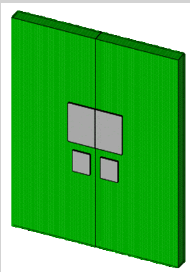
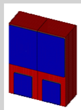
SAND2017-7587PE

Predicting Thermal Mechanical Fatigue of 63Sn37Pb Solder





$$N \approx \left(\frac{a}{\Delta\gamma_{EQPS}} \right)^b$$

$$\Delta w = \frac{1}{N} = \left(\frac{\Delta\gamma_{EQPS}}{a} \right)^b$$

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JOWOG28, AWE, Aldermaston, UK
Aug. 29-Sept. 01, 2017

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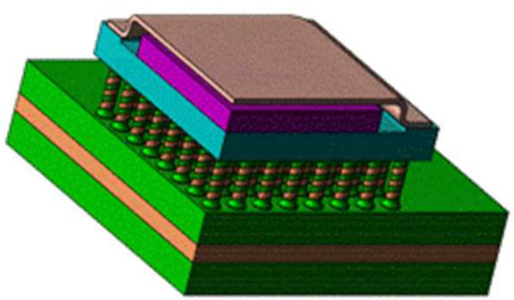
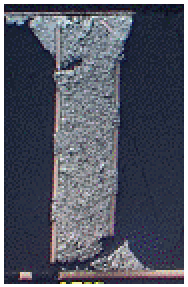
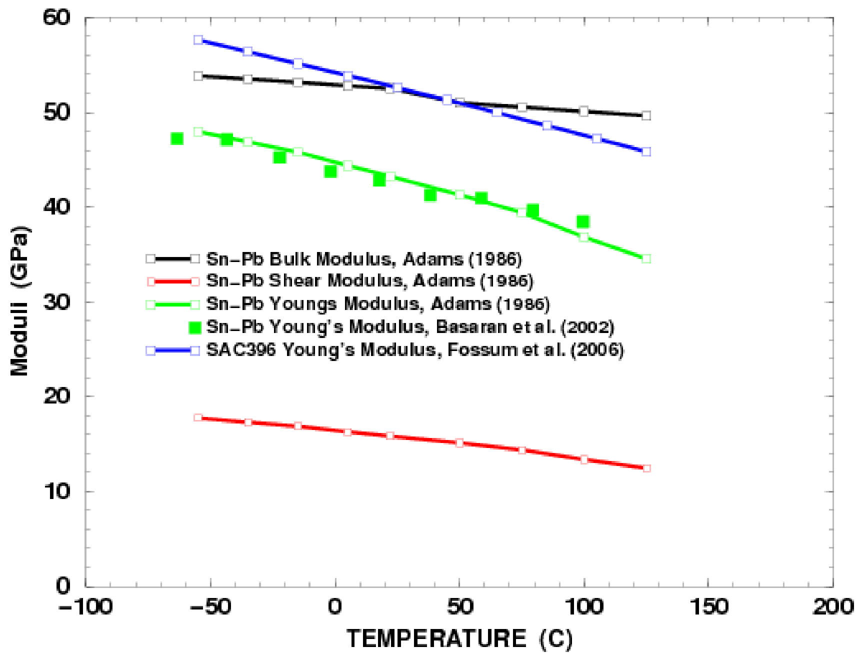
Outline

- Mechanical Behavior of Eutectic 63Sn37Pb and SAC Solder
- Low Cycle Fatigue Failure Criteria
- Unified Creep Plasticity Damage (UCPD) Model for Solder
- Simulating Crack Initiation and Growth
- Applications





Elasticity – 63Sn37Pb and SAC396



E (GPa) = 54.21 – 0.06358θ –2.685x10$^{-5}\theta^2$

θ= temperature (C)

95.5Sn-3.9Ag-0.6Cu solder

G (GPa) = 24.28 – 0.0290θ

K (GPa) = 61.06 – 0.0274θ

θ= temperature (K)

60Sn-40Pb solder

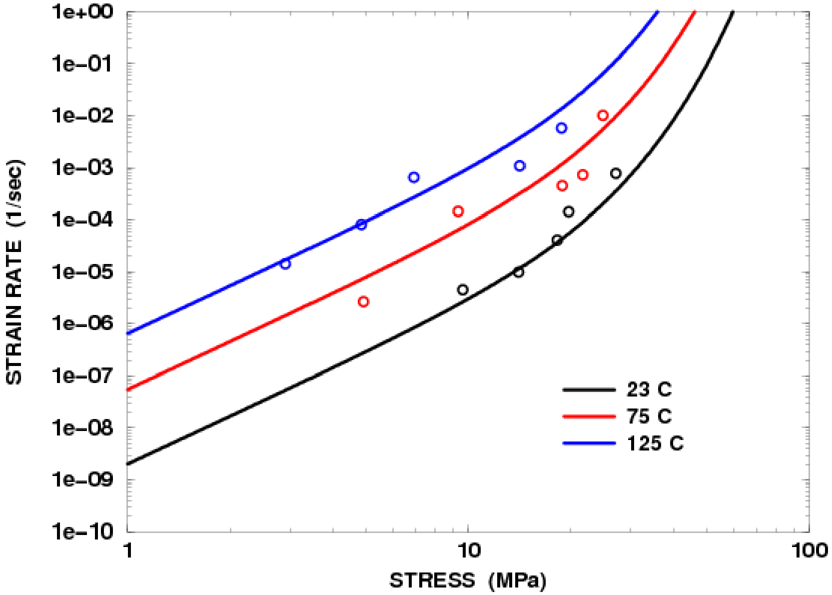
References:

P. Adams, 'Thermal Fatigue of Solder Joints in Micro-electronic Devices,' M.S. Thesis, ME, MIT, Aug.1986.

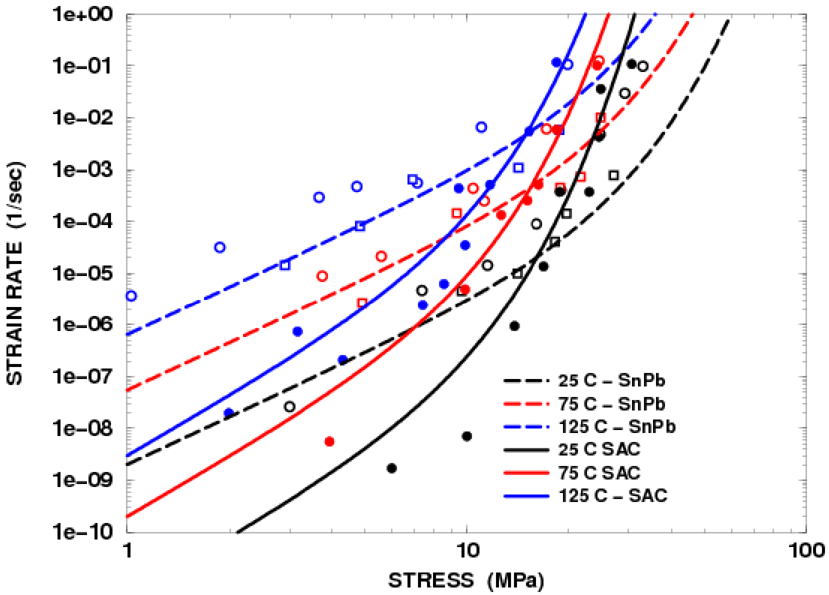
C. Basaran et al., 'Measuring intrinsic elastic modulus of Pb/Sn solder alloys,' *Mech. of Materials*, **34** (2002).

