ART-001
Characterization of Emerging Technologies in Military Systems

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Emerging Technologies

• Leadfree Electronics Solder Interconnects under High Strain Rate Operation and Sustained High and Low Temperature.
  —Strain Rate of 1-100 sec$^{-1}$
  —Sustained Low-Temperature (-65°C)
  —Sustained High-Temperature (+200°C)
  —Prolonged Storage up to 1-year

• Prognostics Health Management Methods for Early Identification of Impending Failure.
Motivation

- In aerospace and defense applications, the electronic components may get exposed to extreme temperatures ranging from -65°C to 200°C in addition to sustained periods of aging in non-climate controlled enclosures.
- Electronics may be subjected to high strain-rates in the neighborhood of 1-100 sec\(^{-1}\) during storage, transport and deployment of systems.
- Analysis tools lag the introduction of new leadfree alloys which percolating into the commercial supply-chain and impact defense electronics which increasingly relies on COTS parts.
Sample Preparation Procedure

Specimen Preparation Setup

Samples Formed in Glass Tubes

Specimen under X-ray inspection
# Test Matrix for High Strain-Rate SAC305, SAC-Q and SAC-R

<table>
<thead>
<tr>
<th>T(°C)</th>
<th>Strain Rate (sec⁻¹)</th>
<th>Aging Duration @100°C (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>-65,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>-55,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>-40,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>0,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>25,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>50,</td>
<td>X</td>
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</tr>
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<td>125,</td>
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</tr>
<tr>
<td>150,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>175,</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>200</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>
SAC305 Stress-Strain curves – 30 Days @100C
SAC305 Stress-Strain curves – 60 Days @100°C
SAC305 Stress-Strain curves – 120 Days @100°C
SAC-Q Stress vs Strain Curves - 60 days @100C
SAC-Q Stress vs Strain Curves - 90 days @100C
Anand Model

Flow Equation:

\[ \varepsilon_p = A \exp \left( -\frac{Q}{RT} \right) \left[ \sinh \left( \frac{\sigma}{S} \right) \right]^{\frac{1}{m}} \]

\[ c = \left( \varepsilon_p, T \right) = \left( \frac{1}{\xi} \right) \sinh^{-1} \left\{ \left[ \frac{\varepsilon_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^m \right\} \]

Stress Equation:

\[ \sigma = \left( \frac{s}{\xi} \right) \sinh^{-1} \left\{ \left[ \frac{\varepsilon_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^m \right\} \]

Anand Model Constants:

- A: Pre-exponential factor
- Q: Activation energy
- R: Universal gas constant
- m: Strain rate sensitivity of stress
- n: Exponent of deformation resistance
- \( \xi \): Stress Multiplier
- \( s \): Coefficient of deformation resistance saturation value
- \( h_0 \): Hardening/Softening constant
- a: Strain rate sensitivity for hardening/softening
- \( s_0 \): Initial value of deformation resistance

\[ c = \frac{\sigma}{s} \]
Anand Model

Evolution Equation:
\[ \dot{s} = \begin{cases} h_0 (|B|)^a \frac{B}{|B|} & (a > 1) \end{cases} \]

Substitute
\[ s = s^* - \left( (s^* - s_0)^{(1-a)} + (a-1)[h_0 (s^*)^{-a} \varepsilon_p] \right)^{1/(1-a)} \]

Integrate
\[ s^* = \dot{s} \left[ \frac{\dot{\varepsilon}_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^n \]

Substitute
\[ s = \dot{s} \left[ \frac{\dot{\varepsilon}_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^n - \left( \dot{s} \left[ \frac{\dot{\varepsilon}_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^n - s_0 \right)^{(1-a)} + (a-1) \left[ h_0 \left( \dot{s} \left[ \frac{\dot{\varepsilon}_p}{A} \exp \left( \frac{Q}{RT} \right) \right]^n \right)^{-a} \right]^n \]

