Experiments Needed to Characterize Solder Joint Behavior

by

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Workshop on Modeling and Data Needs for Lead-Free Solders
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Factors Affecting Fatigue Life of Solder Joints

- Deformation caused by thermomechanical structural incompatibility between package and printed circuit board

- Solder joint response
  - creep behavior (stress vs. strain, time, and temperature dependence)
  - damage mechanisms (crack initiation, damage localization, and crack propagation)
  - fatigue damage accumulation

- Interfacial properties:
  - Pad metallization
  - Intermetallic buildup
  - Initial and evolving microstructure near the interface

Reliability Models for Pb-Free Solder Joint

Predictive reliability models must be based on:

- experimentally observed material’s behavior
- understanding fracture/damage mechanisms

Need for:

- good constitutive equations
- proper damage criteria
- accurate structural analysis

FEM Analysis - Pros and Cons

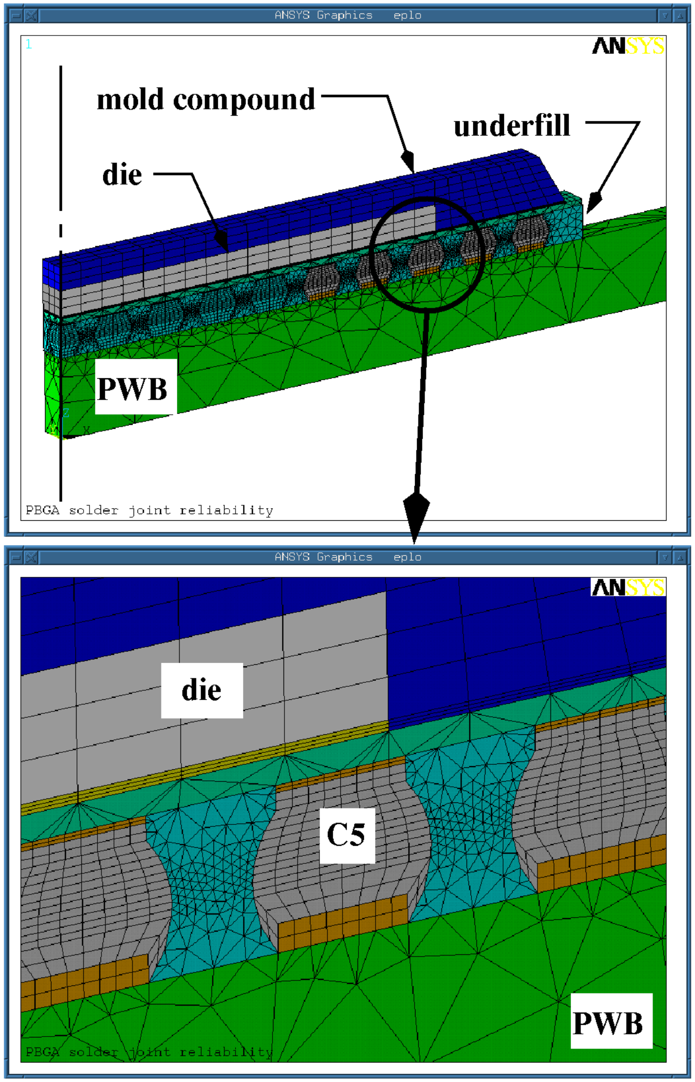
Pros:

- Excellent for a comparable analysis
- Captures structural complexity of packages and assemblies
- Commercial codes have built-in geometrical and physical non-linearity
- Time dependent (creep) analysis is available

Cons:

- Excessive time required to run more sophisticated analysis
- Poor damage criteria
- Requires experimental validation (is not fully predictive)

Sn/Pb C5 Solder Joint Reliability Modeling



Features

- 3-D “slice” geometry
- visco-plastic Sn/Pb solder behavior

Benefits

- assist with reliability trade-off decisions, formation of design rules, and recommendations for current and future designs
- model validation through current and archival SPS test data
- experience with 300+ case studies from 1998 to the present
- quick-turn service (1-2 days for familiar materials and designs, 1-4 weeks for new materials or designs)

“Underfilled BGAs for a Variety of Plastic BGA Package Types and the Impact on Board-Level Reliability,” T. Burnette, Z. Johnson, T. Koschmieder, and W. Oyler, to appear in the Proceedings of the 2001 ECTC Conference.