M.K. Neilsen and P.T. Vianco, 'UCPD Model for Pb-Free Solder,' *J. Electronic Packaging*, **136** (2014).

Creep – 63Sn37Pb and SAC396



63Sn37Pb



SAC396 vs. SnPb

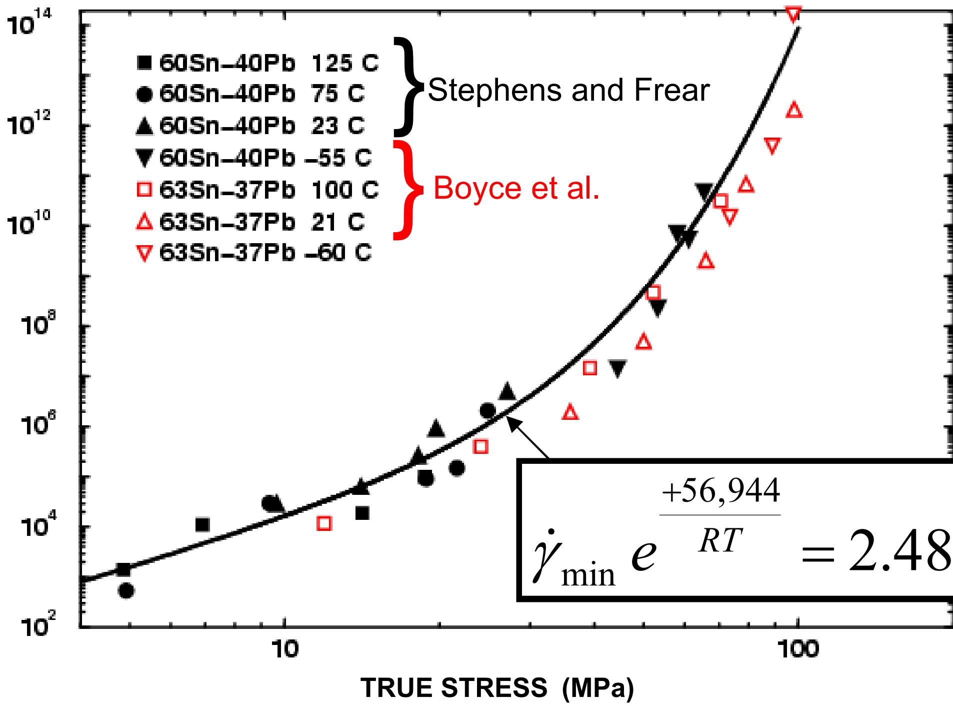
References:

Stephens, J.J., and Frear, D.R., 'Time-Dependent Deformation Behavior of Near-Eutectic 60Sn-40Pb Solder,' *Metallurgical and Materials Transactions A*, **30A**, (1999).

S. Ganesan, M. Pecht, **Lead-free Electronics**, Wiley, (2004).

Zener-Holloman Plot – 63Sn37Pb

$$\dot{\gamma}_{\min} e^{\frac{+56{,}944}{RT}}$$



$$\dot{\gamma}_{\min} e^{\frac{+56{,}944}{RT}} = 2.48x10^4 \left[\sinh(0.0793\sigma)\right]^{3.04}$$

	<u>Strain Rates</u>
Stephens et al.	10^{-6} to 10^{-2}
Boyce et al.	10^{-4} to 10^{2}

References:

Stephens, J.J., and Frear, D.R., 'Time-Dependent Deformation Behavior of Near-Eutectic 60Sn-40Pb Solder,' *Metallurgical and Materials Transactions A*, **30A**, (1999).

Boyce, B., Brewer, L., Perricone, M., and Neilsen,M., 'On the Strain Rate and Temperature-Dependent Tensile Behavior of Eutectic SnPb Solder,' *Journal of Electronic Packaging*, **133**, (2011).

UCP Model for Solder

$$\dot{\boldsymbol{\sigma}} = \mathbf{E} : \dot{\boldsymbol{\varepsilon}}^{e} = \mathbf{E} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{in})$$

$$\dot{D} = \frac{A_1 \dot{\gamma}}{(D - D_0)^{A_3}} - A_2 (D - D_0)^2$$

$$\dot{\boldsymbol{\varepsilon}}^{in} = \frac{3}{2} \dot{\gamma}\, \mathbf{n} = \frac{3}{2} f \sinh^{p}\left(\frac{\tau}{D}\right) \mathbf{n}$$

$$\dot{\mathbf{B}} = \frac{A_4 \dot{\boldsymbol{\varepsilon}}^{in}}{\beta^{A_6}} - A_5 \beta \mathbf{B}$$

$$\mathbf{n} = \frac{\mathbf{s} - \frac{2}{3}\mathbf{B}}{\tau}$$

$$\beta = \sqrt{\frac{2}{3} \mathbf{B} : \mathbf{B}}$$

$$\tau = \sqrt{\frac{3}{2}\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right) : \left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)}$$

Reference:

Boyce, B., Brewer, L., Perricone, M., and Neilsen,M., 'On the Strain Rate and Temperature-Dependent Tensile Behavior of Eutectic Sn-Pb Solder,' *J. Electronic Packaging*, **133**, (2011).