Anand Model Constants:
- A: Pre-exponential factor,
- Q: Activation energy,
- R: Universal gas constant,
- m: Strain rate sensitivity of stress,
- n: Exponent of deformation resistance,
- ξ: Stress Multiplier,
- \( \dot{s} \): Coefficient of deformation resistance saturation value,
- h_0: Hardening/Softening constant,
- a: Strain rate sensitivity for hardening/softening,
- s_0: Initial value of deformation resistance
### SAC305 Anand Constants

<table>
<thead>
<tr>
<th>Constant No.</th>
<th>Anand Constants</th>
<th>Unit</th>
<th>30 Days Aging (At 100°C)</th>
<th>60 Days Aging (At 100°C)</th>
<th>90 Days Aging (At 100°C)</th>
<th>120 Days Aging (At 100°C)</th>
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<tr>
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<td>sec⁻¹</td>
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<td>1459.75</td>
<td>1697</td>
<td>1800</td>
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<td>2</td>
<td>Q/R</td>
<td>1/K</td>
<td>4500</td>
<td>4500</td>
<td>4500</td>
<td>4500</td>
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<tr>
<td>3</td>
<td>m</td>
<td>-</td>
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<td>0.995</td>
<td>0.88</td>
<td>1</td>
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<tr>
<td>4</td>
<td>n</td>
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<td>0.01130</td>
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<tr>
<td>5</td>
<td>ξ</td>
<td>-</td>
<td>6.7</td>
<td>6.7</td>
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<tr>
<td>6</td>
<td>δ</td>
<td>MPa</td>
<td>52.97</td>
<td>54.95</td>
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<td>61.819</td>
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<td>7</td>
<td>h₀</td>
<td>MPa</td>
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<td>57074.03</td>
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<td>73140</td>
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<td>8</td>
<td>a</td>
<td>-</td>
<td>1.0151</td>
<td>1.0082</td>
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<td>s₀</td>
<td>MPa</td>
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# SAC-Q Anand Constants

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<th>Constant No.</th>
<th>Anand Constants</th>
<th>Unit</th>
<th>30 Days Aging (At 100°C)</th>
<th>60 Days Aging (At 100°C)</th>
<th>90 Days Aging (At 100°C)</th>
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<tr>
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<td>$Q/R$</td>
<td>sec^{-1}</td>
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<td>8444</td>
<td>8444</td>
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<tr>
<td>2</td>
<td>$\xi$</td>
<td>1/K</td>
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<td>4.28</td>
<td>4.28</td>
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<td>3</td>
<td>$A$</td>
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<td>0.361</td>
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<td>0.0009</td>
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<td>6</td>
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<td>7</td>
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<td>8</td>
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<td>0.783</td>
<td>0.697</td>
<td>0.73</td>
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<td>9</td>
<td>$\hat{s}$</td>
<td>MPa</td>
<td>47.54</td>
<td>43.95</td>
<td>40.42</td>
</tr>
</tbody>
</table>

$A$: Pre-exponential factor,  
$Q$: Activation energy,  
$R$: Universal gas constant,  
$m$: Strain rate sensitivity of stress,  
$n$: Exponent of Deformation resistance  
$\xi$: Stress Multiplier,  
$\hat{s}$: Coefficient of deformation resistance saturation value,  
$h_0$: Hardening/Softening constant,  
$a$: Strain rate sensitivity for hardening/softening,  
$s_0$: Initial value of deformation resistance
Model Verification - Aging @ 100 °C for 30 days
Actual Mass vs Global FE Model

Cut-Section View of CABGA288.

