Reliability Tests and Assessment for Electronic Products

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Teaching:

Reliability Engineering
Electronics Manufacturing Systems
Quality Design and Control

Research:

Reliability of Electronic Components and Assemblies
Fatigue and Damage Accumulation in Solder Materials

Agenda

- Electronics Manufacturing Industry
- Electronics Reliability Issue
- Reliability Tests for Electronic Products
- Electronics Reliability in Thermal Cycling (Case Study)
- Electronics Reliability Models (Case Study)
- Design of Experiment (DOE) in Electronics Reliability

Electronics Manufacturing

- Electronics manufacturing is unique
  - High level of automation, flexibility, and cost optimization
  - Affordable sophisticated products

- Business challenge: Short product lifecycle
  - Rapid Evolution & New Product Introduction
  - Intel spent 11.5 billion on R&D in 2014 (21% of Total Revenue)

Electronics Manufacturing

- Electronics everywhere

- Materials, designs and manufacturing processes are optimized as a trade-off between cost, quality and reliability
  - Cell phone: cheap and not reliable
  - Aircraft: very expensive and very reliable

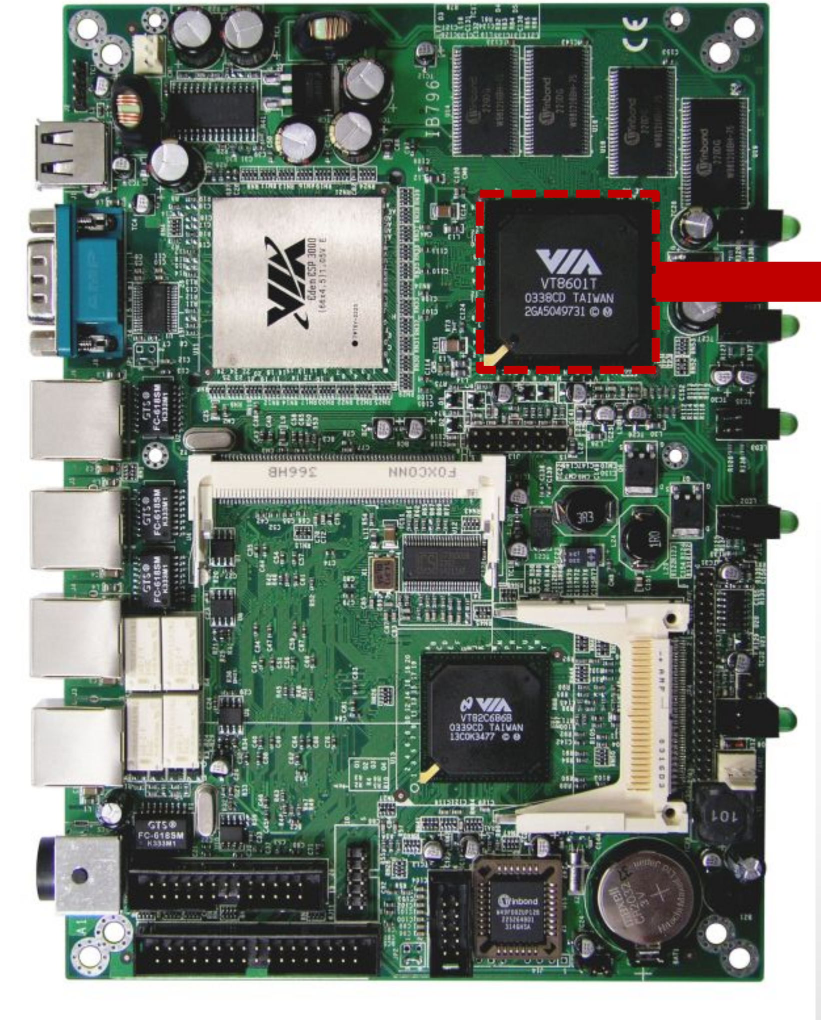
Electronic Products Classification

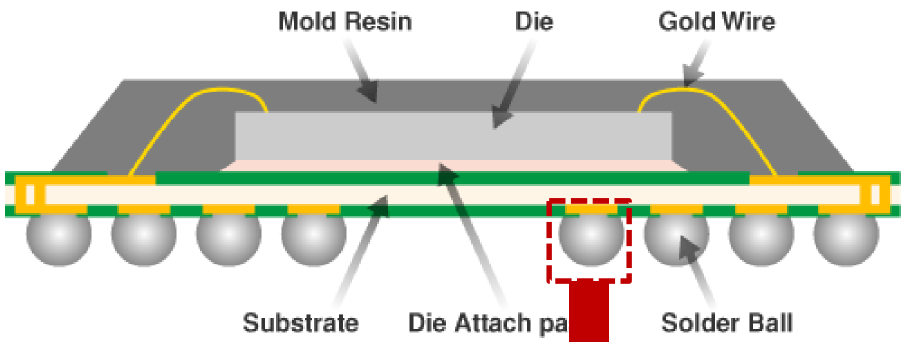
- Class I: Consumer products such as TV, cell phone
  - Service life is less than five years
  - Low cost of failure

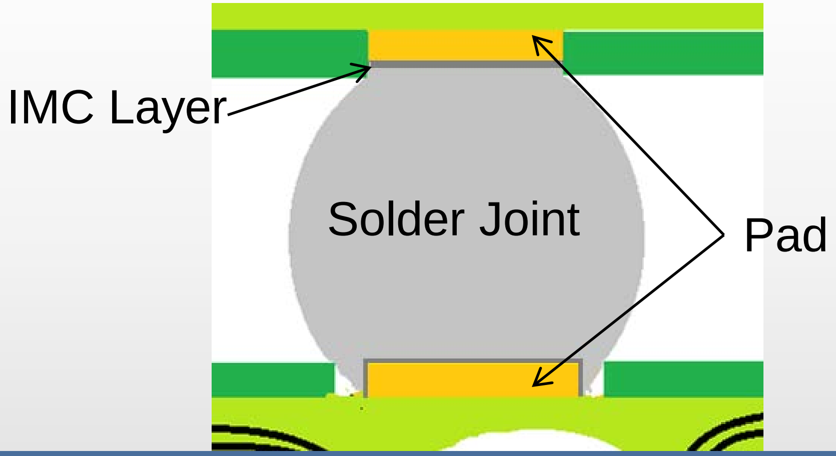
- Class II: Dedicated/Industrial/Telecom products
  - Service life is longer than class I
  - High cost of failure

- Class III: Critical products such as aerospace or medical devices
  - Service life is more than twenty years
  - Failure can be life threatening

Electronic Components



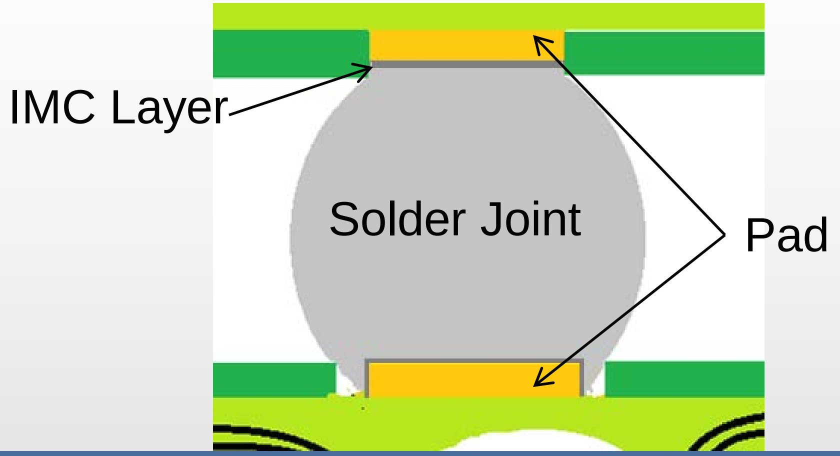




Reliability Issues

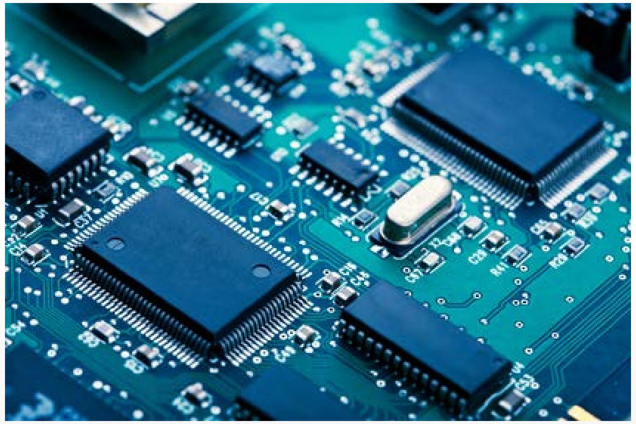
What is Reliability?

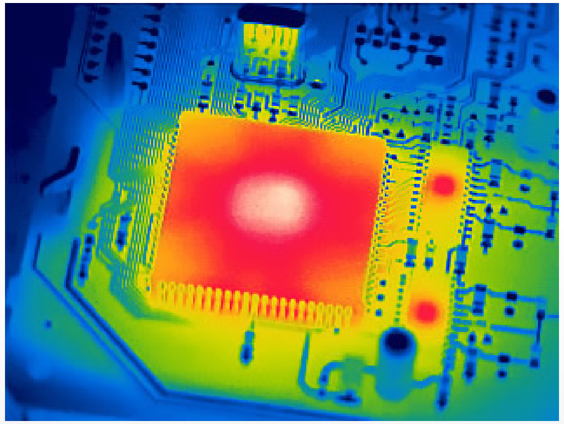
- Reliability is “the ability of a product to function under given conditions and for a specified period of time without exceeding acceptable failure levels”
- Reliability is the major issue for electronic assemblies (any single defect leads to complete failure)
- Solder joints are the weakest connection
- Temperature change is the major threat



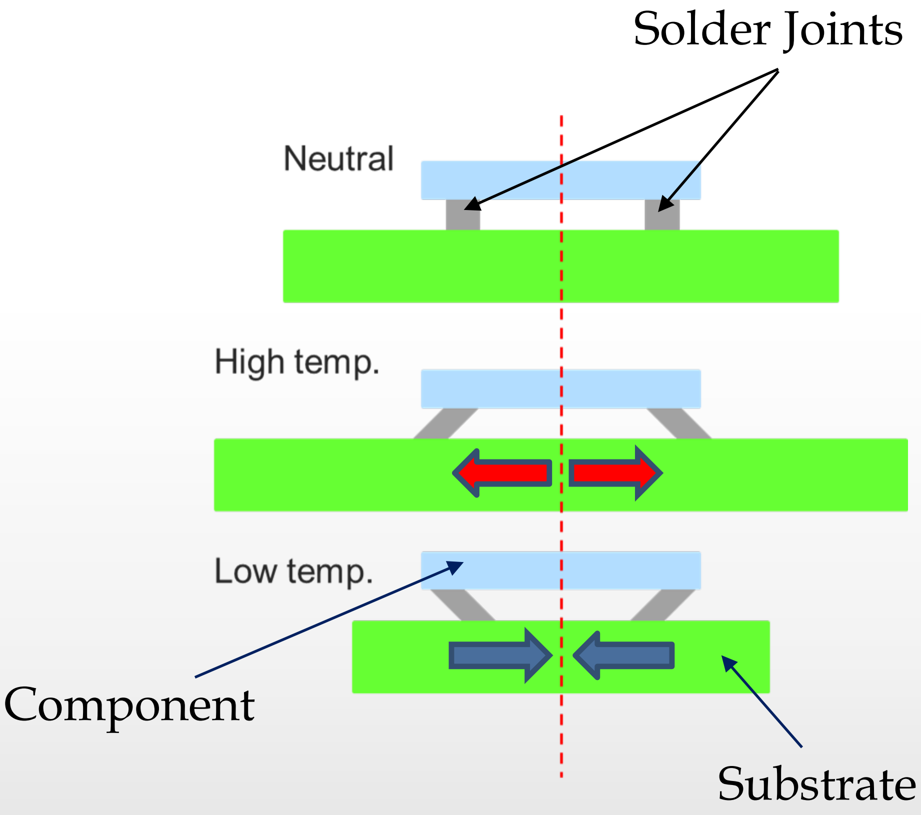
Temperature Variation Effect

- Temperature changes lead to stresses caused by coefficient of thermal expansion mismatch (CTE)

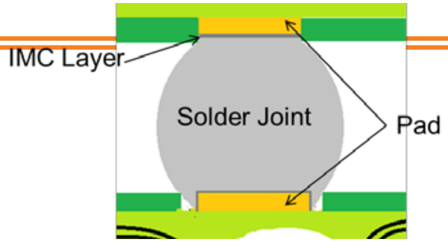




Heat leads to stresses induced by CTE mismatch

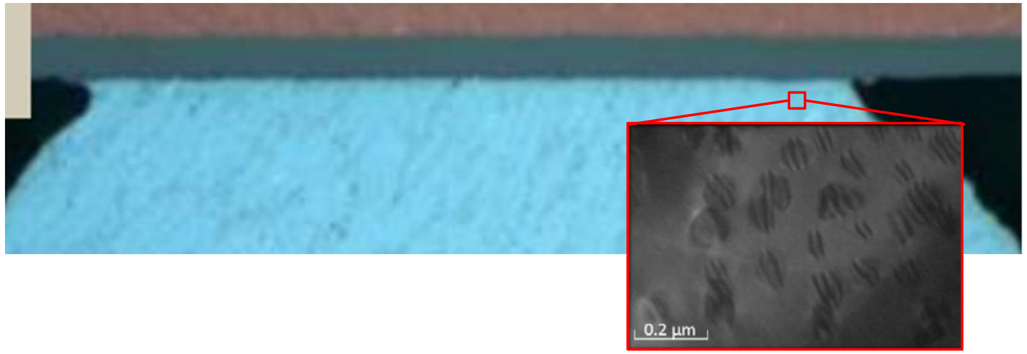


What Does Actually Happen?



