DoD Lead-free Electronics Risk Mitigation: Lead-free Solder Basics for Systems Engineers

SERDP/ESTCP Webinar hosted by CALCE

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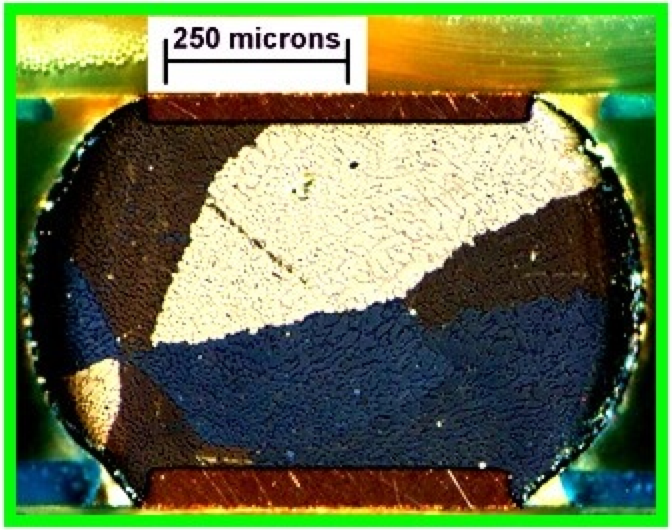
No-Pb Solder Reliability Overview

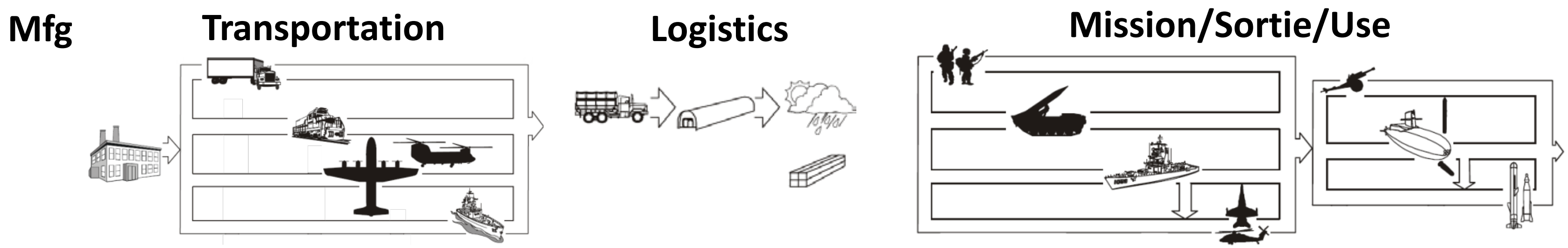


- No-Pb is not a disaster, can be dealt with.
- Reliability can be better, equal to or, worse than SnPb, depending on specifics
- ***Usually***, you are going to be OK with current practices, but there are too many surprises

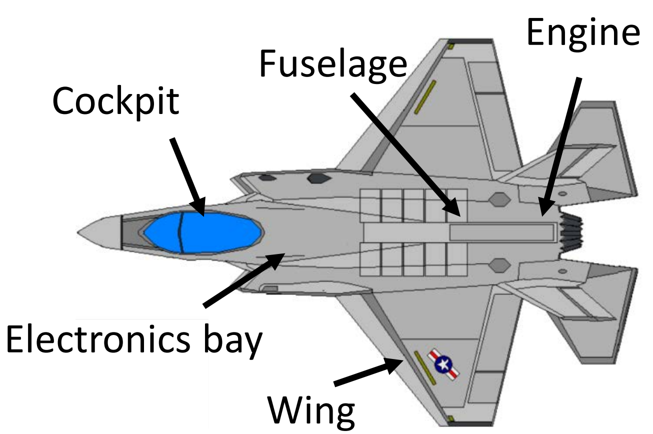
Take Away

- ‘Expect’ surprises – when is similarity analysis not OK?
- General background and outline of practical recommendations.
- Read technical parts of standards and handbooks.
- Final report on underlying SERDP project available

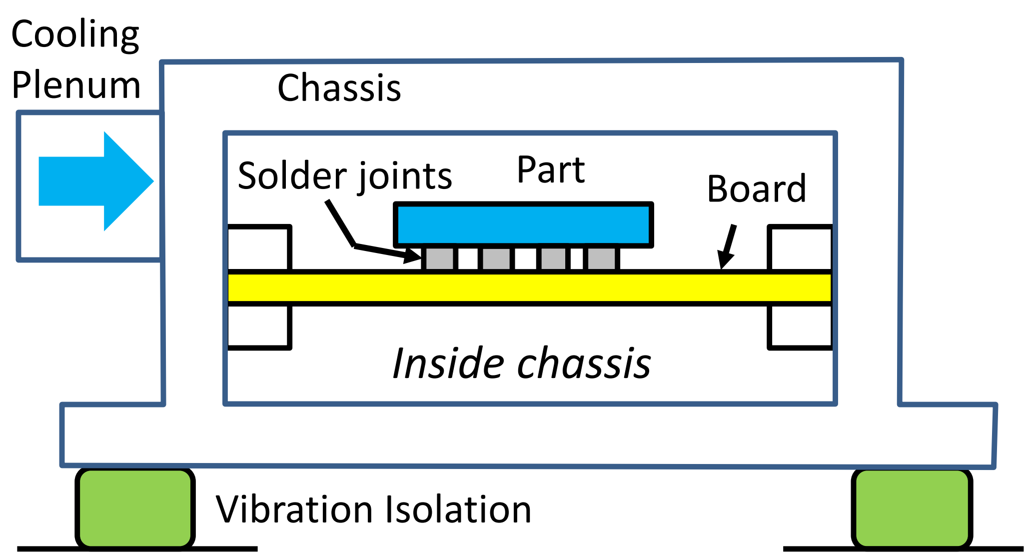
Environment and Solder Loads



MIL-STD-810 Life Cycle Factors



Environmental Zones



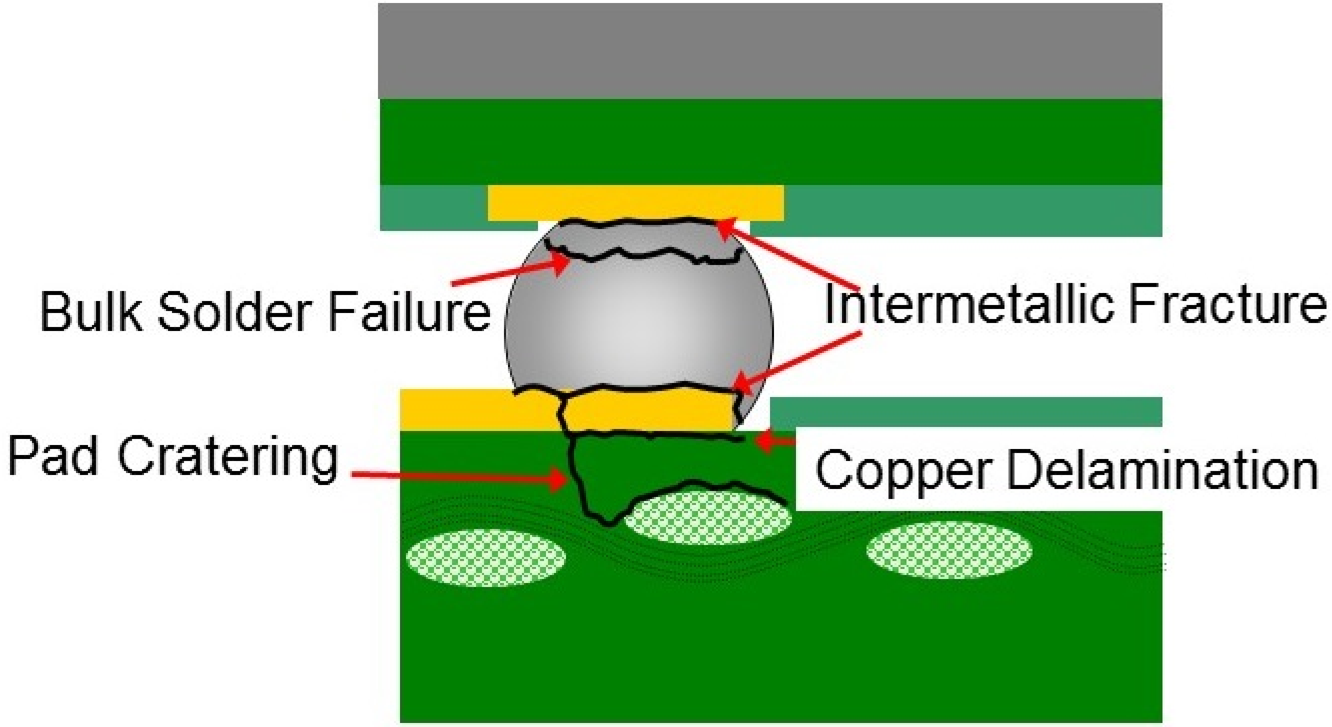
Electronics

System compliance matrix validation tests and analysis requirements

Reliability of Solder Joints

Life under repeated (cyclic) loading is commonly determined by one of several competing factors:

Effects of aging, void growth, electromigration , ...

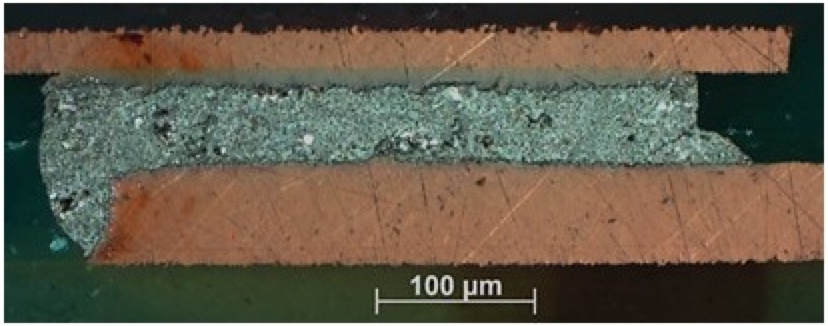


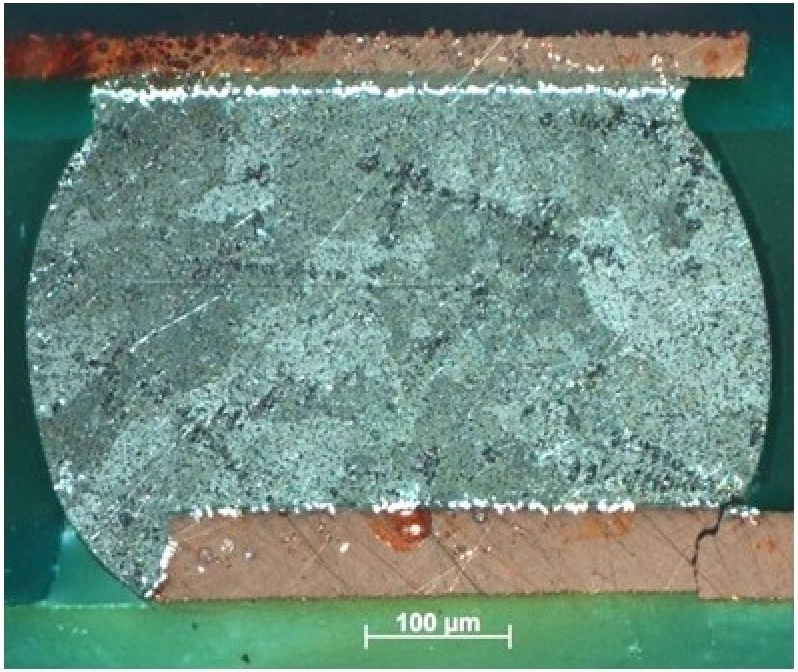
Failure mode may vary with design, process, loading ***and*** solder alloy. Even if we 'just' consider solder failure:

Example:

In thermal cycling, the strain on a joint increases with CTE mismatch, DNP and ΔT.