Low Cycle Fatigue Experimental Data

Sn-Pb Coffin-Manson (Solomon, 1986)

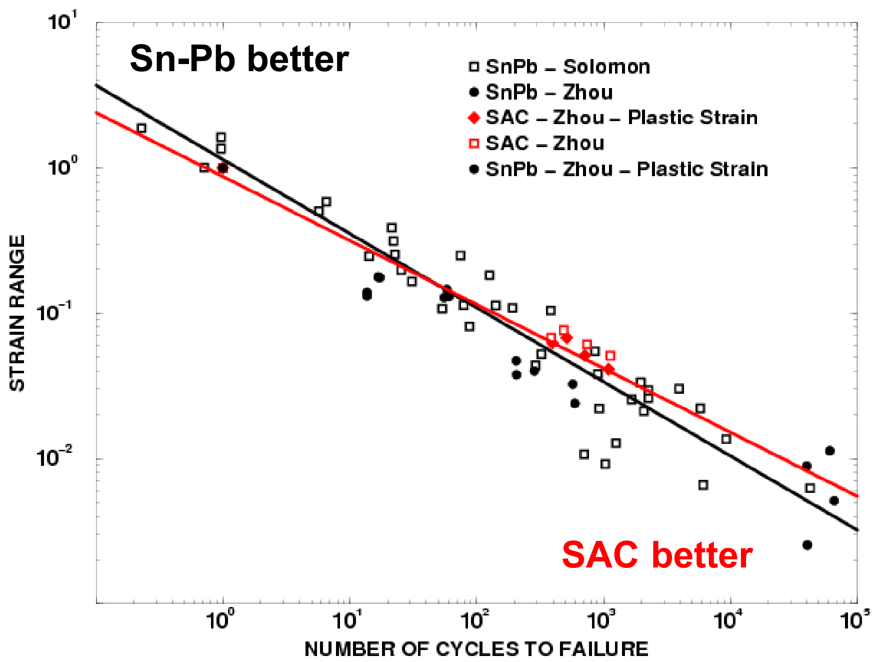
$$N_f = \left(\frac{1.14}{\Delta\gamma_p}\right)^{\frac{1}{0.51}} \approx \left(\frac{1.31636}{\Delta\gamma_{EQPS}}\right)^{1.96078}$$

SAC305 Coffin-Manson (Zhou, 2009)

$$N_f = \frac{1}{2}\left(\frac{1.18}{\Delta\gamma_{EQPS}}\right)^{\frac{1}{0.44}} \approx \left(\frac{0.86985}{\Delta\gamma_{EQPS}}\right)^{2.273}$$

$\Delta\gamma_p =$ plastic shear strain range

$\Delta\gamma_{EQPS} =$ equivalent plastic strain increment from complete load/unload cycle



References: H.D. Solomon, IEEE Trans., CHMT-9, Dec. 1986
Y. Zhou et al., J. Electronic Packaging, Vol. 131, Mar. 2009

UCPD Model for Solder

$$\dot{\boldsymbol{\sigma}} = \mathbf{E} : \dot{\boldsymbol{\varepsilon}}^{e} = \mathbf{E} : (\dot{\boldsymbol{\varepsilon}} - \dot{\boldsymbol{\varepsilon}}^{in})$$

$$\dot{\boldsymbol{\varepsilon}}^{in} = \frac{3}{2}\dot{\gamma}\,\mathbf{n} = \frac{3}{2} f \sinh^{p}\left(\frac{\tau}{D(1-cw)}\right)\mathbf{n}$$

$$\dot{D} = \frac{A_1\,\dot{\gamma}}{(D-D_0)^{A_3}} - A_2 (D-D_0)^2$$

$$\dot{\mathbf{B}} = \frac{A_4\,\dot{\boldsymbol{\varepsilon}}^{in}}{\beta^{A_6}} - A_5\,\beta\,\mathbf{B}$$

$$\mathbf{n} = \frac{\mathbf{s} - \frac{2}{3}\mathbf{B}}{\tau} \qquad \beta = \sqrt{\frac{2}{3}\mathbf{B}:\mathbf{B}}$$

$$\tau = \sqrt{\frac{3}{2}\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right):\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)}$$

$$N = \left(\frac{a}{\Delta\gamma_{EQPS}}\right)^{b}$$

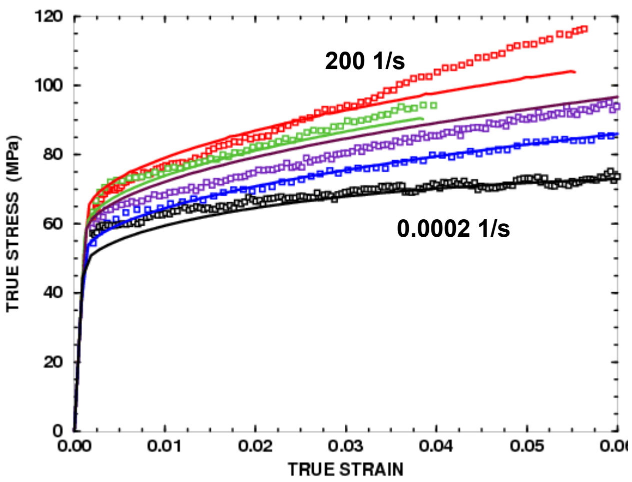
$$\Delta w \approx \frac{1}{N} = \left(\frac{\Delta\gamma_{EQPS}}{a}\right)^{b}$$

$$w = \sum_{i=1}^{m}\Delta w^{i} = \sum_{i=1}^{m}\left(\frac{\Delta\gamma^{i}_{EQPS}}{a}\right)^{b}$$

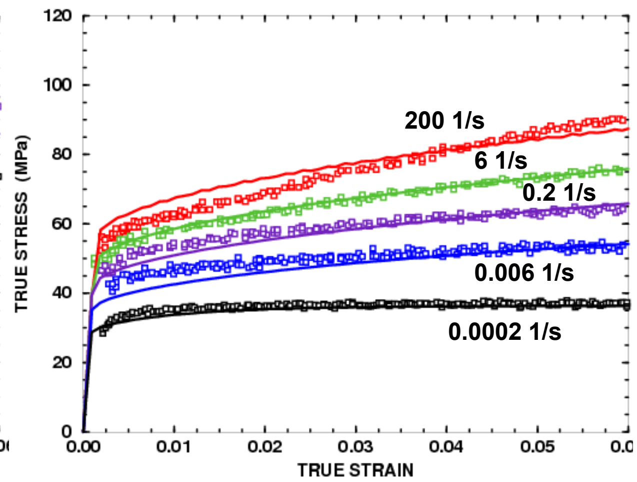
Reference:

M.K. Neilsen and P.T. Vianco, 'UCPD Model for Pb-Free Solder,' *J. Electronic Packaging*, **136** (2014).