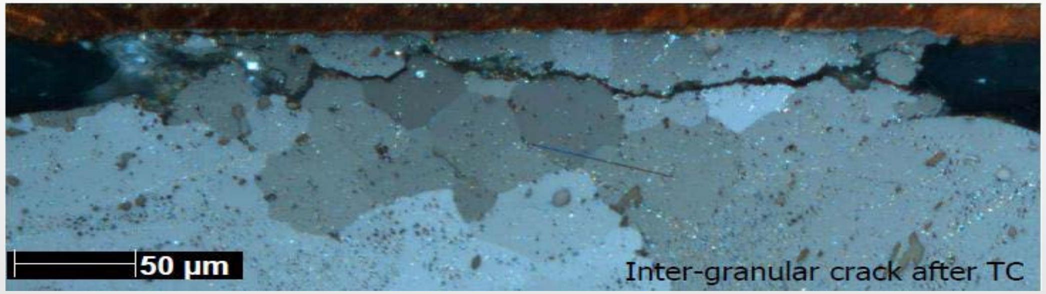
- Damage process in thermal cycling:

Creation and rotation of dislocation cell structure

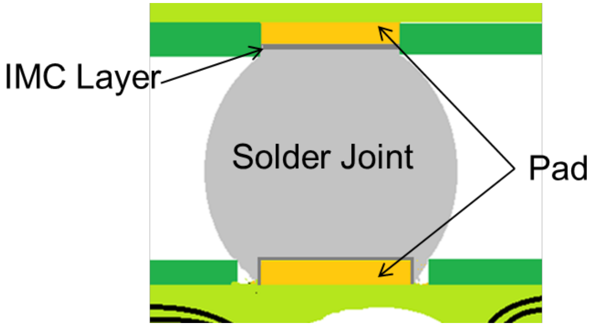


Global recrystallization and continuous growth

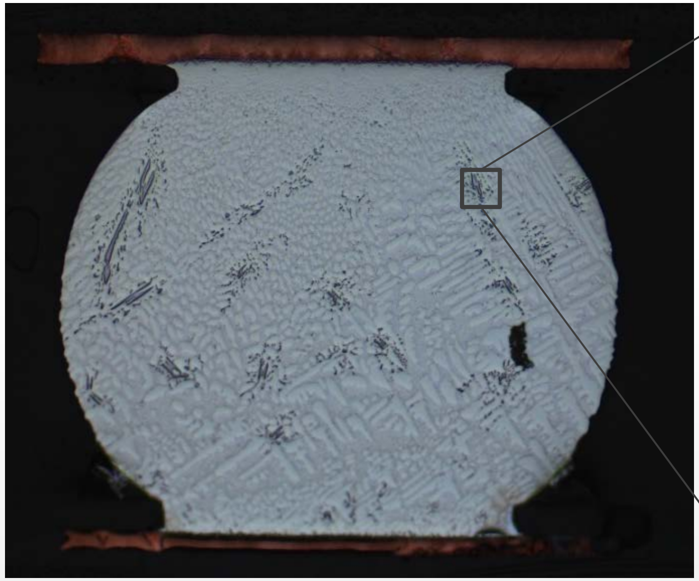
Crack along continuous network of grain boundaries

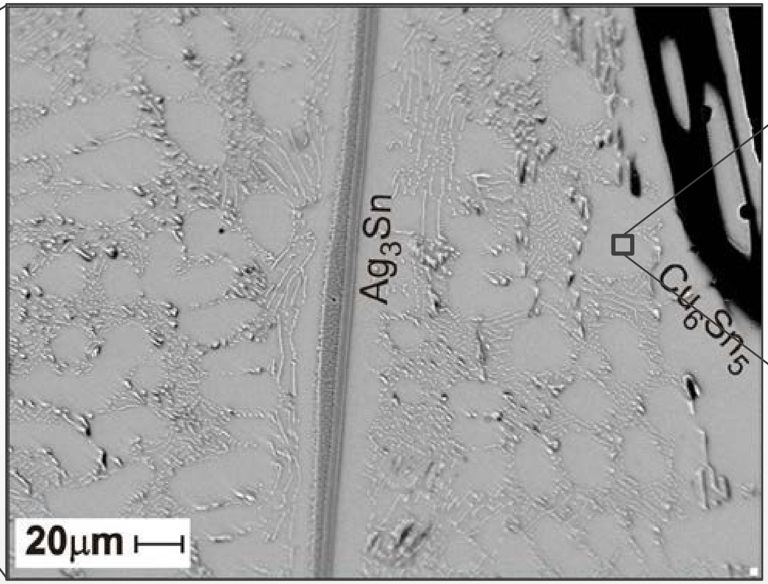


What Does Actually Happen?

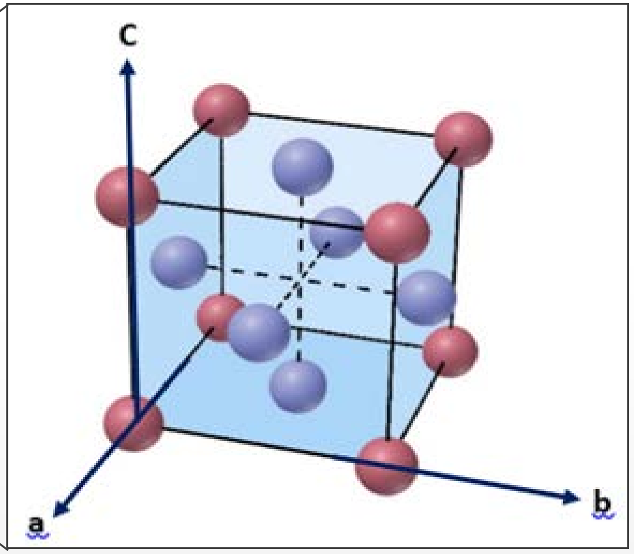


- Reliability depends also on the microstructure!





Distributions of secondary precipitates



highly anisotropic Sn grains

Reliability Tests for Electronic Products

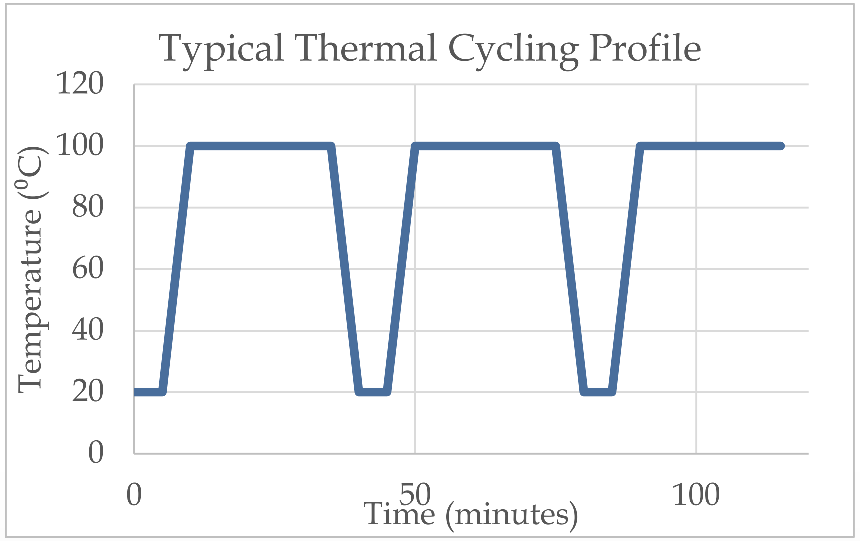
- Thermal Cycling
- Vibration or High Cycling Fatigue (random, fixed frequency, resonance tracking)
- Low Cycling Fatigue
- Mechanical Shock (Drop Test)
- Thermal Shock (air to air, or liquid to liquid)
- Aging (temperature, humidity)

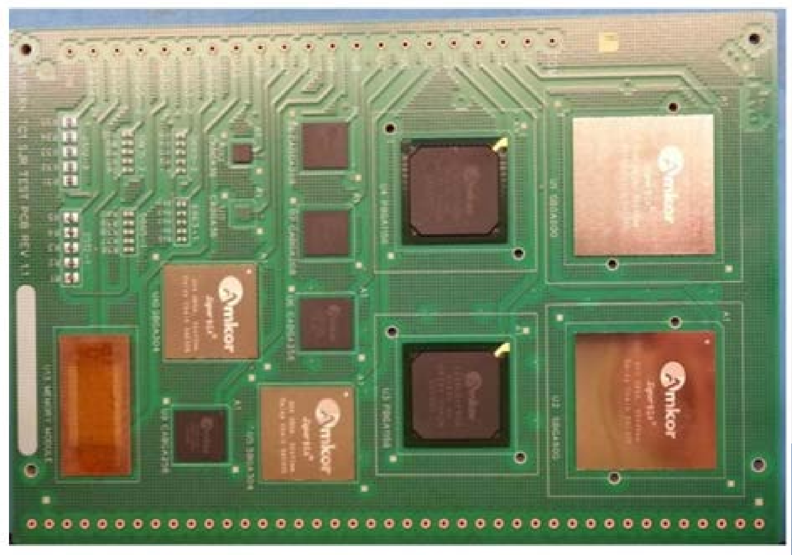
Reliability Tests for Electronic Products

- **Two common reasons for accelerated life tests:**
  - To compare between alternatives (material, design, etc.)
  - To predict life or reliability in real service (requires model)

- **What could affect on electronic assembly life in accelerated tests?**
  1. Component type
  2. Substrate type
  3. Solder paste material
  4. Solder spheres material
  5. Pad material
  6. Flux material
  7. Reflow oven temperature profile
  8. Aging time
  9. Aging temperature
  10. Heatsink
  11. etc.

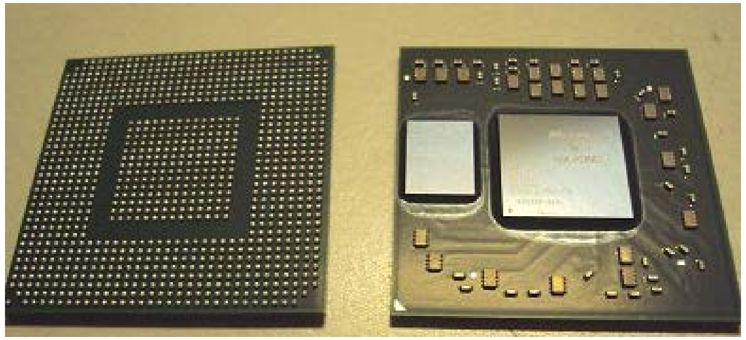
Thermal Cycling Accelerated Tests

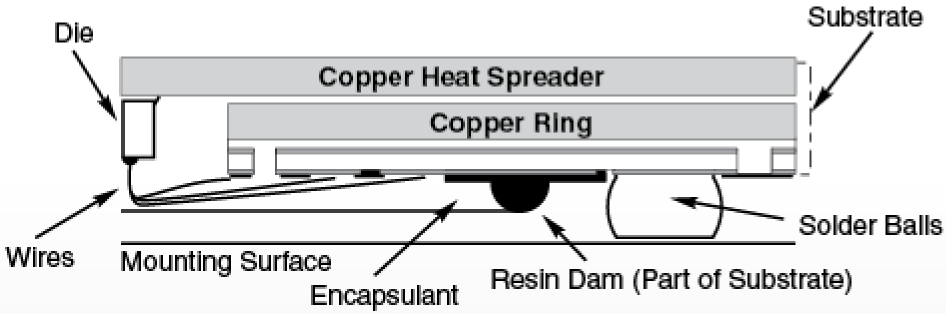




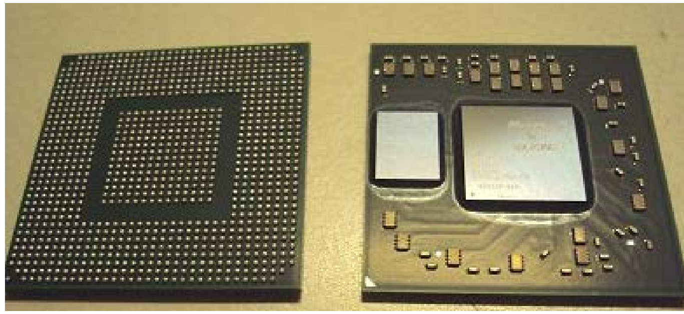
Case Study - Thermal Cycling

- New SBGA (super ball grid array) components
- Three candidate of solder materials (SAC105, SAC305, Innolot)
- Which solder material is better for the thermal cycling reliability?