It ***decreases*** with increasing joint ***height***. This is why the BGA version of a component survives longer than the LGA version:

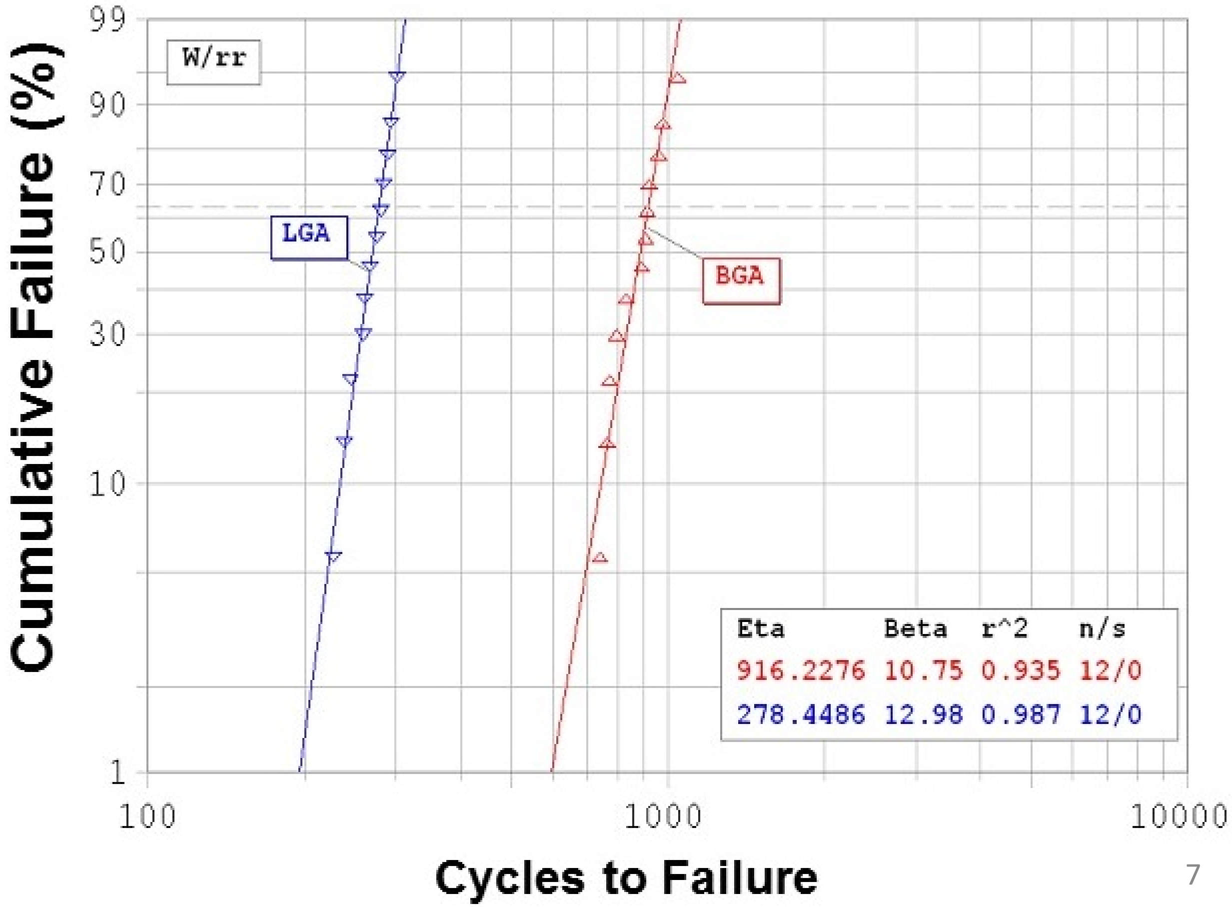




LGA Vs. BGA

In the case of SnPb solder joint they do

3.3x difference:

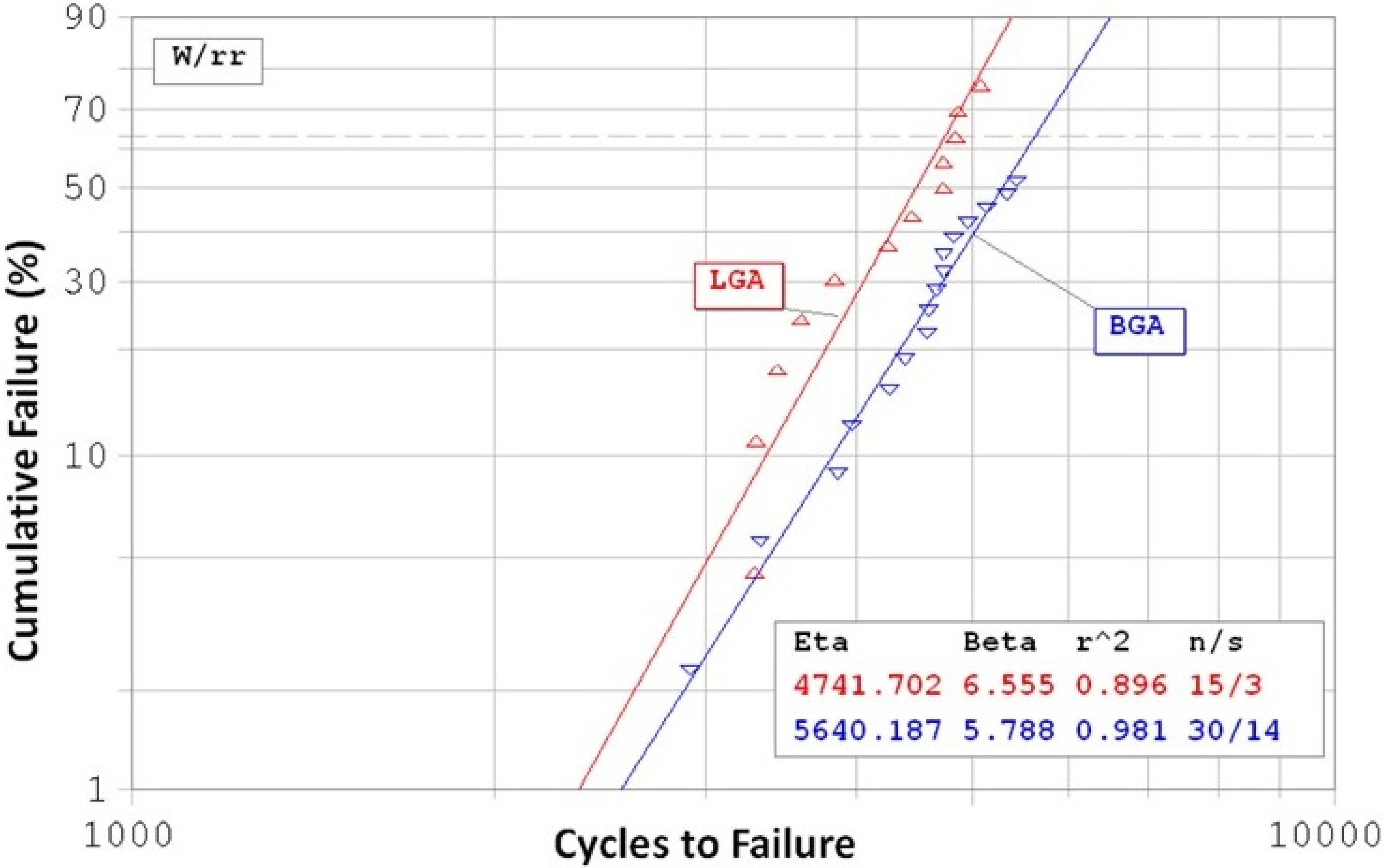


CABGAs and LGAs in -40/125C, 60min dwells

LGA Vs. BGA

Same assemblies as in preceding slide, but with SAC305 joints:

Much smaller difference



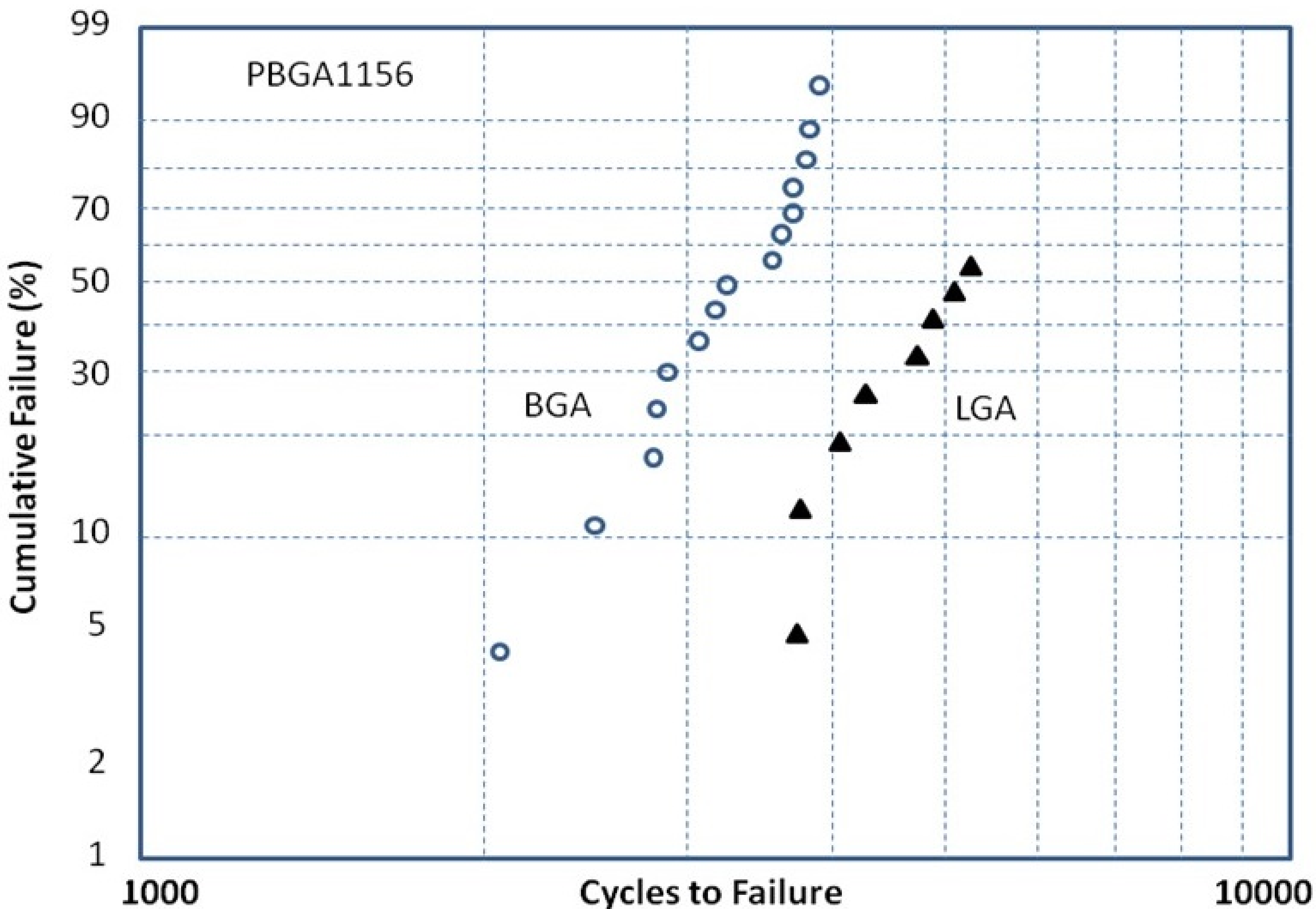
CABGAs and LGAs in -40/125C, 60min dwells

