Unified Creep Plasticity Damage (UCPD) Model for Solder

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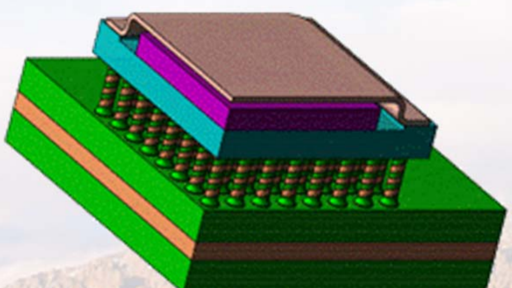
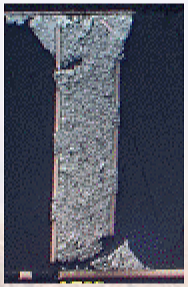
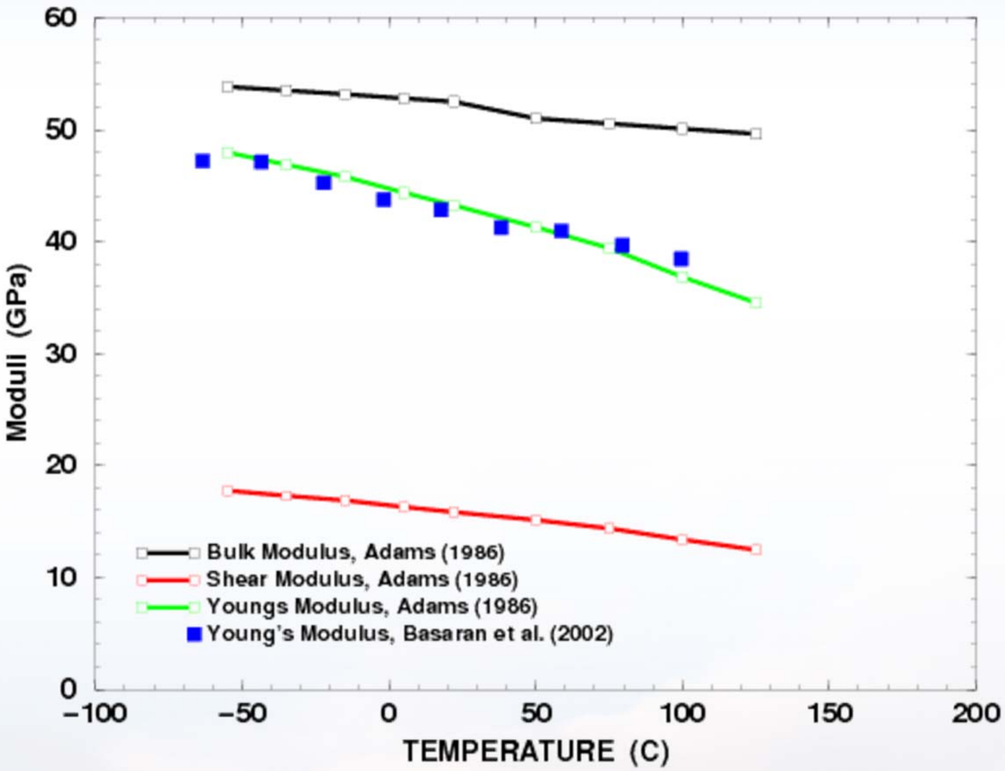
Outline

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





Elasticity – SnPb Solder



G (GPa) = 24.28 – 0.02900θ
K (GPa) = 61.06 – 0.0274θ
θ= temperature (K)