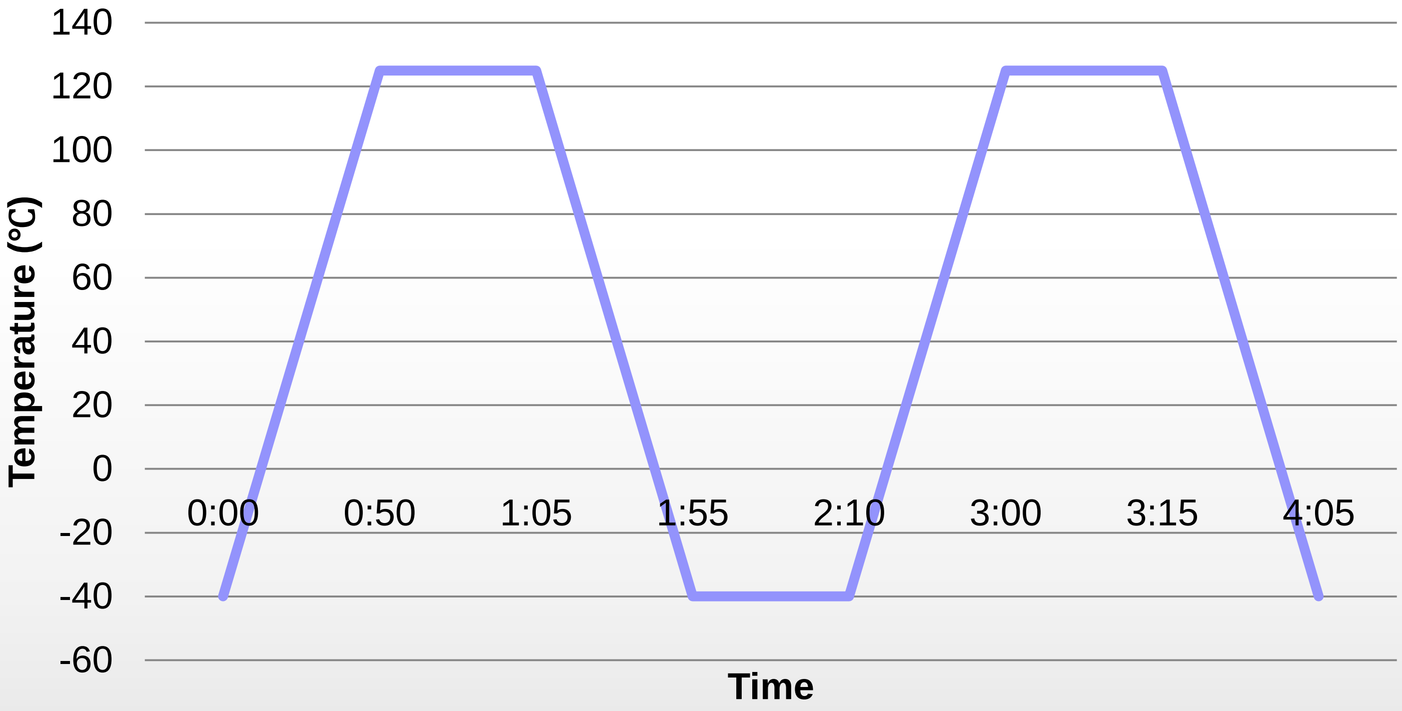




Case Study - Thermal Cycling



- Thermal cycle test profiles:
  -40°c to +125°c, 15min dwell, 15min transition



Case Study - Thermal Cycling

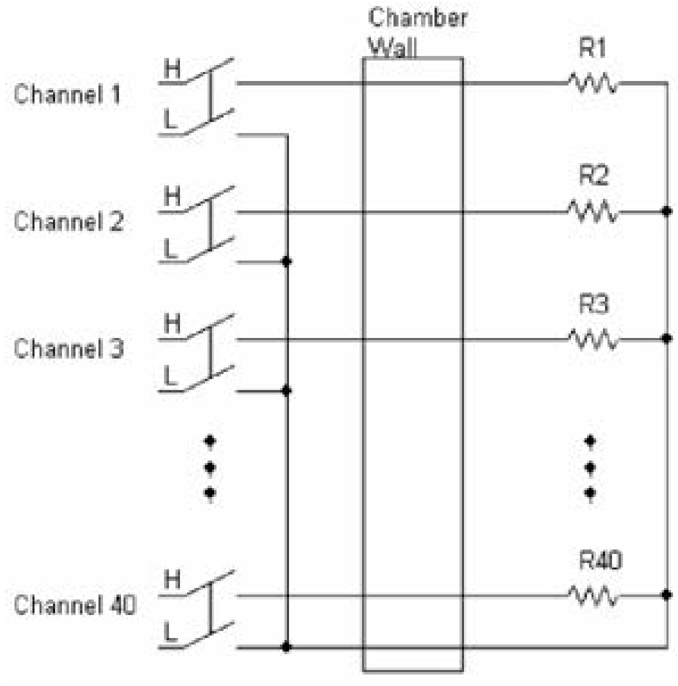
- Experimental Setup

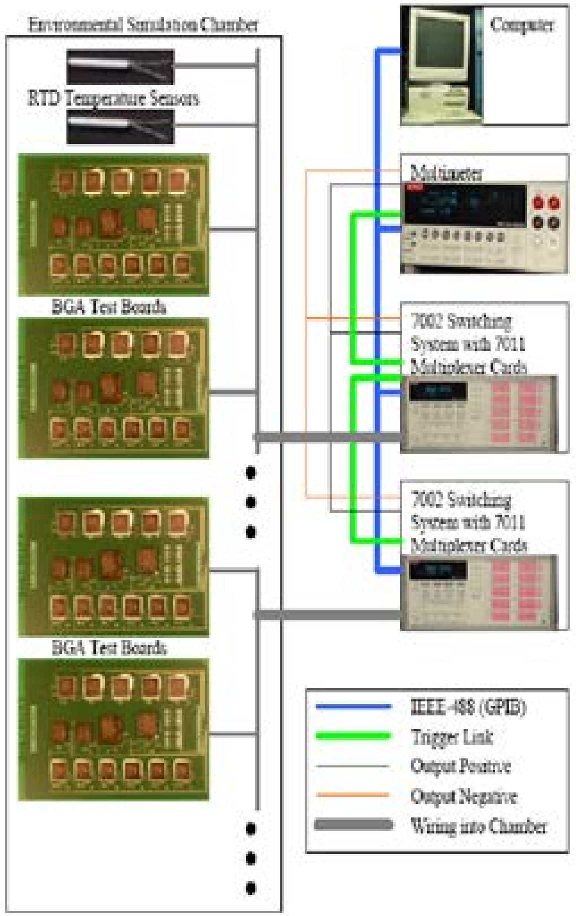
Thermal Cycling Test -40 to 125° C

Case Study - Thermal Cycling

- **Experimental Setup**

Use CAVE's continuous sampling monitoring system

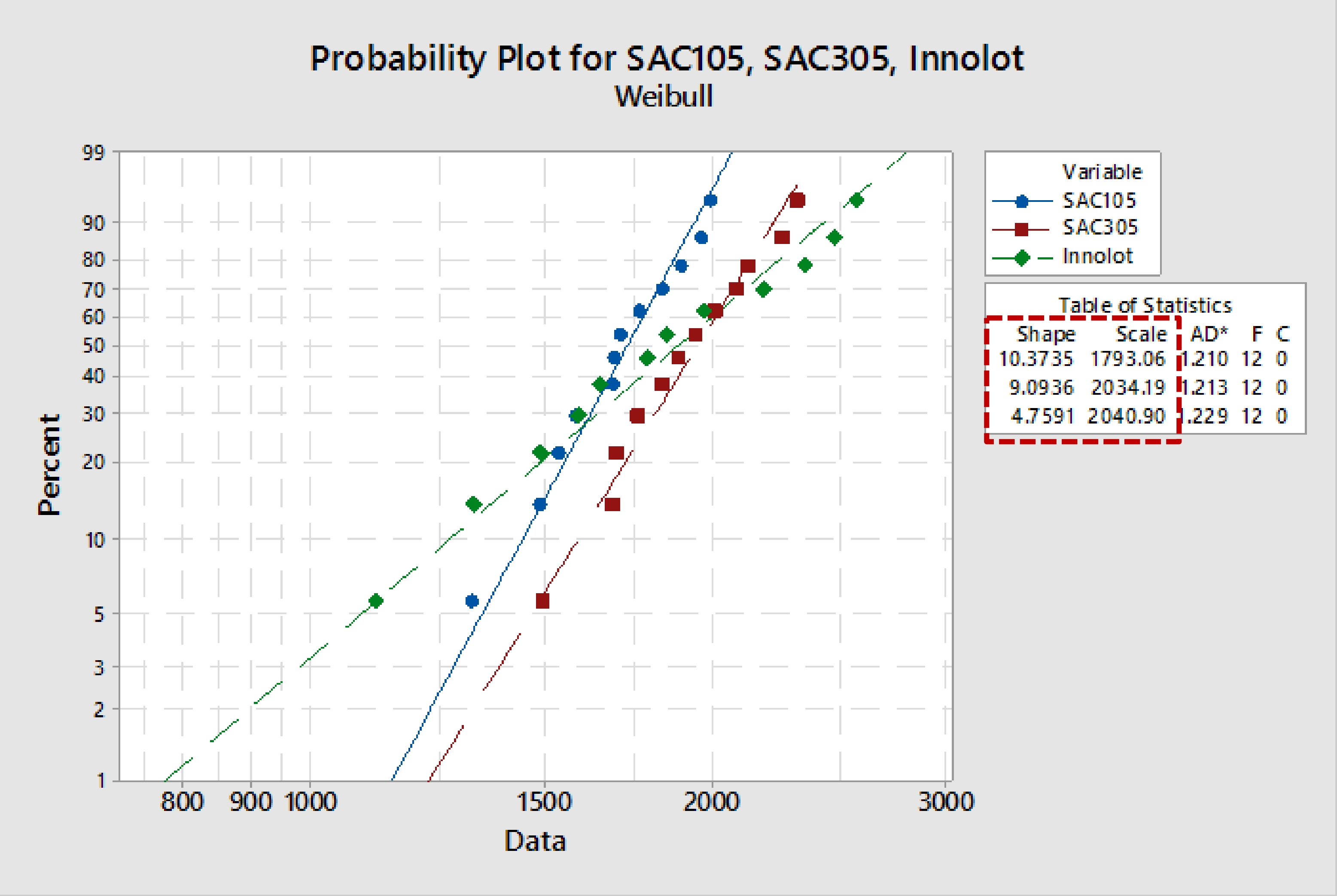




Case Study - Thermal Cycling Results

Data (number of cycles to failure)

SAC305	Innolot	SAC105
1321	1496	1120
1489	1689	1325
1538	1699	1487
1583	1762	1589
1690	1840	1653
1694	1889	1789
1711	1944	1856
1769	2015	1976
1840	2092	2190
1898	2134	2355
1965	2260	2478
1997	2324	2571



Case Study - Reliability

- In many cases, it's misleading to compare only based on the characteristic life (scale parameter). It should be based on:
  - Reliability at specified life (number of cycles), or
  - Number of cycles to accumulate a specified percentile of failure
- When you compare only based on the characteristic life, you are comparing based on the number of cycles to accumulate 63% of failure
- In electronics, we mainly concern about early failure (~1% or so)

Case Study - Reliability

- Reliability at specified life (number of cycles):

$$R(t) = \exp\left[- (t/scale)^{\wedge shape} \right]$$

Alloy	Shape Parameter	Scale Parameter	R(1000)	R(1500)	R(2500)
SAC105	10.37	1793	0.9977	0.8545	~0
SAC305	9.09	2034	0.9984	0.9392	0.0015
Innolot	4.76	2041	0.9670	0.7939	0.072

- It is more practical to compare based on the number of cycles to accumulate a certain percentile failure

Case Study - Reliability

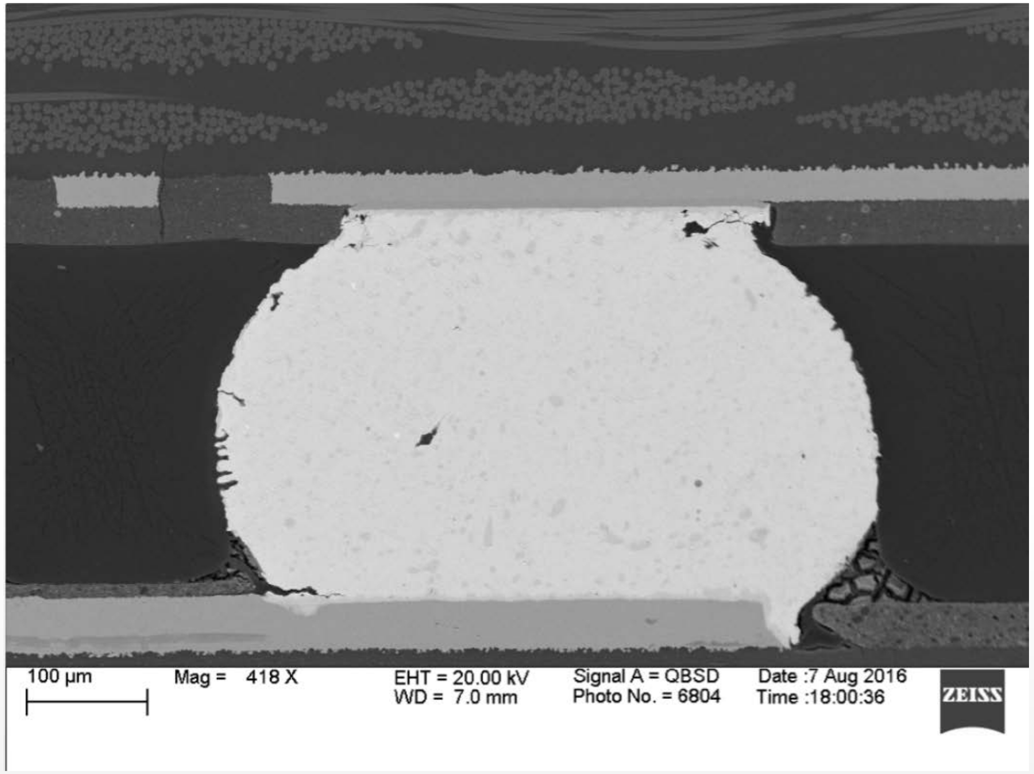
- Percentile of failure = 1 – Reliability

$$R(t) = \exp\left[-(t/scale)^{shape} \right] \Longrightarrow t = scale\left[(-\log R)^{(1/shape)} \right]$$

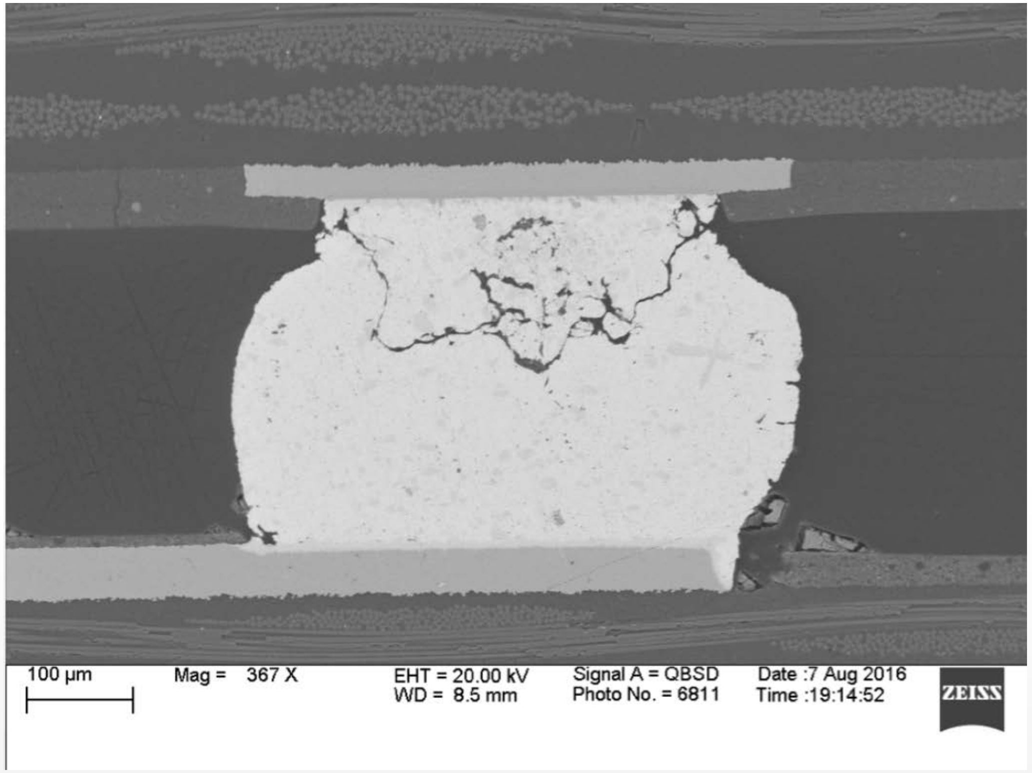
Alloy	Shape Parameter	Scale Parameter	1% failure	5% failure	10% failure
SAC105	10.37	1793	1151	1346	1443
SAC305	9.09	2034	1226	1467	1588
Innolot	4.76	2041	776	1094	1272

- Assumption: the best alloy in the test will perform the same in real service
  - Failure mechanism in test should be same as failure in service