LGA Vs. BGA

Larger components (LGA and BGA) with SAC305 :

Opposite trend

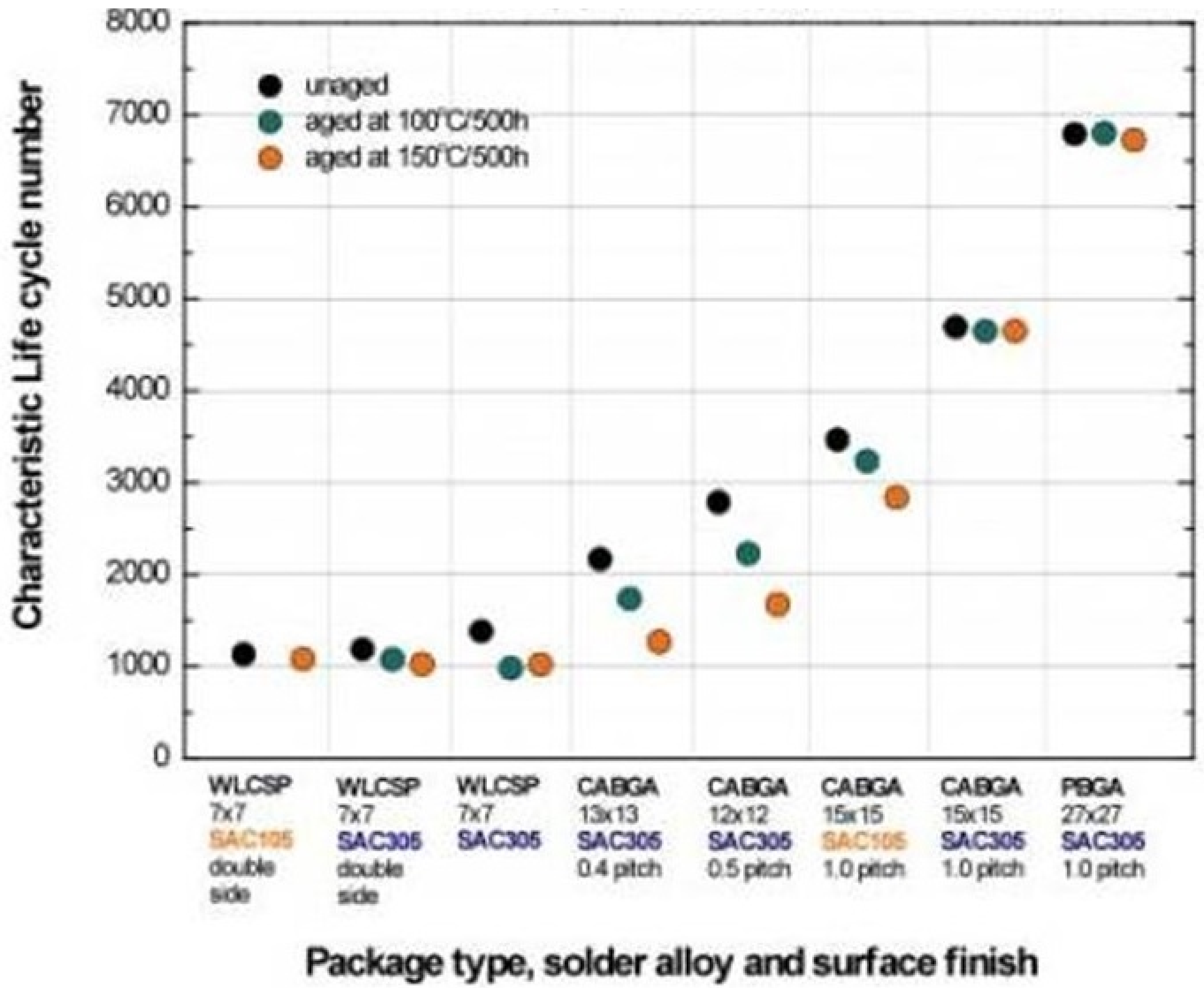
PBGA1156 in -40/125C, 60min dwells



Effects of Aging?

Depend on component and solder alloy

HDPUG found cases where life was ***longer*** after aging



Lee & Ma (Cisco), ECTC 2012

Still, Testing is Testing

Right?

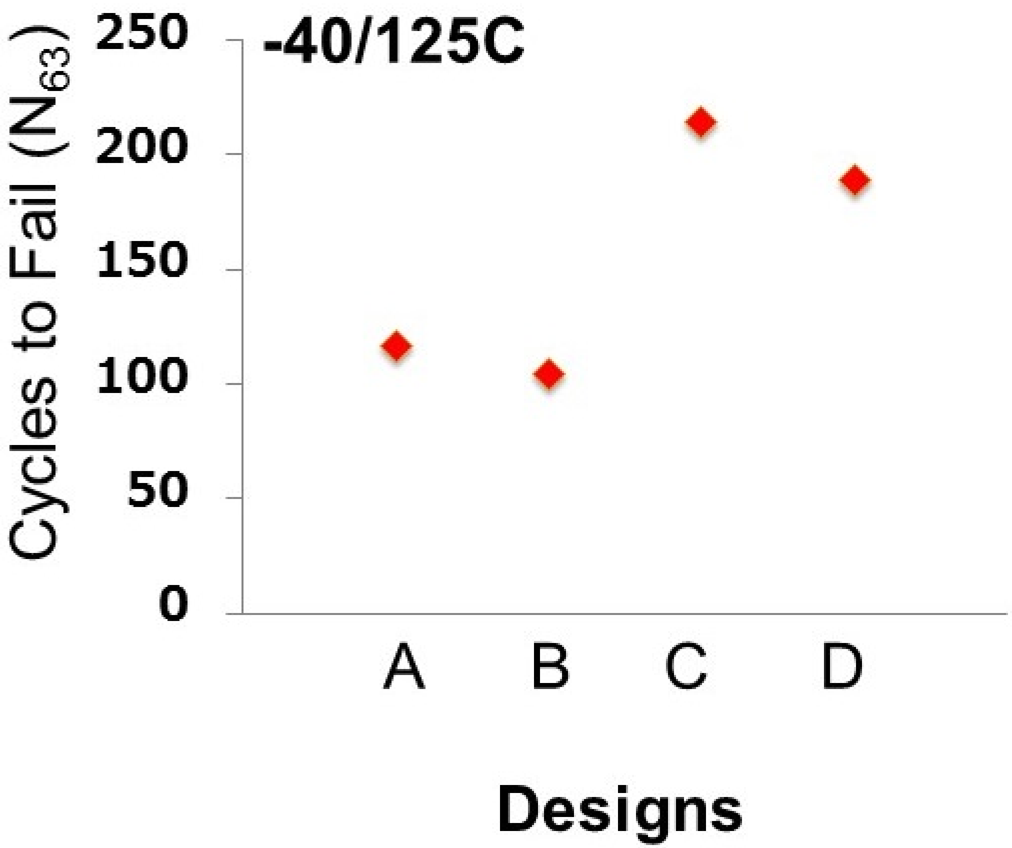
We may have to test each specific design of interest, but ...

Actually, interpretation of accelerated test results may be harder than commonly recognized

‘Best in test’ may not mean ‘best in service’:

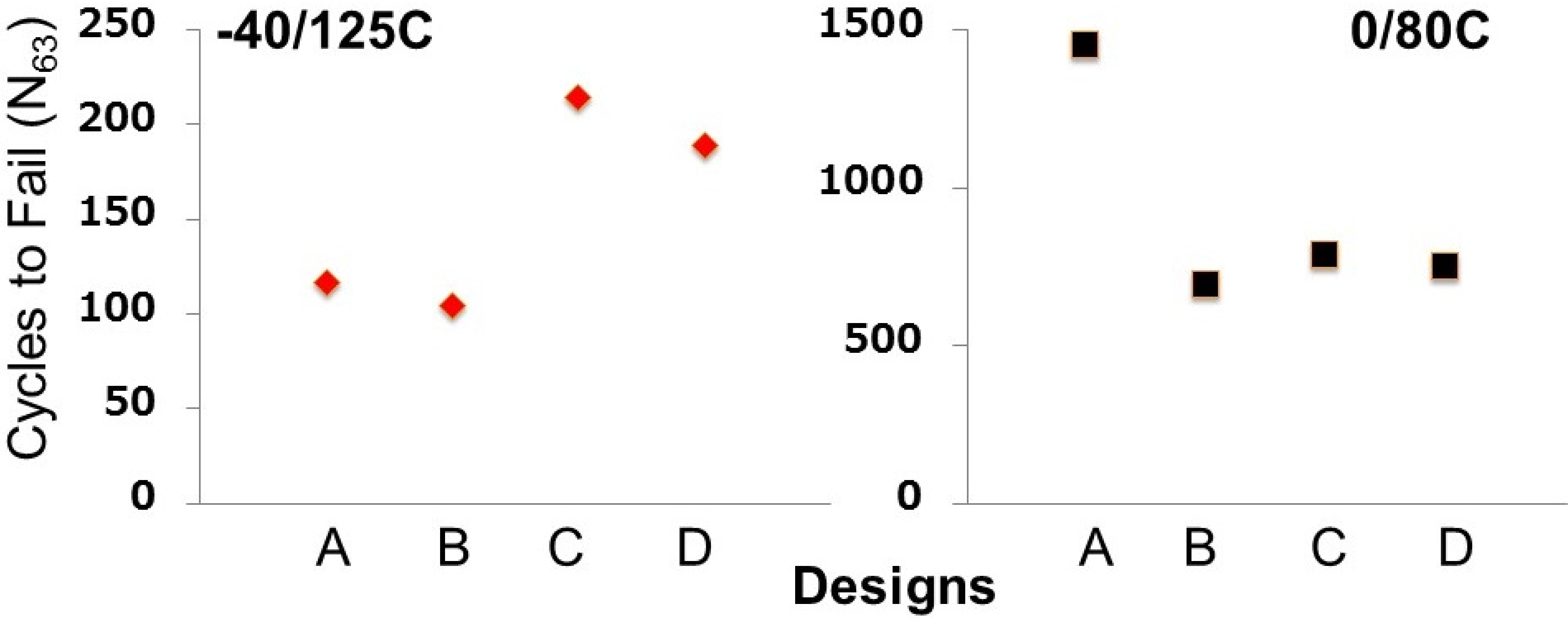
Comparing Designs?

BGA assemblies with SAC305 joints in thermal cycling



Which Design Is Better?

BGA assemblies with SAC305 joints in thermal cycling

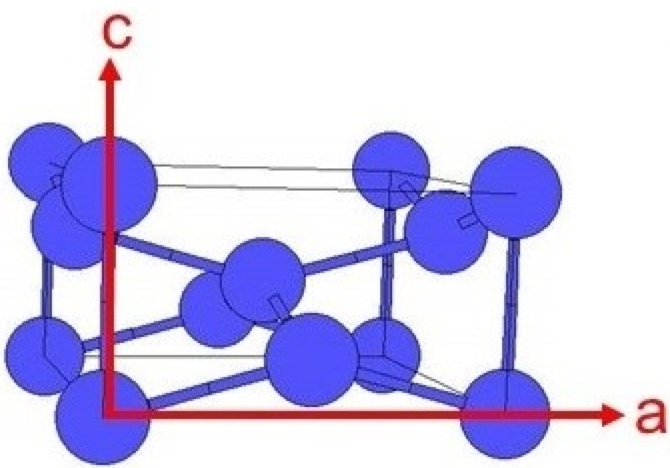


Is this a consistent trend? Would 'A' still be best in even milder cycling? (yes)

Why SnAgCu Behavior is Complex

Essentially Sn crystal with a few percent precipitates. A substantial fraction of most realistic solder joints is single crystal.

