Constitutive and Failure Behavior of SnAgCu Solder Joints

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Constitutive and failure descriptions of SnAgCu solder alloys are of great interest at the present. Commonly, constitutive models that have been successfully used in the past for Sn-Pb solders are used to describe the behavior of SnAgCu solder alloys. Two issues in the characterization of lead-free solders demand careful attention: (i) Lead-free solders show significantly different creep strain evolution with time, stress and temperature and (ii) The building of valid constitutive models from test data derived from tests on solder joints must de-convolute the effects of joint geometry and its influence on stress heterogeneity. In the first part of the talk I will review the common approaches to modeling solder behavior, along with their limitations and then describe our efforts in developing constitutive models of SnAgCu solders that are valid across a wide range of strain rates.

The problem of solder joint fatigue is essentially one of fatigue crack growth. However, there is little work that has been done to arrive at fatigue life estimations by means of tracking of the crack front and its growth. Common fatigue life models such as the Coffin-Manson rule are empirical and therefore, limited in their applicability and in the insight they provide. There are several challenges to employing a fracture mechanics approach to accurately track the growth of a fatigue crack in a solder joint. Key among these, are the facts that the problem involves large-scale yielding, viscoplastic solder behavior and complex geometries. In the second part of the talk, I will describe the various approaches to modeling solder joint fatigue and present our efforts at developing Cohesive Zone Model inspired approaches to predicting crack propagation at solder interfaces.

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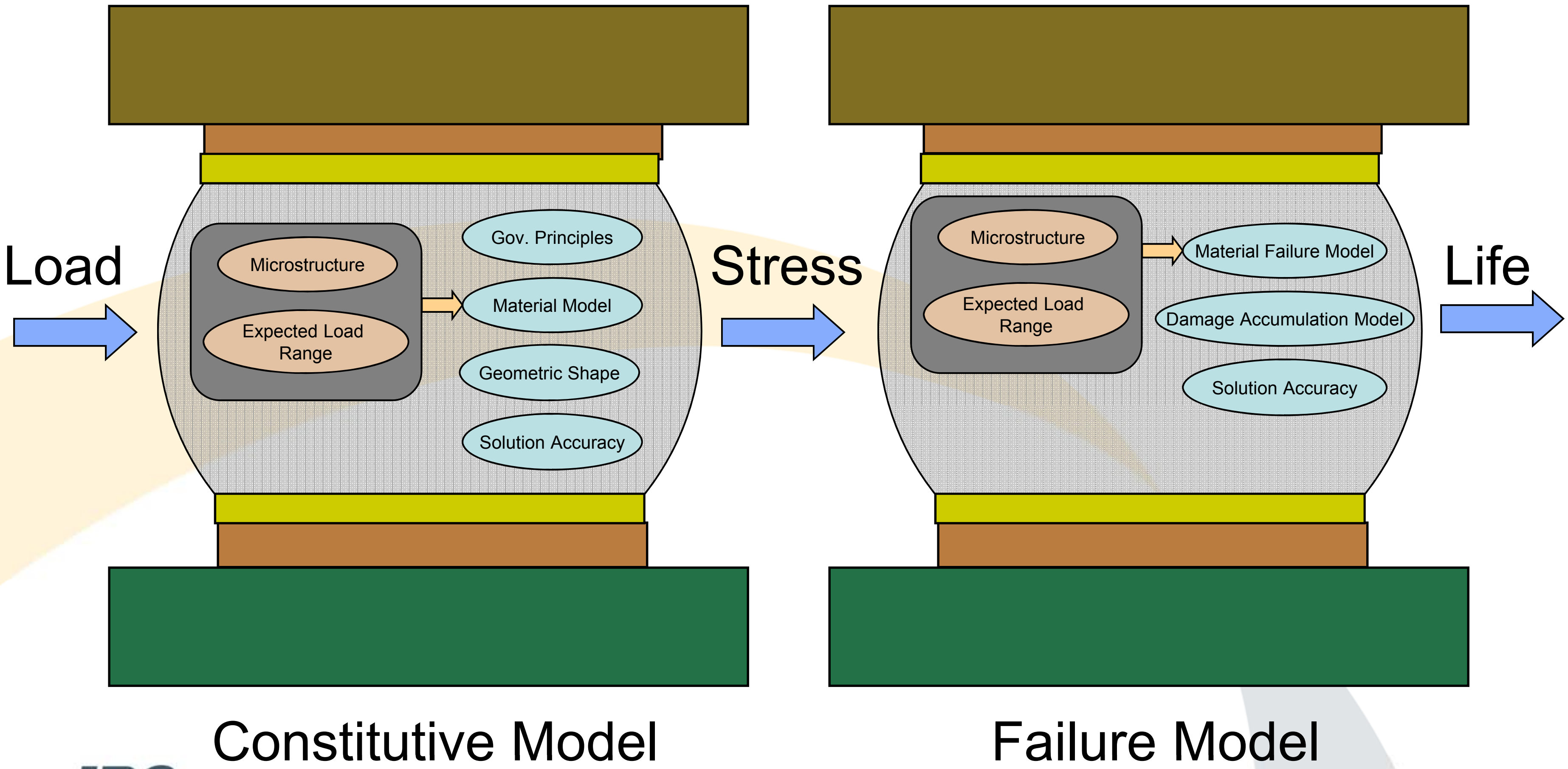
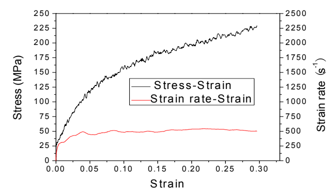
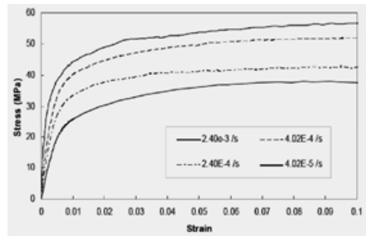
Predicted Life Depends on…



Reliability Modeling Strategy

Material Characterization

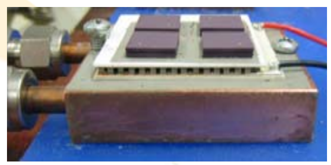


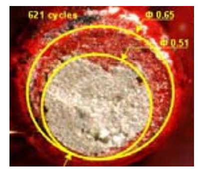


Constitutive Models

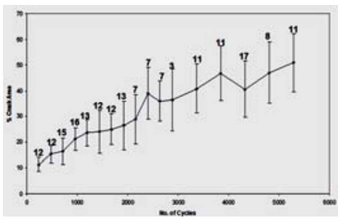
$$\dot{\varepsilon}^{p} = A\exp\left(\frac{-Q}{RT}\right)\left[\sinh\left(\xi\frac{\sigma}{s}\right)\right]^{1/m}$$

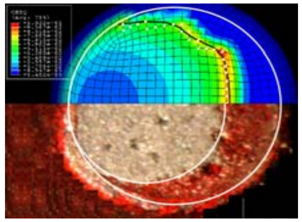
Failure Experiments





Failure Models





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Constitutive Behavior of SnAgCu Solder Alloys – Part I

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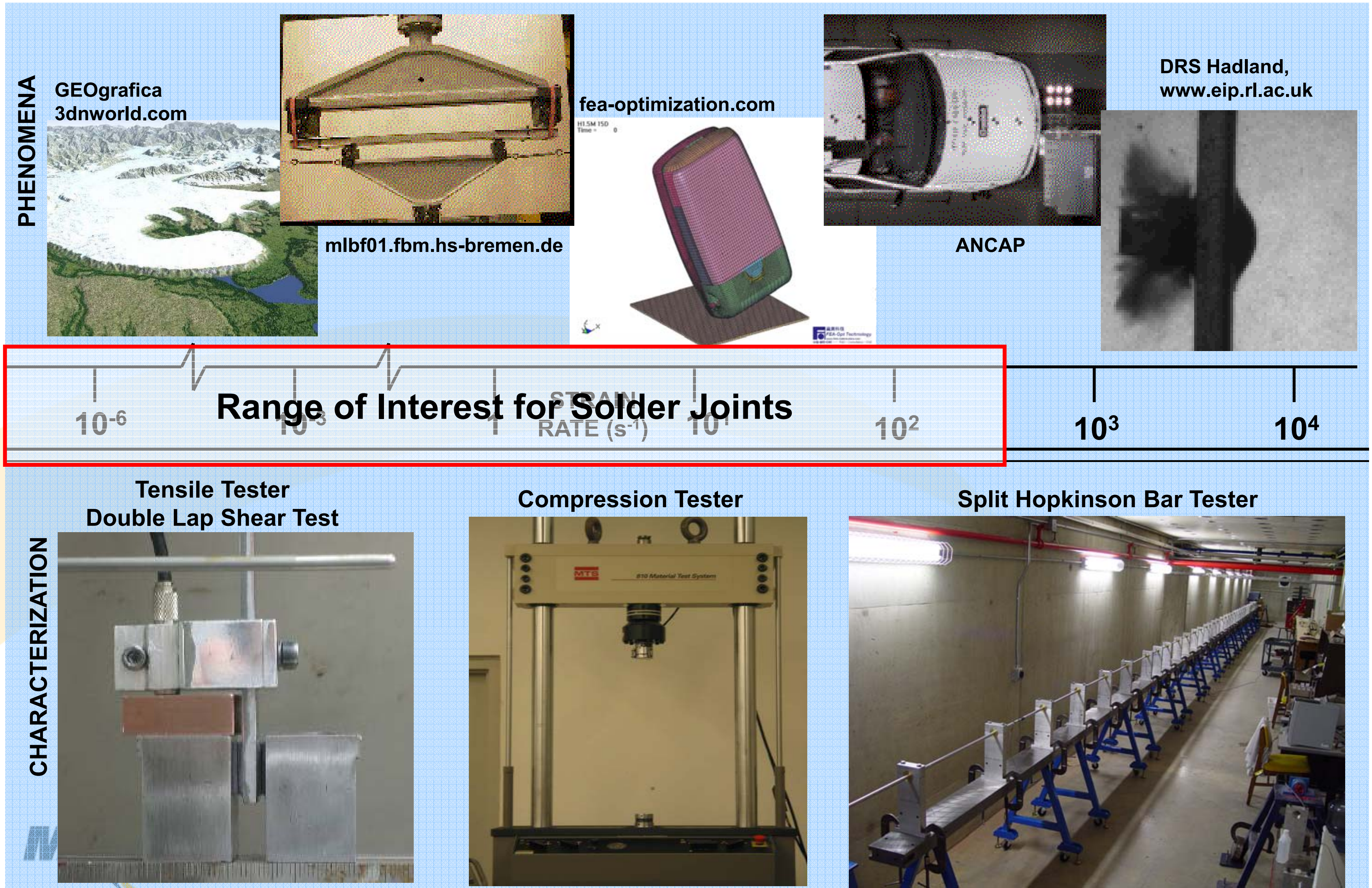
Strain Rate Regimes

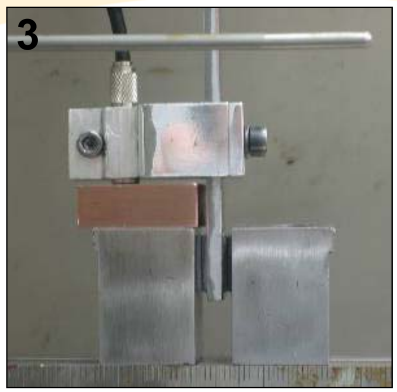


Low Strain Rate Behavior

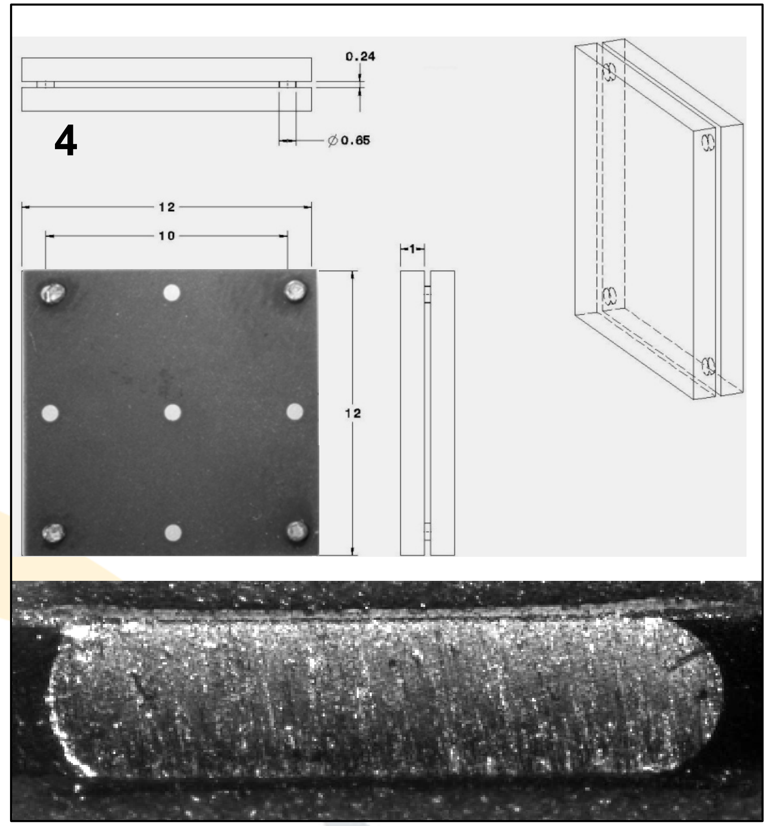
Experimental Set Up

INSTRON
Microtester 5848

Environmental Chamber
Controller EC 1615
(Range -70 C to 250 C)



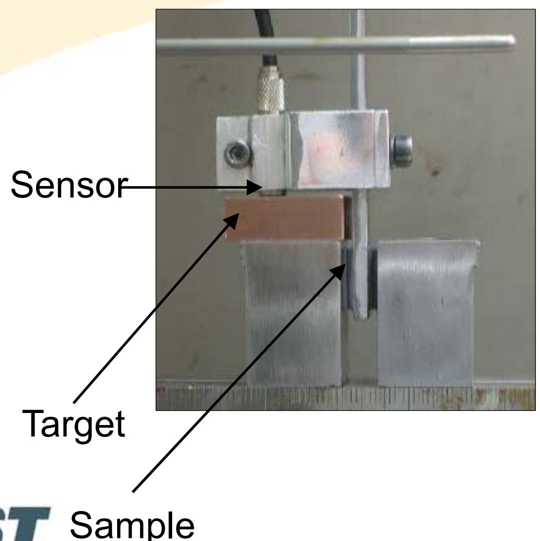
Double lap shear setup with capacitance sensor probe

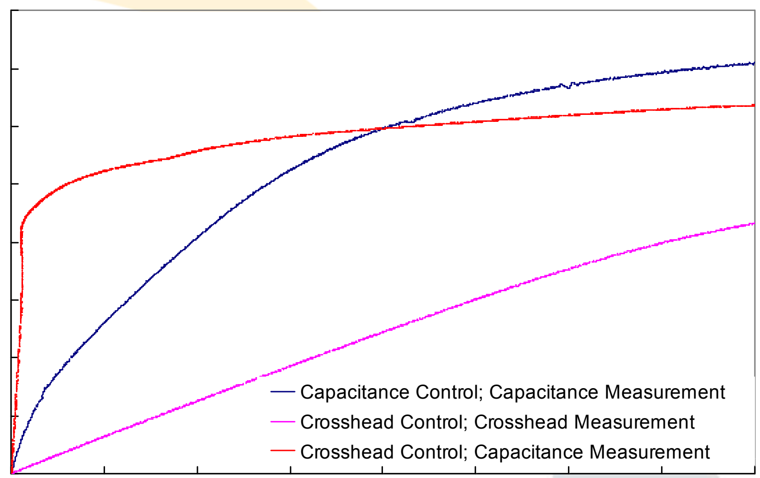


Test Specimen
Alumina coupons
Sn3.8Ag0.7Cu solder joints

Impact of Displacement Control

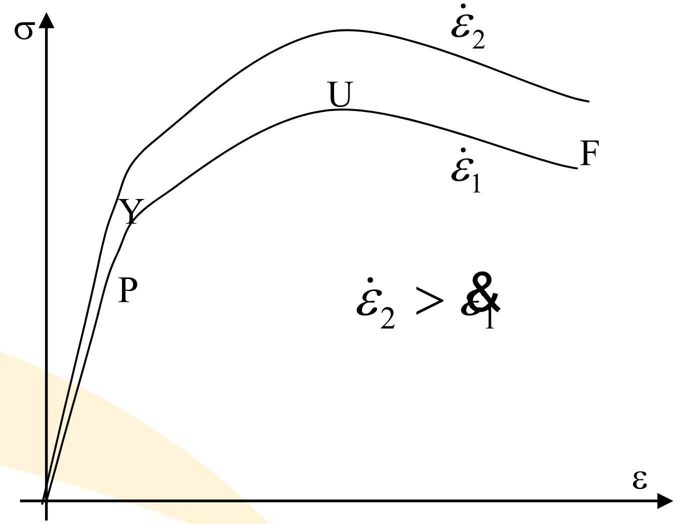
- Need to resolve displacements ~10 nm
- Crosshead control results in load train compliance
- **Displacement control** established by a **closed loop** with capacitance sensor and Instron crosshead displacement