Case Study - Failure Analysis



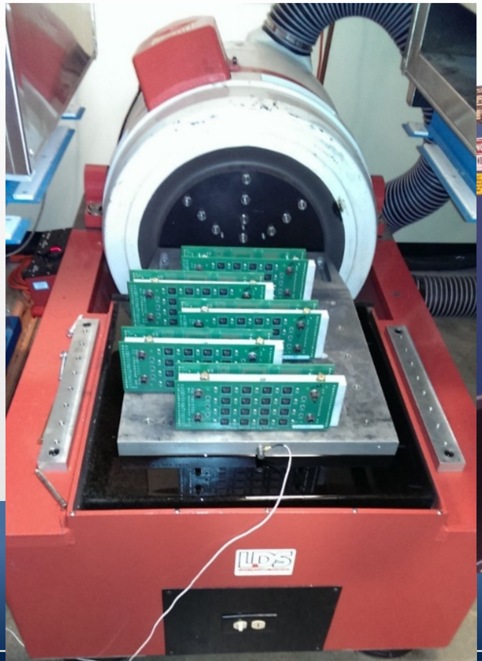
Crack initiate closed to board-side and package side IMC layer



Crack Propagation through the solder bulk

Vibration Test

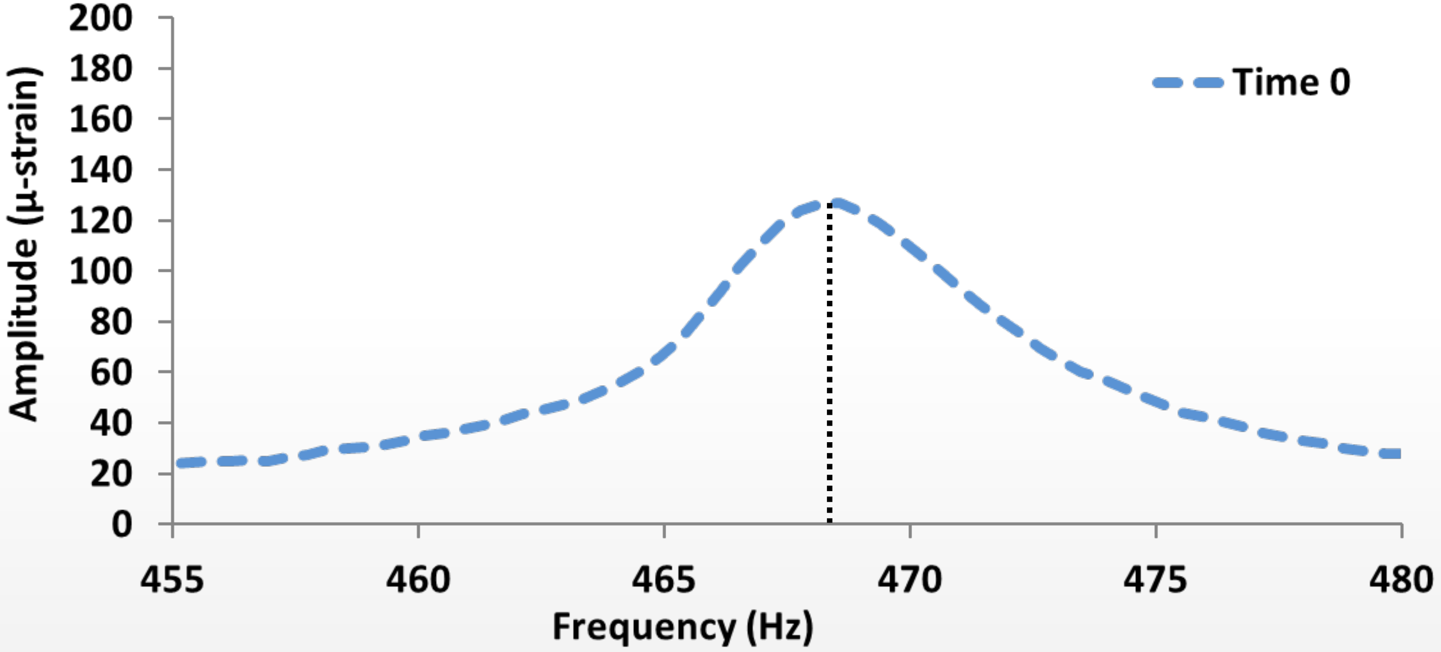
- Many electronic assemblies are under mild vibration in realistic applications (vehicle applications)
- Accelerated vibration tests are used to assess the reliability of those electronic components
- Typical vibration test equipment:
  - Strain Gage System
  - Laser Vibration Sensor
  - Accelerometer



-70°C to +190°C

Sine Vibration Test – Fixed Frequency

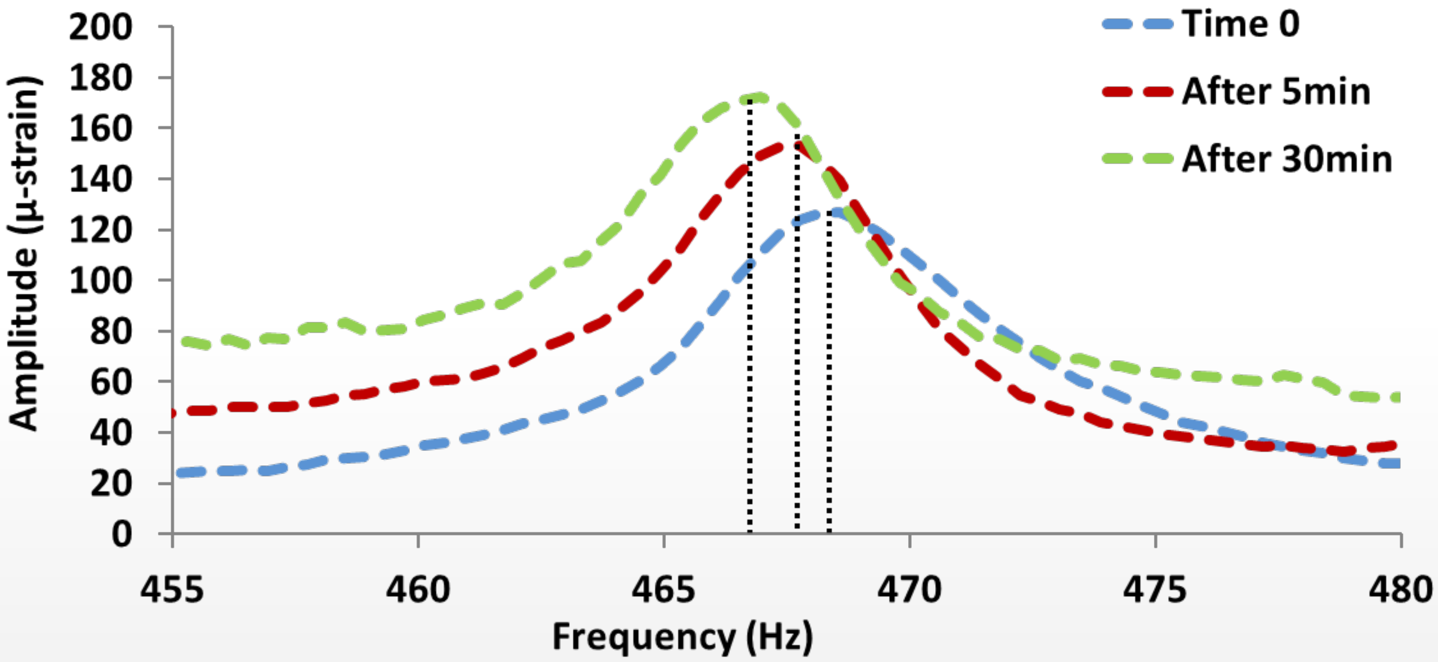
- Sweep test is used to determine the resonance (natural frequency): fixed vibration power (g level) and change frequency



- Then vibration test is performed at fixed g level and fixed frequency (at initial resonance)

Sine Vibration Test – Resonance Tracking

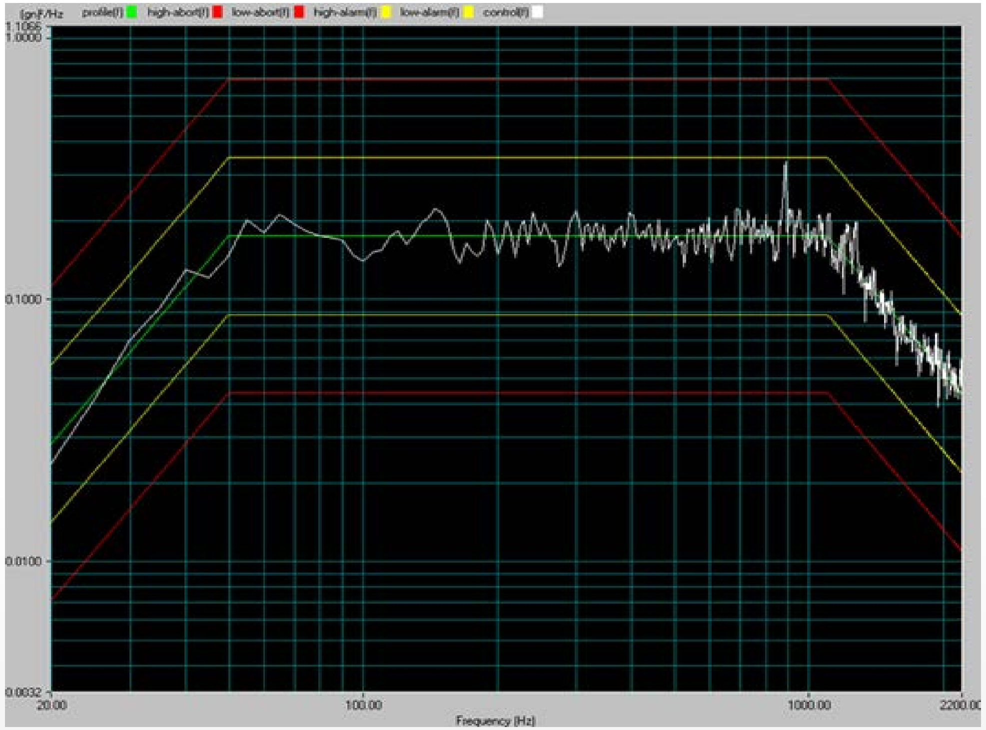
- Resonance typically shifts due to micro-damage in the electronics board or loose of fixture



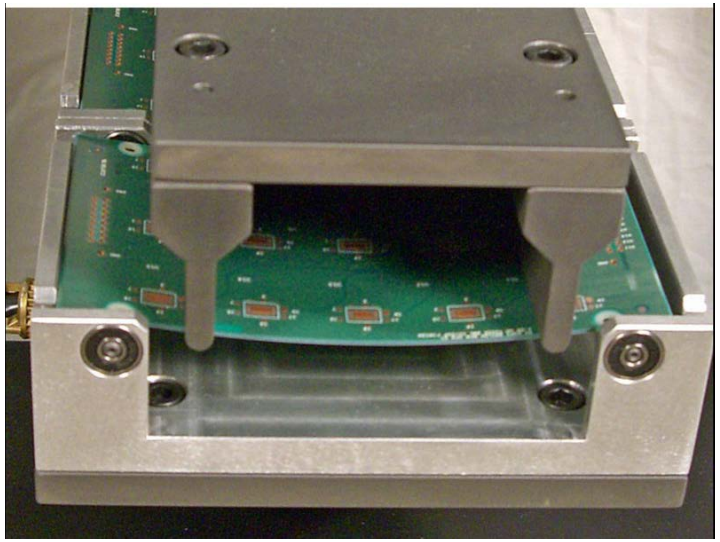
- Vibration test is performed at fixed g level and at 'on-time' resonance

Vibration Test – Random Vibration

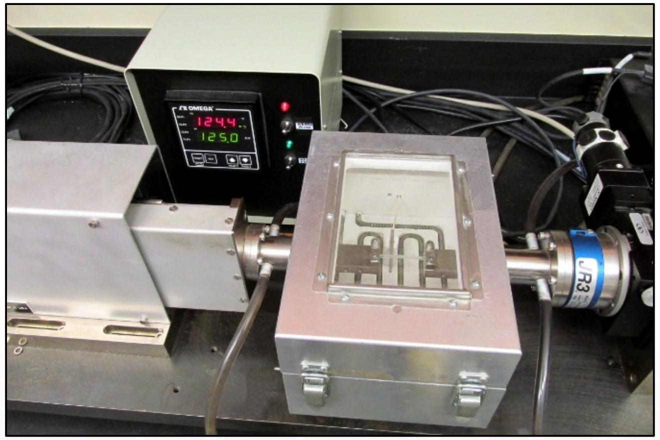
- Random Vibration:
  - Excite all the frequencies in a defined spectrum at any given time
- Very realistic
- Not useful for reliability modeling



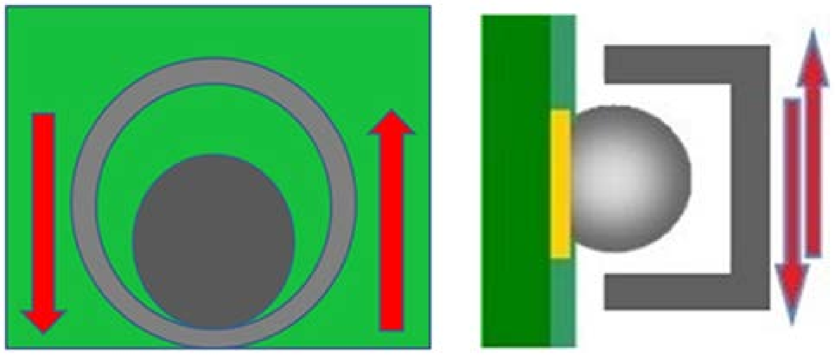
Low Cycling Fatigue

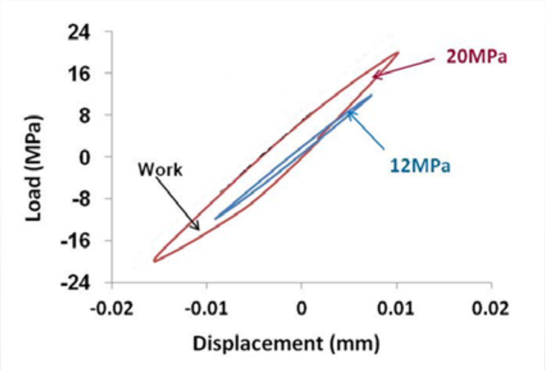


- Bending (three or four points bending) test



- Tension-compression test
- Shear fatigue





Shock

Thermal Shock (Liquid to Liquid)

