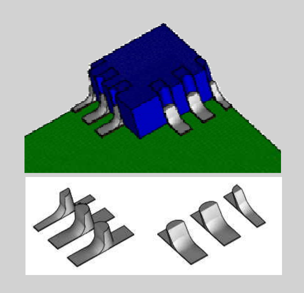
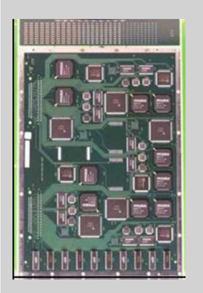
SAND2013-5400C





Unified Creep Plasticity Damage (UCPD) Model for SAC396 Solder

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

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

Mike Neilsen and Paul Vianco

Sandia National Laboratories
New Mexico, USA

InterPACK2013-73074
July 16-18, 2013, Burlingame, CA, USA

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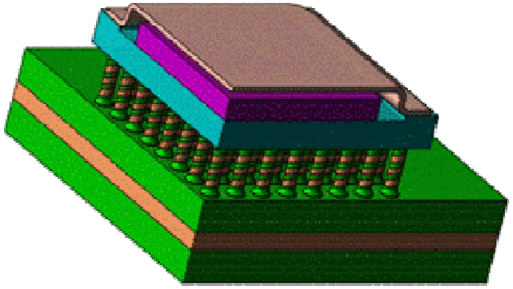
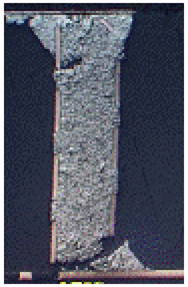
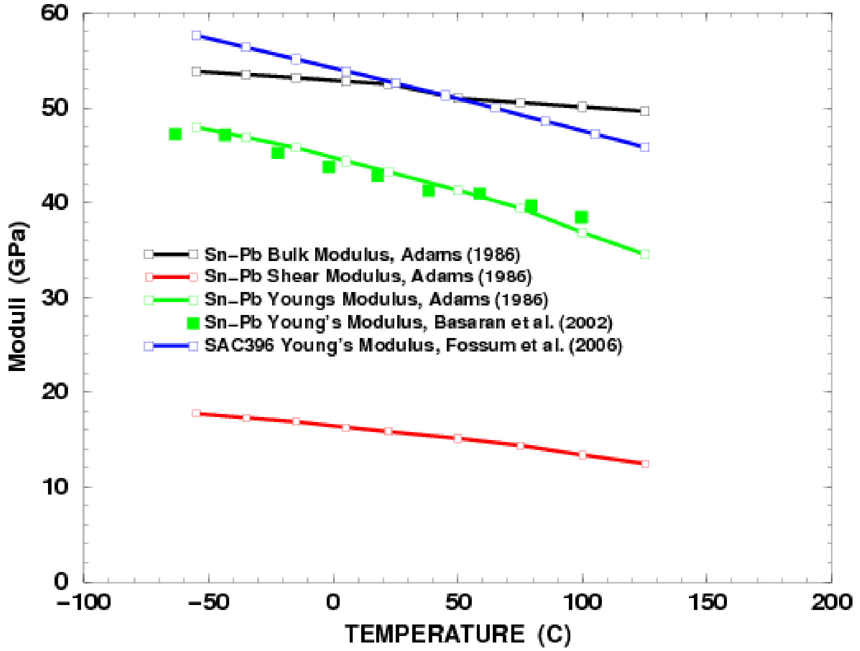
Outline

- Mechanical Behavior of Eutectic 63Sn-37Pb and SAC Solder
- Low Cycle Fatigue Failure Criteria
- Unified Creep Plasticity Damage (UCPD) Model for Solder
- Simulating Crack Initiation and Growth
- Applications





Elasticity – SnPb 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)