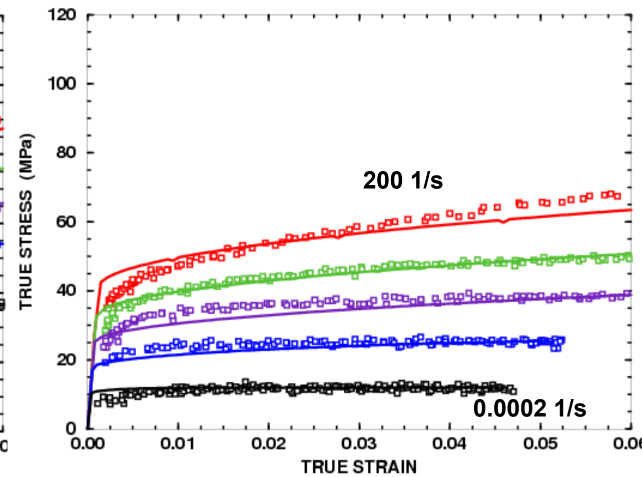
63Sn-37Pb Solder



-60 °C isothermal tests



21 °C isothermal tests



100 °C isothermal tests

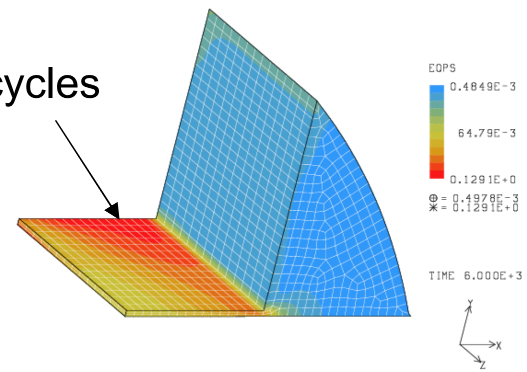
*Comparison of UCPD model predictions (solid lines) with experimental data (symbols) for **wide range of strain rates** from 0.0002 per second to 200.0 per second.*

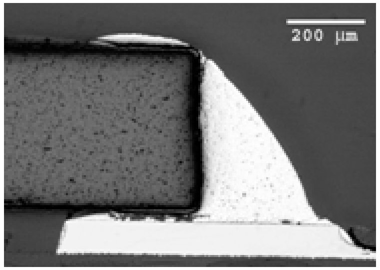
*Ref: Boyce, B., Brewer, L., Perricone, M., and Neilsen,M., 'On the Strain Rate and Temperature-Dependent Tensile Behavior of Eutectic Sn-Pb Solder,' J. Electronic Packaging, **133**, Sept. 2011.*

Solder Life Prediction

1. Simulate 1 or a few thermal cycles.
2. Compute increment in equivalent plastic strain or damage in worst element
3. Generate Lifetime Prediction using Coffin-Manson relationship

Crack Starts Here at 100 cycles





500 cycles

Cycles to Generate Electrical Open = ???
Need to Model Crack Initiation and Growth

Challenges for Modeling Crack Growth

Problem: Capture Effects of 100's or 1000's of Thermal Cycles with Simulation that Runs in a Reasonable Amount of Time

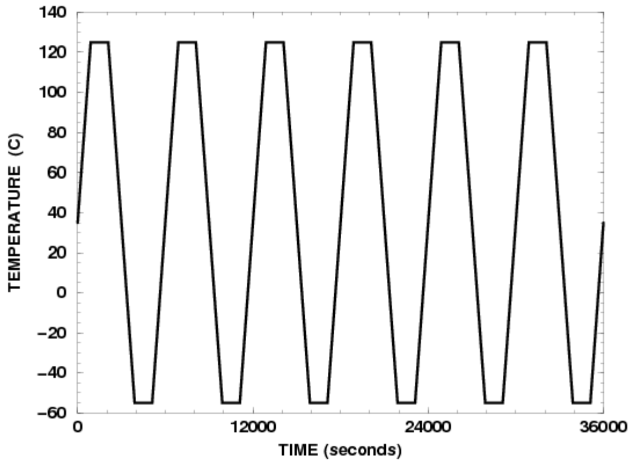
Solution: Accelerated Simulation – Acceleration Factor Applied to Damage.

Problem: Capture Geometry Changes Due to Introduction and Growth of Crack

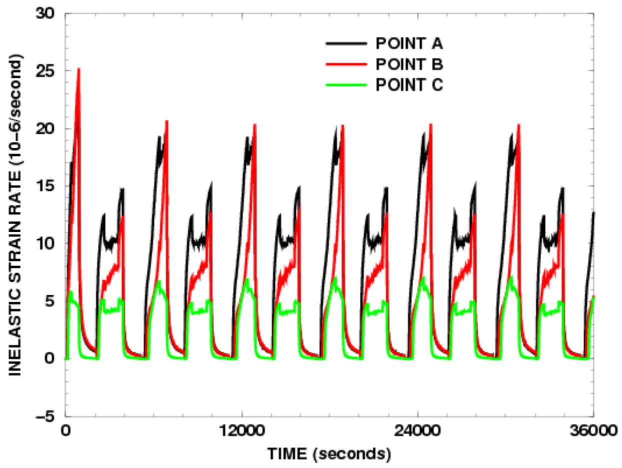
Solution: Smeared Cracking Approach – Replace Cracked Elements with Very Flexible Elastic Material.

What to do about local model giving mesh dependent solutions ?

