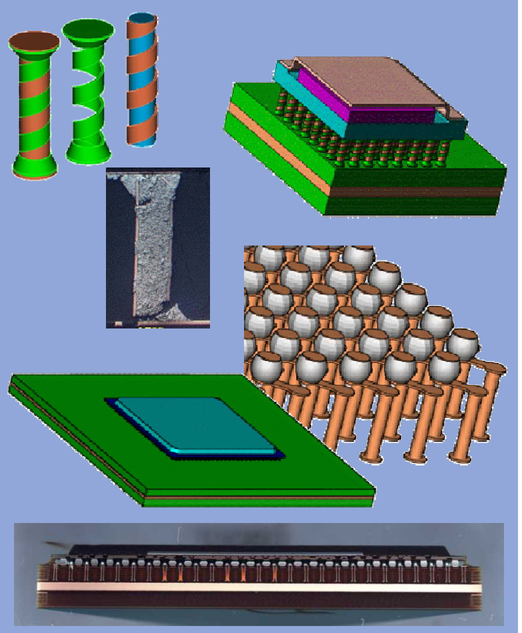
Component Science and Mechanics



SAND2013-0641P

TurboSIP
Solder Interconnect Predictor

Darrel Frear, Steve Burchett, John Stephens, Jr.
Paul Vianco, Mike Neilsen

Sandia National Laboratories

Exceptional service in the national interest

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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
- TurboSIP Solder Interconnect Predictor
- Comparison with SRS™ and Sherlock™
- Solar Panel Lifetime Predictions

Solder R-D-A at Sandia

Research

- ❑ Experimental investigation – physics of failure
- ❑ Constitutive models for Sn-Pb and Pb-free solders
- ❑ Failure criteria for thermal mechanical fatigue

Development

- ❑ Capability to model crack initiation and growth
- ❑ Material characterization/parameters for a variety of solders

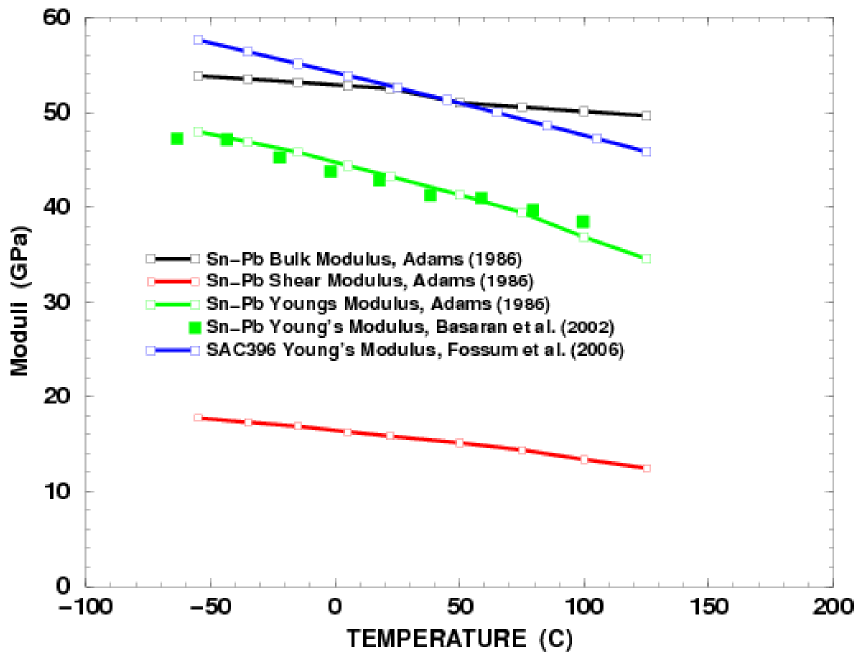
Application

- ❑ TurboSIP Solder Interconnect Predictor tool
- ❑ Finite element analyses for defense, energy, and satellite programs

Research to capabilities and tools to support customers as fast as possible

… but no faster.

Elasticity – 63Sn37Pb and SAC396



E (GPa) = $54.21 - 0.06358\theta - 2.685\text{x}10^{-5}\theta^2$

θ= temperature (C)

95.5Sn-3.9Ag-0.6Cu solder

G (GPa) = $24.28 - 0.0290\theta$

K (GPa) = $61.06 - 0.0274\theta$

θ= temperature (K)

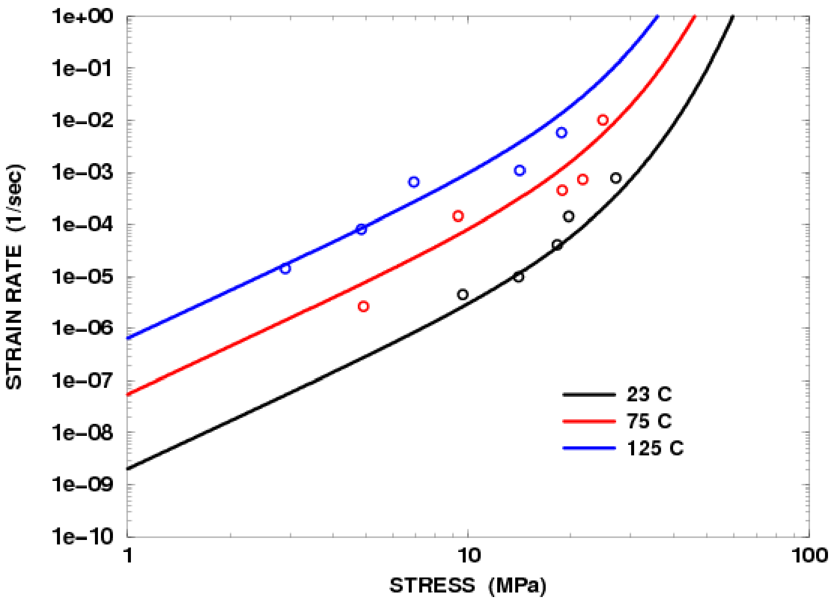
60Sn-40Pb solder

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

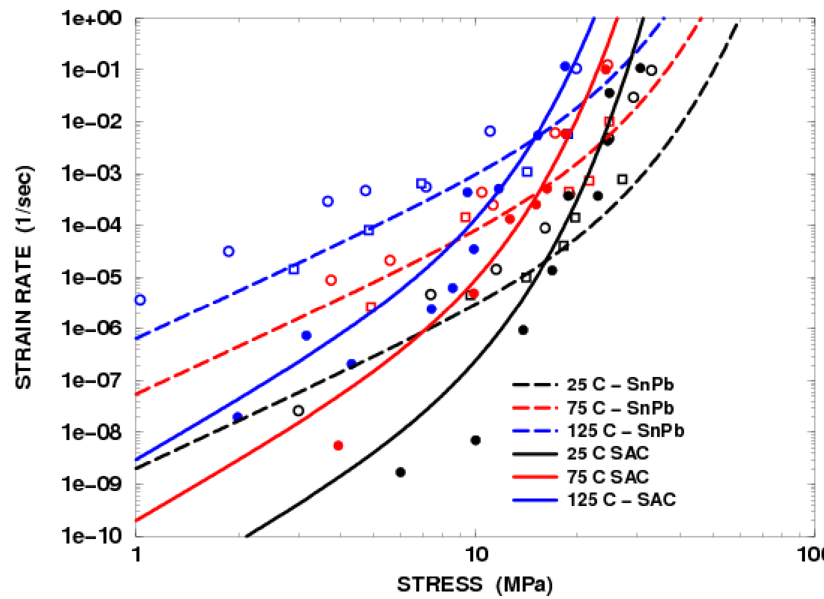
C. Basaran et al., 'Measuring intrinsic elastic modulus of Pb/Sn solder alloys,' Mech. of Materials, ***34*** *(2002).*

A. Fossum et al., '..Viscoplastic Damage Model for Lead-Free Solder,' J. Electronic Packaging, ***128*** *(2006).*

Creep – 63Sn37Pb and SAC396



63Sn37Pb



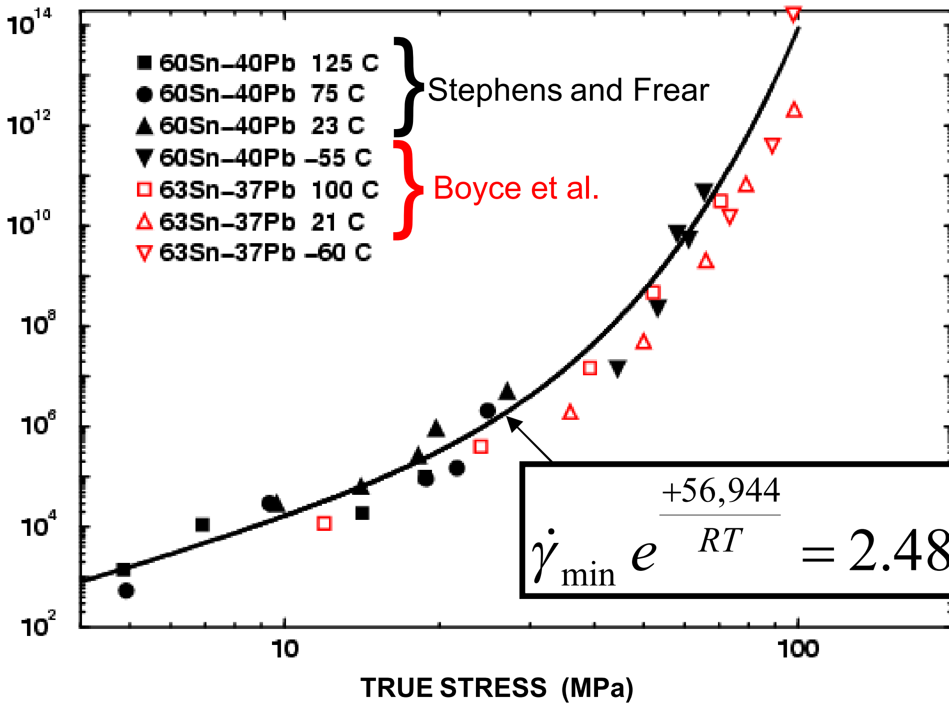
SAC396 vs. SnPb

References: Stephens, J.J., and Frear, D.R., 'Time-Dependent Deformation Behavior of Near-Eutectic 60Sn-40Pb Solder,' Metallurgical and Materials Transactions A, 30A, pp. 1301-1313, May 1999.

S. Ganesan, M. Pecht, 'Lead-free Electronics,' Wiley, 2004.

Zener-Holloman Plot – SnPb

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



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

	Strain Rates
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, pp. 1301-1313, May 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,Vol. 133, Sept. 2011.

Unified Creep Plasticity (UCP) Model for Solder

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

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

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

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

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

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

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

Reference: Boyce, B., Brewer, L., Perricone, M., and Neilsen,M., ‘On the Strain Rate and Temperature-Dependent Tensile Behavior of Eutectic Sn-Pb Solder,’ Journal of Electronic Packaging,Vol. 133, Sept. 2011.

