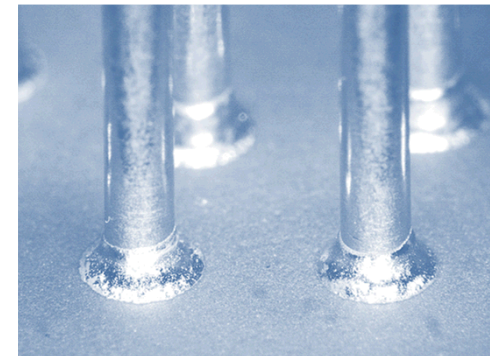


Understanding the Reliability of Solder Joints Used in Advanced Structural and Electronics Applications

Paul T. Vianco, Ph.D.

Sandia National Laboratories*
Albuquerque, NM 87185

Contact: ptvianc@sandia.gov

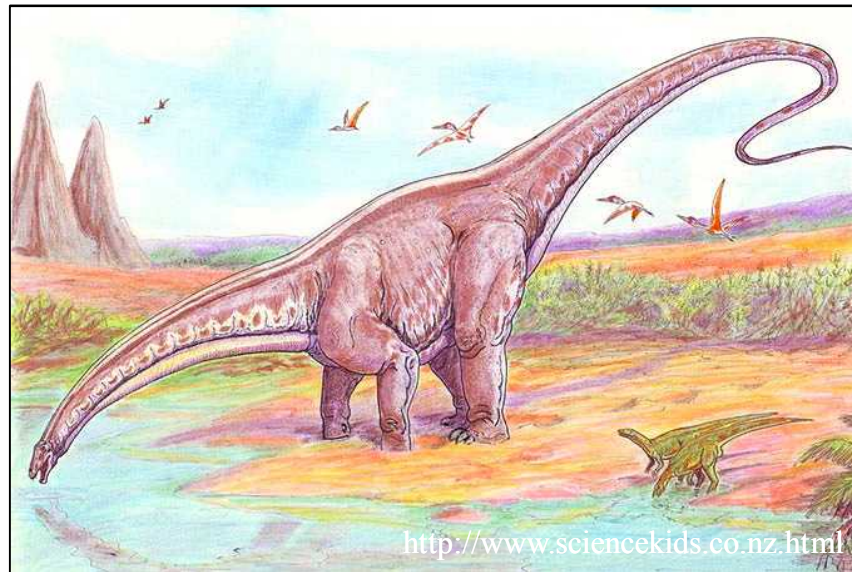


*Sandia National Laboratories is a multi-program laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



Thank You !

- ◆ I would like to extend my sincere gratitude to the American Welding Society for the honor of presenting the **2016 Comfort A. Adams Lecture** to you, today.
- ◆ Looking back in history ...



This is the first time that the Comfort A. Adams lecture has addressed soldering technology.

Outline

◆ Introduction

◆ Materials

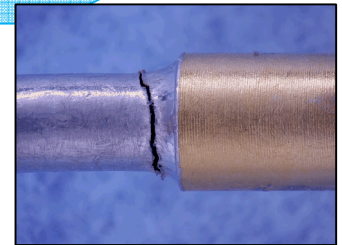
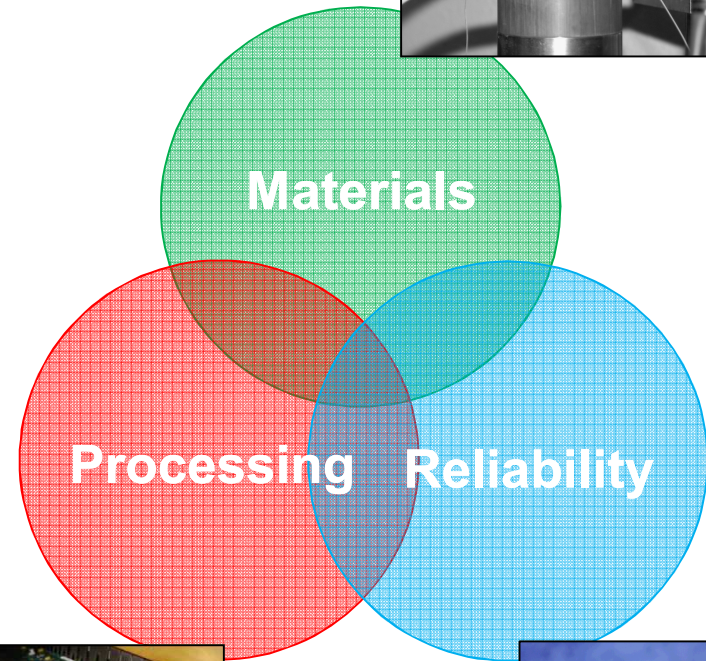
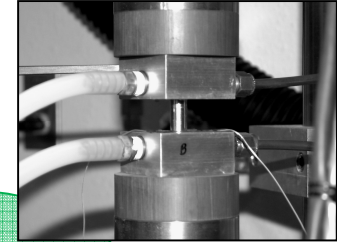
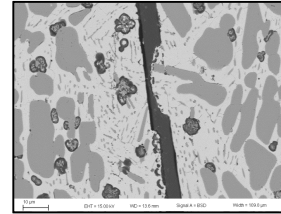
- Solderability
- Mechanical performance

◆ Processing

◆ Reliability

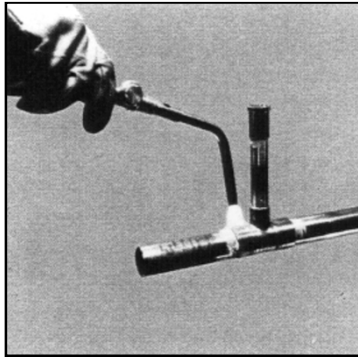
- Interface reactions
- Solder joint fatigue
 - Empirical studies
 - Computational modeling

◆ Summary



Introduction

- ◆ **Soldering technology** has two *general* categories: structural applications and electronic applications.



Structural applications

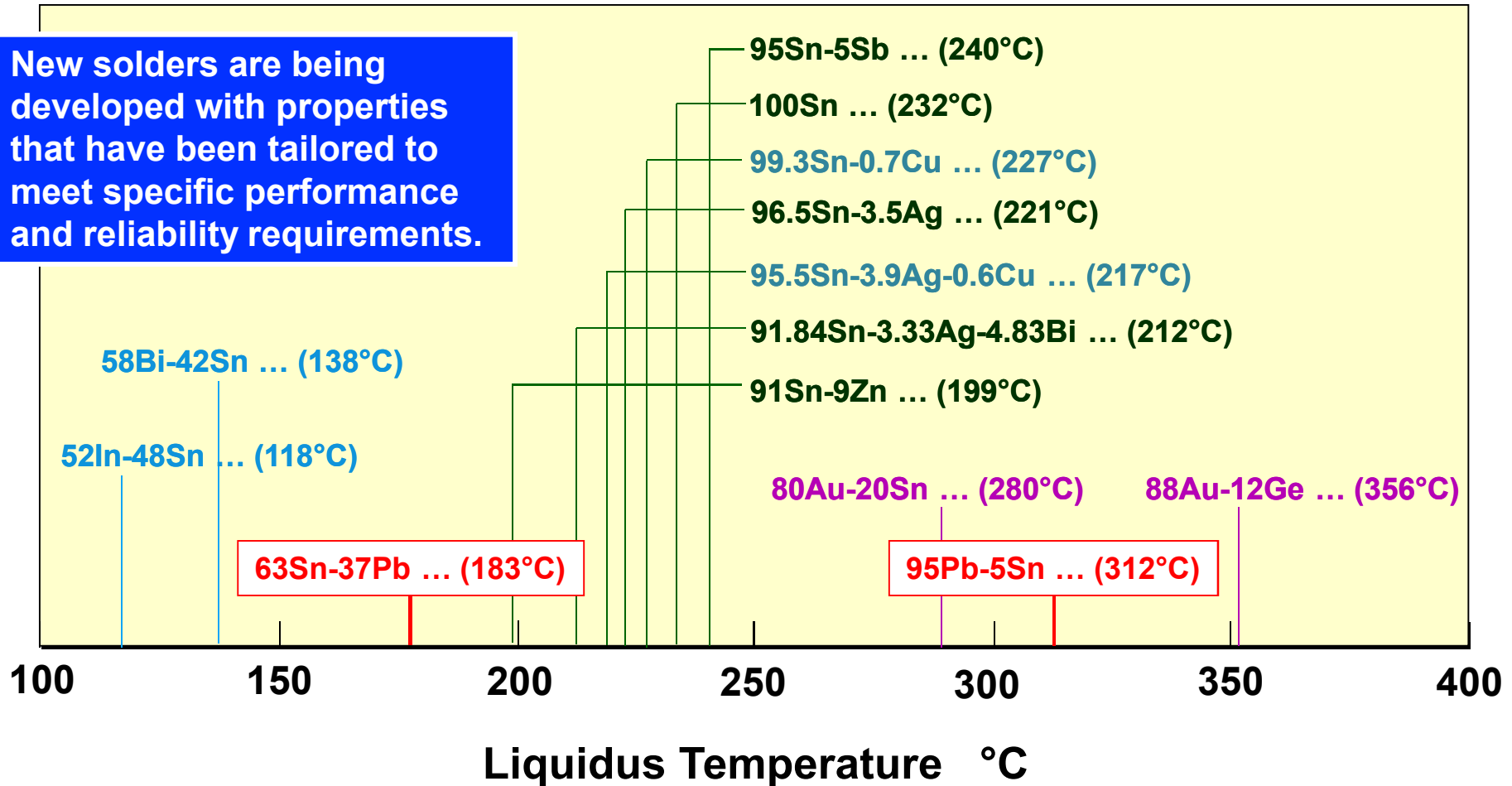


Electronic applications

Materials - Solderability

- ◆ A **solder filler metal** is defined as a metal alloy having a liquidus temperature that is *less than 450°C (842°F)*.

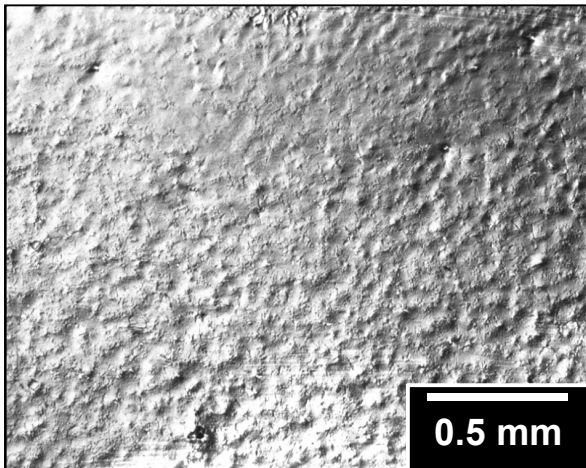
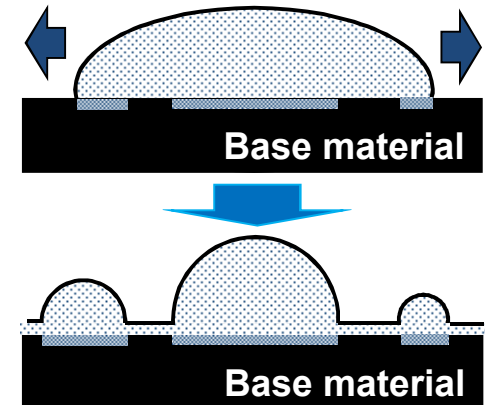
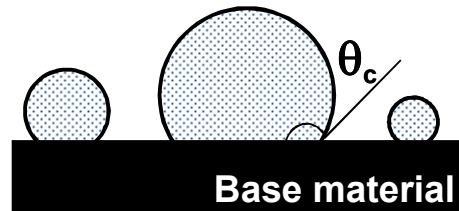
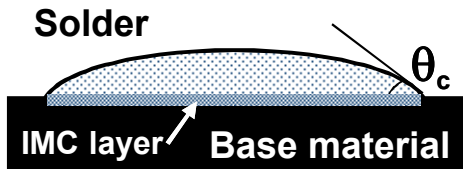
New solders are being developed with properties that have been tailored to meet specific performance and reliability requirements.



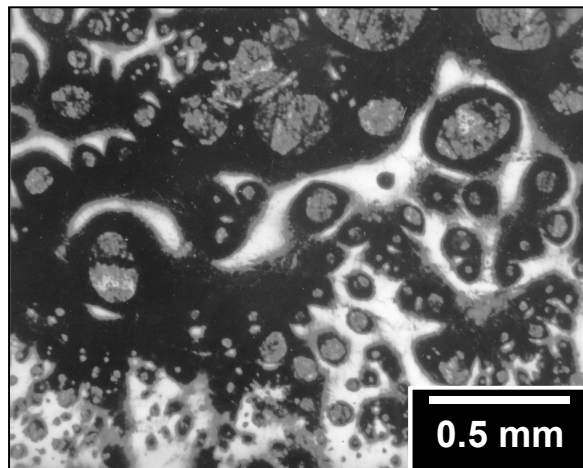
Materials - Solderability

◆ **Solderability** refers to the capability of the molten filler metal to wet-and-spread on the base material surface.

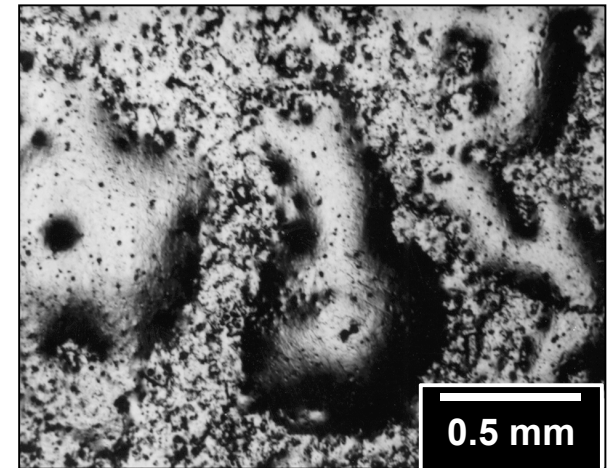
- **Wetting:** *form a metallurgical bond*
- There are three solderability conditions:



Wetting



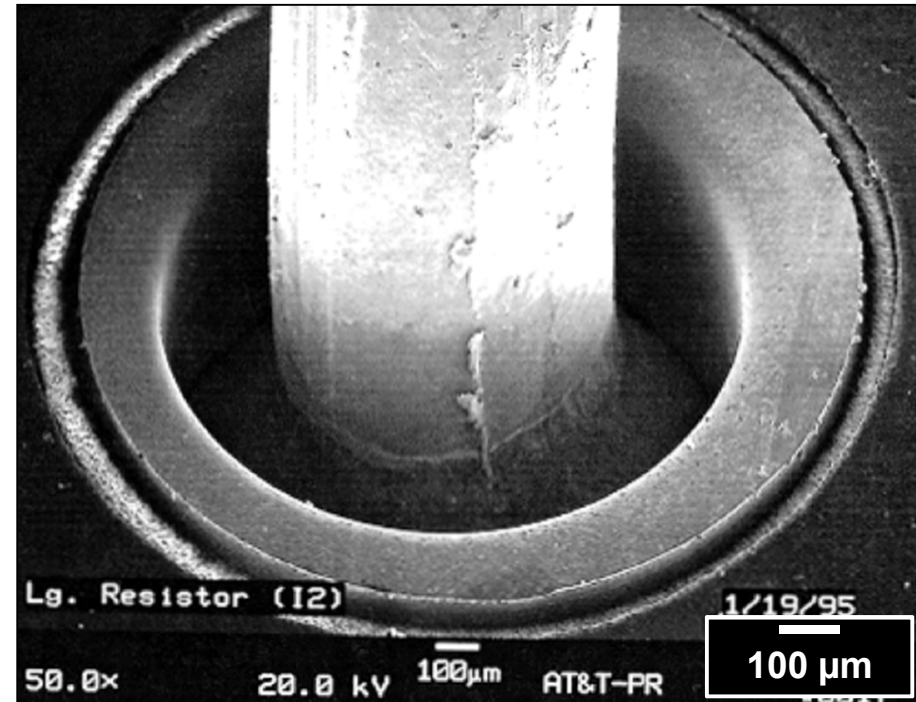
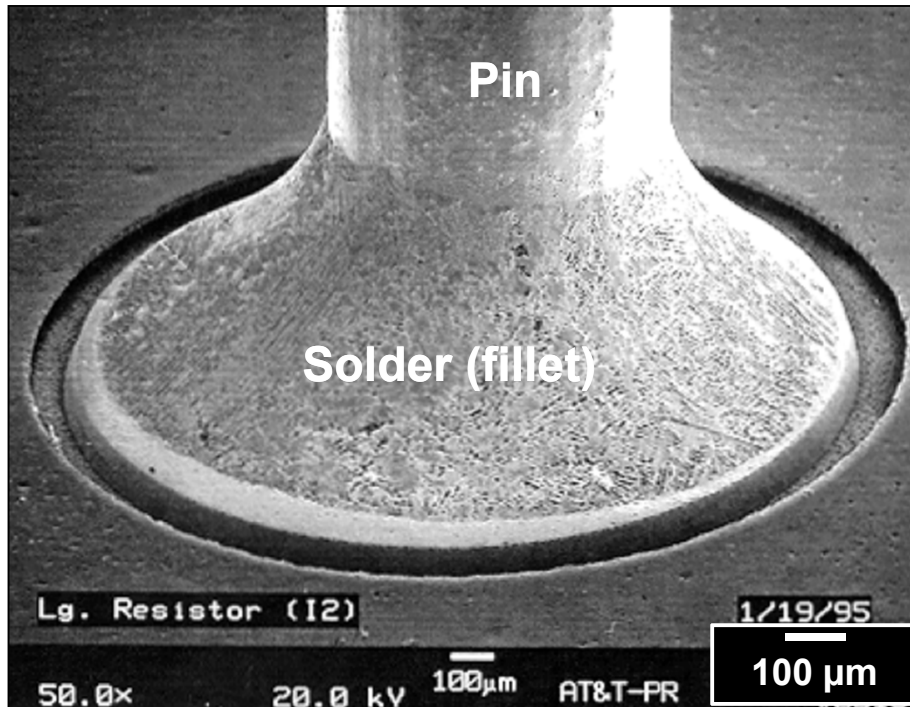
Non-wetting



Dewetting

Materials - Solderability

- ◆ **Solderability** controls the final joint geometry (fillet size, voids, etc.), which in turn, affects **long-term reliability**.



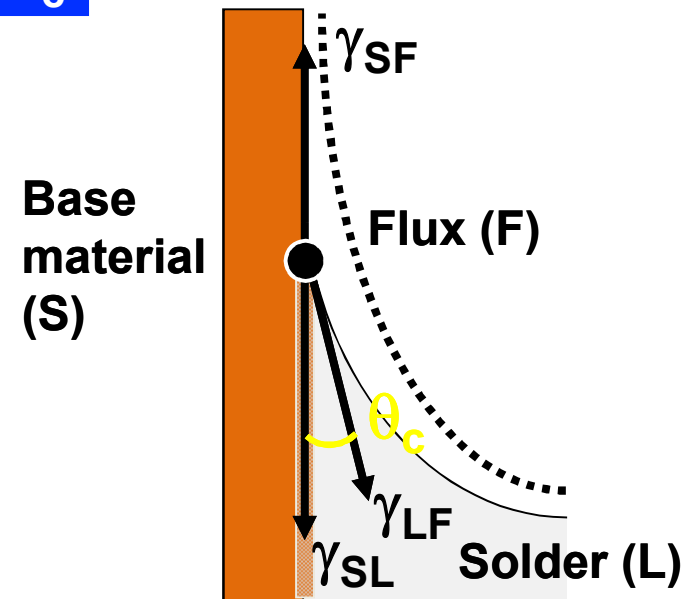
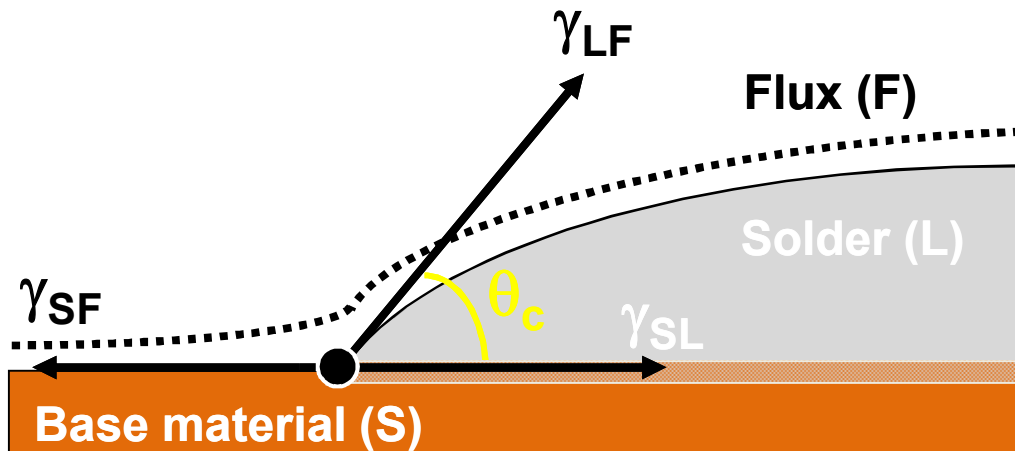
58Bi-42 Sn solder

- In this instance, the flux was not properly engineered for such a **low** soldering process temperature – 160°C.

Materials - Solderability

- ◆ **Solderability** is measured by the contact angle, θ_c , which at equilibrium, is calculated from Young's equation:

$$\gamma_{SF} - \gamma_{SL} = \gamma_{LF} \cos \theta_c$$

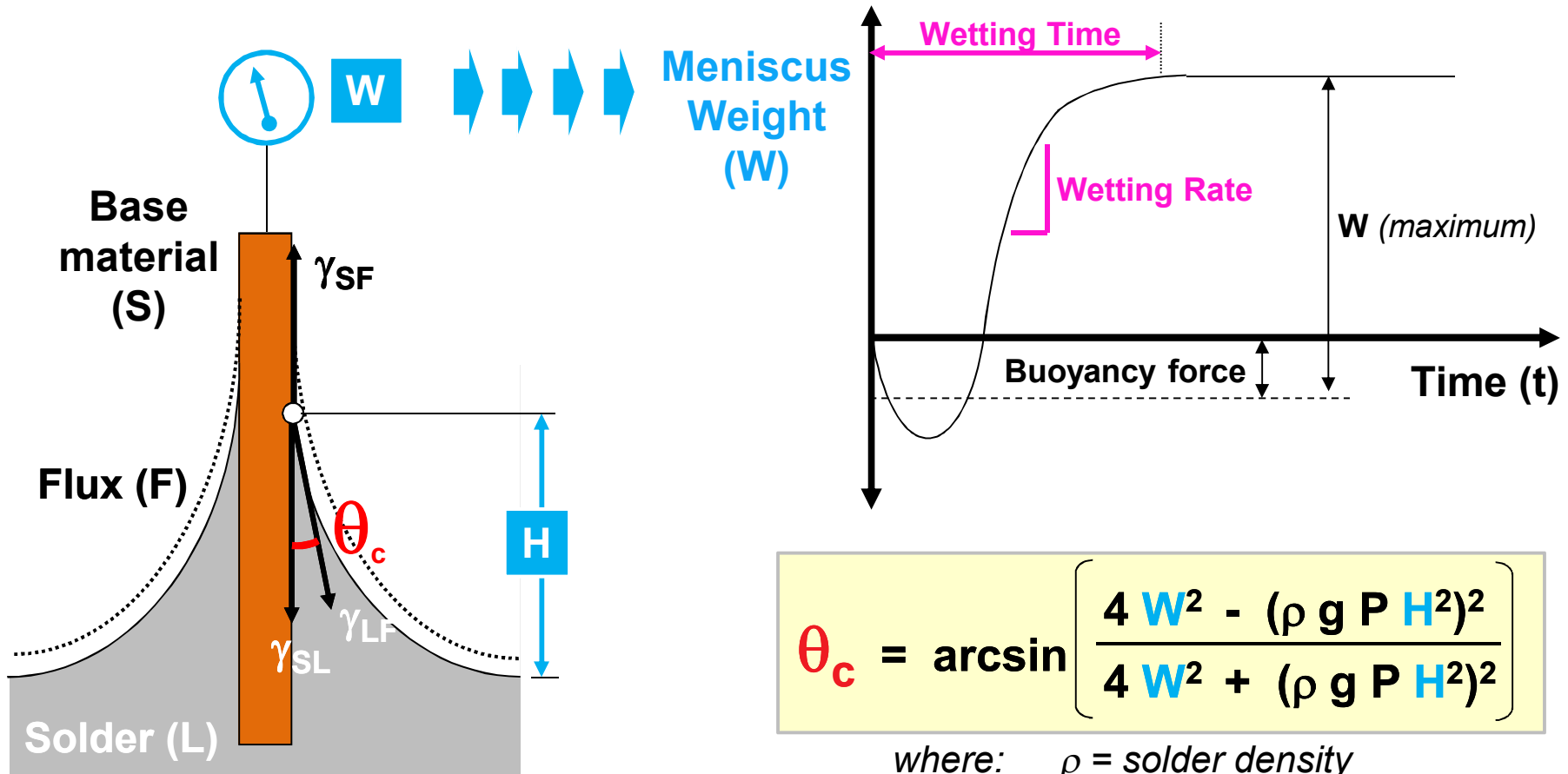


- ◆ Solderability is optimized by *minimizing* θ_c :

- Minimize γ_{LF}
- Maximize $\gamma_{SF} - \gamma_{SL}$

Materials - Solderability

- ◆ **Meniscus height-wetting balance test** assesses θ_c for the base material / flux / solder alloy system.



$$\theta_c = \arcsin \left[\frac{4 W^2 - (\rho g P H^2)^2}{4 W^2 + (\rho g P H^2)^2} \right]$$

where: ρ = solder density
 g = accn. due to gravity
 P = sample perimeter

Materials - Solderability

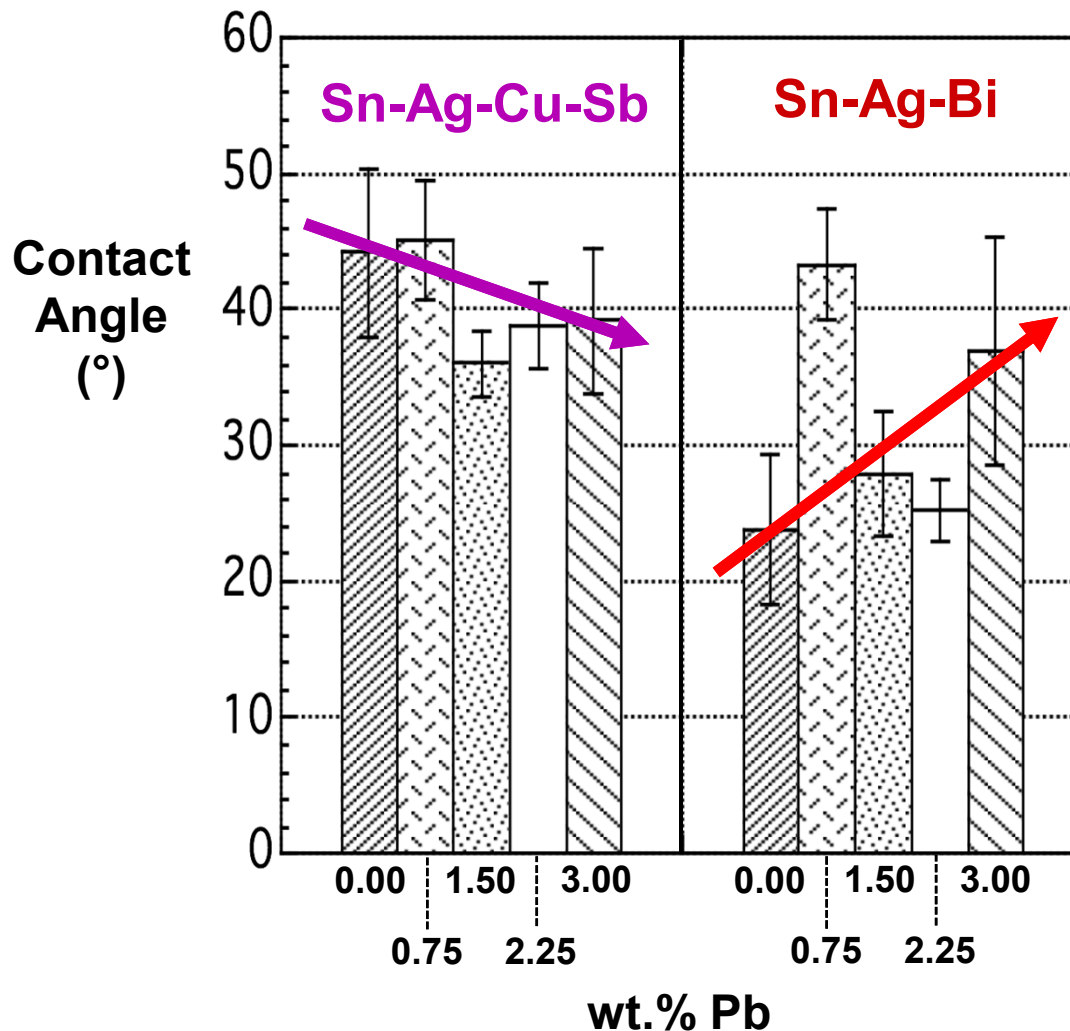
- ◆ Typical θ_c and γ_{LF} values are listed below:

Solder (wt.%)	Temp. (°C)	γ_{LF} (dyne/cm)	θ_c (°)
95.5Sn-3.9Ag-0.6Cu	260	497±16	40±1.0
	245	444±17	39±1.0
	230	485±27	42±1.4
96.5Sn-3.5Ag	260	460±30	36±3
60Sn-40Pb	260	380±10	17±4
58Bi-42Sn	215	310±50	37±7
Substrate: OFHC Cu; Flux: RMA ,1:1 IPOH			

- ◆ Bi and Pb additions lower θ_c by reducing γ_{LF} .
- ◆ Temperature has a limited effect on either θ_c or γ_{LF} .