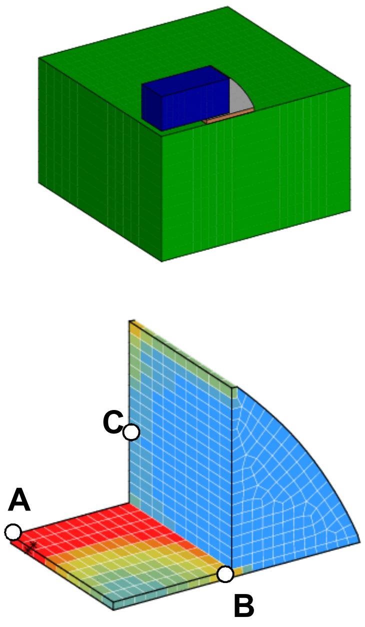
Acceleration of Simulations - UCPD



Temperature History



Strain Rate History



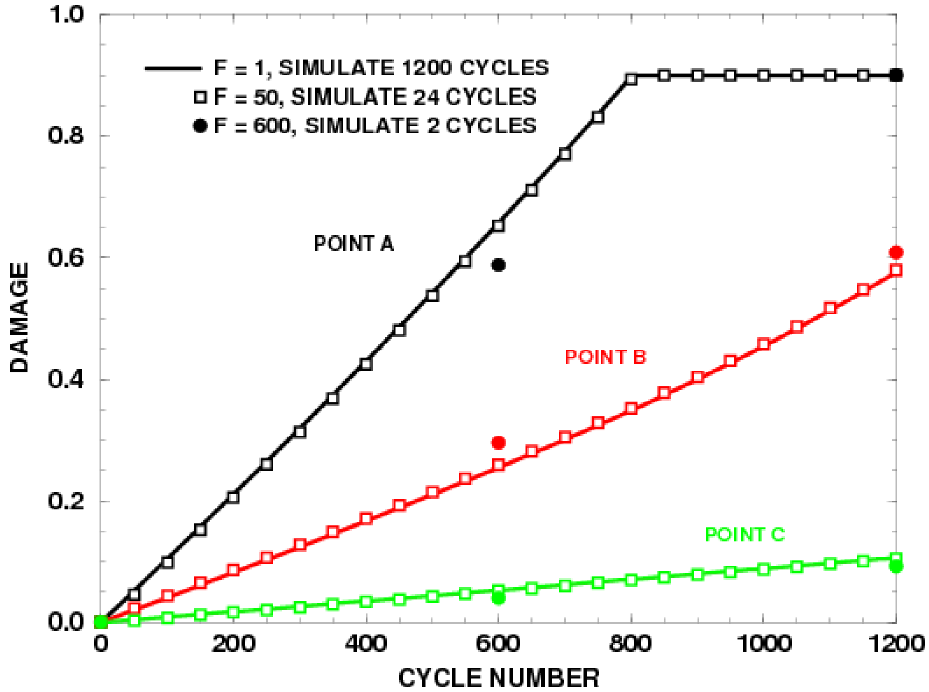
If inelastic rate histories vary little with cycle number then:

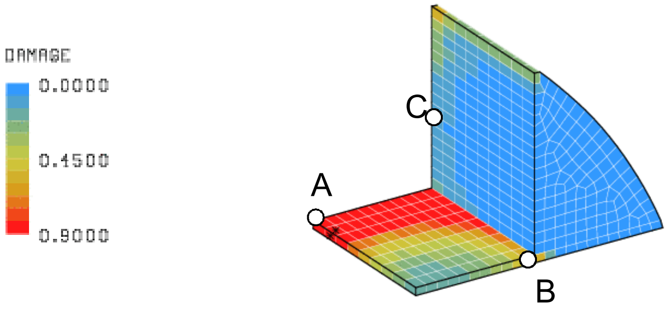
apply acceleration factor, ***F***, to damage rate equation

to capture effects of ***F*** cycles with each simulation cycle

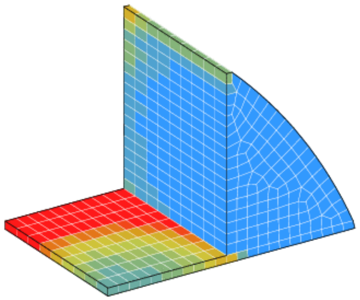
$$w = \sum_{i=1}^{m} F \Delta w^i = \sum_{i=1}^{m} F \left(\frac{\Delta \gamma^i_{EQPS}}{a} \right)^b$$

Acceleration of Simulations - UCPD

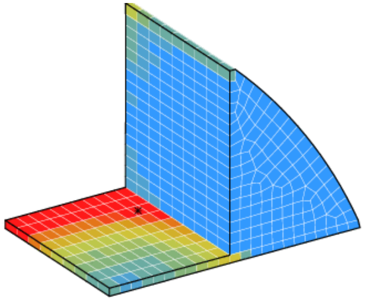




F = 1, simulated 1200 cycles



F = 50, simulated 24 cycles

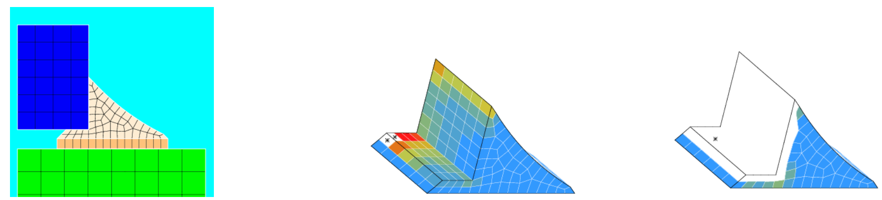


F = 600, simulated 2 cycles

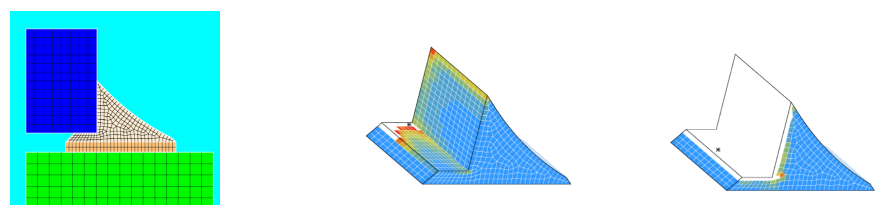
So does this really work ?   Yes.

Eliminating Mesh Dependence

$$w = \sum_{i=1}^{m} F\left(\frac{\Delta\gamma_{EQPS}^{i}}{a}\right)^{b}$$

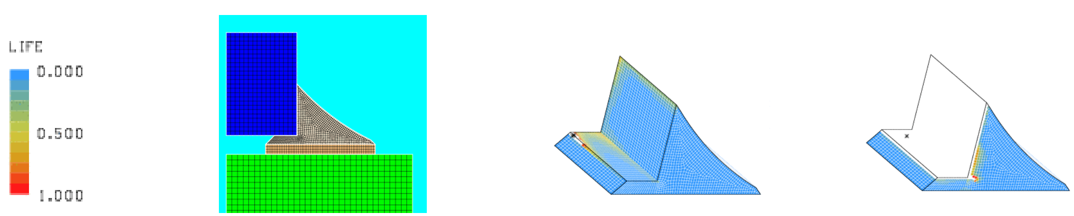


318 solder elements | 4,000 cycles | 61,500 cycles



2,782 solder elements | 2,000 cycles | 39,500 cycles

$$Life = \frac{w}{w_{fail}} = \frac{w}{0.9}$$



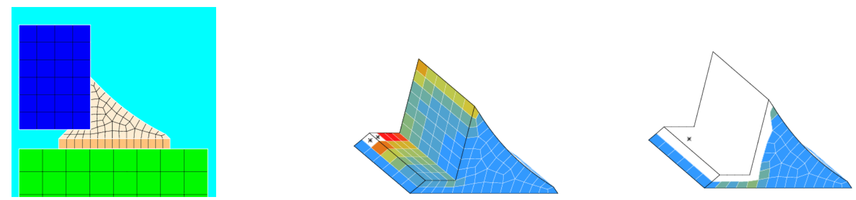
22,152 solder elements | 600 cycles | 24,000 cycles