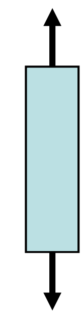


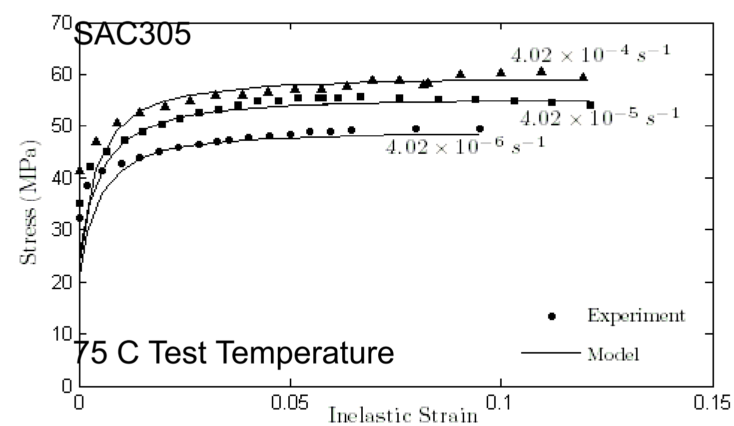


Monotonic Behavior

- Response depends on strain rate
  - Materials “stronger” at higher strain rate
- No clearly identifiable proportional limit in SnAgCu alloys
- Elastic, nearly perfectly plastic behavior





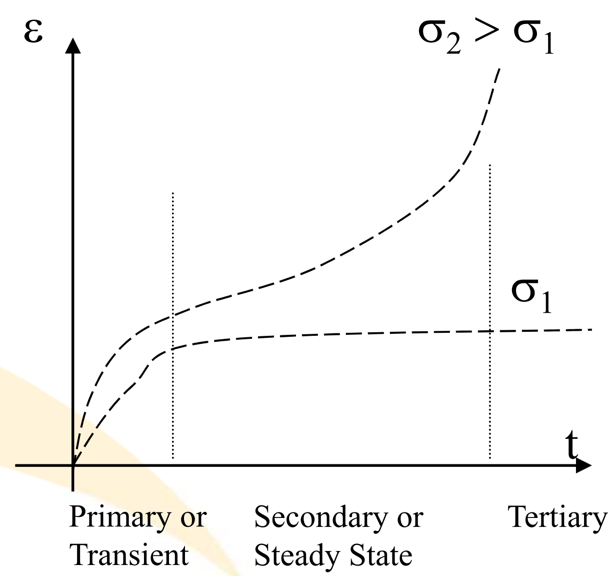


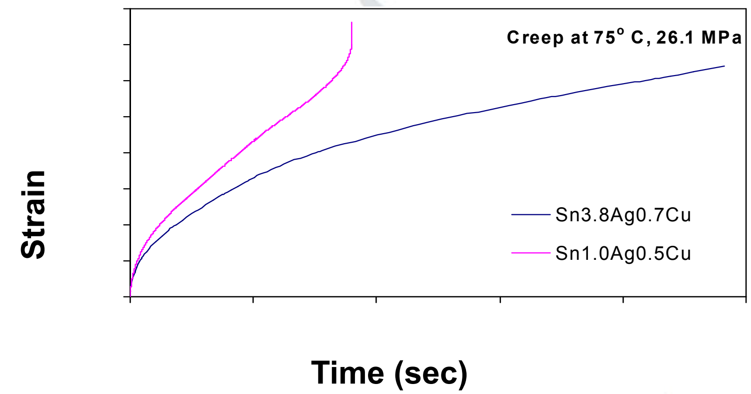
Creep Behavior

- Nature of response depends on stress level and temperature
  - Typically occurs when $\frac{T}{T_m} \geq 0.3$
  - Operating temperature is a high fraction of melting point. At 100° C for example

$$\frac{T}{T_m} \geq 0.7 \quad \text{for Sn3.8 Ag0.7Cu solder}$$

- Historically, in SnPb alloys, only secondary creep considered





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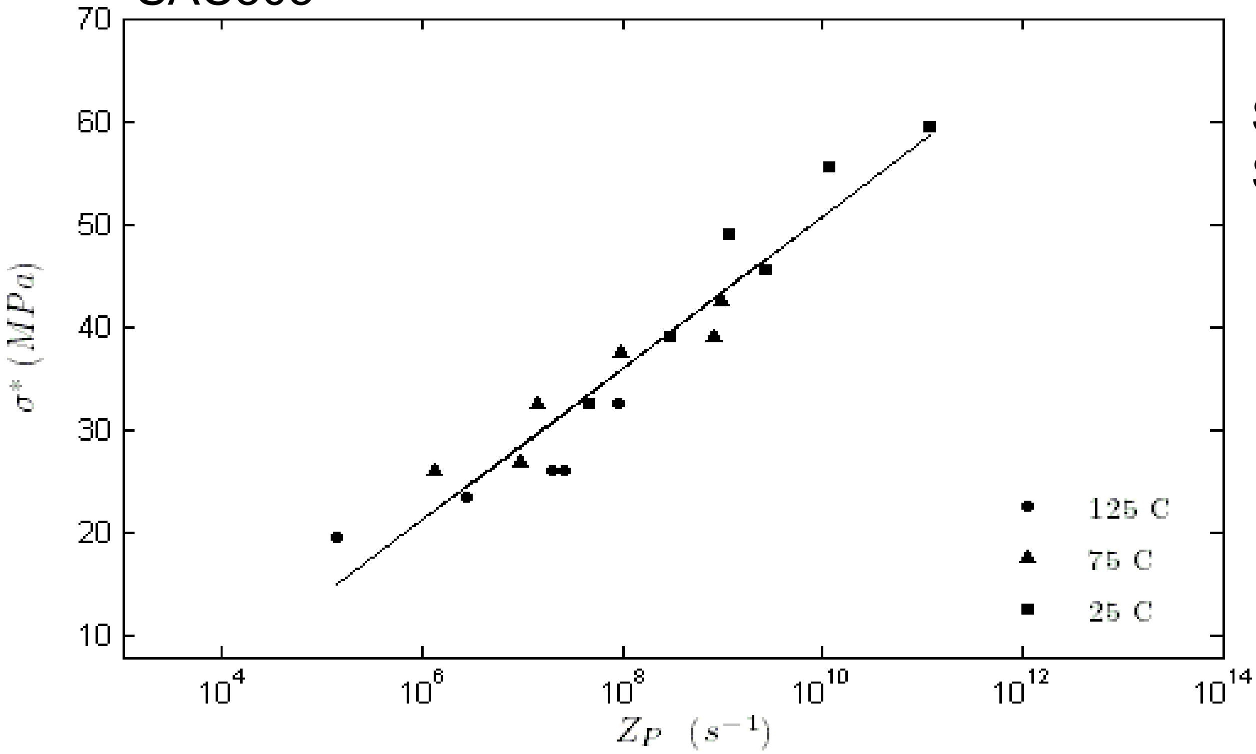
Zener Hollomon Plots

SAC305

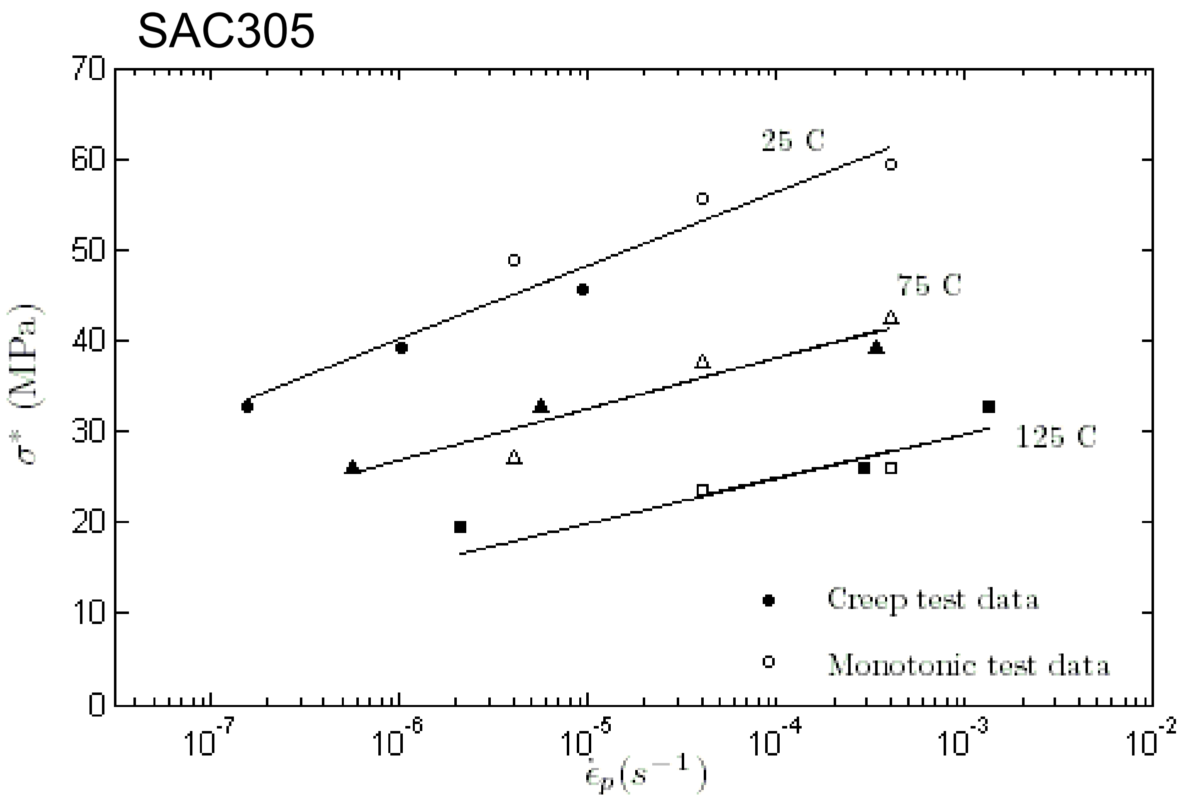


Similar results for SAC387 and SAC105

$$Z_P = \dot{\varepsilon} e^{\frac{Q}{RT}}$$

Strain rate and temperature effects equivalent!

Monotonic Vs. Creep Data

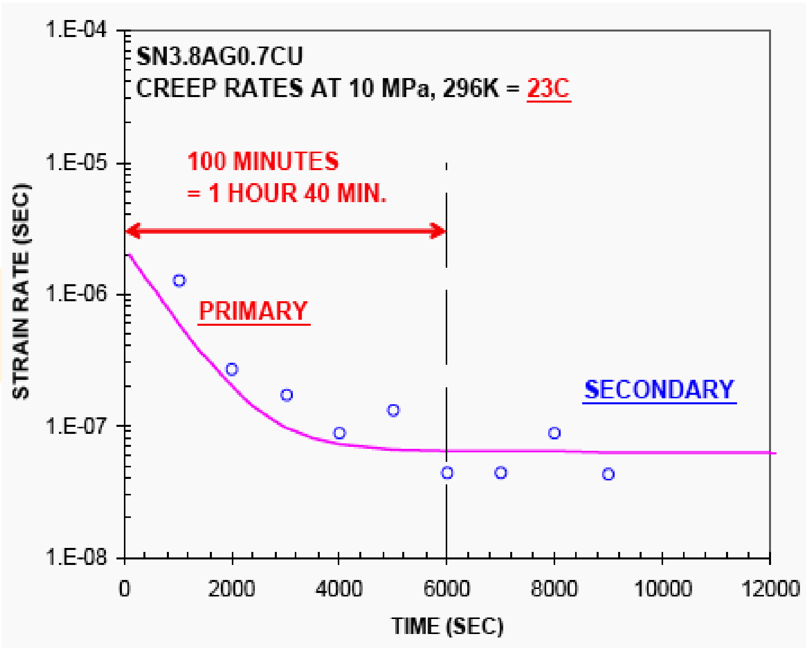


Similar results for SAC387 and SAC105

Monotonic and creep data consistent!

Primary creep

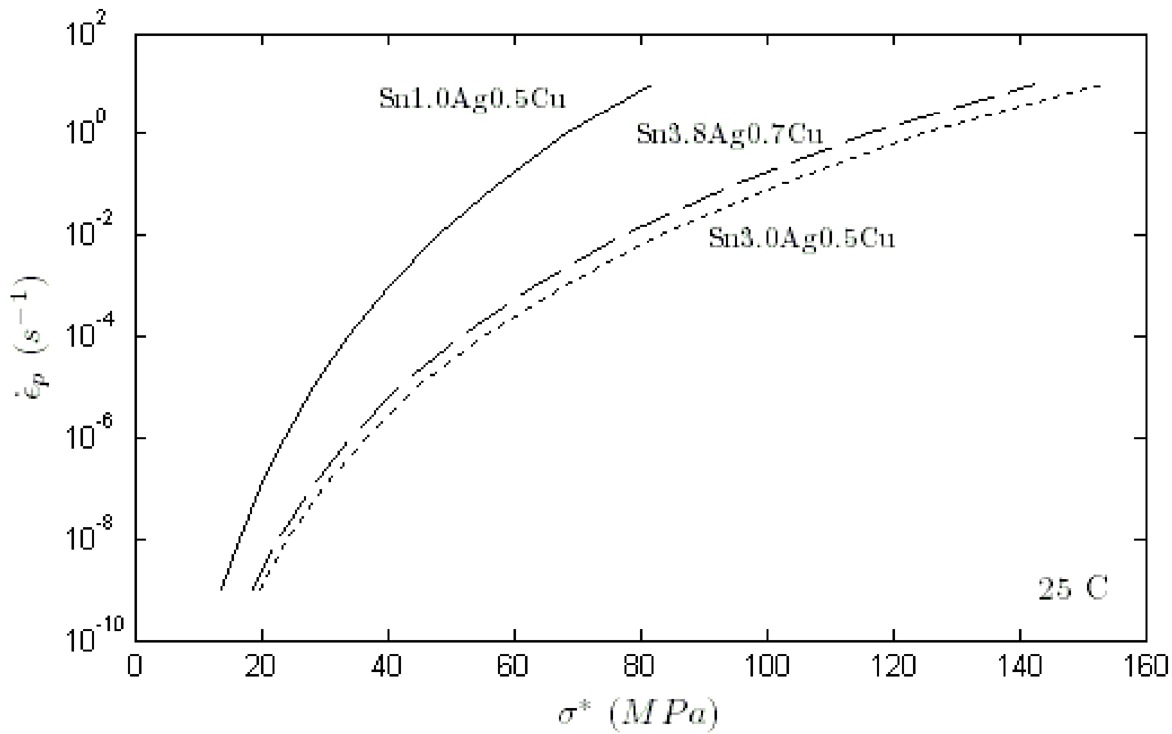
Reference	Temperature (C)	Stress (MPa)	Primary Creep (approximate duration in minutes)	Secondary Creep (approximate duration in minutes)
Mysore et al. (SAC305)	25	49.39	16.6	62.5
	75	35.28	15.0	91.6
	75	42.32	1.0	4.1
	125	28.22	1.3	5.4
	125	35.28	0.4	1.3
Clech et al. (SAC387)	23	10	100	NA
	110	10	17.0	50.0
Bhate et al. (SAC387)	25	26.10	16.0	NA
		52.20	5.0	50.0
	75	32.60	11.0	NA
		39.10	1.0	NA
	125	13.00	250.0	NA



Clech (2005)

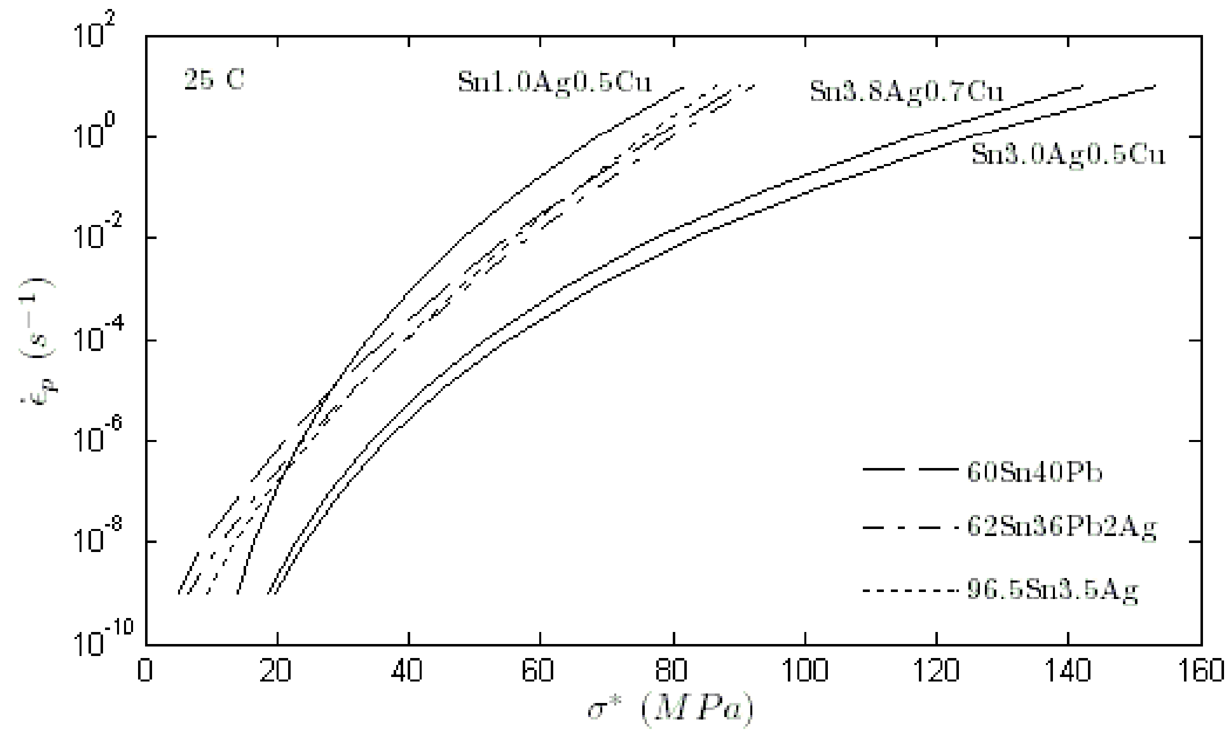
Significant primary creep duration!