Low Cycle Fatigue Experimental Data

Sn-Pb Coffin-Manson (Solomon, 1986)

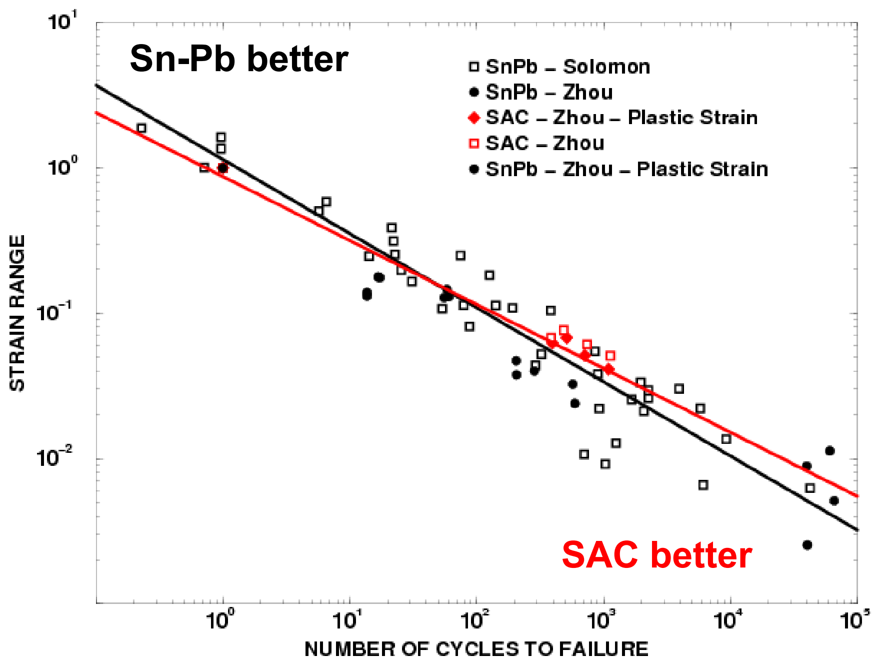
$$N_f = \left(\frac{1.14}{\Delta\gamma_p}\right)^{\frac{1}{0.51}} \approx \left(\frac{1.31636}{\Delta\gamma_{EQPS}}\right)^{1.96078}$$

SAC305 Coffin-Manson (Zhou, 2009)

$$N_f = \frac{1}{2}\left(\frac{1.18}{\Delta\gamma_p}\right)^{\frac{1}{0.44}} \approx \left(\frac{1.004}{\Delta\gamma_{EQPS}}\right)^{2.273}$$

$\Delta\gamma_p =$ 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, March 2009

Existing Damage Models for Solder

Solomon (1986) Experimental Solder Data →

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

Fossum et al. (2006)

$$\dot{\omega} = \frac{p}{H}\left\{\left[\ln\left(\frac{1}{\omega}\right)\right]^{(1+p)/p}\right\}\omega Q(\sigma)$$

$$N_f = f(\sigma) \neq g(\Delta\gamma_{EQPS})$$

Wei et al. (2006)

$$\dot{\omega} = \frac{Y_d}{Y_{hf}}\dot{\varepsilon}^{in}$$

Failure when $\omega = \omega_{critical}$

→

$$N_f \approx \left(\frac{C}{\Delta\gamma_{EQPS}}\right)^{1.0}$$

References: Solomon, IEEE Trans., CHMT-9, Dec. 86

Fossum et al., J. Electronic Packaging, Vol. 128, March 2006

Wei et al., Intl. J. Damage Mechanics, Vol. 15, April 2006

UCPD Model for Solder

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

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

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

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

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

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

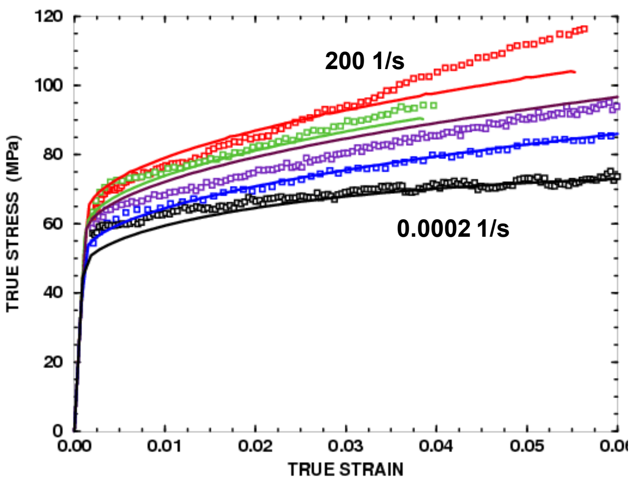
Damage evolution motivated by Coffin-Manson Equation

$$N_f \approx \left(\frac{\alpha}{\Delta\gamma_{EQPS}}\right)^{\beta}$$

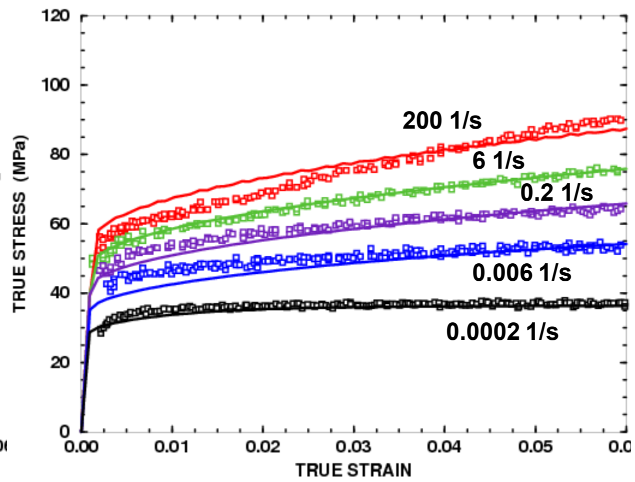
$$\Delta w = \frac{1}{N_f} \approx \left(\frac{\Delta\gamma_{EQPS}}{\alpha}\right)^{\beta}$$

$$\dot{w} = \frac{\beta}{\alpha^{\beta}}\left(\gamma^{i}_{EQPS}\right)^{(\beta-1)}\dot{\gamma}$$

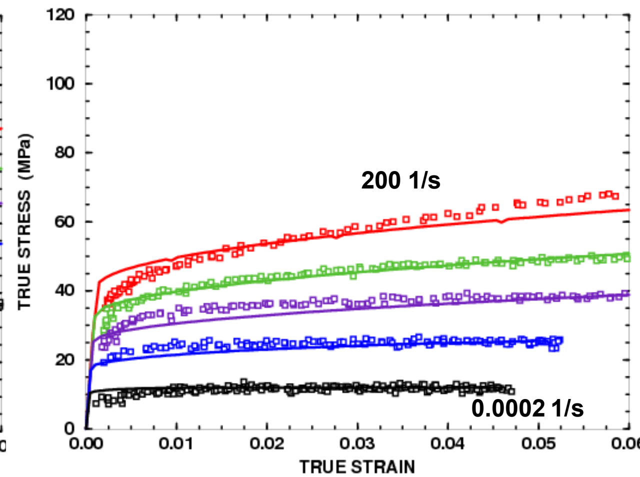
63Sn37Pb Solder Stress-Strain Curves



-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.*

*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**, Sept. 2011.*

SAC396 Solder Stress – Strain Curves

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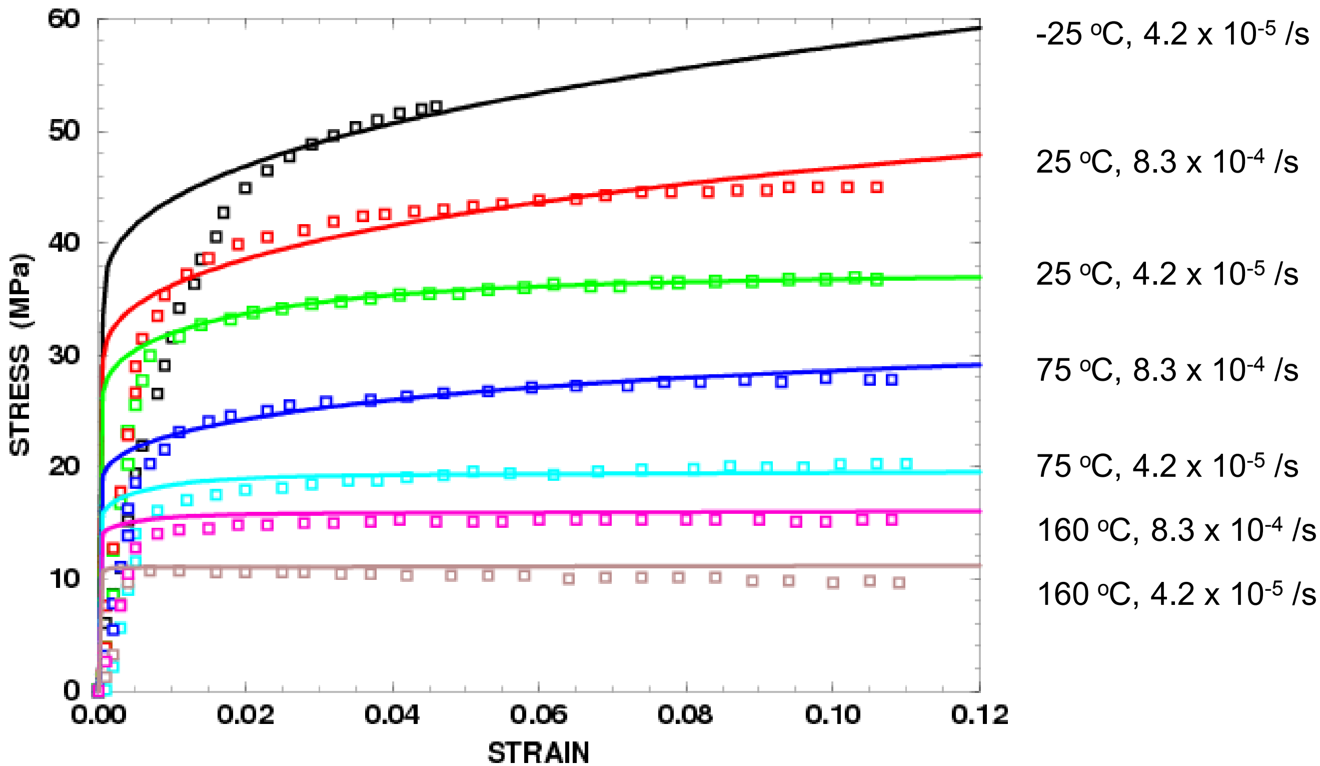


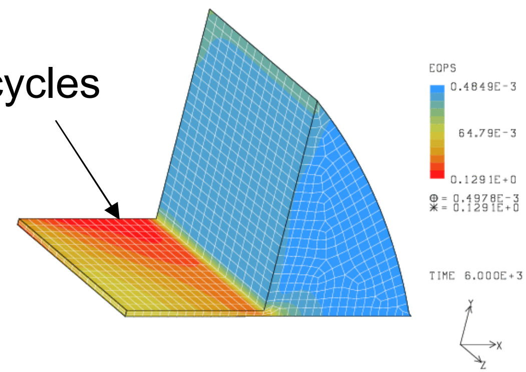
Fit with Elastic Moduli from Dynamic Modulus Measurements

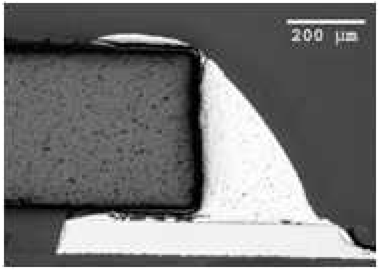
Reference: Fossum et al., J. Electronic Packaging, Vol. 128, March 2006

Solder Joint 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

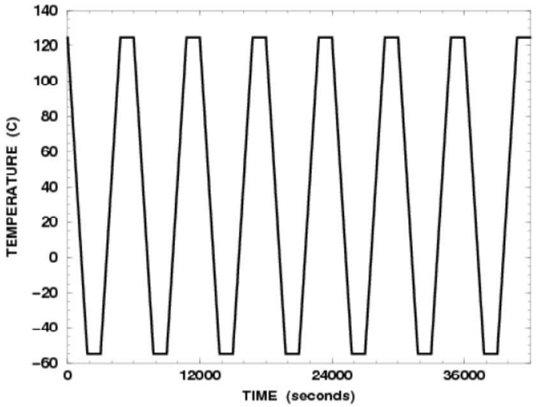
Solution: Accelerated Simulation – Acceleration Factor Applied to Damage.