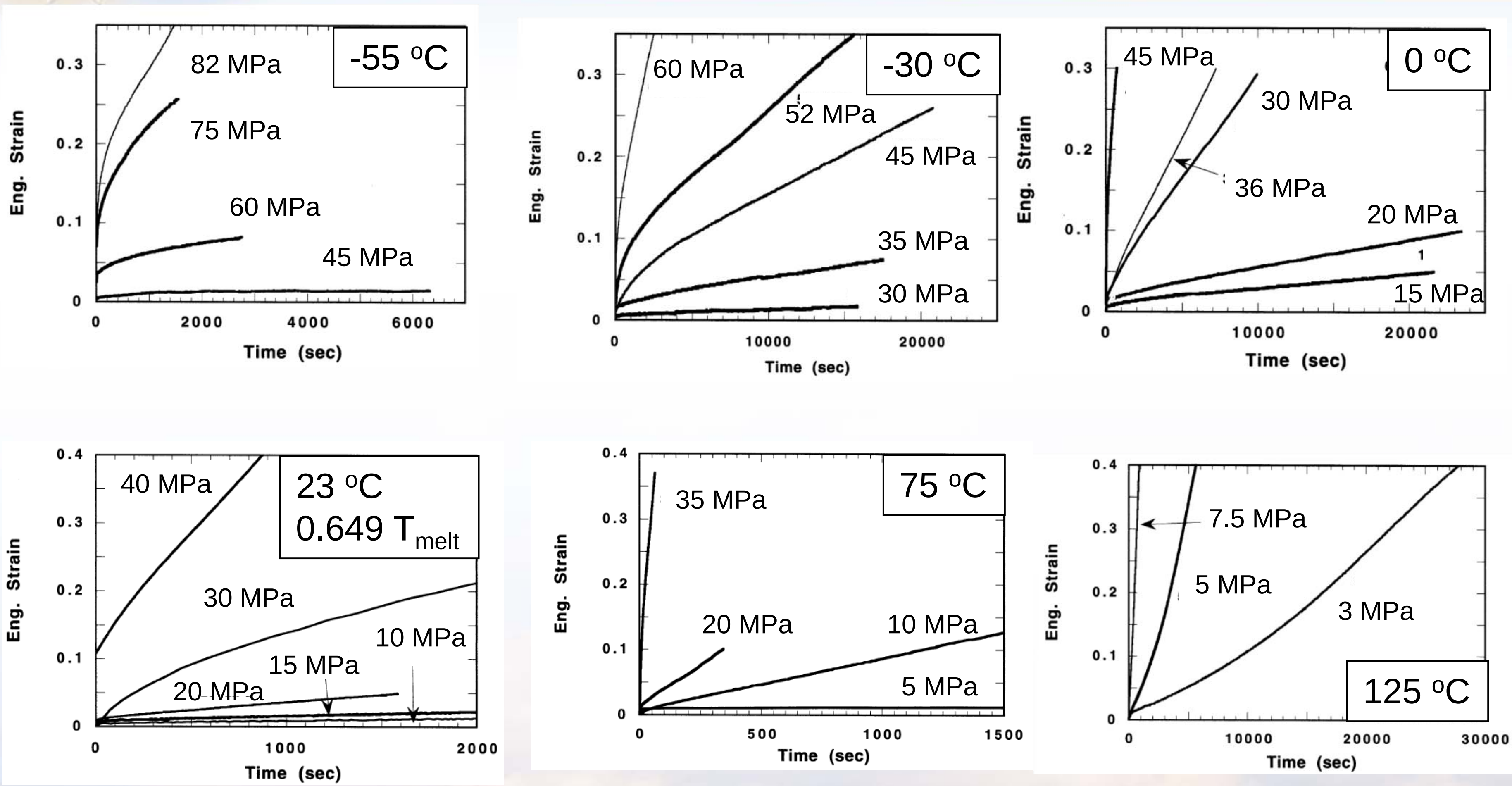
60Sn-40Pb solder

Cu ~ 130 GPa
Al_2O_3 ~ 270 GPa
FR-4 ~ 20 GPa

Ref: P. Adams, 'Thermal Fatigue of Solder Joints in Micro-electronic Devices,' M.S. Thesis, Mechanical Engineering, Massachusetts Institute of Technology, August 1986.

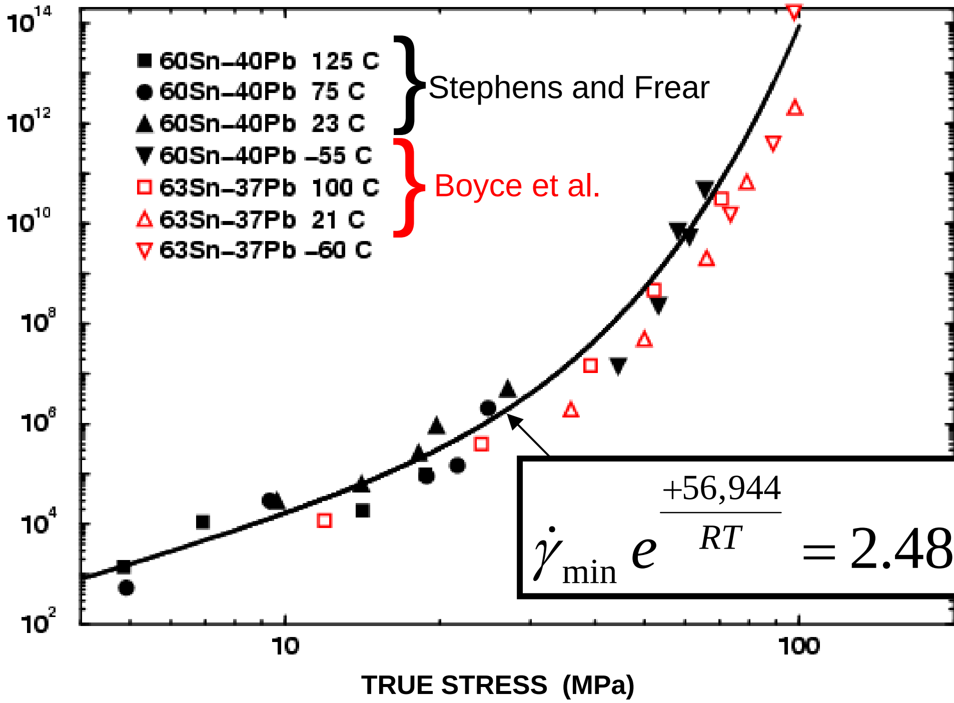
*C. Basaran, and J. Jianbin, 'Measuring intrinsic elastic modulus of Pb/Sn solder alloys,' Mechanics of Materials **34** (2002) 349–362.*

Compressive Creep Data (Stephens and Frear, 1999)



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.