Hot Bath: Ambient to +160°C

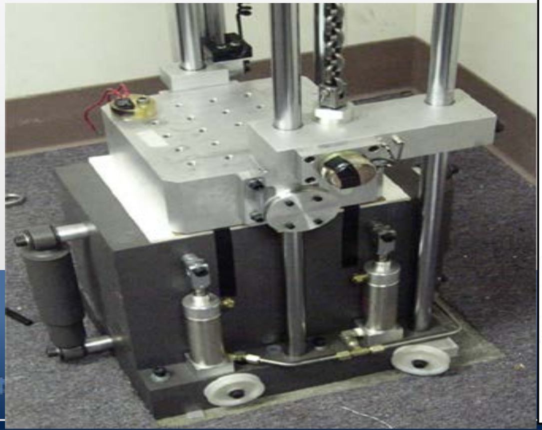
Cold Bath: Ambient to -75°C

Thermal Shock (Air to Air)

Hot : +200°C
Cold -73°C

Mechanical Shock

Drop Test



Reliability Models

- To predict the fatigue life under conditions of interest
- Most common reliability models are 'Covariate Models'
- 'Covariate Models': Assume a reliability distribution (i.e. Weibull), and define one or more of the distribution parameters as a function of operating variables (operating temperature, voltage, stress, humidity, dimensions, frequency, etc.)
- Thousands of reliability models have been published
- In many cases, accelerated life test is used to find constants/parameters to use such a reliability model

Example: Thermal Cycling Model

- To predict the reliability of SnAgCu solder joints in thermal cycling
- Reliability distribution is Weibull:

$$\text{Characteristic Life} = \psi \,/\, \{1 + \frac{\alpha}{\beta} * t_{dwell}\}$$

Ψ = the dislocation density

α = dislocation generation during 'steady state'

β = the work done during the initial part of the dwell

- Accelerated life test is used to find constants/parameters to use such a reliability model

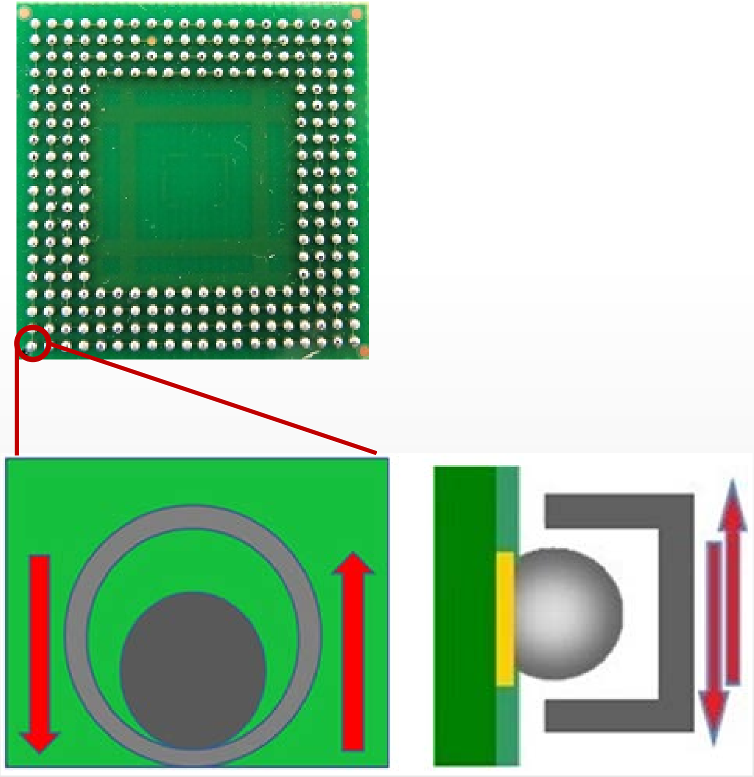
How To Develop a Reliability Model

Case Study of Isothermal Cycling of Individual Solder Joint

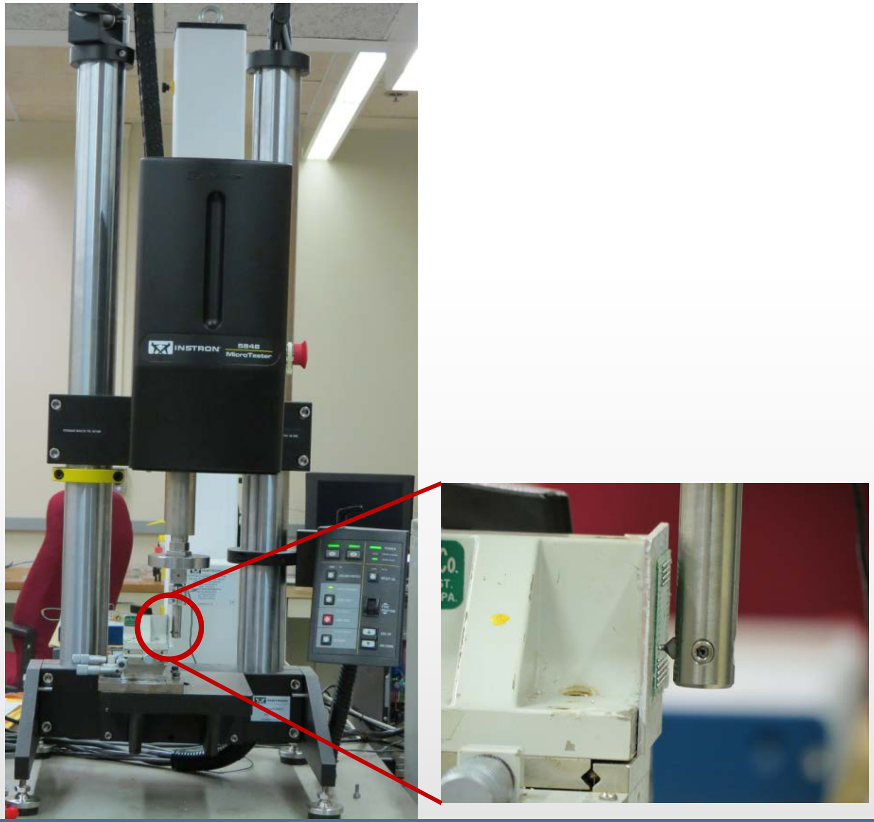
- There is no one approach to develop a reliability model
- Develop a general model to predict fatigue life of solder joints under varying stress cycling
  - SAC305 Alloy (Sn 96.5%, Ag 3%, Cu 0.5%)
  - Room Temperature
  - Fresh material (no aging)

Experiment

Individual solder joints were soldered onto copper pads on typical BGA substrates

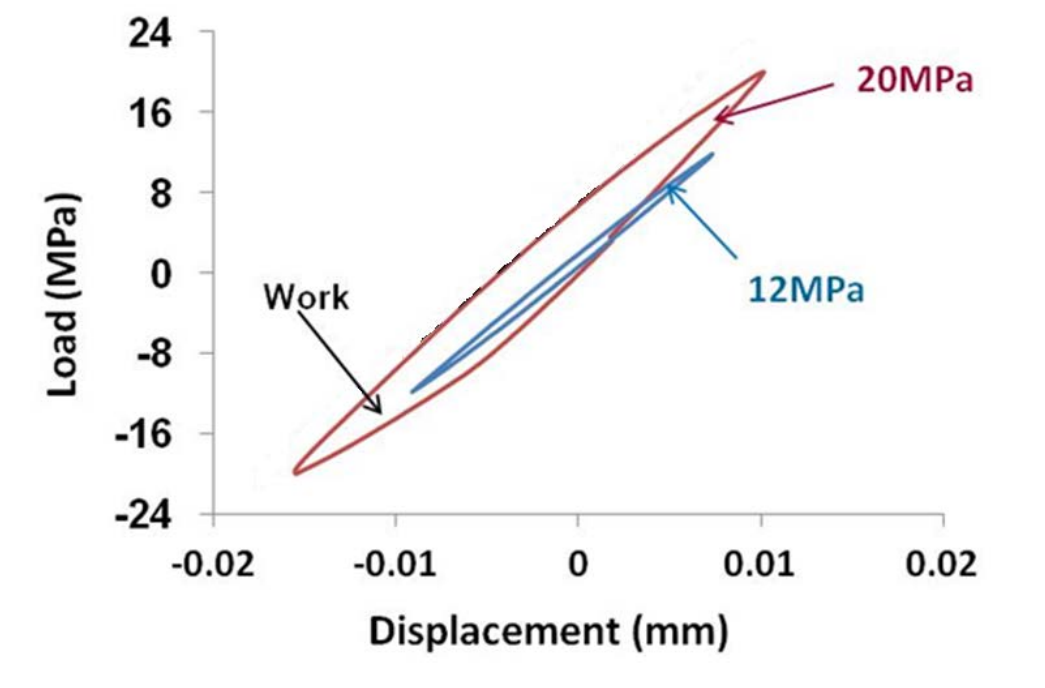


Isothermal shear cycling using an Instron Micromechanical tester



Experiment (cont'd)

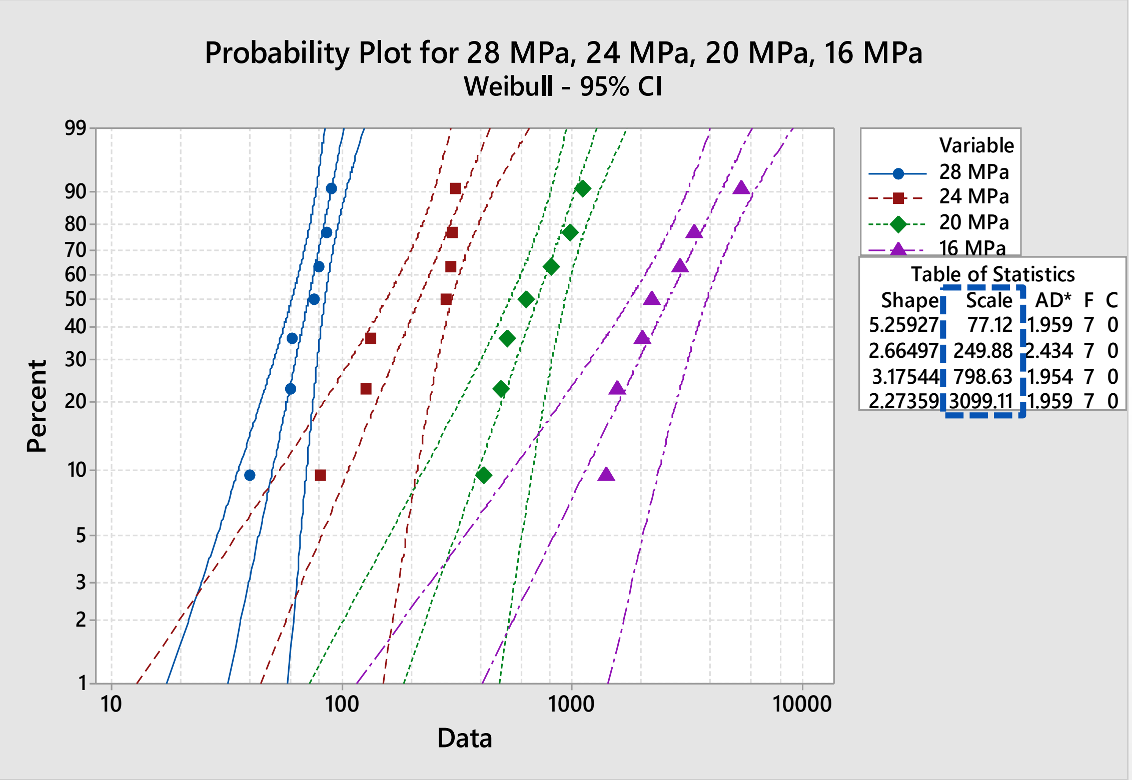
- The Instron tester records the load and displacement data continuously, providing a hysteresis loop for each cycle
- Area within loop gives inelastic energy (work)