Comparison of SnAgCu Alloys



- SAC305 and SAC387 behave similarly
- SAC105 softer than SAC305 and SAC387

Comparison with SnPb Alloys



- SAC305 and SAC387 better creep resistance over load range
- SAC105 creep resistance better only at lower loads

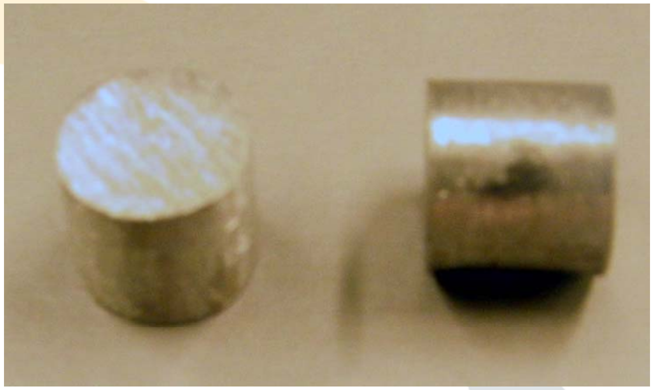
High Strain Rate Behavior

Compression Test Setup and Specimen

Intermediate Strain Rate: $0.001s^{-1}$ to $31s^{-1}$

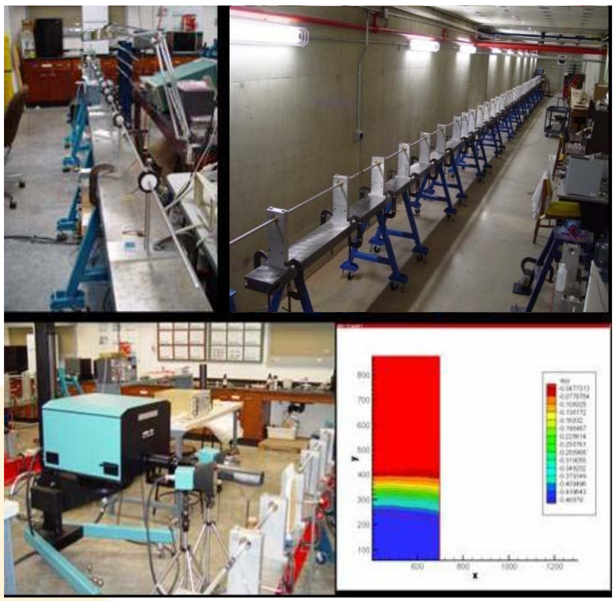
Test Specimen:
5mm x ⌀5mm

Alloy: Sn3.8Ag0.7Cu



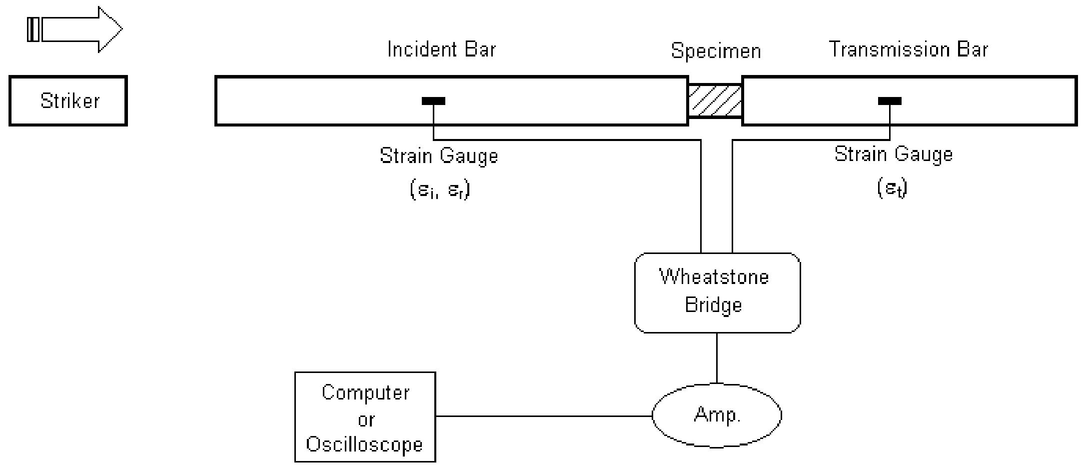
Split Hopkinson Bar Test Setup

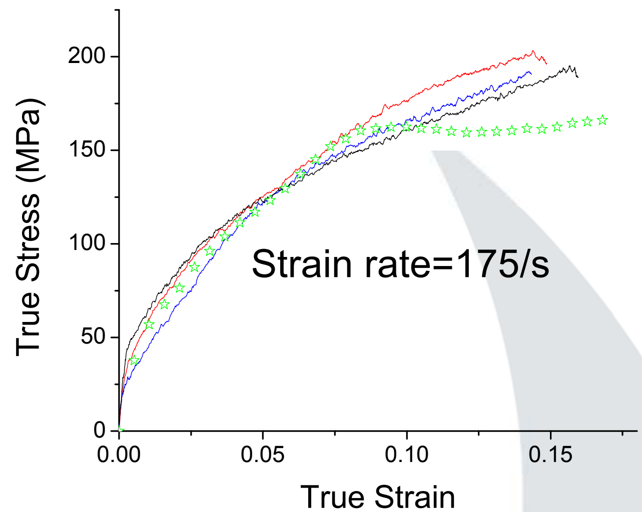
High Strain Rate: $175s^{-1}$ and $500s^{-1}$



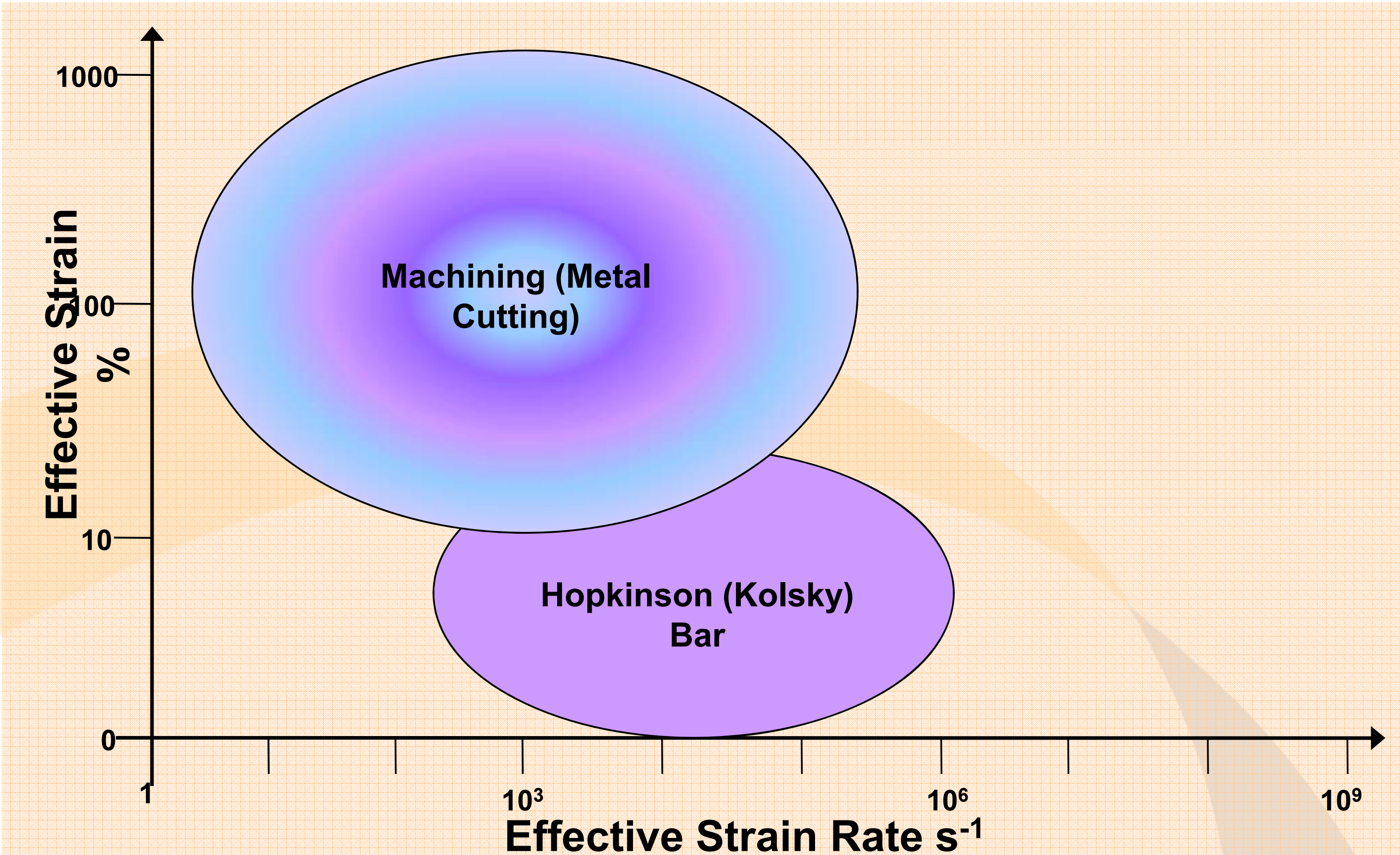
Dynamic Test Setup at McDonnel Douglas Composite Material Laboratory at Purdue University (W. Chen)

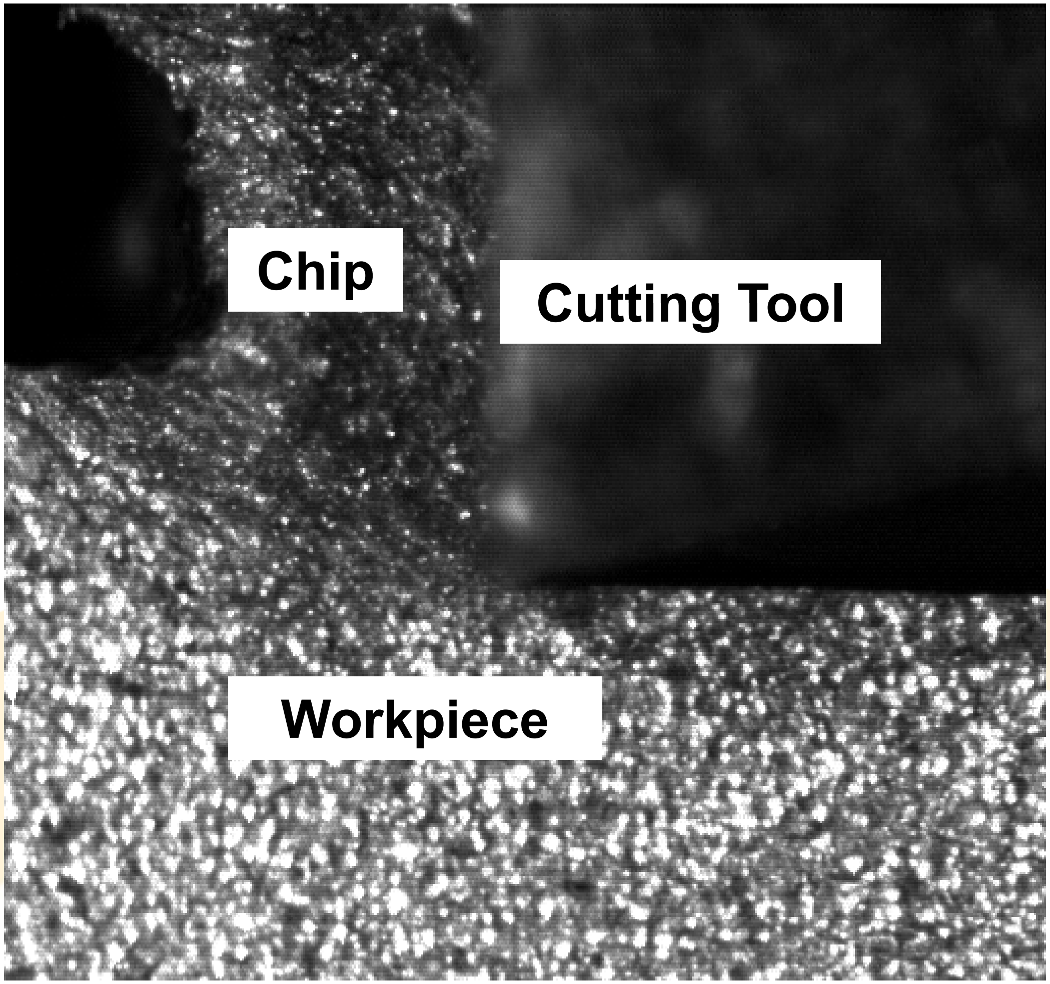
High speed digital camera (1024x1024 pixel resolution; 2,000,000 frames per second)





Test Methods For High Strain Rate Characterization



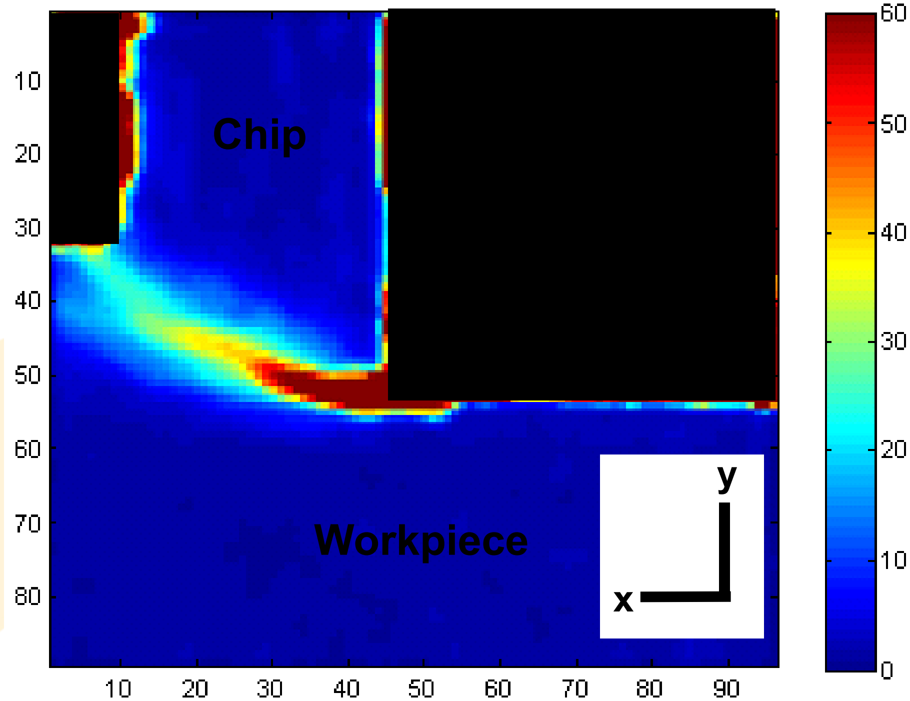


Test Specifications:

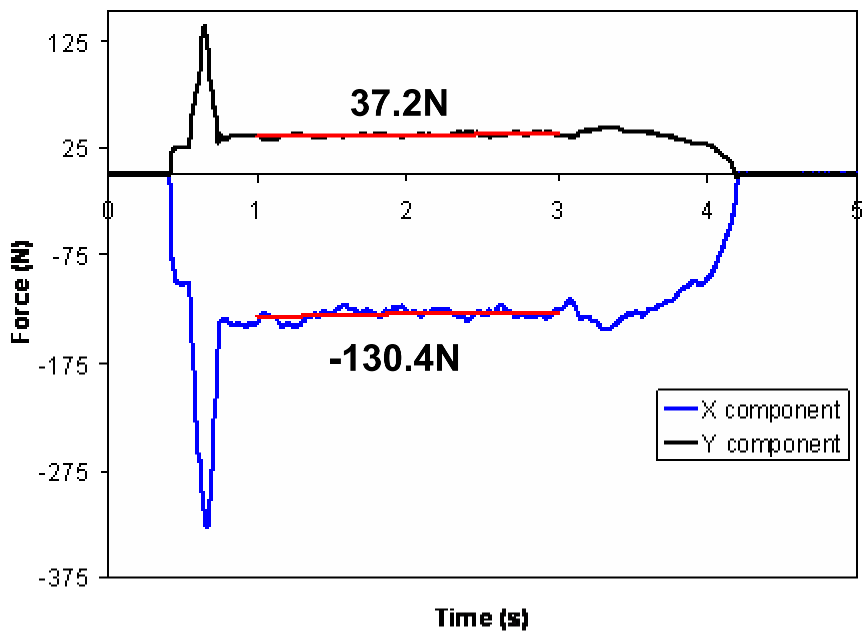
- Cutting speed: 10mm/sec
- Depth of cut: 250 micrometer
- Rake angle of the tool: 0 degree
- Image frame rate: 250 frames/sec