Zener-Holloman Plot



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

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

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

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.

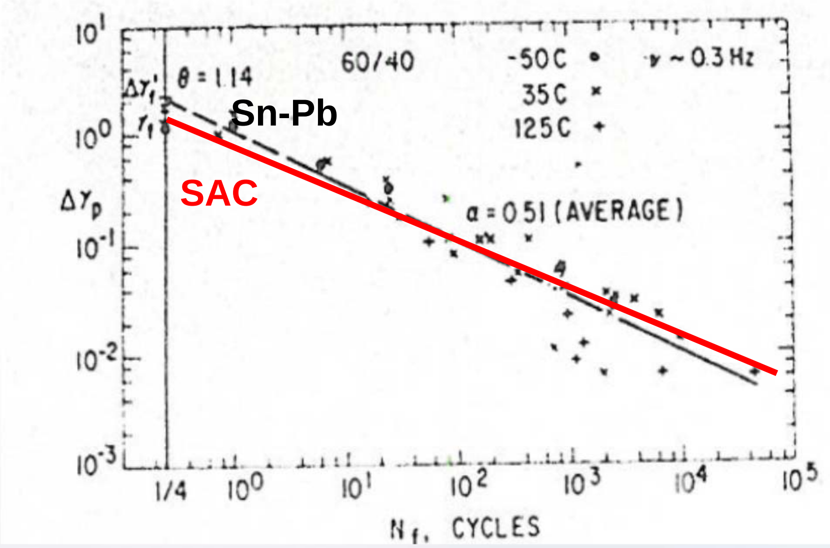
Boyce, B., Brewer, L., Perricone, M., and Neilsen,M., 'On the Strain Rate and Temperature-Dependent Tensile Behavior of Eutectic Sn-Pb Solder,' Journal of Electronic Packaging, ~Dec. 2011.

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

Ref: H.D. Solomon, IEEE Trans., CHMT-9, Dec. 86
Y. Zhou et al., J. Electronic Packaging, Vol. 131, March 2009

UCPD Model for Solder

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

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

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

$$\dot{\mathbf{B}} = \frac{A_4 \dot{\boldsymbol{\varepsilon}}^{in}}{b^{A_6}} - A_5 \sqrt{\frac{2}{3}\mathbf{B}:\mathbf{B}}\;\mathbf{B}$$

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

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

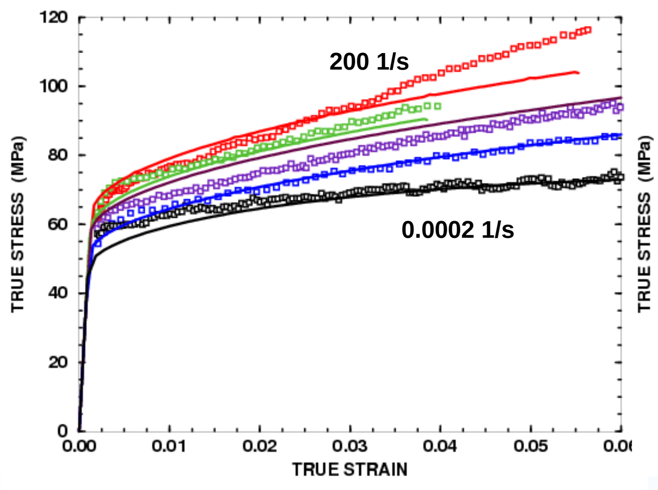
$$\Delta w = \frac{1}{N_f} \approx \left(\frac{\Delta\gamma_{EQPS}}{1.31636}\right)^{1.96078}$$

$$\dot{w} = \frac{1.96078}{1.31636^{1.96078}} \left(\gamma^{i}_{EQPS}\right)^{0.96078} \dot{\gamma}$$

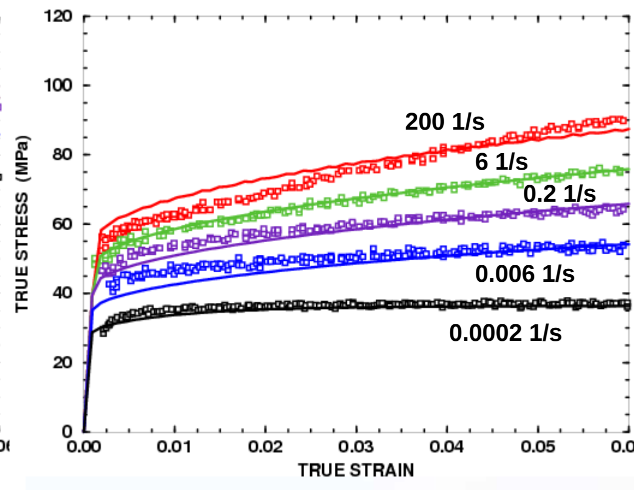
UCPD Model Parameters – 63Sn37Pb

Temperature (^oC)	-60	21	100
Young's Modulus (MPa)	48,276	43,255	36,860
Poisson's Ratio	0.380	0.390	0.400
Flow Rate ln(f)	-44.63	-20.09	-10.72
Sinh Exponent, p	7.1778	4.2074	3.7151
Isotropic Hardening, A_1 (MPa^{A3+1})	270.67	193.44	167.76
Isotropic Recovery, A_2 (1/MPa-sec)	0.37891×10^{-3}	1.8074×10^{-3}	8.3128×10^{-3}
Isotropic Exponent, A_3	0.970		
Kinematic Hardening, A_4 (MPa^{A6+1})	0.0		
Kinematic Recov., A_5 1/(MPa-sec)	0.0		
Kinematic Exponent, A_6	1.0		
Flow Stress, D_0 (MPa)	8.2759		
Damage Parameter, a	1.31636		
Damage Parameter, b	1.96078		
Damage Parameter, c	0.500		