Materials - Solderability

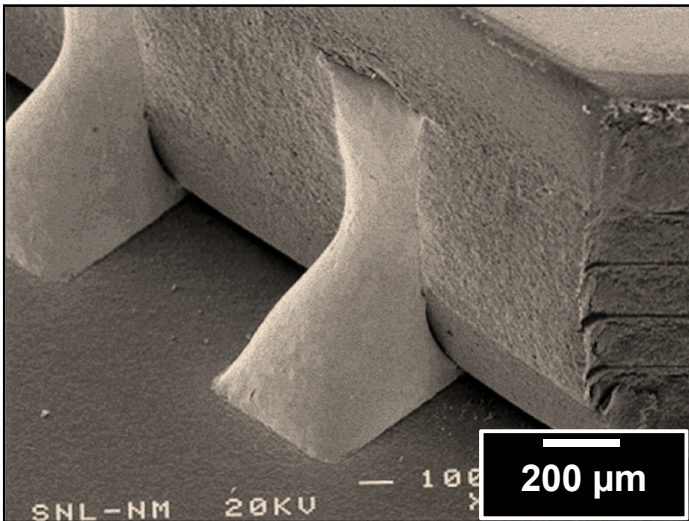
- ◆ Rules-of-thumb are not always hard-and-fast ...



Pb additions do not always reduce the contact angle

Materials – Mechanical Performance

- ◆ At room temperature, **solder alloys** are performing at temperatures that are equivalent to conditions in the **combustion chamber of an operating jet engine !!!**

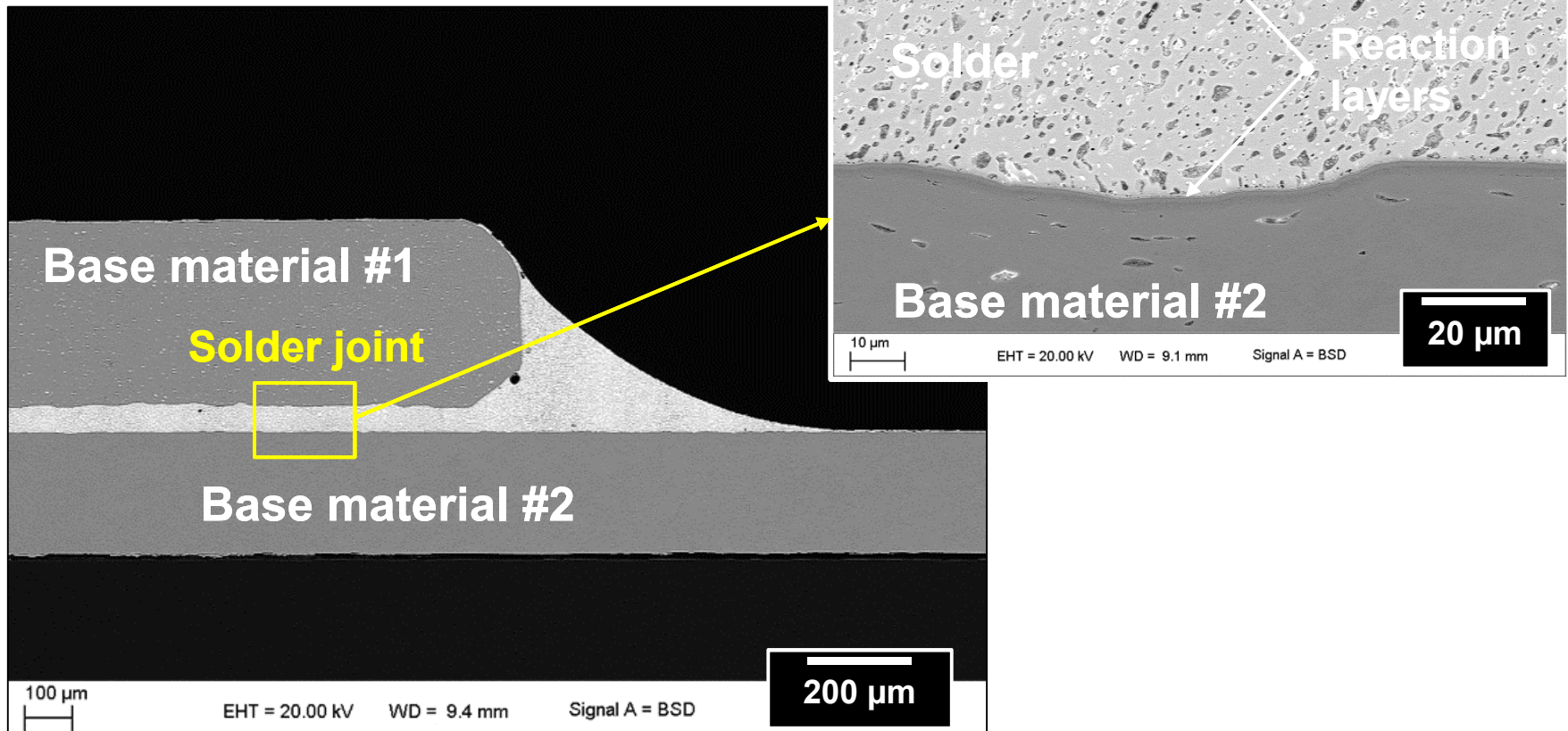


It's **HOT** ... *even when it's not ...*

Materials – Mechanical Performance

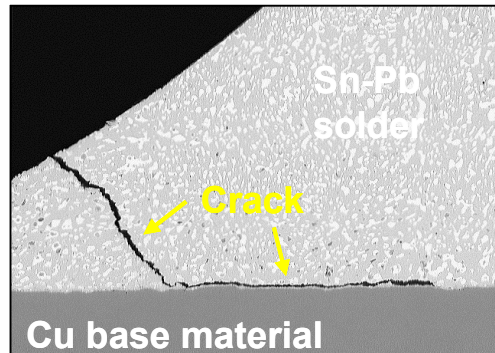
◆ The solder joint is a “system.”

- Base materials
- Solder (filler metal)
- Interfaces (reaction layers)

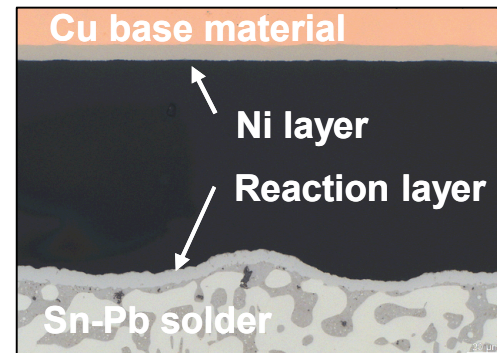


Materials – Mechanical Performance

- ◆ The base materials are stronger than the filler metals.
 - Solder joint failures occur in the filler metal or at an interface.

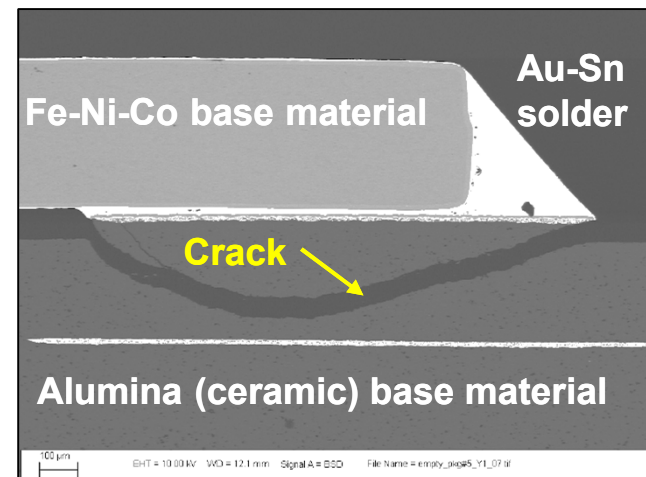


Solder (bulk) failure



Interface failure

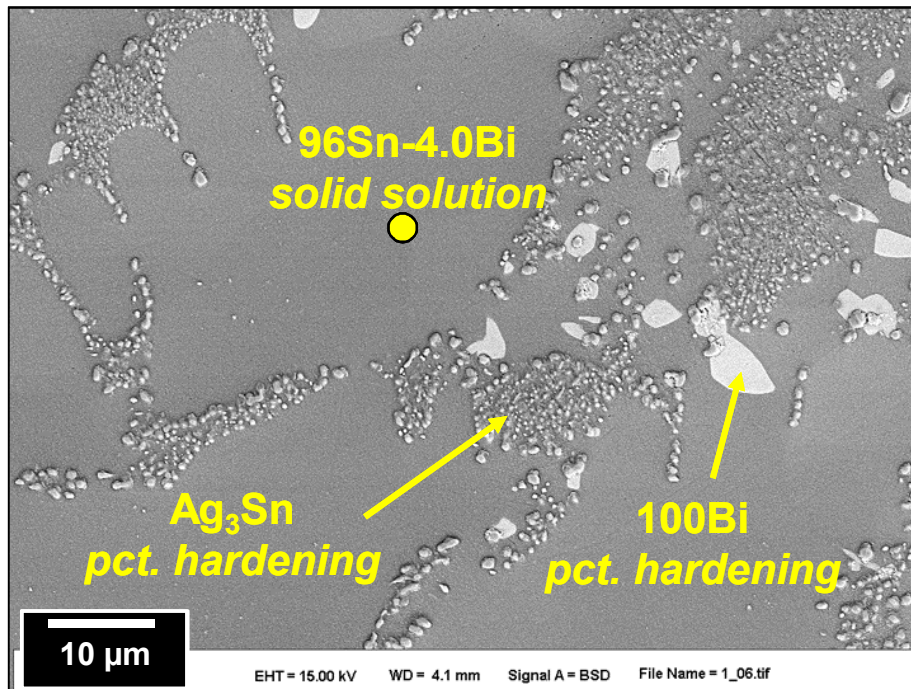
- ◆ The exception occurs under the combination of large loads, a **high-strength solder**, and a **ceramic base material**.



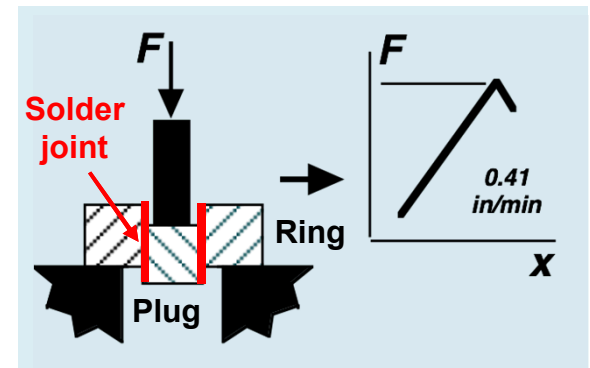
Materials – Mechanical Performance

- ◆ Solders are engineered using the same strengthening mechanisms that are found in high-performance alloys:
 - Precipitation hardening
 - Solution strengthening

91.84Sn – 3.33Ag – 4.83Bi



Ring-and-Plug Shear Test

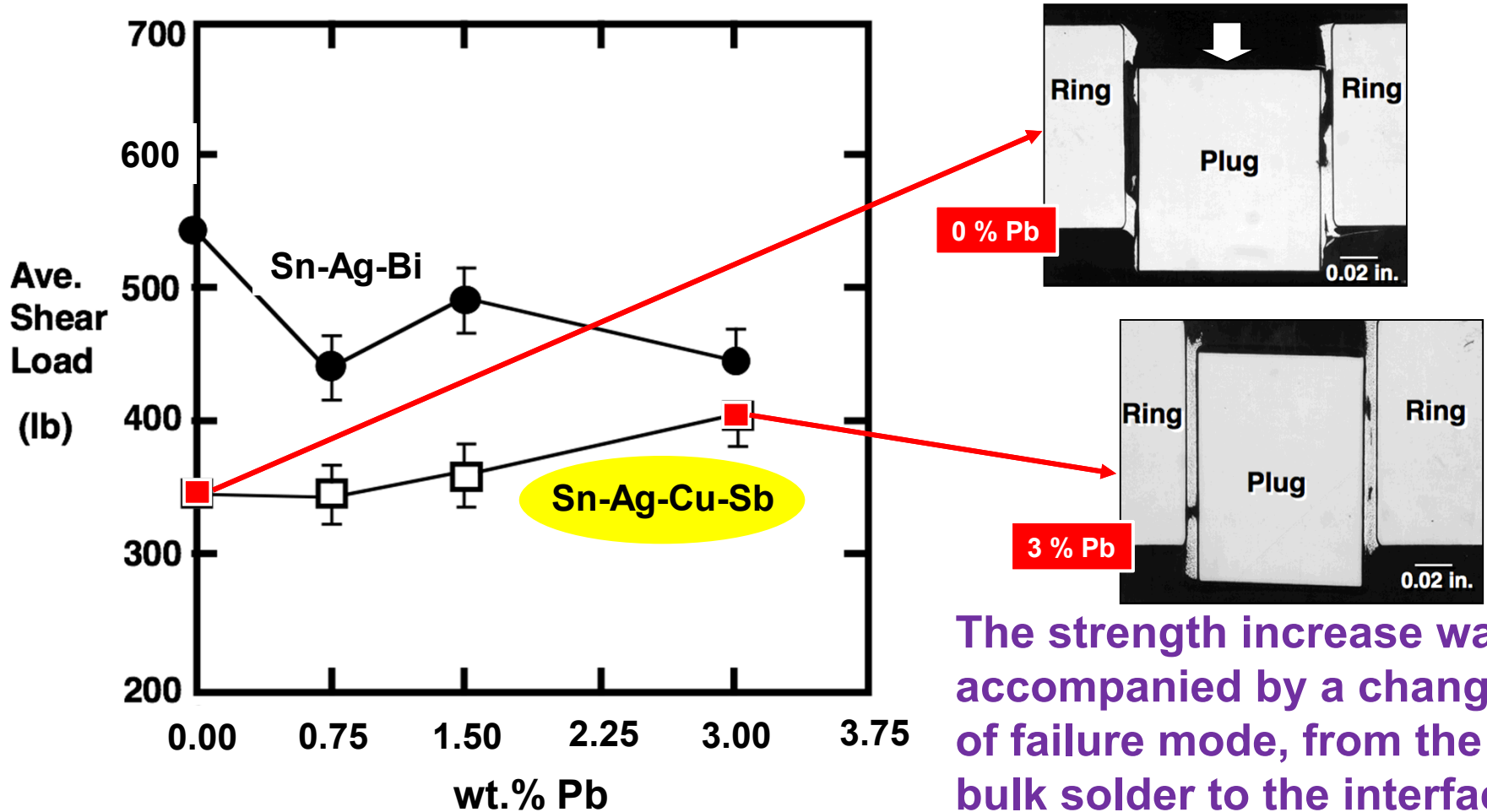


<u>Solder</u>	<u>Stress (psi)</u>
Sn-Pb	5840
Sn-Ag	7970
Sn-Ag-Bi	11800



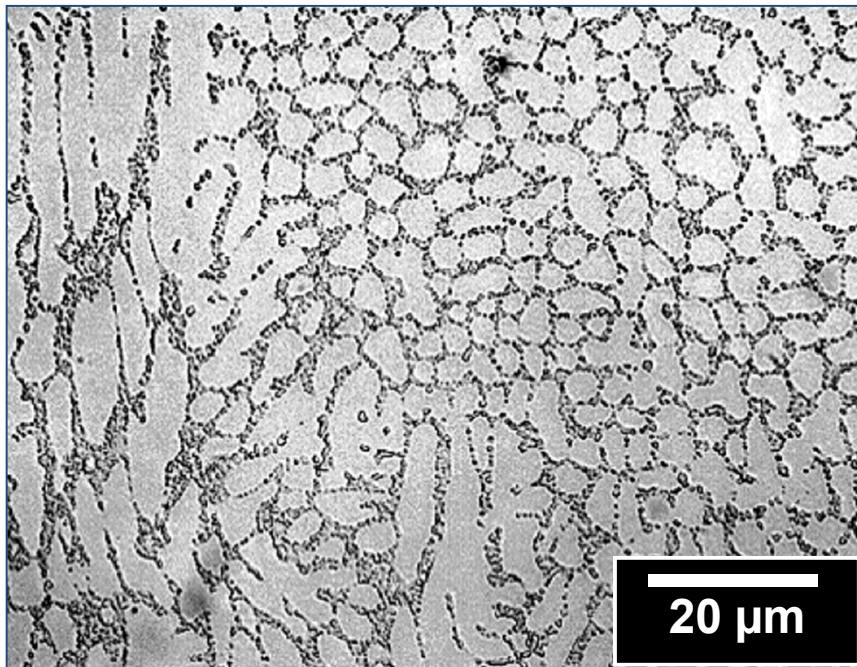
Materials – Mechanical Performance

- ◆ Alloy additions can have unexpected effects.
 - Additions of 0 – 3.75 wt.% Pb were made to two alloys.

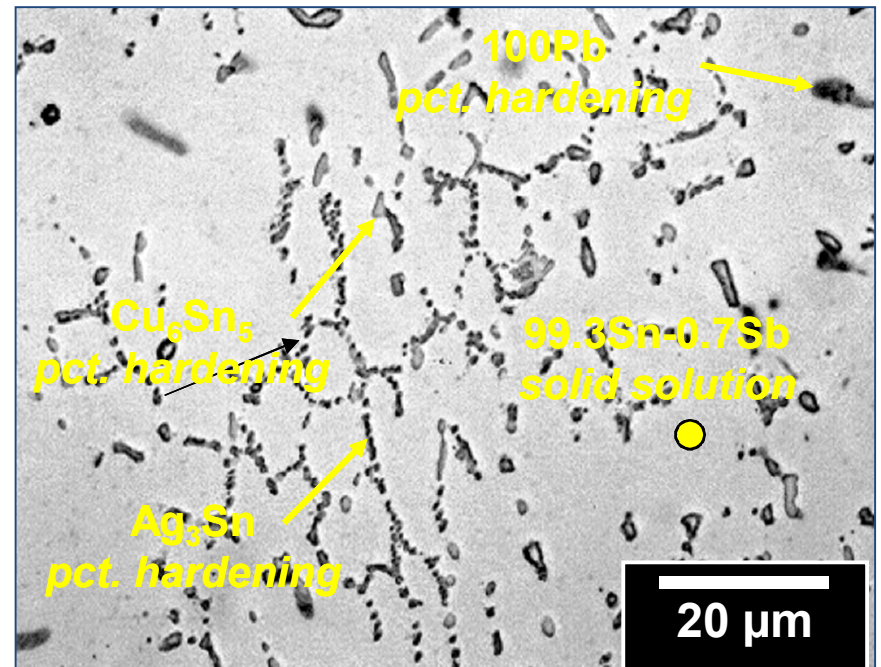


Materials – Mechanical Performance

- ◆ **Sn-Ag-Cu-Sb:** The addition of Pb broke up the Ag_3Sn particle network, *thereby enhancing the precipitation hardening effect.*



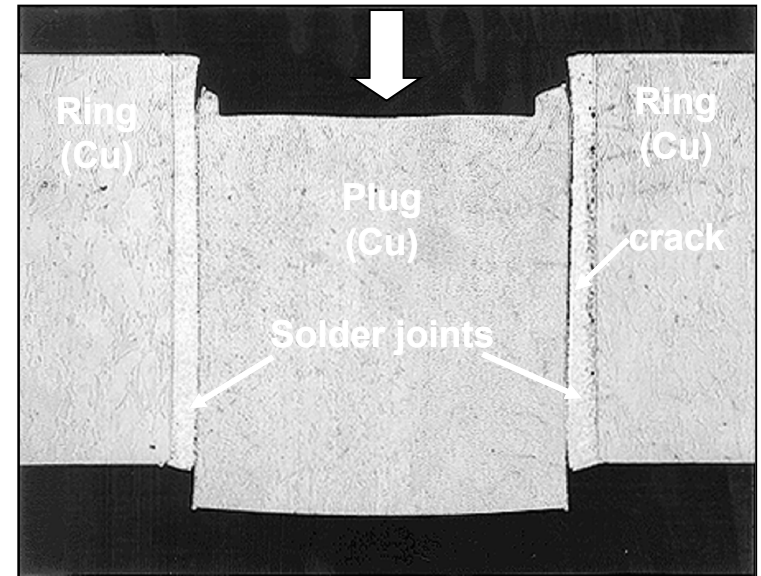
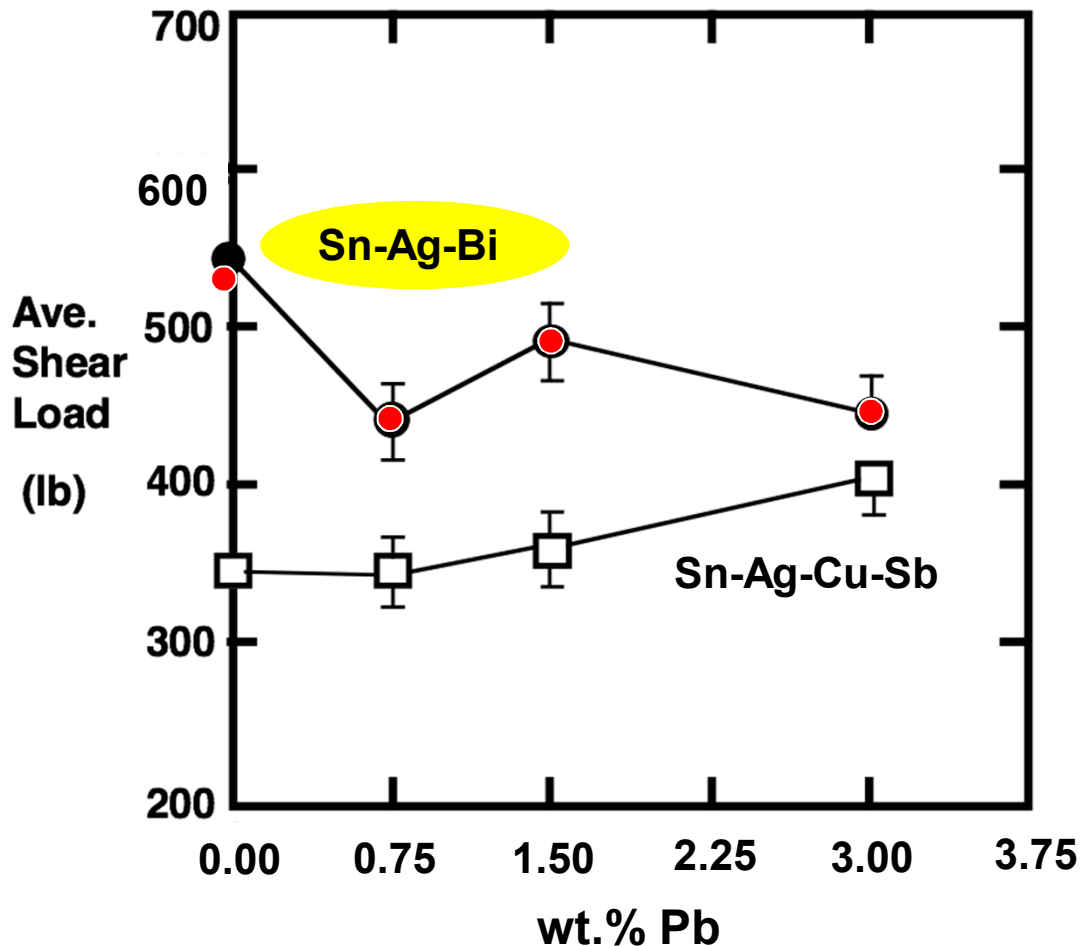
0.00 % Pb



3.00 % Pb

Materials – Mechanical Performance

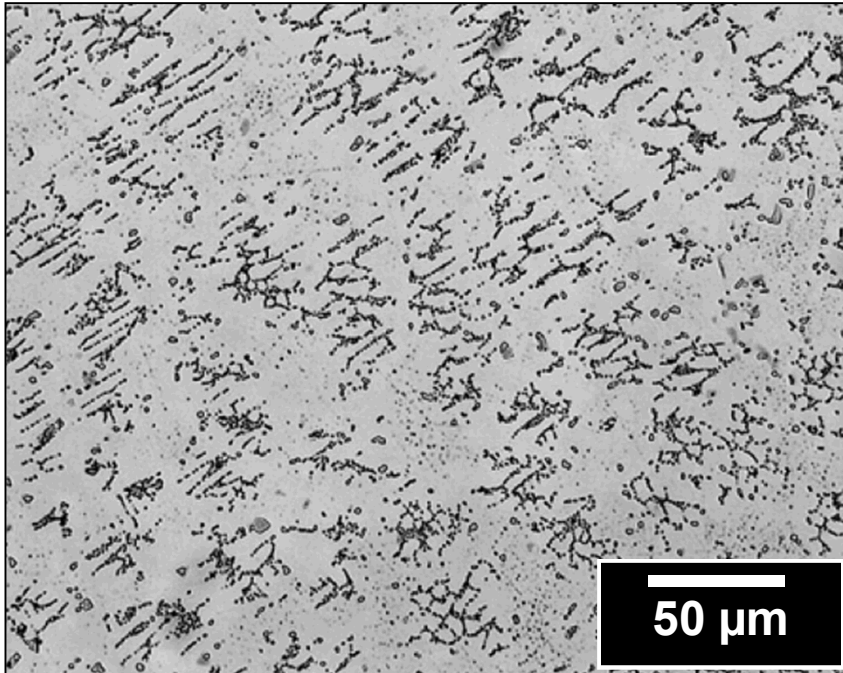
- ◆ **Sn-Ag-Bi:** The fracture path remained along the solder/base material interface for all Pb additions.



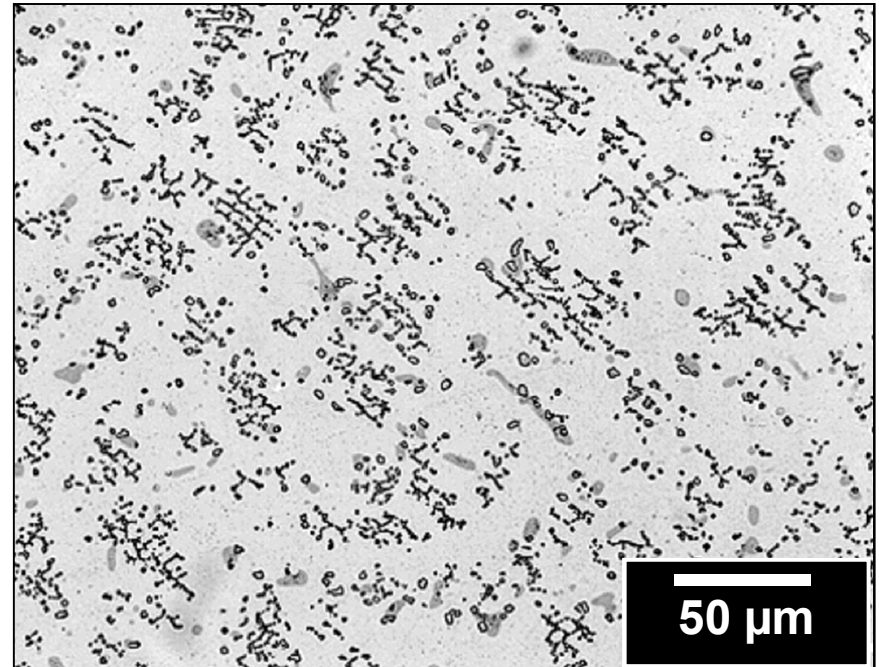
The nominal strength remained greater than the ≈ 400 lb. level above which failure occurs typically at the interface.