Response of Sn3.8Ag0.7Cu Solder

Effective Strain Rate

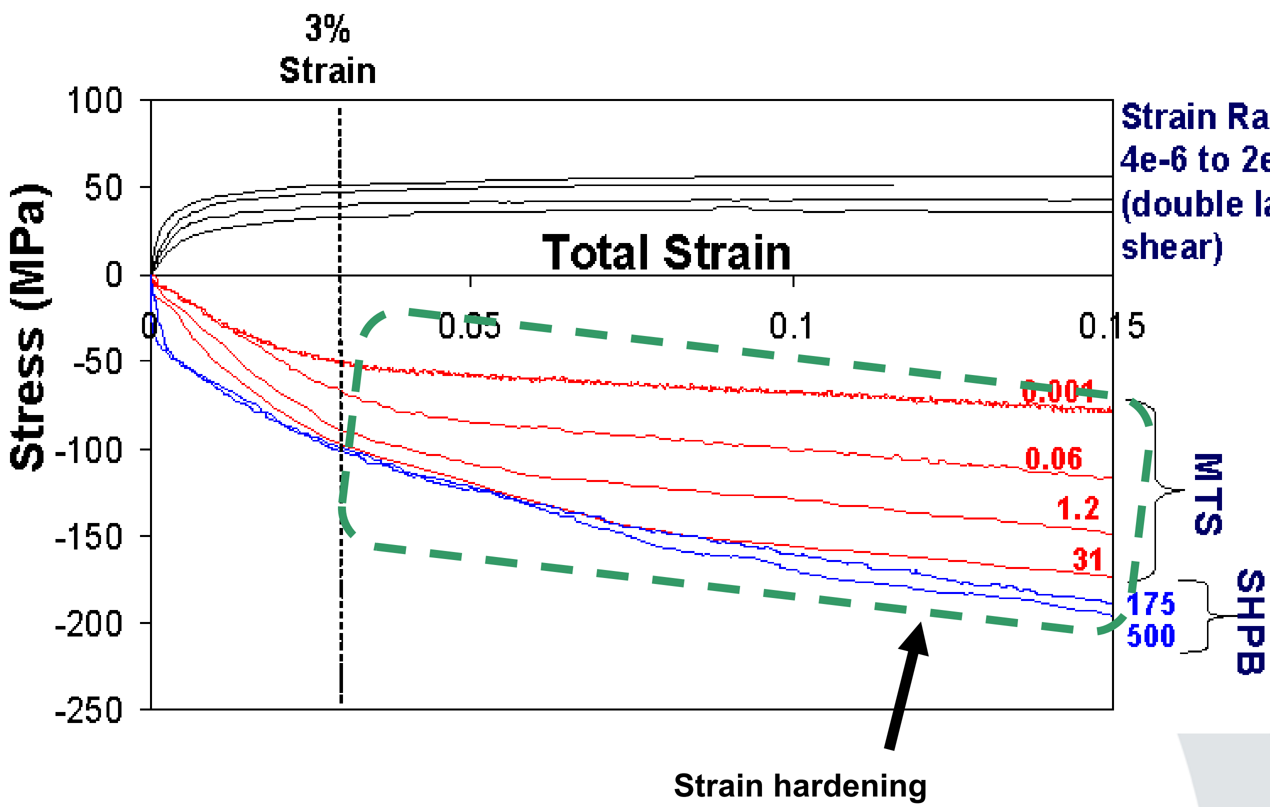


Forces Acting on Cutting Tool

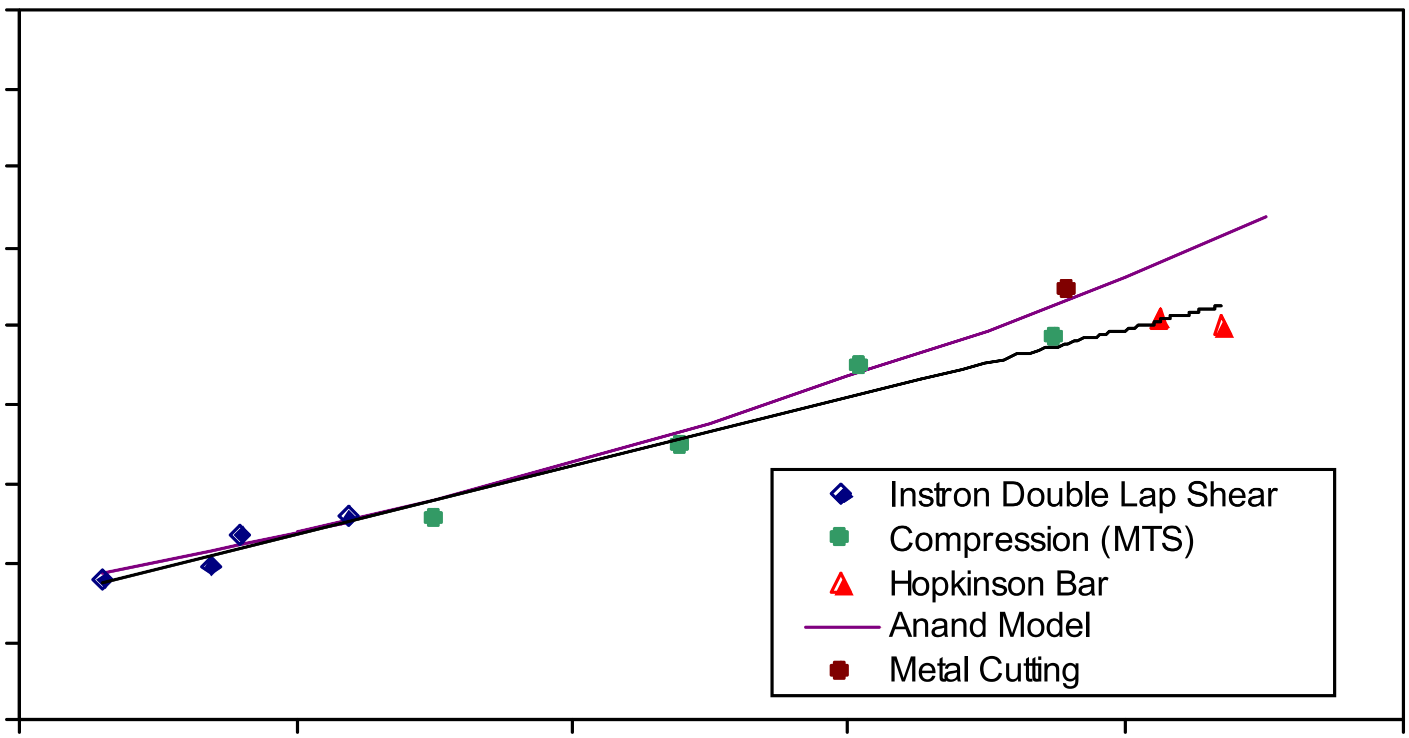


- **Strain rate (in concentrated region): 38 s^{-1}**
- **Shear Stress: 110MPa**

Summary of Test Data

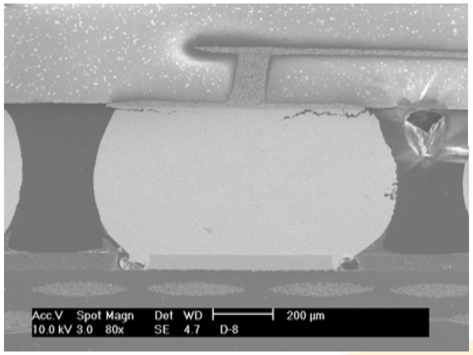


Model Fit to Data

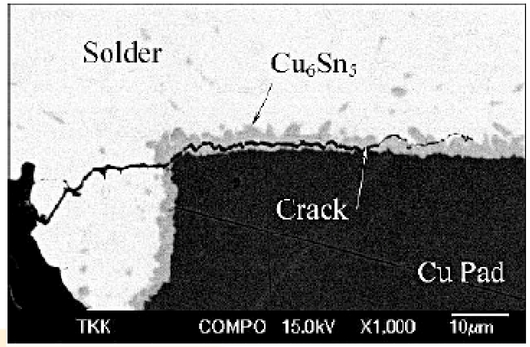


Implications of Rate-Dependent Behavior

Failure Observations



Thermal Cycling (HDPUG)

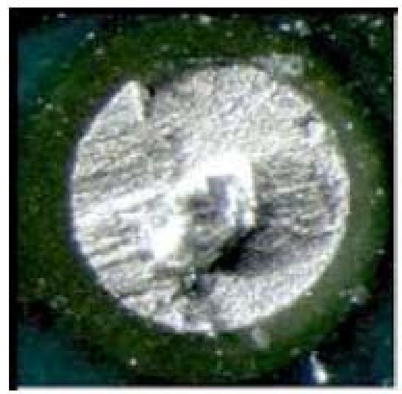


Drop Test

Drop Test (Luan 2007)

Ball Shear Test

10mm/s – bulk fracture

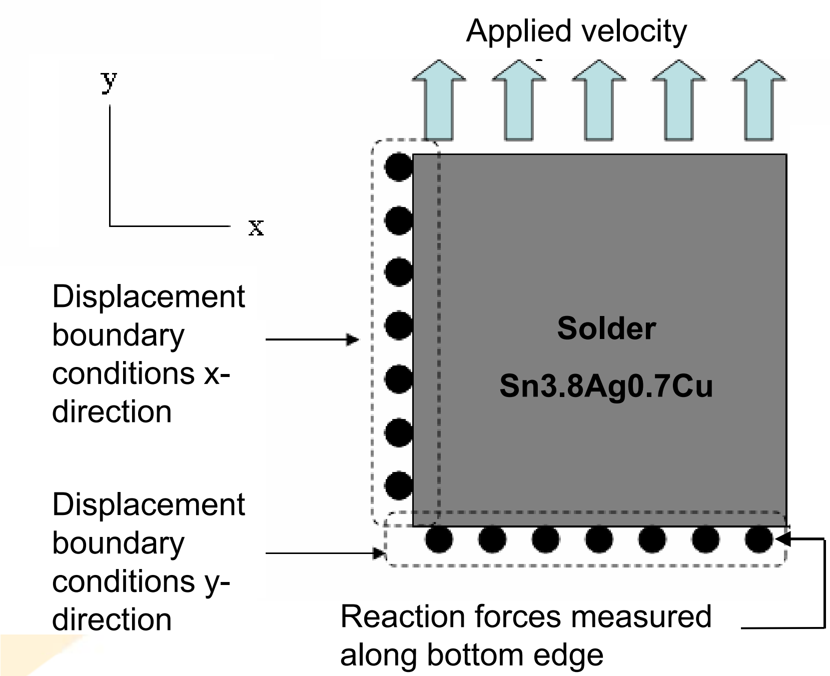


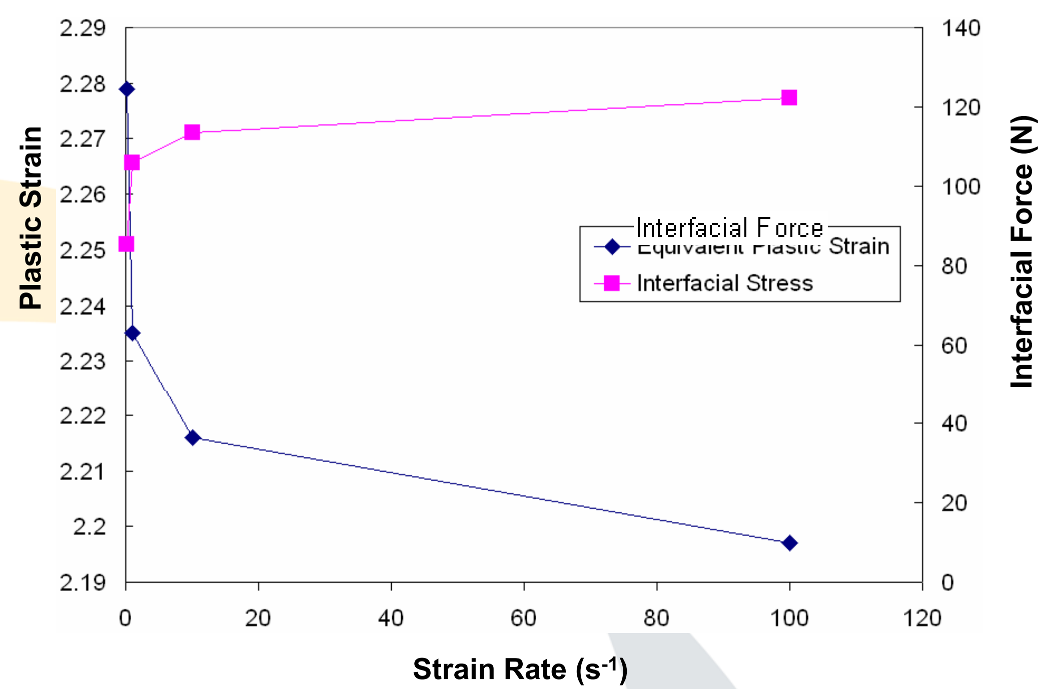
1000mm/s – partial fracture

10,000mm/s – interface fracture
(Kaulfersch 2007)

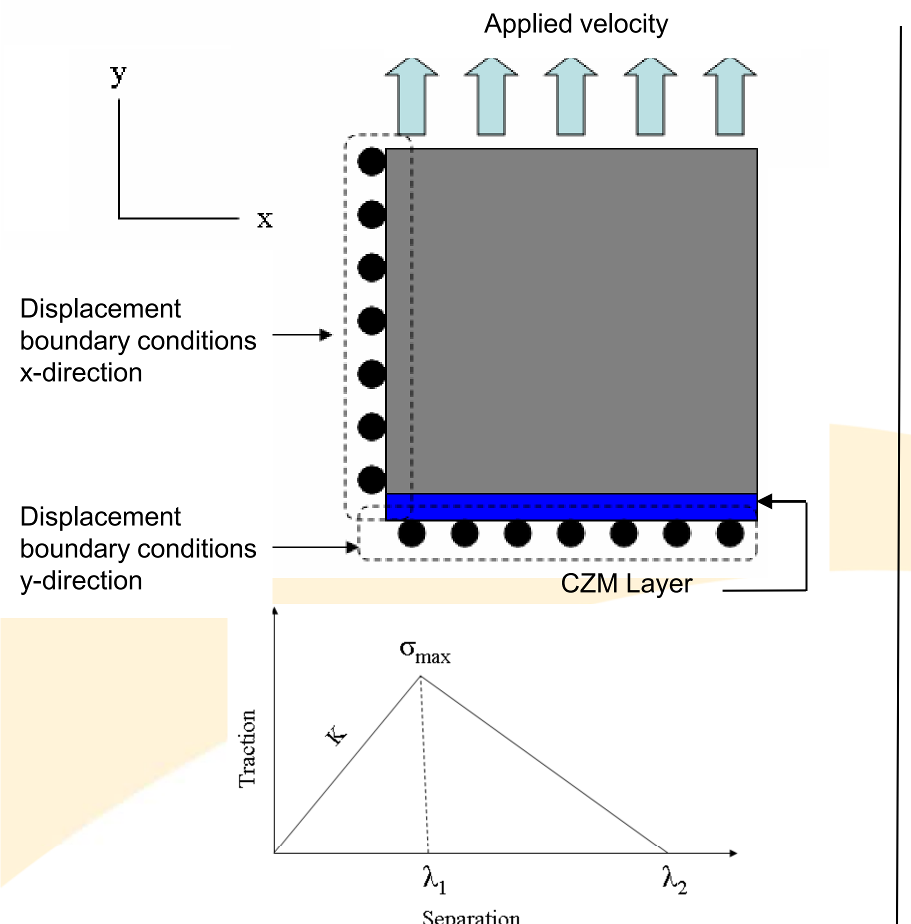
- Bulk solder, interface failure, or a combination?
- Function of strain rate dependence of IMC, solder, and interface

Localization at High Strain Rate

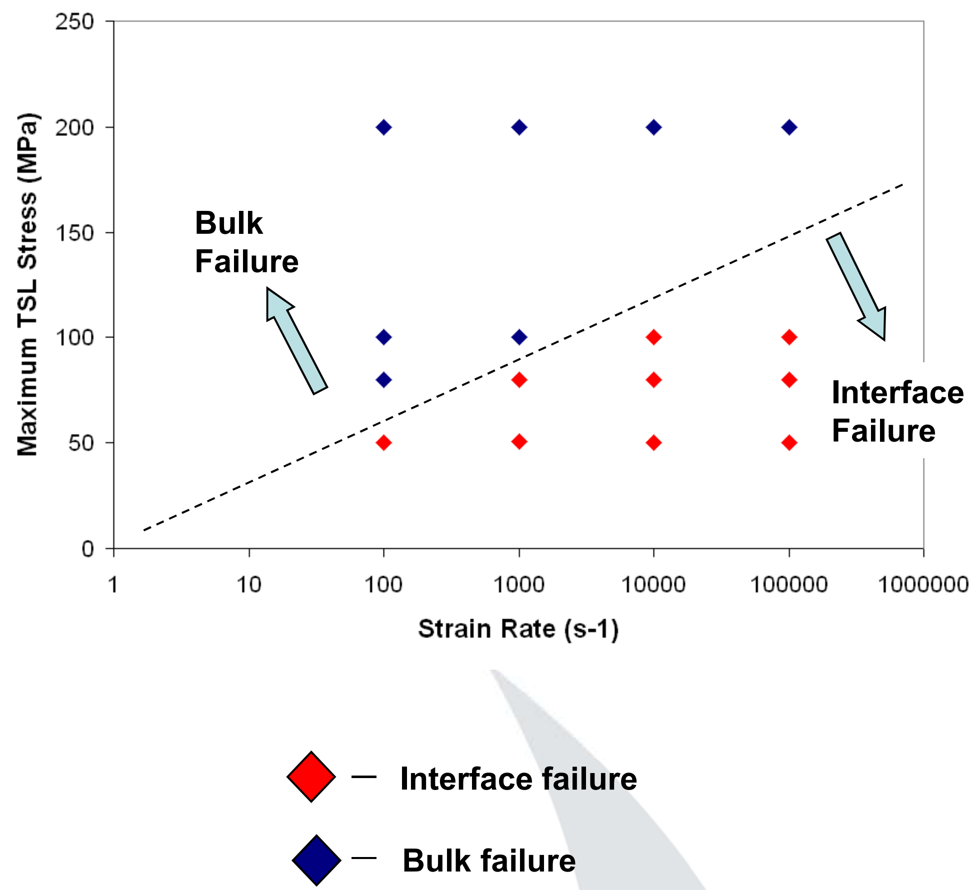




Fracture Simulations using Cohesive Zone Model



Bilinear traction separation law used in the cohesive zone elements along the solder interface; σ_{max} is varied, cohesive energy kept constant