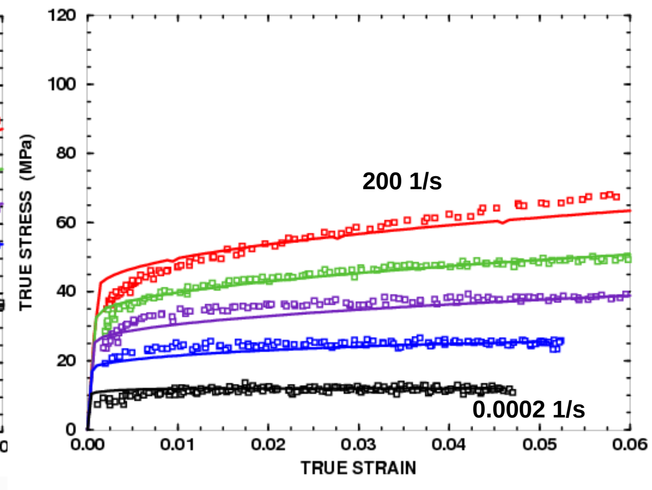
63Sn-37Pb Solder



-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.*

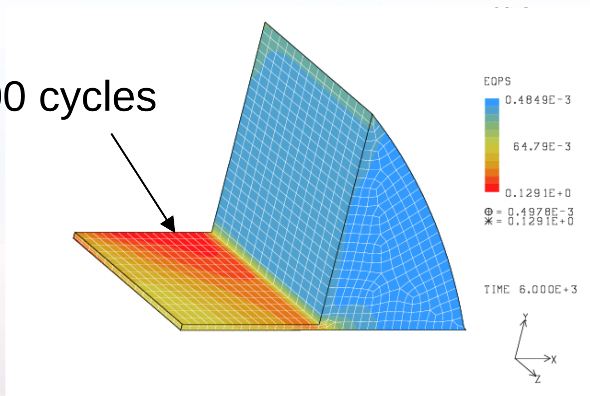
Solder Joint Life Prediction

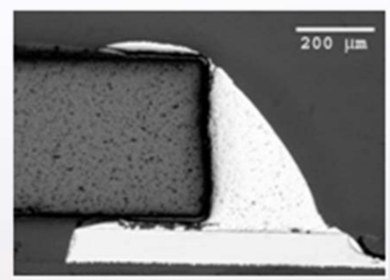
1. Simulate 1 or a few thermal cycles.
2. Compute increment in equivalent plastic strain in worst element
3. Generate Lifetime Prediction using Coffin-Manson relationship or others

Coffin-Manson:

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

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.

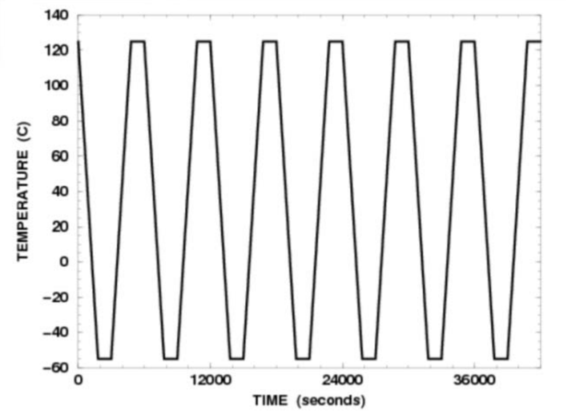
Problem: Capture Geometry Changes Due to Introduction and Growth of Crack

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

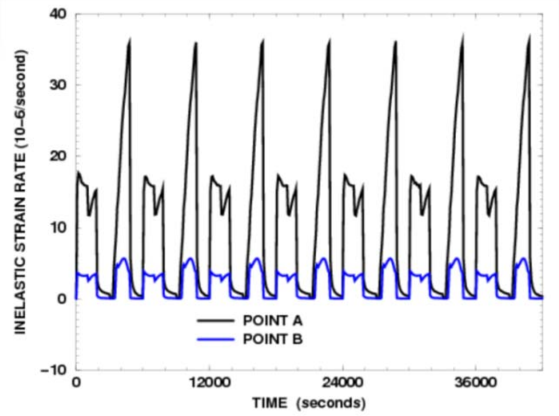
No Remeshing Needed !!

Effects of Mesh Refinement ??