Materials – Mechanical Performance

- ◆ **Sn-Ag-Bi:** The Pb additions did not affect the alloy microstructure on the larger size scale.



0.00 % Pb

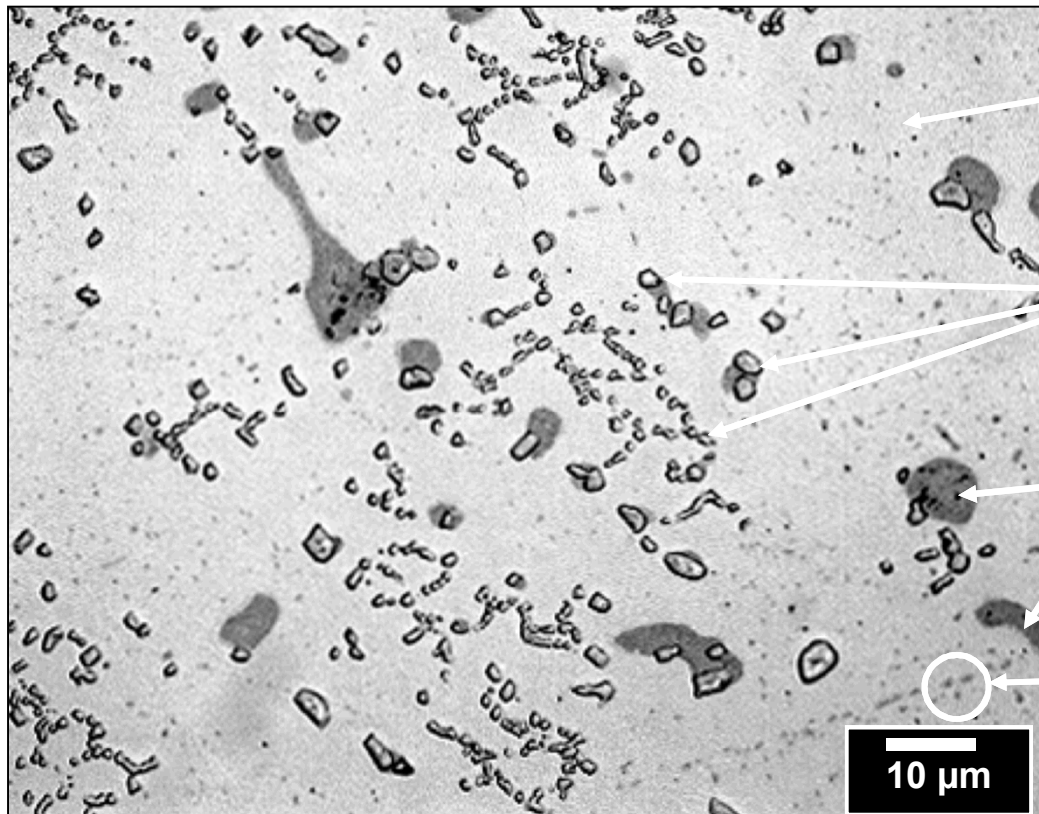


3.00 % Pb

- ◆ **But ...**

Materials – Mechanical Performance

- ◆ ... The Pb additions altered the **small-scale phase distributions** within the Sn-Ag-Bi microstructure.
 - The Pb scavenged Bi from the solid-solution phase, thus *reducing the solid-solution strengthening effect*.



96.5Sn-3.5Bi
Solid solution

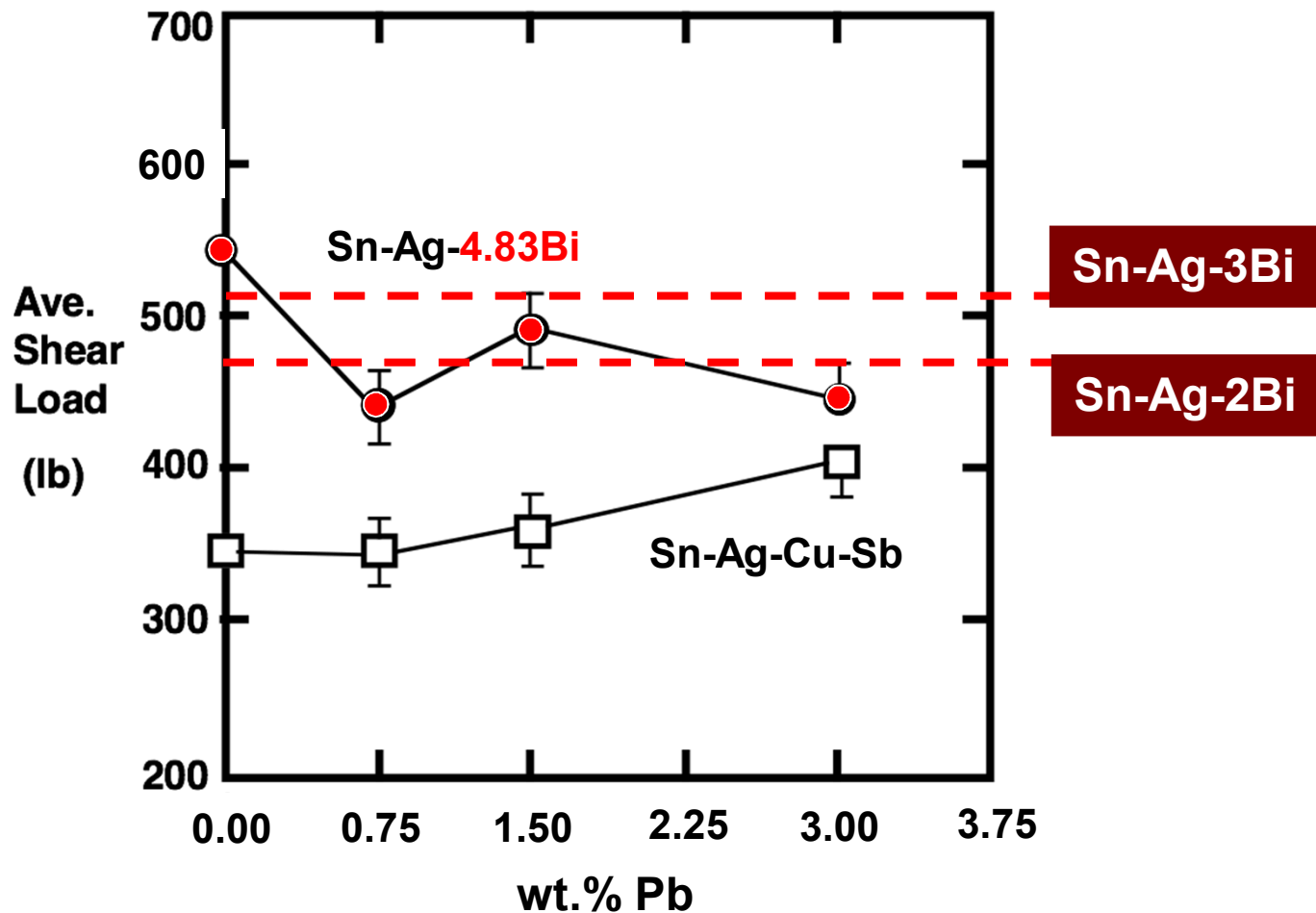
Ag₃Sn

64Pb-**33Bi**-3Sn

63Sn-24Pb-**13Bi**

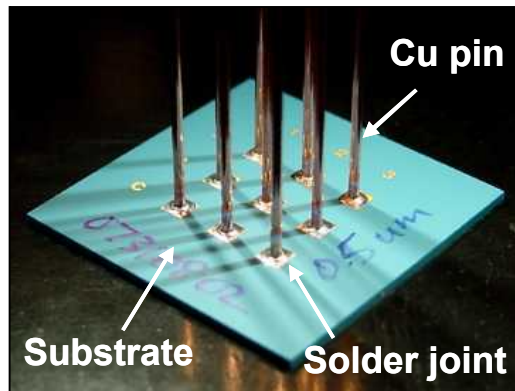
Materials – Mechanical Performance

- ◆ Ring-and-plug shear tests performed on Sn-Ag-XBi ($X = 2, 3 \text{ wt.}\%$) confirmed a similar drop of strength.

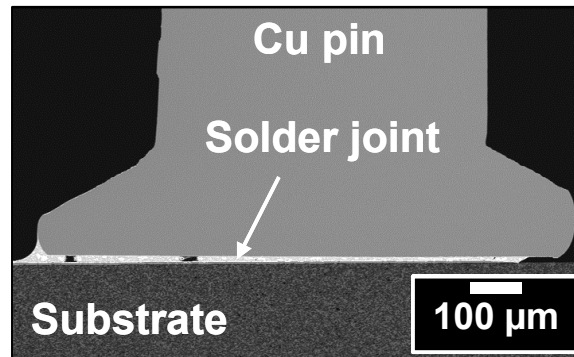


Materials – Mechanical Performance

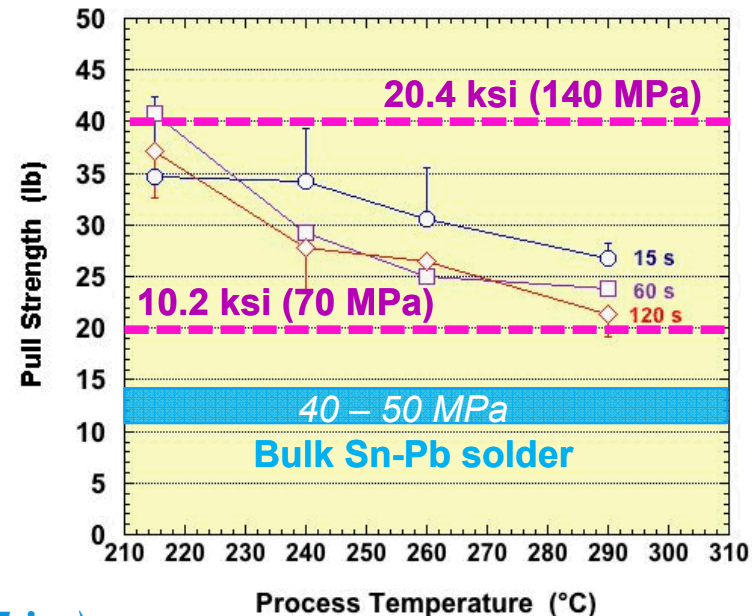
- ◆ **Bulk solder strength** is not always the controlling factor of joint strength ... there is also **gap thickness**.



*Pin-pull test specimen
(10 mm/min)*

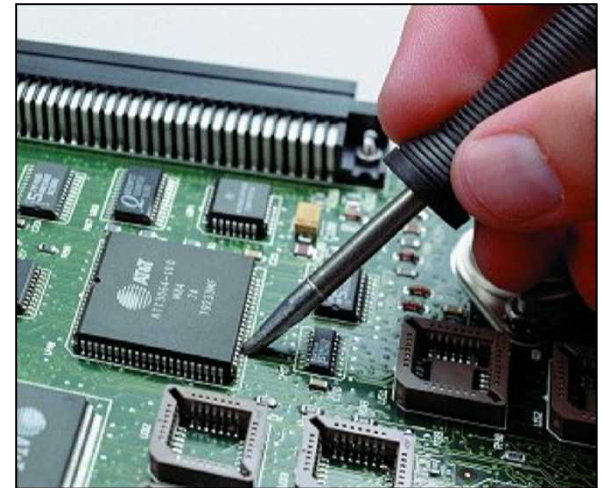
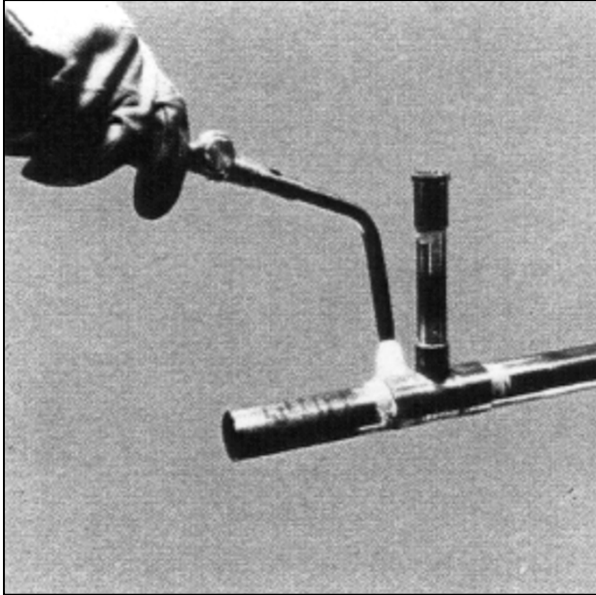


Solder joint gap: 12 μm (0.0005 in.)



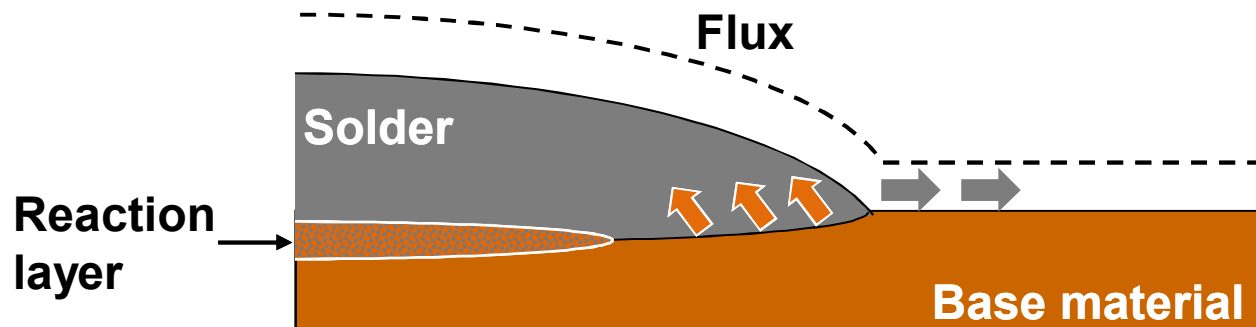
- The joint geometry constrains deformation in the solder.
- ◆ Constitutive (computational) modeling takes account of this effect: bulk and joint mechanical properties.

Processing



Processing

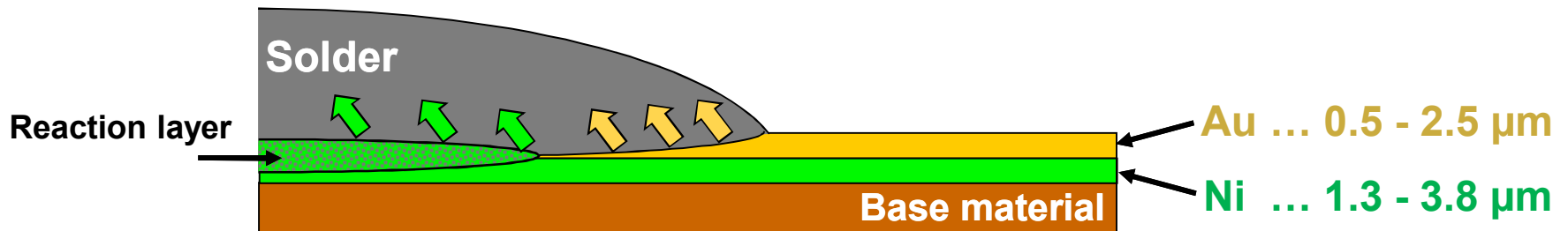
- ◆ Processes are based upon **solderability performance**.
 - **Solderability** refers to the capability of the molten filler metal to **wet-and-spread** on the base material surface.
 - **Wetting**: formation of a metallurgical bond (reaction layer).
 - **Spreading**: spontaneous coverage by the molten alloy.



- ◆ There are three consequences of the wetting process:
 - **Base material dissolution**
 - **Changing the solder alloy composition**
 - **Reaction layer formation**

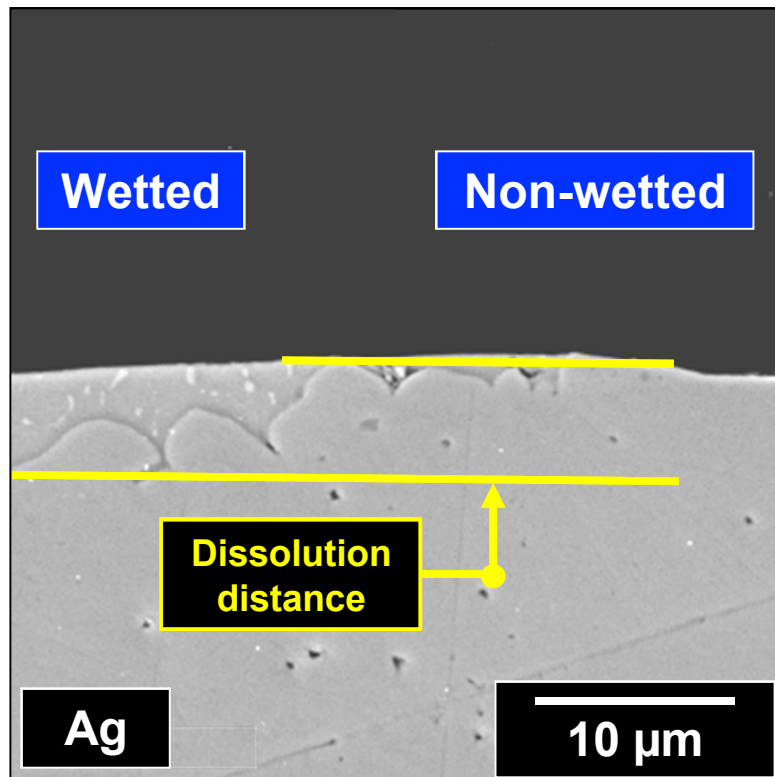
Processing

- ◆ **Surface finishes** are used to augment the solderability of a base material.
- ◆ The surface finish typically has these layers:
 - **Solderable finish:** serves as the “stand-in base material” to which is made the metallurgical bond (e.g., Ni)
 - **Protective finish:** protects the solderability of the solderable finish and is *fully dissolved* into the molten solder (e.g., Au).

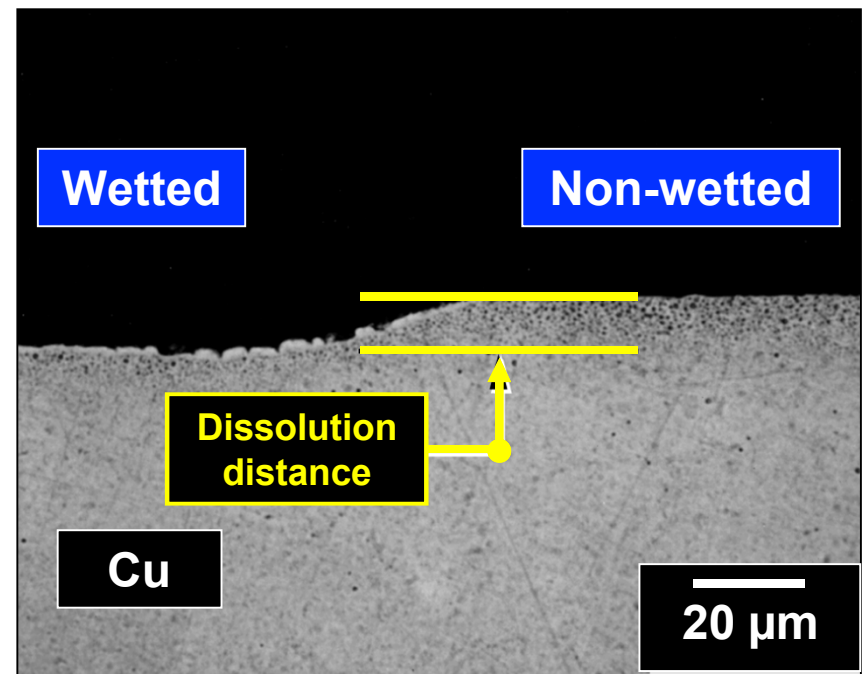


Processing

- ◆ Base material dissolution results in a loss of structure (or solderable layer) cross section:



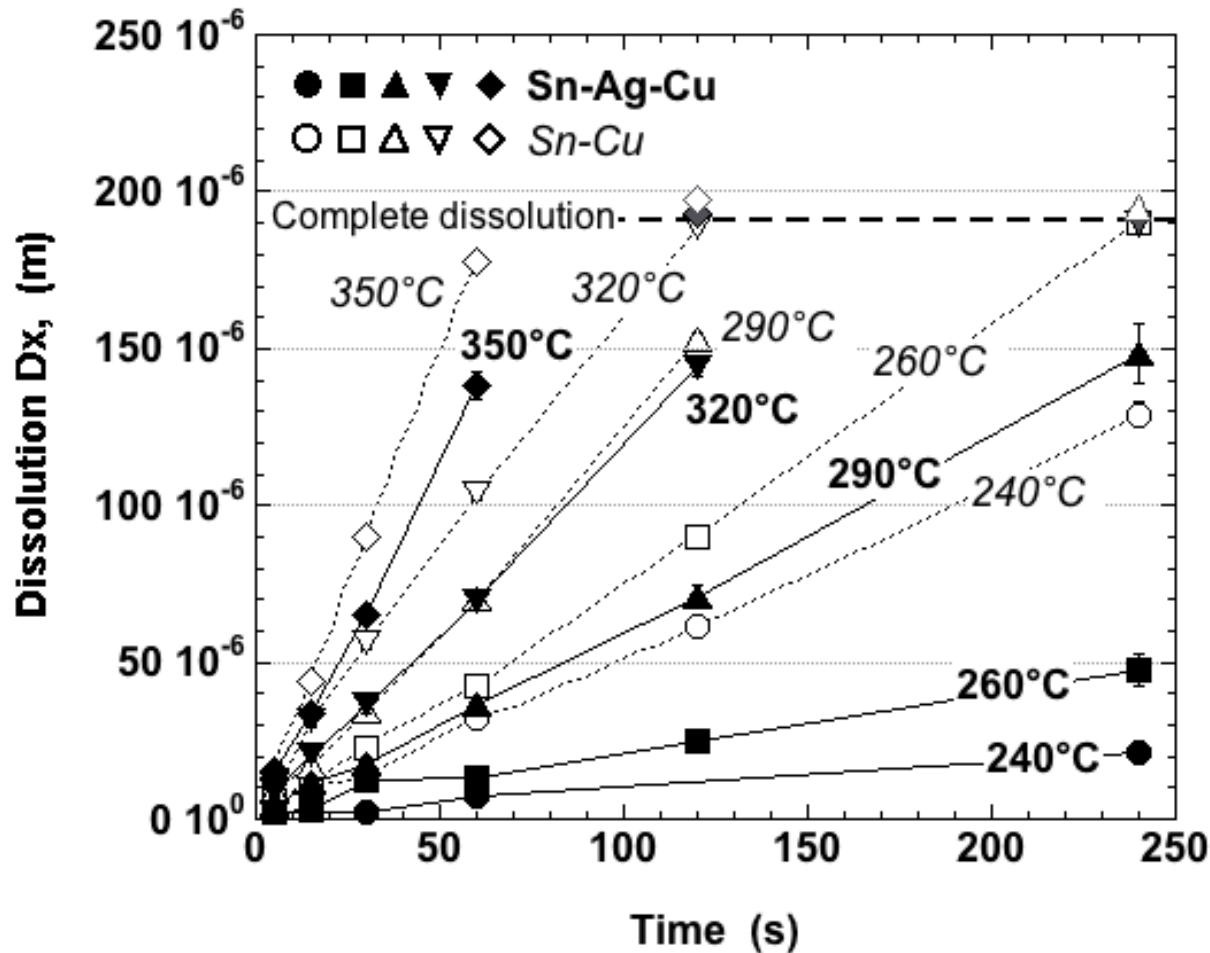
Sn-Ag-Cu, 290°C, 60 s



Sn-Pb, 300°C, 60 s

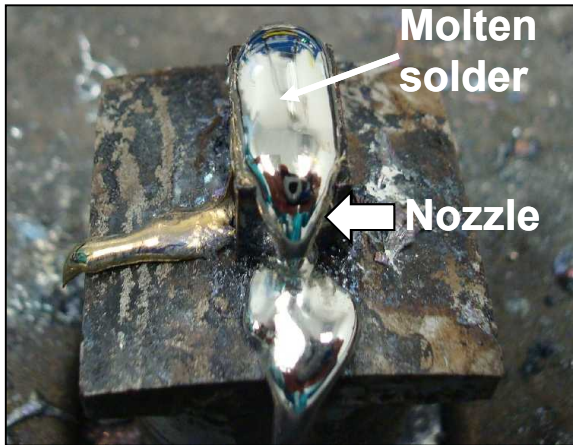
Processing

- ◆ The silver (Ag) in the Sn-Ag-Cu solder slowed the rate of Ag base material dissolution versus Sn-Cu solder.

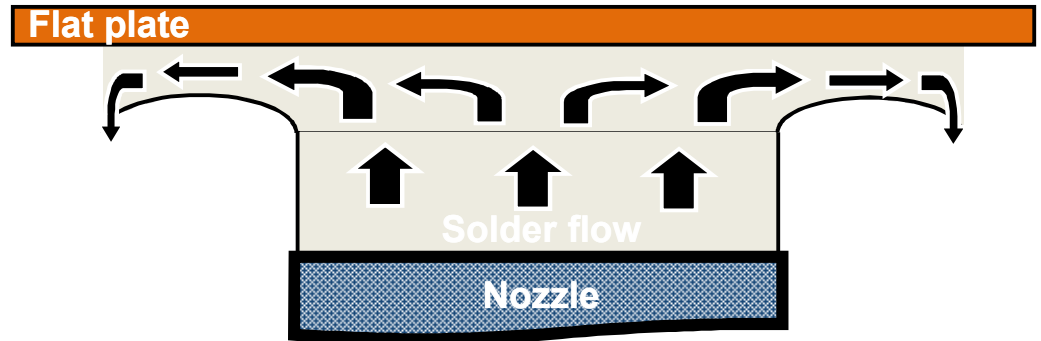


Processing

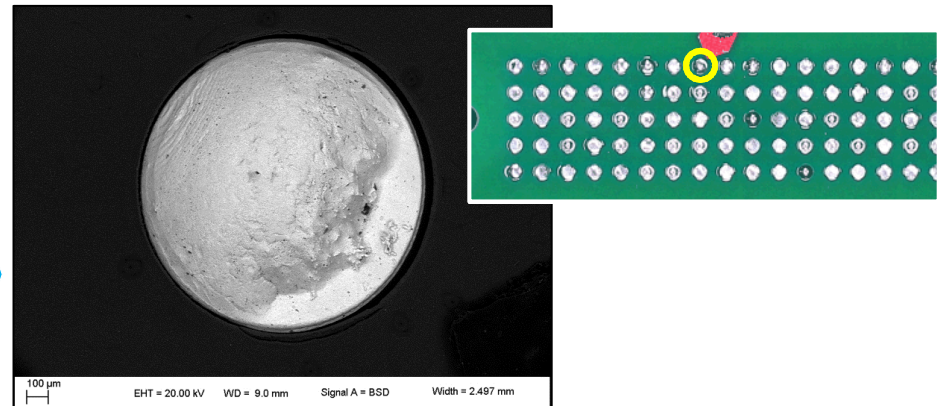
- ◆ The soldering process is a **fluid mechanics** problem.
 - The solder fountain is used to assemble connectors and other large form-factor components to printed circuit boards.