Fatigue Fracture in Solder Joints – Part II

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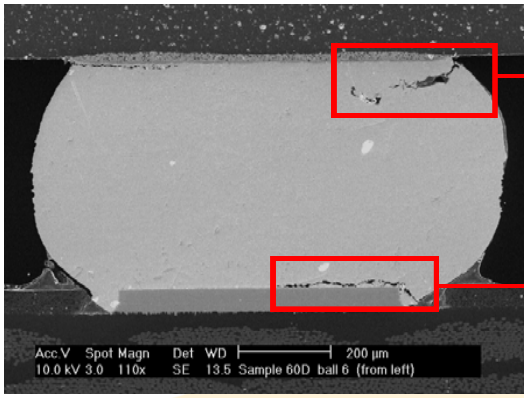
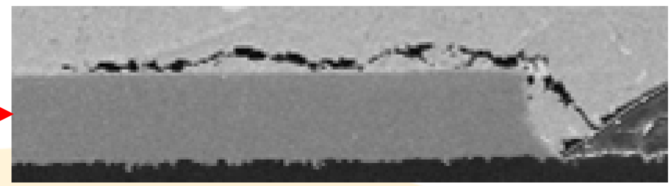
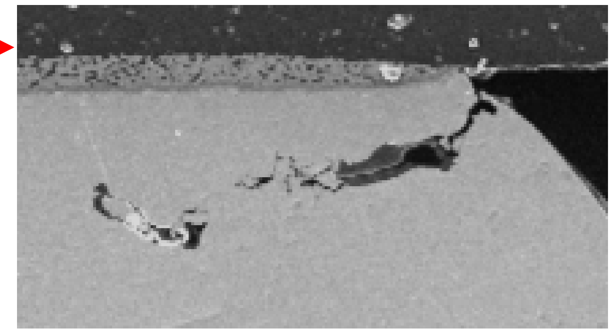
Crack Growth in Solder Joints



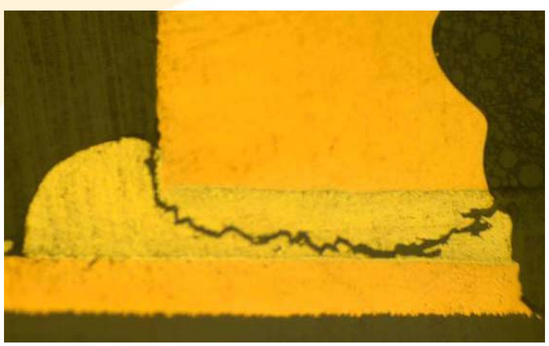
CBGA 29mm, 1.27mm pitch, 483 pads
Accelerated thermal cycling (0-100^{o}C)

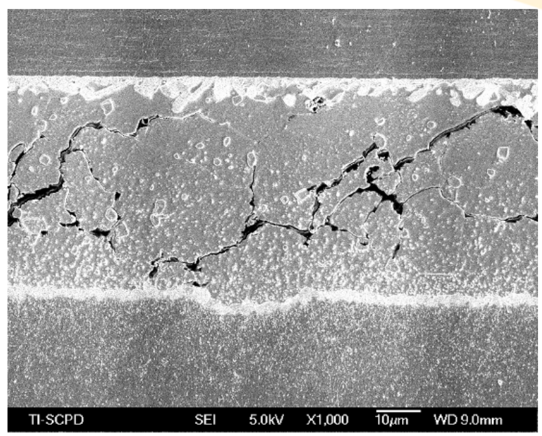


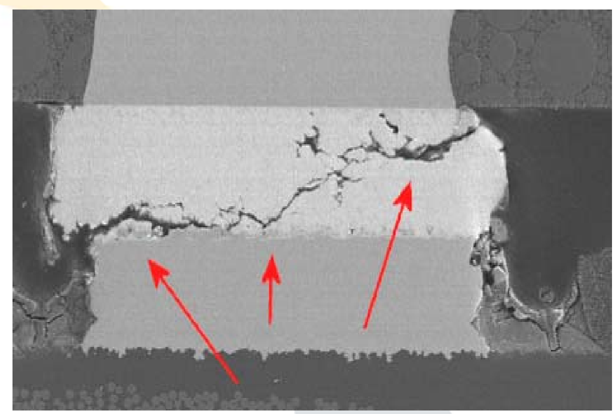


Courtesy HDPUG

QFN, 0.5mm pitch, 64 I/Os, 4mm square
Accelerated thermal cycling (-40 to 125^{o}C)







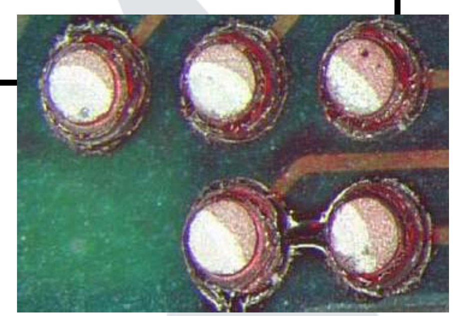
Courtesy TI

Introduction

- Failure models typically empirical
  - Geometry, package construction dependent
  - Fracture not modeled explicitly
- Few non-empirical failure models
  - A new model for hierarchical fracture processes

Fatigue Failure Modeling Approaches

Empirical	Damage Mechanics	Paris Law
$N_f = \left(\dfrac{C}{\Delta\varepsilon^p}\right)^{\frac{1}{m}}$	$N_f = \dfrac{1-(1-D_f)^{k+1}}{(k+1)L}$	$\dfrac{da}{dN} = C_1(\Delta K)^m$
✓ Ease of use ✗ Constant rate of damage assumed ✗ Physics and crack growth not described	✓ Allows for incorporation of physics of failure ✗ Computationally expensive for all cycles ✗ Crack growth not described	✓Describes crack growth ✓Demonstrated validity ✗Not valid for large plasticity or large cracks ✗ Limiting assumptions (self-similar crack growth, constant-amplitude loading)



Towashiraporn et. al. (2004)

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Limitations of Fracture Mechanics

- Linear Elastic Fracture Mechanics (G, K)
  - Linear elastic materials or small-scale yielding
- Elastic-Plastic Fracture Mechanics (J-integral, CTOA, CTOD)
  - Applicable for deformation plasticity, impractical measures
- Paris Law $\frac{da}{dN} = C_1(\Delta K)^m$ **or** $\frac{da}{dN} = C_2(\Delta J)^n$
  - Self-similar crack growth, small-scale yielding

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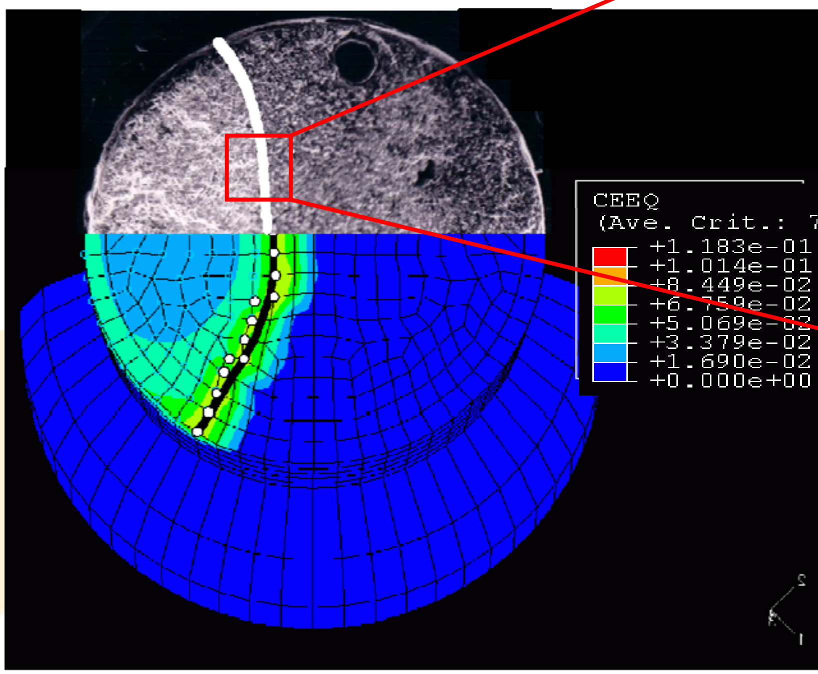
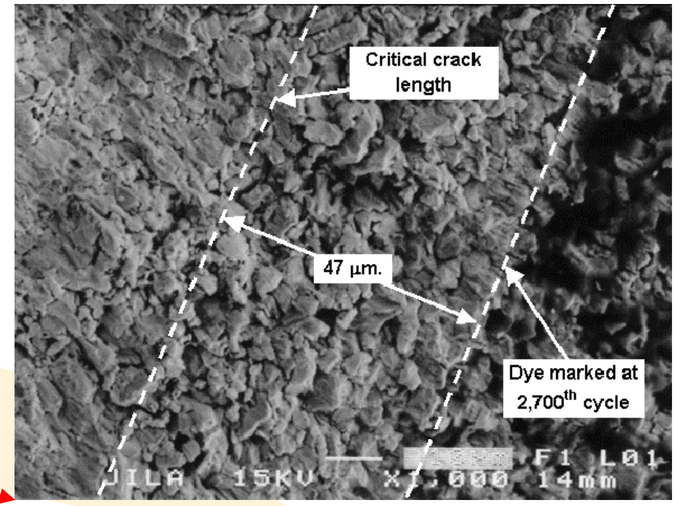
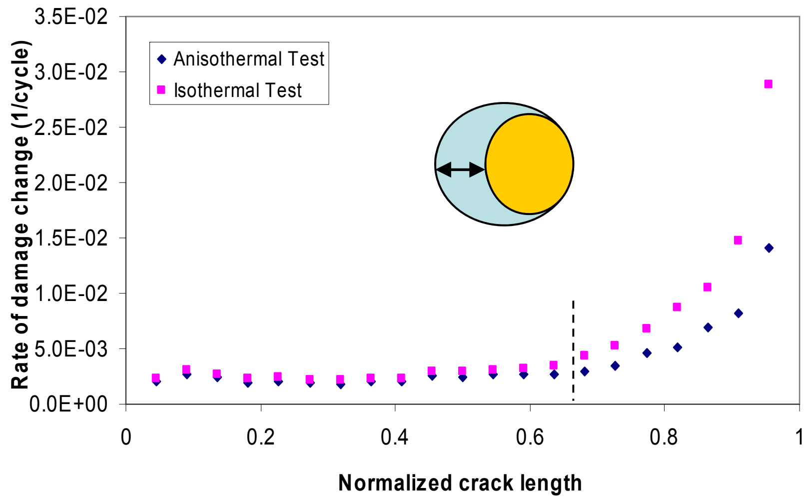
Hybrid Damage Model

Sn-Pb solder joints (Towashiraporn et. al., 2003, 2005)

$$D = 1 - \exp\left[-\left(\frac{\xi}{\xi_c}\right)^{\beta}\right]$$



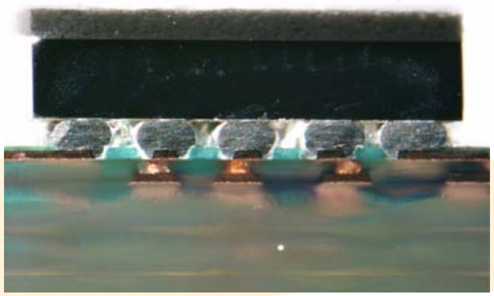


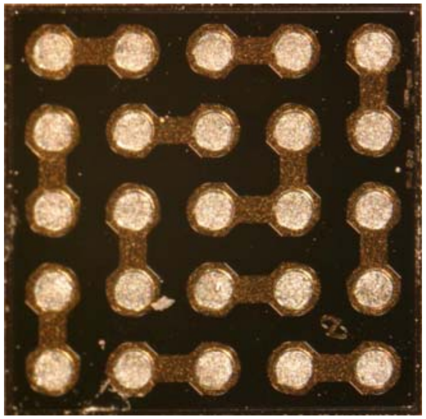


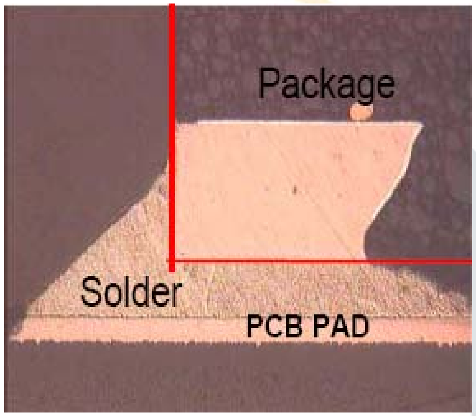
Application to SnAgCu Solder Joints

Chip Scale Package
(1.56 mm)

Quad Flat No-leads Package
(4 mm)



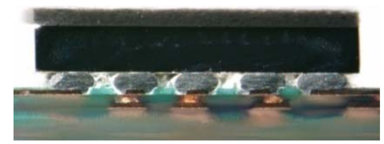




Crack Growth in CSP Solder Joints

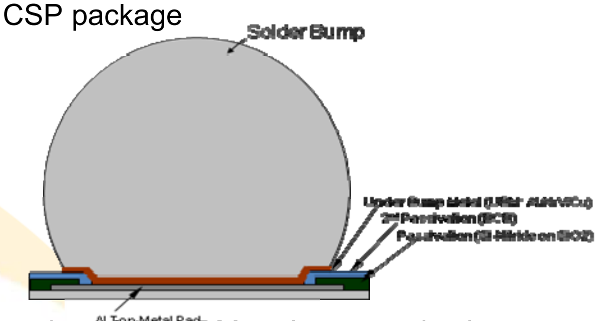
Test Specimen and Test Conditions

- 50 I/O chip scale packages



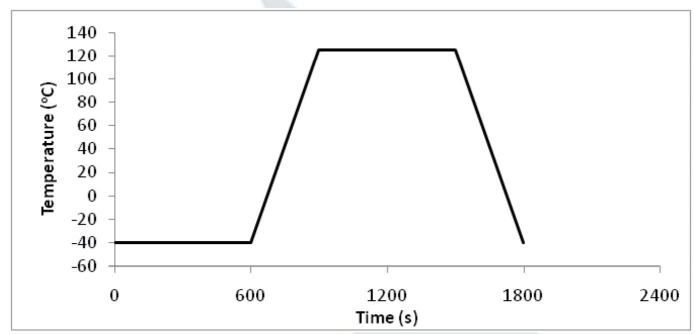
Cross-sectional image of the wafer-level CSP package

- SAC387 solder
  - 0.3 mm pitch
  - 165 µm pad diameter
  - 134 µm standoff height



Geometries of the UBM and two passivation layers

- Silicon substrate - 3.5x3.5x0.3 mm
- Accelerated thermal cycling
- Failure analysis every 240 cycles



Temperature profile used in the ATC

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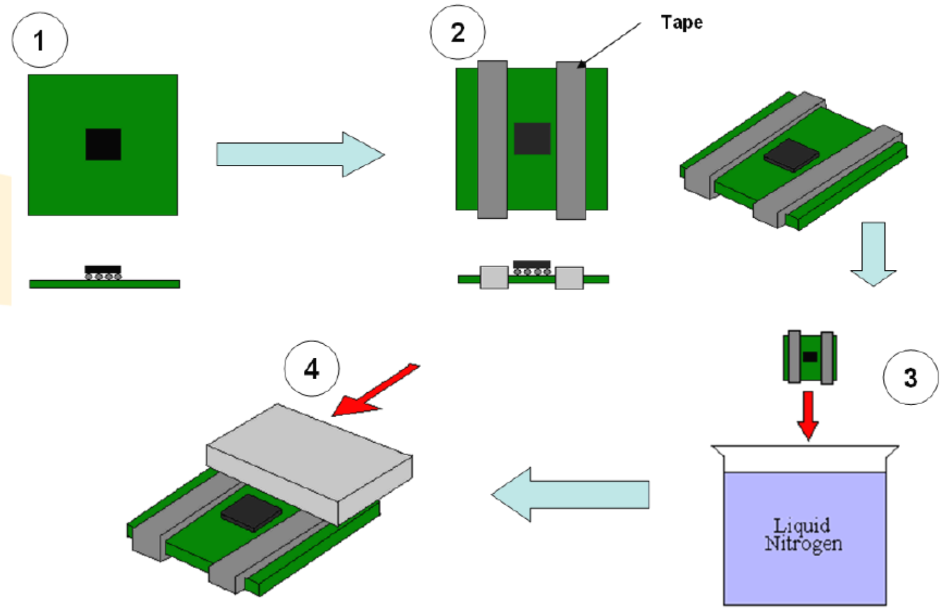
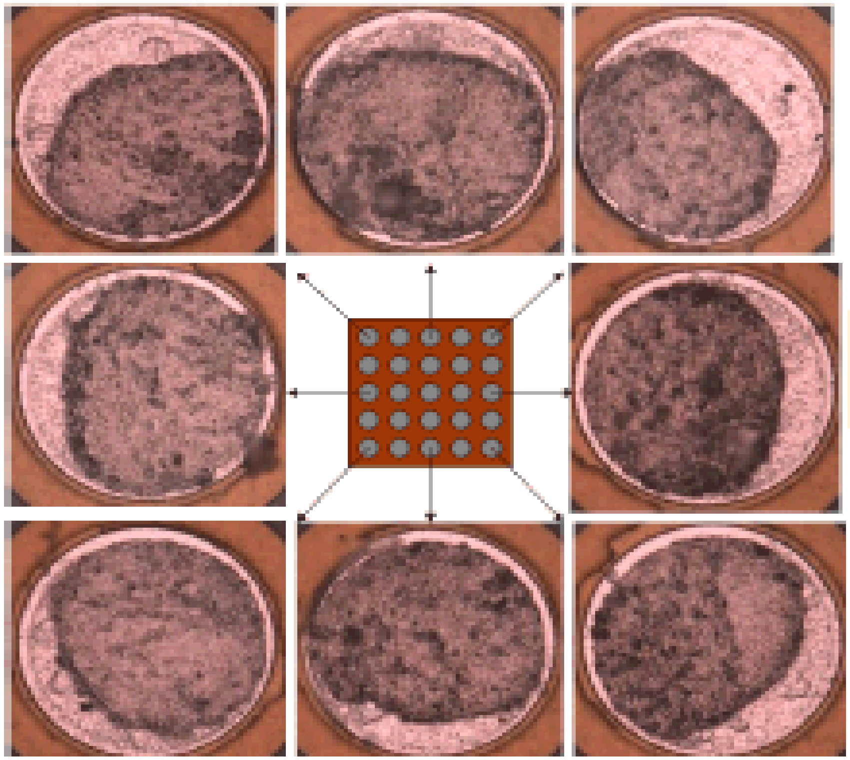
Failure Analysis Technique

- Failure analysis performed every 240 cycles
  - Tape wrapped around PCB
  - Liquid nitrogen used to embrittle solder joints
  - Mechanically pried
  - No dye marker
- Differentiated fracture morphology
- Optical microscopy performed
  - ScionImage
  - Crack length
  - Crack area

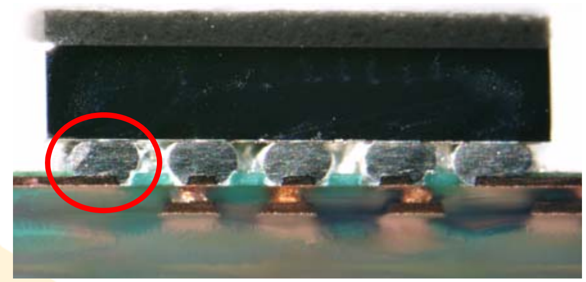


Prying procedure used remove the component for visual observation of crack front growth

Observations of Crack Fronts



Crack front at 960 thermal cycles for the corner and mid-edge joints in a CSP package.