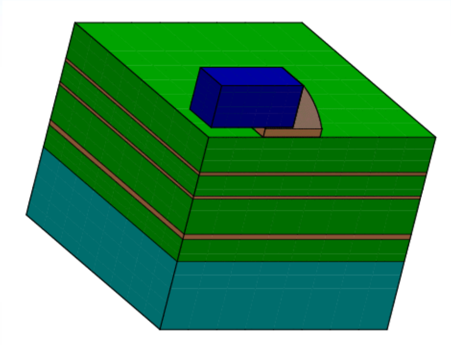
Acceleration of Simulations - UCPD



Temperature History



Strain Rate History



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

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

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

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

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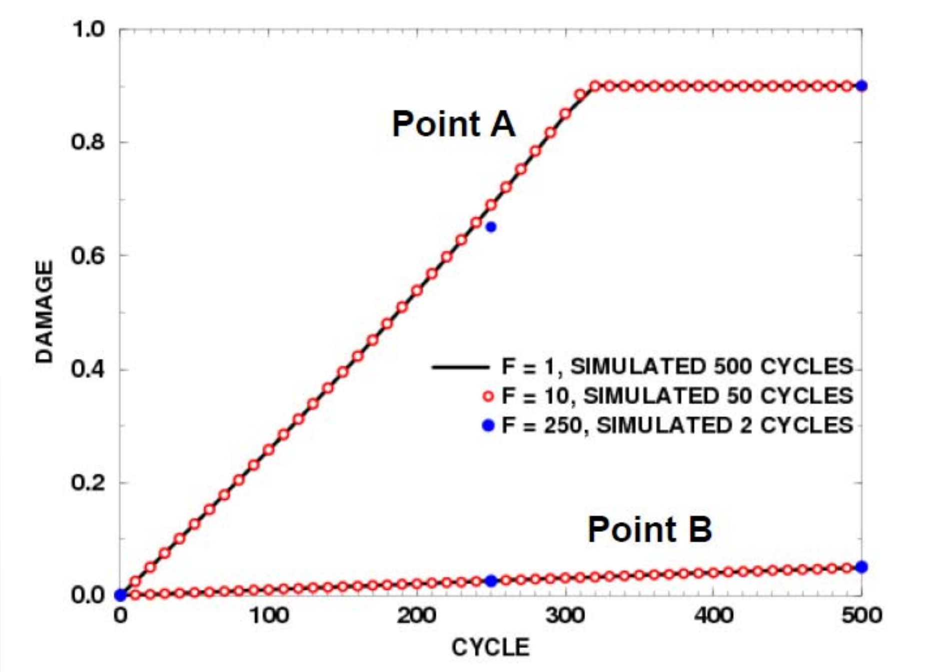
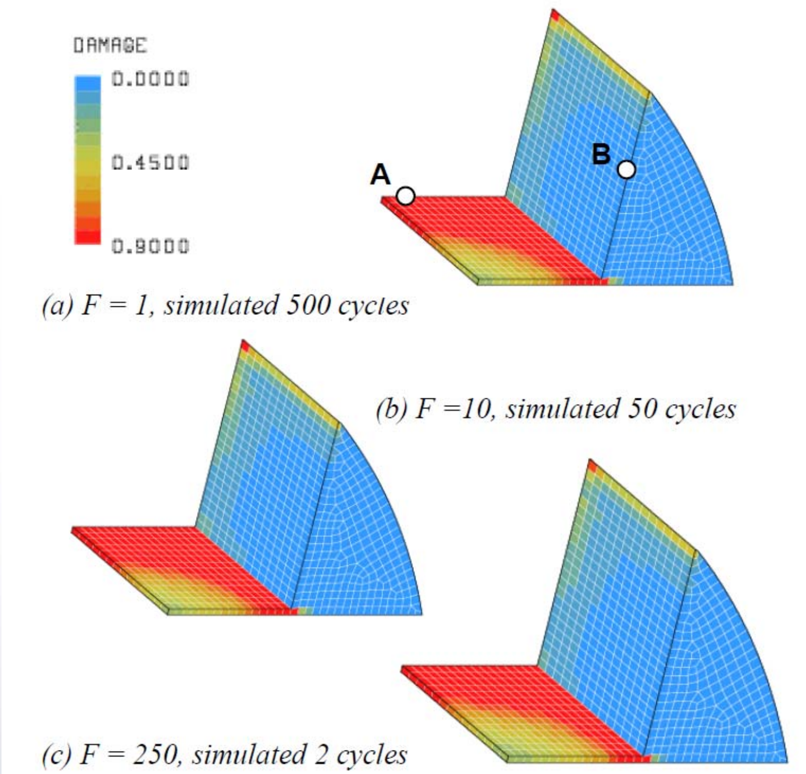
Acceleration of Simulations - UCPD