Simple Fatigue Models for Solder Joints

Pros:

- Easy to use
- It is possible to incorporate sophisticated damage criteria
- Accurate life projections between test and field conditions

Cons:

- Simplistic structural analysis
- Not suitable for design optimization
- Need for experimental verification
- Empirical (C-M like) models must always be verified

Constitutive Equations

Goodness of a constitutive model is measured by:

- the quality of fit to experimental data
- number of used parameters
- simplicity of model validation (calibration of parameters)

Any constitutive models must always satisfy the principle of objectivity

Generalized Power-Law Description

Creep Flow Mechanism:

$$\dot{\varepsilon}_{ij}^{c} = M_{ij}\, \dot{e}_{eq}$$

Microstructural Tensor:

$$M_{ij} = N_{ij} + q\, N_{ik}\, N_{kj}$$

$$N_{ij} = (n_i\, s_j + s_i\, n_j) \qquad \dot{n}_i = -\dot{\zeta}\, s_i \qquad \dot{e}_{eq} = \frac{\partial}{\partial t}[\varepsilon_{eq}^{p}\, e^{-\zeta/q}]$$

Creep flow is triggered by stress

$$N_{ij} = N_{ij}(\sigma_{kl}) \text{ and } \dot{\varepsilon}_{eq}^{p} = \dot{\varepsilon}_{eq}^{p}(\sigma_{eq})$$

Zubelewicz, 1993

Generalized Power-Law Description

$$N_{ij} = N_{ij}(\sigma_{kl})$$

$$N_{ij} = \frac{2\sin(\varphi/3)}{\sqrt{3}\cos\varphi}\left(\delta_{ij} - \frac{3S_{ik}S_{kj}}{2J_2}\right) + \frac{\cos(2\varphi/3)\,S_{ij}}{\sqrt{J_2}\cos\varphi}$$

$$\varphi = \arcsin J_3\left(\frac{27}{4J_2^3}\right)^{1/2}, \quad S_{ij} = \sigma_{ij} - \tfrac{1}{3}\delta_{ij}\,\sigma_{kk}$$

Von Mises Formulation:

$$N_{ij} = \frac{S_{ij}}{\sqrt{J_2}}$$

Generalized Power-Law Description
(Evolution of internal structure not included)

Generalized Power-Law Creep Equation:

$$\dot{\varepsilon}^{p} = \Lambda_o \, e^{-\frac{\Delta G}{R\,T}} \left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n}$$

$$n = \frac{D_n}{T} e^{\left(\sigma_{eq} / \sigma_1\right)}$$

Constants: $\Lambda_o, \ \Delta G, \ \sigma_o, \ D_n, \ \sigma_1, \ (q = 0, \zeta = 0)$

$$\dot{\sigma}_{ij} = E_{ijkl}(\dot{\varepsilon}^{t}_{kl} - M_{kl} \ \dot{\varepsilon}^{p})$$

Zubelewicz, et al., 1999

Yield Stress, Model Predictions (...)

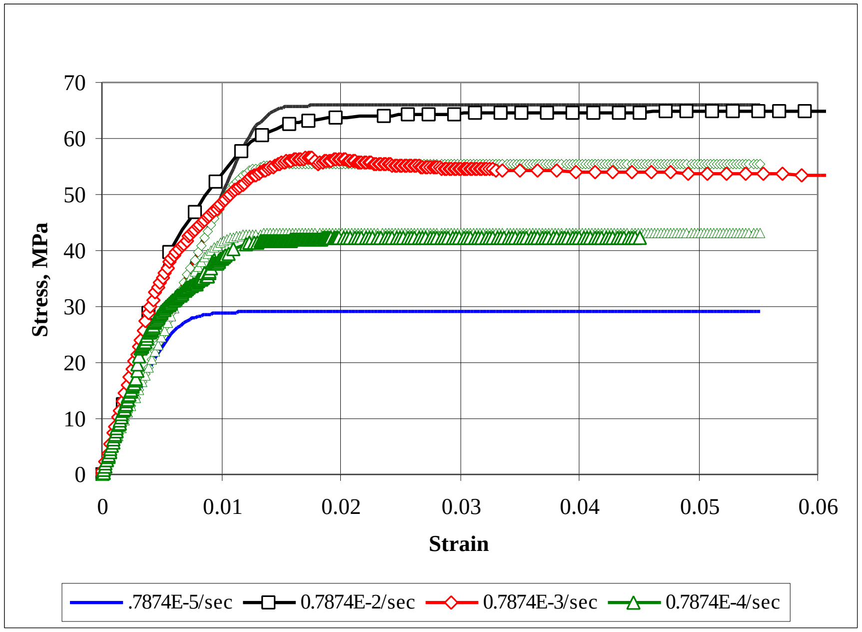
	$\dot{\varepsilon}_t = 0.8\ 10^{-2}/\sec$	$\dot{\varepsilon}_t = 0.8\ 10^{-3}/\sec$	$\dot{\varepsilon}_t = 0.8\ 10^{-4}/\sec$	$\dot{\varepsilon}_t = 0.8\ 10^{-5}/\sec$
$T = 218^oK$	70.3 Mpa (65.9 MPa)	57.9 MPa (55.5MPa)	43.1 MPa (43.1 MPa)	(29.1 MPa)
$T = 293^oK$	53.7 MPa (56.3 MPa)	40.0 Mpa (39.4 MPa)	21.3 MPa (20.7 MPa)	6.6 MPa (8.1 MPa)
$T = 353^oK$	38.2 MPa (47.5 MPa)	24.4 MPa (25.1 MPa)	8.5 MPa (8.4 MPa)	2.5 MPa (2.5 MPa)
$T = 398^oK$	28.2 MPa (40.1 MPa)	15.4 MPa (15.6 MPa)	4.9 MPa (4.1 MPa)	1.2 MPa (1.1 MPa)