“Solder Fountain”

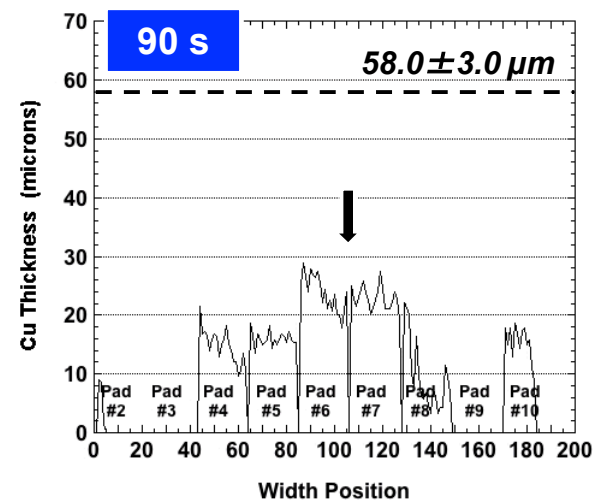
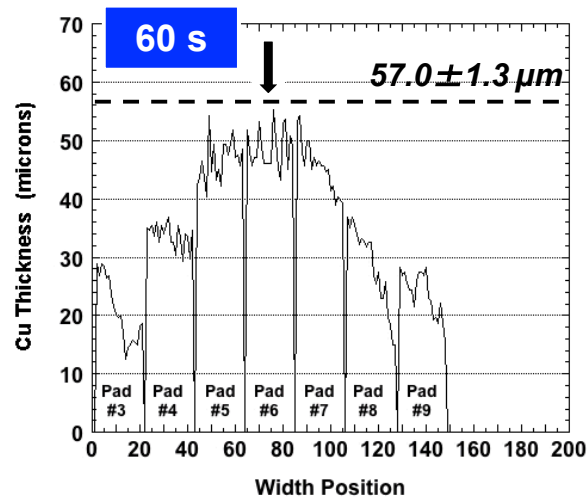
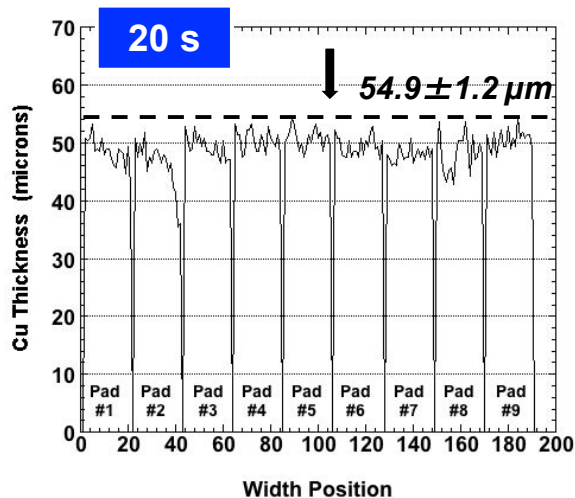
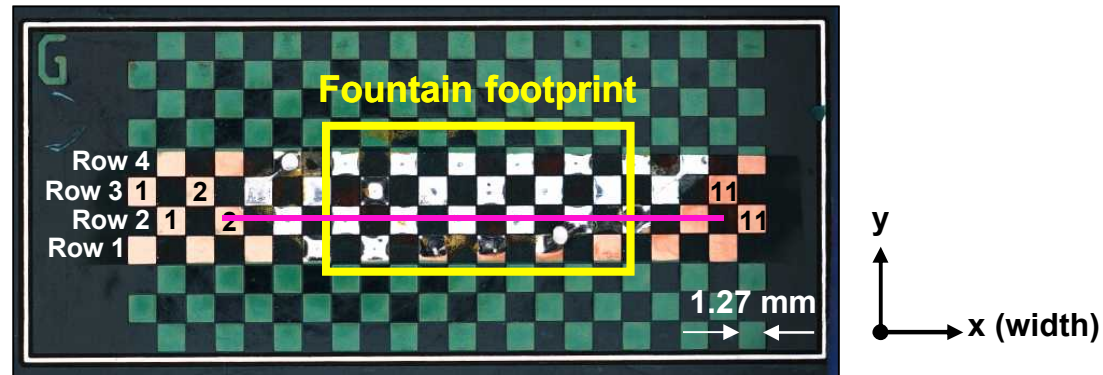


- Skips and other “unexpected” defects were observed in the solder coating. ➡ ➡ ➡



Processing

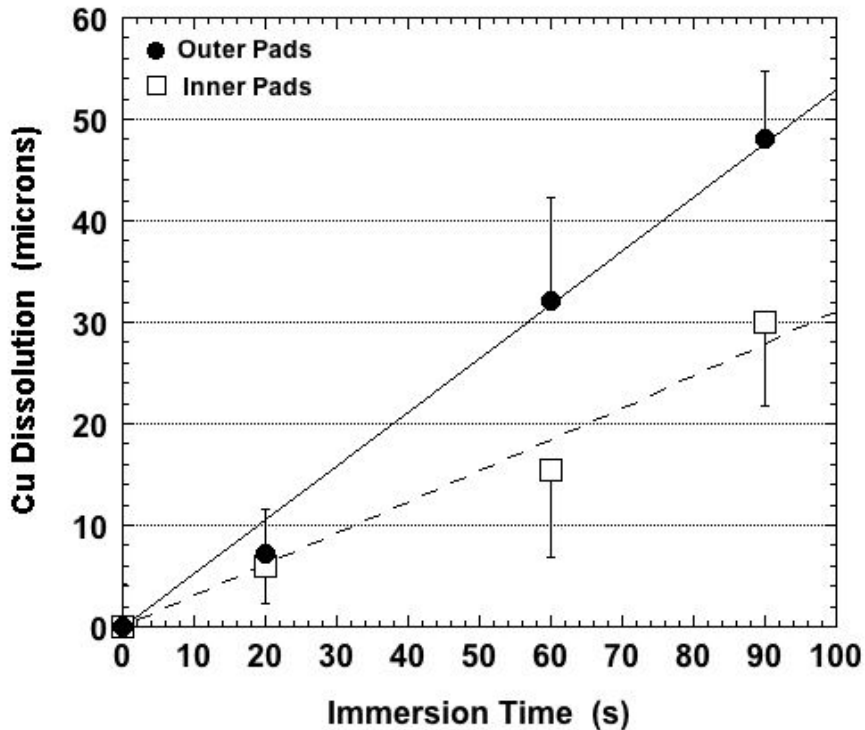
- ◆ A circuit board "grid" was used to investigate the spatial (x, y) behavior of an impinging, molten solder fountain.



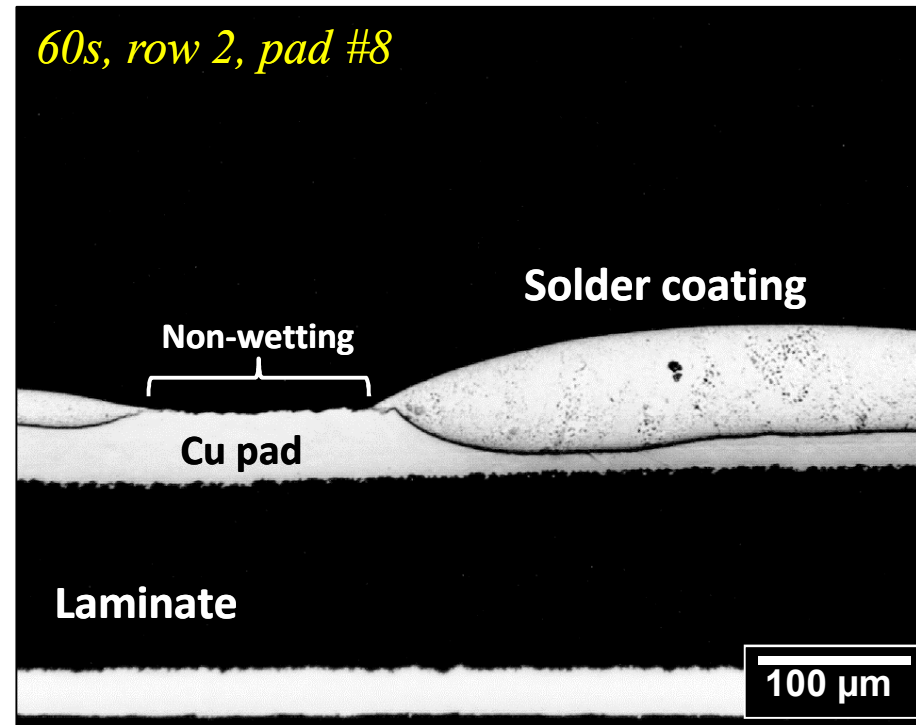
Processing

- ◆ The extent of base material dissolution had two scales:
 - “Large size scale” ... ≈ 10 mm
 - “Small size scale” ... ≈ 0.5 mm

Large size scale

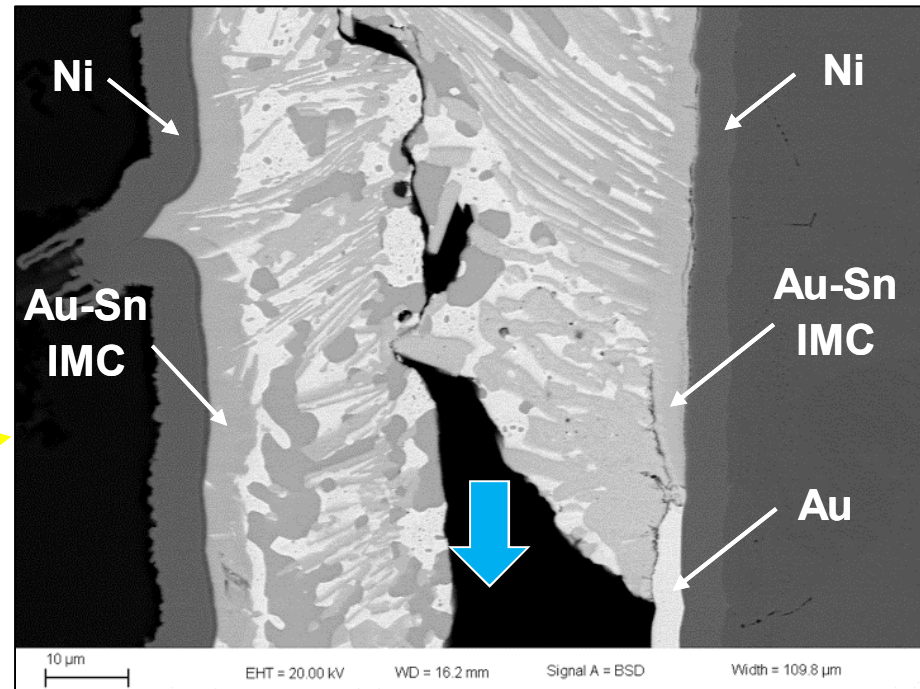
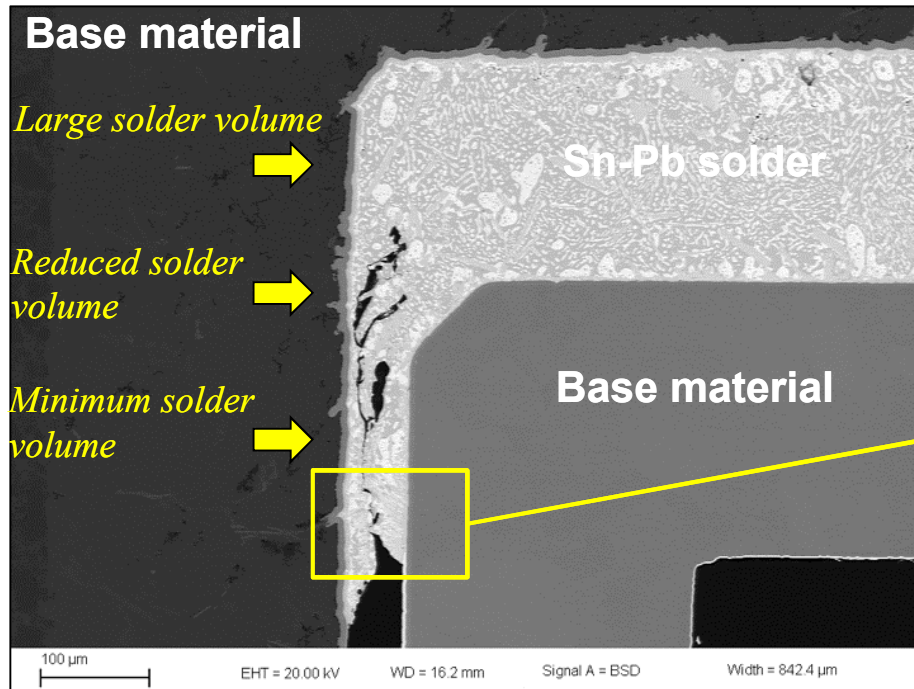


Small size scale



Processing

- ◆ Base material dissolution can change the solder composition and thus, its melting properties.
 - Increasing the solidus temperature (T_s) and/or liquidus temperature (T_l) can lead to constitutional solidification.

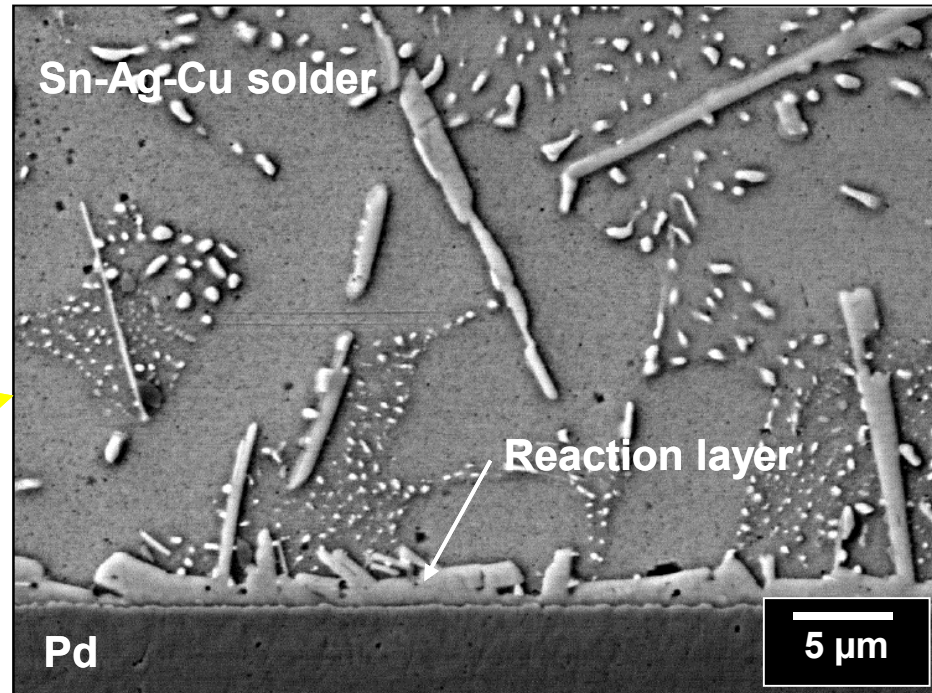
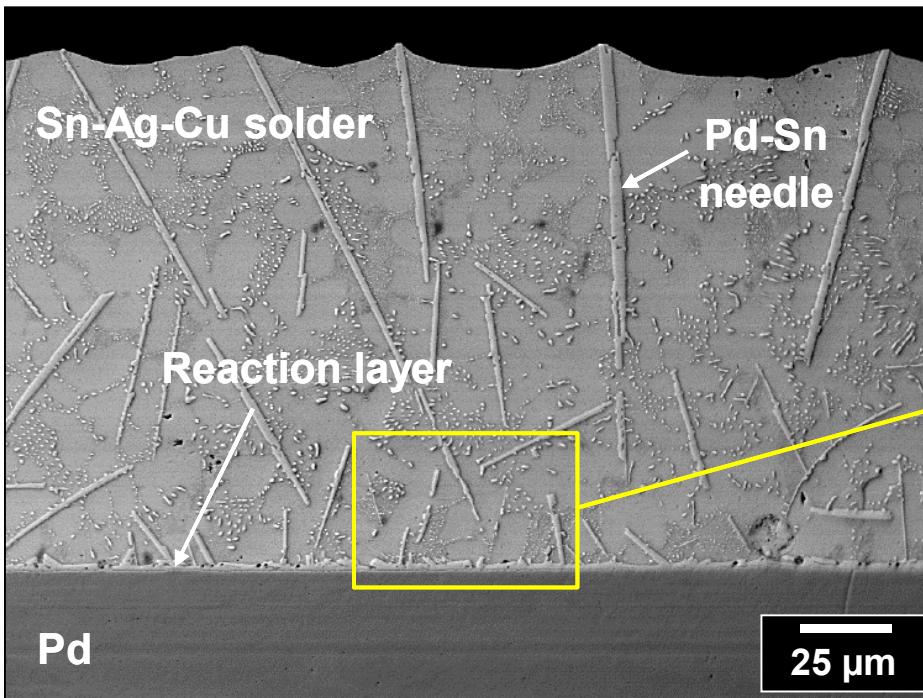


- An excessively thick Au protective finish caused the Sn-Pb solder to solidify prior to filling the gap.

Processing

◆ Base material dissolution can change the *solid* solder alloy composition:

- There is a change to the solder's bulk mechanical properties and its interface microstructure.

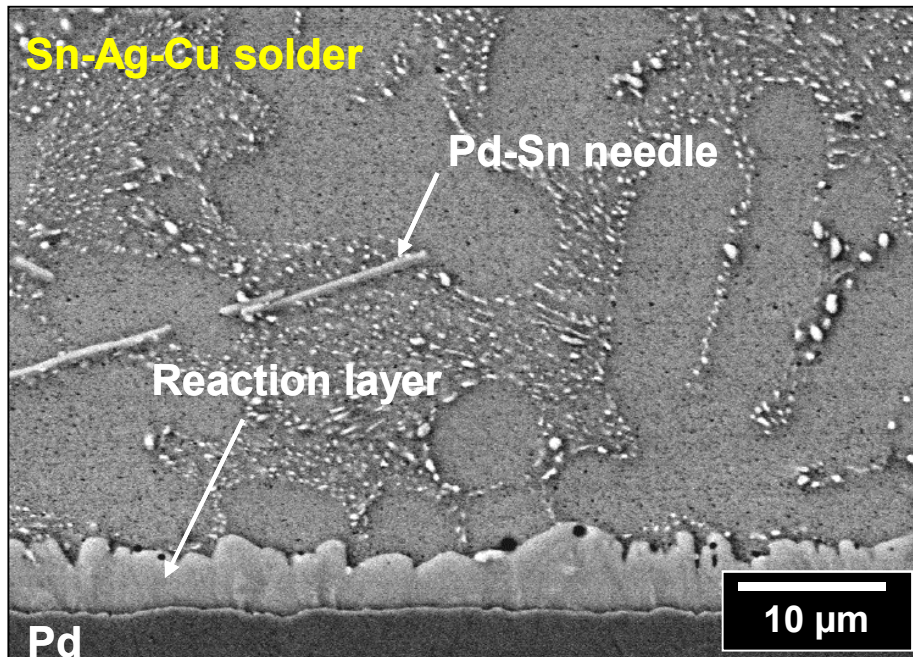


Sn-Ag-Cu, 350°C, 5s

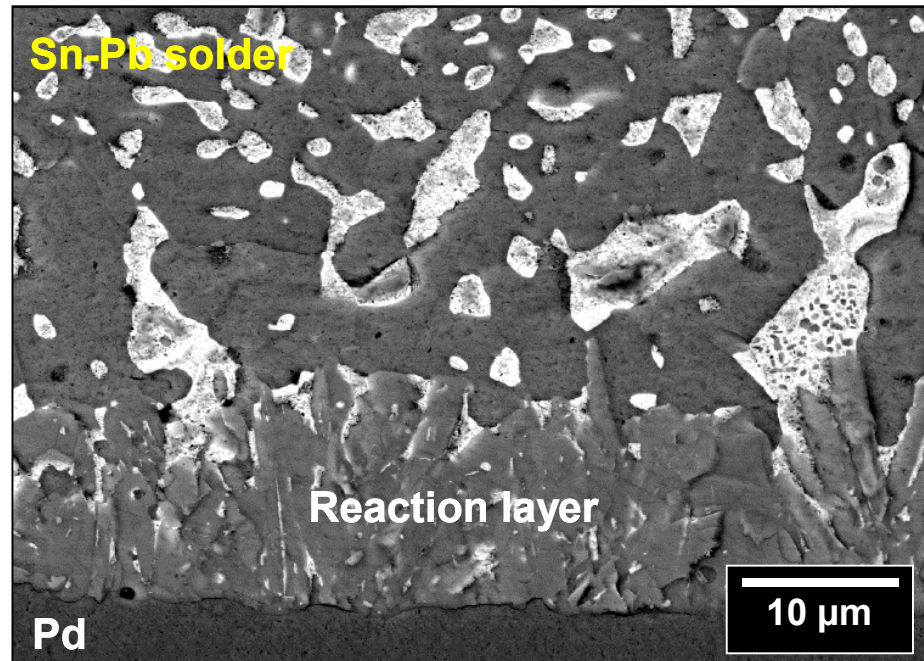
Processing

◆ **Interface reaction layer** composition and thickness are a function of the base material and solder alloy.

- Sn-Ag-Cu solder
 - Sn-Pb solder
- } **290°C, 5 s.**



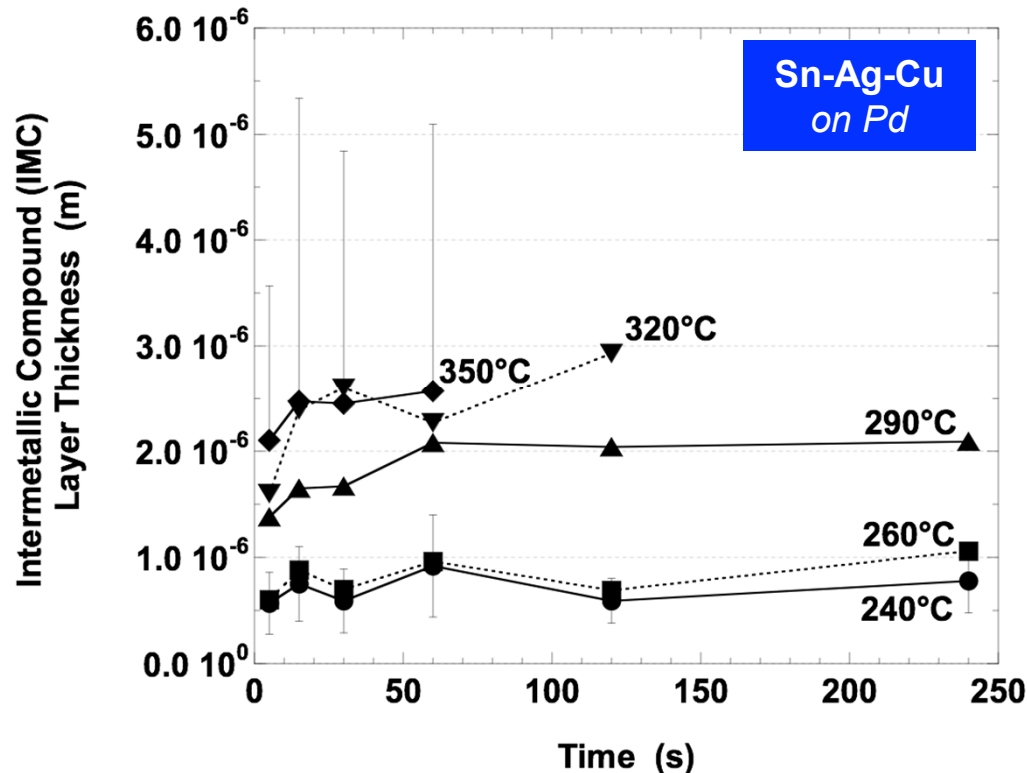
Sn-Ag-Cu: 290°C, 5s



Sn-Pb: 290°C, 5s

Processing

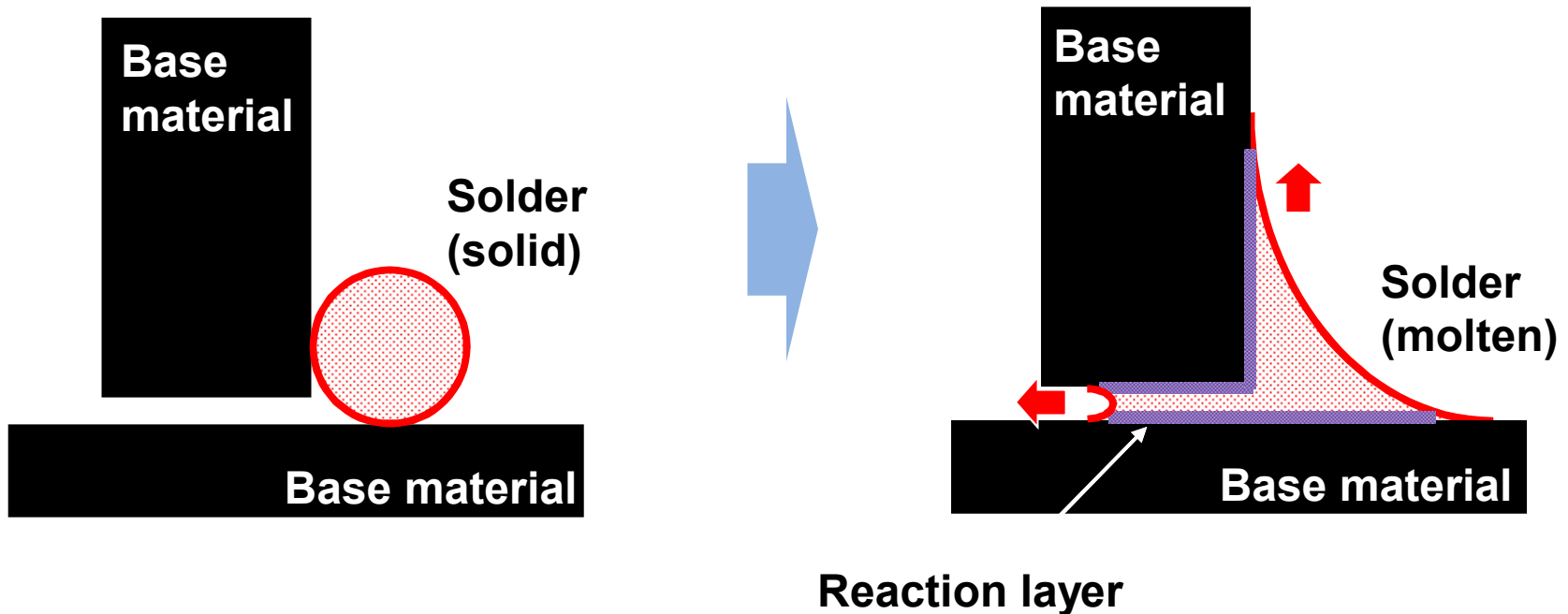
- ◆ **“Liquid” interface reactions:** Layer growth tends to quickly level-off as a function of time at temperature.



- ◆ Reaction layer thicknesses of $\lesssim 5 \mu\text{m}$ generally do not pose a significant risk to performance or reliability.

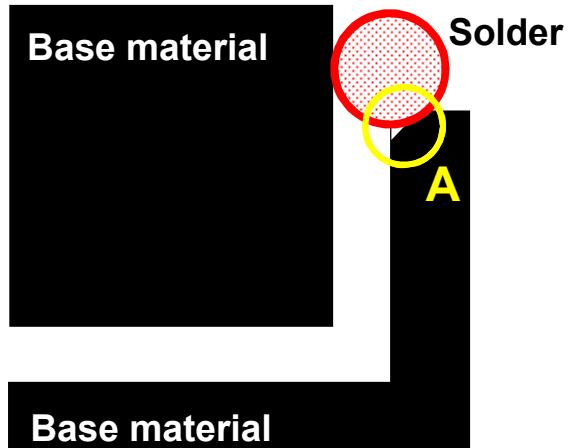
Processing

- ◆ Solderability is also about **spontaneous spreading**.
- ◆ **Spreading** is a function of the solder and base material compositions; flux; as well as **joint geometry**.

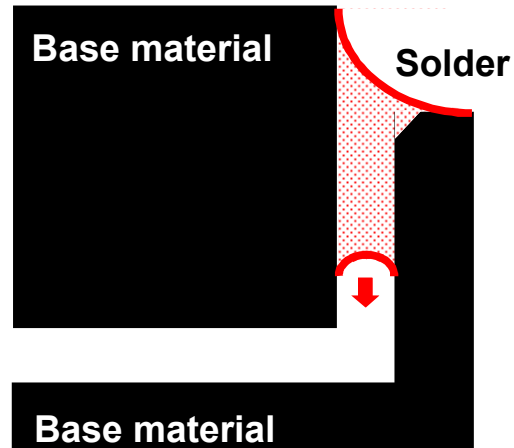


Processing

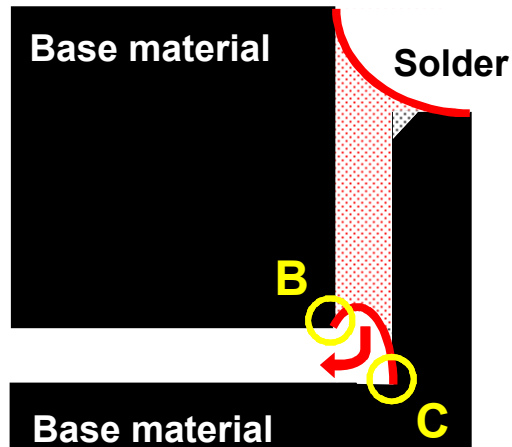
- ◆ Molten solders “do not like” to turn corners.



