain region size



We are Nitinol.<sup>TM</sup>

---

**Hazard Probability**  
**Volume fraction of inclusions**  
**Critical strain region probability**  
**Putting everything together**  
**Online resources**



# Hazard Probabilities: VAR Material



VAR Material	unit	Threshold 0.40%
Probability of an inclusion larger than zero	[1] %	0.75%
Probability of a critical strain region larger than zero	[2] %	2.56%

# Hazard Probabilities: VAR Material



VAR Material	unit	Threshold 0.40%
Probability of an inclusion larger than zero	[1] %	0.75%
Probability of a critical strain region larger than zero	[2] %	2.56%
Hazard probability for model ([1] * [2])	[3] %	0.02%
Hazard probability for the model, PPM ([3]*10^6)	[4] PPM	192

# Hazard Probabilities: VAR Material



VAR Material	unit	Threshold 0.40%
Probability of an inclusion larger than zero	[1] %	0.75%
Probability of a critical strain region larger than zero	[2] %	2.56%
Hazard probability for model ([1] * [2])	[3] %	0.02%
Hazard probability for the model, PPM ([3]*10^6)	[4] PPM	192
Number of repeating features in device	[5] N	180
Hazard probability for the device	[6] %	3.46%
Hazard probability for the device, PPM	[7] PPM	34,560

# Hazard Probabilities: VAR Material



VAR Material	unit	Threshold	Threshold	Threshold
		0.40%	0.60%	0.80%
Probability of an inclusion larger than zero	[1] %	0.75%	0.75%	0.75%
Probability of a critical strain region larger than zero	[2] %	2.56%	0.84%	0.38%
Hazard probability for model ([1] * [2])	[3] %	0.02%	0.01%	0.00%
Hazard probability for the model, PPM ([3]*10^6)	[4] PPM	192	63	29
Number of repeating features in device	[5] N	180	180	180
Hazard probability for the device	[6] %	3.46%	1.13%	0.51%
Hazard probability for the device, PPM	[7] PPM	34,560	11,340	5,130

# Hazard Probabilities: High Purity VAR Material



High Purity VAR Material	unit	Threshold			
		0.40%	0.60%	0.80%	
Probability of an inclusion larger than zero	[1]	%	0.12%	0.12%	0.12%
Probability of a critical strain region larger than zero	[2]	%	2.56%	0.84%	0.38%
Hazard probability for model (inclusion >0 coincident with strain region >0) ([1] * [2])	[3]	%	0.00%	0.00%	0.00%
Hazard probability for the model, PPM ([3]*10^6)	[4]	PPM	31	10	5
Number of repeating features in device	[5]	N	180	180	180
Hazard probability for the device	[6]	%	0.55%	0.18%	0.08%
Hazard probability for the device, PPM	[7]	PPM	5,530	1,814	821