(a) F = 1, simulated 500 cycles

(b) F =10, simulated 50 cycles

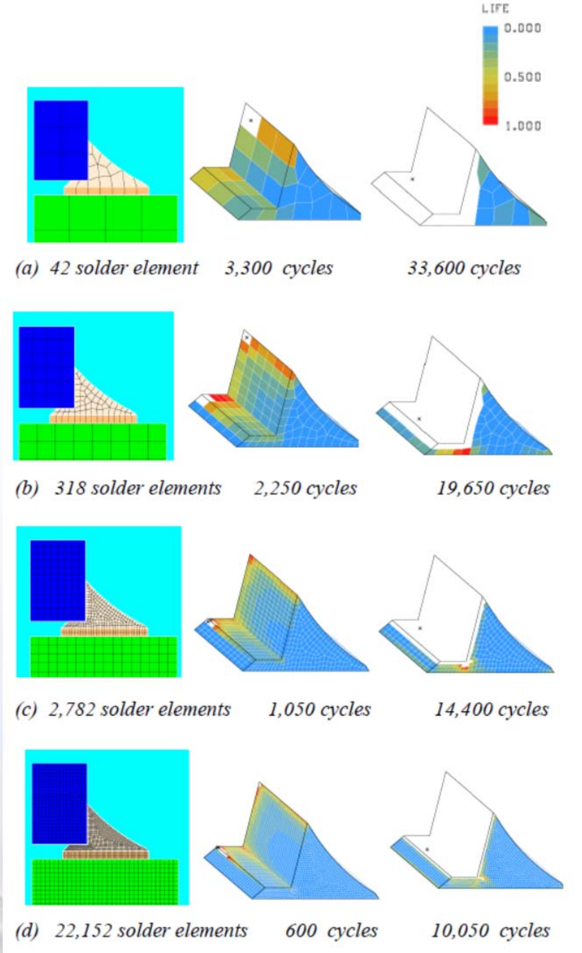
(c) F = 250, simulated 2 cycles

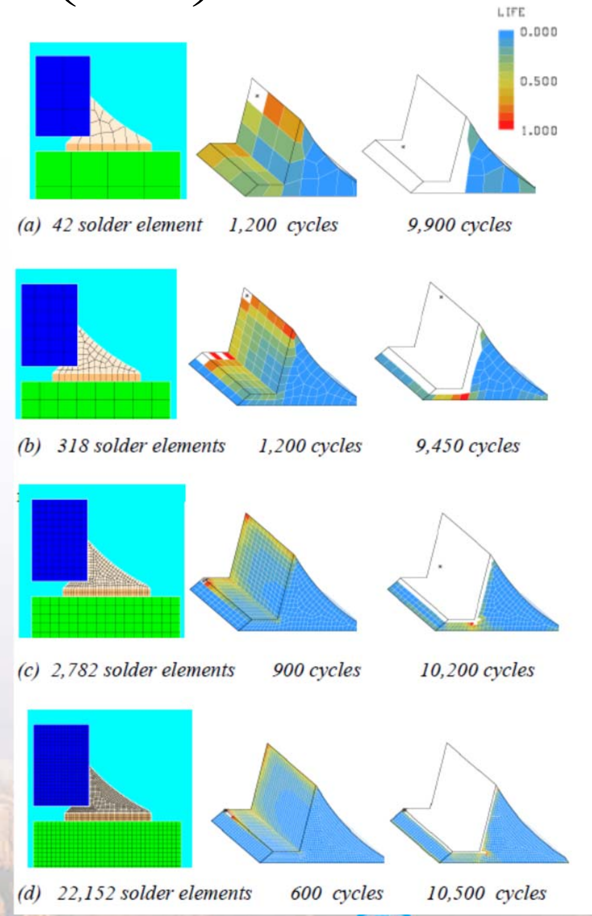
So does this really work ? Yes.

Failure Modeling – Diffuse Crack - UCPD

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

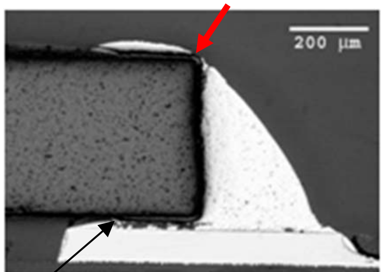
$$\dot{w} = \left(\frac{V^{1/3}}{\lambda}\right)^d \frac{Fb}{a^b}\left(\gamma^i_{EQPS}\right)^{(b-1)}\dot{\gamma}$$