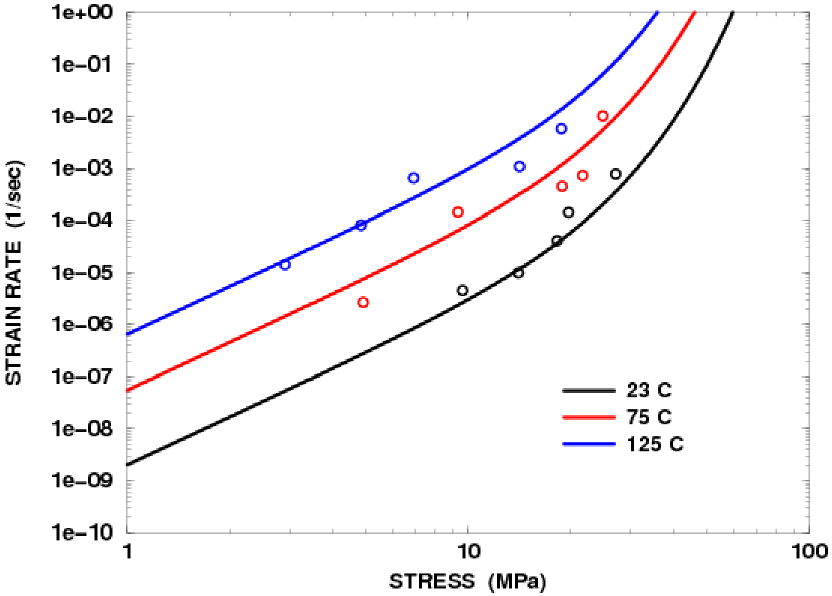
60Sn-40Pb solder

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

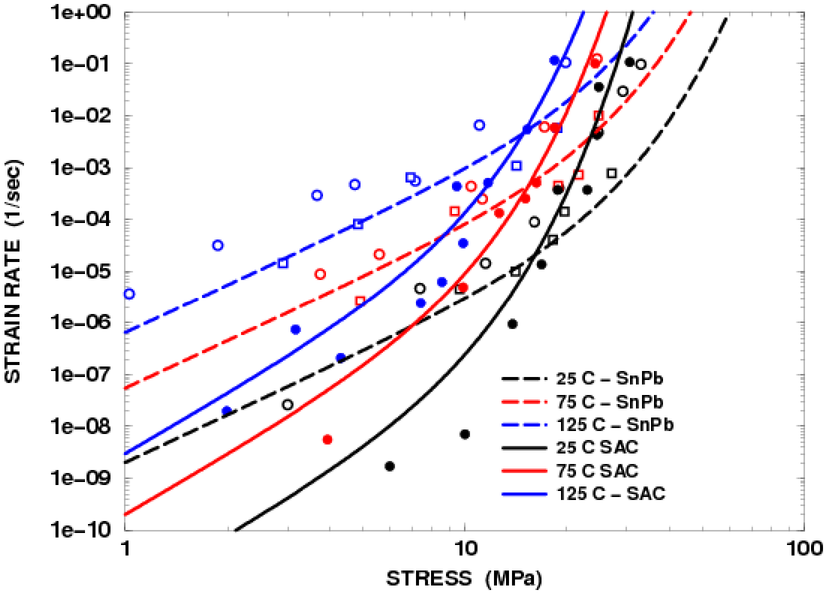
C. Basaran et al., 'Measuring intrinsic elastic modulus of Pb/Sn solder alloys,' Mech. of Materials, ***34*** *(2002).*

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

Creep – SnPb and SAC396



63Sn37Pb

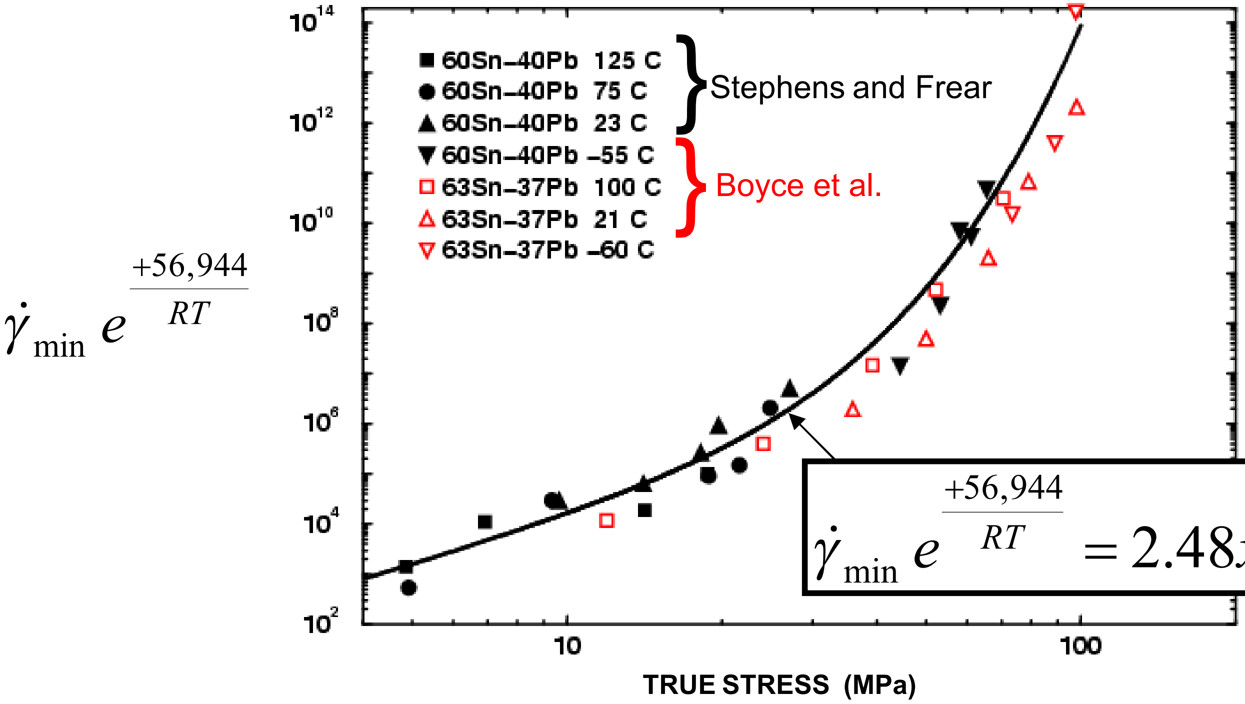


SAC396 vs. SnPb

Ref: 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



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

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

Ref: 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.