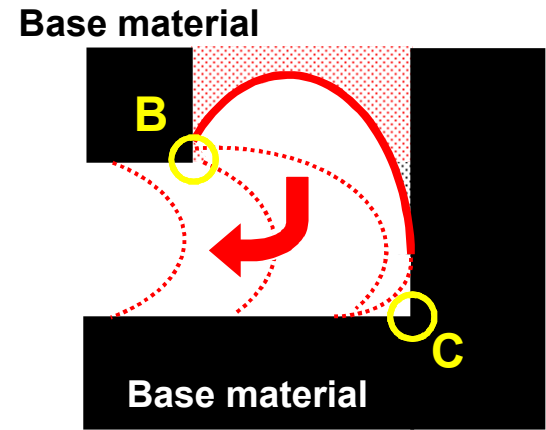
(a)



(b)



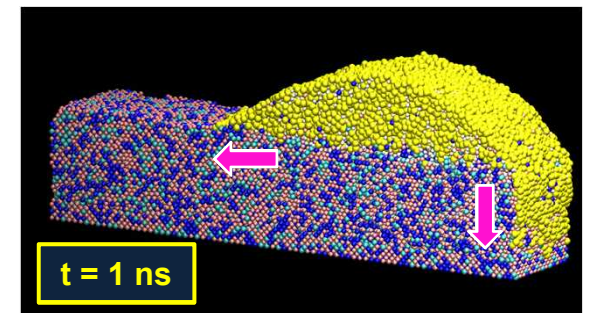
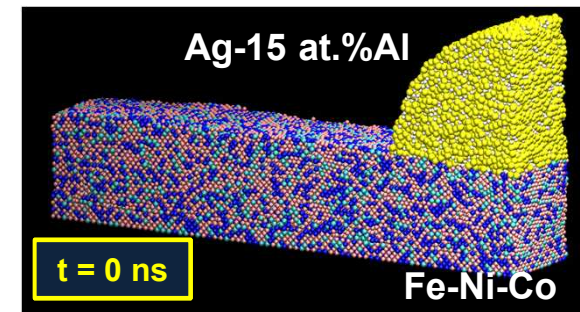
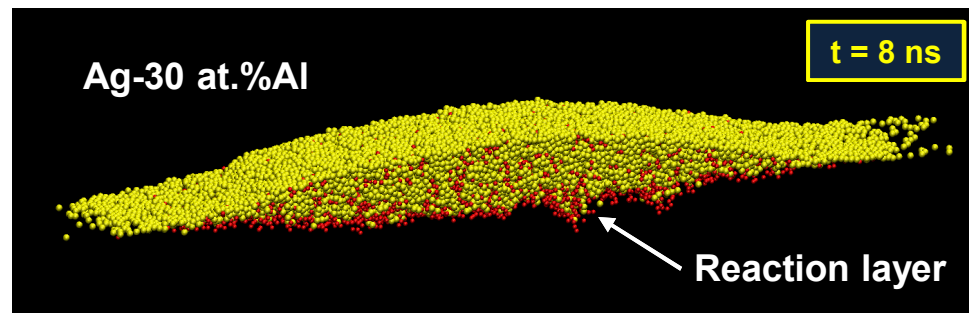
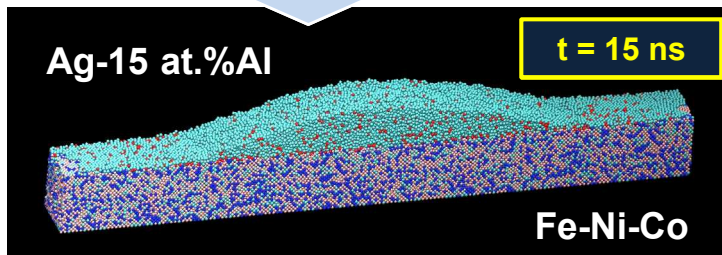
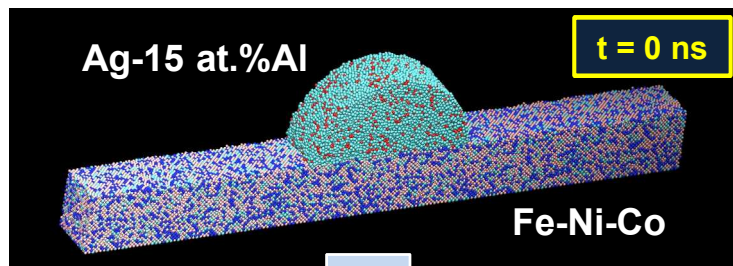
(c)



(d)

Processing

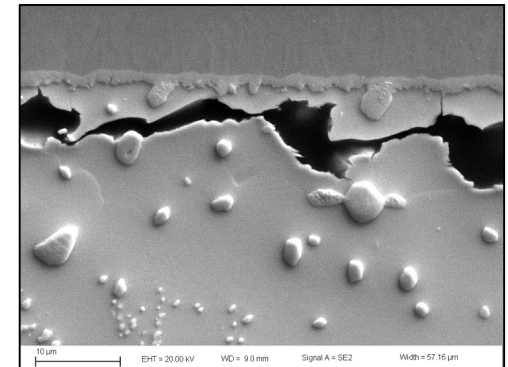
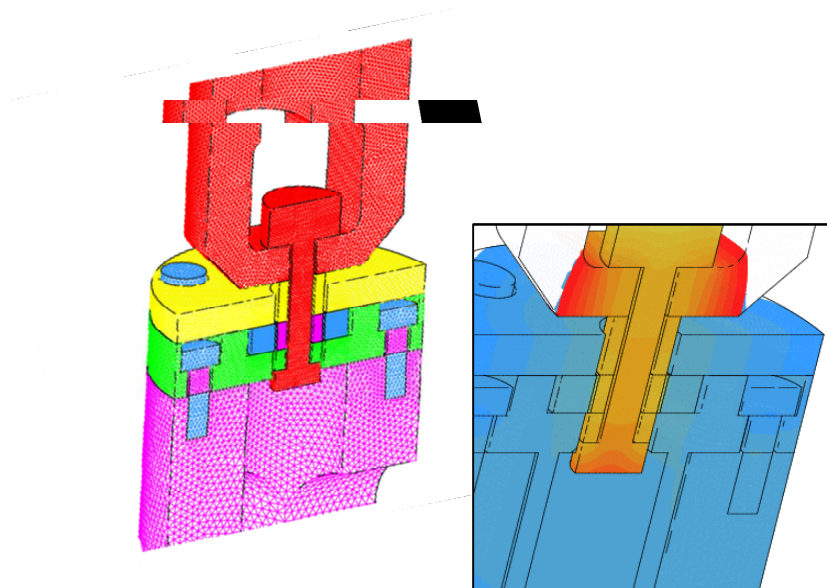
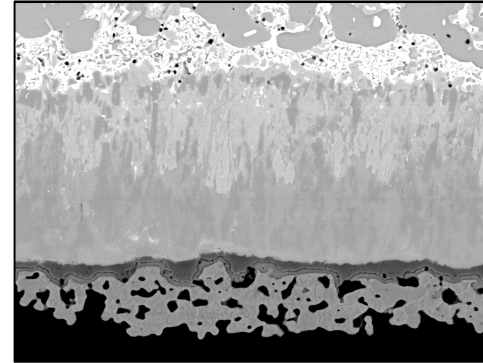
- ◆ **Molecular dynamics simulations** are being developed that model interface reactions as well as liquid flow.
 - This effort is being spearheaded in **brazing technology**.



The models can now take into account the effects of geometry.

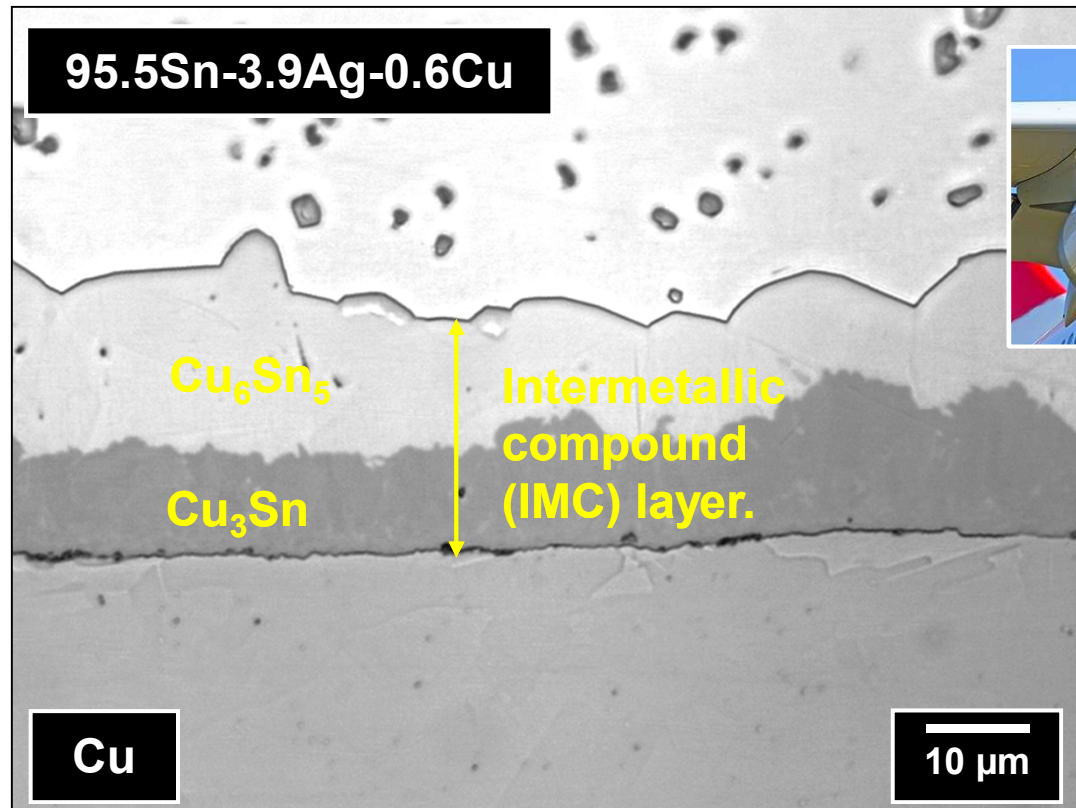
Reliability

- ◆ Interface reactions
- ◆ Solder joint fatigue
 - Empirical studies
 - Computational modeling



Reliability – Interface Reactions

- ◆ After solidification, solid-state reactions continue to take place at the **solder / base material interface**:
 - Interfaces are non-equilibrium structures
 - Solid-state diffusion readily occurs in the solder.

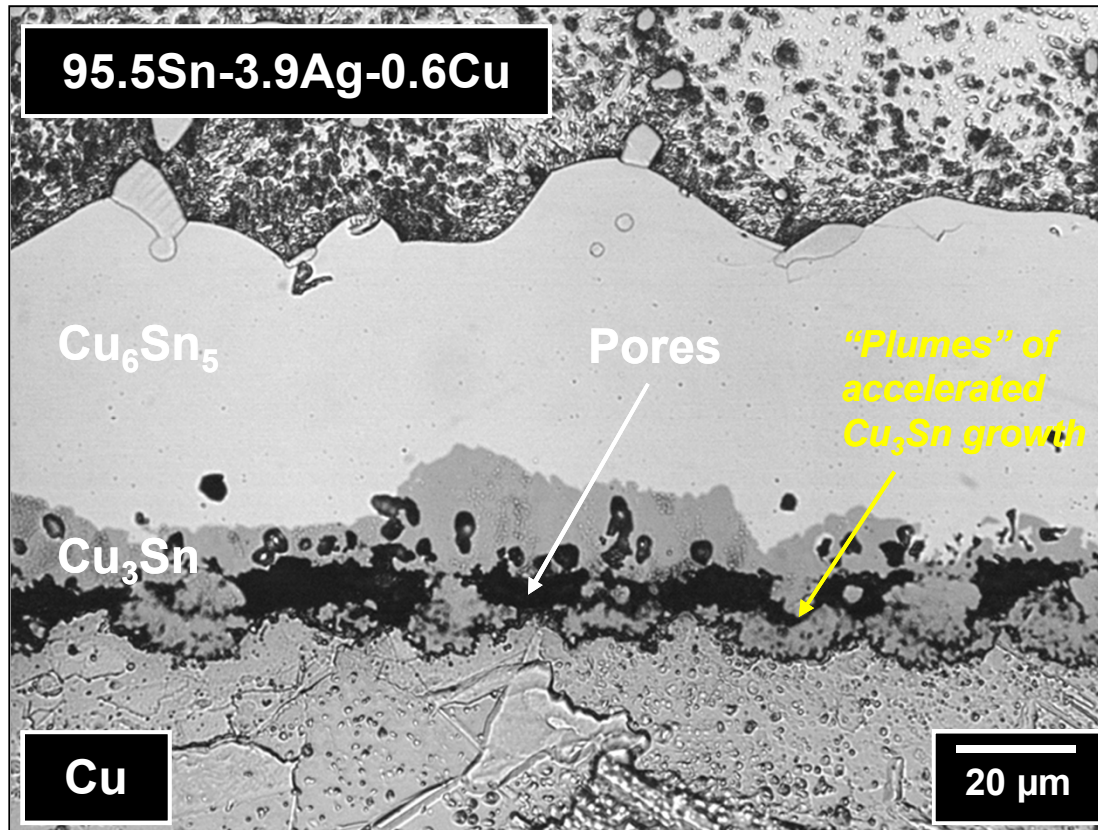


Remember ...

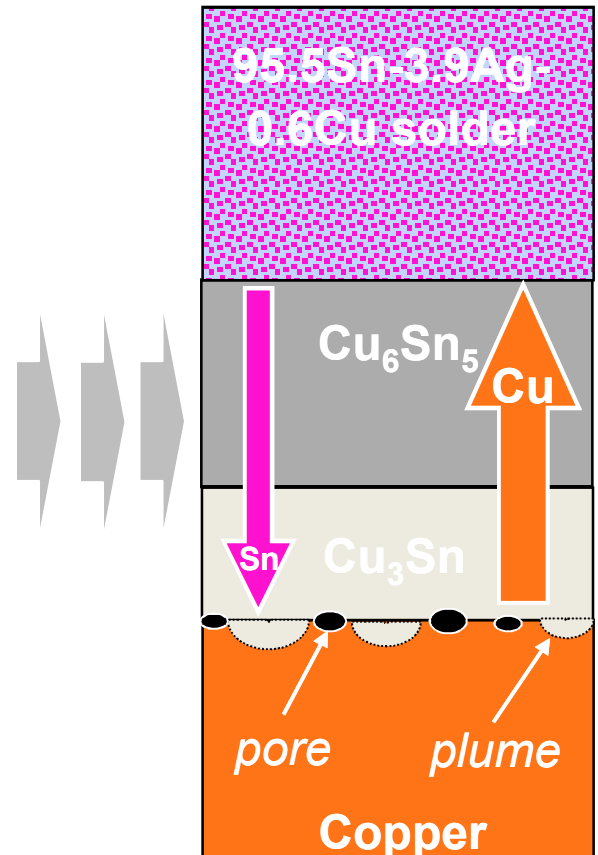
*135°C,
300 days*

Reliability – Interface Reactions

- ◆ When those reactions become excessively rapid, the interface microstructure jeopardizes joint reliability.

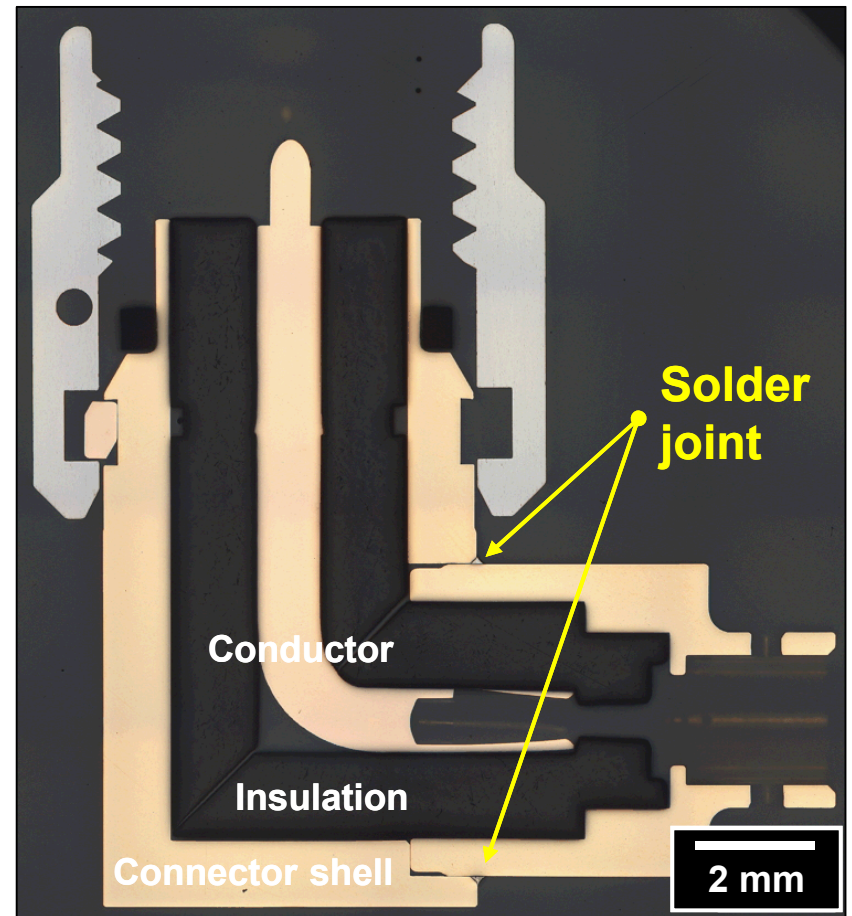
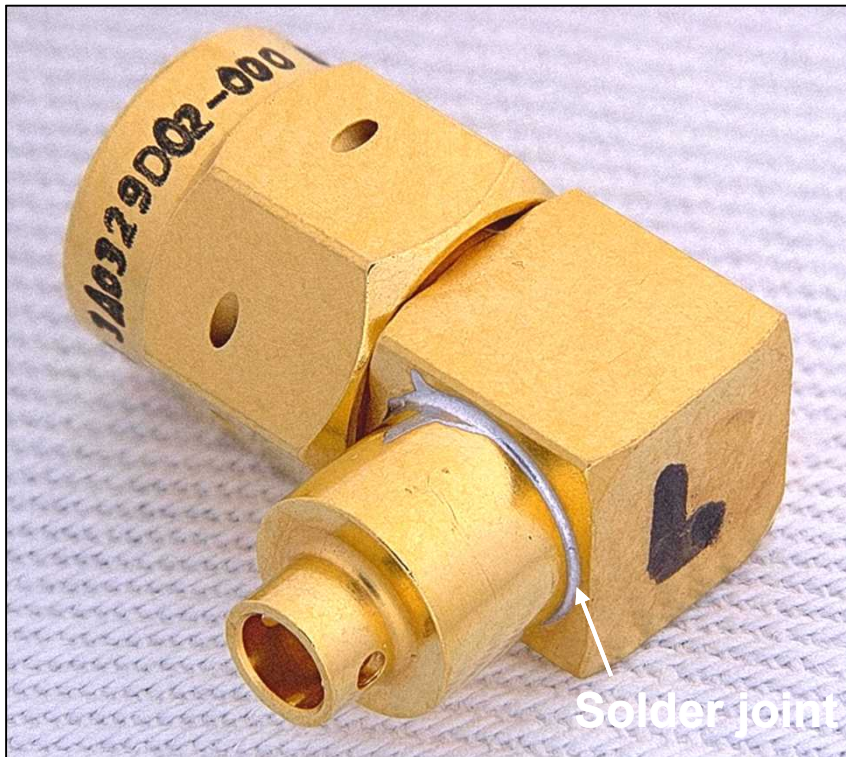


205°C, 300 days



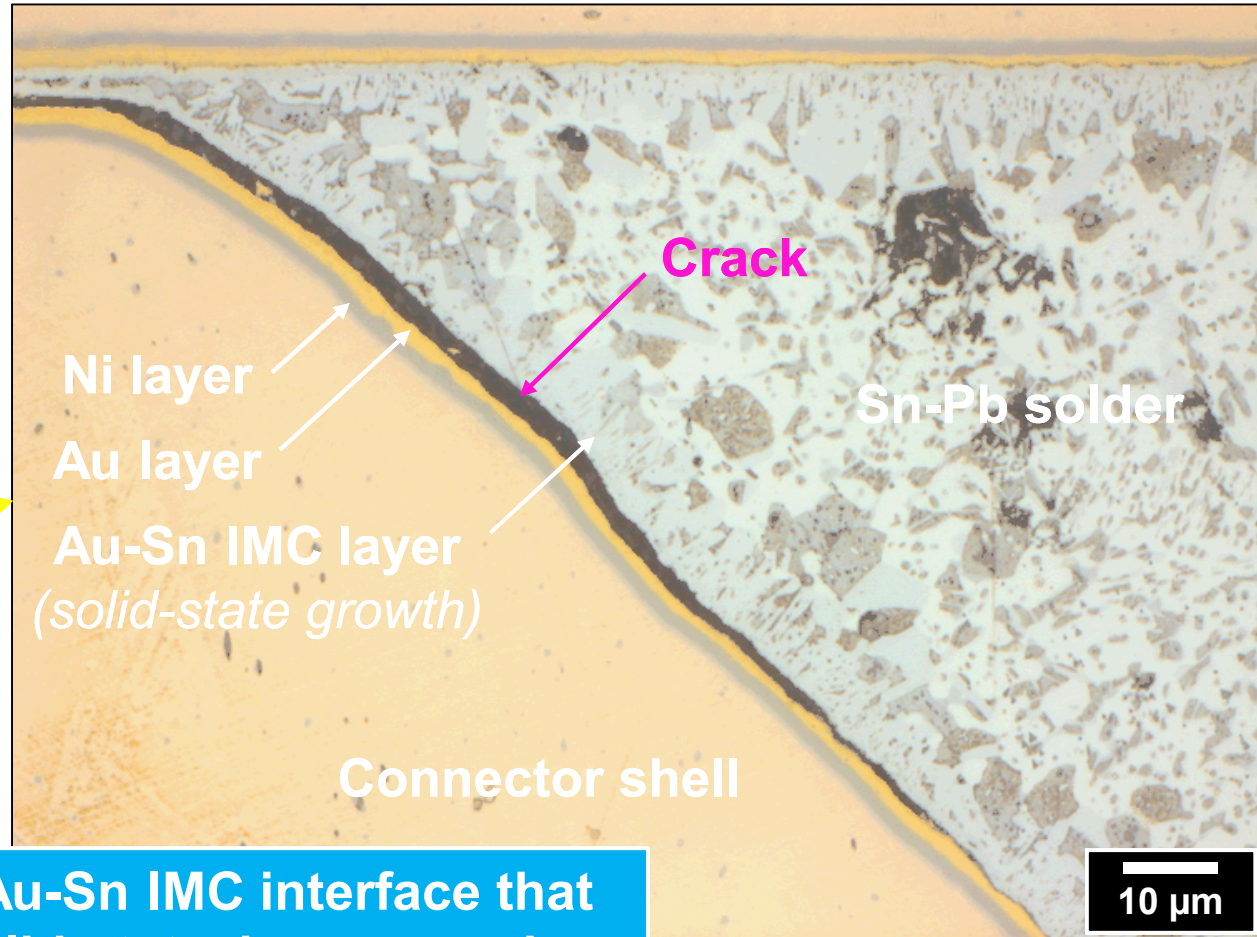
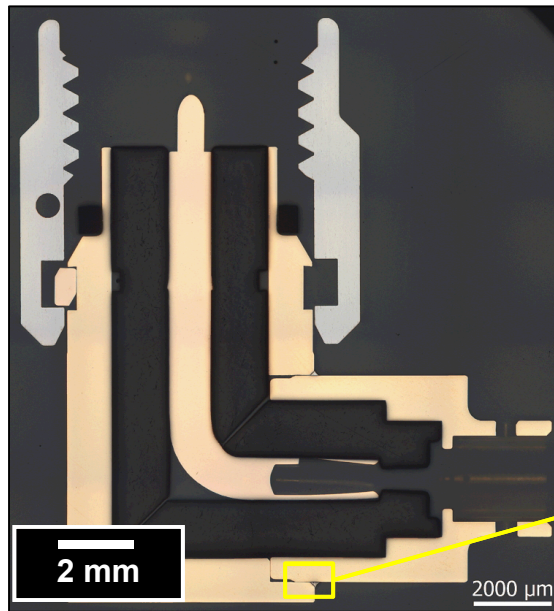
Reliability – Interface Reactions

- ◆ These layered structures can accelerate failure modes.
 - *Example: Sn-Pb solder joint used to assemble a connector*



Reliability – Interface Reactions

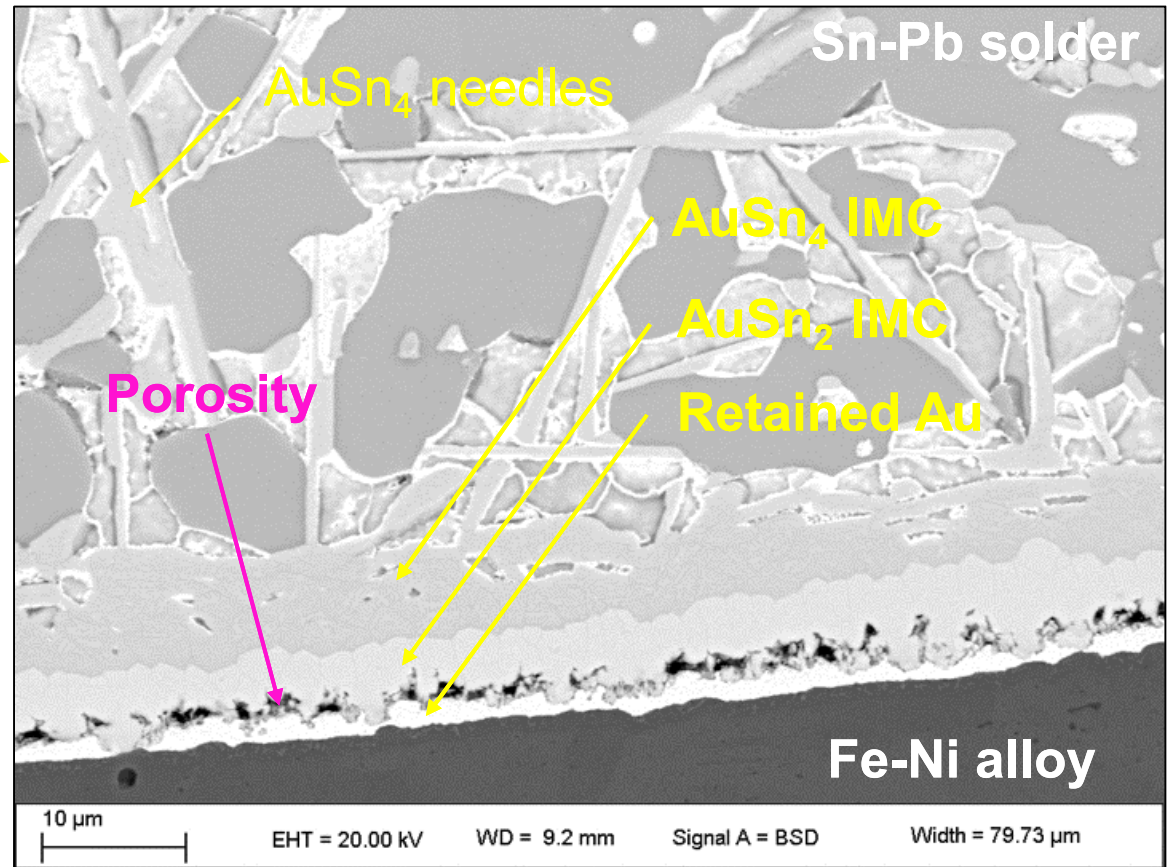
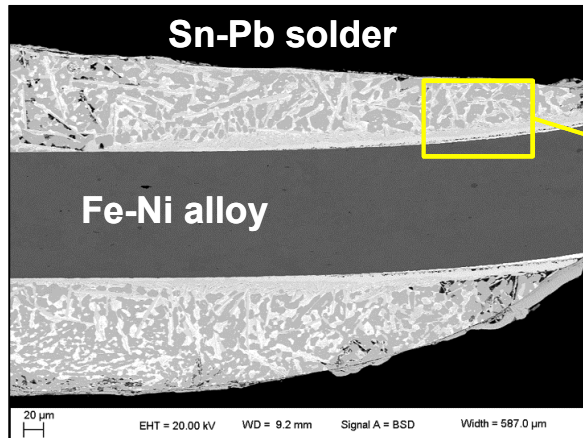
- ◆ The soldering process failed to remove the entire Au (protective) finish from the connector shell surface.



The retained Au / Au-Sn IMC interface that is formed in the solid-state, is very weak.