The crystal structure is ***extremely*** anisotropic:



a=5.832A, c=3.182A

- ***Fatigue resistance*** lowest when either a- or b-axis is parallel to load
- c direction expands and shrinks more with a temperature change, making for greatest ***crack driving force*** along c-axis in thermal cycling

Scatter in properties and fatigue life
– ***practical*** consequence (?):

Statistics

We cannot control orientations of joints → major contributions to statistical variations

Failure distribution cannot be Weibull (or log-normal, or …)

This has major consequences for low-life outliers (very early failure):

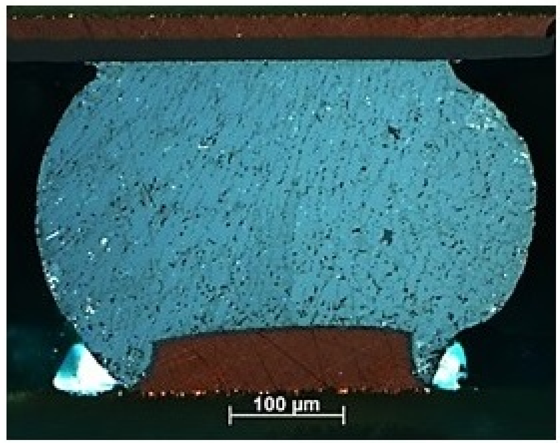
- Occur more often (more likely to be included in typical test sample size) in vibration, drop, bending, …
- Easily missed in thermal cycling (a few in a thousand?)

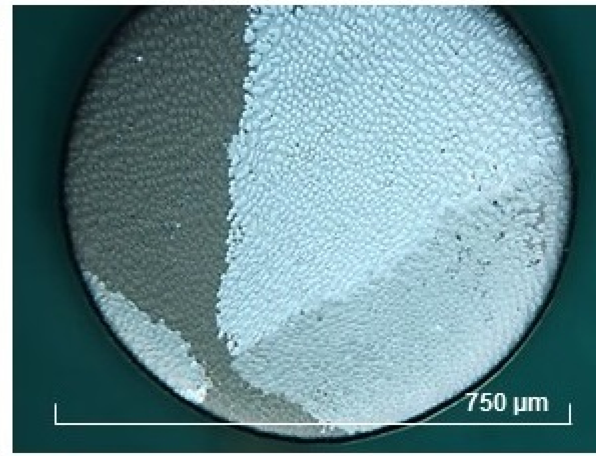
Need design margin adjustment (how much -- TBD)

Why SnAgCu Behavior is Complex

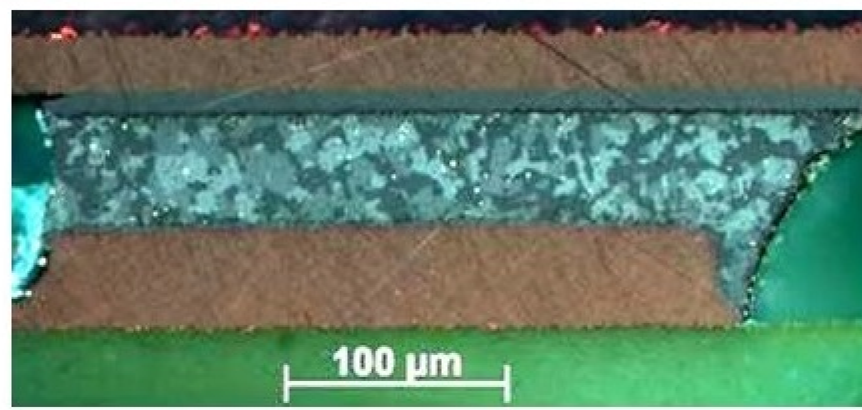
The same alloy may give different Sn grain morphologies .

Single grain or
'beach ball'





Interlaced twinning

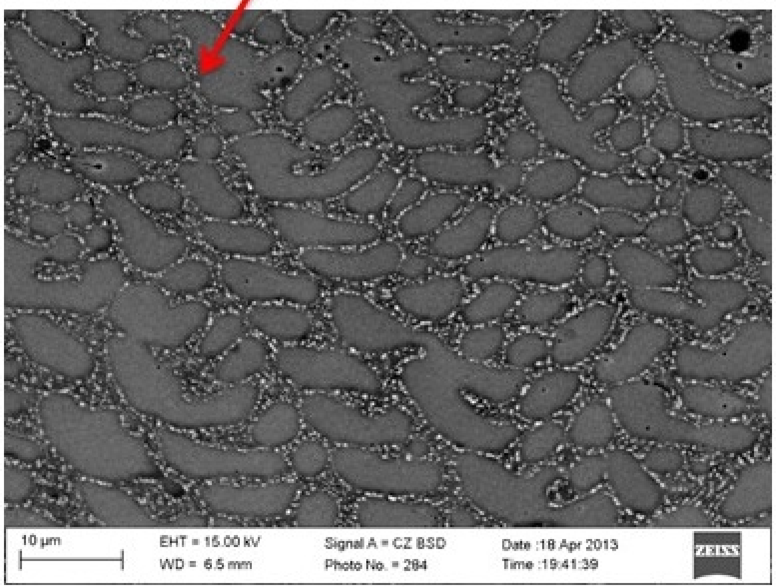


The properties of these morphologies are ***different***

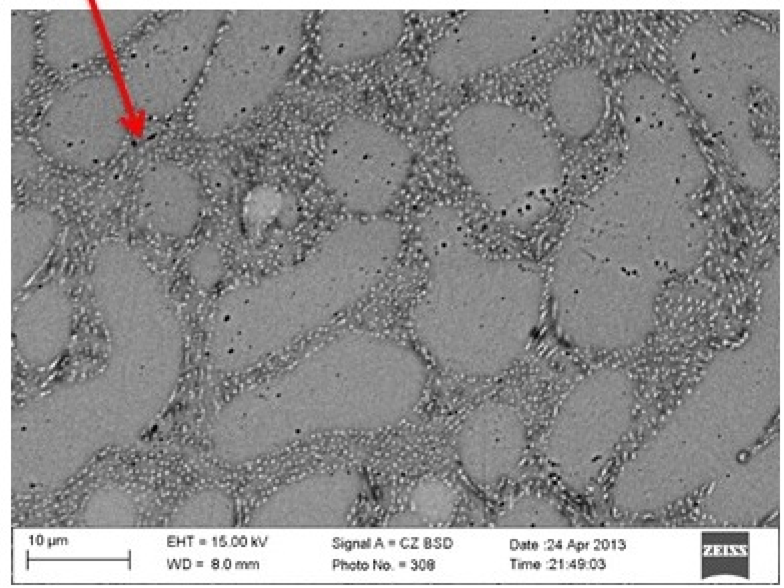
SnAgCu Microstructure

In general: Major effects of joint design, pad finishes, process and aging due to variations in Ag_3Sn precipitate distributions

12 mil diameter joint

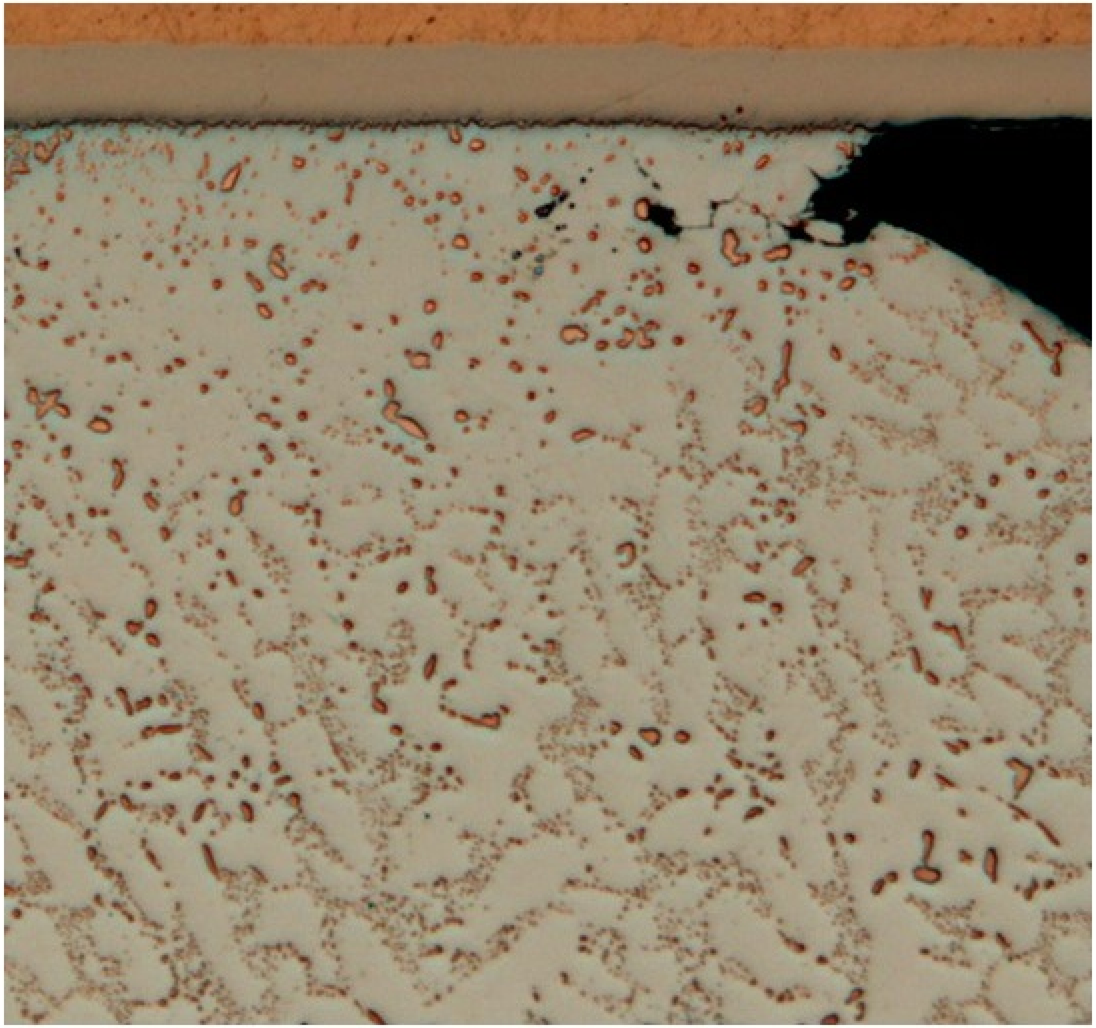


30 mil diameter joint



Effect of Cycling

Precipitates coarsen in thermal cycling, in particular in high strain region



Leads to ***major*** variations in solder properties

What can you do?