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

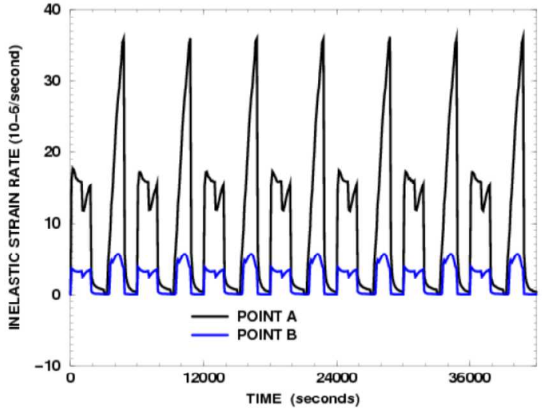
Solution: Smeared Cracking Approach – Replace Cracked Elements with Weak Elastic Material.

What to do about local model giving mesh dependent solutions ?

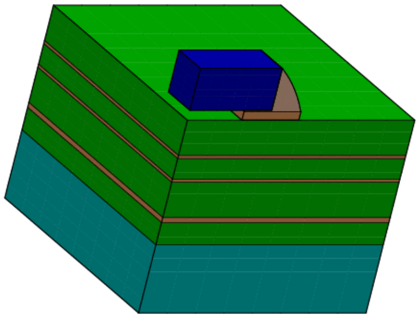
Acceleration of Simulations - UCPD



Temperature History



Strain Rate History



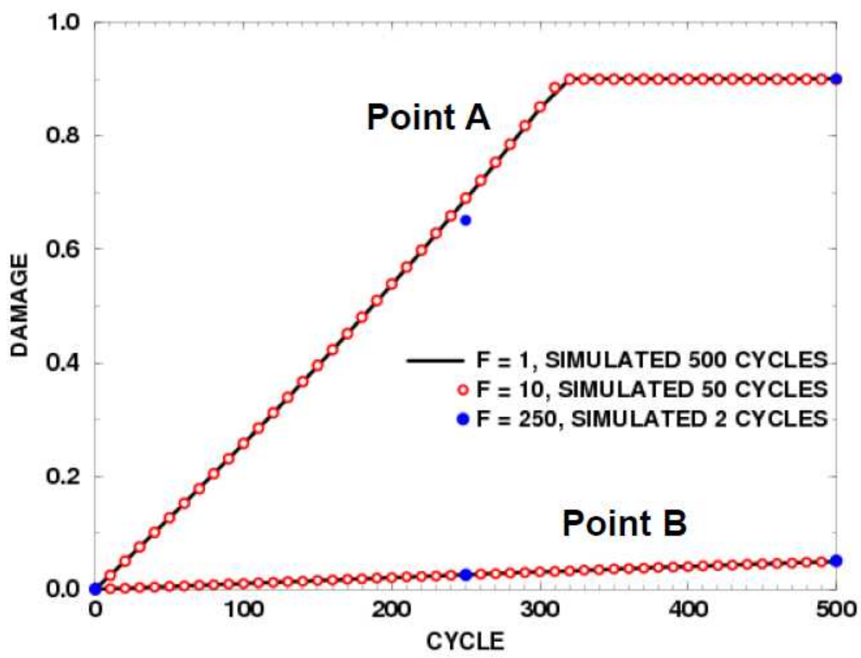
If the inelastic rate histories do not change between cycles then:

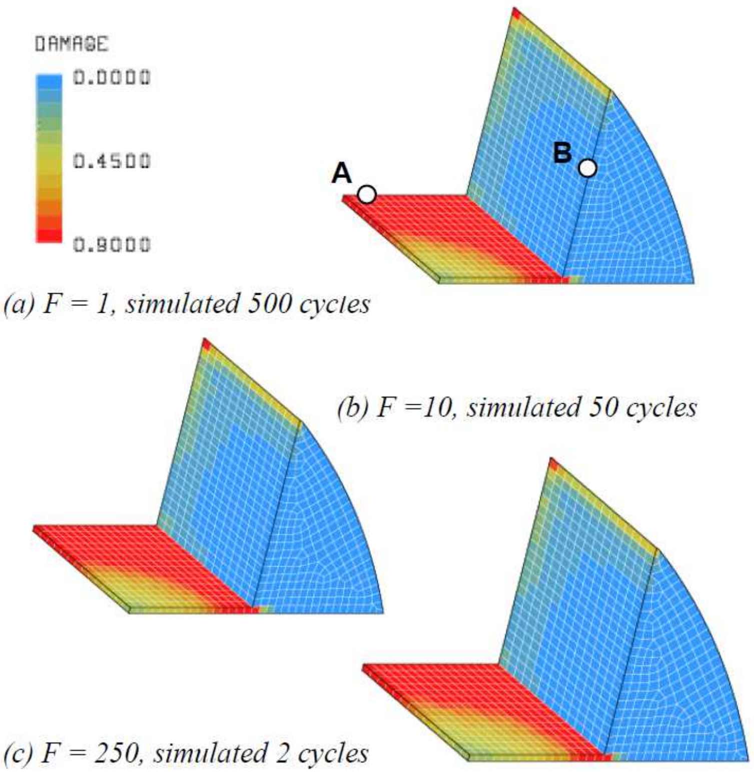
$$\dot{w} = \frac{\beta}{\alpha^{\beta}} \left(\gamma^{i}_{EQPS} \right)^{(\beta - 1)} \dot{\gamma}$$

Can just apply acceleration factor, ***F***, to damage rate eqn.

$$\dot{w} = \frac{F\beta}{\alpha^{\beta}} \left(\gamma^{i}_{EQPS} \right)^{(\beta - 1)} \dot{\gamma}$$

Acceleration of Simulations - UCPD





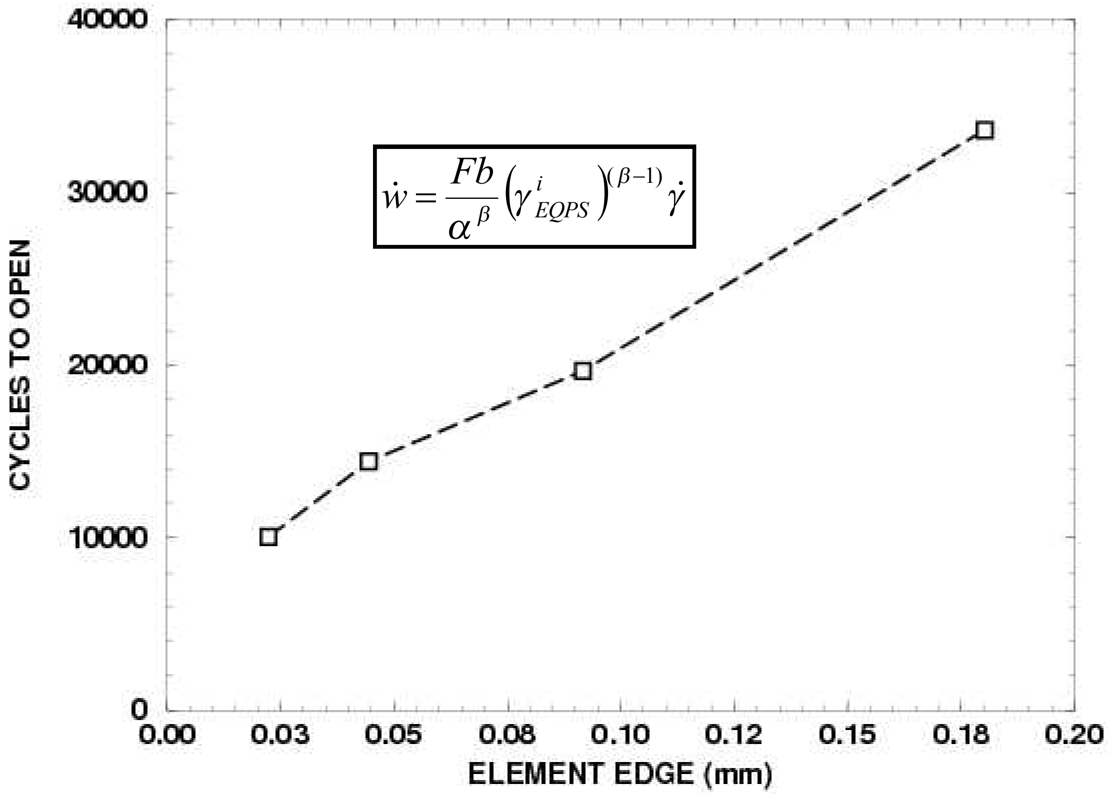
(a) F = 1, simulated 500 cycles

(b) F =10, simulated 50 cycles

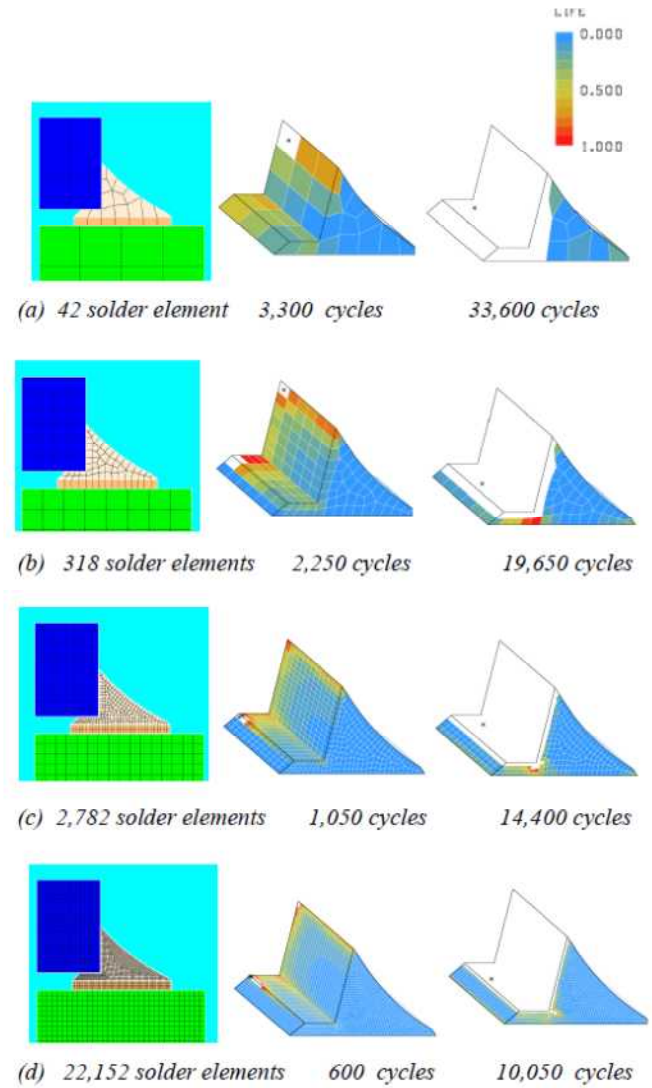
(c) F = 250, simulated 2 cycles

So does this really work ? Yes.