Zubelewicz, et al., 1999, (Experimental data by Tyan Niu)

$$E = 5\ GPa, \nu = 0.3,\ \sigma_o = 40.2\ MPa,$$

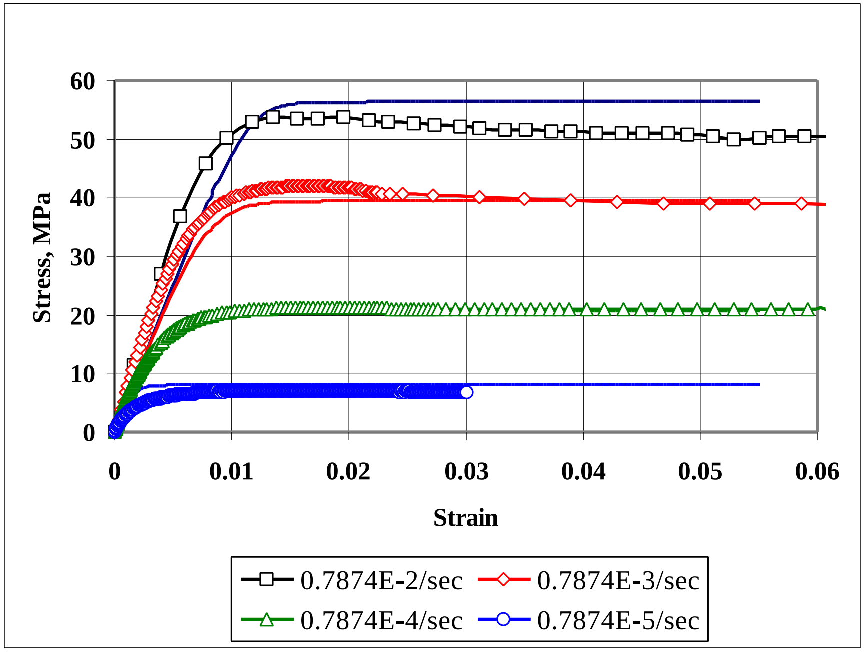
$$\Lambda_o = 3.8437/\sec,\ \Delta G = 20.456\ kJ/mol$$

$$\sigma_1 = 60.0\ MPa,\ D_n = 750^oK\ .$$



Uniaxial stress-strain diagram for 63Sn-37Pb at -55°C.

Zubelewicz, et al., 1999



Uniaxial stress-strain diagram for 63Sn-37Pb wire at 20°C

Zubelewicz, et al., 1999

Fracture Mechanisms in Ductile Materials

- **Cottrel (1964) - Concept of Geometrically Necessary Dislocations**

Whenever glide surfaces are plastically bent or twisted, in fact, dislocations are necessary to accommodate the non-uniform strains.

- **Cavitation Process:**

It is assumed that cavities nucleate and grow when a deforming (creeping) material is incapable of satisfying the requirement of kinematical continuity (compatibility).

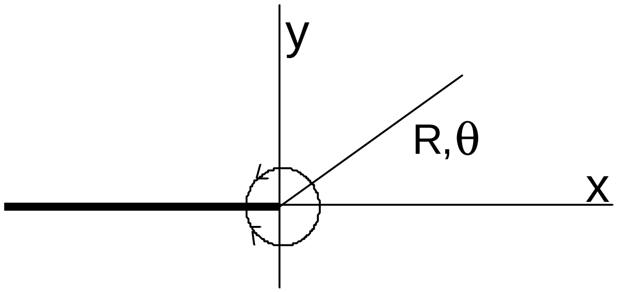
Further Physical Hypothesis:

- stresses must satisfy equilibrium conditions
- boundary conditions must be satisfied
- kinematical compatibity conditions must be satisfied
- dissipation energy due to cavitation must be non-negative
- void sintering (or material compressibility) is not allowed
- search solution(s) for which the geometrically necessary cavitation (or energy dissipation due to cavitation) has lowest possible value.