If you are modeling:

“Smart” Constitutive Laws for Solder Properties

Solder microstructures can change dramatically during service

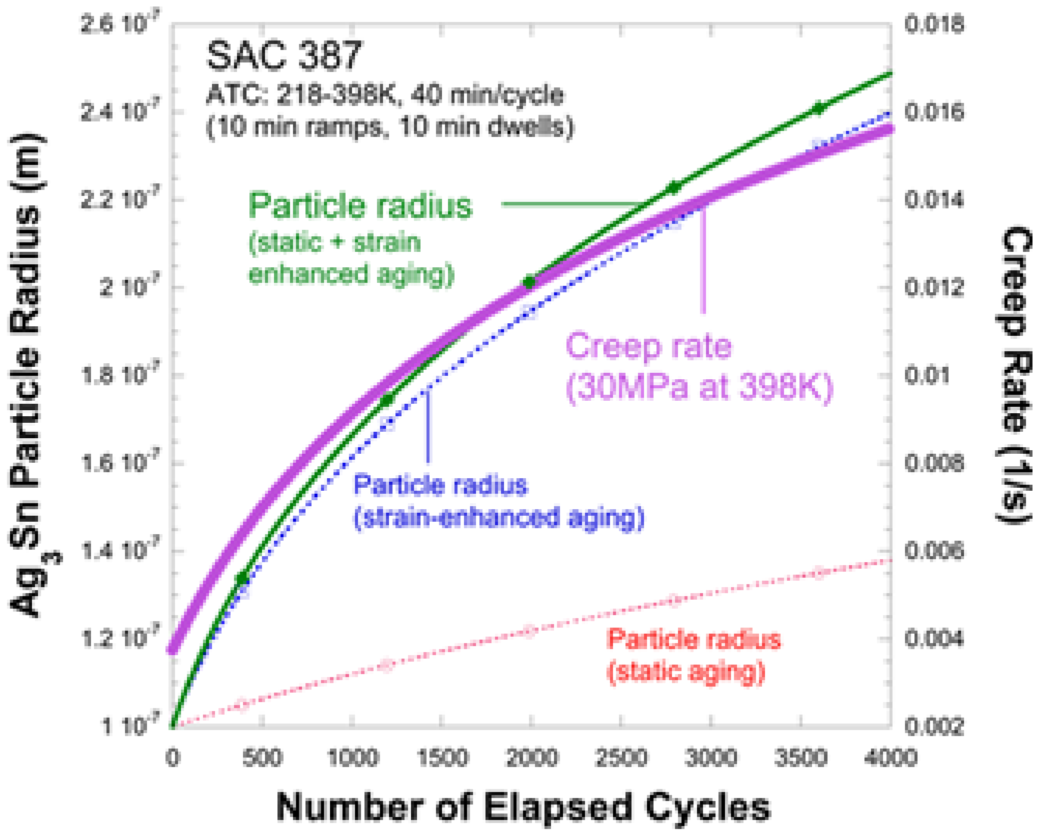
↓

This changes material properties (**creep**, fatigue, fracture)

↓

Need to use ***adaptive*** constitutive laws, that continually self-adjust with microstructural changes during service

Precipitate Size and Creep Rate change, *Especially* at Elevated T or in Thermal Cycling



- Precipitate size increases in both isothermal aging and thermo-mechanical cycling
- Precipitate size more than doubled after 4000 cycles of -55/125C
- <u>*Creep rate*</u> more than quadruples at the highest temperature (125°C, 30 MPa)

Reliability Assessment

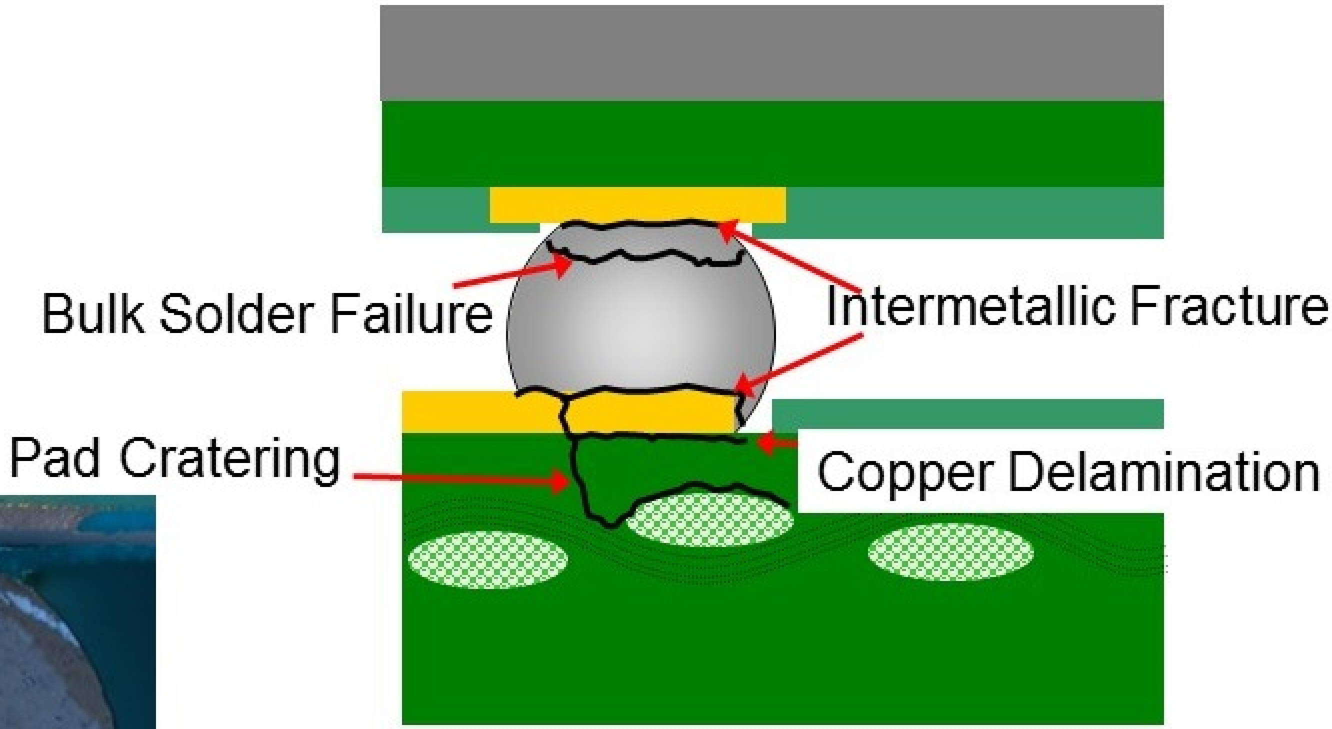
- ✓ A subset of reliability engineers are concerned with absolute life in service (20 years? good enough?)
- ✓ Most focus on 'engineering' tests done to compare (materials, designs, processes – 'similar' product, …). Still need to tell us ***something*** about performance in service

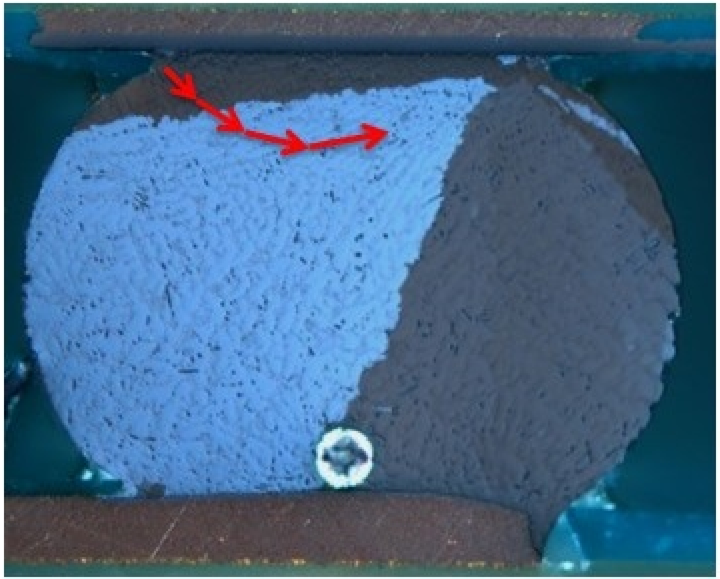
Accelerated test procedures and interpretation of results?

We rely on our mechanistic understanding (model) to help you with that

Damage and Failure

Vibration, cyclic bending, repeated drops, ... at constant temperature often lead to IMC failure or cratering





Depend on solder properties (alloy, pad finishes, process, aging, ...)

Isothermal Failure

Drop etc

- ✓ SnAgCu is less ductile than SnPb and fracture closer to pad

  → fracture toughness (shock resistance at low T) more sensitive to IMC morphology.

- ✓ Can usually be improved by carefully designed aging (limited time at 125-150C) to soften solder and smoothen IMC surface.

Vibration

- ✓ ***Long*** term vibration leads to solder failure ***through*** the grains

‘Modeling’ Vibration

Damage scales with the inelastic work per cycle, even if amplitudes and frequencies vary

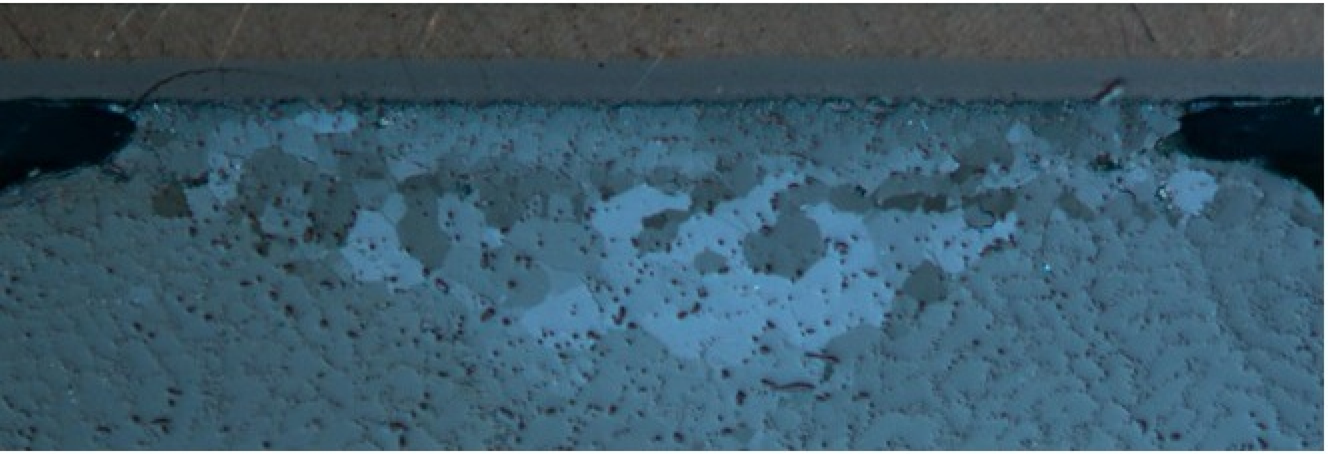
Random vibration commonly interpreted based on Miner’s rule of linear damage accumulation

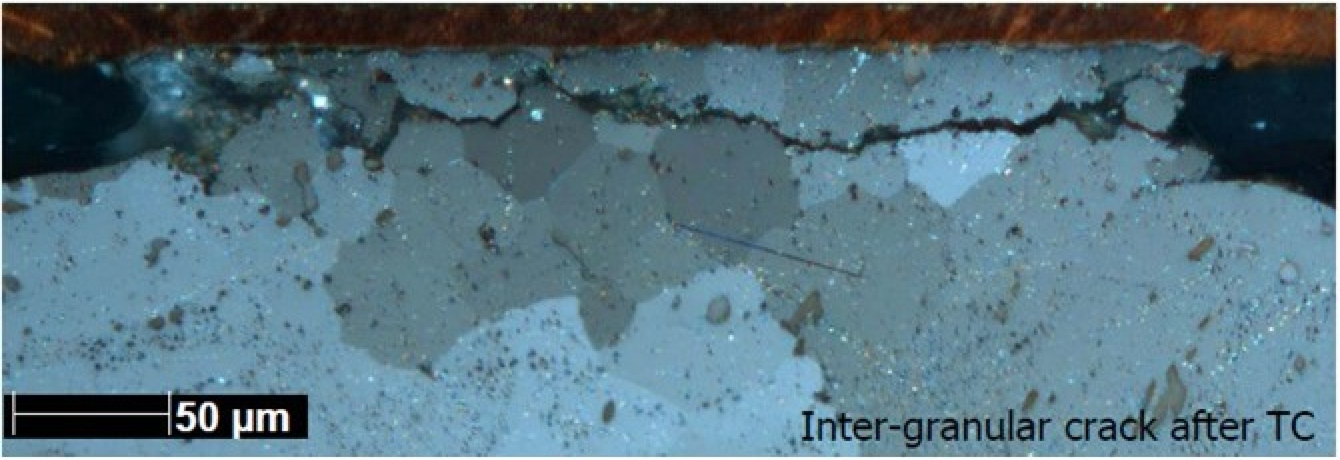
This and other current damage accumulation rules do not apply to SnAgCu.