UCP Model for Solder

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

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

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

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

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

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

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

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.*

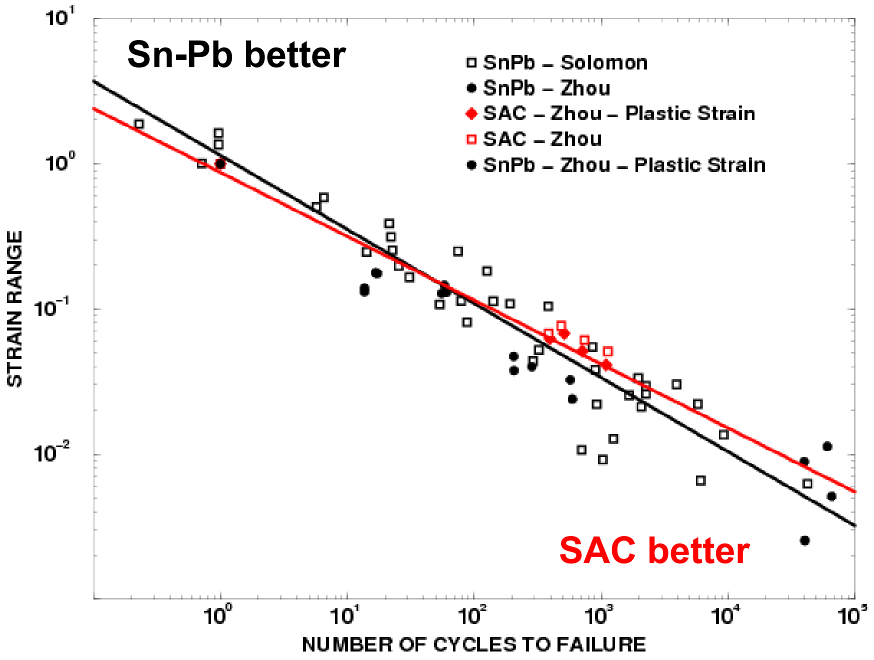
Low Cycle Fatigue Experimental Data

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

Existing Damage Models for Solder

Solomon (1986) *Experimental Solder Data* →

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

Fossum et al. (2006)

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

$$N = f(\sigma) \neq g\left(\Delta\gamma_{EQPS}\right)$$

Wei et al. (2006)

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

→

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

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

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

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

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

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

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

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

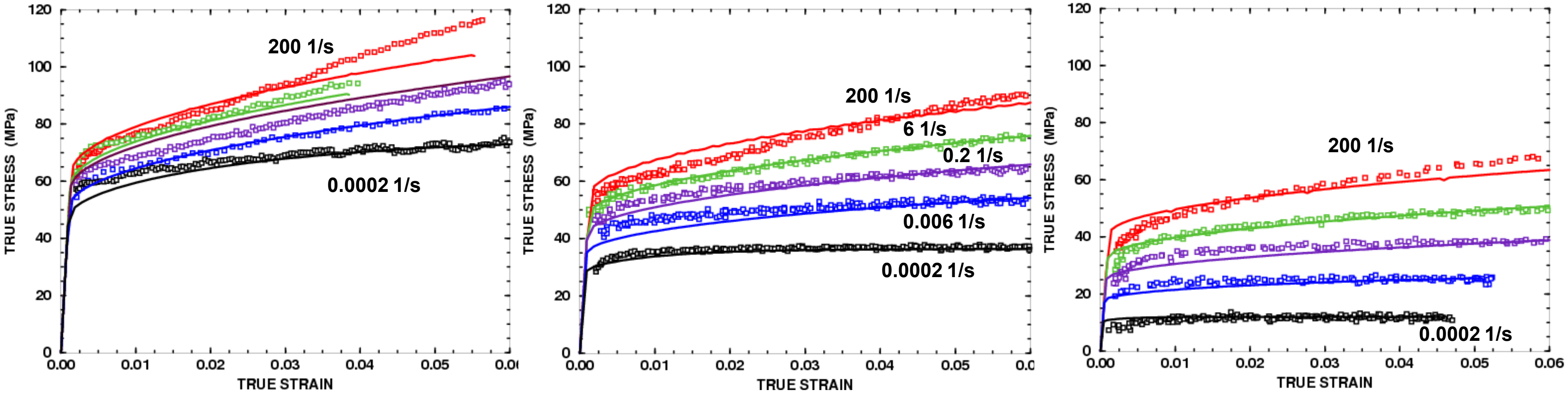
$$\tau = \sqrt{\frac{3}{2}\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right):\left(\mathbf{s} - \frac{2}{3}\mathbf{B}\right)}$$