Reliability – Interface Reactions

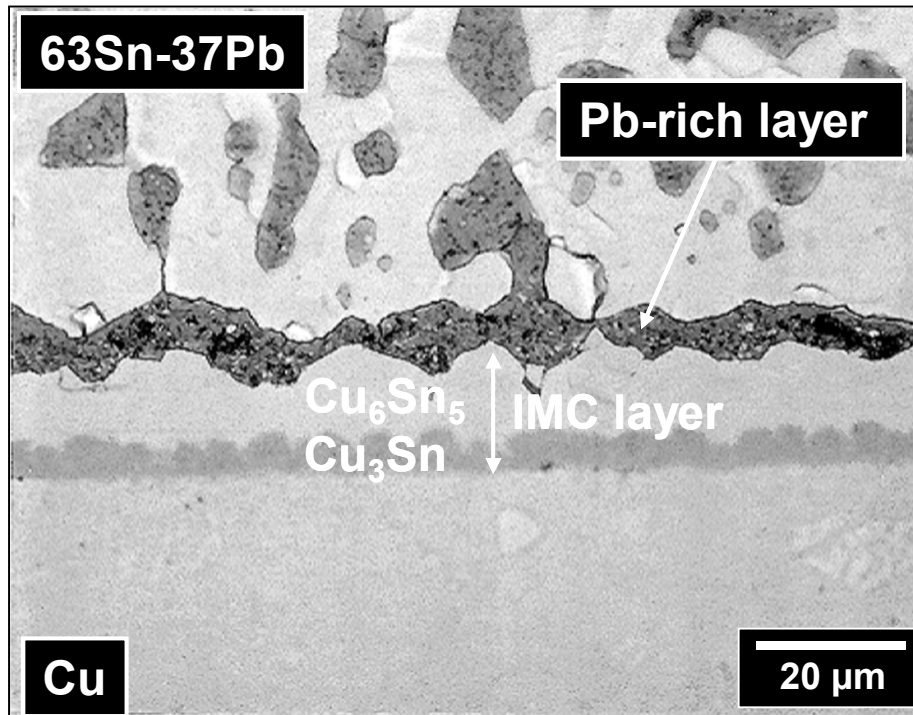
- ◆ The weak Au/Au-Sn IMC interface is due to formation of Kirkendall porosity during the solid-state reaction.



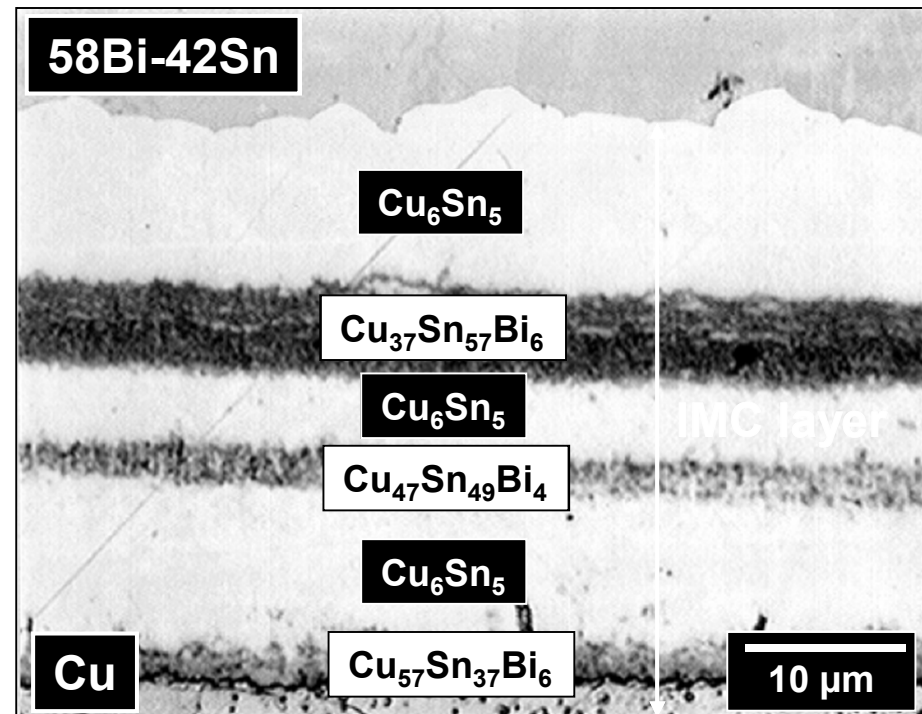
These phenomena take place *at room temperature*.

Reliability – Interface Reactions

- ◆ Interface reactions depend upon solder composition.
 - Elements in the solder, which are rejected by the interface reaction, form a layered microstructure.



135°C, 40 days

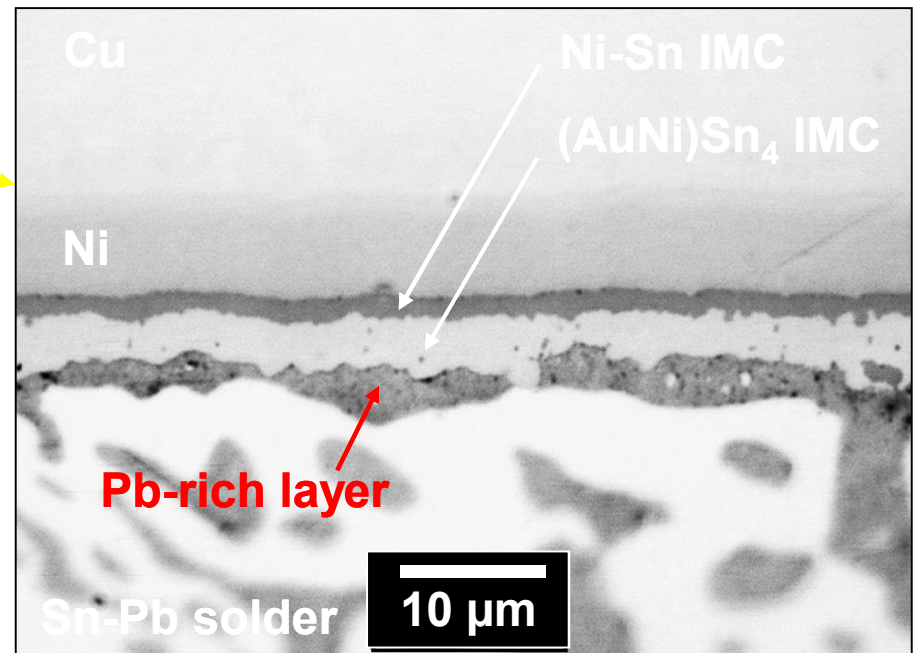
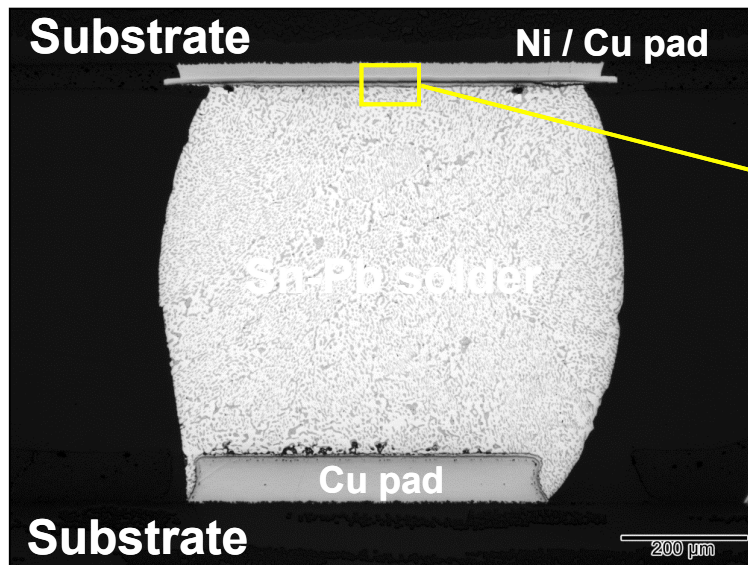


120°C, 40 days

Layered interfaces create paths of easy crack propagation.

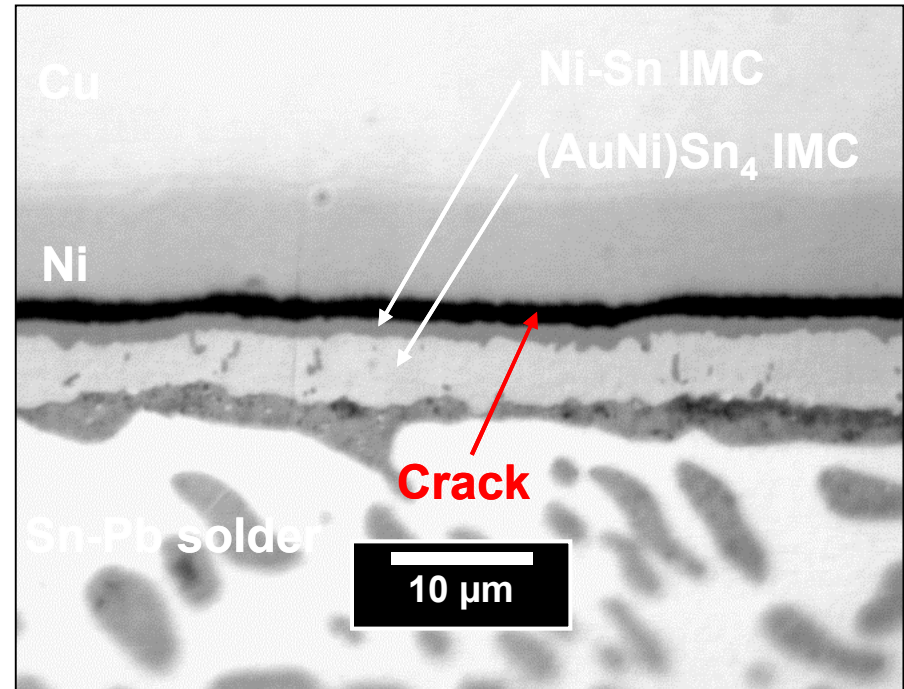
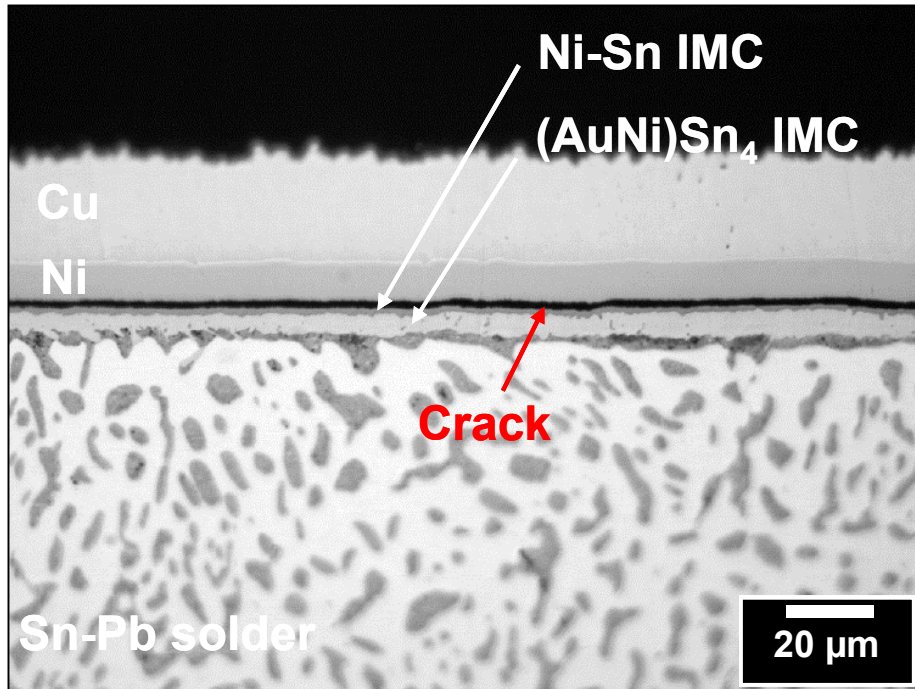
Reliability – Interface Reactions

- ◆ *Combinations* of solid-state diffusion/reaction steps can lead to a mechanically weak, interface microstructure.
- ◆ *“Return-of-Au” phenomenon*:
 - Gold protective finish that has dissolved into solder, returns to the Ni or Cu layer by solid-state diffusion.



Reliability – Interface Reactions

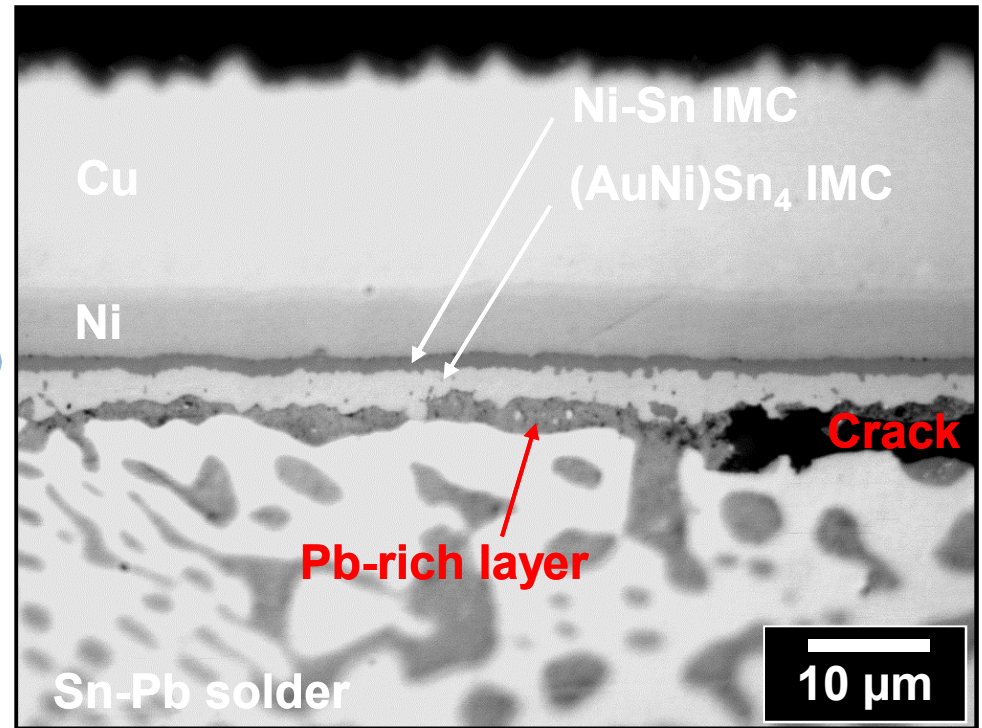
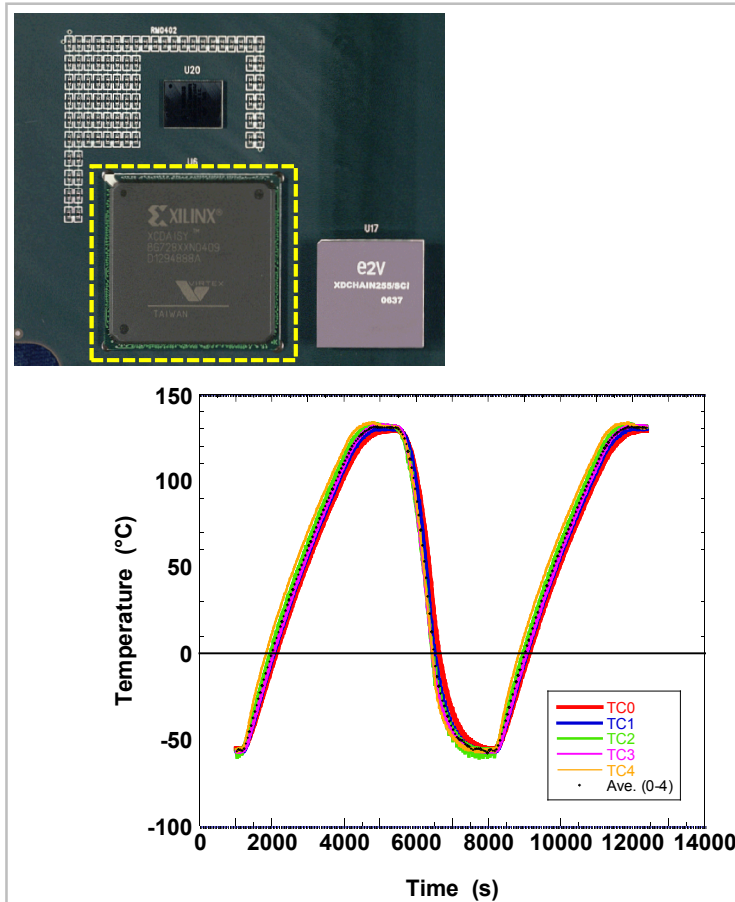
- ◆ The presence of the additional $(\text{AuNi})\text{Sn}_4$ IMC layer increases the risk of brittle fracture under **shock loads**.



- ◆ The formation of a $(\text{AuNi})\text{Sn}_4$ IMC layer forced crack propagation to the Ni / Ni-Sn IMC interface.

Reliability – Interface Reactions

- ◆ But then, under **temperature cycling environments** ...

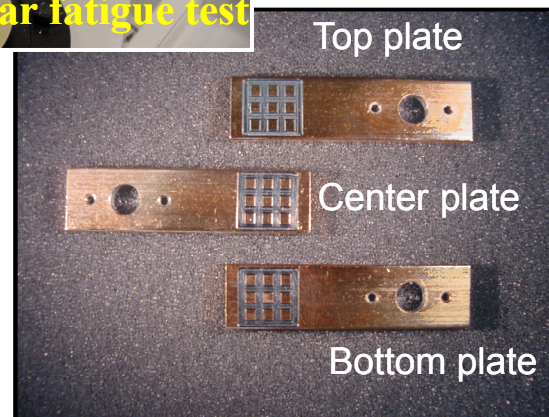
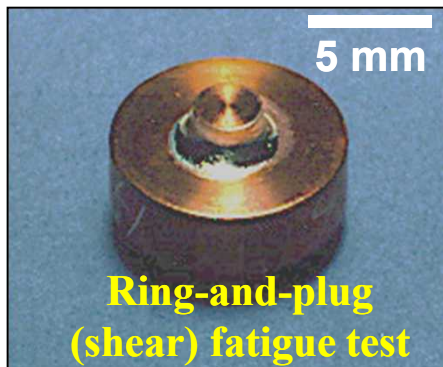
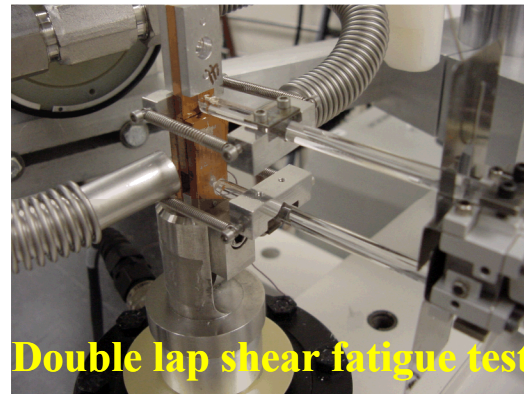
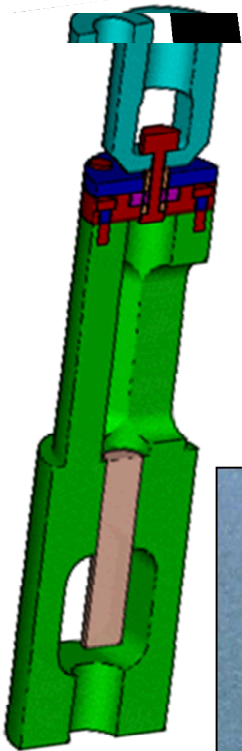


-55°C / 125°C; 15 min holds; 750 cycles

- ◆ The **Pb-rich layer** provided an easier path for the propagation of TMF cracks, causing a **loss of fatigue life**.

Reliability – Solder Joint Fatigue

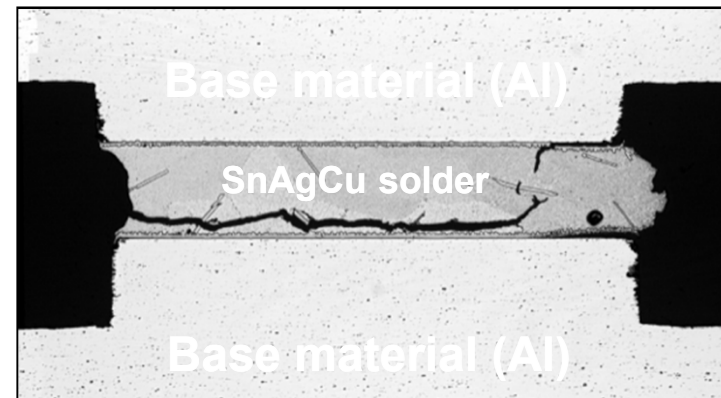
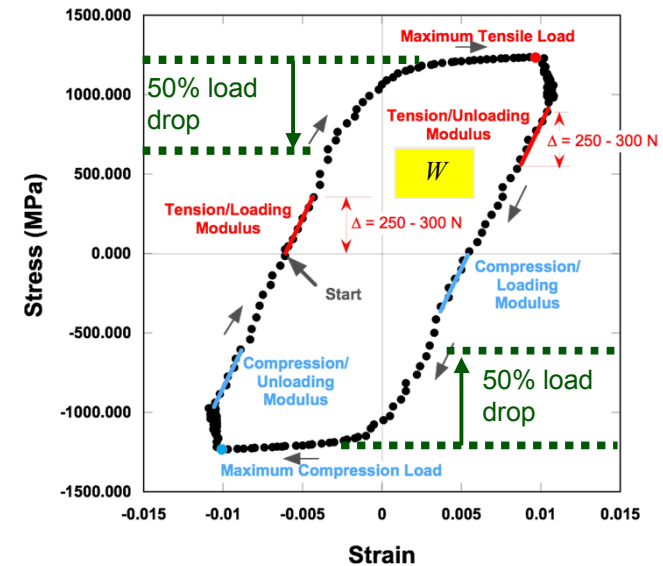
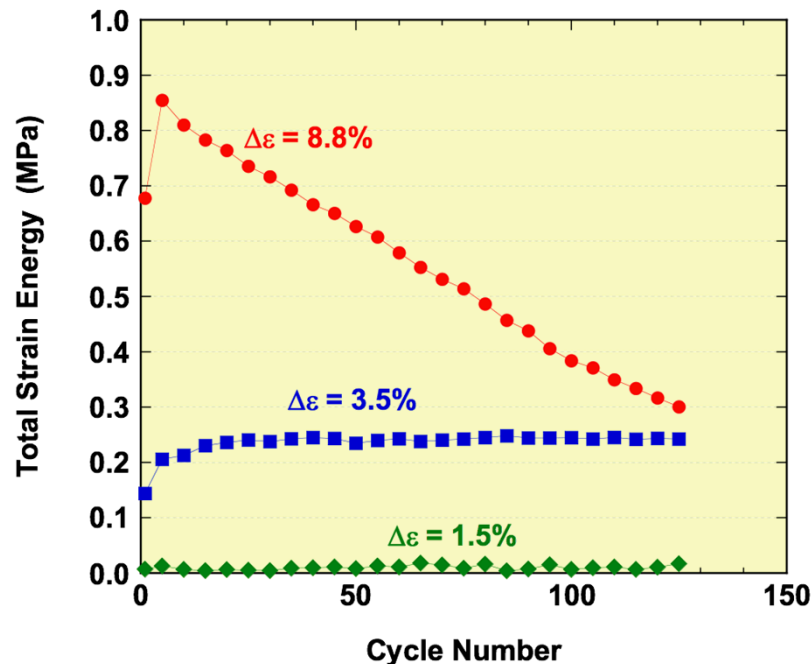
- ◆ **Empirical methods** are based largely upon the testing of *applicable* solder joint configurations.
 - Recall, there is very little correlation between the bulk solder properties and those of the solder joint structure.



Reliability – Solder Joint Fatigue

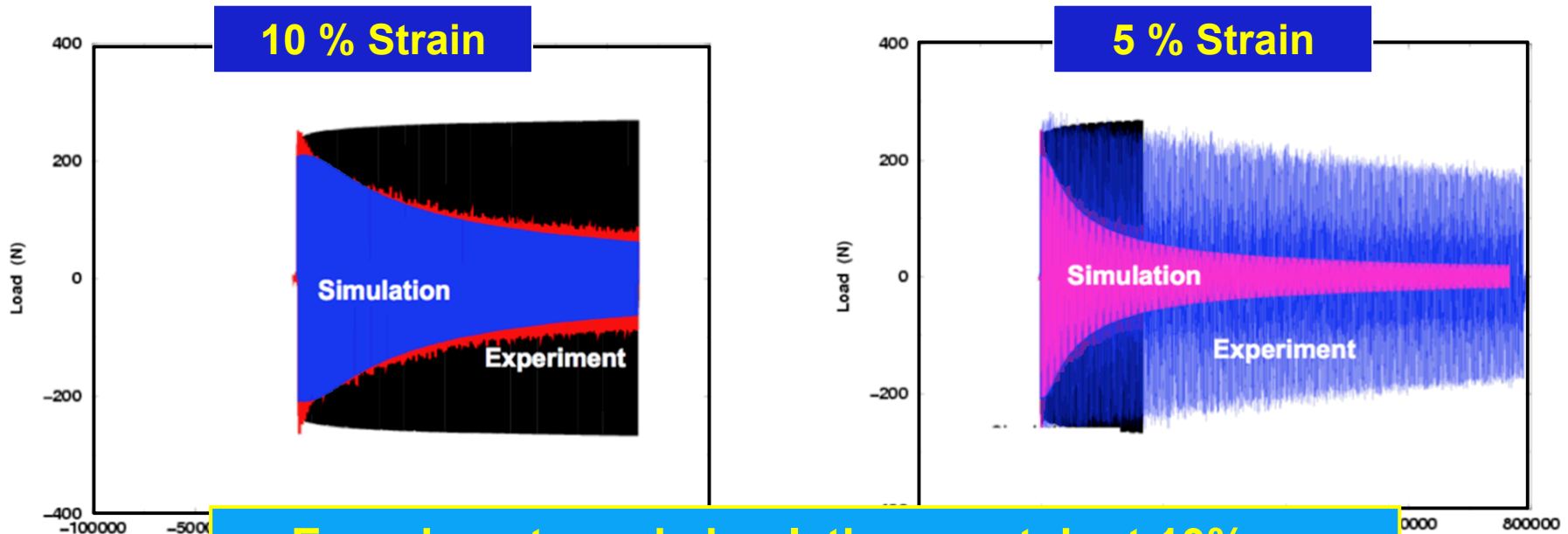
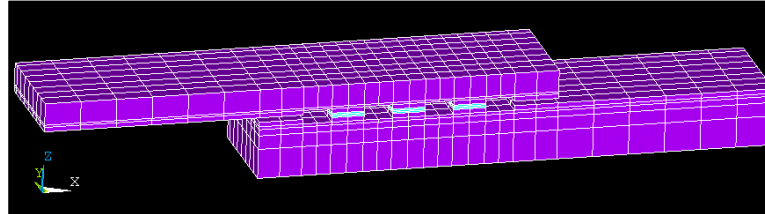
◆ Isothermal fatigue: The limited work has not addressed several interesting phenomena:

- e.g., the significant improvement in fatigue life when decreasing from $\approx 9\%$ total strain to $\approx 4\%$.



Reliability – Solder Joint Fatigue

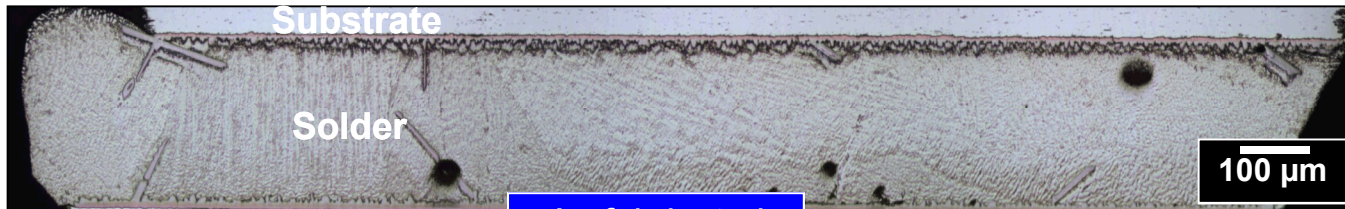
- ◆ This fatigue behavior of Sn-based solders has also been documented in constitutive modeling studies.