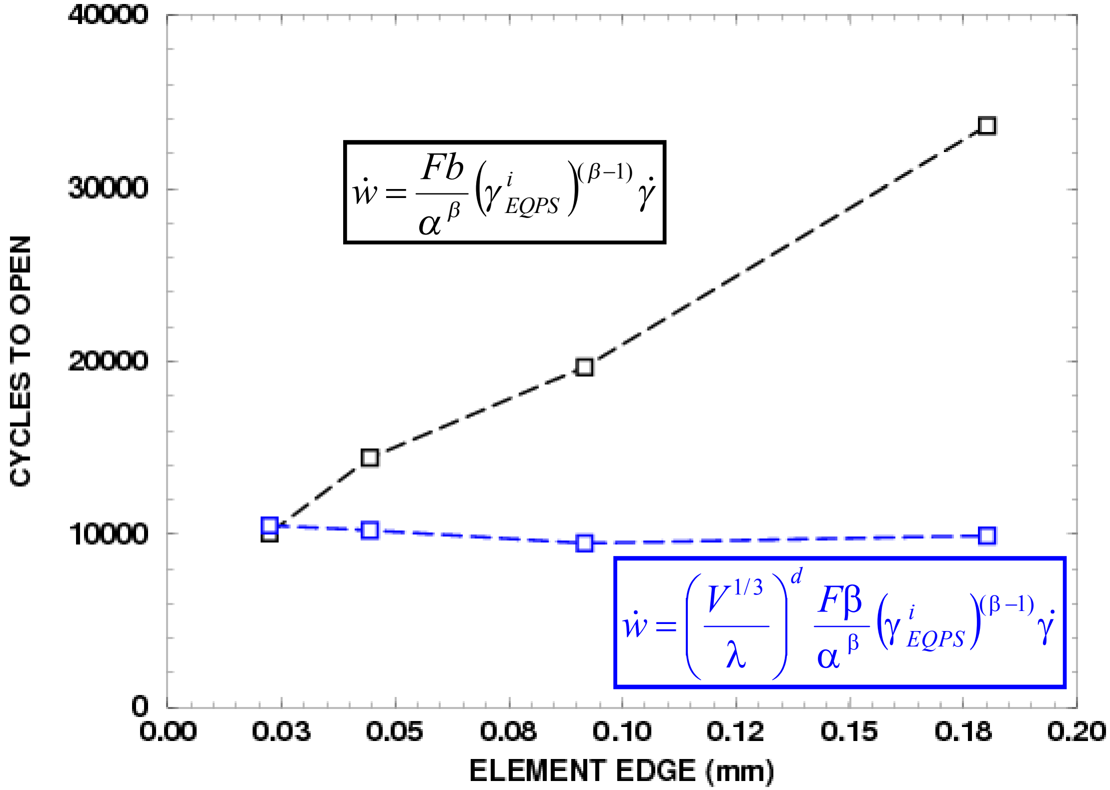
Eliminating Mesh Dependence



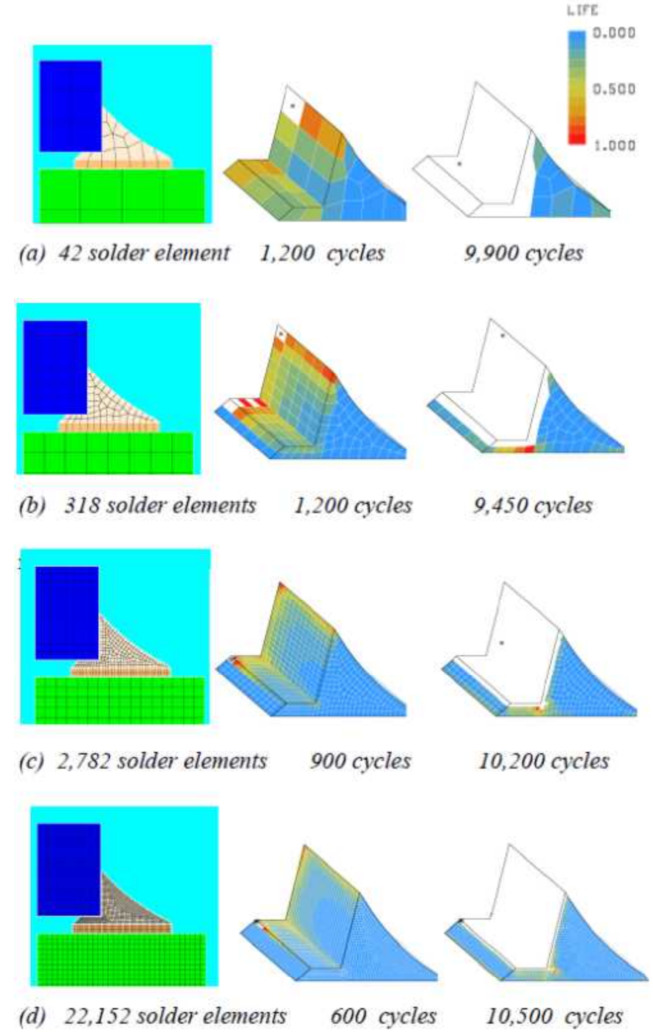
$$\text{Life} = \frac{\omega}{\omega_{critical}}$$



Eliminating Mesh Dependence



$$\lambda = 0.0254\text{mm},\ d = 0.61$$



TurboSIP – Finite Element Based Tool

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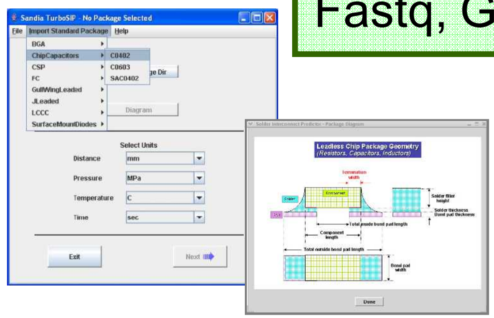
User Input - GUI
Geometry Material Props.

Mesh Generation Tools:
Fastq, Gen3d, Gjoin, Grepos



Finite Element Code:
JAS-3D

Solder **I**nterconnect **P**redictor

TMF Lifetime Prediction

Material Models:
Eutectic Sn-Pb Solder Model
UCPD Model for Pb-free Solder

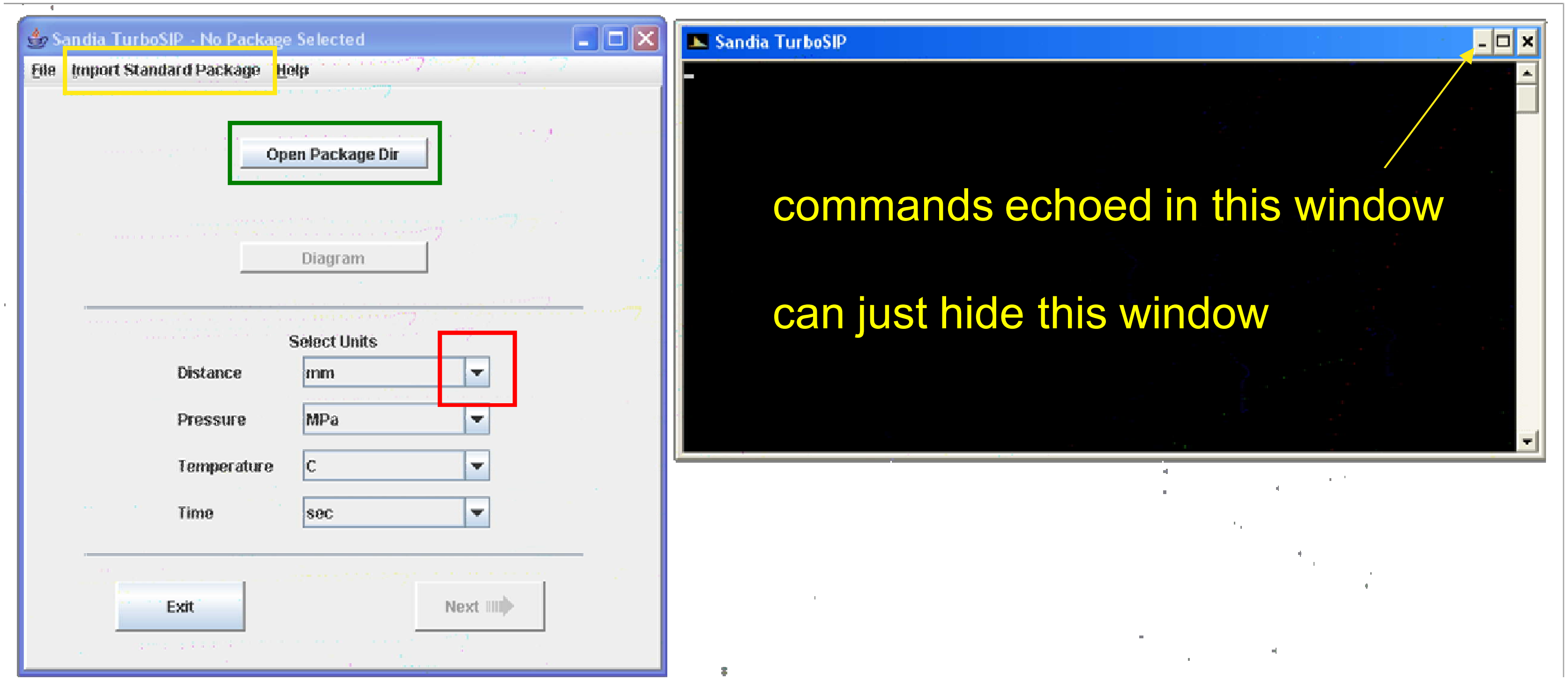
Post-Processing:
BLOT, ImageMagick

TurboSIP – Execution

Step 1. Start just like other Windows applications – get two windows below

Step 2. Select package type or open existing working folder

Step 3. Select units for input geometry (in or mm) and material parameters.



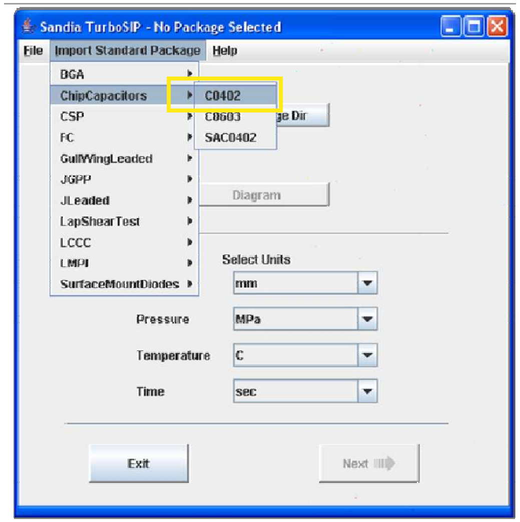
TurboSIP – Execution

Sandia National Laboratories

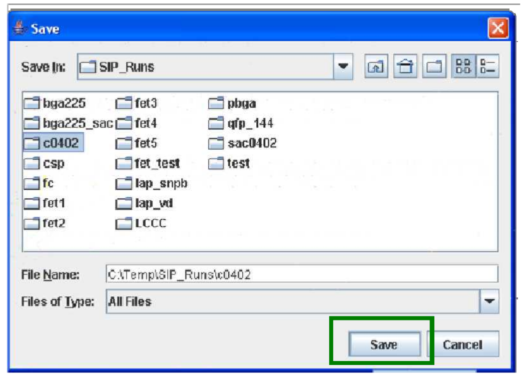
Step 4. For this example, start new project with C0402 Chip Capacitor.