Eliminating Mesh Dependence

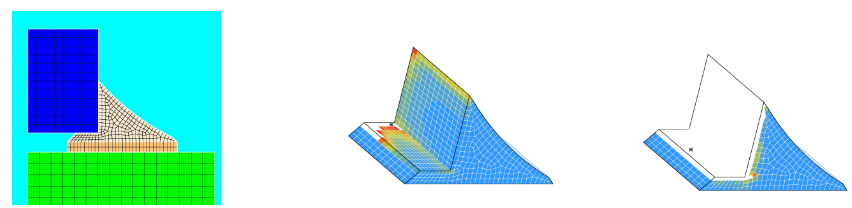
$$w = \sum_{i=1}^{m} \left(\frac{V^{1/3}}{\lambda} \right)^{d} F \left(\frac{\Delta \gamma_{EQPS}^{i}}{a} \right)^{b}$$

$$\lambda = 0.0254\text{mm}, \; d = 0.675$$

$$V = element\, volume$$

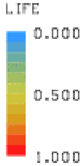


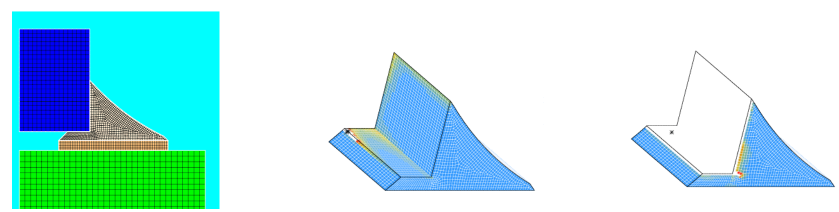
318 solder elements | 2,000 cycles | 24,750 cycles



2,782 solder elements | 1,000 cycles | 25,750 cycles

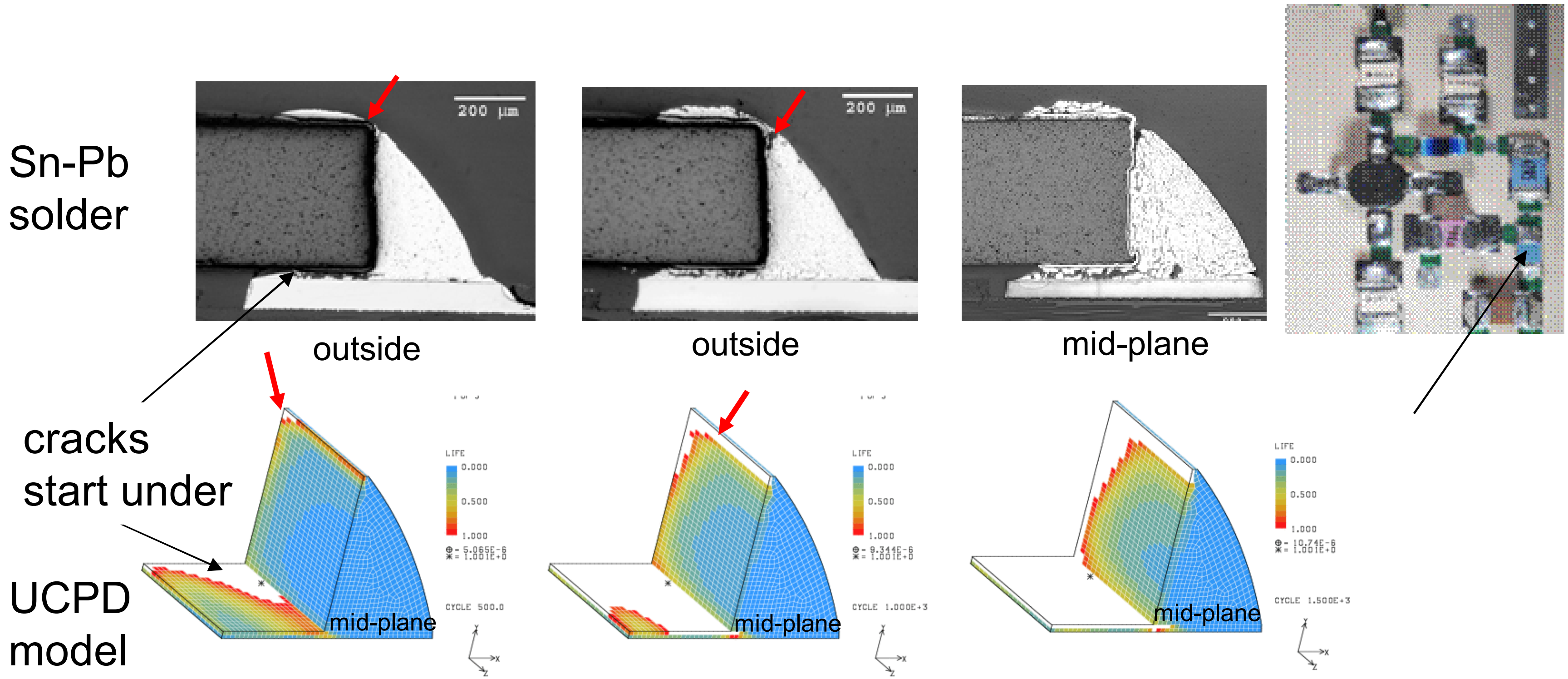
$$Life = \frac{w}{w_{fail}} = \frac{w}{0.9}$$