Approach

- Find statically admissible state of stresses (equilibrium equations are satisfied)
- Power-law constitutive equations for a non-dilatant creep flow determined (n=3)
- Determine kinematically admissible state of dilatant deformation compatible with the stress state and constitutive equations
- Define and satisfy boundary conditions
- Replace constitutive equation for cavitation with a criterion of an energy minimum due to cavitation. Several local minima can be identified

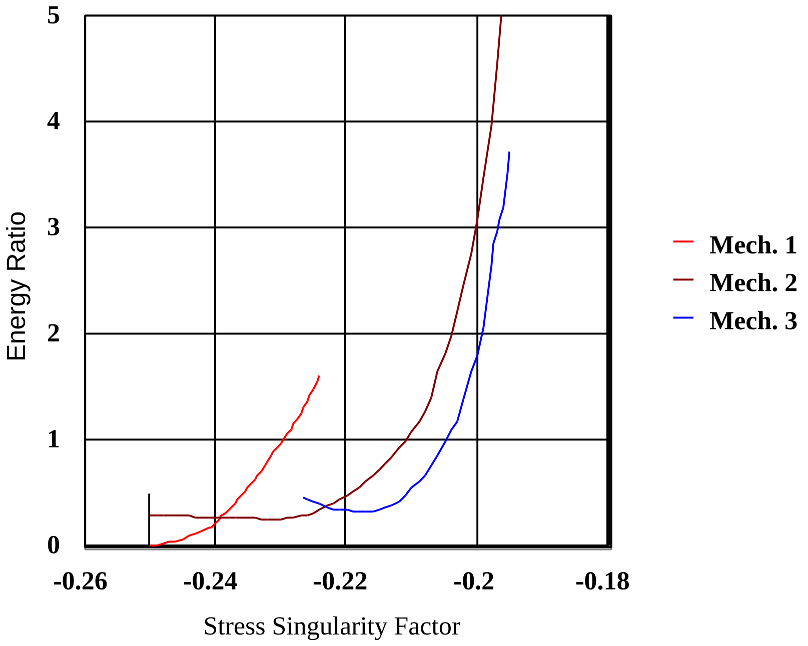
Mode I Crack Problem

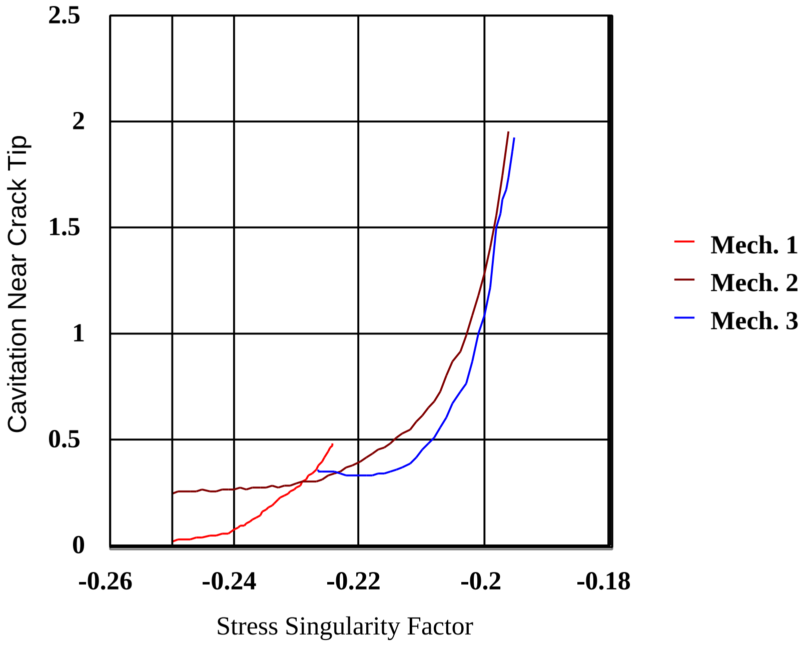


Plot of Energy ratio versus Stress Exponent , $(n = 3)$

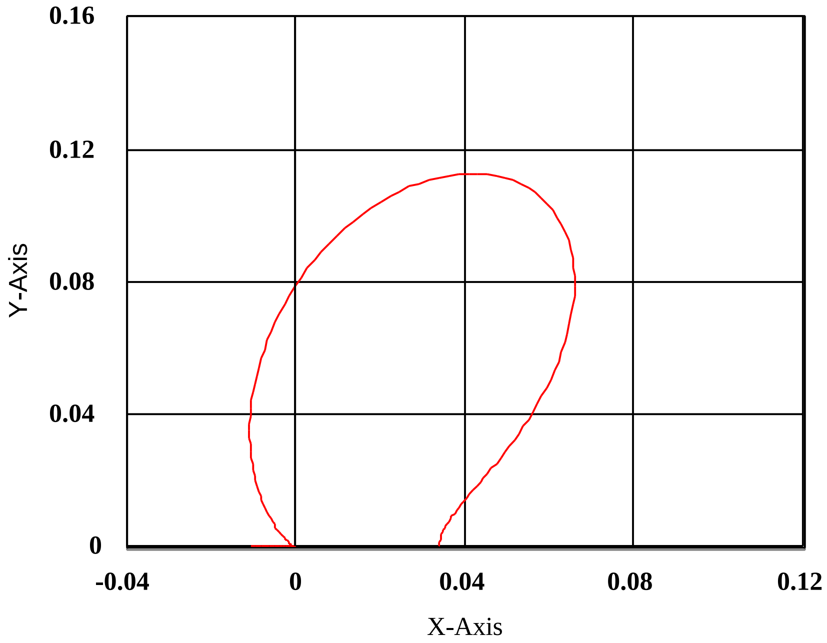
$$\frac{\dot W^{c}}{\dot W^{s}} = \frac{\dot W^{c}}{\dot W^{s}}[\lambda,\ (A_1,\ D_n)],\quad \text{where}\quad \dot W^{c} = \frac{1}{2}\int_V I_\sigma\, \dot I_\varepsilon\, dV,\quad \text{and}\quad \dot W^{s} = \int_V \sigma_{eq}\, \dot e_{eq}\, dV,$$

$$\sigma_{ij} = R^{\lambda}\, \tilde\sigma_{ij}\, [\lambda, \theta, (A_1, D_n)] \qquad \dot I_\varepsilon = R^{3\lambda}\, \tilde I_\varepsilon\, [\lambda, \theta, (A_1, D_n)]$$