# Future Improvements

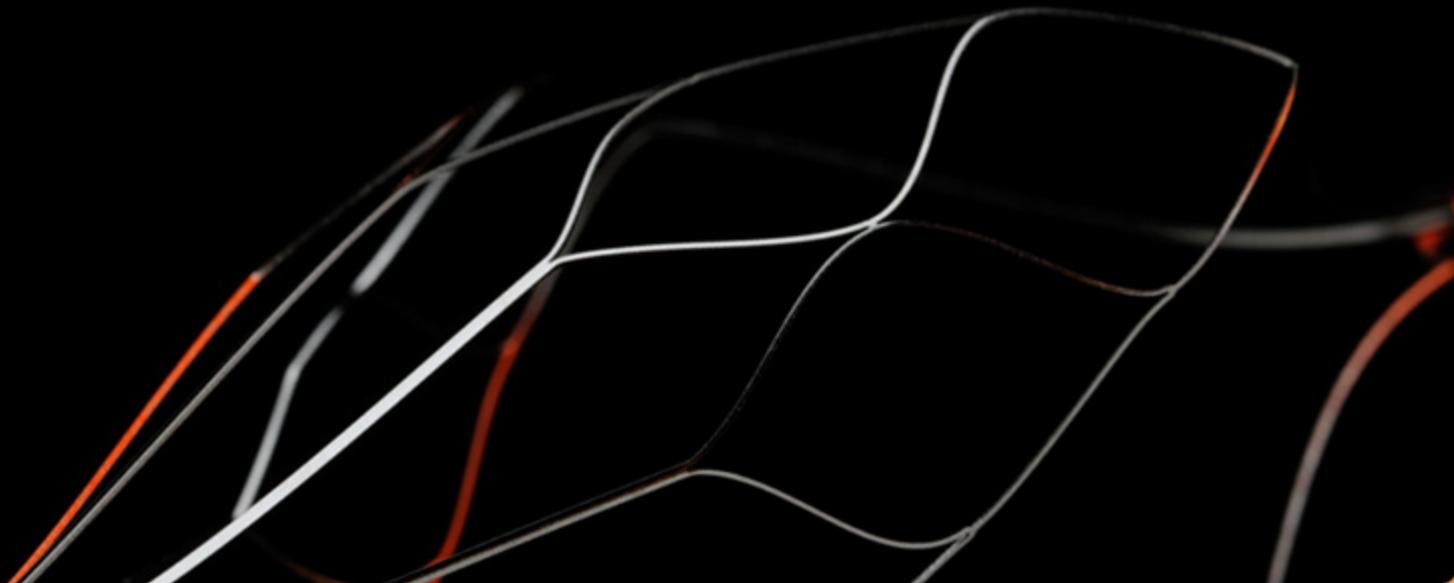


- Extend script to consider strain amplitude threshold **as a function of mean strain**
- Improve **speed** of script, and automate analysis
- **Extend** hazard analysis to incorporate probability as a function of critical strain region size and inclusion size
- **Compare** these predictions with physical testing results

We are Nitinol.<sup>TM</sup>

---

**Hazard Probability**  
**Volume fraction of inclusions**  
**Critical strain region probability**  
**Putting everything together**  
**Online resources**



# More details available online



- Python code, this presentation, and related resources are shared publically on GitHub
- <https://github.com/cbonsig/strain-amplitude-volume-fraction>

A screenshot of a GitHub repository page for 'cbonsig/strain-amplitude-volume-fraction'. The page shows a commit history with 5 commits, 1 branch (master), 0 releases, and 1 contributor. The commits include adding sample data, an example file, a LICENSE file, a README, results from ImageJ, and SMST data. The latest commit was made 9 minutes ago.

The README.md file contains the following content:

## strain-amplitude-volume-fraction

*Craig Bonsignore*  
*Nitinol Devives & Components, Inc*

Resources related to strain amplitude volume fraction method for evaluating nitinol fatigue durability.

1. **SMST\_2014\_Volume\_Fraction.pdf** Presentation from SMST-2014 explaining the method, using the resources available here.
2. **Step\_By\_Step\_Volume\_Fraction.pdf** Detailed explanation of the process used to generate volume fraction data from a set of metallographic cross section images.
3. **Sample\_Image.jpg** A sample metallographic cross section. The scale of this image is 500x. 250 pixels = 500 microns.
4. **Results\_from\_ImageJ\_Particle\_Analysis.txt** Results exported from ImageJ, after importing Sample\_Image.jpg, applying a default threshold setting to isolate inclusions, and applying "analyze particles" to quantify the number of inclusions. ImageJ saves this data with a default extension of .XLS, but the format is actually just a tab delimited text file.
5. **2014\_Sample\_Data.jmp** JMP data table containing the sample data from above, plus some additional

# Comments and feedback: use GitHub “Issue”



The screenshot shows a GitHub repository page for [cbonsig / strain-amplitude-volume-fraction](#). The top navigation bar includes links for This repository, Search or type a command, Explore, Gist, Blog, Help, and the user's profile cbonsig. The main content area displays the Issues tab, which is currently selected. It shows a summary of issues: 0 Open and 0 Closed. A green button labeled "New Issue" is visible. Below this, there are sections for "Everyone's Issues" (0), "Assigned to you" (0), "Created by you" (0), and "Mentioning you" (0). A message indicates "No issues to show. [Create a new issue.](#)". On the right side, there is a sidebar with various icons for repository management, such as Unwatch, Star, Fork, and a gear for settings. At the bottom left, it says "No milestone selected" with a dropdown menu icon. A note at the bottom right mentions "Keyboard shortcuts available" with a keyboard icon.