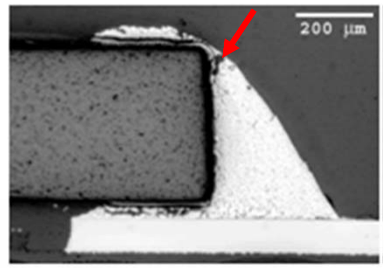


Sandia R23 UCPD Solder

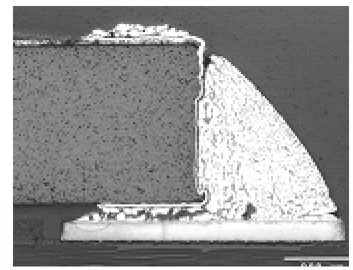
Sn-Pb solder



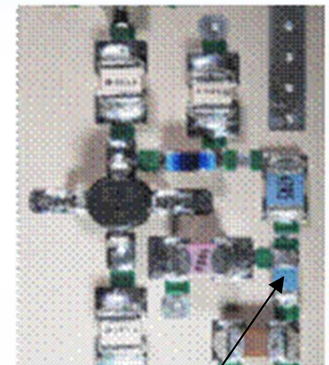
outside



outside

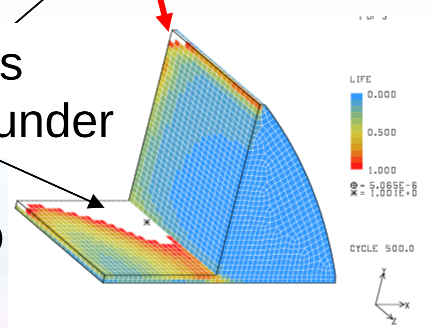


mid-plane

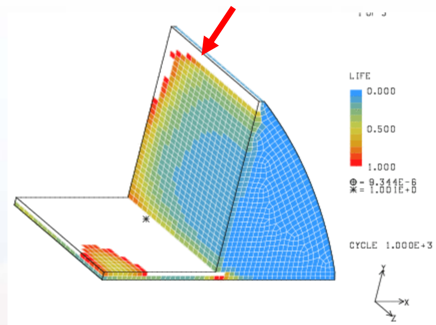


cracks start under

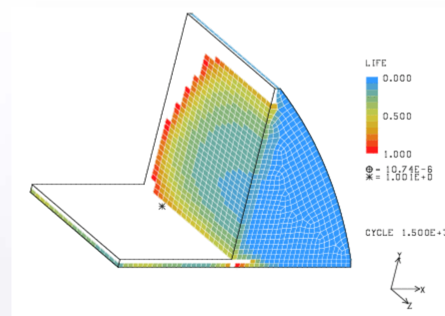
UCPD model



500 cycles



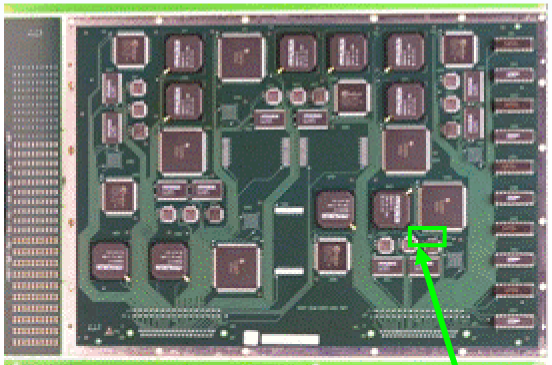
1000 cycles

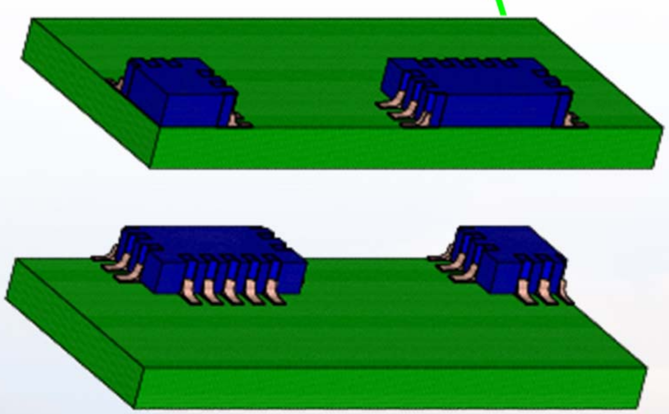


1500 cycles

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

CLCC-20 UCPD Solder

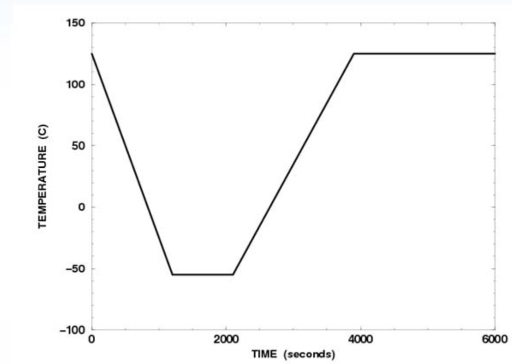


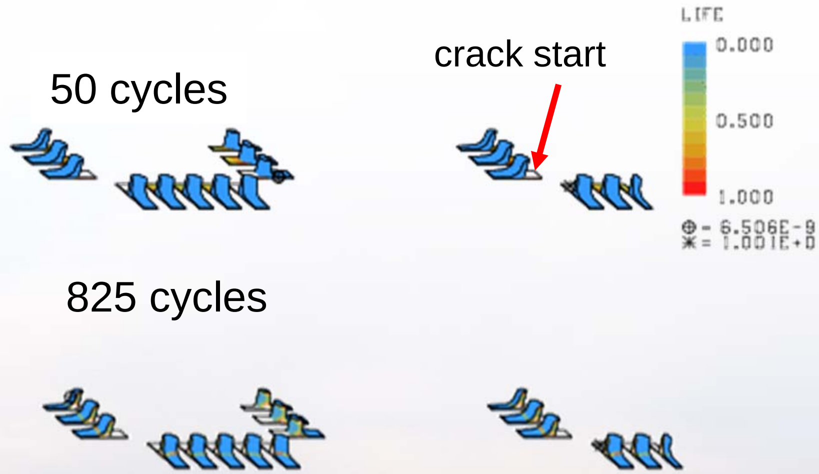


CLCC-20 - Finite Element Model – ¼ symmetry

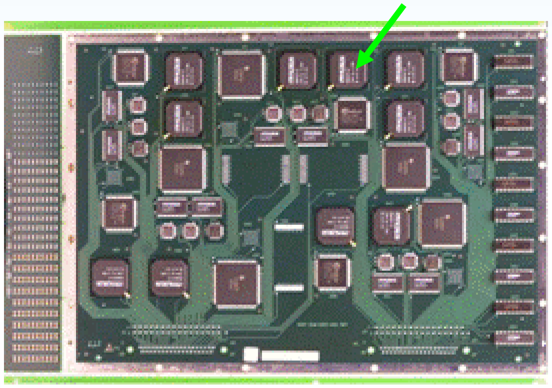
Experiment: 63Sn37Pb solder
First Failure: 455 cycles
N10: 469 cycles
N63: 727 cycles

Model: 63Sn37Pb solder
Crack start: 50 cycles
Electrical open: 850 cycles