Step 5. Choose C:\Temp\SIP_Runs\c0402 as working folder. Click Save

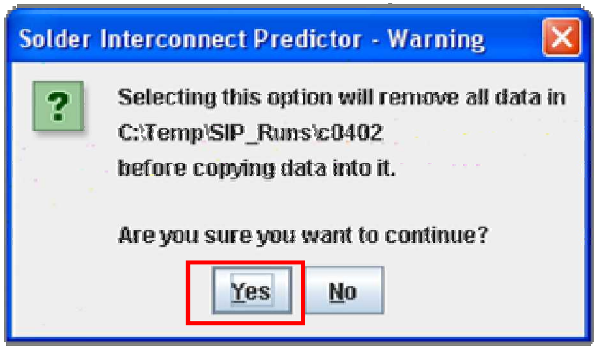
Step 6. Make sure selected folder can be erased BEFORE Clicking Yes !!!



Step 4.



Step 5.



Step 6.

TurboSIP – Execution

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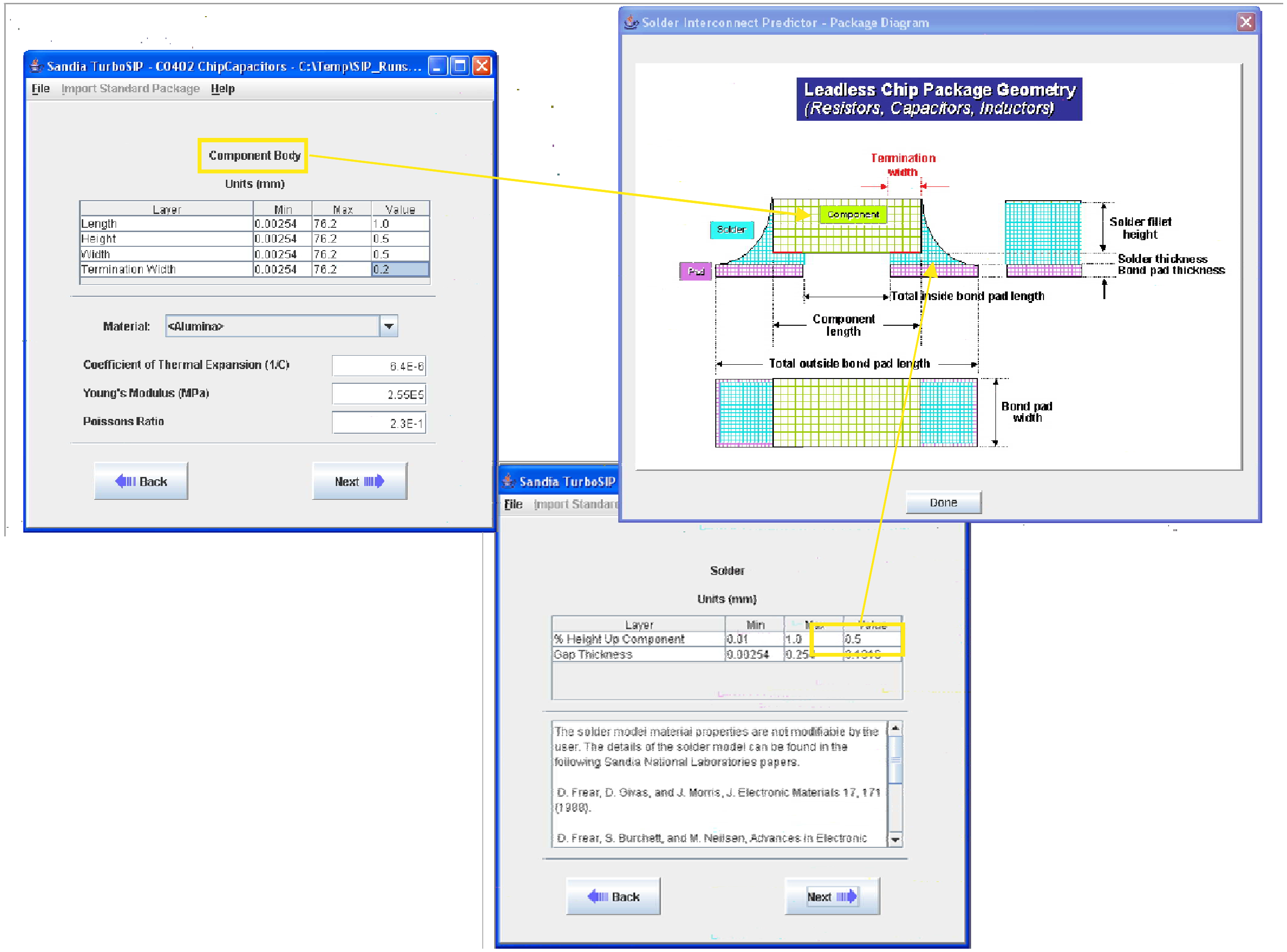
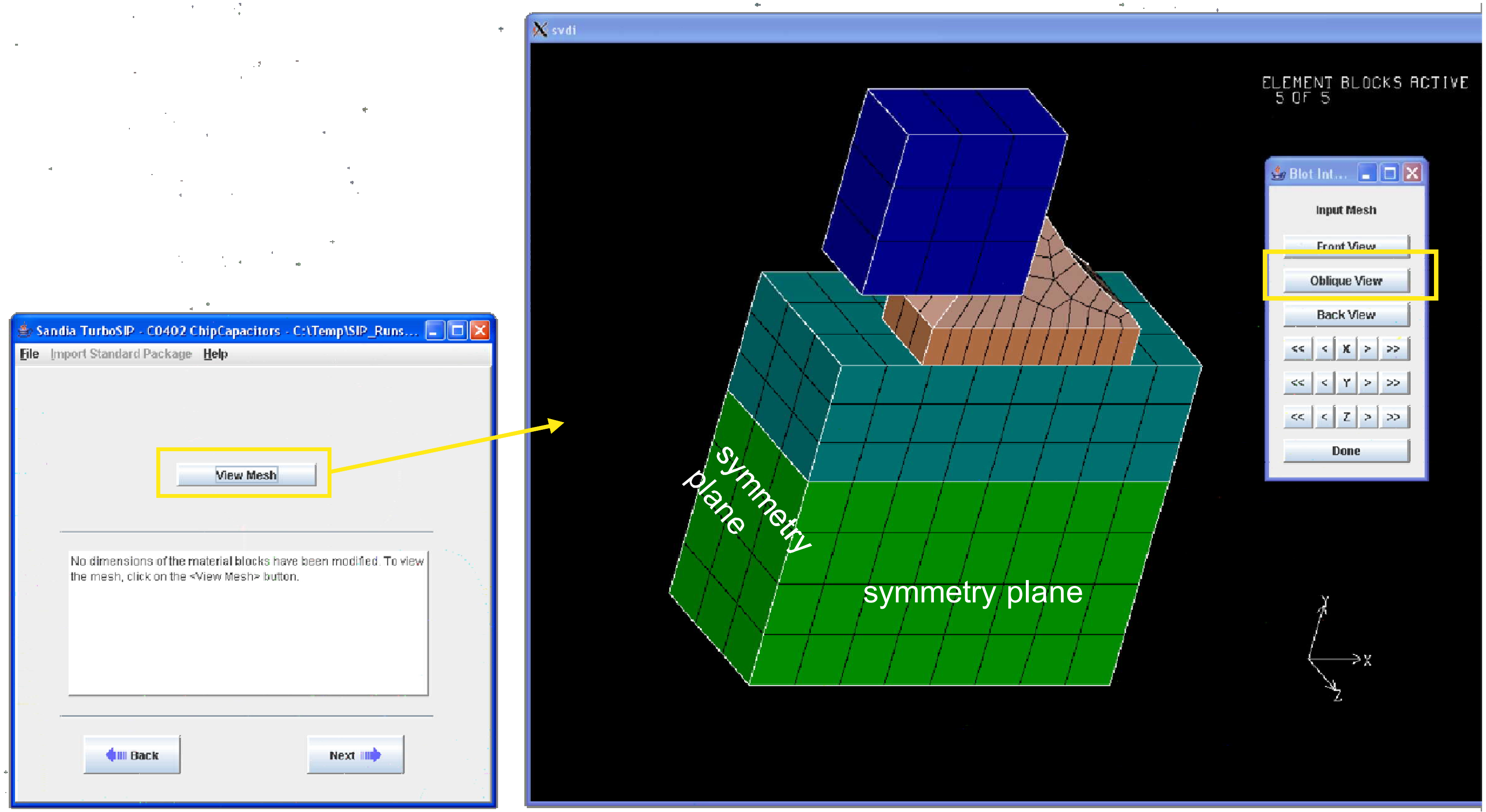
Step 7. Select Geometric Dimensions and Material Parameters



TurboSIP – Execution

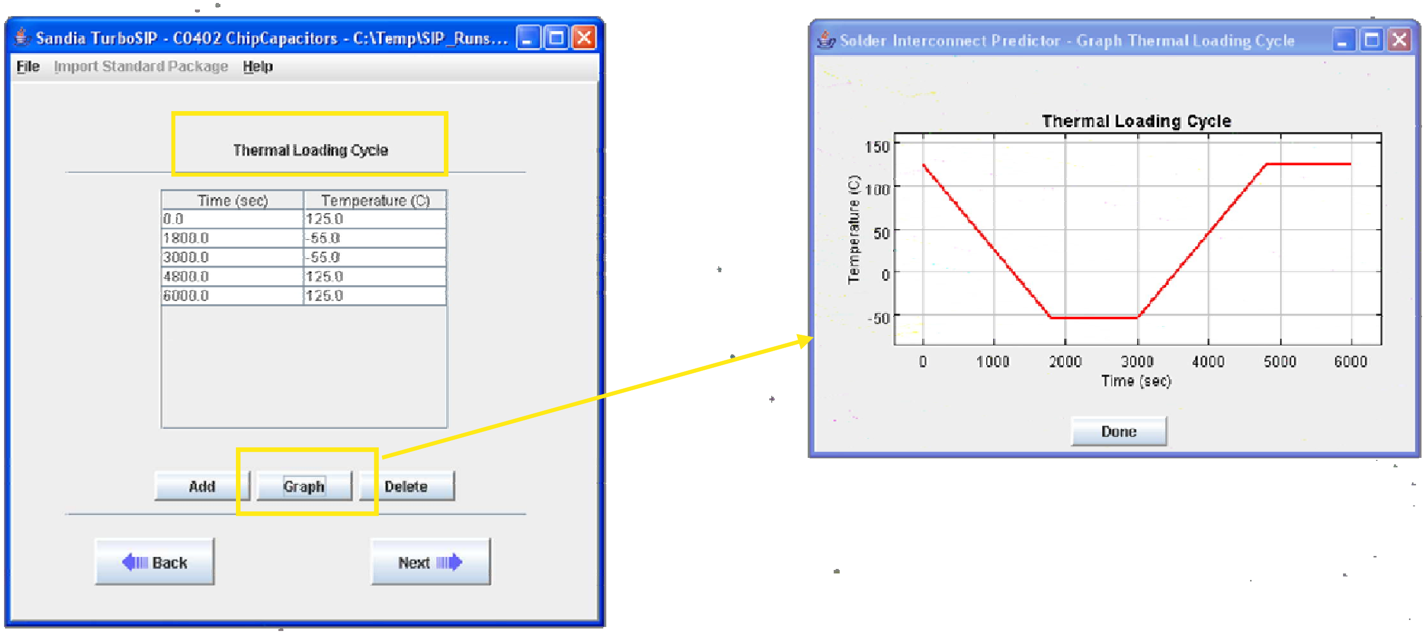
Step 8. Regenerate mesh (automatic) and look at mesh for reasonable number and shape of elements.