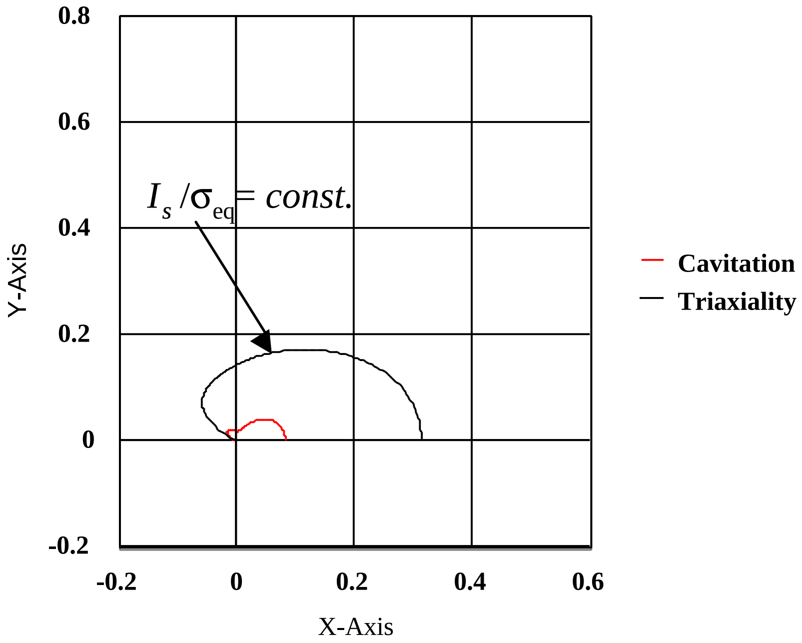




Fracture Mechanism 1

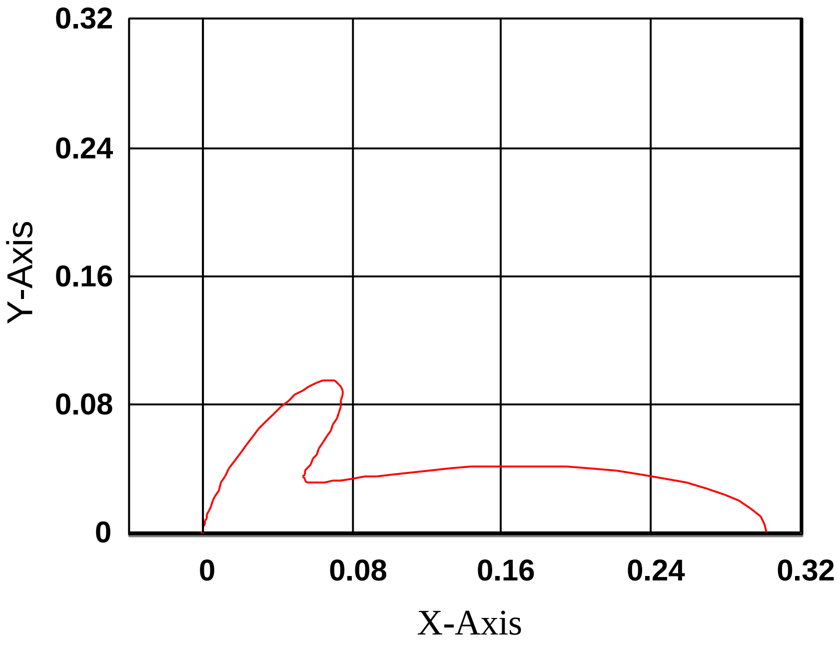


Contour of Constant Equivalent Stress

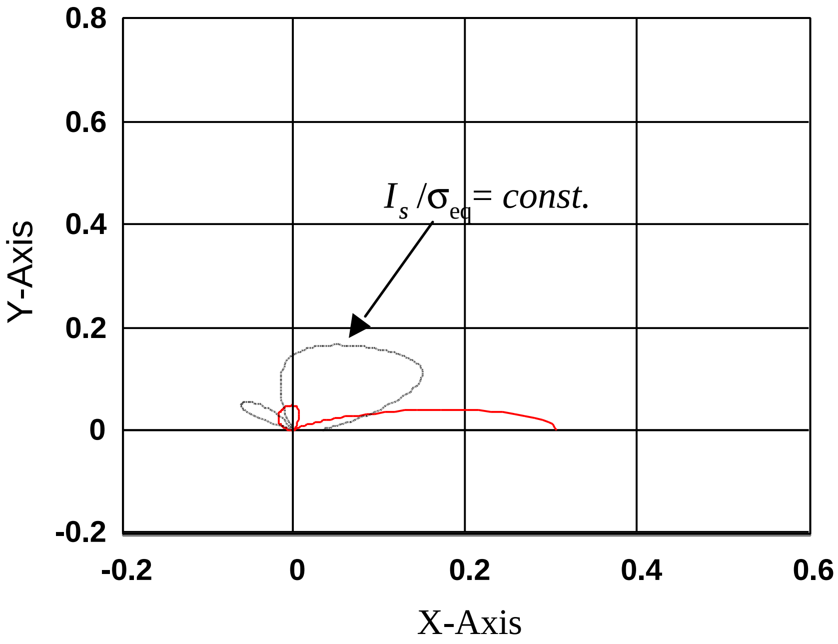


Contours of Constant Cavitation and Stress Triaxiality Ratio

Fracture Mechanism 2

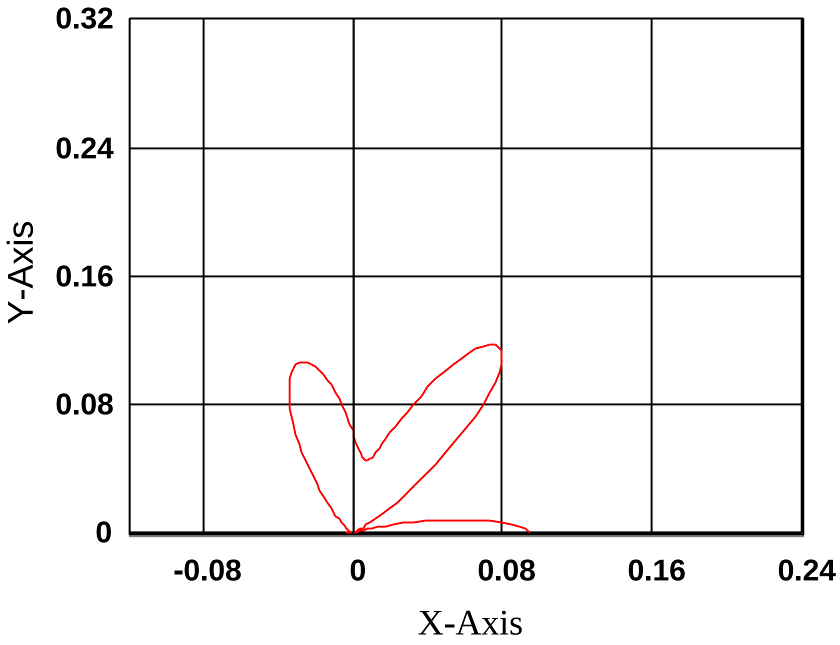


Contour of constant equivalent stress, λ = - 0.23