22,152 solder elements | 750 cycles | 26,000 cycles

Sandia R23 63Sn37Pb Solder



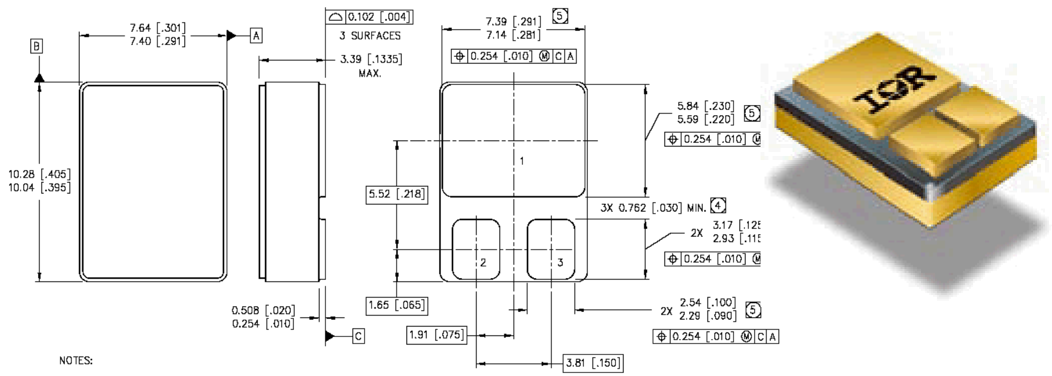
500 cycles *1000 cycles* *1500 cycles*

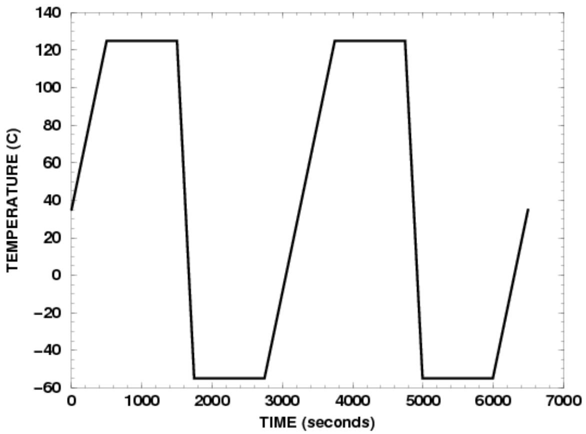
Accelerated Aging -55 to 125 Thermal Cycles

Failure based on damage w = 0.90

White elements = cracked elements.

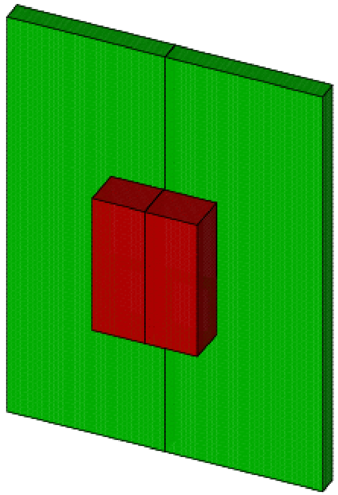
SMD-0.5 63Sn37Pb Solder



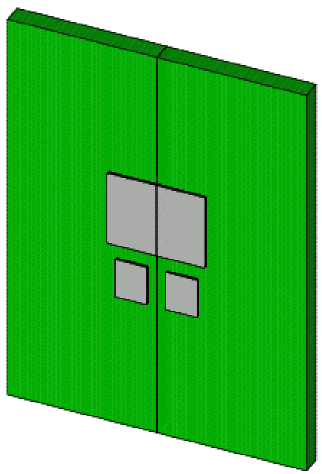


Case Outline and Dimensions - SMD-0.5 (Ceramic Lid)
Reference http://www.irf.com/product-info/hi-rel/gssurface.html