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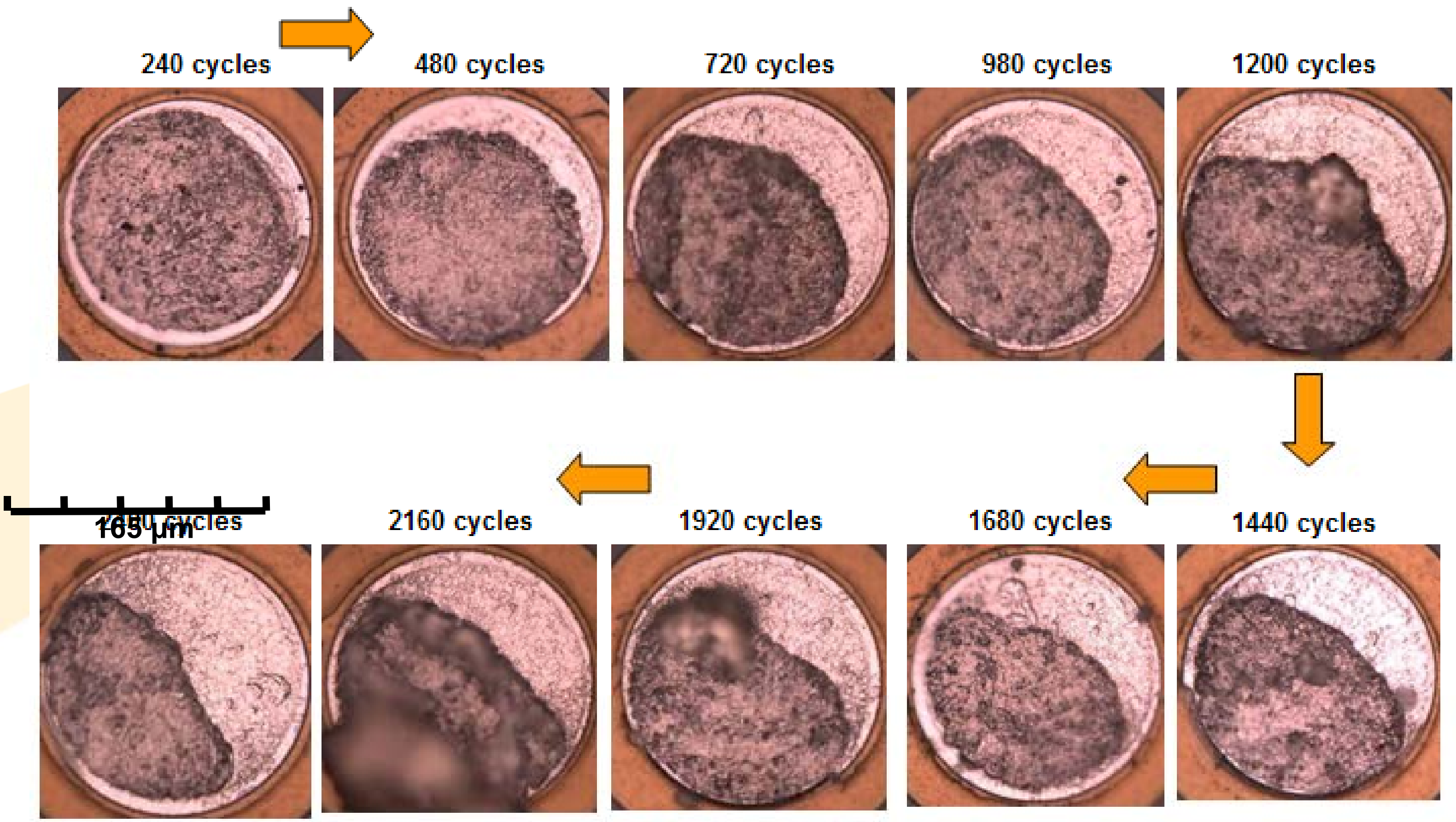
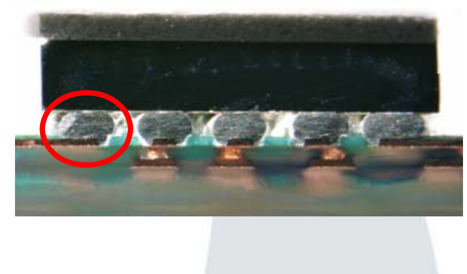
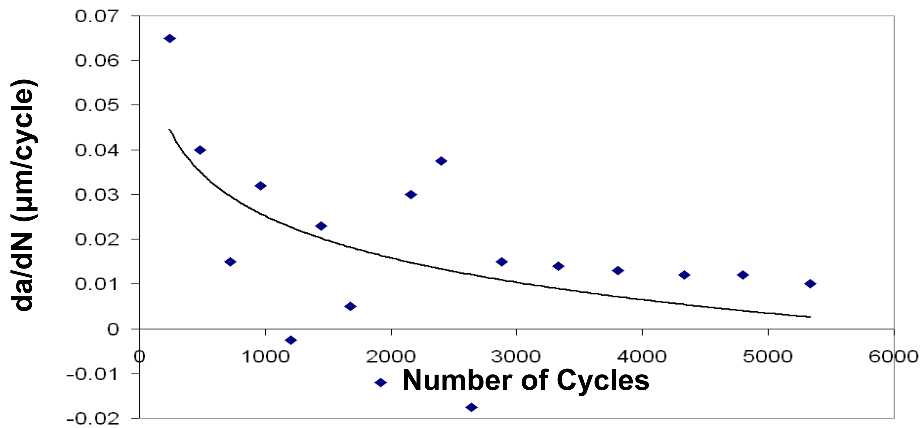
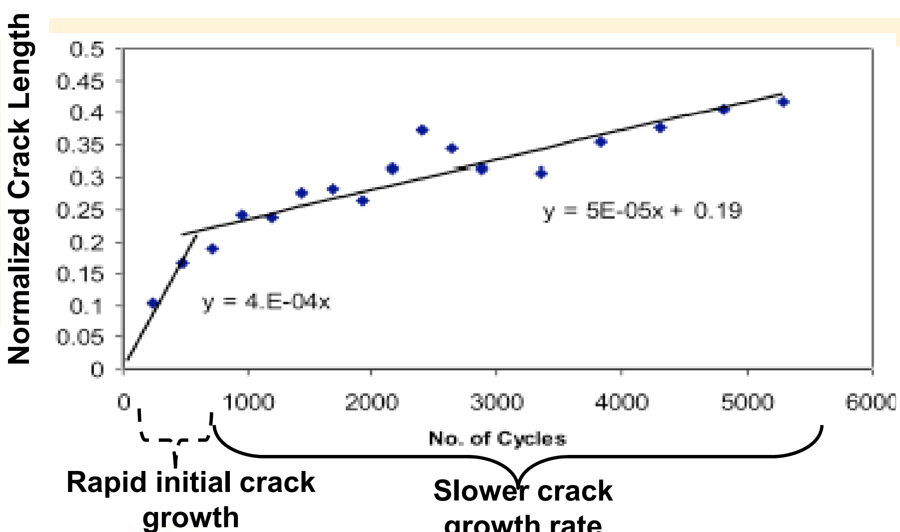
Progress of Crack

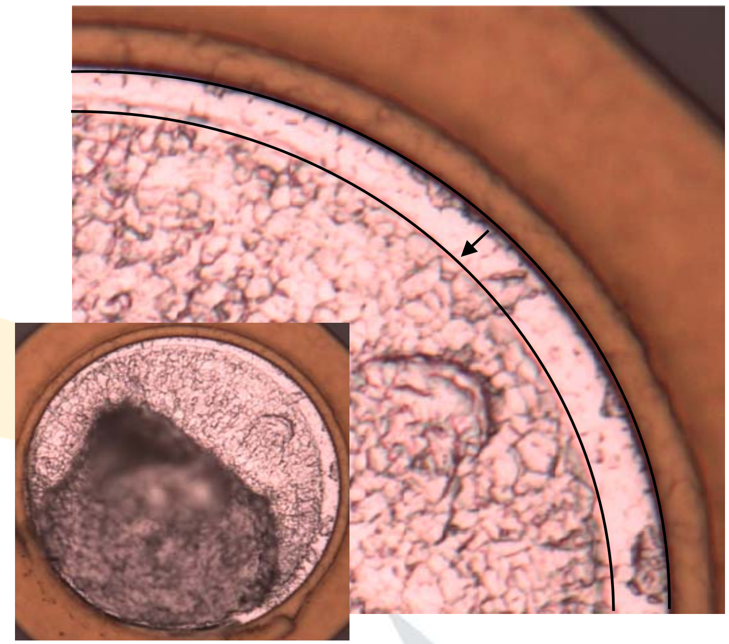


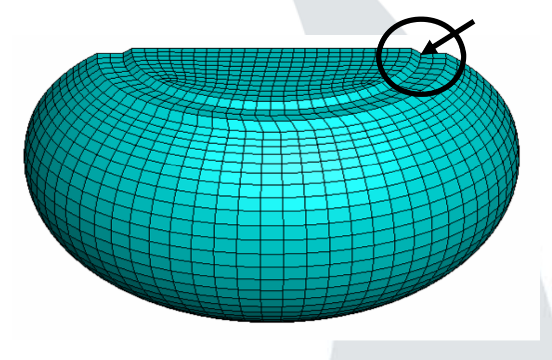


Geometry Dependence of Fatigue Crack Growth









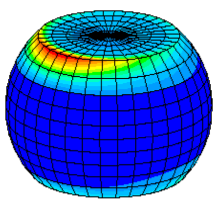
Computational Procedure

Dissipation Extrapolation

$$W_{n+1} \approx W_n + \left.\frac{\partial W}{\partial N}\right|_n (N_{n+1} - N_n)$$

Failure Probability Estimation

$$p_f = 1 - \exp\left[-\frac{W}{W_c}\right]$$



Simulation of Two Cycles for New Configuration

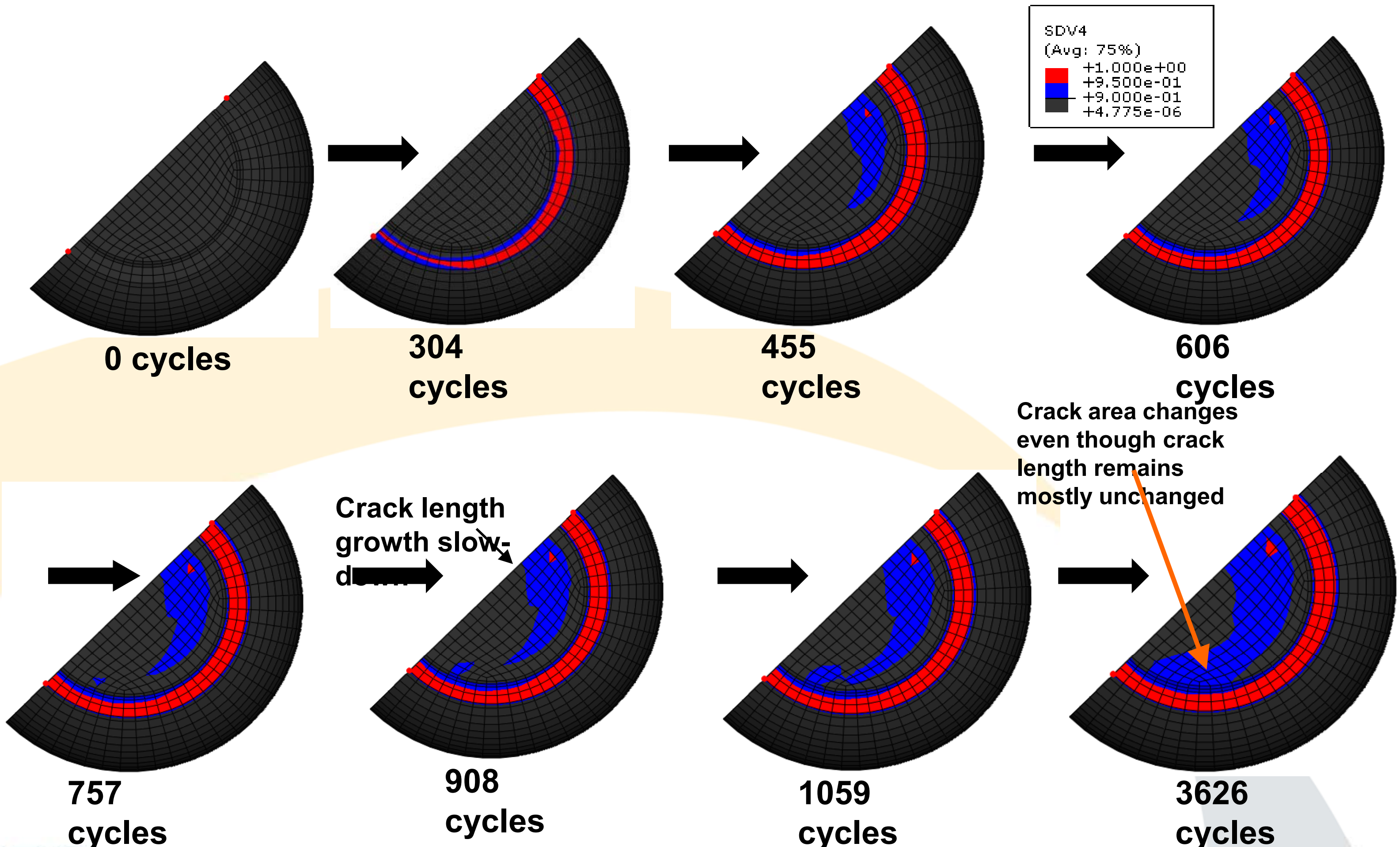
- stabilization cycle

- extrapolation cycle

Crack Propagation if $p_f > p_{f(critical)}$

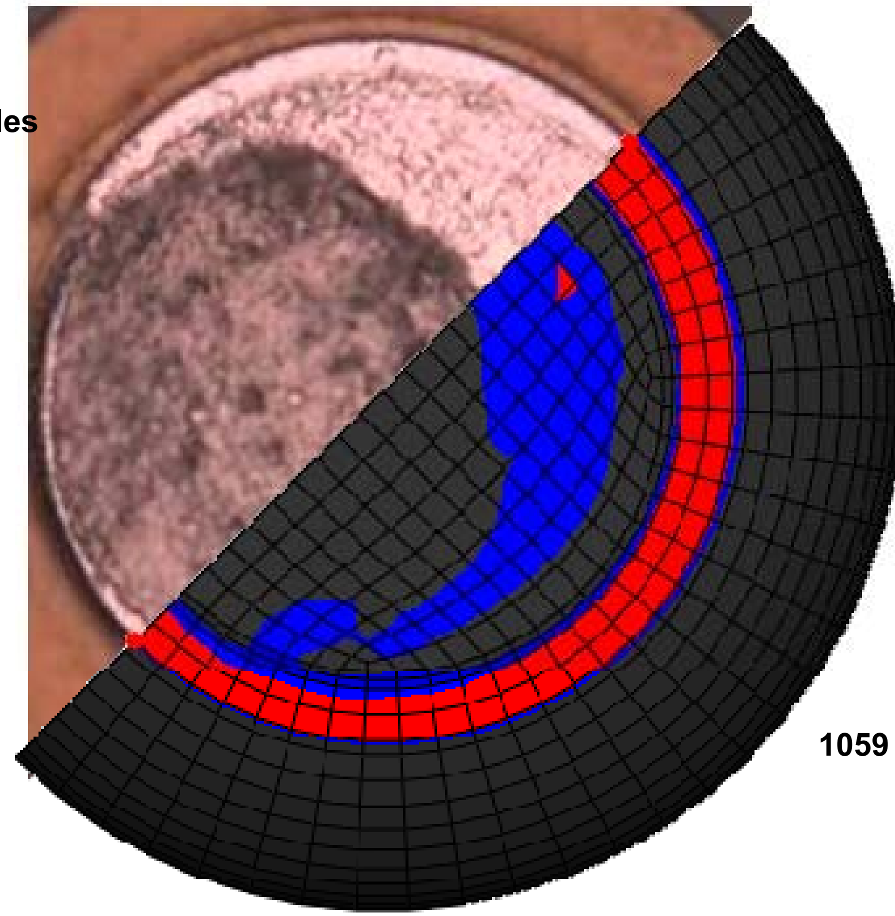
Need to accurately compute W at every material point!