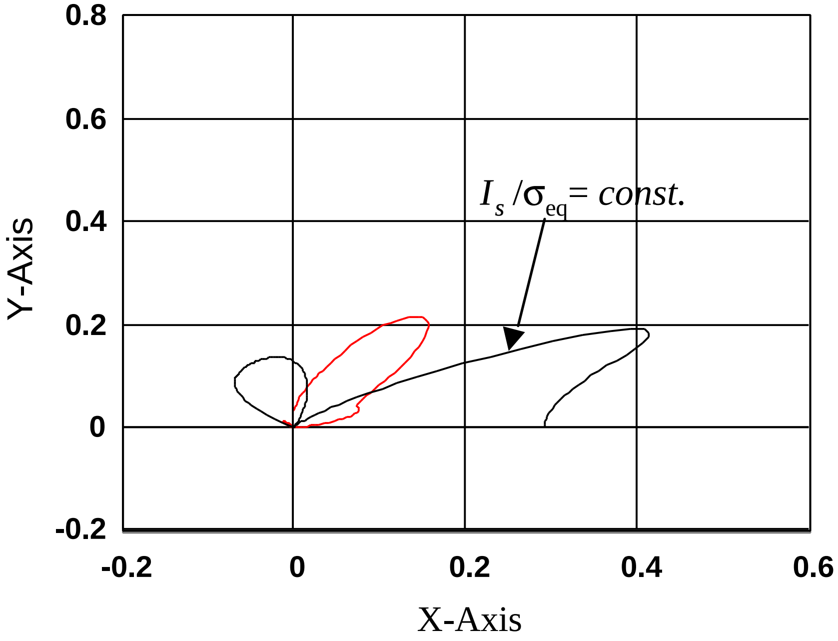


Contours of constant cavitation and stress triaxiality ratio, λ = -0.23

Fracture Mechanism 3



Contour of constant equivalent stress, $\lambda = -\,0.225$



Contours of constant cavitation and stress triaxiality ratio, $\lambda = -0.225$

Fatigue Models

- Thermomechanical Cycling - Mechanism 2