We supply practical rule that does seem to apply for amplitude variations (work ongoing).

Damage and Failure

Thermal cycling leads first to recrystallization across high strain region, and then cracking along network of grain boundaries





Process is understood:

scaling with work during high temperature dwell

Damage and Failure

Recrystallization usually cannot start until the precipitates have coarsened

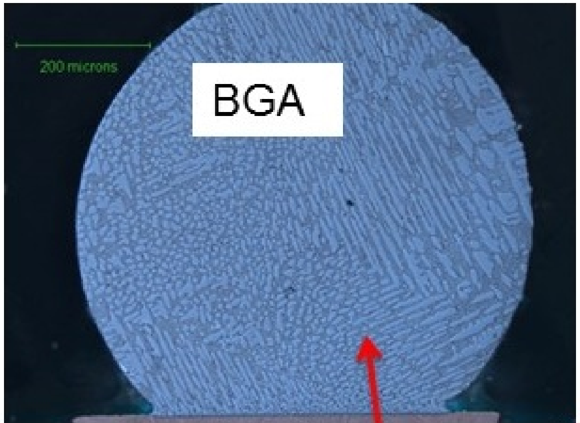
More coarsening needed if

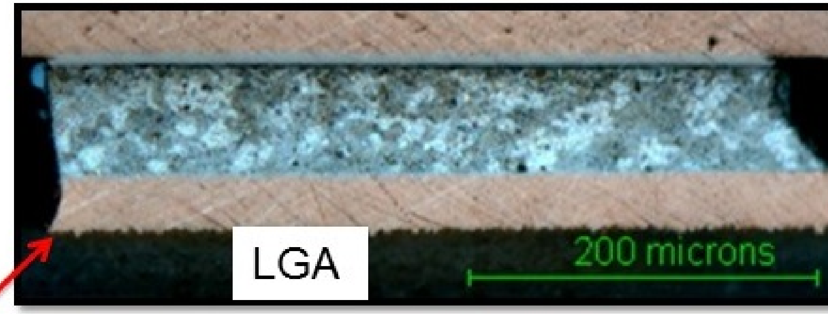
a) initial distribution is denser
b) strain range is smaller

(smaller component, or milder cycle)

Design/process recommendation (?): Smaller joints or faster cooling from reflow give denser initial distribution -> longer life

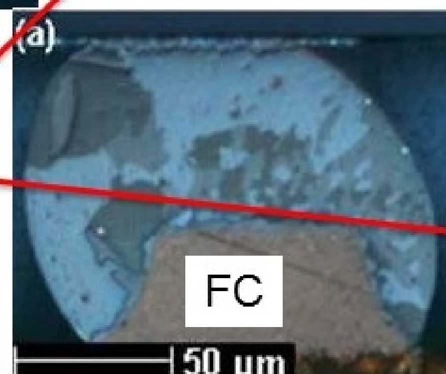
Solder Joint Configurations

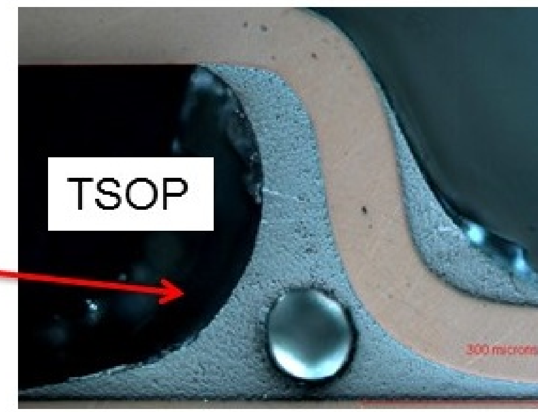




Recrystallization controls damage to

Not necessarily in





Modeling Thermal Cycling

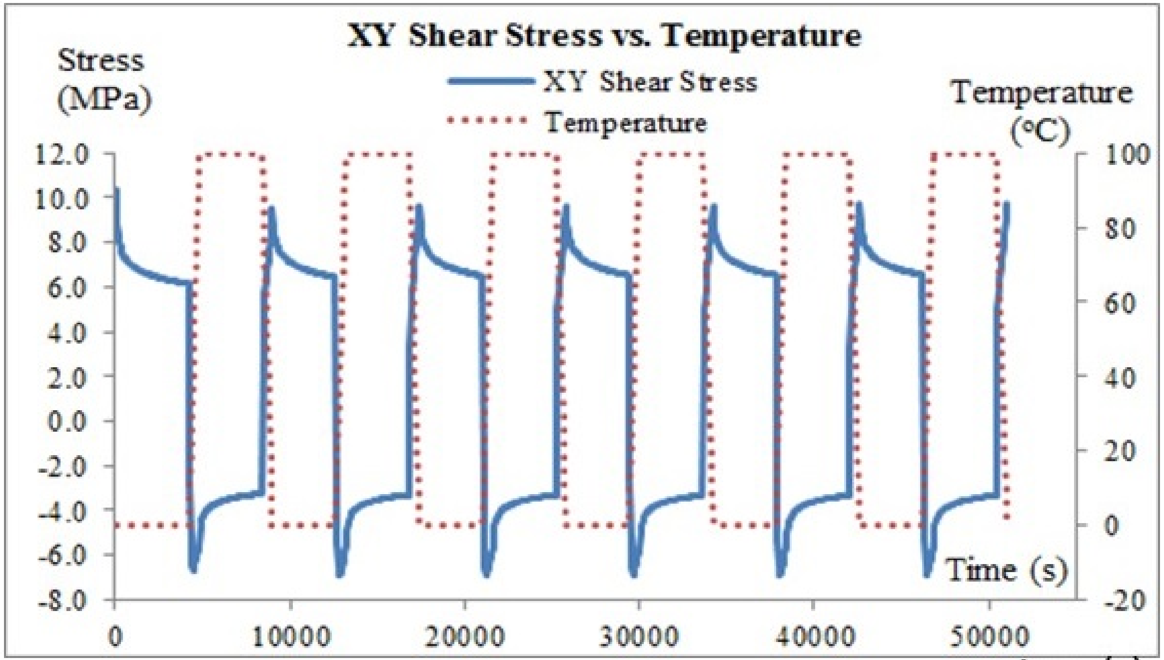
FEM (design optimization, reliability assessment):

1) calculate stresses, strains vs. time and temperature

2) assume damage function

Modeling Thermal Cycling

Calculate stresses and strains:



time (s)

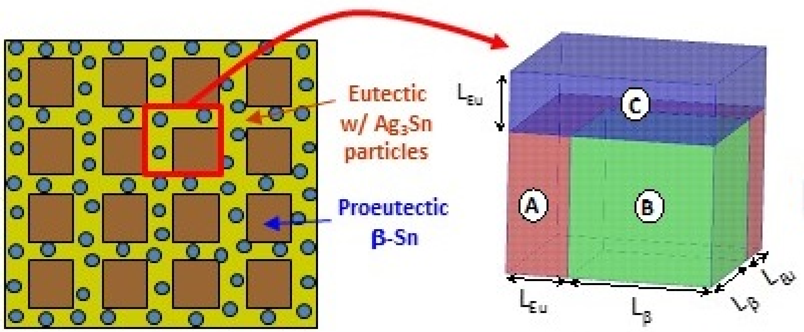
Need constitutive relations. The ones commonly used

(i) ignore ongoing coarsening of precipitates

(ii) miss effects of different creep mechanism after cycling

FEM of Thermal Cycling (or Vibration?)

Microstructurally Adaptive Creep Model



Model Schematic

Unit cell in 3D

Composite Model

Solder creep depends on eutectic and β-Sn:

$$\dot{\varepsilon}_{solder} = f(\dot{\varepsilon}_{Eu}, \dot{\varepsilon}_{Sn}, V_{Eu}, V_{Sn})$$

$$\xi_{Eu} = fn(aging) = f(d_p), \quad \xi_{Sn} \neq fn(aging)$$

Determine Sn and Eutectic creep props.

Put in Model to get creep of ANY SAC solder

Predict **Microstructure** and **Creep Response** of SAC alloys with any history

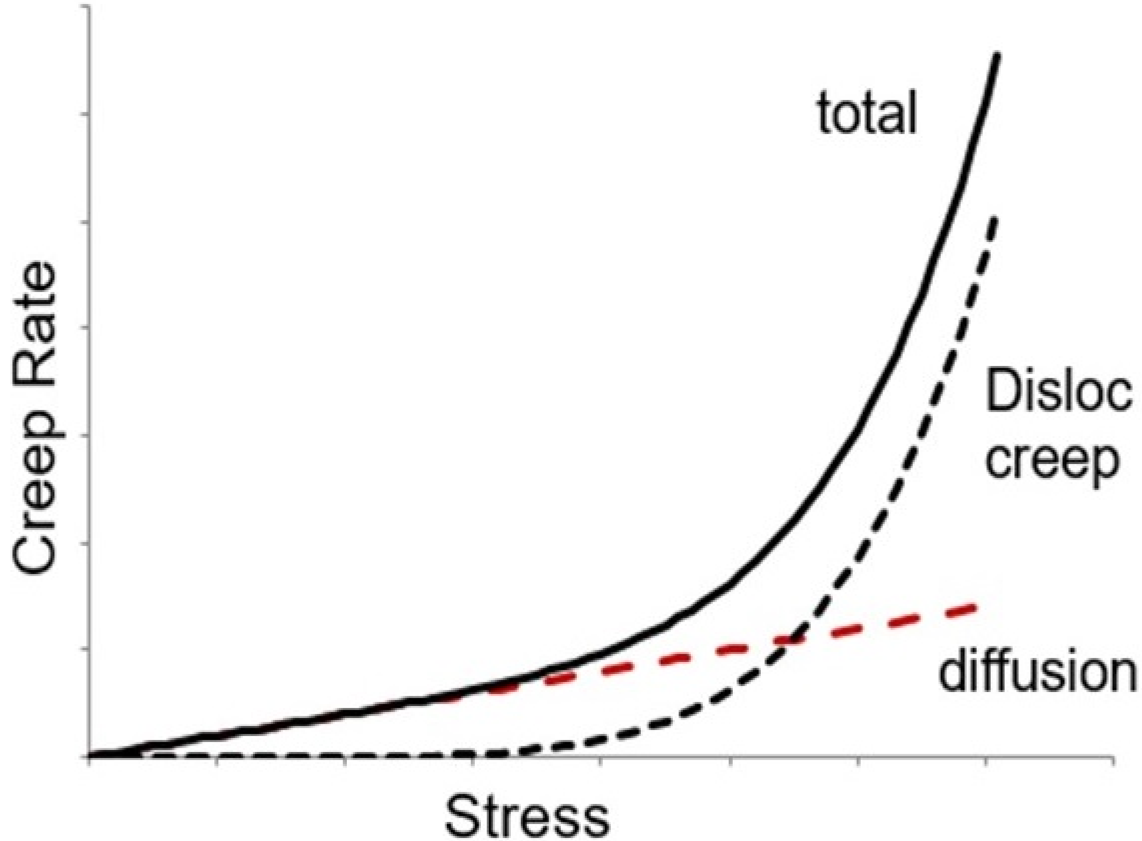
Enables iterative updating of creep model in FEM as microstructure changes

If computational complexity is an issue, use a simplified approach:
(1) predict microstructure near end of desired lifetime;
(2) then, predict creep-model for that microstructure;
(3) then, put creep-model in FEM

Creep Mechanisms

Steady state creep rate vs. stress: Sum of dislocation and diffusion creep.