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

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

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

63Sn-37Pb Solder



-60 ^oC isothermal tests

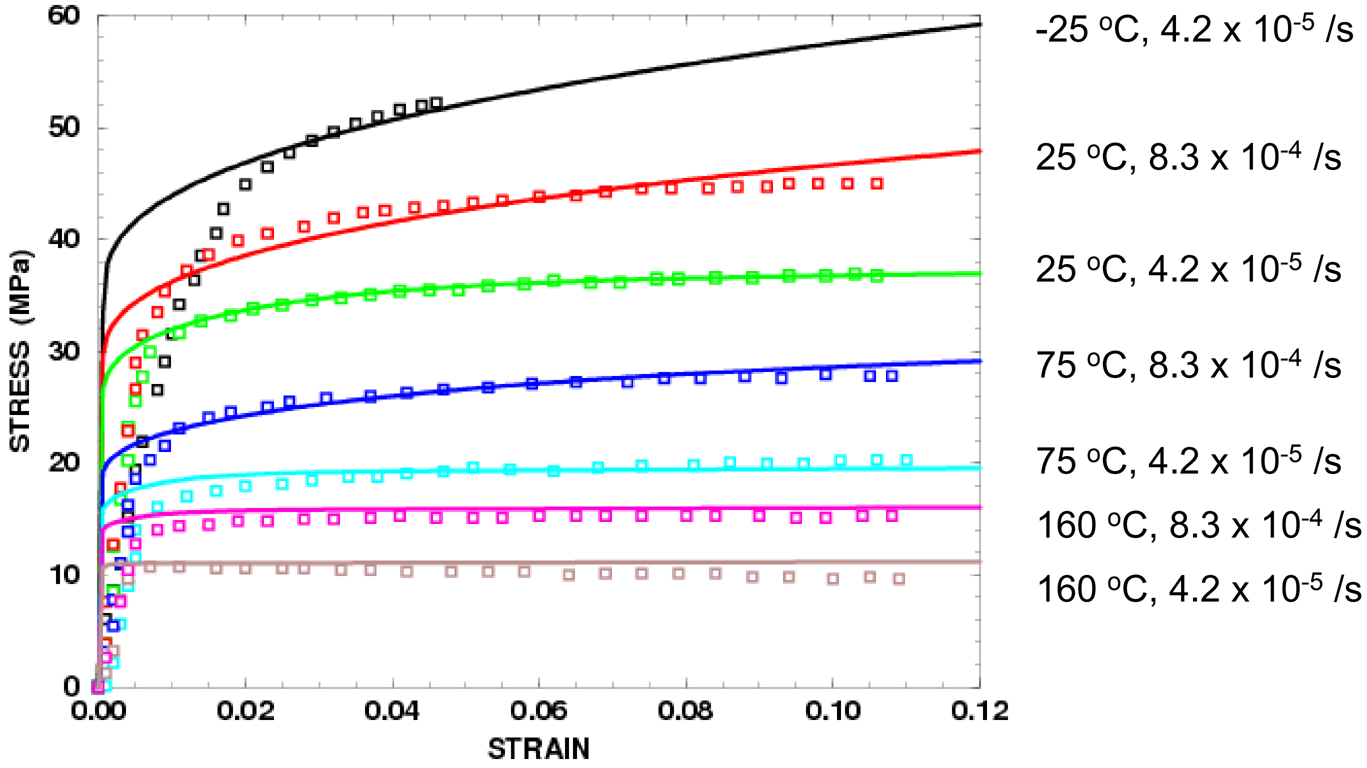
21 ^oC isothermal tests

100 ^oC 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.*

SAC396 Solder



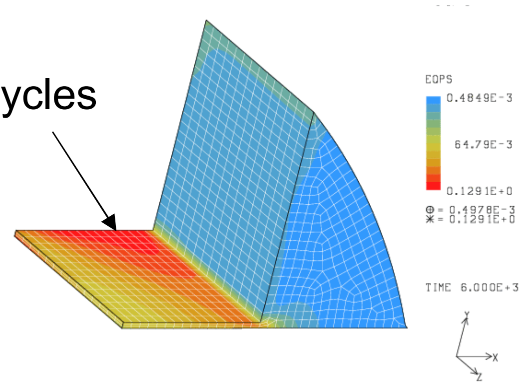
Fit with Elastic Moduli from Dynamic Modulus Measurements