- Isothermal Fatigue - Mechanism 3

Hypothesis: Fatigue damage is cause by an irreversible plastic deformation

$e_{eq} = \varepsilon^p e^{\kappa}$ where $\kappa = \varsigma / q$

ς - microstructural mobility

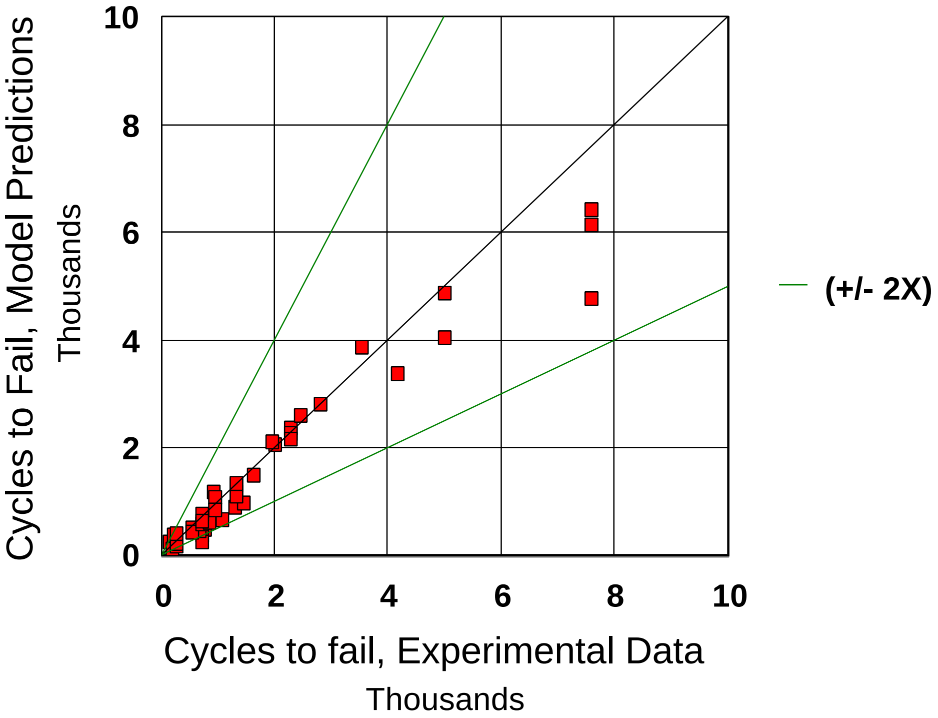
q - readiness for cavitation $\dot{\kappa} = \kappa_o - k_o \, e^{\frac{-\Delta G}{RT}} \kappa$