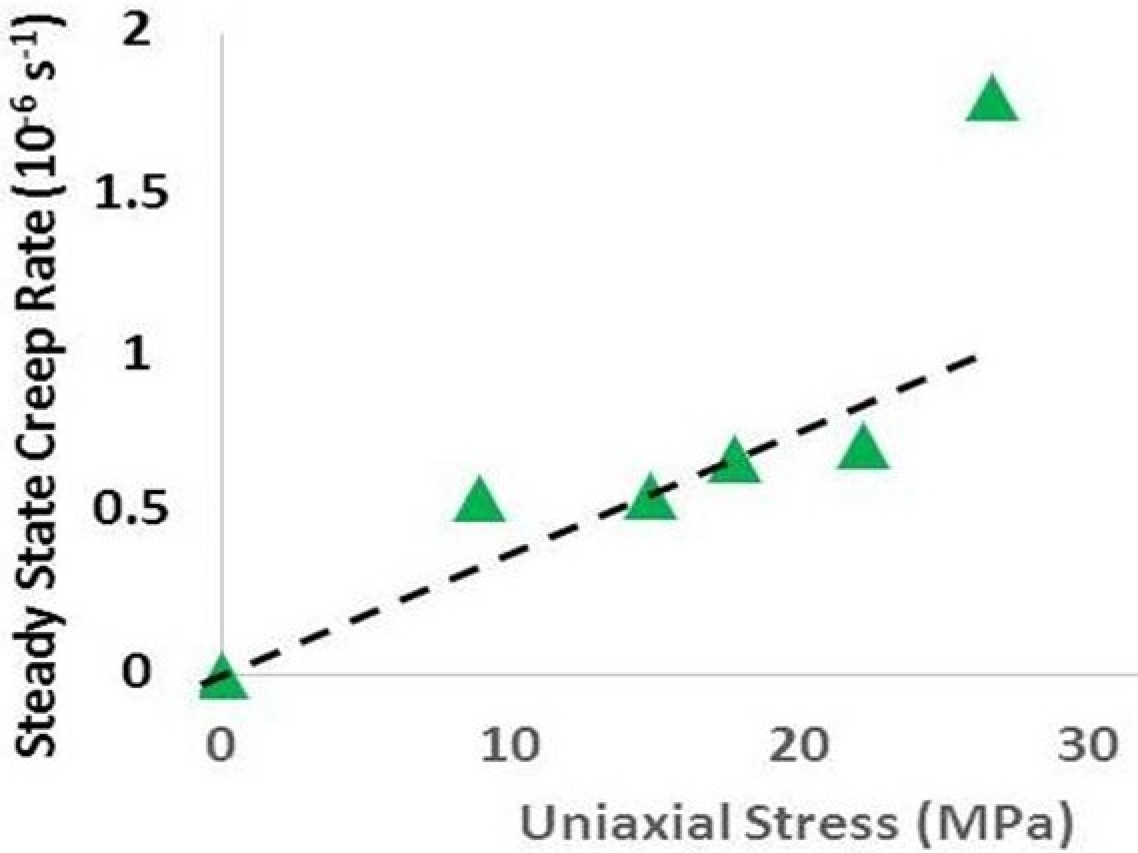
Diffusion creep commonly assumed negligible except at very low stresses



Constitutive relations therefore assume proportionality to stress to power of 6 or more

Steady State Creep

Steady state creep of SAC305 at RT after thermal cycling to a few percent of total life



Diffusion creep up to ~22MPa

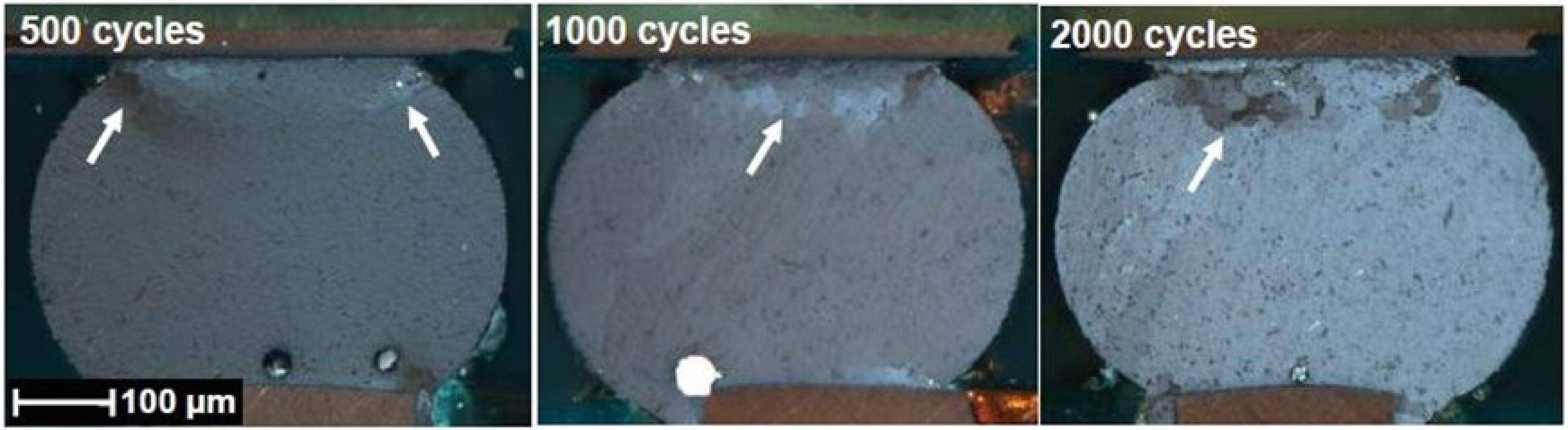
Power of 1, not 6, dominates important part of the cycle

Modeling Thermal Cycling

Damage function (BGA, CSP, TSOP):

i) rate of temperature and cycling driven precipitate coarsening (predict when recrystallization can start)

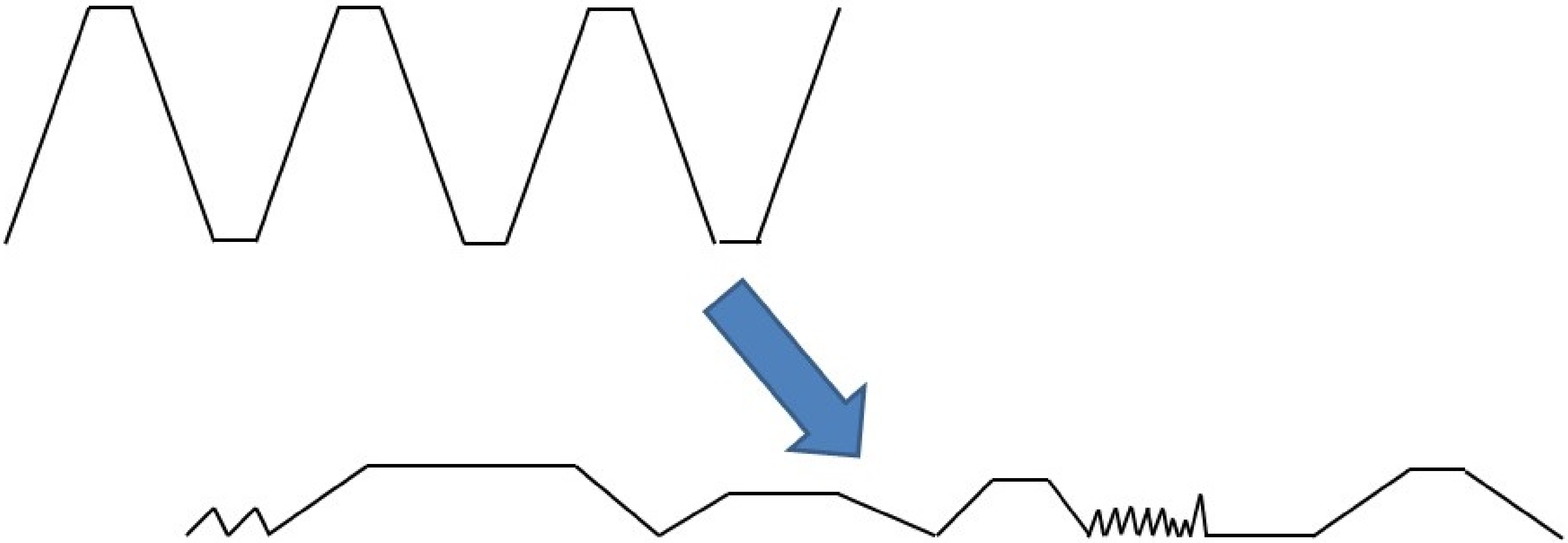
ii) rate of recrystallization scales with work at high temperature



Damage Accumulation

Realistic applications are more complex than standard tests.

Our understanding (and model) can handle that



We understand combinations of different ***types*** of loading (vibration, thermal cycling, …), but no quantitative model (yet)

Accelerated Test Recommendations

Vibration:

i) Keep amplitude low enough to suppress resonance shifts

ii) Single (narrow range) frequency testing easier to extrapolate to service than random vibration results

Accelerated Testing

Thermal cycling life is

most sensitive to high T and dwell time there

less sensitive to low T and dwell time beyond 10 minutes

insensitive to ramp rates

i) valid comparisons should include effects of precipitate coarsening ->

don't pre-age

limit strain ranges so N>2,000

ii) pre-aging and higher acceleration does give conservative life prediction

Combine Thermal Cycling & Vibration

Realistic service often combines these ***and*** amplitude variations:

- We know what to expect, but serious work needed for quantitative model
- Not easy to 'simulate' realistic combinations in accelerated test. Randomly chosen combination unlikely to even give you 'a feel for things'
- Different damage modes (transgranular cracking vs. recrystallization) -> thermal cycling before/during will strongly accelerate damage in vibration.

ESS

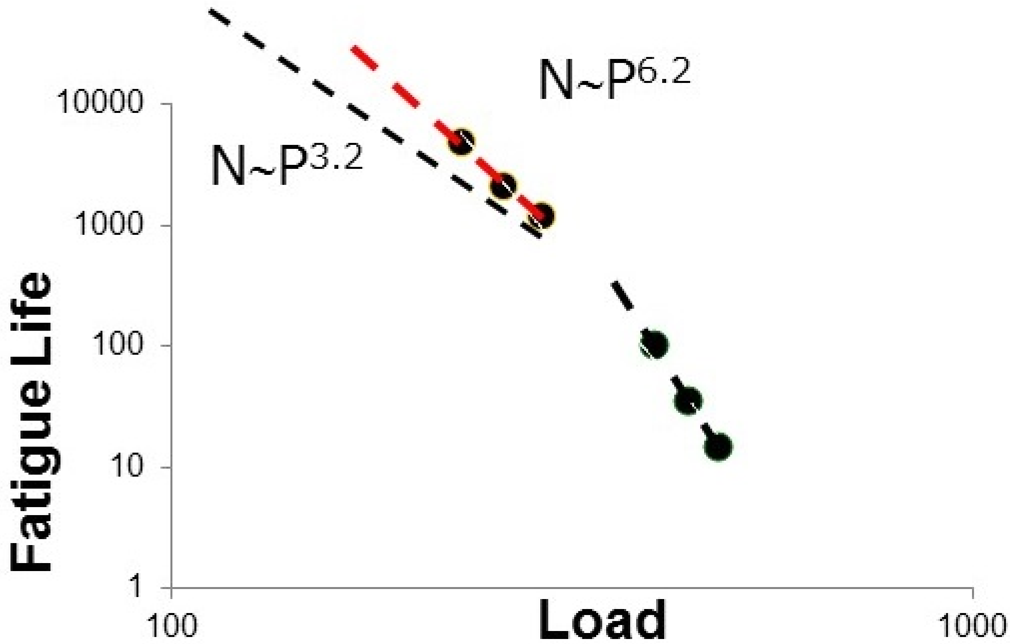
Environmental Stress Screening protocols vary.