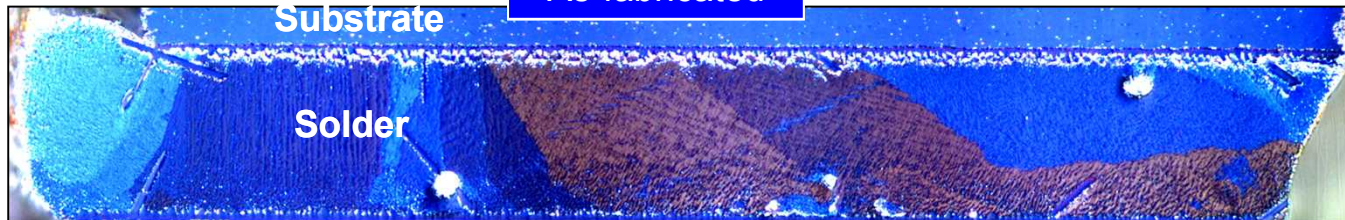
- Experiments and simulations match at 10% strain, but not so well at a reduced strain of 5%.

Reliability – Solder Joint Fatigue

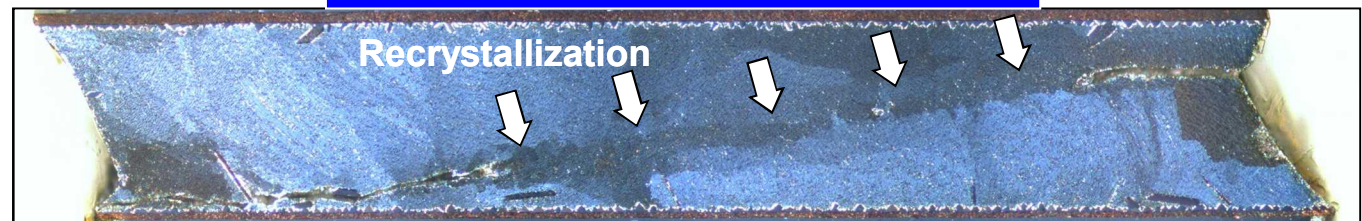
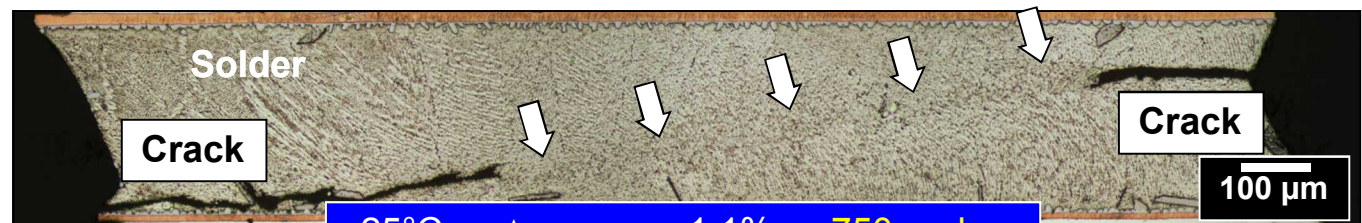
- ◆ The onset and magnitude of **dynamic recrystallization** likely has a significant role in the fatigue behavior.



Bright-field



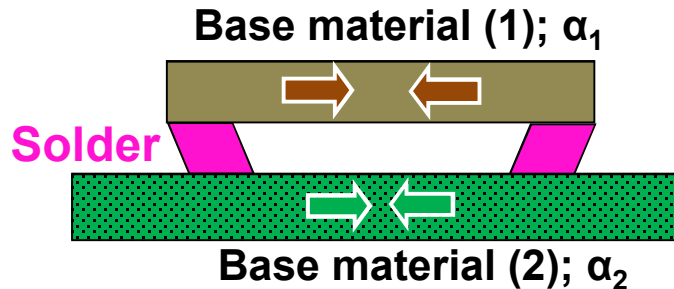
Polarized light



Reliability – Solder Joint Fatigue

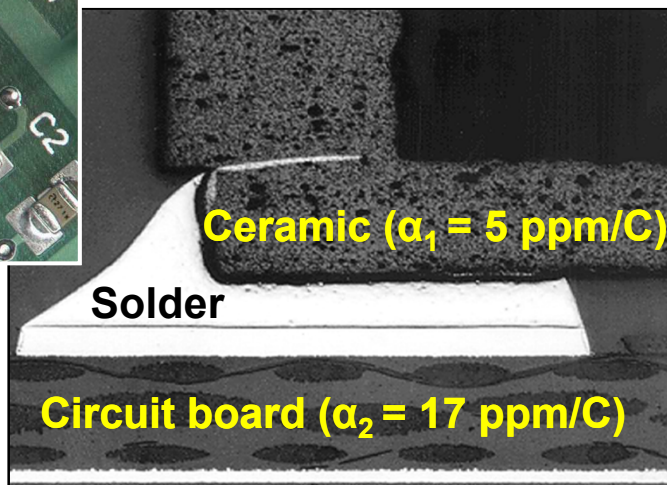
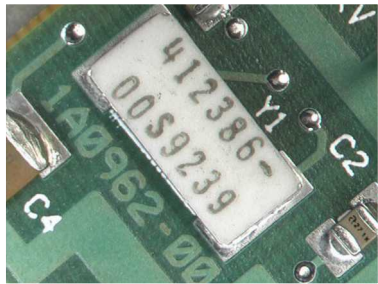
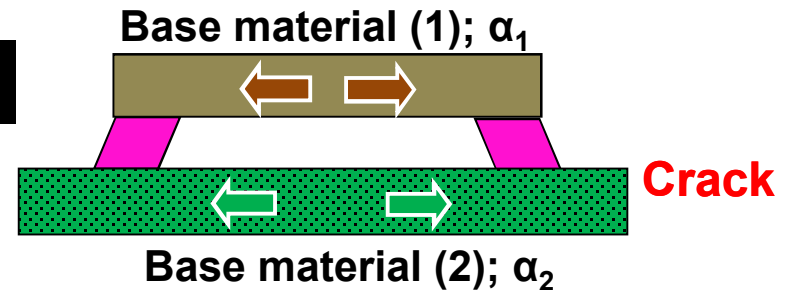
- ◆ A failure mode is **thermal mechanical fatigue (TMF)**.
 - Combination of temperature cycling and the mismatch of base material, coefficients of thermal expansion (CTE), α .

Cooling ... contraction

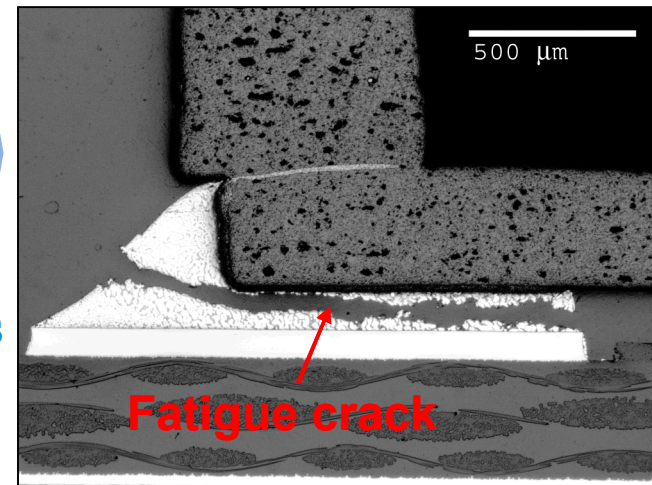


Heating ... expansion

$$\alpha_2 < \alpha_1$$

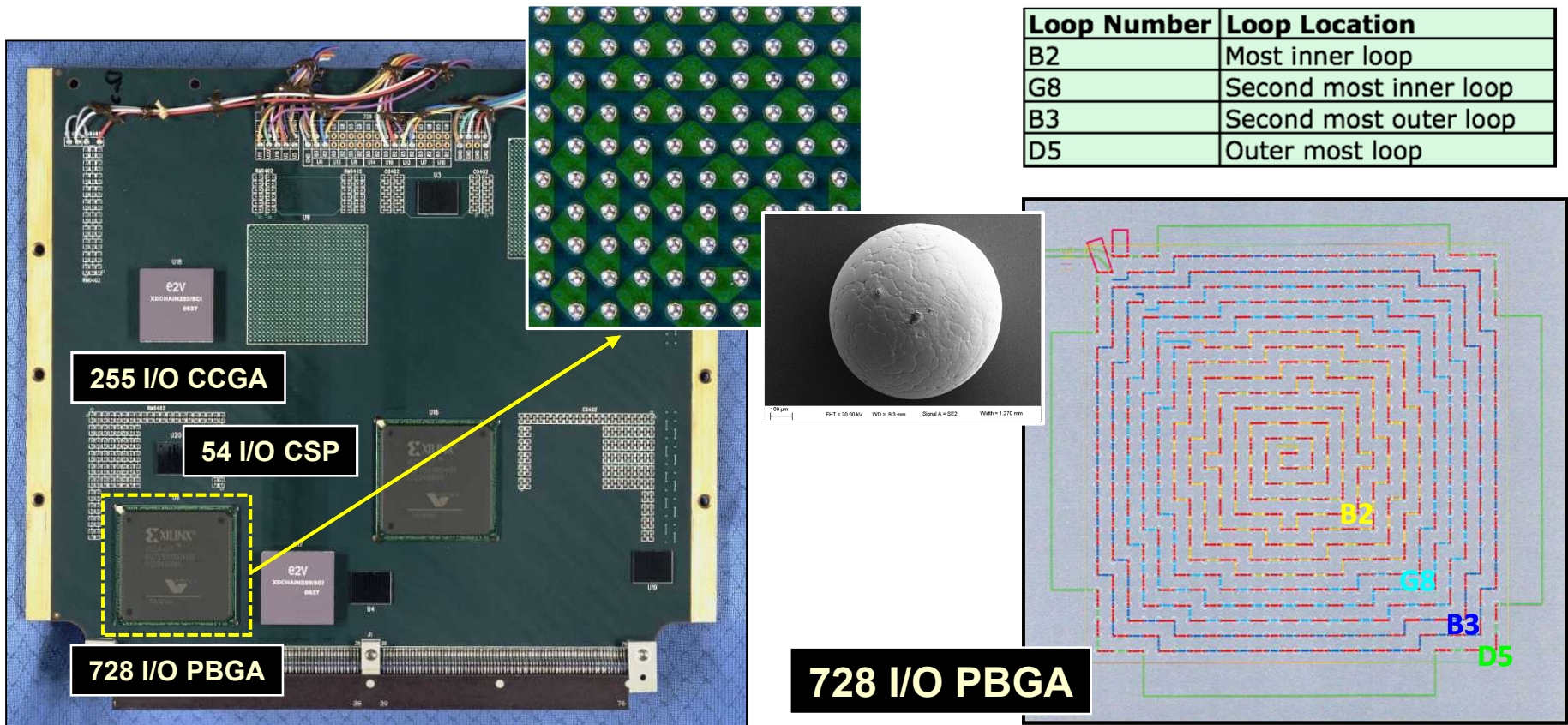


1000 cycles
-55°C/125°C



Reliability – Solder Joint Fatigue

- ◆ **Temperature cycling** is used to assess the resistance of solder joints to **thermal mechanical fatigue (TMF)**.
 - The test vehicle uses daisy chain loops to establish signal continuity, the metric for solder joints failure.



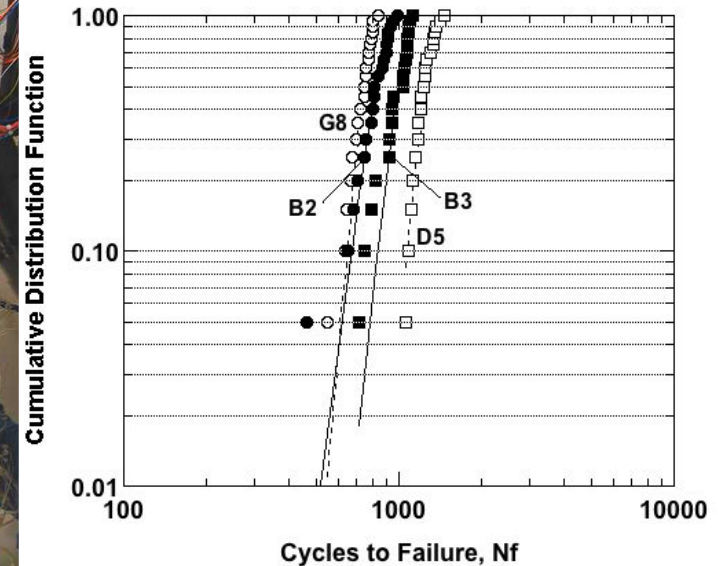
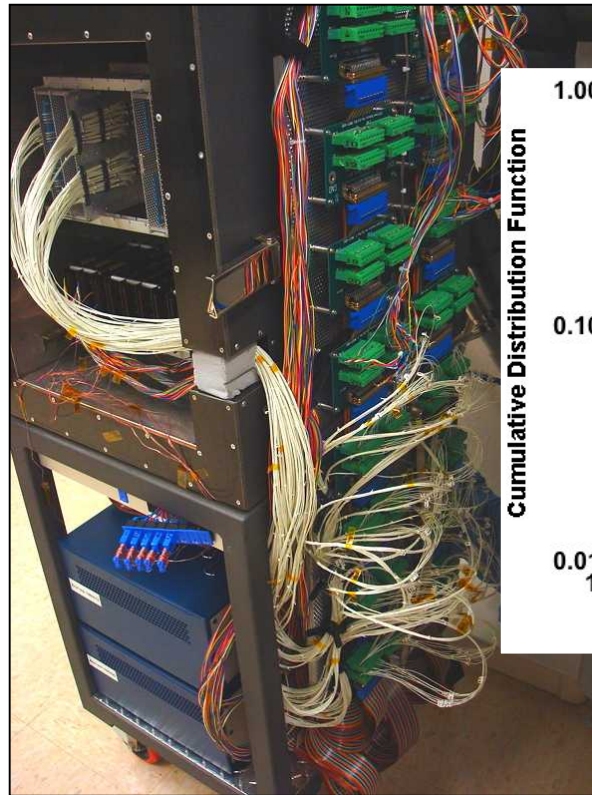
Reliability – Solder Joint Fatigue

- ◆ Solder joints do not fail “cleanly” under shear strain.
- ◆ Daisy chain continuity is monitored by **event detectors**.



Test vehicles: wired and stacked in the thermal cycling chamber.

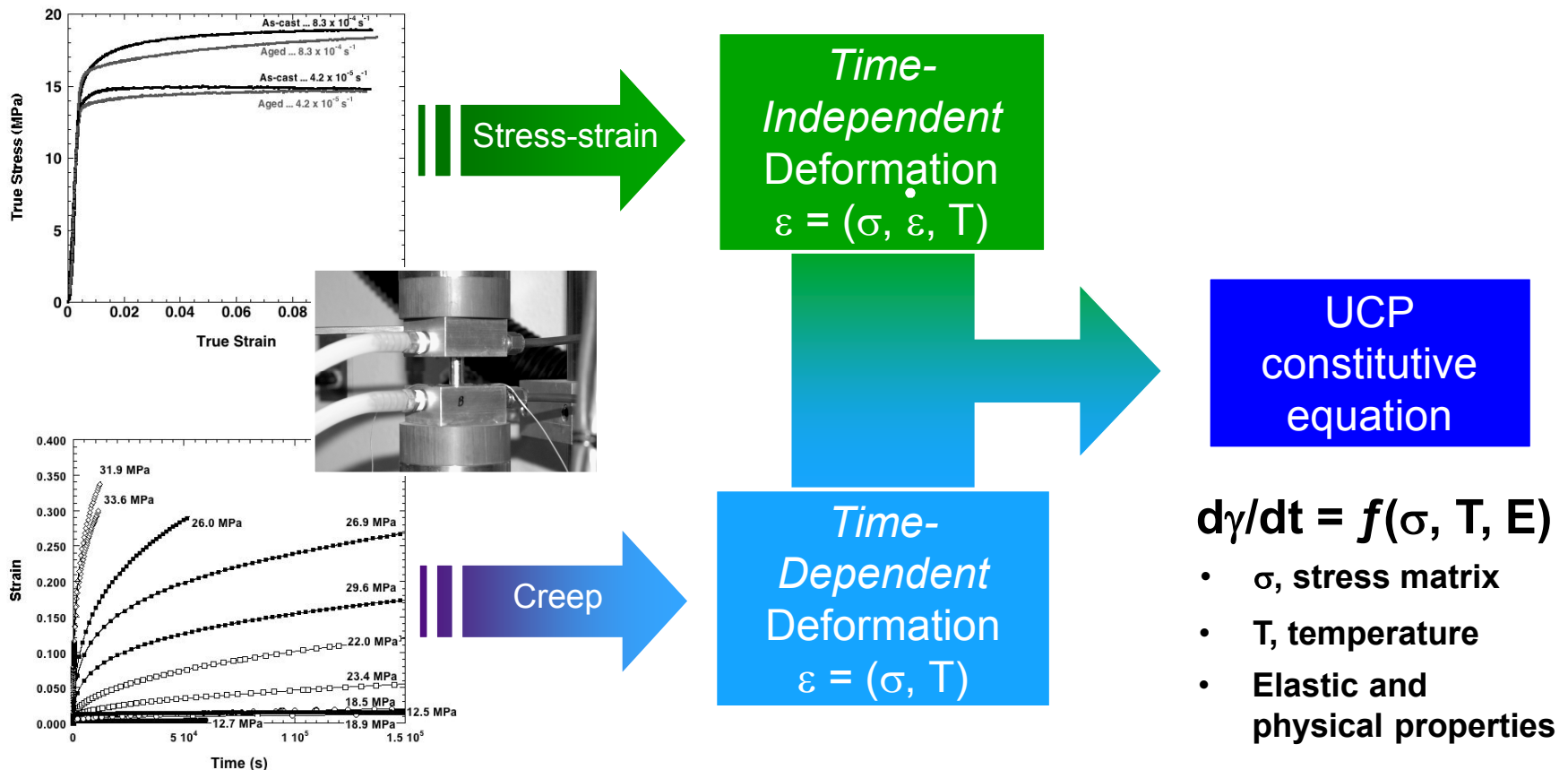
Wiring is attached to the event detectors.



Data analysis using the Weibull statistics

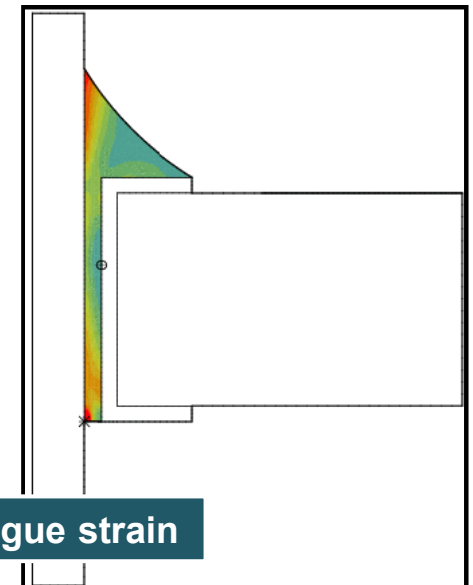
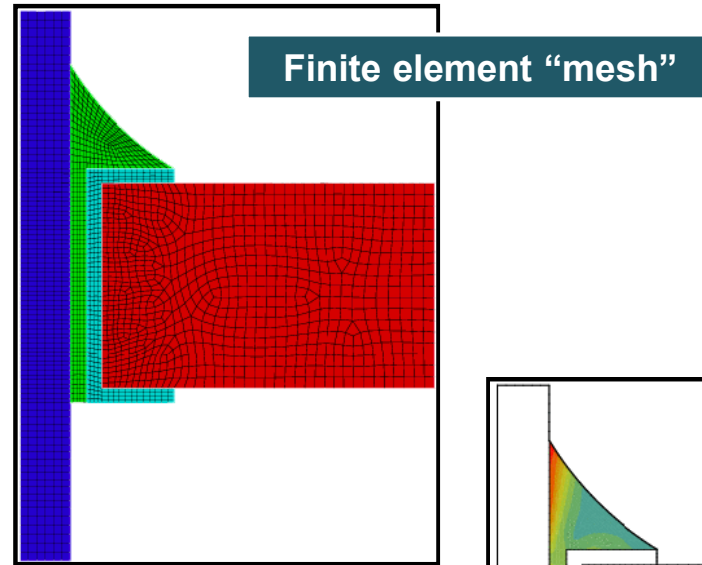
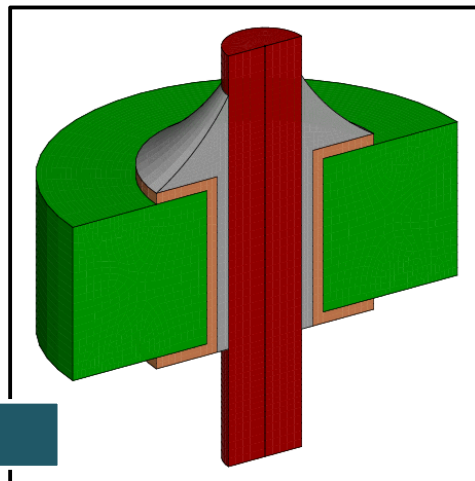
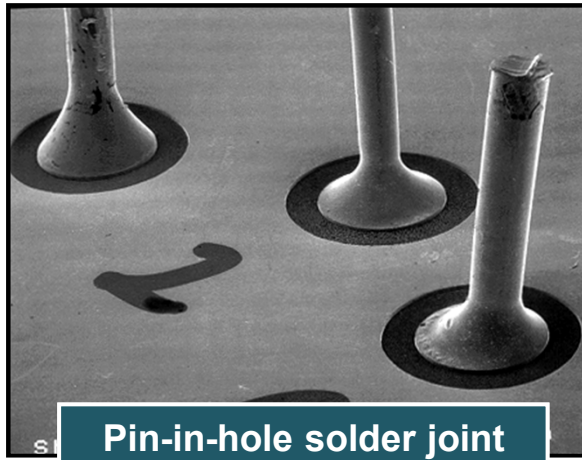
Reliability – Solder Joint Fatigue

- ◆ The **computational modeling** approach is based upon the development of **unified creep-plasticity equation**.
 - Combine time-independent and time-dependent deformations



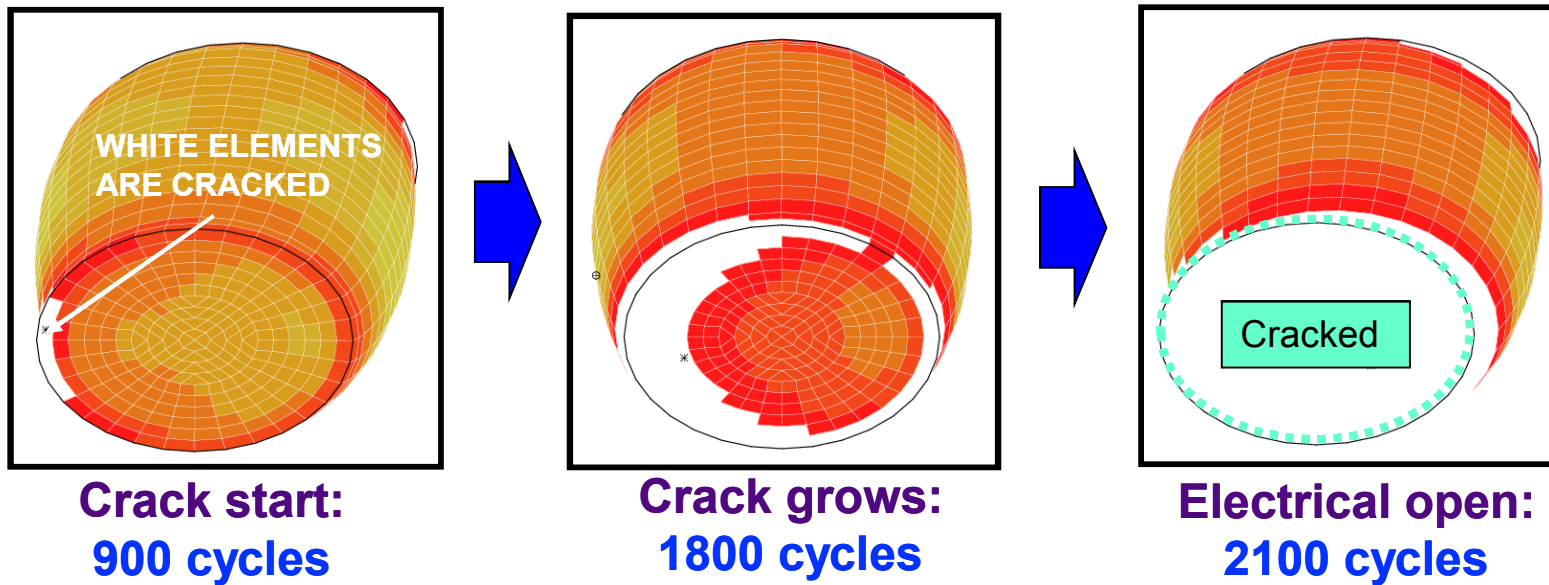
Reliability – Solder Joint Fatigue

- ◆ The unified creep-plasticity equation is then applied to the solder joint structure using **finite element models**.



Reliability – Solder Joint Fatigue

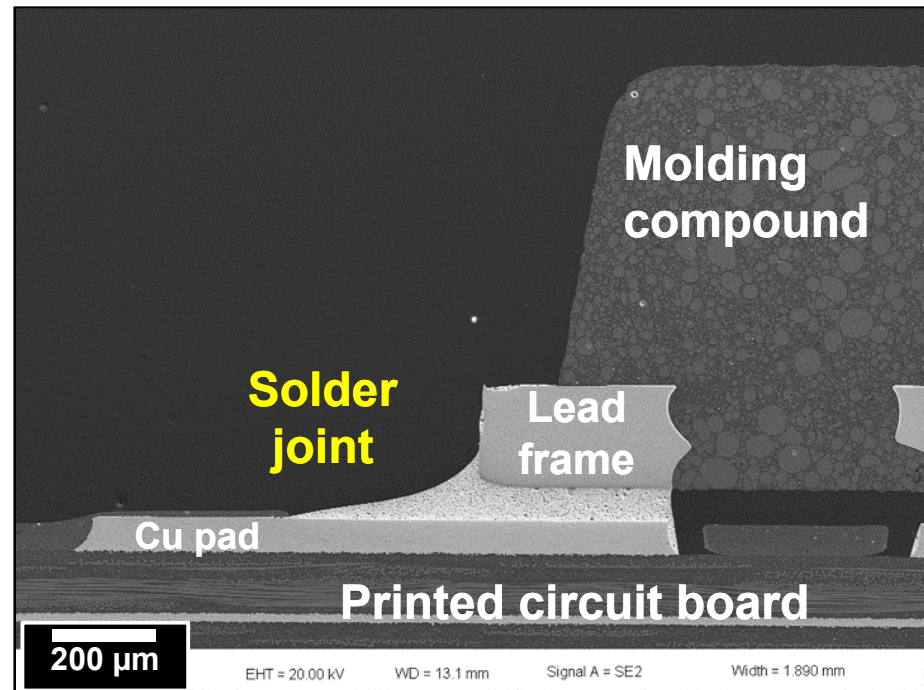
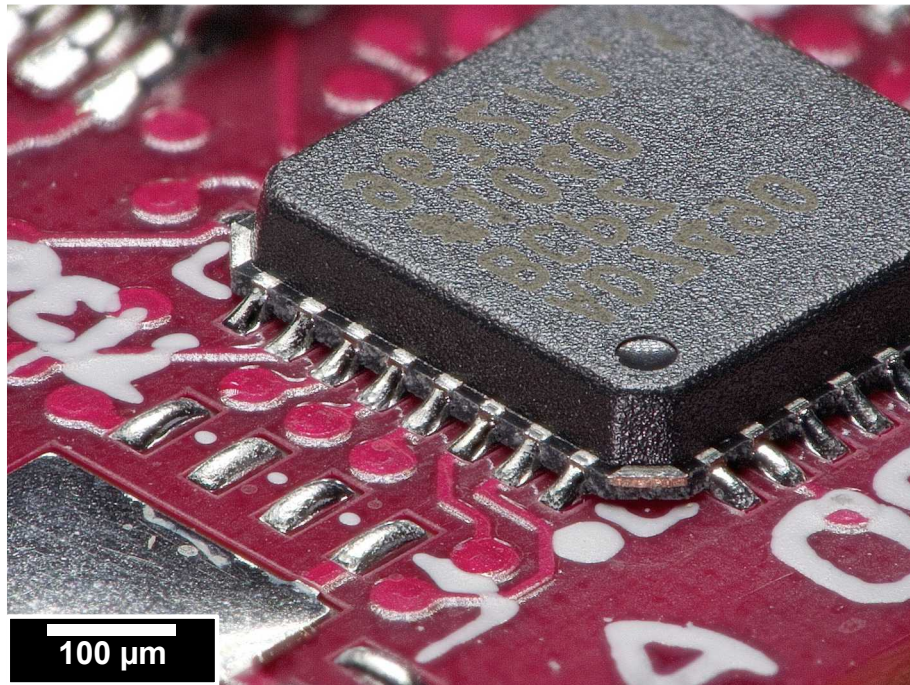
- ◆ The solder fatigue models now have the capacity to **predict crack growth** in the solder joint, as well.