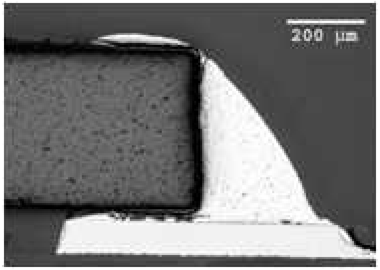
Reference: Fossum et al., J. Electronic Packaging, Vol. 128, March 2006

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

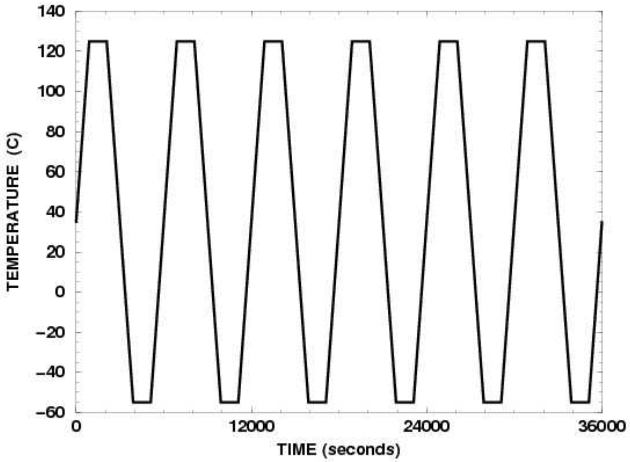
Solution: Accelerated Simulation – Acceleration Factor Applied to Damage.

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

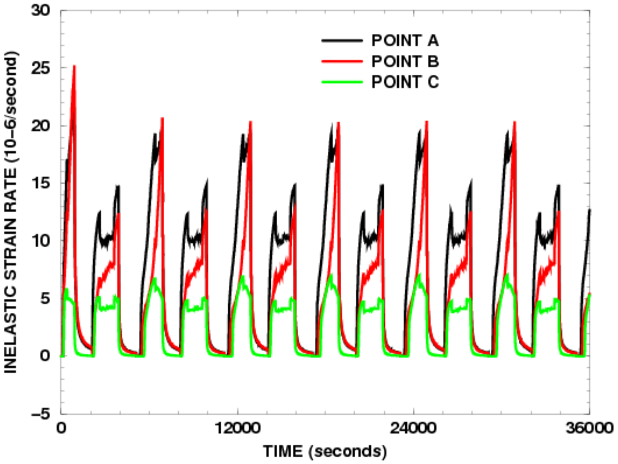
Solution: Smeared Cracking Approach – Replace Cracked Elements with Weak Elastic Material.

What to do about local model giving mesh dependent solutions ?

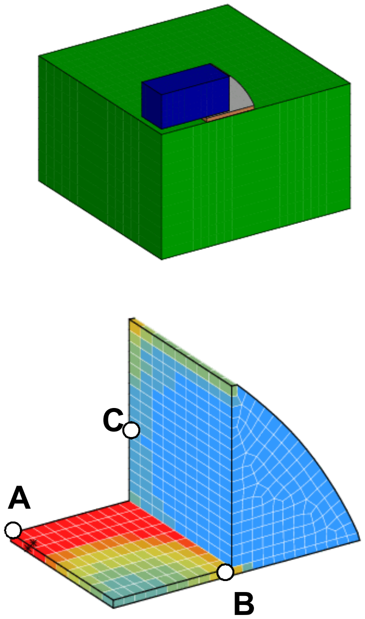
Acceleration of Simulations - UCPD



Temperature History



Strain Rate History



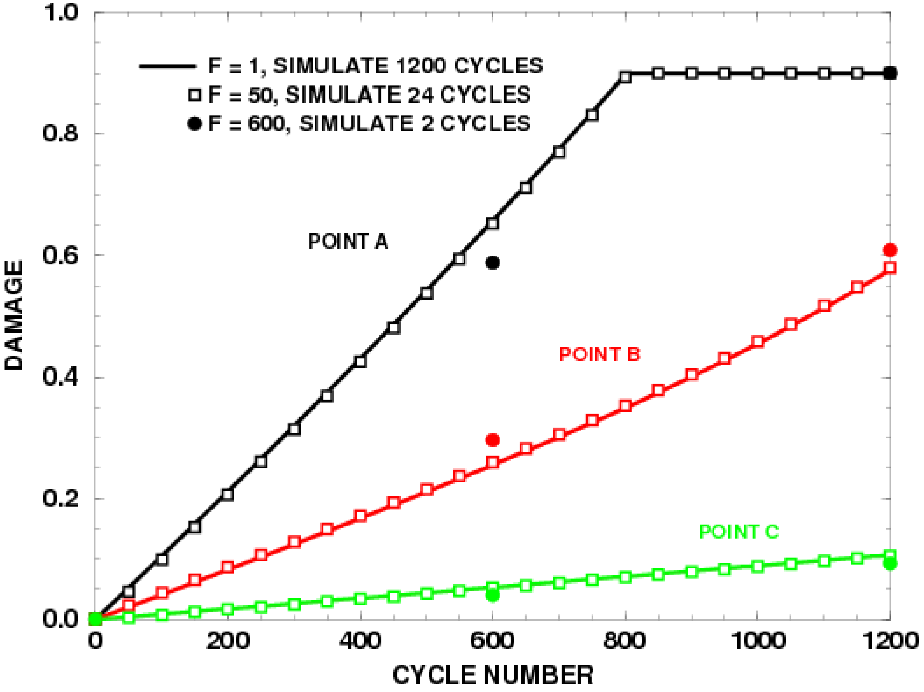
If the inelastic rate histories do not change between cycles then:

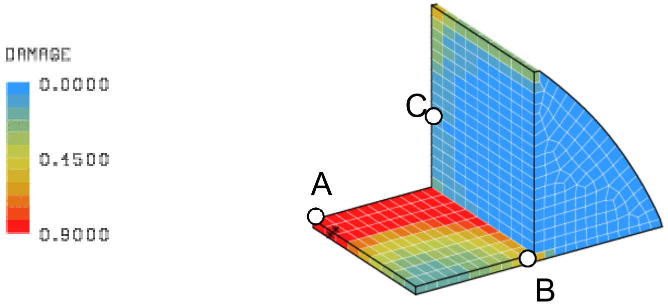
$$\dot{w} = \frac{b}{a^b}\left(\gamma^{i}_{EQPS}\right)^{(b-1)}\dot{\gamma}$$

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

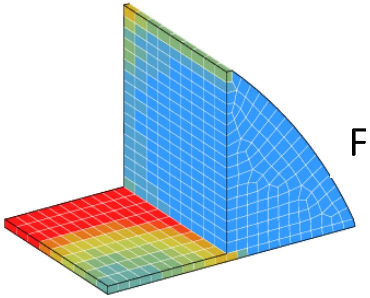
$$\dot{w} = \frac{Fb}{a^b}\left(\gamma^{i}_{EQPS}\right)^{(b-1)}\dot{\gamma}$$

Acceleration of Simulations - UCPD

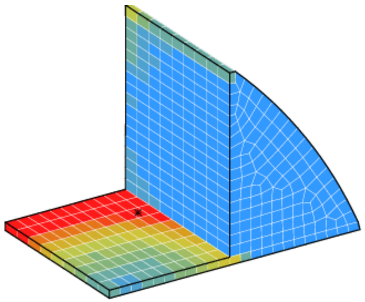




F = 1, simulated 1200 cycles



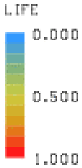
F = 50, simulated 24 cycles



F = 600, simulated 2 cycles

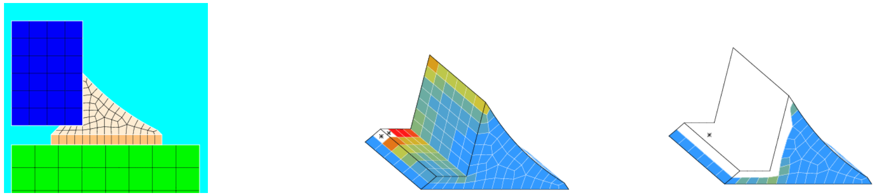
So does this really work ? Yes.

Eliminating Mesh Dependence

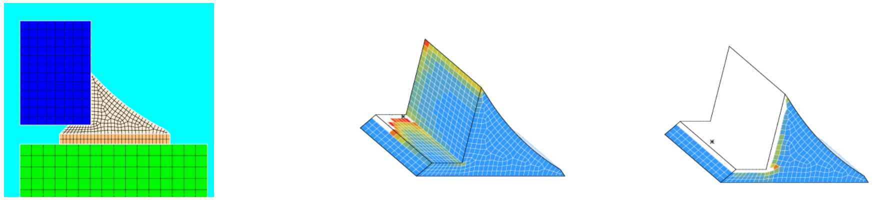


$$Life = \frac{w}{w_{fail}} = \frac{w}{0.9}$$

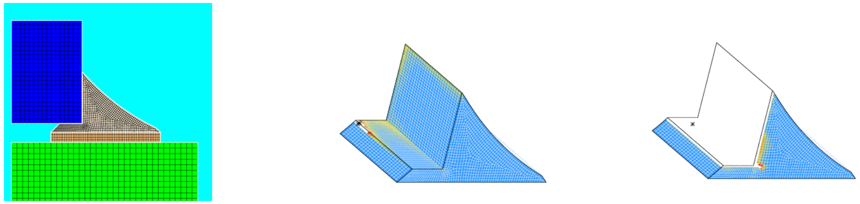
$$\dot{w} = \frac{Fb}{a^b}\left(\gamma^{i}_{EQPS}\right)^{(b-1)}\dot{\gamma}$$