If graphics window does not open make sure Xming is running then click View Mesh again.



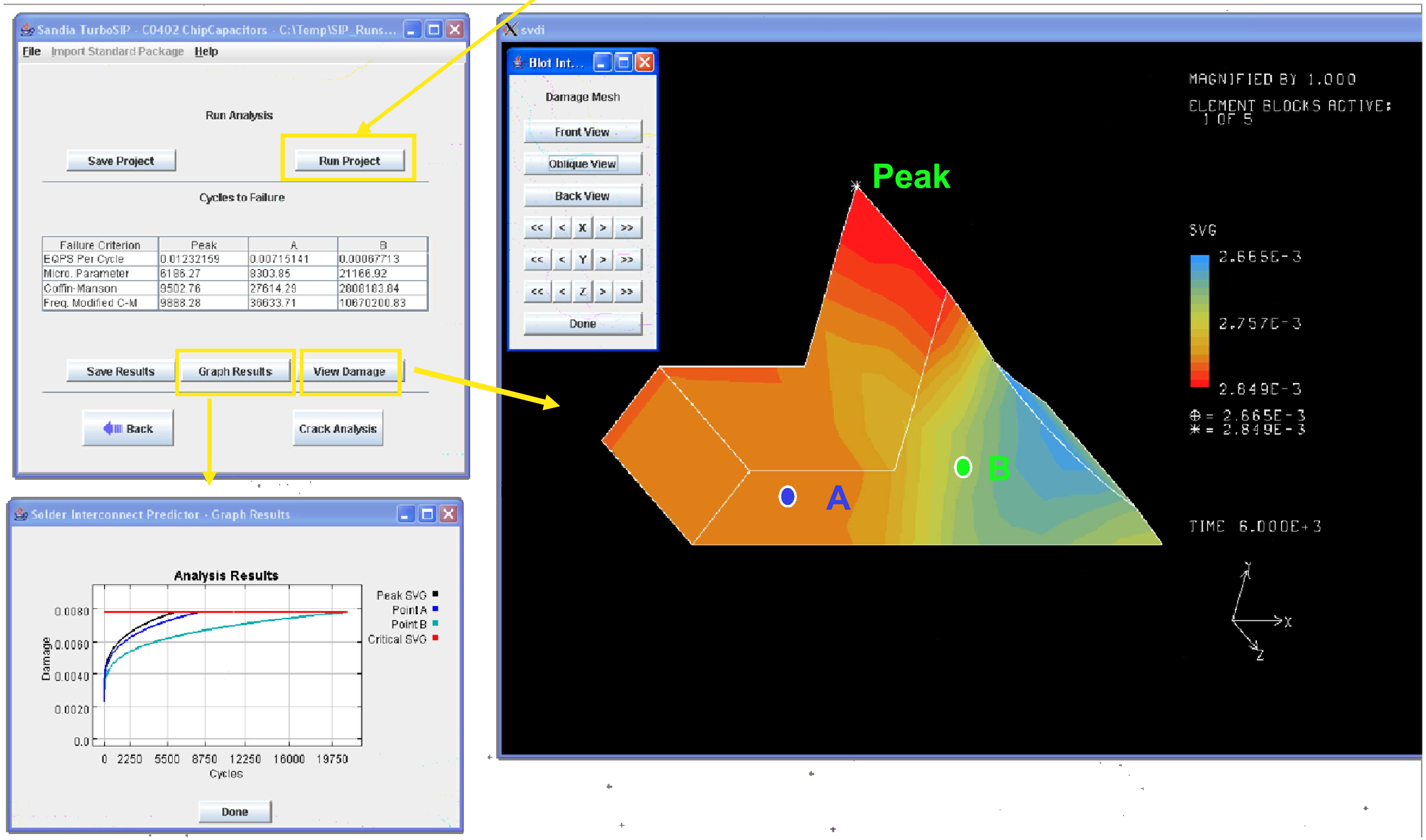
TurboSIP – Execution

Step 9. Prescribe temperature history with ramp for first leg.



TurboSIP – Execution

Step 10. Run simulation by pressing Run Project, wait, and View Results.



TurboSIP – Execution

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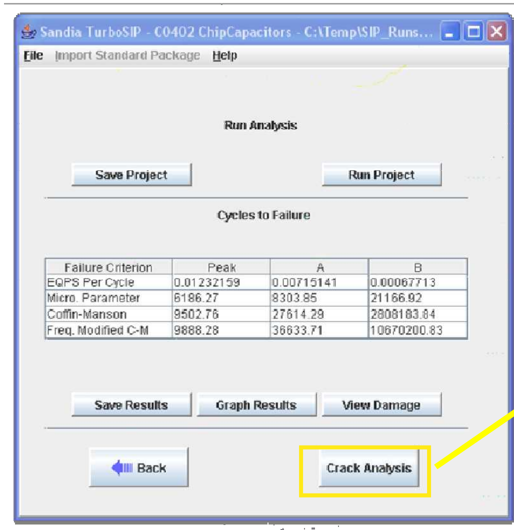
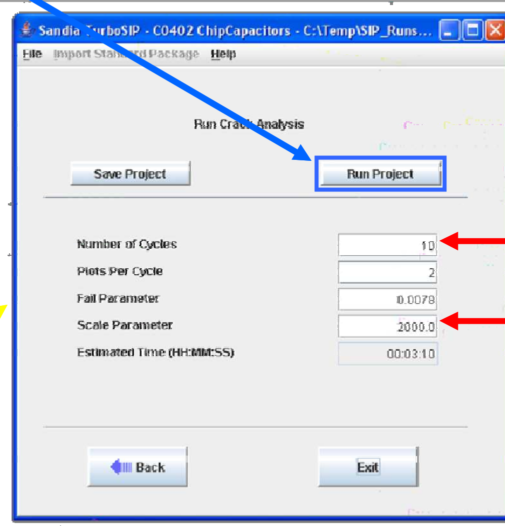
Step 11. Simulate crack growth by pressing Crack Analysis button.

Step 12. Specify Number of Cycles to Simulate and Scale Parameter on next window.

Step 13. Click on Run Project



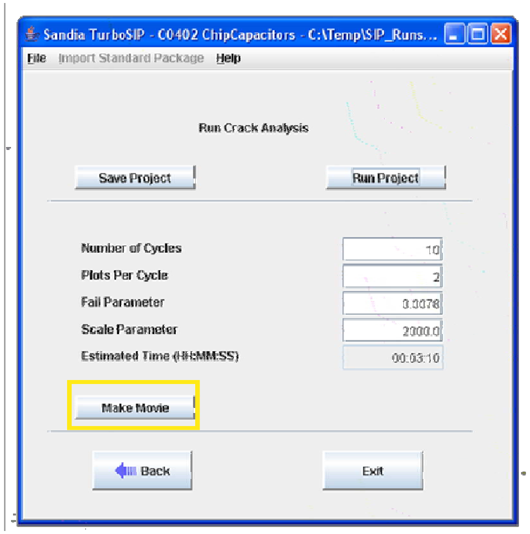


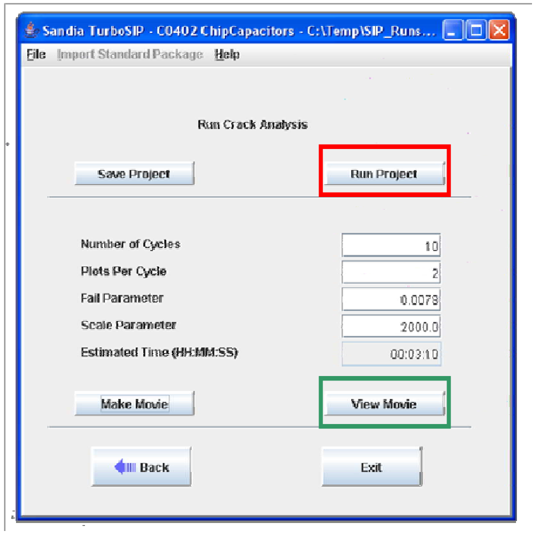
scale of 2,000 means that each simulation cycle will generate the same damage as 2,000 actual cycles

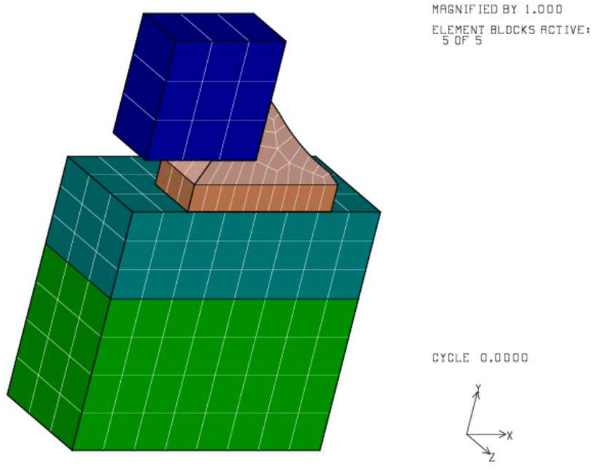
TurboSIP – Execution

Step 13. Make movie of crack growth with Make Movie button.

Step 14. View animation with View Movie button. Rerun crack simulation with different number of cycles as needed with Run Project.