Simulation of Fracture Progression



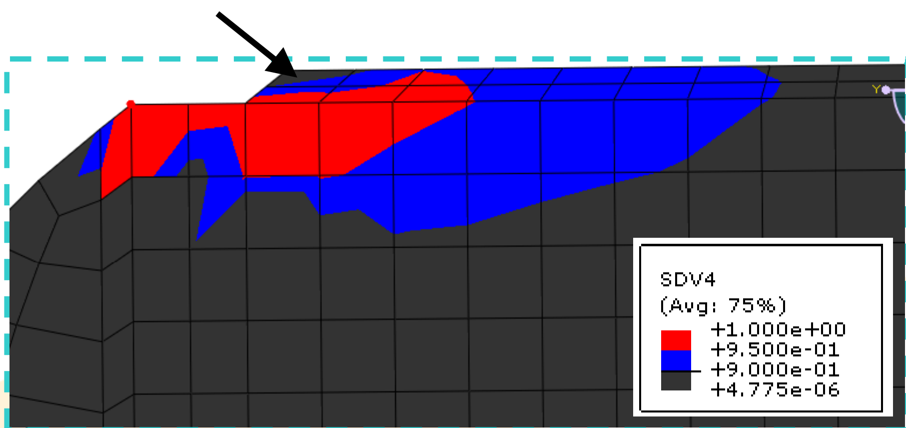
Test versus Simulation

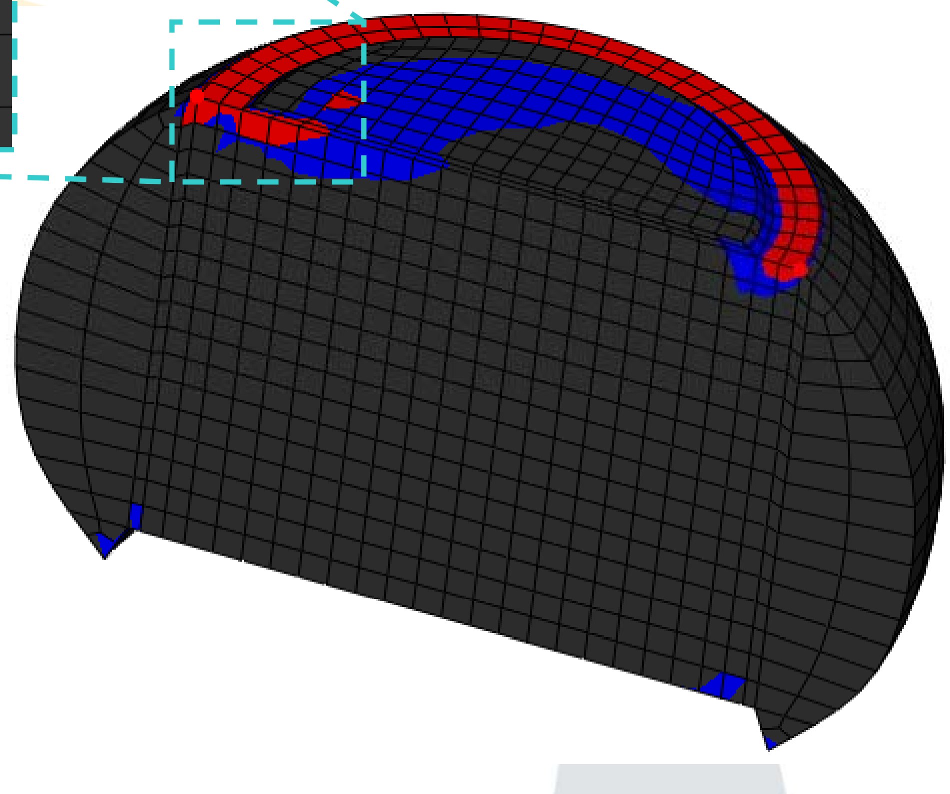
980 Cycles



1059 Cycles

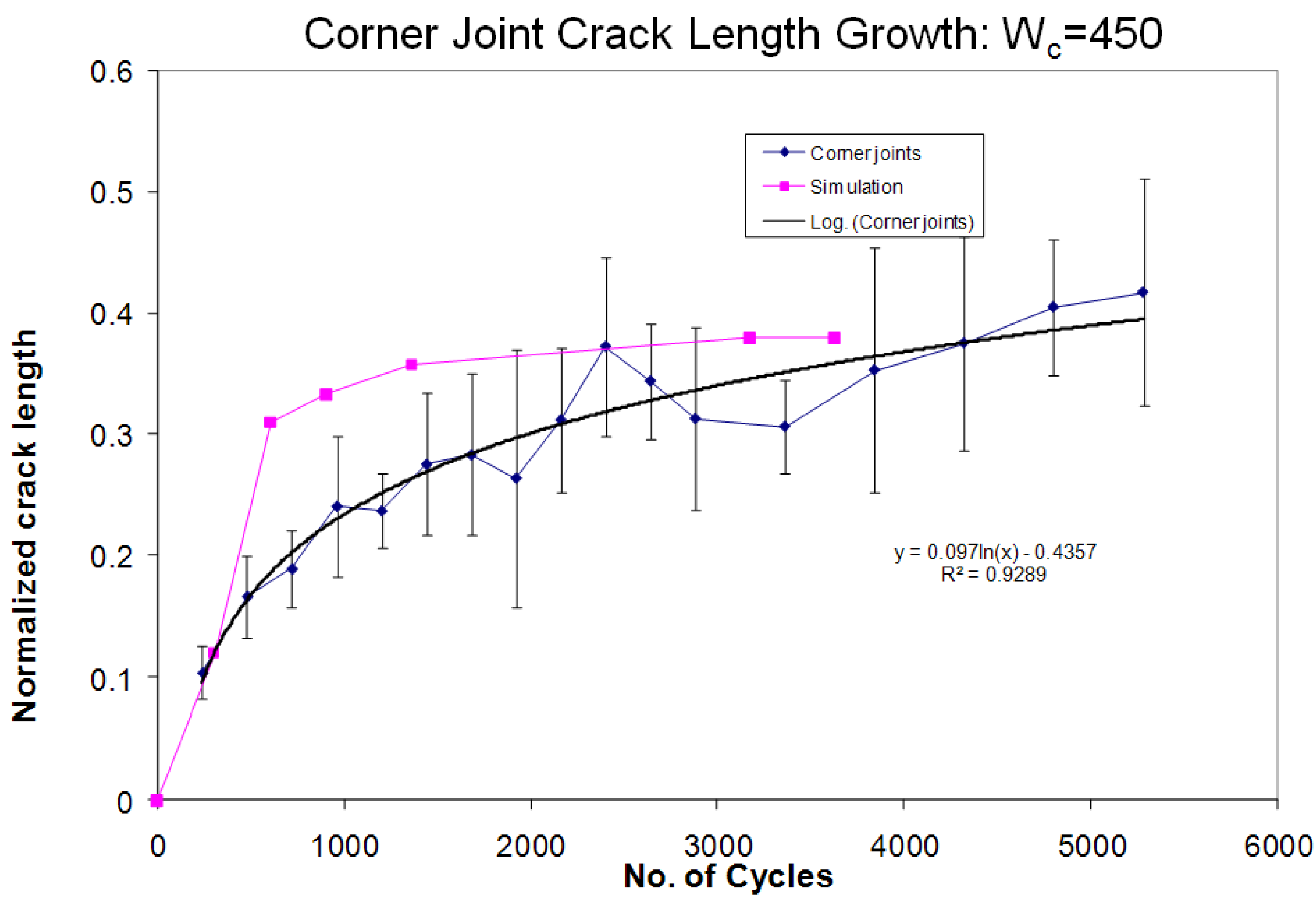
Geometry Influence on Fracture Morphology





- UBM structure causes crack to briefly propagate into the bulk under interface before re-emerging

Comparison of Crack Progression

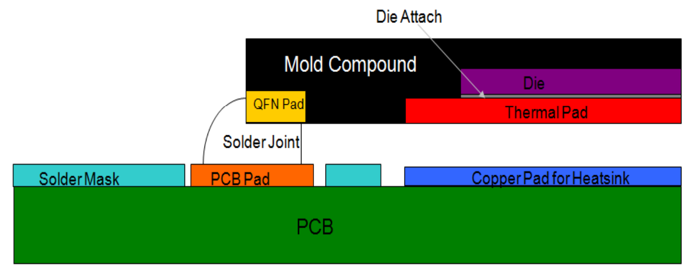


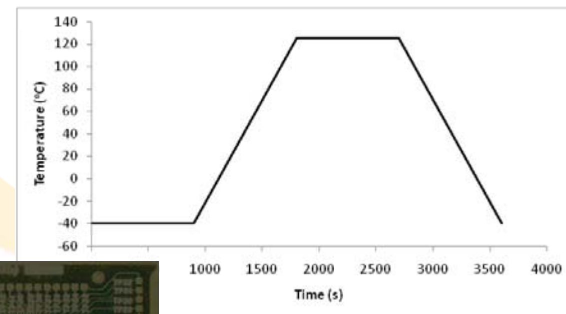
Crack growth statistics of the simulated and experimental results.

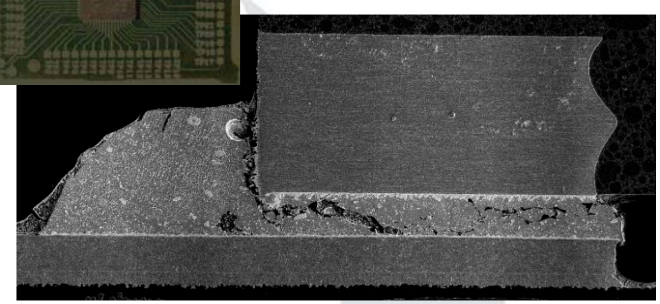
Crack Growth in QFN Solder Joints

Test Specimen and Test Conditions

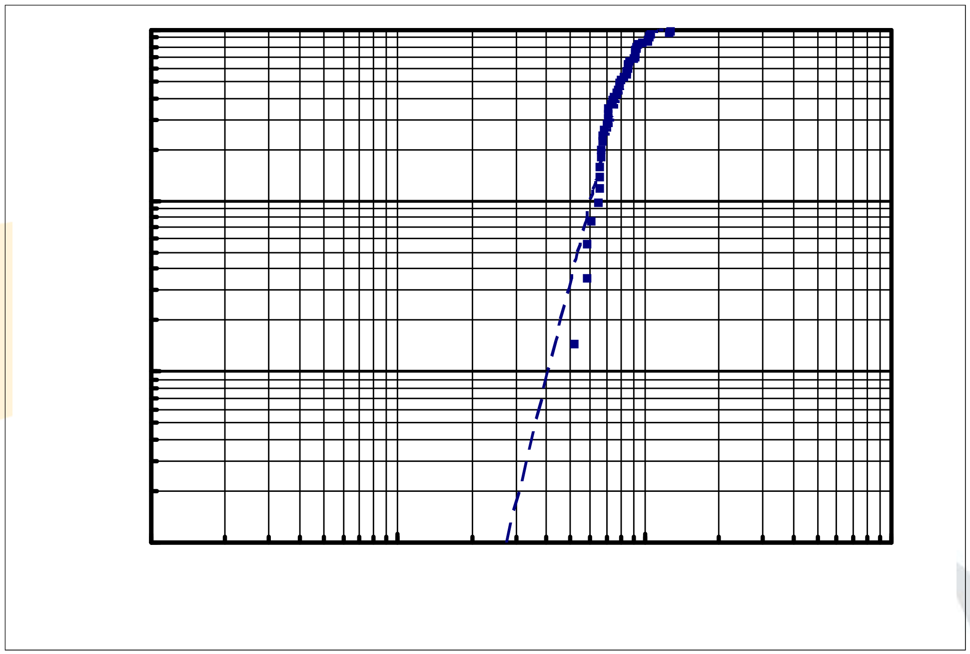
- 48 0.5 mm pitch QFN packages
- SAC387 solder
  - 64 joints
  - Standoff height: 60µm
  - Landing pad: 0.233x0.725mm
- FR-4 board – 93 mills
- Silicon die within 1 mm thick mold compound
- ATC conditions as shown
- Failure when electrical resistance is 10.6 Ohms







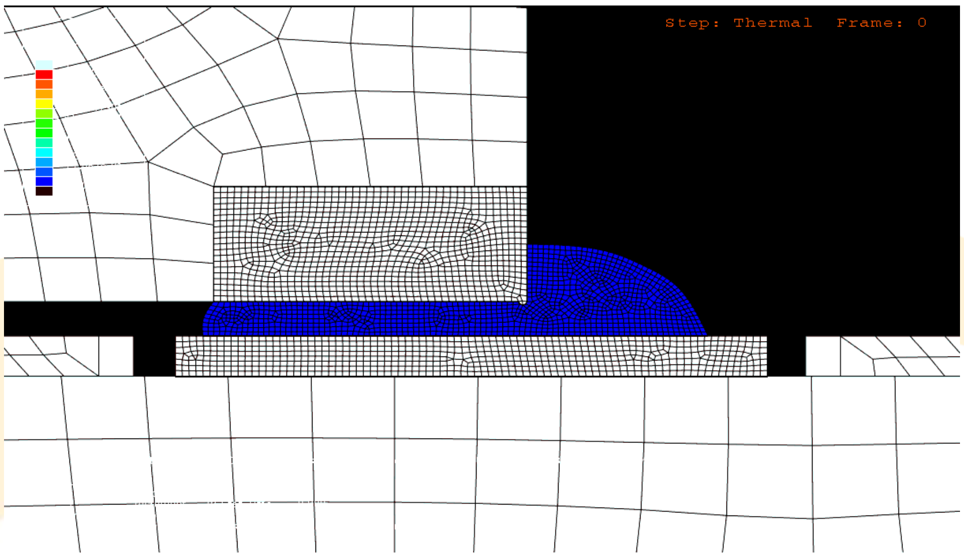
Test Results and Weibull Fit

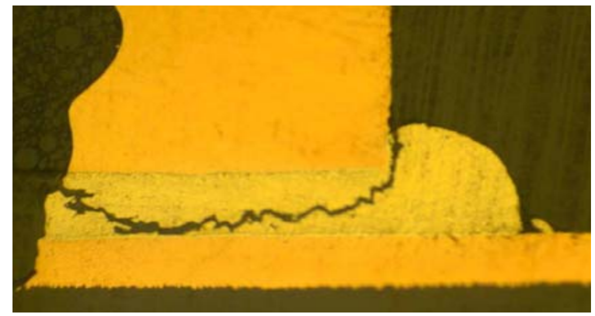


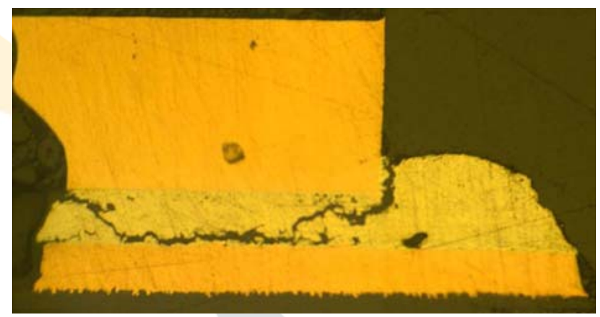
Cumulative Failure Statistics		
0.1%	1.00%	63.20%
275	406	884

Weibull Reliability Parameters		
β	η	R^2
5.91	883.9	96.07

Fatigue Crack Growth



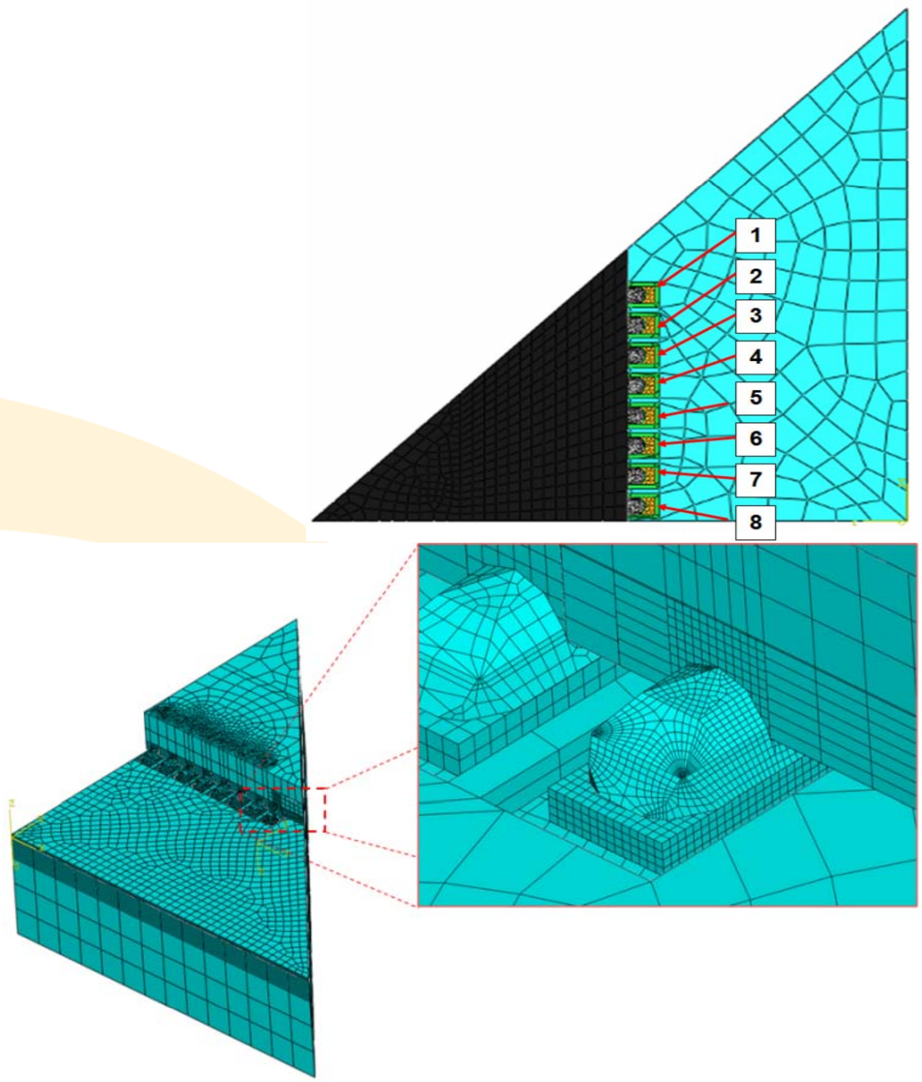




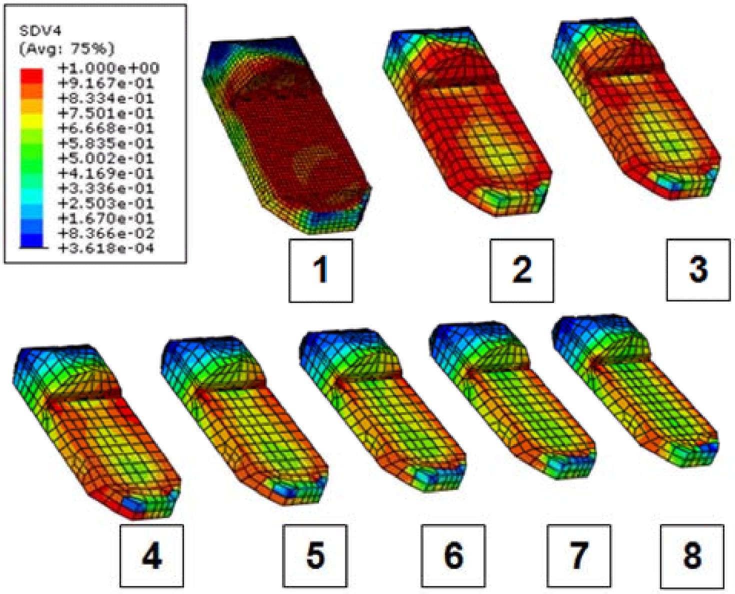
- Multiple crack initiation locations
- Strong influence of geometry on failure