318 solder elements 4,000 cycles 61,500 cycles

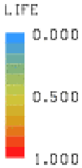


2,782 solder elements 2,000 cycles 39,500 cycles



22,152 solder elements 600 cycles 24,000 cycles

Eliminating Mesh Dependence

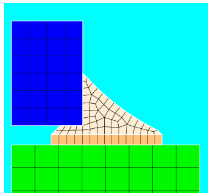


$$Life = \frac{w}{w_{fail}} = \frac{w}{0.9}$$

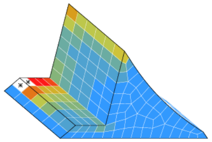
$$\dot{w} = \left(\frac{V^{1/3}}{\lambda}\right)^{d} \frac{Fb}{a^{b}} \left(\gamma^{i}_{EQPS}\right)^{(b-1)} \dot{\gamma}$$

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

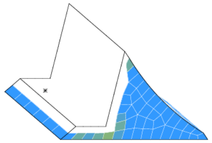
$$V = element\ volume$$



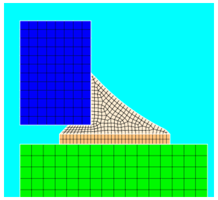
318 solder elements



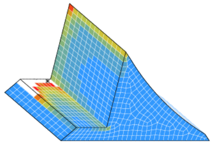
2,000 cycles



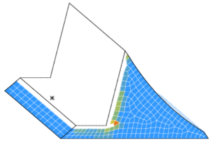
24,750 cycles



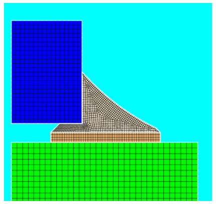
2,782 solder elements



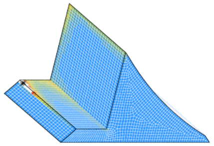
1,000 cycles



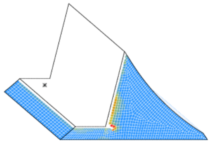
25,750 cycles



22,152 solder elements



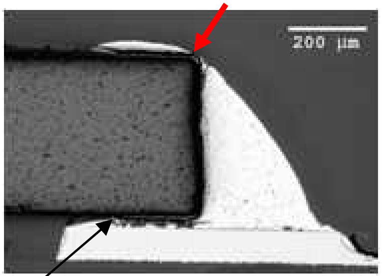
750 cycles



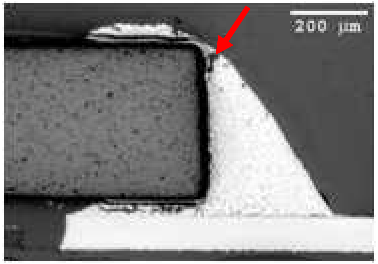
26,000 cycles

Sandia R23 Sn-Pb Solder

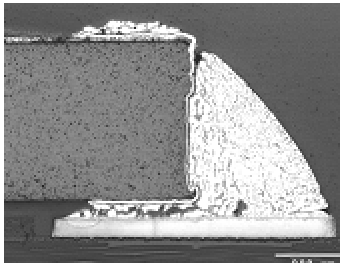
Sn-Pb
solder



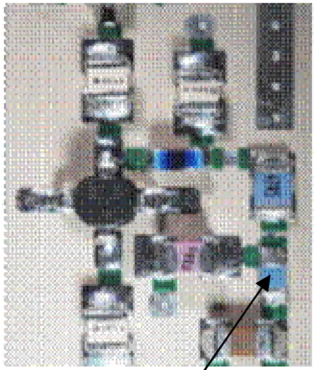