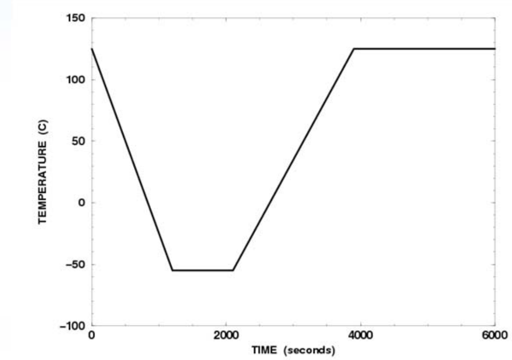


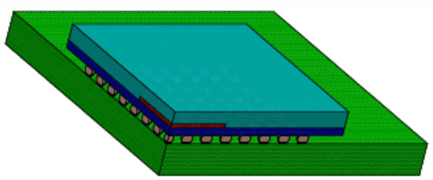
BGA225 UCPD Solder

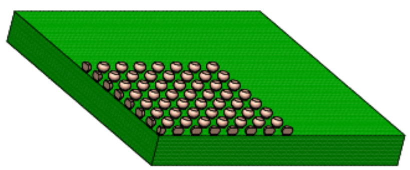


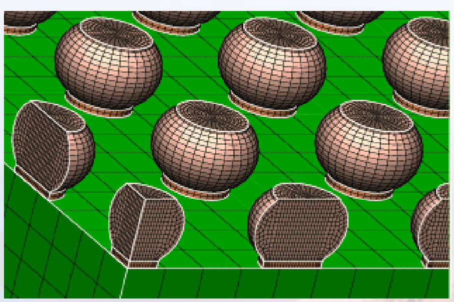
Experiment: 63Sn37Pb solder
First Failure (Open): 1068 cycles
N10: 1822 cycles
N63: 2686 cycles

Model: 63Sn37Pb solder
Electrical open: 1750 cycles

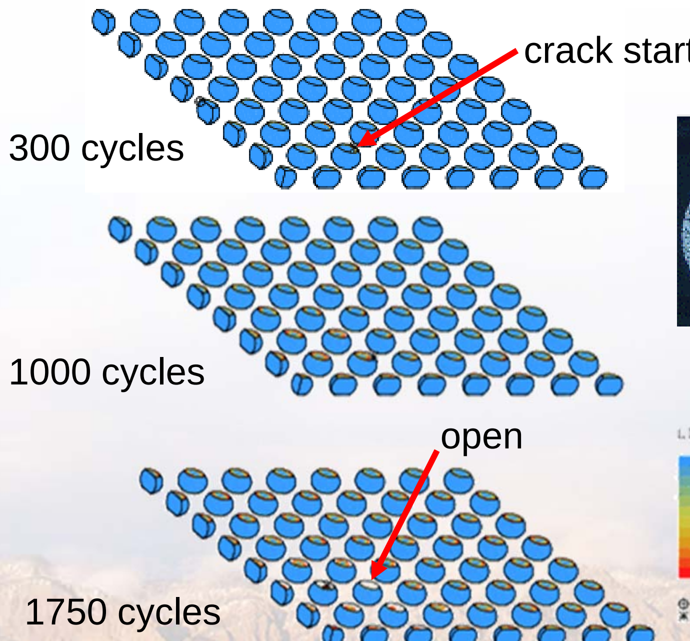


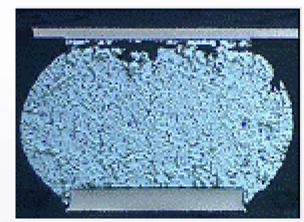


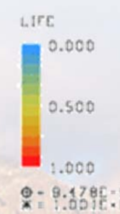




BGA225 - Finite Element Model – ¼ symmetry







Summary

- Eutectic 63Sn-37Pb Solder exhibits a variety of complex behavior in use (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 UCP Model was developed for solder with damage based on an empirical Coffin-Manson low-cycle fatigue failure criterion
- Any suggestions for better damage evolution equations for low cycle fatigue of solder would be much appreciated