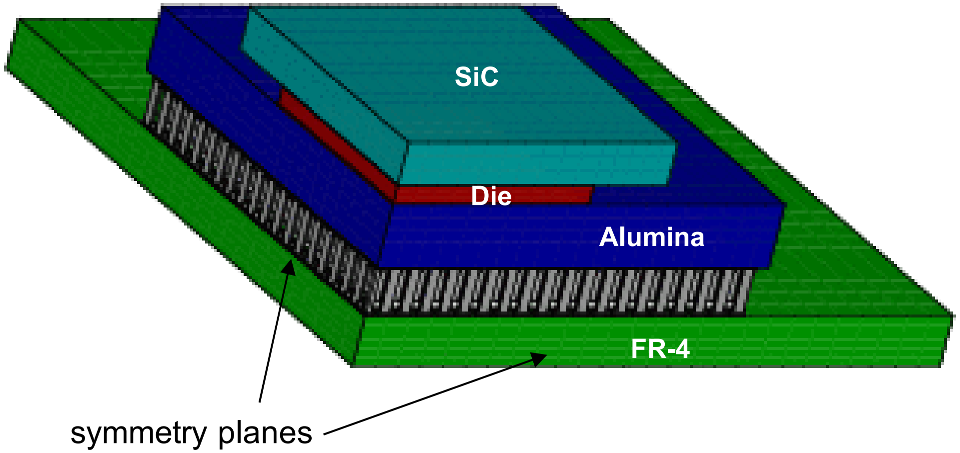


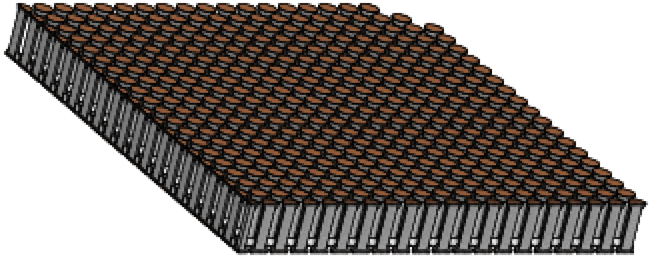
$$\text{Life} = \frac{\omega}{\omega_{critical}}$$

Comparison with SRS™ and Sherlock™

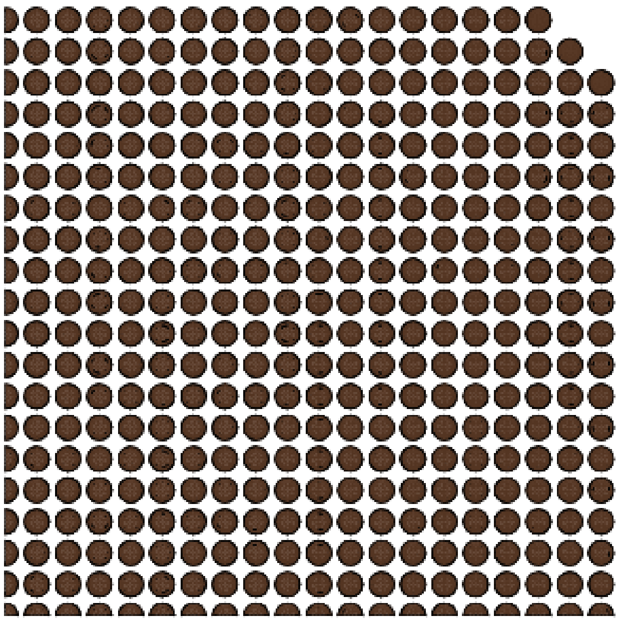
Software	Models Used	Solder(s)	Environments	Support/Other
Solder Reliability Solutions – SRS™ J.Clech	analytical/empirical	eutectic Sn/Pb only	thermal cycling	yes for a fee
Sherlock™ DFR Solutions	analytical/empirical finite element to get model shapes/freq.	eutectic Sn/Pb SAC305	thermal cycling shock vibration	yes
TurboSIP Sandia Labs	finite element*	eutectic Sn/Pb SAC396 (other can be added)	thermal cycling (working on shock/vib)	limited/export controlled software
SIP Lite	analytical/empirical	eutectic Sn/Pb	thermal cycling	limited

TurboSIP Flexibility to Study New Materials



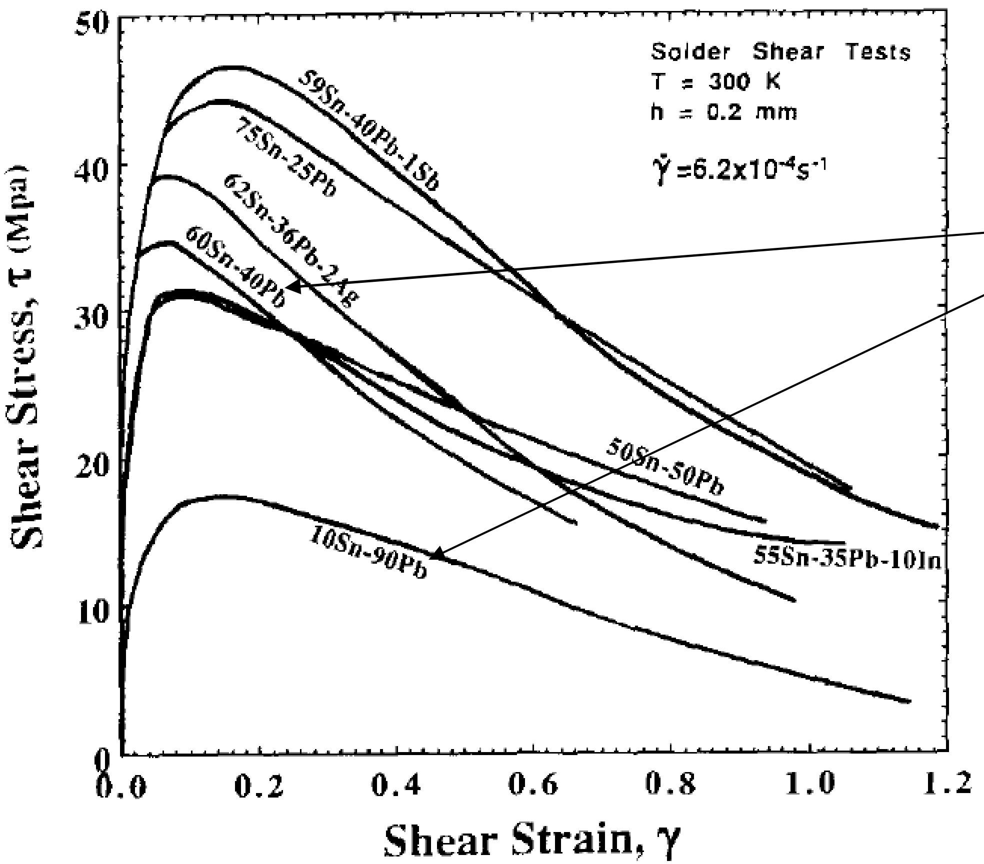


solder joints / cu pads



Ceramic Column Grid Array with 90Pb10Sn Columns and 63Sn37Pb Joints

TurboSIP Flexibility to Study New Materials



90Pb10Sn is actually much weaker than 63Sn-37Pb

90Pb10Sn modeled as 63Sn37Pb with α = 0.60

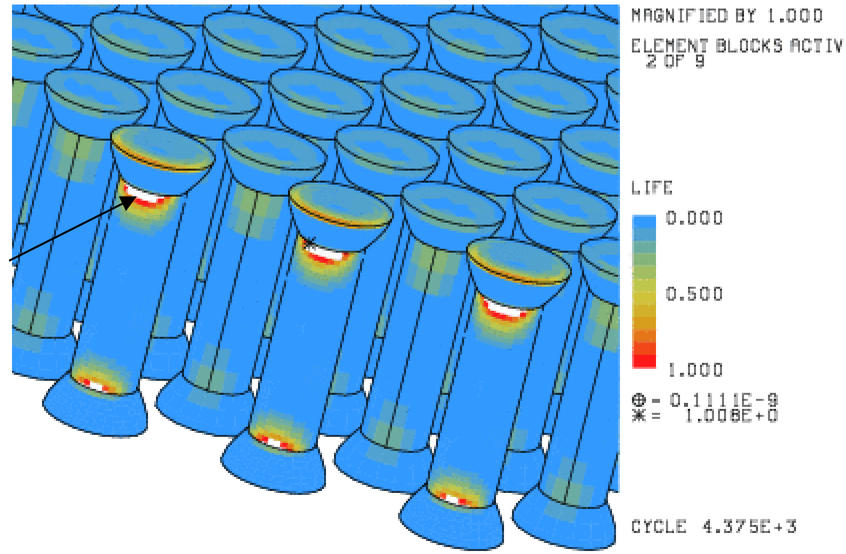
Reference: Z. Guo et al., Journal of Phase Equilibria, Vol. 13, No. 3, 1992.

TurboSIP Flexibility to Study New Materials

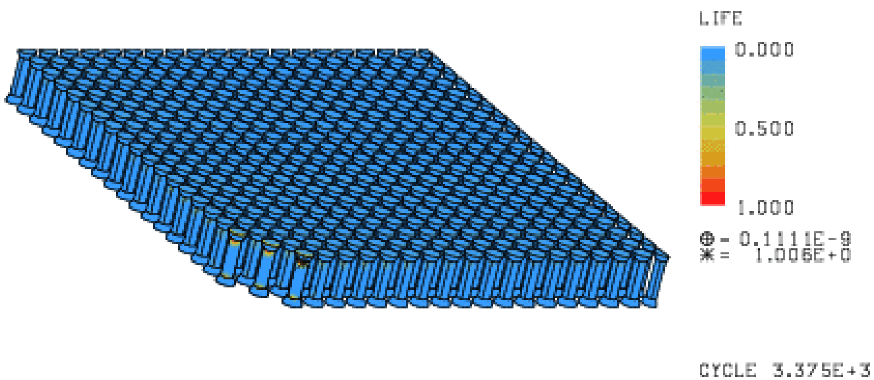
predictions: crack start at 3625 cycles
open at ~ 5000 cycles

Typical IBM Column Failure
Image from IBM.com

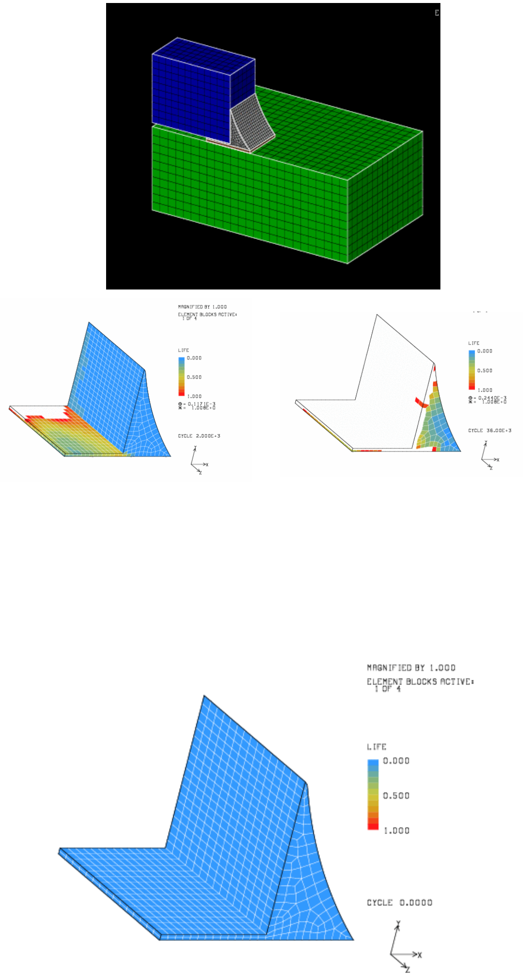
crack predicted here
crack observed here
in 90Pb/10Sn column