outside



outside

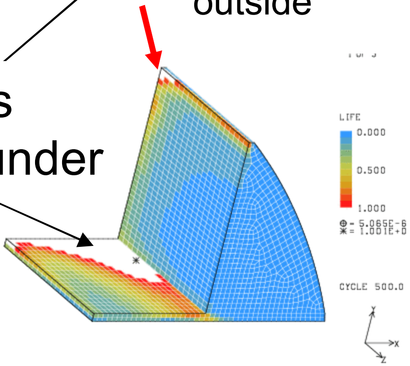


mid-plane

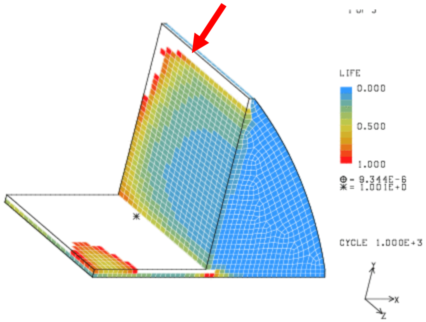


cracks
start under

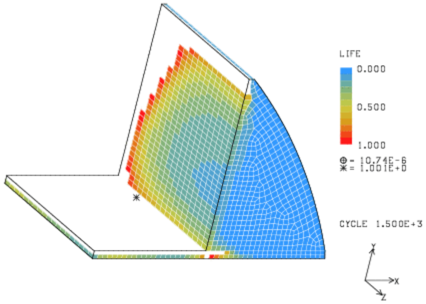
UCPD
model



500 cycles



1000 cycles



1500 cycles

Accelerated Aging -55 to 125 Thermal Cycles

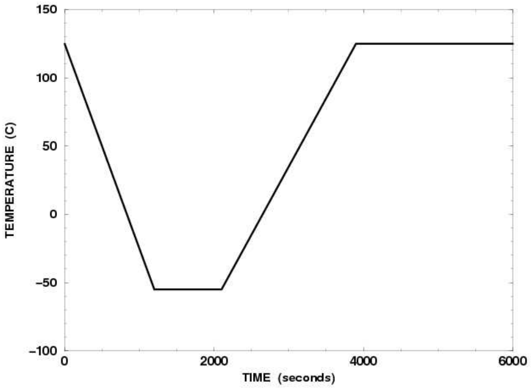
Failure based on damage w = 0.90

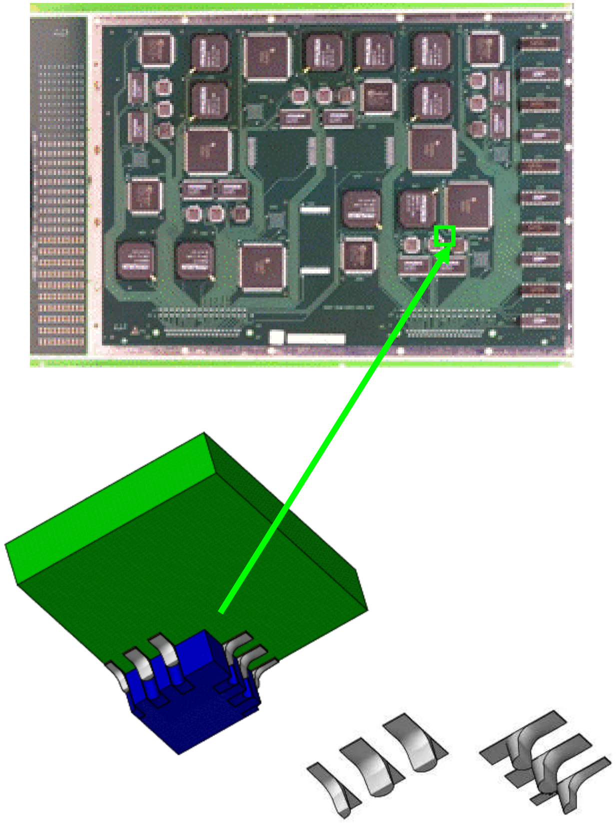
White elements = cracked elements.

JCAA/JGPP CLCC-20 SAC Solder

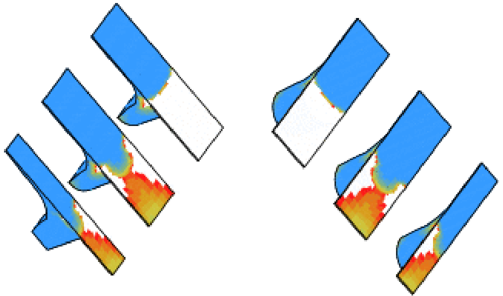
Experiment: SAC305 solder
First Failure: 315 cycles
N63: 952 cycles

Model: SAC396 solder
Significant cracking: 350 cycles
Electrical open: 900 cycles

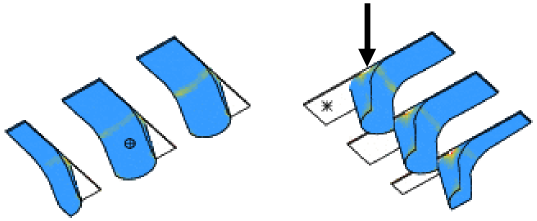




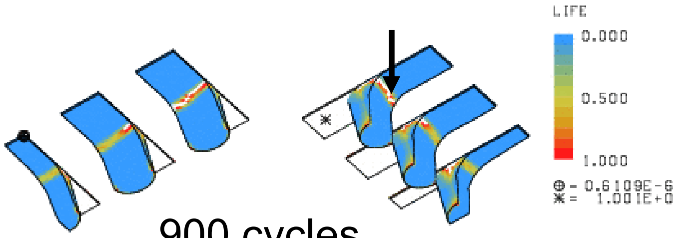
CLCC-20 - Finite Element Model – ¼ symmetry



350 cycles



350 cycles



900 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)
- Existing damage evolution equations did not capture low-cycle fatigue failure of solder which has cycles to failure ~ inelastic strain range^2
- A new UCPD Model was developed for solder with damage based on an empirical Coffin-Manson low-cycle fatigue failure criterion
- Any low-cycle fatigue data for SAC solder would be much appreciated