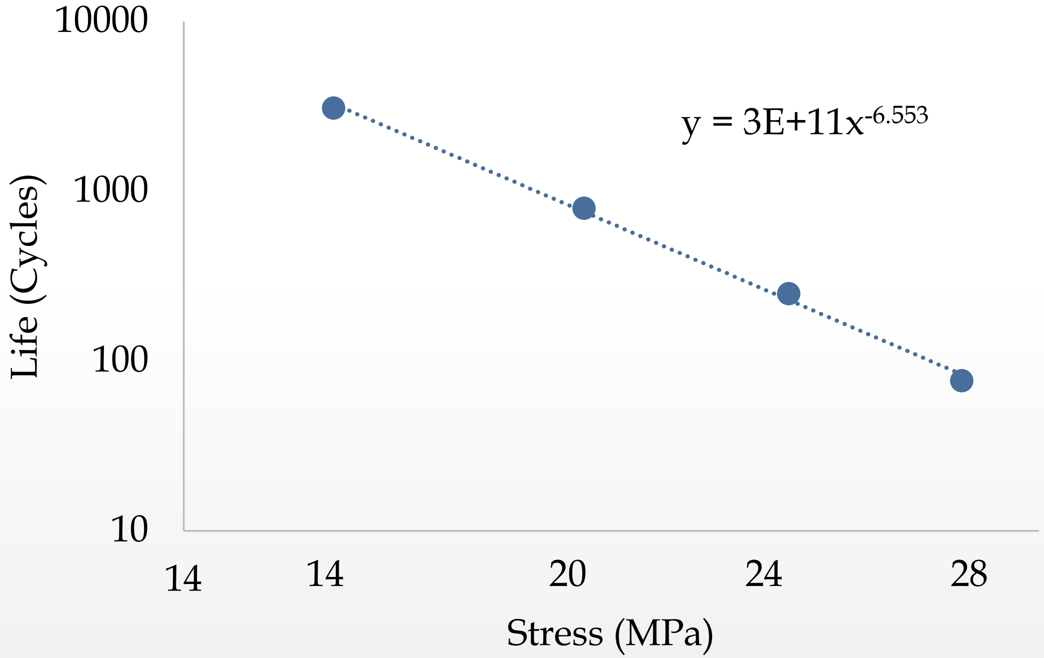


Stress	Replicates
28MPa	7
24 MPa	7
20 MPa	7
16 MPa	7

Fatigue Life vs. Stress

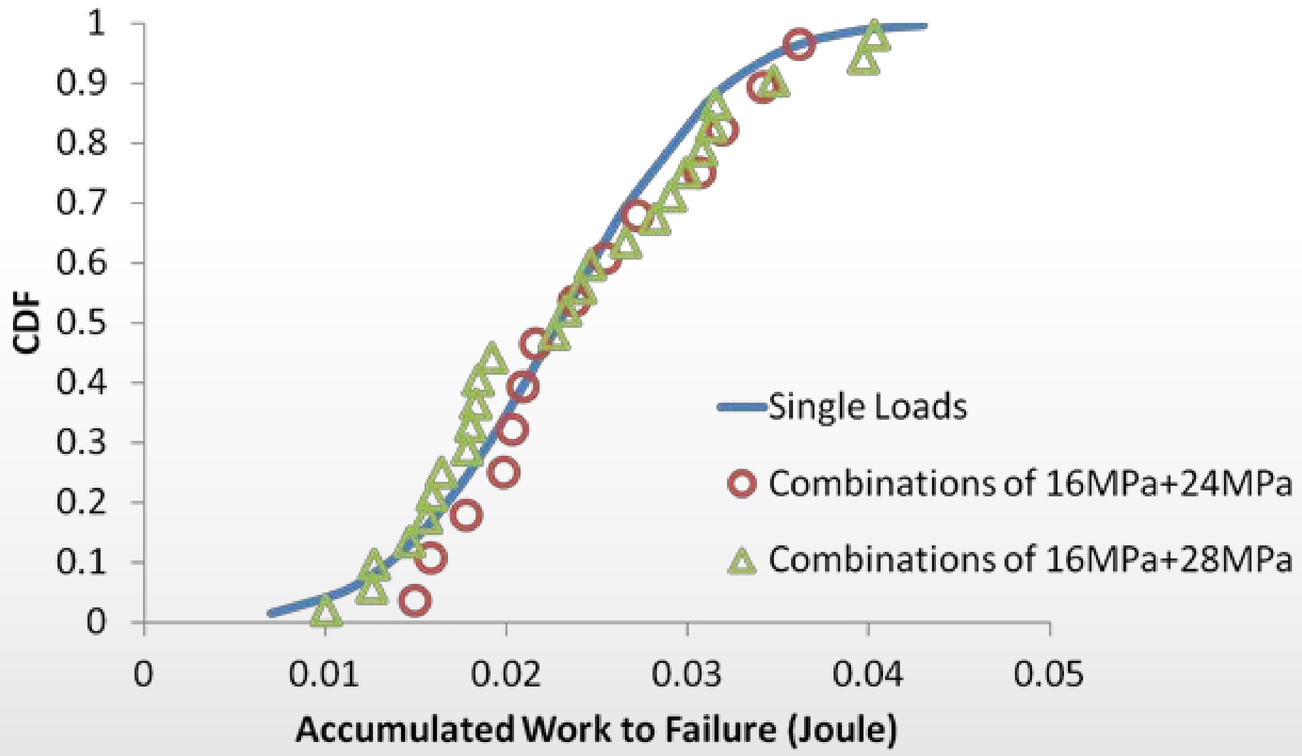
- Fatigue life is a power equation of Stress ($N = a\, \sigma^{-c}$)





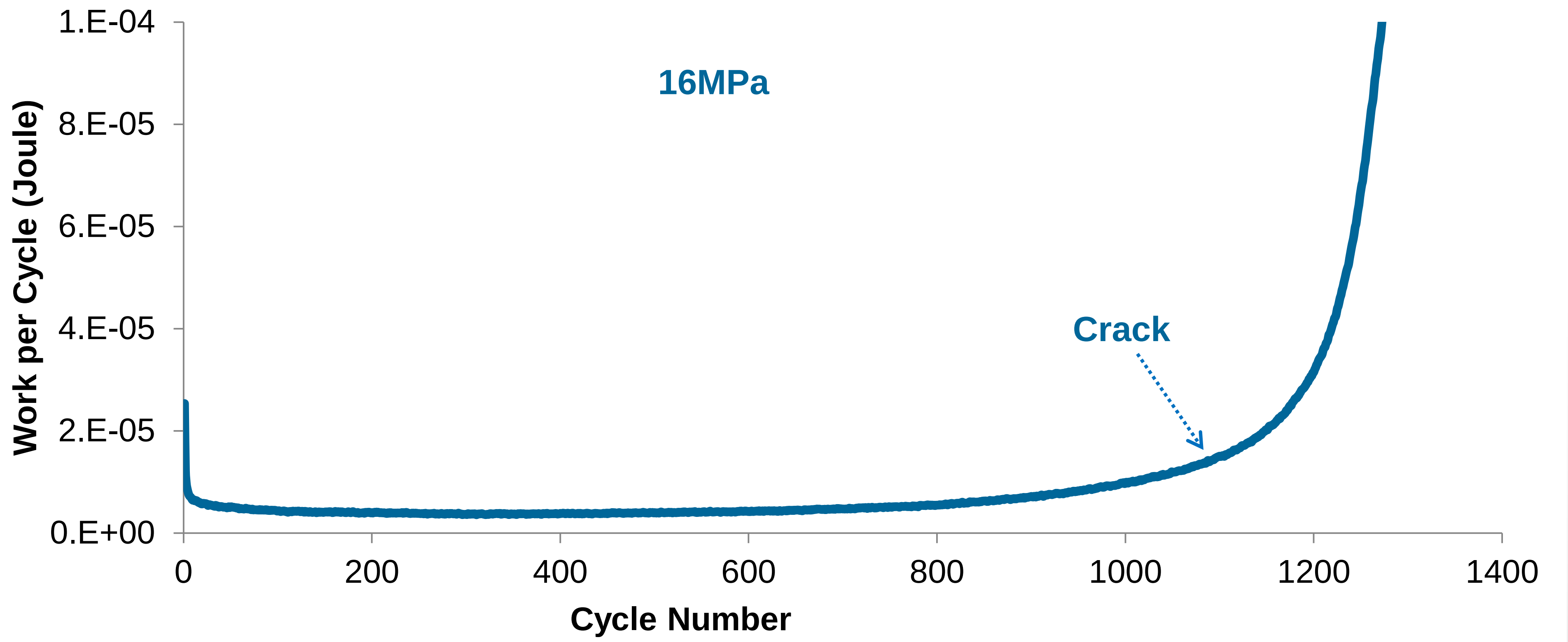
Inelastic Work Accumulation is Constant

- The accumulated work to failure is almost constant regardless to stress value or loading conditions



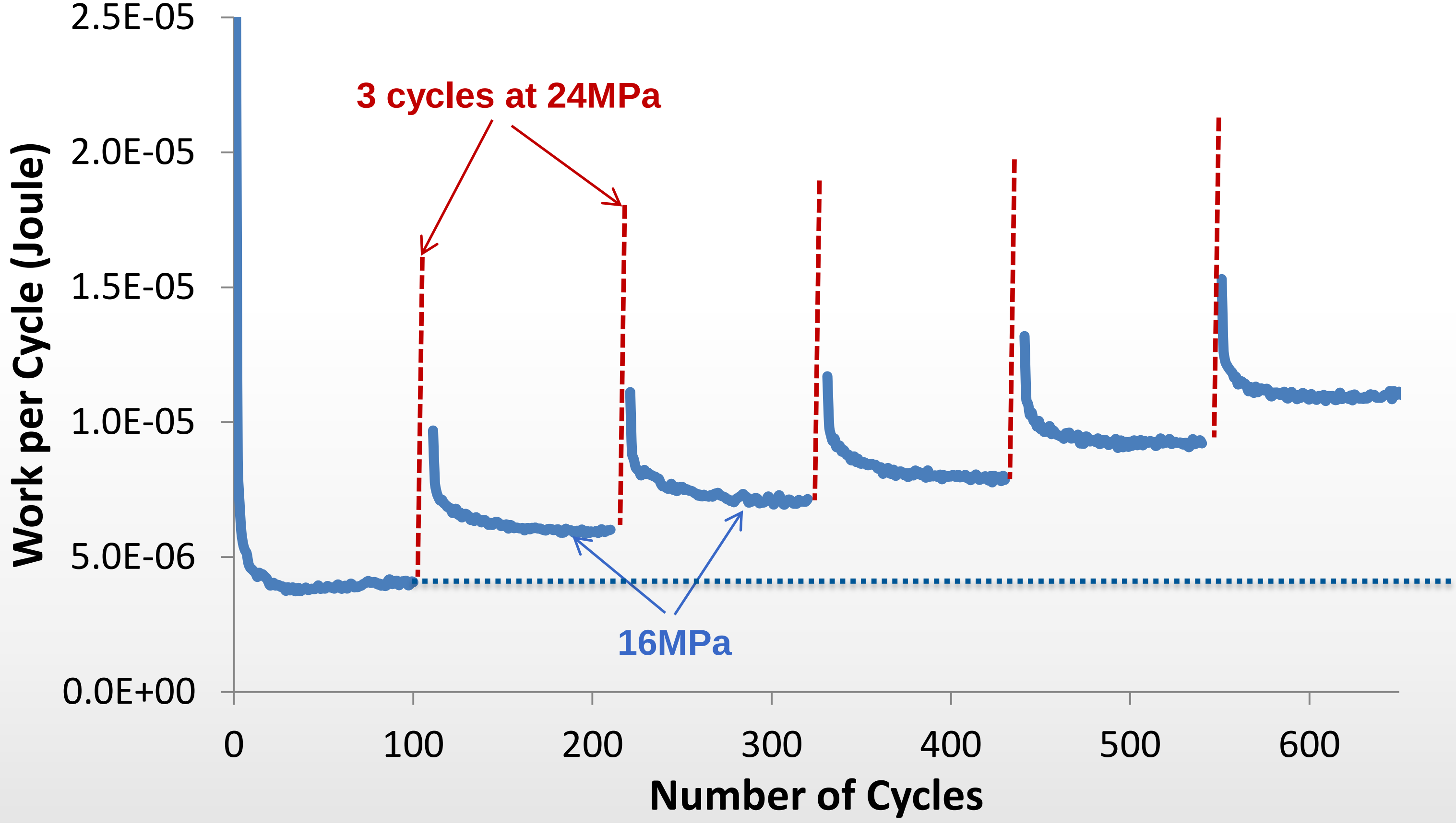
Inelastic Work – Fixed Amplitude

- Inelastic work describes the fatigue life behavior of solder joint:



Inelastic Work – Varying Stress

- Work is amplified in after each excursion to higher amplitude



New Damage Accumulation Rule

- The phenomenon of damage acceleration together with the concept of constant work accumulation has led to a new rule:

$$1 = \sum_{i=1}^{s} f(i) \frac{n_{mi}}{N_m} + \frac{n_{hi}}{N_h}$$

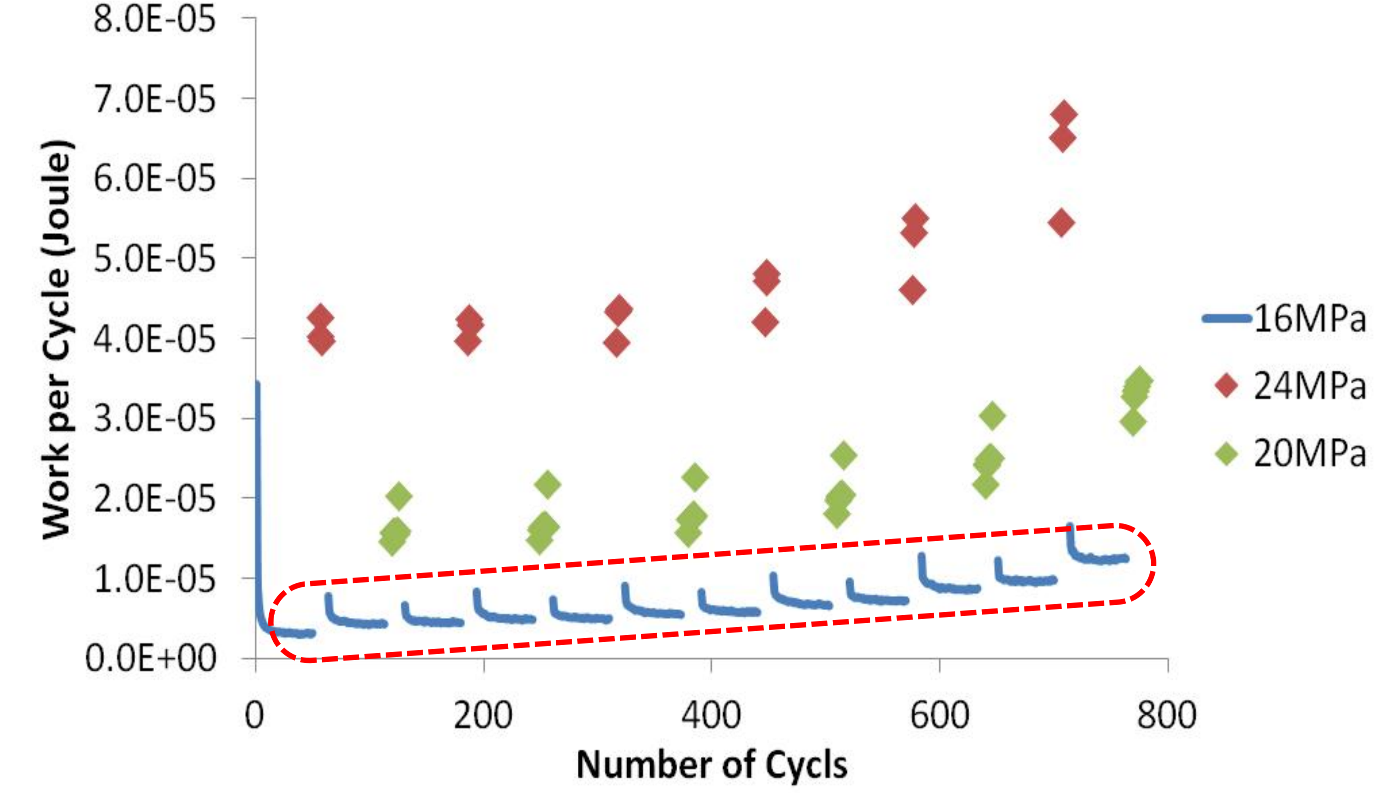
- Where f(i) is the damage acceleration function that can be represented by work amplification
- This rule is for the combination of two alternating amplitudes
- Realistic applications include more than two amplitudes
- Still need to generalize to combinations of more than 2 amplitudes

Combinations of Three Amplitudes

- Due to the variability: measured the effect of sequence of amplitudes on the same solder joint (paired comparison)