Global Model of Test Vehicle

Weight comparison of Test Vehicle

Material Properties

<table>
<thead>
<tr>
<th>Package Assembly</th>
<th>E (MPa)</th>
<th>Poisson's Ratio</th>
<th>Density (tonne/mm^3)</th>
<th>Element Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solder Joints</td>
<td>42000</td>
<td>0.34</td>
<td>8.40E-09</td>
<td>VISC0107</td>
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<td>EMC</td>
<td>23500</td>
<td>0.25</td>
<td>1.65E-09</td>
<td>SOLID 45</td>
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<td>Silicon Die</td>
<td>162000</td>
<td>0.28</td>
<td>2.33E-09</td>
<td>SOLID 45</td>
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<td>Die Attach</td>
<td>2760</td>
<td>0.35</td>
<td>7.80E-09</td>
<td>SOLID 45</td>
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<tr>
<td>BT Substrate</td>
<td>17400</td>
<td>0.28</td>
<td>1.80E-09</td>
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<td>Copper Pad</td>
<td>129000</td>
<td>0.34</td>
<td>8.82E-09</td>
<td>SOLID 45</td>
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<tr>
<td>PCB</td>
<td>23.8</td>
<td>0.39</td>
<td>1.80E-09</td>
<td>SOLID 45</td>
</tr>
</tbody>
</table>
Resistance Measurement Set-up

SAC105 Package U2
55 C; 5 G

Typical Resistance Data
Life-Resistance Data: SAC105 @ 5g
Life-Resistance Data: SAC305 @ 5g

25°C

- SAC305 Package U1: 25 C; 5 G
- SAC305 Package U2: 25 C; 5 G
- SAC305 Package U6: 25 C; 5 G

55°C

- SAC305 Package U1: 55 C; 5 G
- SAC305 Package U2: 55 C; 5 G
- SAC305 Package U6: 55 C; 5 G

155°C

- SAC305 Package U1: 155 C; 5 G
- SAC305 Package U2: 155 C; 5 G
- SAC305 Package U6: 155 C; 5 G
FE-Global Model

Mass and Rigid Element at Screw holes of PCB

Global model of Test Vehicle

Cut-Section View of CABGA288

Multiply by mass

Desired Input Excitation

Input Tabular Force Data

Output Acceleration from the Mass node at 14g and 360Hz
Hysteresis Loop of Critical Solder Joint
Prognostics for Risk Mitigation

- Sensitivity of sensor locations in predicting failure during Vibration
- Study the changes in the two selected feature vectors at different locations of the PCB during vibration
- Investigating the importance of different strain components in predicting failure
- Comparison of the effect of prognostication based on sensor location for two board assemblies
Prognostics State-of-Art

<table>
<thead>
<tr>
<th>Author</th>
<th>Reported Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jie Gu 2008</td>
<td>Prognostics and Health management using Physics of Failure approaches</td>
</tr>
<tr>
<td>Schwabacher 2009, Vicare 2006</td>
<td><strong>Data driven approaches</strong> using statistics and probability techniques</td>
</tr>
<tr>
<td>Lall 2009, Lall 2012, Lall 2014</td>
<td>Prognostics based on <strong>Resistance Spectroscopy</strong> measurements</td>
</tr>
<tr>
<td>Lall 2017</td>
<td>Health Monitoring of electronic components from <strong>Strain Measurements</strong></td>
</tr>
<tr>
<td>Liu J 2009</td>
<td><strong>Model based approaches</strong></td>
</tr>
</tbody>
</table>
Test Setup for Test board-1

- Natural frequency: 340 Hz
- Frequency Range of vibration: from 330 Hz to 350 Hz

Figure 1: Shaker with the heating chamber on top

Figure 2: Front side of the test board -1

Figure 3: Back side of the test board -1

Figure 5: PCB board inside the heating chamber with strain gauge

- **Strain gauge** fixed on back side of the PCB
- **Strain rosette** fixed on back side of the PCB
Test Setup for Test Board-2

- Natural frequency - 380 Hz
- Frequency Range of vibration from 370 Hz to 390 Hz

Figure 1: Shaker with the heating chamber on top

Figure 2: PCB board with packages

Figure 3: Schematic diagram of the symmetric position of strain gauges on the packages

Figure 4: PCB board with strain gauges fixed to the back side of the board

Figure 5: PCB board inside the heating chamber
Data Acquisition

- Vibration Acceleration level- 5G
- Ambient Temperature-25 Degree Celsius

There are **50 strain signals** captured at different **instances of vibration**
- The **Red instances** represent the strain signal captured **before failure** of electronic package
- The **blue represents** after **failure strain signals**