Fatigue Formula:

$$\boxed{N_f \left[(\Delta\varepsilon^p)^n_{1st\ half\ of\ a\ cycle} + (\Delta\varepsilon^p)^n_{2nd\ half\ of\ a\ cycle} \right] = \psi_d}$$

Zubelewicz and Sammakia, 1998

Experimental Data versus Model Predictions

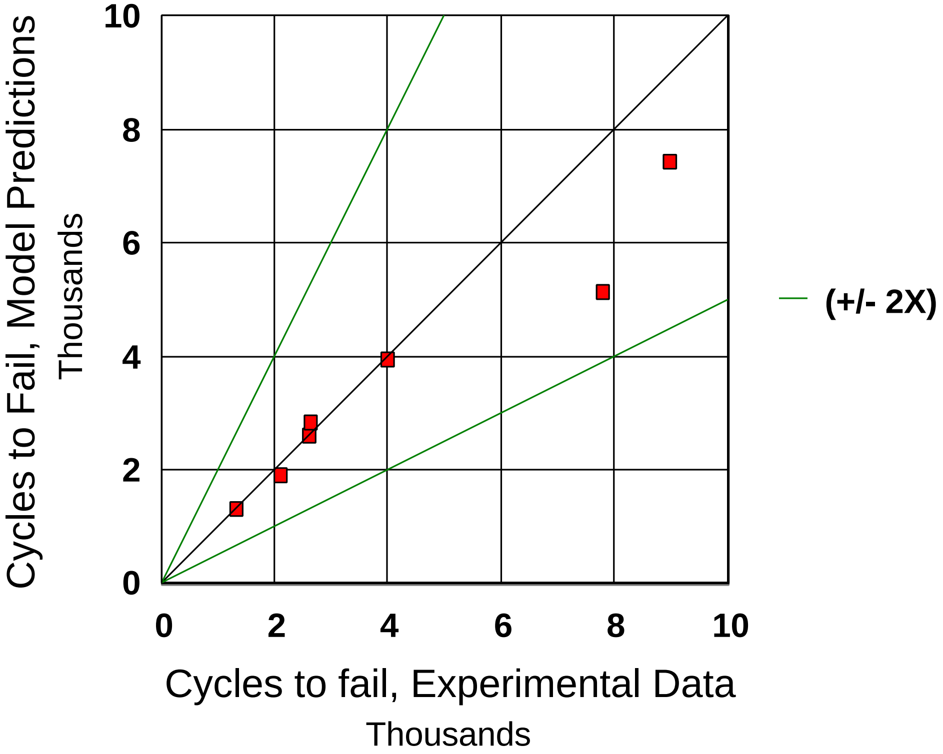


Strain range: 0.003 to 0.02, Temperature: 25 to 80 °C, Ramp Time: 1 up to 180 Sec., Dwell: 0 to 600 sec.

Solder Program at Northwestern University

directed by Drs. Keer and Fine, 1986-1992

PBGA Fatigue Data versus Model Predictions



Cyclic Frequency: 5.5 10^{-4} to 2.2 10^{-2}/sec. , ΔT: 100 to 60ºC , T_{max}: 85 to 125ºC

Data from Zubelewicz and Sammakia, 1998

PBGA Power-Cycling Data versus Model Predictions

Temperature	192 cycles per day	96 cycles per day	48 cycles per day
25 to 125 C	2,613 (2,612)	2,106 (1,925)	1,322 (1,323)
25 to 105 C	7,800 (5,144)	3,991 (3,977)	2,621 (2,850)
25 to 85 C	23,576* (12,027)	13,877 (9,737)	8,980 (7,455)

( ) - Model Predictions
* - Estimated cycles to fail

Zubelewicz and Sammakia, 1998

Conclusions

Fundamental Properties:

- SAC and Pb/Sn show different behavior
  - constitutive equations
  - damage criteria and fatigue equations
  - fatigue (acceleration factor) equations
- Damage localization observed but not well understood
- Intermetallics are important

What is useful for the industry:

- Valid reliability requirements for various applications
- Predictive acceleration factor methodology