Volume weighted probabilistic methods for nitinol lifetime prediction

Craig Bonsignore
Karthikeyan Senthilnathan
Ali Shamimi

Confluent Medical Technologies | Fremont California
> 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
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.
Introduction

> Volumetric FEA methods
Sub-µm x-ray computed tomography
Monte-Carlo risk assessment
Resources
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
Typical point cloud

strain amplitude vs. mean strain
SWT point cloud

Smith-Watson-Topper

(maximum stress) \times (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)
Introduction
Volumetric FEA methods

> Sub-µm x-ray computed tomography
Monte-Carlo risk assessment

Resources
Standard VAR (SE508)

High Purity VAR (SE508-ELI)
Approximation of inclusion volumetric probability

X = inclusion volume (µm^3)
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.

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 (0.50\(\mu\)m\(^3\) voxel)
Image segmentation by machine learning

Fiji [1] is just ImageJ [2]

Trainable Weka Segmentation [3]

Voxel Classification

Train classifier to identify probability of each voxel as:

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

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

SE508-ELI inclusion segmentation colored by volume

Volumetric distribution of inclusions

*note log-log scales*
√Area fit to Extreme Value Distribution per Urbano

Inclusion density, Gumbel location and scaling parameters

### SE508 Inclusion Distribution Parameters

<table>
<thead>
<tr>
<th>plane</th>
<th>cutoff (µm^3)</th>
<th>inclusion density (1/mm^3)</th>
<th>Gumbel µ (µm)</th>
<th>Gumbel σ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>xy (transverse)</td>
<td>8</td>
<td>7,475</td>
<td>2.84</td>
<td>1.36</td>
</tr>
<tr>
<td>yz (longitudinal)</td>
<td>8</td>
<td>7,475</td>
<td>3.59</td>
<td>1.96</td>
</tr>
<tr>
<td>xz (longitudinal)</td>
<td>8</td>
<td>7,475</td>
<td>3.55</td>
<td>1.86</td>
</tr>
</tbody>
</table>

### ELI Inclusion Distribution Parameters

<table>
<thead>
<tr>
<th>plane</th>
<th>cutoff (µm^3)</th>
<th>inclusion density (1/mm^3)</th>
<th>Gumbel µ (µm)</th>
<th>Gumbel σ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>xy (transverse)</td>
<td>8</td>
<td>340</td>
<td>1.77</td>
<td>0.40</td>
</tr>
<tr>
<td>yz (longitudinal)</td>
<td>8</td>
<td>340</td>
<td>2.06</td>
<td>0.40</td>
</tr>
<tr>
<td>xz (longitudinal)</td>
<td>8</td>
<td>340</td>
<td>2.27</td>
<td>0.45</td>
</tr>
</tbody>
</table>

Fingerprint by Mitchell Eva, from the Noun Project
Introduction
Volumetric FEA methods
Sub-µm x-ray computed tomography

> Monte-Carlo risk assessment

Resources
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 \((0,1)\).
“Fortune cloud”: $\Delta \sigma$ vs. $\sqrt{\text{area}}$ (single run SE508, ELI)
Estimating stress intensity factor $K$ by Murakami’s $\sqrt{\text{area}}$

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

Figure 7 shows the relationship between the maximum stress intensity factor $K_{\text{max}}$ and $\sqrt{\text{area}}$ for surface cracks (elastic analysis) (24)(35). (See also (20)(66).)
K and ΔK in each plane, at each integration point

\[ K_x = 0.65 \cdot \sqrt{\sigma_x \cdot \sqrt{\text{area}_{yz}}} \]
\[ K_y = 0.65 \cdot \sqrt{\sigma_y \cdot \sqrt{\text{area}_{xz}}} \]
\[ K_z = 0.65 \cdot \sqrt{\sigma_z \cdot \sqrt{\text{area}_{xy}}} \]
\[ \Delta K_x = 0.65 \cdot \sqrt{\Delta \sigma_x \cdot \sqrt{\text{area}_{yz}}} \]
\[ \Delta K_y = 0.65 \cdot \sqrt{\Delta \sigma_y \cdot \sqrt{\text{area}_{xz}}} \]
\[ \Delta K_z = 0.65 \cdot \sqrt{\Delta \sigma_z \cdot \sqrt{\text{area}_{xy}}} \]
“K point cloud” (single run SE508, ELI)
Next: repeat many times, record $\Delta K_{\text{max}}$ and $K$
Maximum stress intensity factors for 500+500 runs

stress intensity factor: maximum $\Delta K$ and corresponding $K$

for 500 monte carlo runs with each material

<table>
<thead>
<tr>
<th>r</th>
<th>theta</th>
<th>Z</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>$\Delta K_{\text{max}}$</th>
<th>$\Delta K_{\text{max}}$</th>
<th>$\Delta K_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

material
- eii
- es508
“Fortune plot” for 500+500 runs

max. $\Delta K_z$ by cyclic stress and defect (inclusion) size

unluckiest combination at upper right: largest defect at highest cyclic stress
$\Delta K_{\text{max}}$ for 500+500 runs

maximum delta stress intensity factor
for 500 monte carlo runs with each material

<table>
<thead>
<tr>
<th>$r$</th>
<th>theta</th>
<th>$Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image-url" alt="Graph" /></td>
<td><img src="image-url" alt="Graph" /></td>
<td><img src="image-url" alt="Graph" /></td>
</tr>
</tbody>
</table>
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
• $K$, $\Delta K$ 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