<table>
<thead>
<tr>
<th>SL:No</th>
<th>Time (Minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>34</td>
<td>420</td>
</tr>
<tr>
<td>35</td>
<td>450</td>
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<tr>
<td>36</td>
<td>480</td>
</tr>
<tr>
<td>48</td>
<td>840</td>
</tr>
<tr>
<td>49</td>
<td>870</td>
</tr>
<tr>
<td>50</td>
<td>900</td>
</tr>
</tbody>
</table>

Red Series- Before Failure
Blue Series- After Failure
Strain Signals for Test Board-1

C1-C6 from the back side

C7 and C8 from the front side

C1-C3 are the strain signals from strain rosette

C4-C8 are the strain signals from strain gauges

Strain signals C1 to C4 from the back side

Sampling frequency is at 10,000 Hz and Sampling Time is for 100 Sec

Strain signals C5 to C8 from the back and front side
Strain Signals for Test Board-2

C1, C2, C3 and C4 are strain signals from different locations of test board-2.

Sampling frequency is at 10,000 Hz and Sampling Time is for 100 Sec.

Splitting of each strain signal (C1 to C4)
Test Matrix and FFT of the Strain Signals

- Peak Frequency Amplitudes are same for (C1 to C4).
- Peak frequency is seen at the Natural Frequency of the board.
- Low Amplitude frequency components are not visible.

\[
DFT = \sum_{n=0}^{N} x_n e^{-i2\pi\frac{kn}{N}}
\]

N = Number of samples
n = sum over n sequence of length N
k = integer from 0 to N

Test Matrix (X)-Strain Signal

Row: 1  Strain Signal at SL No: 1
\vdots
Row: 50  Strain Signal at SL No: 50_{50 \times 10^6}

Test Matrix (F)- FFT(Strain Signal)

Row: 1  FFT at SL No: 1
\vdots
Row: 50  FFT at SL No: 50_{50 \times 10^4}

Figure 11: FFT (Abs) of the strain signal (C1-C4) from 1-3000 Hz at 1 Minute
FFT of Strain Signals (C1-C4)

Figure 12: FFT (Abs) of the strain signal (C1-C4) from 500-3000 Hz at 40 Minute

Figure 13: FFT (Abs) of the strain signal (C1-C4) from 500-3000 Hz at 450 Minute

- Corresponding frequency components for strain signal C4 at 40 and 450 minutes of vibration
- Lower frequency components change considerably with vibration time
- This behavior is same for C1, C2, and C3 as well.
FFT of Strain Signals (C5-C8)

Figure 12: FFT (Abs) of the strain signal (C5-C8) from 500-3000 Hz at 40 Minute

- Corresponding frequency components for strain signal C8 at 40 and 450 minutes of vibration
- Lower amplitude frequency components change considerably with vibration time

Figure 13: FFT (Abs) of the strain signal (C5-C8) from 500-3000 Hz at 450 Minute

FFT of Before failure Strain Signal

FFT of After failure Strain Signal
Feature Vectors Used in the Analysis

Each strain signal is analyzed in the following manner to find the pattern for the two feature vectors:

**Test Matrix (X)-Strain Signal C1**

- Row: 1  Strain Signal at SL No: 1
- Row: 50 Strain Signal at SL No: 50_{50\times10^6}

**Test Matrix (F1)- FFT of Strain Signal**

- Row: 1  FFT at SL No: 1
- Row: 50 FFT at SL No: 50_{50\times10^4}

PCA Analysis on F1

Feature Vector-1

**Test Matrix (F2)- IF of Strain Signal**

- Row: 1  IF at SL No: 1
- Row: 50 IF at SL No: 50_{50\times10^4}

PCA Analysis on F2

Feature Vector-2

**Calculation for Instantaneous Frequency (IF)**

Let the signal be \( x(t) \) and the analytical equivalent of the signal is \( Z(t) = x(t) + jH \{x(t)\} = a(t)e^{j\phi(t)} \)