- Example: Repeating the sequence

16MPa + 24MPa + 16MPa + 20MPa



General Model

- Based on the constant accumulated inelastic work to failure a general damage accumulation model is proposed:

$$1 = \sum_{i} M_i \frac{n_i}{N_i}$$

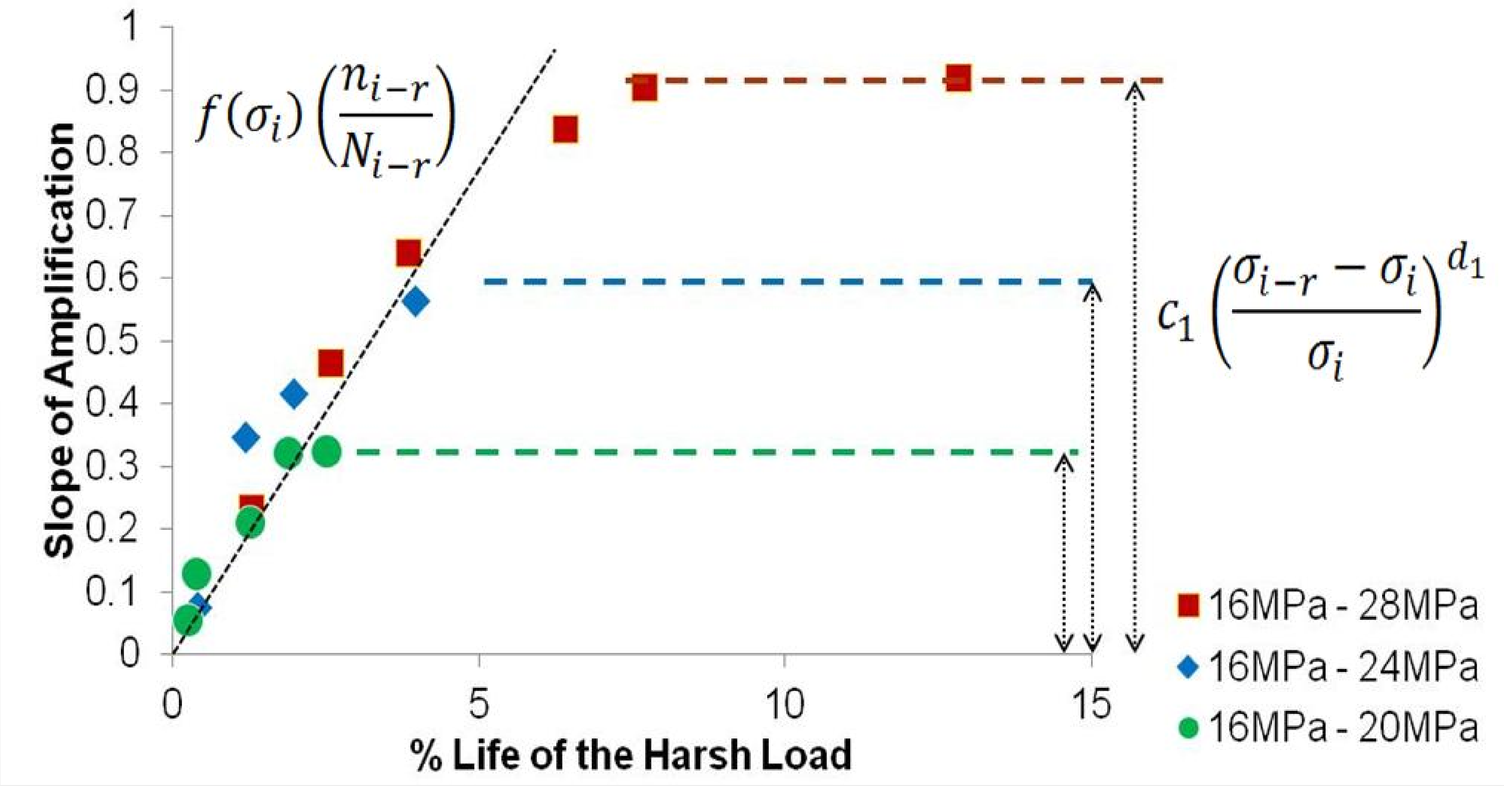
- M_i is a multiplier representing the loading history, calculated:

$$M_i = \prod_{r=1}^{r=i-1} A_{i,i-r}$$

$A_{i,i\text{-}r}$ is the damage acceleration factor at stress σ_i due to the effect of stress $\sigma_{i\text{-}r}$

General Model (cont'd)

- Behavior of the damage acceleration factor ($A_{i,i\text{-}r}$):



Final Isothermal Damage Interaction Model

- To predict the fatigue life of SnAgCu solder joints in varying amplitude cycling at room temperature:

$$1 = \sum_i \left(\frac{n_i}{N_i} \times \prod_{r=1}^{r=i-1} (A_{i,i-r}) \right)$$

$$A_{i,i-r} = \begin{cases} 1 & , \sigma_i \geq \sigma_{i-r} \\ 1 & , \sigma_{i-r} \leq \sigma_{i-r-1} \\ 1 + min \left\{ f(\sigma_i) \left(\frac{n_{i-r}}{N_{i-r}} \right), \; c_1 \left(\frac{\sigma_{i-r} - \sigma_i}{\sigma_i} \right)^{d_1} \right\} & , otherwise \end{cases}$$

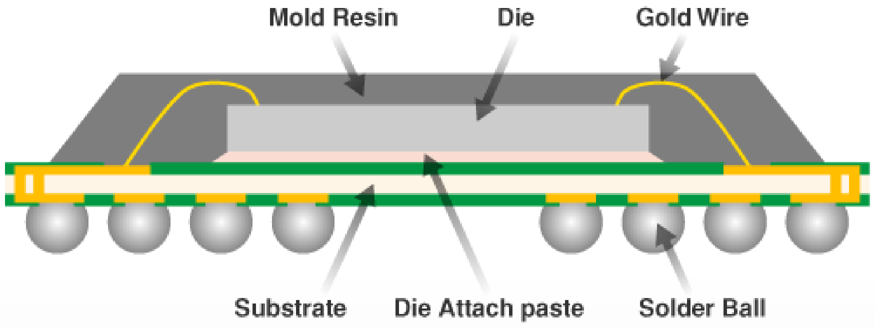
- Accelerated life test is used to find constants/parameters to use such a reliability model

Design of Experiment (DOE) Case Study
Thermal Cycling Accelerated Test

Study the life of CABGA (Chip Array Ball Grid Array) in thermal cycling with temperature (-40C to 125C)

Response: Life (cycles)

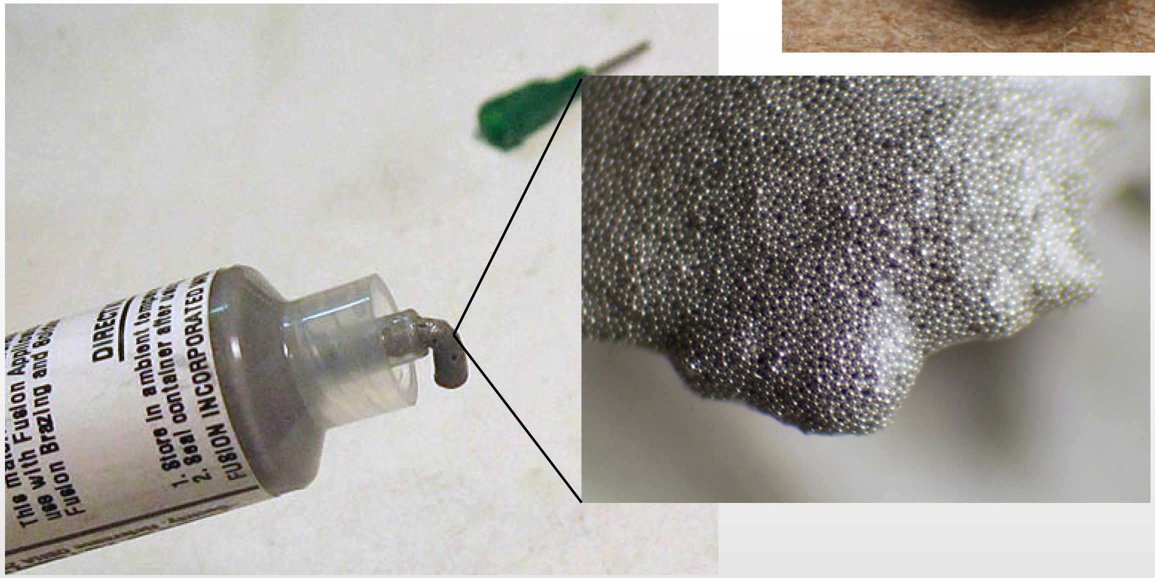
Factors (6 Factors):

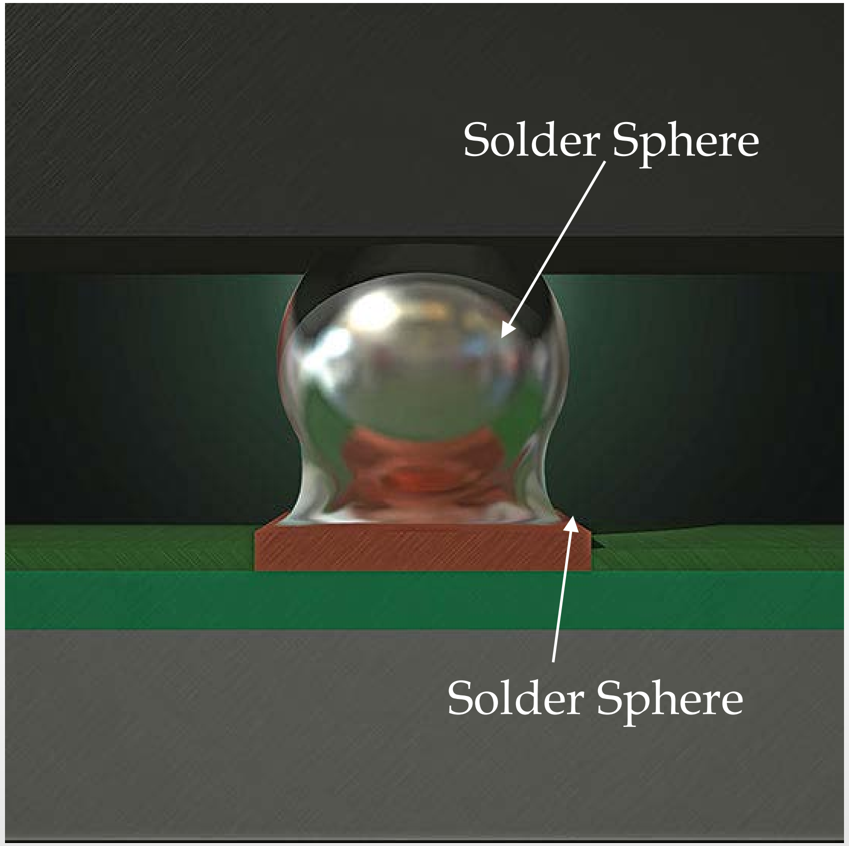


Factor	Type	Levels	Values
Substrate	Fixed	2	FR406, Megtron6
Solder Paste	Fixed	3	Innolot, SAC305, SnPb
Reflow Profile	Fixed	2	TC1-Bot, TC1-Top
Aging (Months)	Fixed	4	0, 6, 12, 24
Aging Temp. (Celsius)	Fixed	3	25, 50, 75
Solder Spheres	Fixed	5	Innolot, SAC-Y, SAC105, SAC305, SnPb

Solder Sphere & Solder Paste

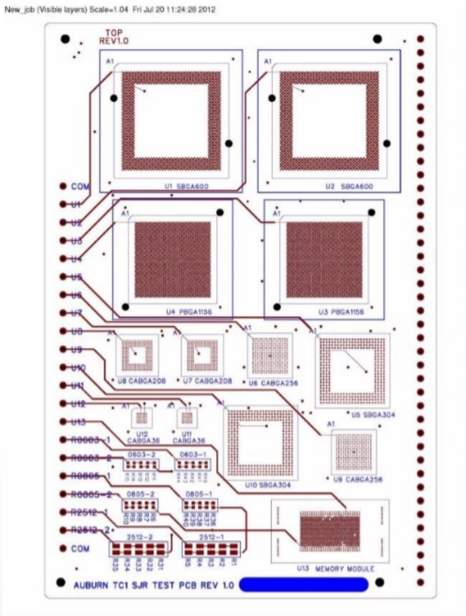
Solder Paste Material: Innolot, SAC305, SnPb
Solder Sphere Matrial: Innolot, SAC-Y, SAC105, SAC305, SnPb

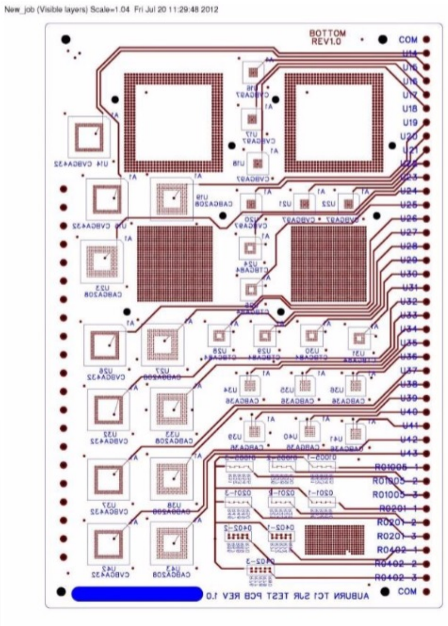
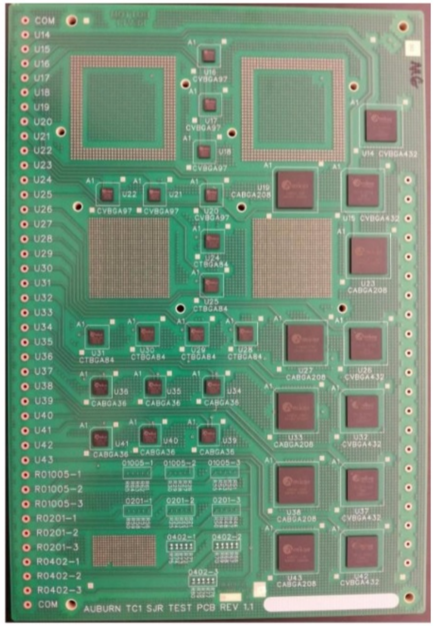