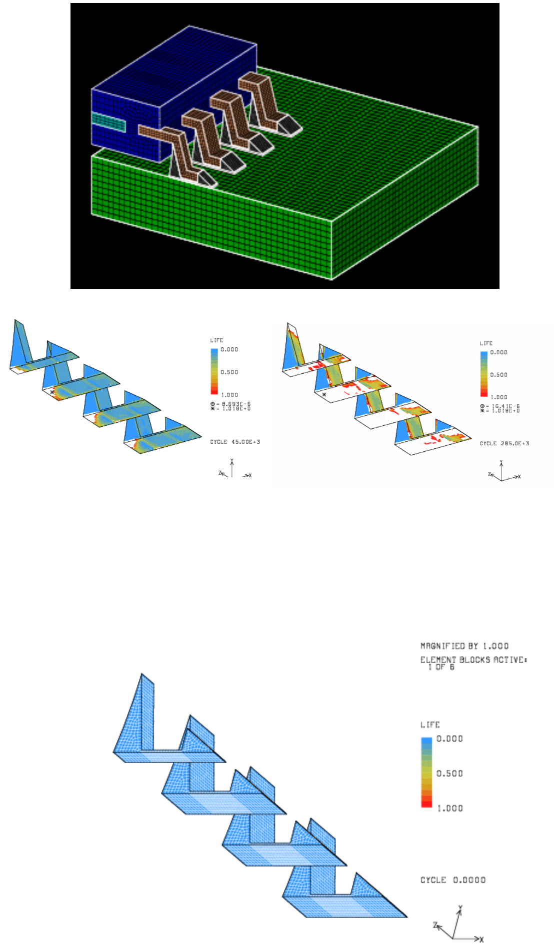
model prediction at 4375 cycles



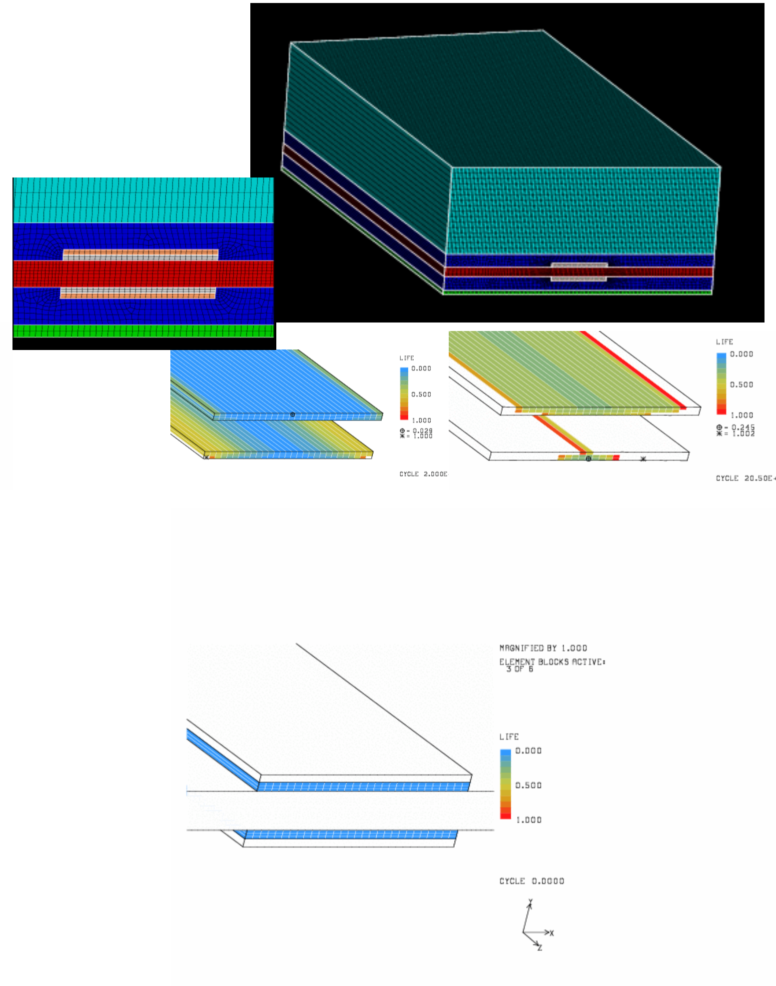
TurboSIP Flexibility to Study New Geometry



C1206



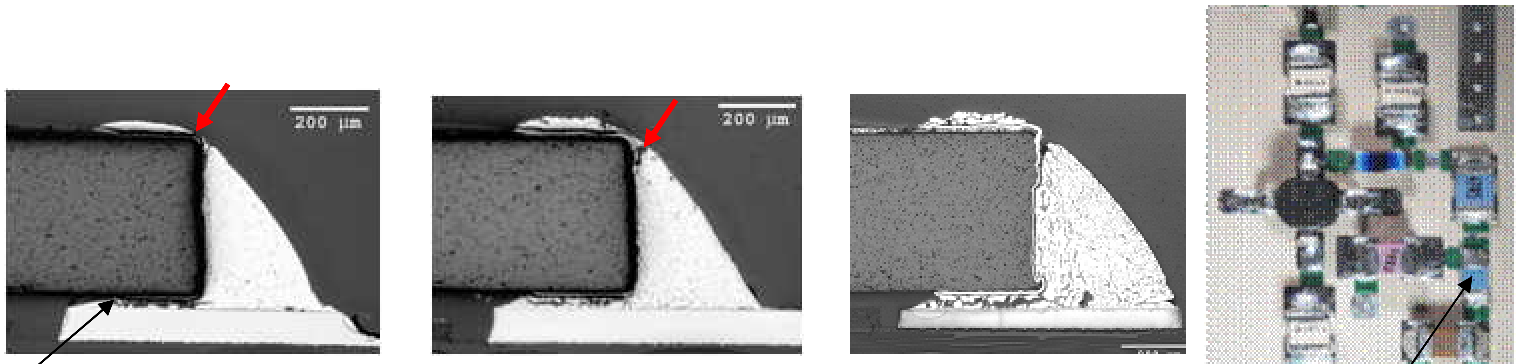
SOIC-14



Solar Panel Cu Conductor

Validation - Sandia R23 UCPD Solder

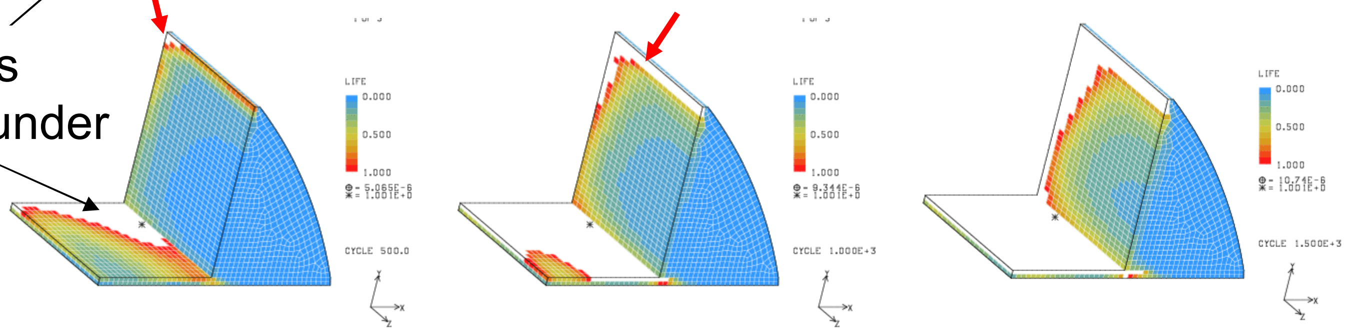
Sn-Pb solder



outside | outside | mid-plane

cracks start under

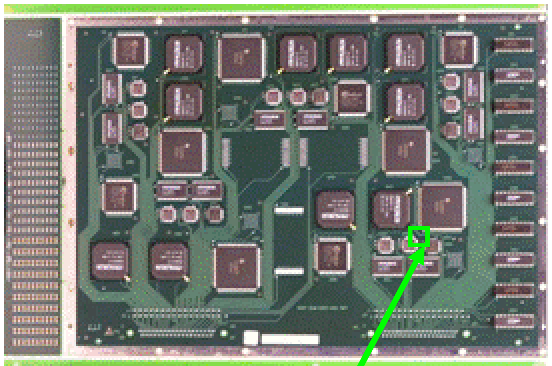
UCPD model



500 cycles | *1000 cycles* | *1500 cycles*

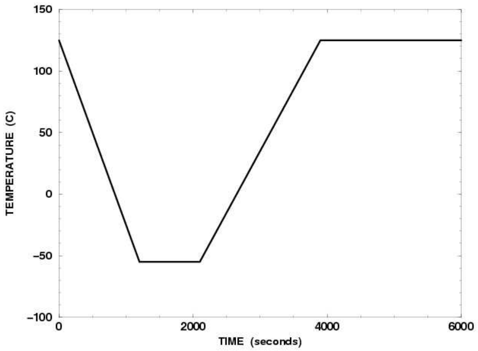
Accelerated Aging -55 to 125 Thermal Cycles
Failure based on damage $w = 0.90$
White elements = cracked elements.

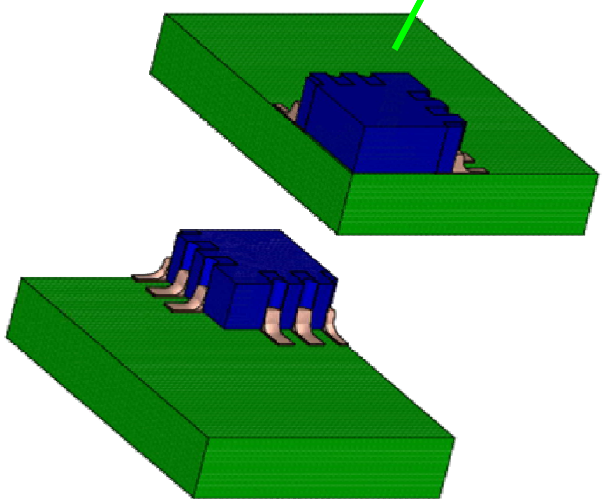
Validation - CLCC-20 SnPb Solder



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

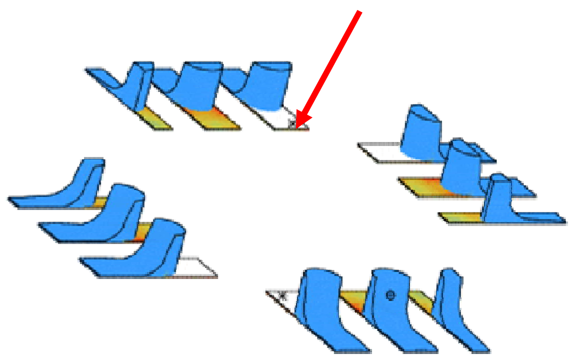
Model: 63Sn37Pb solder
Electrical open: 975 cycles



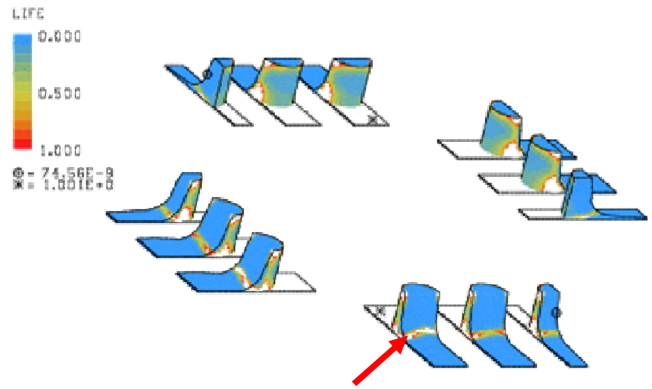


CLCC-20 - Finite Element Model – ¼ symmetry

crack start



50 cycles



975 cycles

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