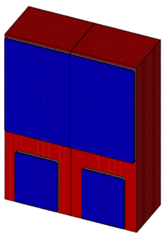
Temperature history



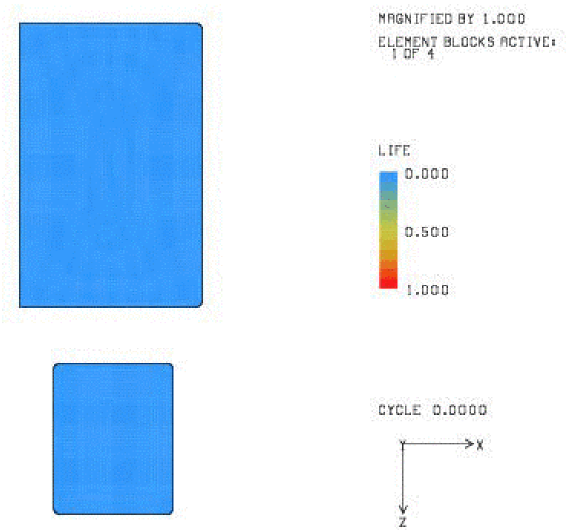
Model – top view



pwb, pads, and solder

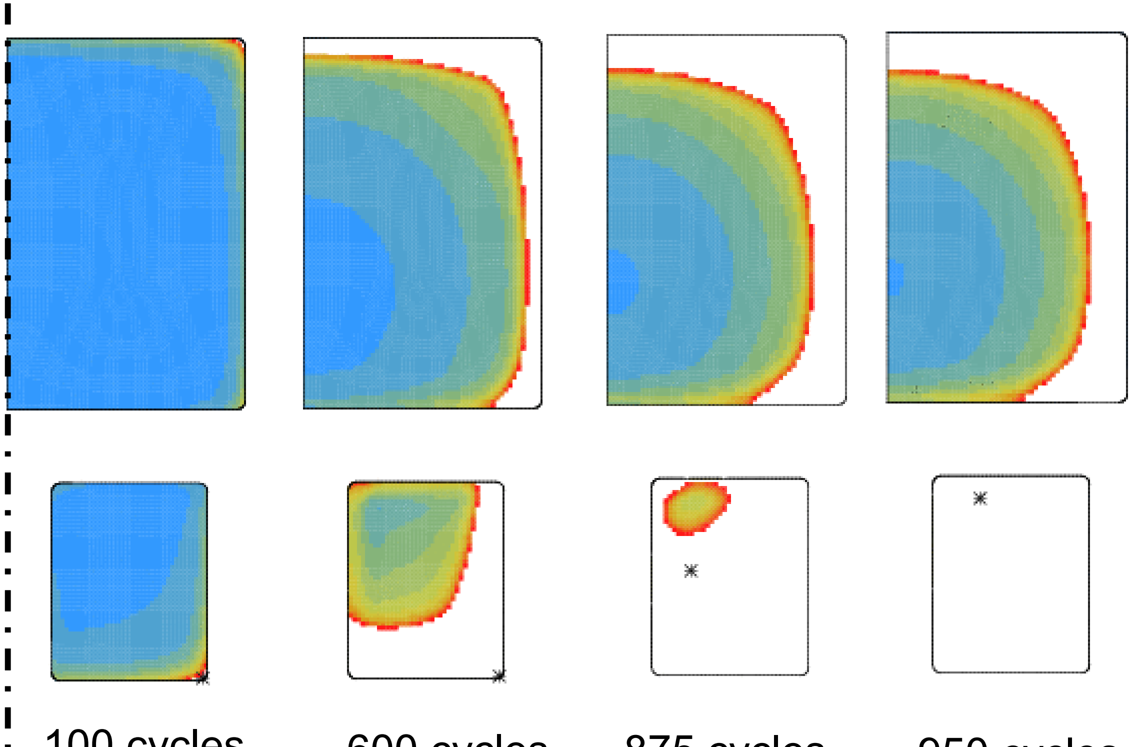


SMD-0.5

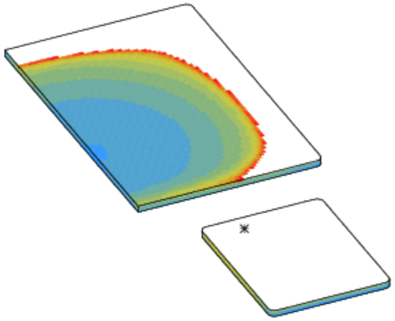


SMD-0.5 63Sn37Pb Solder

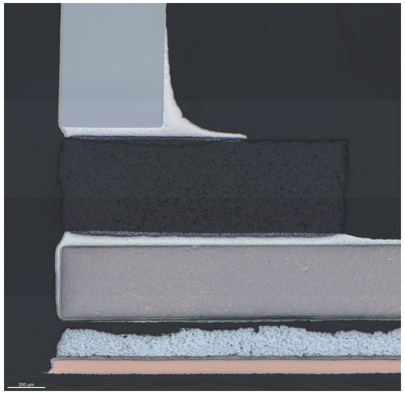
Model: Open at 950 cycles with 5 mil solder
Experiment: Open at 1009 cycles



100 cycles | 600 cycles | 875 cycles | 950 cycles

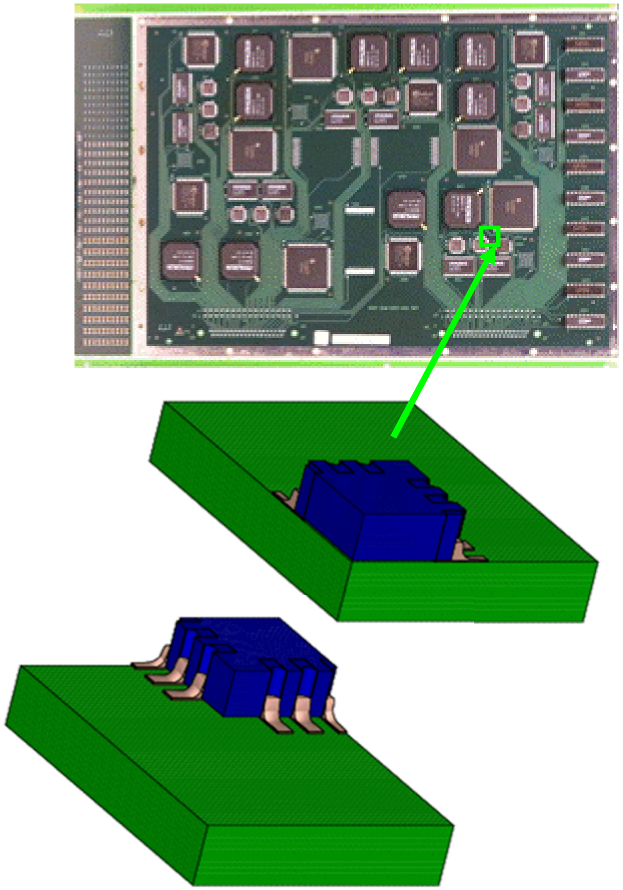


950 cycles
Model



1009 cycles
Experiment

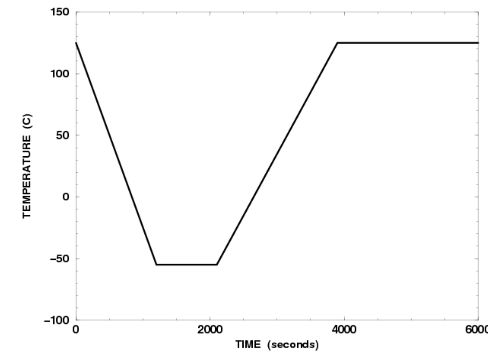
CLCC-20 63Sn37Pb Solder

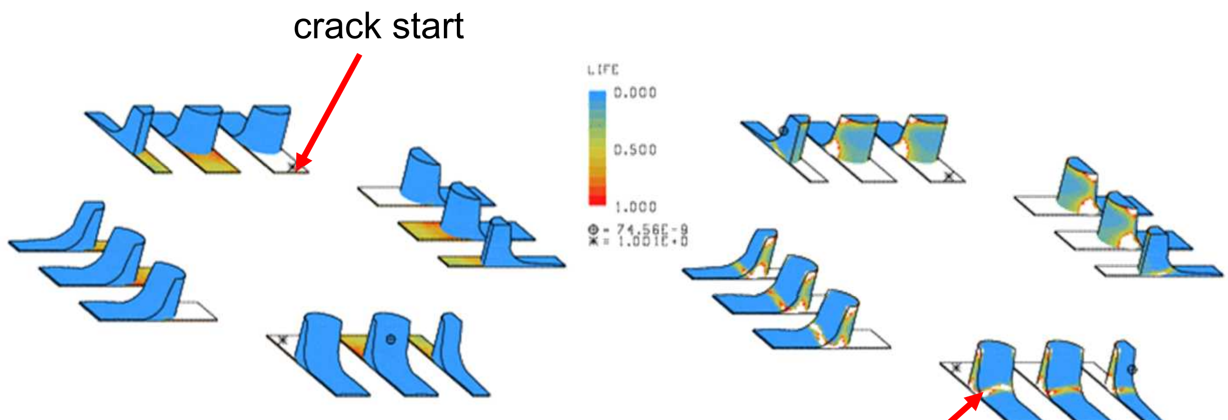


CLCC-20 - Finite Element Model – ¼ symmetry

Experiment: 63Sn37Pb solder
First Failure: 455 cycles
N10: 469 cycles
N63: 727 cycles

Model: 63Sn37Pb solder
Electrical open: 975 cycles





50 cycles

975 cycles

Reference: D. Hillman et al.,'JCAA/JG-PP No-Lead Solder Project: -55^{o}C to 125^{o}C Thermal Cycle Testing Final Report,Rockwell Collins, May 2006.

Summary

- Solder exhibits a variety of complex behavior (Creep, Plasticity, Damage)
- A new UCPD Model was developed for solder with damage based on an empirical Coffin-Manson low-cycle fatigue failure criterion
- Model does not require remeshing with crack growth and instead uses diffuse cracking approach and replaces cracked solder with very flexible elastic material
- Model was validated by comparing model predictions with experimental data for a variety of component types