- Aerospace industry needs some ESS – temperature and vibration – to ensure the thousands of parts and interconnects are working.
- In the tin-lead days, ESS was also designed to cull out manufacturing defects without significantly reducing life (say more than 10%).
- Hughes tailoring effort was attempt to test assemblies with known defects and see if ESS would catch them.
- Many just use the more conservative NAVMAT P-9492.

- **Problem: We can only check for 10% by accelerated testing.**

Example – pre-damage

Effect on fatigue life:



Change in 'acceleration factor': A 10% reduction in accelerated test life may mean 40x reduction in extrapolated service life (from 10 years to 3 months?)

ESS

Usually ESS consists of

- Some thermal cycles to make sure everything is working (including test equipment and software timing)
- Vibration (in a few axes),
- More thermal cycles to detect failures from vibration

- o Vibration fractures very fine because motions so small
- o Vibration often not monitored electrically (wears out test cabling and connectors, difficult to catch open circuit glitch)
- o Thermal cycling helps open cracks longer.

ESS

- In the case of lead free thermal cycling cracks may also be fine, but electrical failure can be measured during static bend after cycling.

- Worst we can do: Thermal cycling.
  - ✓ Won't reveal defects not caught by vibration
  - ✓ Recrystallization will not be complete,
    but precipitates will be coarsened →
    recrystallization in milder thermal cycling (in service) will be accelerated – and ***then*** vibration in service …

- 'Best': Vibration only.

ESS -- Recommendations

If you do want the ‘benefits’ of thermal cycling:

1) Start with 1 thermal cycle
2) Do vibration only at lowest practical amplitude (greater than service, of course)

   -- account for new acceleration factor (lower vibration amplitude will have least effect on that)

3) Finish with 1 thermal cycle

One way or the other: ESS changes the acceleration factors in subsequent thermal cycling or vibration. You can no longer use whatever is proposed by someone who did not consider ESS

Summary

- ✓ Properties are determined by microstructure
- ✓ Initial microstructure depends on design and process
- ✓ Microstructure keeps changing with storage and use conditions
- ✓ Life in vibration likely scaling with work per cycle, but Miner's rule doesn't work
- ✓ Life in thermal cycling determined by precipitate coarsening plus work during high temperature dwell (not total work in cycle)
- ✓ This leads to surprises and greatly complicates
  - test requirements/protocols and interpretation of results ('best in test' often not 'best in service')
  - modeling
- ✓ Modeling requires our new constitutive relations, damage functions, and damage accumulation rules (for SnAgCu)
- ✓ Your ESS does much more damage than you think!

❑ **Similar work needed on non-SnAgCu alloys !!**

APPENDIX

"There are three rules for writing a novel. Unfortunately, nobody knows what they are"

- W. Somerset Maugham

Practical References

file:///C:/Users/pborgese/Downloads/WP-1752-FR.pdf

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- G. Parks, B. Arfaei, M. Benedict, E. Cotts, M. Lu, and E. Perfecto, "**The Dependence of the Sn Grain Structure of Pb-free Solder Joints on Composition and Geometry**", Proc. ECTC (2012) pp. 703-709
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- Z. Huang, P. Kumar, I. Dutta, J. H. L. Pang, R. Sidhu, M. Renavikar and R. Mahajan, "**High strain rate fracture behavior of Sn-Ag-Cu solder joints on Cu substrates**", ASME- Proceedings on InterPACK (2011) 763-771. http://dx.doi.org/10.1115/IPACK2011-52220.
- Z. Huang, P. Kumar, I. Dutta, J. H. L. Pang, R. Sidhu, M. Renavikar and R. Mahajan, "**Fracture Mechanism Map for the Fracture of Microelectronic Pb-free Joints under Dynamic Loading Conditions**", IEEE – 12^{th} Proceedings of EPTC (2010) 298-303. (*Best Paper Award)*

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- L. Yang, "**Lead-Free Solder Reliability in Combined Environments**", Ph. D. Dissertation, Dept. of Systems Science & Industrial Engineering, Binghamton University, 2011
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Presentations

- A. Qasaimeh, Y. Jaradat, and L. Yang, "**Mechanical Fatigue Study of Lead Free Alloys: Correlations with Strain Energy Density**", presentation at AREA Consortium meeting March 9, 2011
- L. Wentlent, M. Meilunas, and P. Borgesen, "**On the Microstructure of Pb-free TSOP, QFN, and LGA Solder Joints – Consequences for Thermal Cycling Performance and Acceleration Factors**", presentation at AREA Consortium meeting March 9, 2011
- T. Tashtoush, L. Yin, and P. Borgesen, "**Effects of Pb-free Solder Joint Size on mechanical Properties & Aging Kinetics**", presentation at AREA Consortium meeting March 9, 2011
- Y. Jaradat, A. Qasaimeh, L. Yin, and L. Yang, "**On the Evolution of the Properties and Microstructure of Backward Compatible Solder Joints during Cycling and Aging,** presentation at AREA Consortium meeting March 9, 2011

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- P. Borgesen, "**Assessment of Life of Lead Free Solder Joints Under Realistic Service Conditions: Practical Consequences**", presentation at AREA Consortium meeting March 9, 2011
- T. Tashtoush, "**Effects of Solder Joint Dimensions on Aging Kinetics**", presentation at AREA Consortium meeting October 6, 2010
- A. Qasaimeh, "**Recrystallization Behavior of Lead Free Solder under Thermal and Isothermal Cycling**", presentation at AREA Consortium meeting October 6, 2010
- L. Yang, "**Effects of Varying Amplitudes on Solder Joint Life at RT**", presentation at AREA Consortium meeting October 6, 2010

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- Y. Jaradat and P. Kondos, "**Backward Compatible Assembly – What Really Happens?**", presentation at AREA Consortium meeting October 6, 2010
- P. Borgesen and L. Wentlent, "**Damage Mechanisms and Acceleration Factors for No-Pb TSOP, LGA, and QFN Type Assemblies in Thermal Cycling**", presentation at IEEC meeting, Binghamton University, June 3, 2011
- A. Qasaimeh and L. Wentlent, "**On the track of a damage function for cycling of SnAgCu**", presentation at AREA Consortium meeting June 15, 2011
- Y. Jaradat, A. Qasaimeh, and L. Yang, "**Lead-Free Solder Behavior in Varying Amplitude Cycling Environments**", presentation at AREA Consortium meeting June 15, 2011
- L. Wentlent, R. Drake, J. Owens, A. Qasaimeh, and Y. Jaradat, "**Energy, Lifetimes, Mixed Loading … Oh My!**", presentation at AREA Consortium meeting June 15, 2011

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- P. Borgesen, "**Reliability Model Outline – Lead Free Solder Joints in Thermal Cycling**", presentation at AREA Consortium meeting October 12, 2011
- Y. Jaradat, A. Qasaimeh, J. Chen, J. Owens, and L. Yang, "**Effects of Varying Cycling Amplitudes - can we understand and model them?**", presentation at AREA Consortium meeting October 12, 2011
- A. Qasaimeh, "**Damage Evolution in Thermal and Isothermal Cycling**", presentation at AREA Consortium meeting October 12, 2011
- A. Qasaimeh, Y. Jaradat, L. Yang, and P. Borgesen, "**Damage Evolution in Thermal and Isothermal Cycling**", presentation at AREA Consortium meeting March 7, 2012
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- P. Borgesen, "**Predicting Life in Thermal Cycling**", presentation at AREA Consortium meeting March 7, 2012
- P. Borgesen, "**Predictions of Life in Long Term Service -- Update**", presentation at AREA Consortium meeting June 7, 2012
- M. Obaidat, S. Hamasha, and P. Borgesen, "**Fatigue Life Under Realistic Service Conditions – What predictions and testing are really about**", presentation at AREA Consortium meeting October 3, 2012
- P. Borgesen and J. Jiang, "**A Mechanistically Justified Model – Lead Free Solder Joints in Thermal Cycling**", presentation at AREA Consortium meeting February 14, 2013
- S. Hamasha, M. Obaidat, and P. Borgesen, "**Comparing Lead Free Solder Alloys in Terms of Reliability**", presentation at AREA Consortium meeting February 14, 2013

Presentations

- P. Borgesen, "**Lead Free Solder Joint Fatigue Failure in Thermal and Isothermal Cycling**", presentation at PERM meeting, 2012
- P. Borgesen, "**Model for Lead Free Solder in Thermal Cycling**", presentation at PERM meeting June, 2013
- S. Shirazi, "**Thermal Cycling: The Mechanisms Behind Surprising Trends**", presentation at AREA Consortium meeting June, 2013
- S. Hamasha and M. Obaidat, "**Isothermal Cycling of Lead-Free Solder Joints under Variable Loading Conditions**, presentation at AREA Consortium meeting June, 2013
- S. Hamasha, "**Isothermal Cycling of Solder Joints Under Varying Amplitudes**", presentation at AREA Consortium meeting September, 2013
- P. Borgesen, "**Lead Free Models – Updates and Plans**", presentation at AREA Consortium meeting September, 2013

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- G. Parks, M. Lu, E. Perfecto, and E. Cotts, "**Relation between the Sn Grain Structure of Pb-free Solder Joints, Composition and Geometry**", presented at MST2012.
- F. Mutuku, Y. Xing and E. Cotts, "**The Effect of Reflow Parameters and Composition on the Microstructure of near eutectic SnAgCu solder joints**", presented at MST2012.
- F. Mutuku and E. Cotts, "**Effect of Reflow Parameters on the Precipitate Microstructure of SnAgCu**", presentation at MST2012, Pittsburgh, PA
- B. Arfaei, E. Cotts, and P. Borgesen, "**Microstructure of SnAgCu Solder Joints**", presentation at AREA Consortium meeting June 15, 2011
- B. Arfaei, L. Yin, E. Cotts, and P. Borgesen, "**The Effect of Microstructure on the Reliability of Lead Free Solder Joints**", presented at the TMS Annual Meeting (Orlando, March 2012)
- B. Arfaei, S. Joshi, P. Borgesen, "**Failure Mechanism of Lead Free Solders in Thermal Cycling Test**", presented at MS&T 2012 (Pittsburg, October 2012)

Presentations

- G. Parks and E. Cotts, "**The solidification temperature of near eutectic SnAg and SnAgCu alloys as a function of impurity content**", MST2011, Columbus, OH 2011
- M. Gao and E. Cotts, "**Interfacial Reactions at Pogo Probe Pins/Sn-Ag-Cu Solder Interfaces**", Poster Presentation at the TMS Annual Meeting, San Diego, 2011.
- B. Arfaei and E. Cotts, "**Effect of Solidification Temperature on the Microstructure of SnAgCu Solder Joints**", presentation at TMS Annual Meeting, San Diego, CA, 2010.
- B. Arfaei, Y. Xing, and E. Cotts, "**Nucleation and Solidification of Sn in Pb Free SnAgCu Solder Joints**", TMS Annual Meeting, Seattle, WA, 2010.

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- B. Arfaei, L. Yin, E. Cotts, and P. Borgesen, "**The Effect of Microstructure on the Reliability of Lead Free Solder Joints**", Presentation at the TMS Annual Meeting, 2012
- E. Cotts, "**Effect of Solidification Temperature on the Microstructure of SnAgCu Solder Joints**", presentation at IBM Fishkill, July 2012
- E. Cotts, "**Effect of Solidification Temperature on the Microstructure of SnAgCu Solder Joints**", presentation at Washington State Materials Science Department, Pullman, WA, July 2012
- G. Parks and E. Cotts, "**Effect of Composition and Solidification Temperature on the Microstructure of SnAg**", presentation at MST2012, Pittsburgh, PA