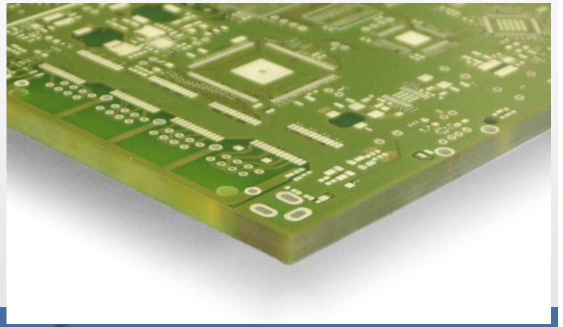
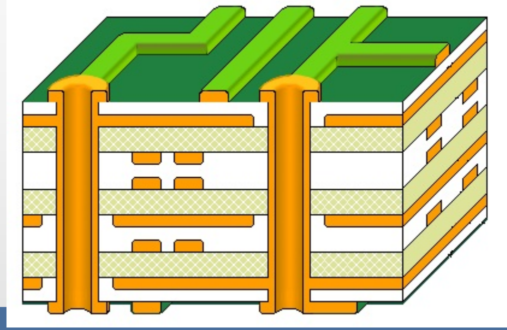
Printed Circuit Board (Substrate)

Substrate Type(PCB): FR406, Megtron6



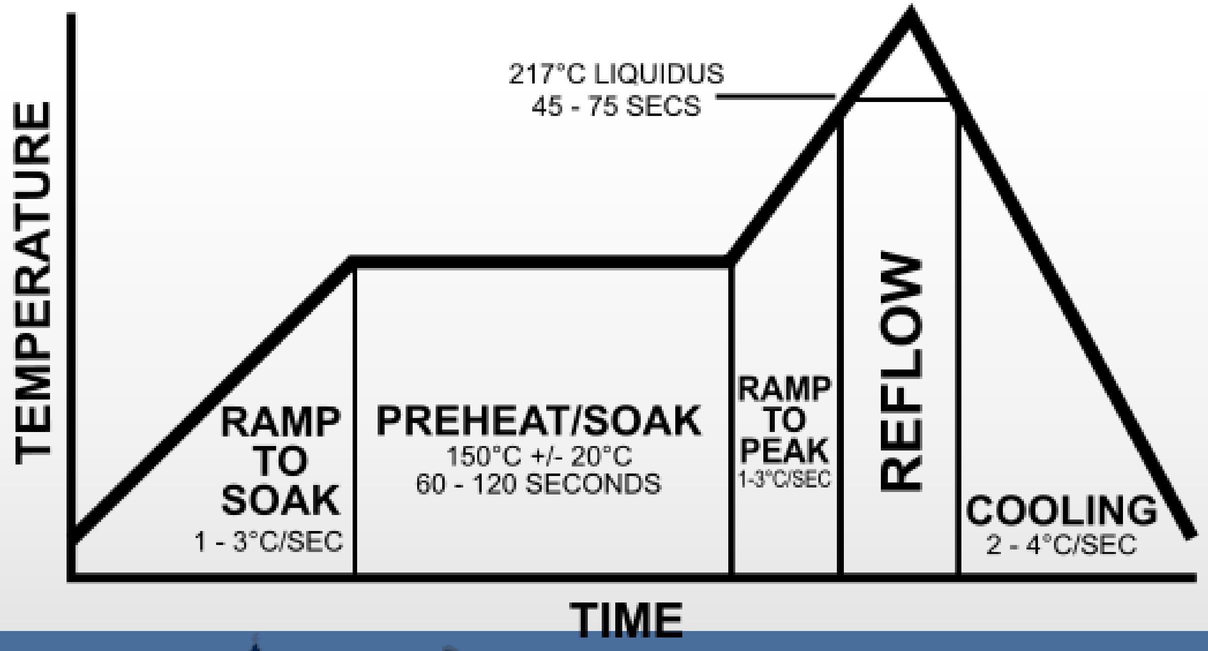



Solder Sphere

Reflow Temperature Profile

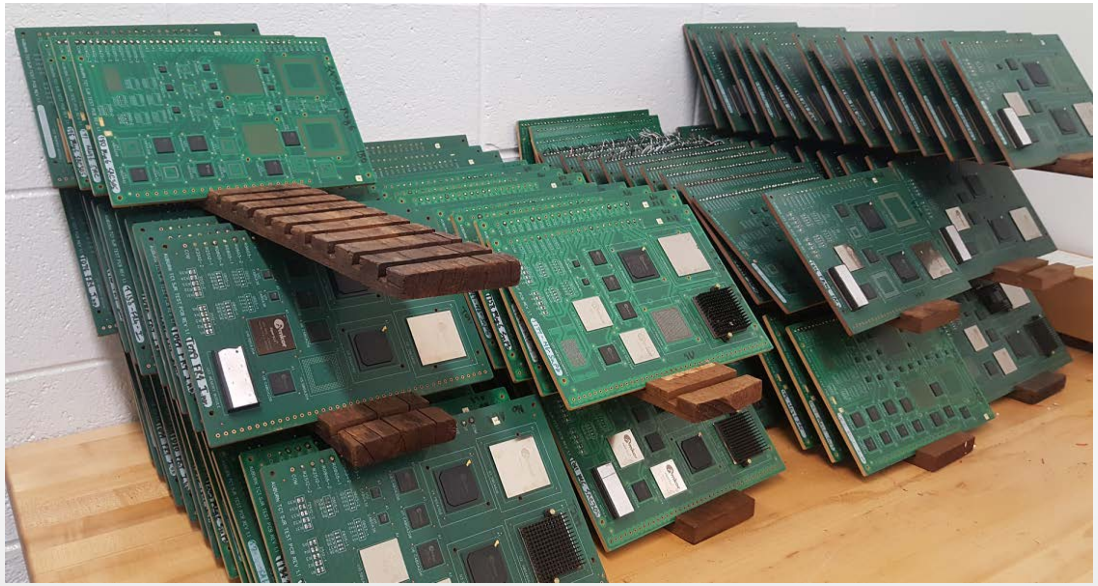
Reflow Profile: TC1-Bot, TC1-Top
TC1-Bot: Max Temp = 250C
TC1-Top: Max Temp = 240C



Reflow oven

Aging Time and Temperature

- Aging time: 0, 6, 12, 24 months
- Aging Temperature: 25, 50, 75 C

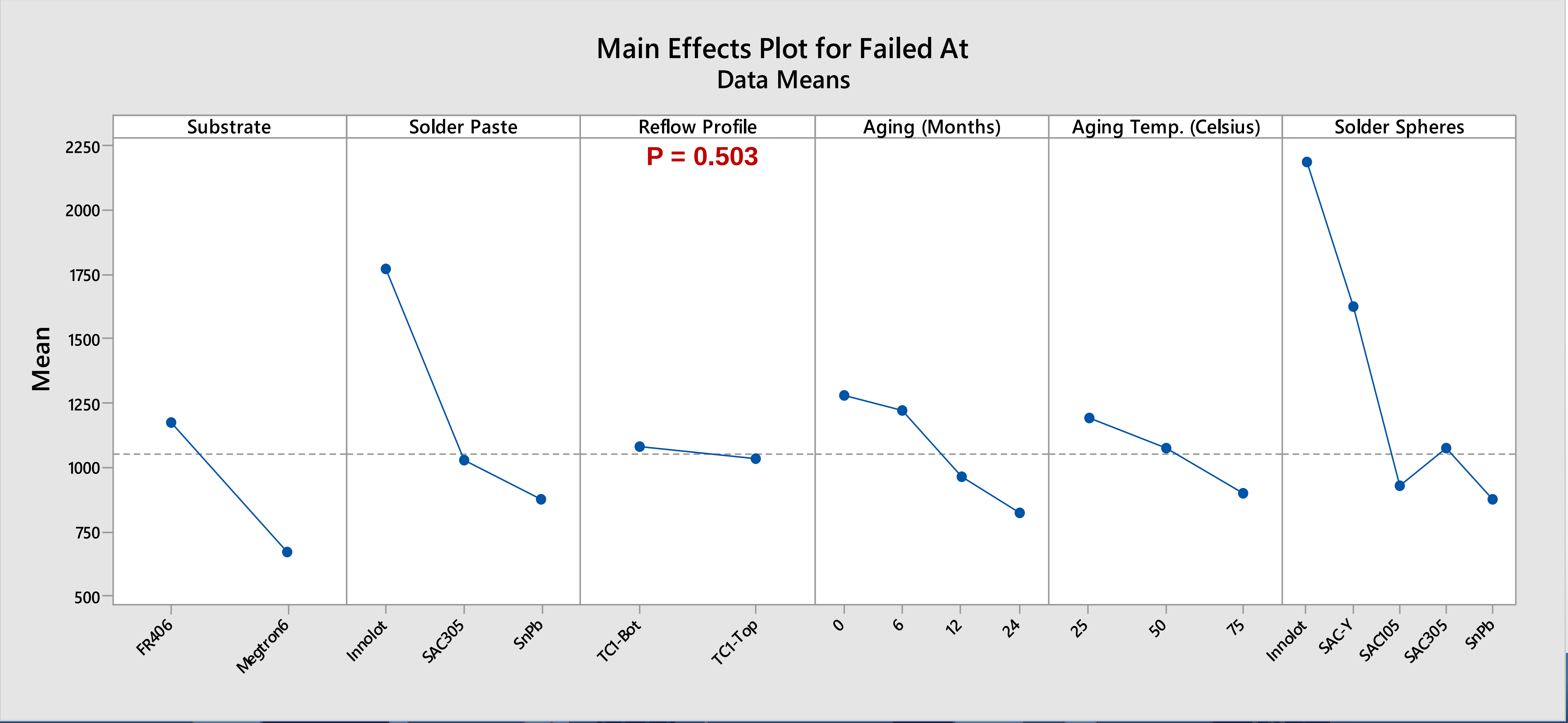


DOE (ANOVA Results using Minitab)

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Substrate	1	54188884	54188884	702.44	0.000
Solder Paste	2	2483844	1241922	16.10	0.000
Reflow Profile	1	34603	34603	0.45	0.503
Aging (Months)	3	11372539	3790846	49.14	0.000
Aging Temp. (Celsius)	2	2916828	1458414	18.91	0.000
Solder Spheres	4	2262082	4644264	22.69	0.000
Substrate*Reflow Profile	1	1357223	1357223	17.59	0.000
Substrate*Aging (Months)	3	472048	157349	2.04	0.106
Substrate*Solder Spheres	4	55785814	13946453	180.79	0.000
Solder Paste*Reflow Profile	2	358360	179180	2.32	0.098
Reflow Profile*Aging (Months)	3	242075	80692	1.05	0.371
Reflow Profile*Aging Temp. (Celsius)	2	12826	6413	0.08	0.920

Main Effect Plots



Interaction Effect Plots

Best Combination

- Innolot Solder paste and Innolat solder sphere on FR406 Substrate

- Innolot is more expensive!!!

Summary

- Electronics Manufacturing Industry
- Electronics Reliability Issue
- Reliability Tests for Electronic Products
- Electronics Reliability in Thermal Cycling (Case Study)
- Electronics Reliability Models (Case Study)
- Design of Experiment (DOE) in Electronics Reliability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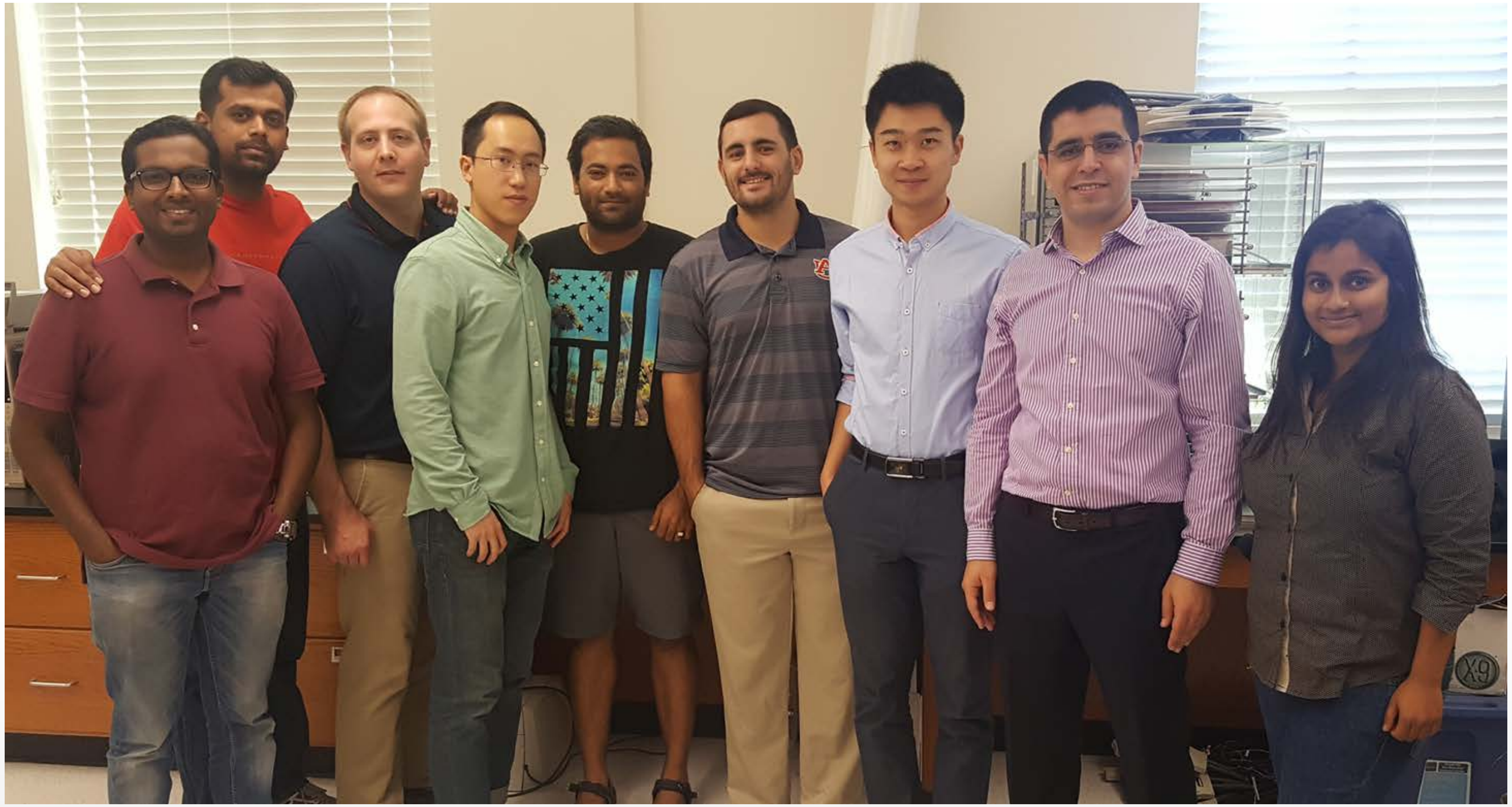

Left to right: Anto, Francy, Thomas, Sinan, Sharath, Seth, Cong, Sa’d, Gayatri

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