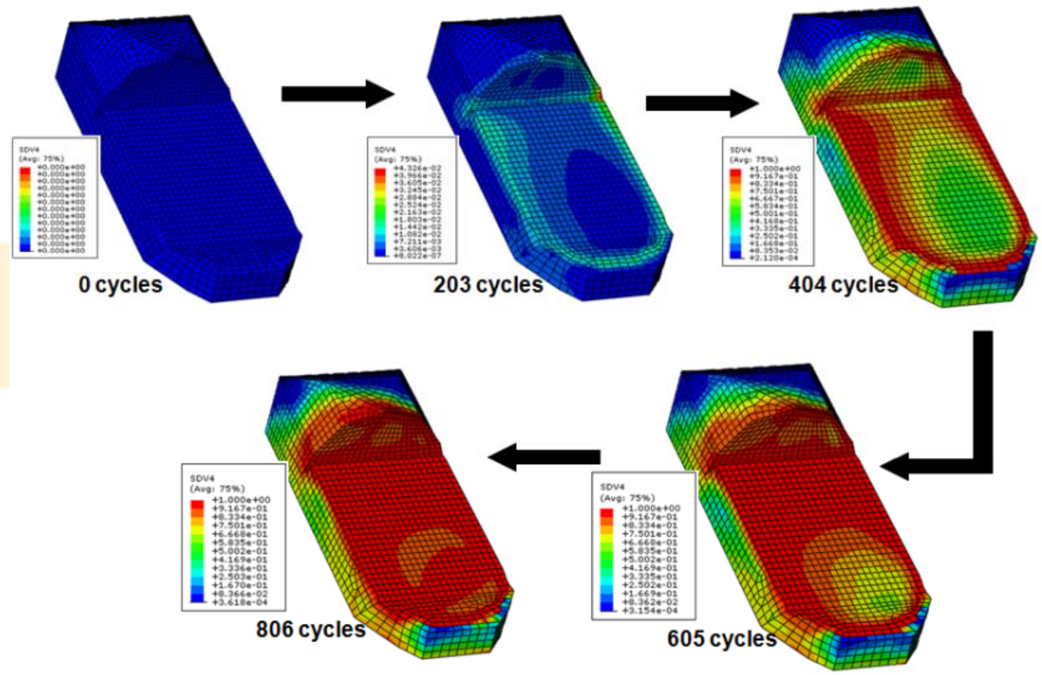
Details of FE Model

- 1/8th geometry
- Solder material behavior
  - Time hardening creep
  - Rate independent plastic properties
- FR-4
  - Temperature dependent, anisotropic elastic properties
- Passivation layer
- 65,820 elements
  - Solder joints –5,655 elements
- Isothermal boundary conditions

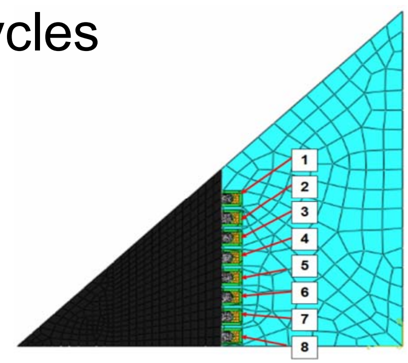


Failure Progression

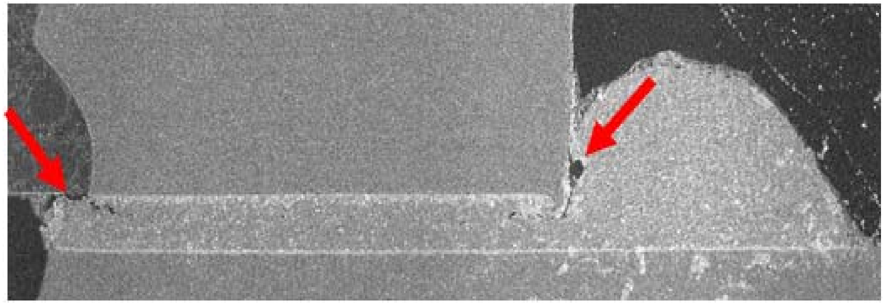


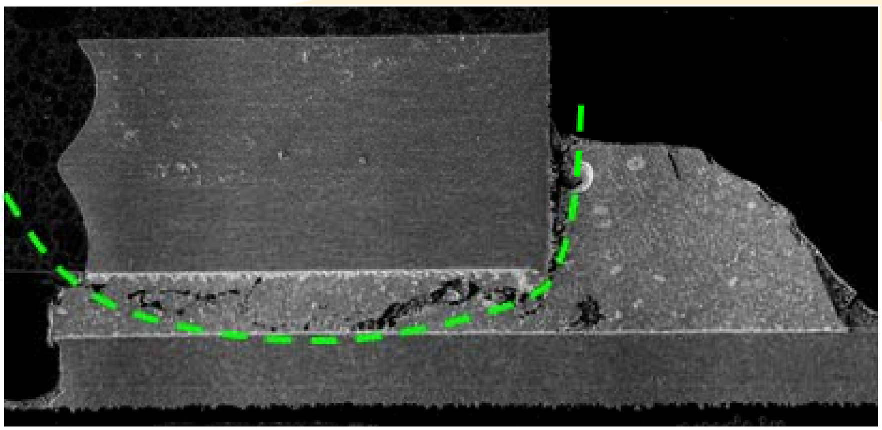


- Predicted life – 806 cycles
- Furthest joint fails first

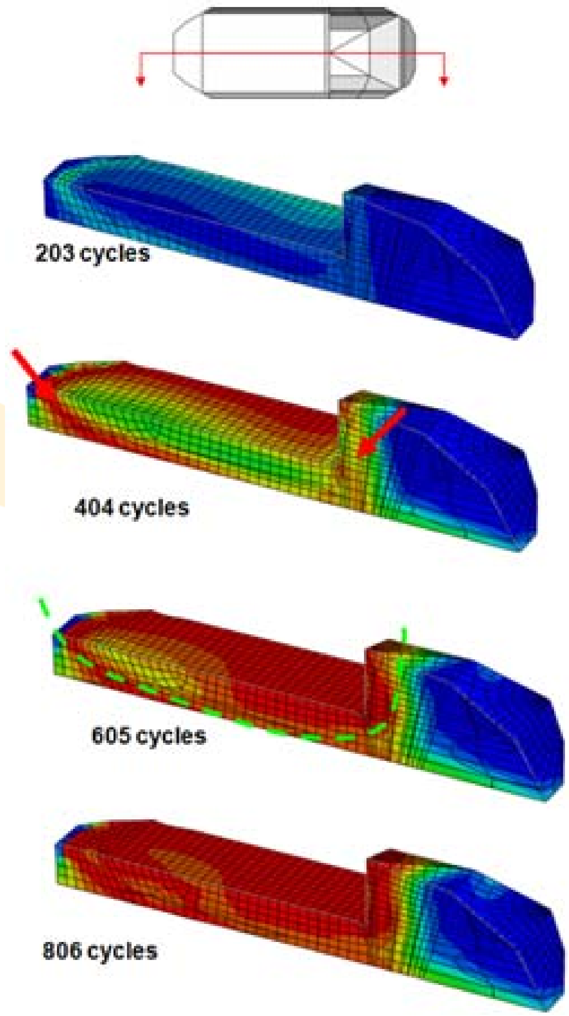


Comparison to Observed Trajectories

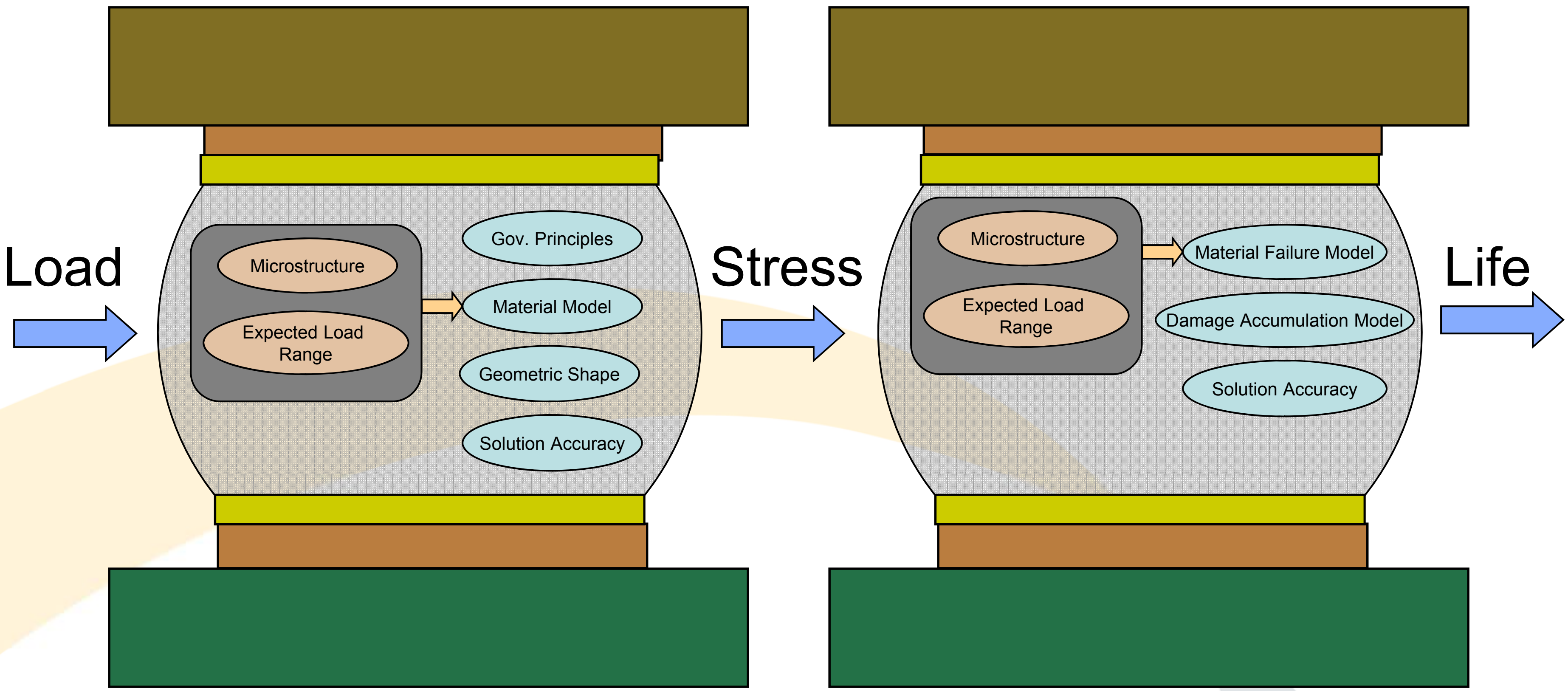




- Fracture initiates at two points
- Fracture not at interface



Summary



Accurate physical models can lead to accurate *package-independent reliability **predictions***!

Related Journal Publications

- D. Bhate, G. Subbarayan, L. Nguyen, J. Zhao, D. Edwards, "Singularities at Solder Joint Interfaces and their Effects on Fracture Models," ASME Journal of Electronic Packaging, under review.
- X. Nie, D. Chan, D. Bhate, W. Chen, G. Subbarayan, and I. Dutta, "Intermediate and High-Strain Rate Behavior of Sn3.8Ag0.7Cu and Sn1.0Ag0.5Cu Solder Alloys: Constitutive Models and their Demonstration" IEEE Transactions on Components and Packaging Technologies.K. Mysore, G. Subbarayan, V. Gupta, R. Zhang, "Constitutive and Aging Behavior of Sn3.0Ag0.5Cu Solder Alloy," IEEE Transactions, Electronics Packaging Manufacturing, in press.
- D. Bhate, G. Subbarayan, J. Zhao, V. Gupta, and D. Edwards "Improved Solder Joint Fatigue Models through Reduced Geometry Dependence of Empirical Fits" ASME Transactions Journal of Electronic Packaging, in press.
- I. Dutta, P. Kumar, and G. Subbarayan, "Microstructural Coarsening in Sn-Ag Based Solders and Its Effects on Mechanical Properties," Journal of Metals (JOM), vol. 61, no. 6, pp. 29-38, TMS, 2009.
- D. Bhate, D. Chan, G. Subbarayan, T.C. Chiu, V. Gupta and D. Edwards "Constitutive Behavior of Sn3.8Ag0.7Cu and Sn1.0Ag0.5Cu older Alloys at Creep and Low Strain Rate Regimes," IEEE Transactions on Components and Packaging Technology, vol. 31, no. 3, pp. 622-633, 2008.
- D. Bhate, D. Chan, G. Subbarayan, and L. Nguyen, "A Nonlinear Fracture Mechanics Perspective on Solder Joint Failure: Going beyond the Coffin-Manson Equation," ASME Journal of Electronic Packaging, vol. 130, no. 2, pp. 021003-021012, 2008.
- P. Towashiraporn, G. Subbarayan and C.S. Desai. "A Hybrid Model for Computationally Efficient Fatigue Fracture Simulations at Microelectronic Assembly Interfaces." International Journal of Solids and Structures, vol. 42, pp. 4468-4483, 2005.
- P. Towashiraporn, K. Gall, G. Subbarayan, B. McIlvanie, B.C. Hunter, D. Love, and R. Sullivan. "Powercycling Thermal Fatigue of Sn-Pb Solder Joints in a Chip-Scale Package." International Journal of Fatigue, vol. 26, pp. 497-510, 2004.
- P. Towashiraporn, G. Subbarayan, B. McIlvanie, B.C. Hunter, D. Love, and R. Sullivan. "The Effect of Model Building on the Accuracy of Fatigue Life Predictions in Electronic Packages." Microelectronics Reliability, vol. 44, no. 1, pp. 115-127, 2004.
- P. Towashiraporn, G. Subbarayan, B. McIlvanie, B.C. Hunter, D. Love, and R. Sullivan. "Predictive Reliability Models through Validated Correlation between Power Cycling and Thermal Cycling Accelerated Life Tests." Soldering and Surface Mount Technology, vol. 14, no. 3, pp. 51-60, 2002.

Recent Conference Publications

- D. Chan, X. Nie, D. Bhate, G. Subbarayan, W. Chen, and I. Dutta, "High Strain Rate Behavior of Sn3.8Ag0.7Cu Solder Alloys and Its Influence on the Fracture Location within Solder Joints," In proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS, and NEMS (Interpack '09), July 19-23, San Franciso, CA, 2009, ASME, Paper number IPACK2009-89404, 2009.
- D. Chan, D. Bhate, G. Subbarayan, J. Zhao, D. Edwards, "Predicting Crack Growth and Fatigue Lives of QFN Solder Joints using a Multiscale Fracture Model," In proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS, and NEMS (Interpack '09), July 19-23, San Franciso, CA, 2009, ASME, Paper number IPACK2009-89403, 2009.
- D. Chan, D. Bhate, G. Subbarayan, L. Nguyen, "Characterization of Crack Fronts in a WLCSP Package: Experiments and Models for Application of a Multiscale Fracture Theory," In proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS, and NEMS (Interpack '09), July 19-23, San Franciso, CA, 2009, ASME, Paper number IPACK2009-89402, 2009.
- K. Mysore, S. Chavali, D. Chan, G. Subbarayan, I. Dutta, V. Gupta, D. Edwards, "Mechanistic Model for Aging Influenced Steady State Flow Behavior of Sn3.8Ag0.7Cu Solder Alloys," In proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS, and NEMS (Interpack '09), July 19-23, San Franciso, CA, 2009, ASME, Paper number IPACK2009-89401.
- D. Bhate, K. Mysore, and G. Subbarayan, "A Multiscale Damage Accumulation Theory for Solder Joint Failure," In proceedings of the ASME/Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems, MEMS, and NEMS (Interpack '09), July 19-23, San Franciso, CA, 2009, ASME, Paper number IPACK2009-89399.

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