\( H \{x(t)\} \) Hilbert transform of \( x(t) \)

- Instantaneous Amplitude = \( a(t) \)
- Instantaneous Phase = \( \phi(t) \)
- Instantaneous Frequency = \( \omega(t) = \phi'(t) \)
Feature Vectors-1 Used in the Analysis

Shows the variation of the **first and second principal components** for feature vector-1

The variance of the **first 10 principal components** are plotted with vibration time.
Feature Vectors-2 Used in the Analysis

Shows the variation of the first and second principal components for feature vector-2

The variance of the first 10 principal components are plotted with vibration time.
Two Feature Vectors Used in the Analysis

**Feature Vector-1**
PCA on FFT (500-2000)Hz

**Feature Vector-2**
PCA on IF of the Signal

The **sudden increase in the variance** values just before failure is taken as the identification for failure.
Analysis-1 (Analysis on the Strain Rosette Signals)

**Analysis-1**
Studies the variation of the feature vectors-1 and 2 for normal and shear strain using strain rosette

- **Comparison Analysis** on Strain signal C1, C2 and C3
- C1 and C3 shear strain components whereas C2 is normal strain

Failure time - 450 minutes
Failure data points
Analysis-1 (Analysis on the Strain Rosette Signals)

Feature vector variation for C1 and C3

The shear strain components were not able to pattern indicating failure
Analysis-2 (Analysis on the Strain Signals C4)

- Studies the variation of the feature vectors-1 and 2 with different distances from the package
- C4 is exact opposite position to the package on the back side of the PCB

Comparison Analysis on Strain signal C4
Analysis-2 (Analysis on the Strain Signals C5)

Analysis-2

- C5 is middle position from the package to the fixture on the back side of PCB
Analysis-2 (Analysis on the Strain Signals C6)

C6 is farthest position from the package and close to the fixture on the back side of PCB

Comparison Analysis on Strain signal C6

After Failure points
Failure time - 450 minutes
Analysis-3 (Analysis on the Strain Signals C7)

- Studies the variation of the feature vectors-1 and 2 for strain signals from on the package
- C7 is corner position of the package on the front side of the PCB

Comparison Analysis on Strain signal C7

Failure time-450 minutes
Analysis-3 (Analysis on the Strain Signals C8)

C8 is corner position of the package parallel to C7 on the front side of the PCB

Analysis-3

Comparison Analysis on Strain signal C8

After Failure points
Failure time - 450 minutes
Analysis on test board-2

Case-1

Failure time of the packages
C2- 450 minutes
C4- 2750 minutes

- Only two packages failed and are captured by the strain gauges
- They are not close enough

Case-2

Failure time of the packages
C1- 600 minutes
C2- 270 minutes
C3- 27 minutes

- Seven packages failed and three are captured by the strain gauges
- The failures are close enough and other packages fail close by as well
Analysis with Test Board-2 for Case-1

- Feature vector for C2 has increasing behavior with some noise present
- Feature vector for C4 is the perfect behavior for identification of failure

Failure time:
- 2750 minutes
- 450 minutes
Summary and Conclusions

**High Strain-Rate Properties after Prolonged Storage**
- Low-and-high temperatures effects on mechanical properties of solder-alloys have been characterized.
- Measurements indicate that material properties are sensitive to both operational temperature and strain rate.
- Exposure to lower temperatures in the neighborhood of -65°C resulted in an increase in the UTS and YS values.
- UTS and YS values show a reduction with the increase aging time.
- 9-anand parameters extracted from stress-strain data.

**Feature Vectors for PHM Under Overlapping Stresses**
- Demonstrated strain-based feature vectors from the PCB surfaces.
- Data shows the importance of variance of the PCA and IF based feature vectors on the identification of impending failure.
- Fidelity of the feature vectors with distance of the strain signals from package failure-locations has been quantified.
- Case-1 of test board-2 looked at the behavior feature vectors when there are not many packages fail - FV is able to predict failure
- Case-2 of test board-2 looked at the behavior feature vectors when there are many packages fail - increasing variation of FV