- ◆ The advantages of the crack growth model are:
 - Document the morphology of crack propagation.
 - Determine load-bearing capacitor of partially cracked joints.
- ◆ Crack growth predictions are validated by empirical data.

Reliability – Solder Joint Fatigue

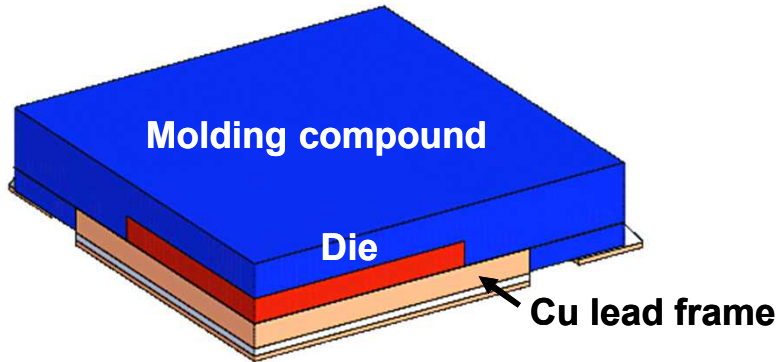
- ◆ The **crack propagation model** is demonstrated for the popular **quad flat, no-lead (QFN)** electronic package.



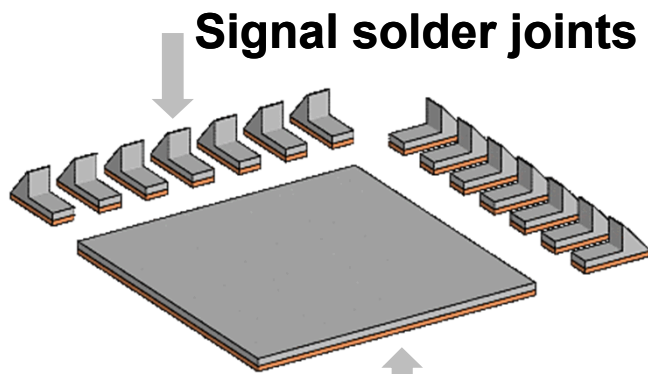
- ◆ There are so many variants of the QFN package that **empirical reliability testing is both cost and schedule prohibitive**, which leaves computational modeling.

Reliability – Solder Joint Fatigue

- ◆ The computational model predicts crack behavior.

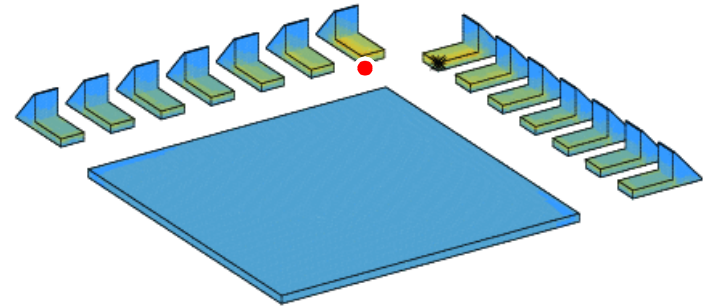


QPFN package and solder joints (*quarter-symmetry*)

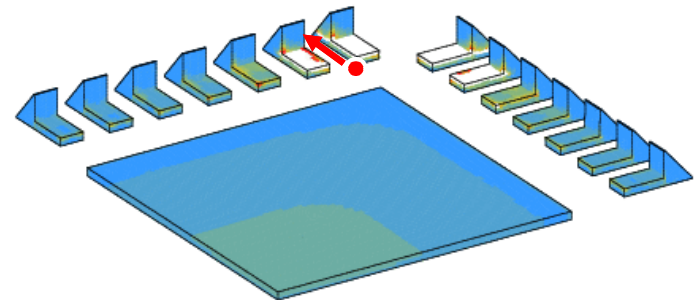


Paddle solder joint

Crack initiation ... 1800 cycles

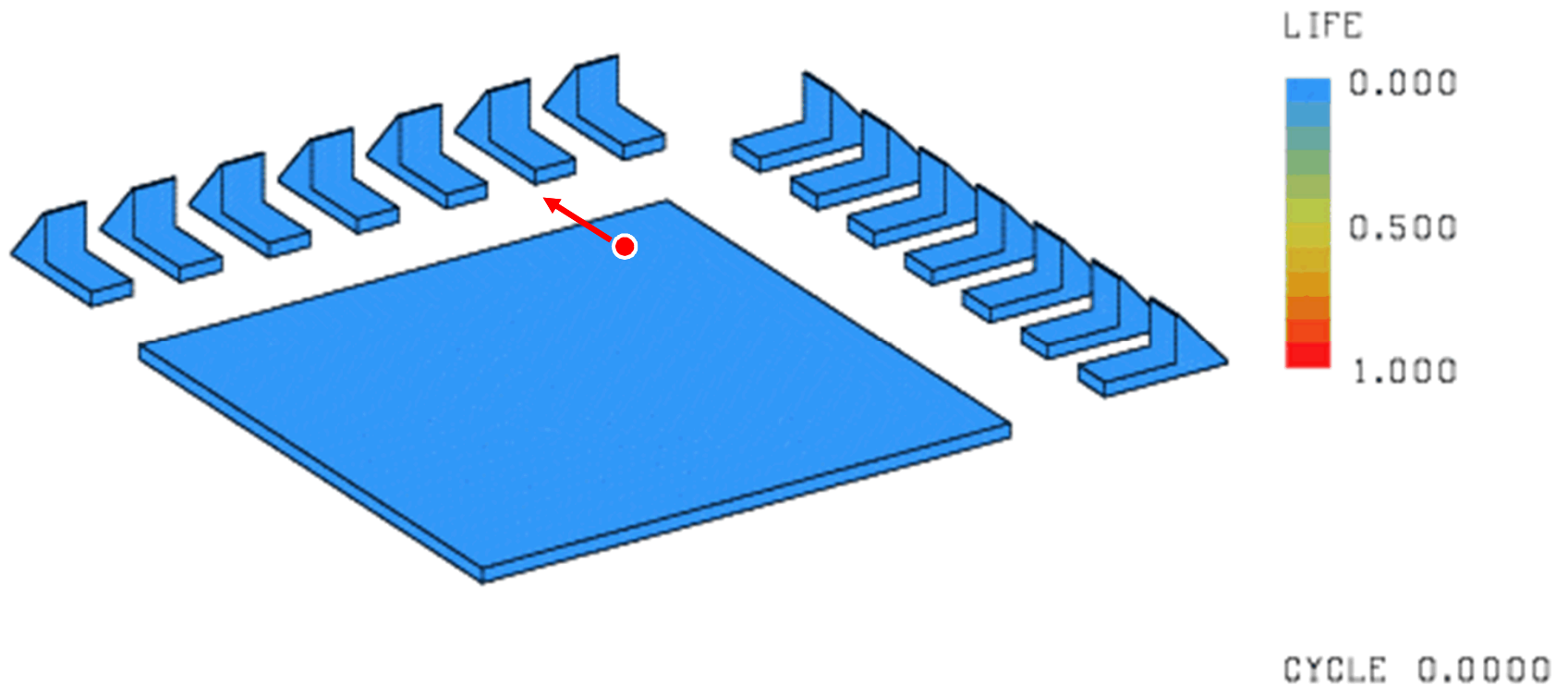


100% crack ... 7800 cycles



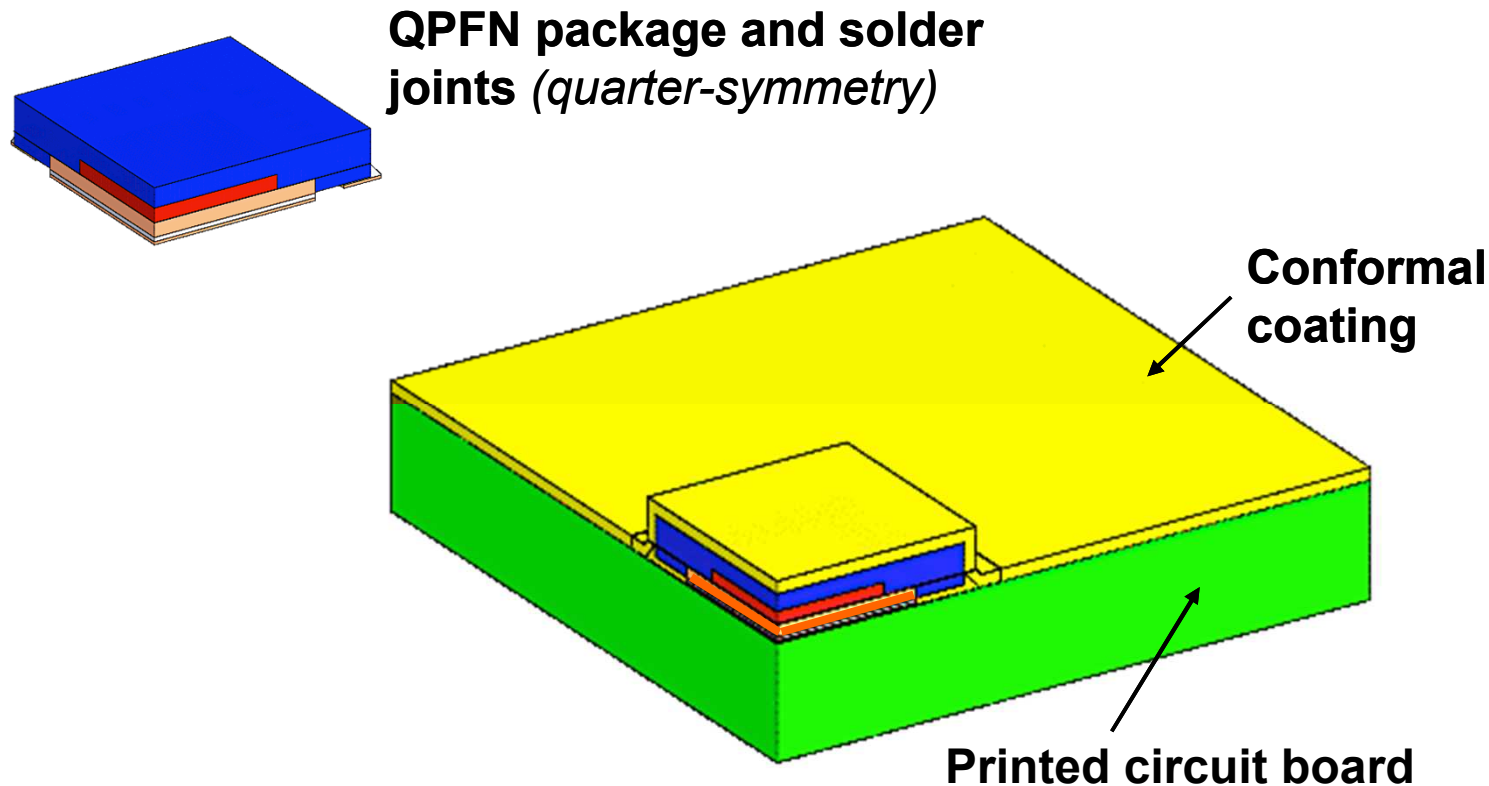
Reliability – Solder Joint Fatigue

- ◆ The software creates a movie of the crack propagation.



Reliability – Solder Joint Fatigue

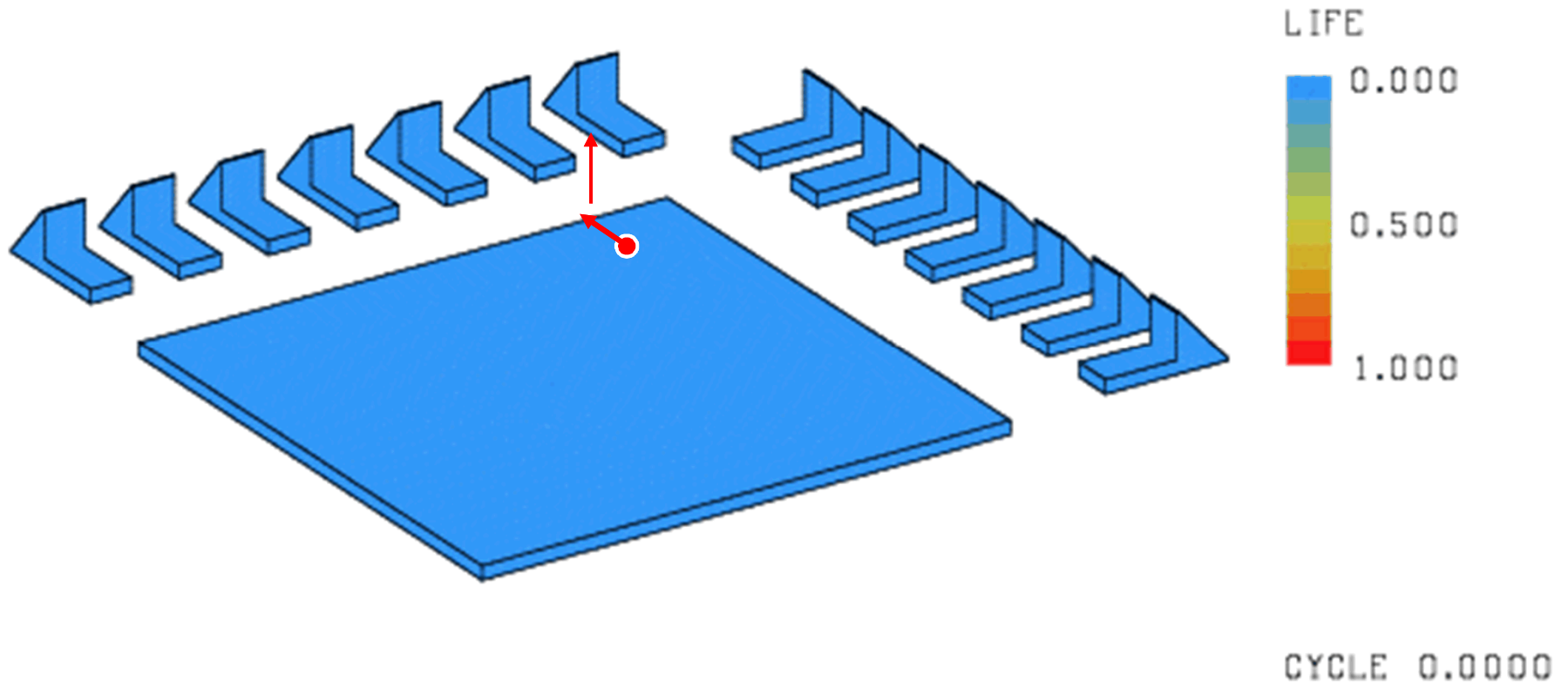
- ◆ The presence of coatings that flow under the package have a significant effect on fatigue crack growth.
 - Movies visualize the change in crack propagation.



Reliability – Solder Joint Fatigue

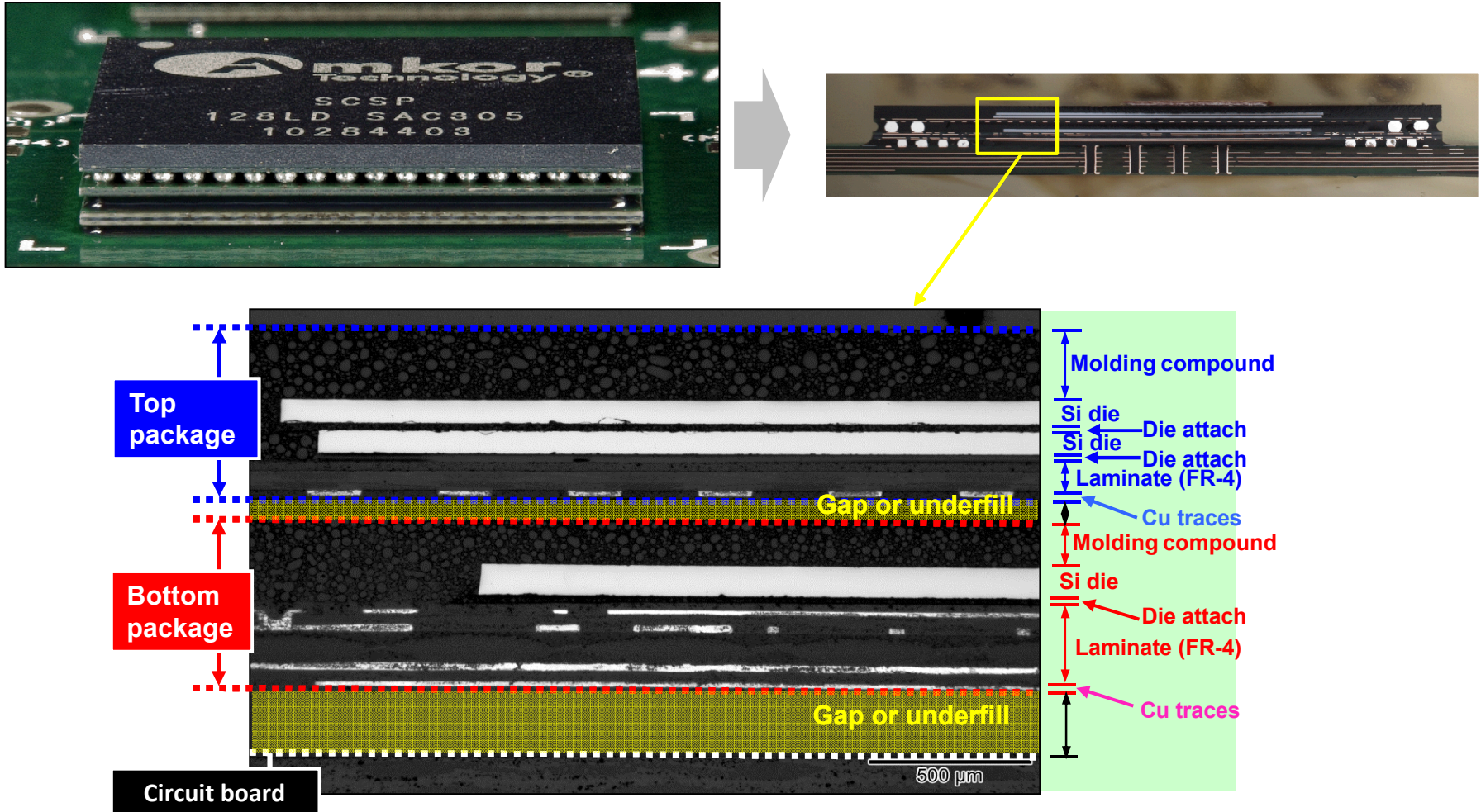
- ◆ The conformal coating altered the crack path.

100% crack ... 160 cycles



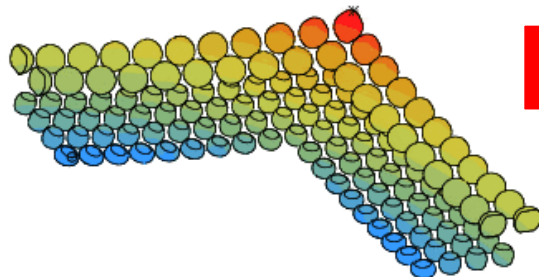
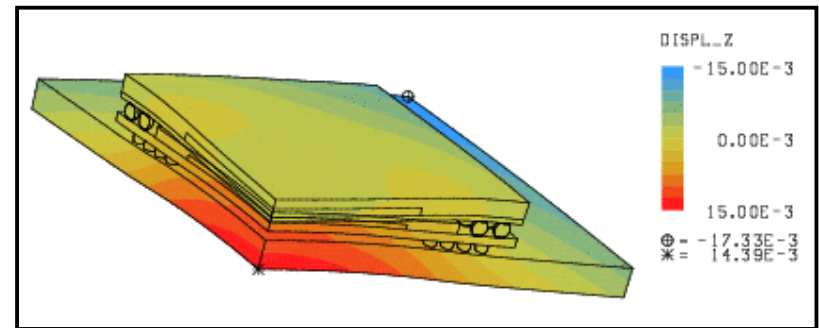
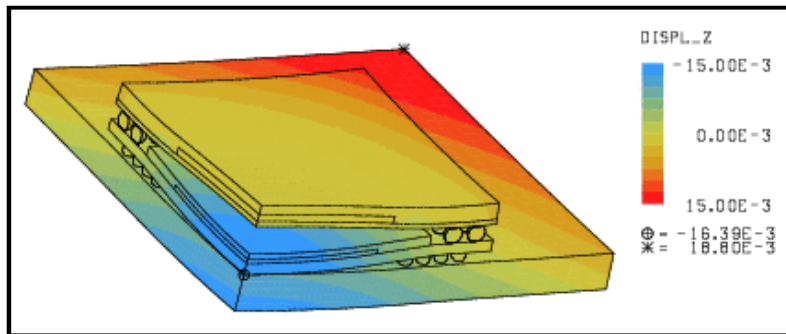
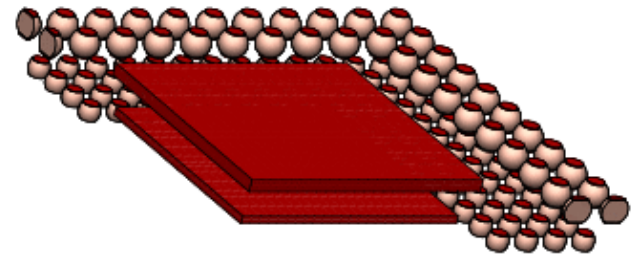
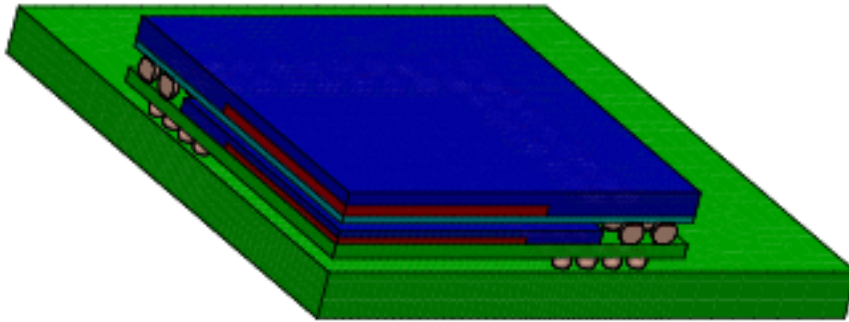
Reliability – Solder Joint Fatigue

- ◆ **Stacked package technology** presents very complex structures that are well suited for numerical models.

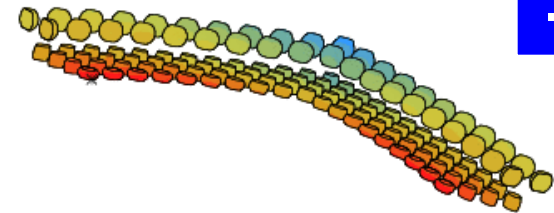


Reliability – Solder Joint Fatigue

- ◆ Computational modeling predicts behaviors that are not intuitively obvious due to the complex construction.



125C

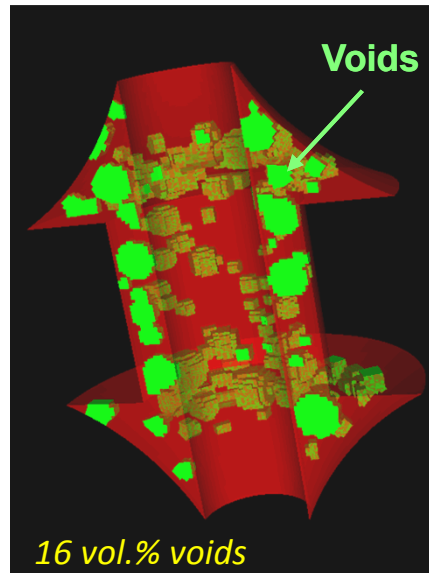
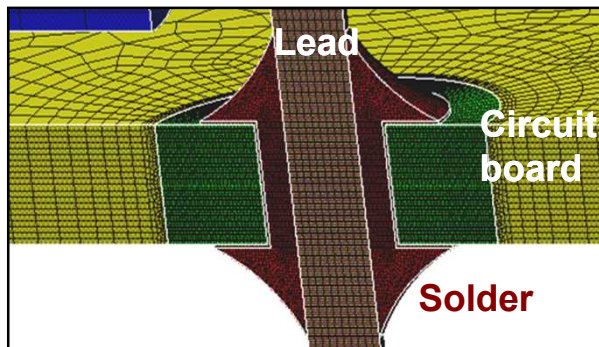
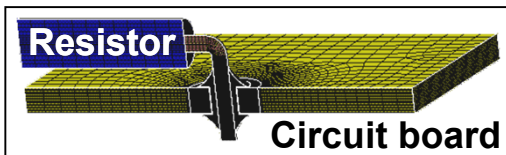


-55C

Reliability – Solder Joint Fatigue

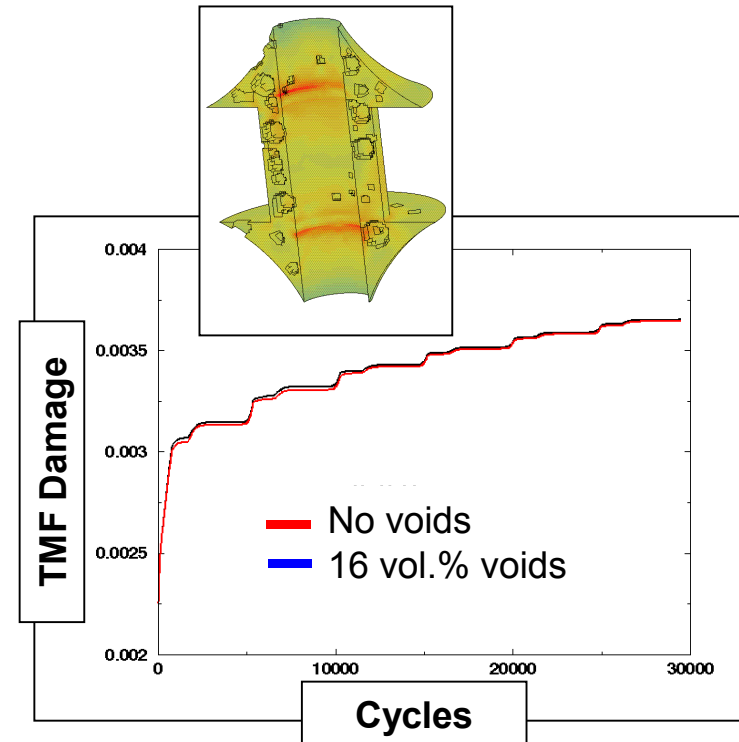
- ◆ Computational modeling predicts behaviors that are not intuitively obvious due to the complex construction.

Finite element mesh



Void sizes and distribution replicated observations of an actual solder joint.

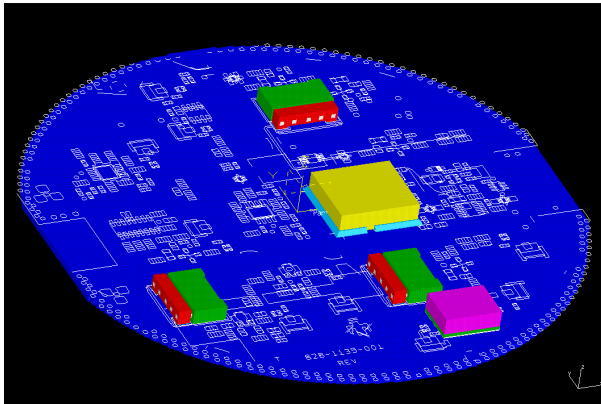
Model prediction



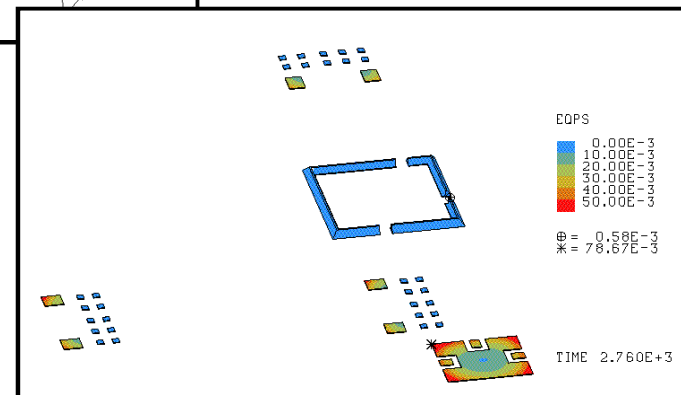
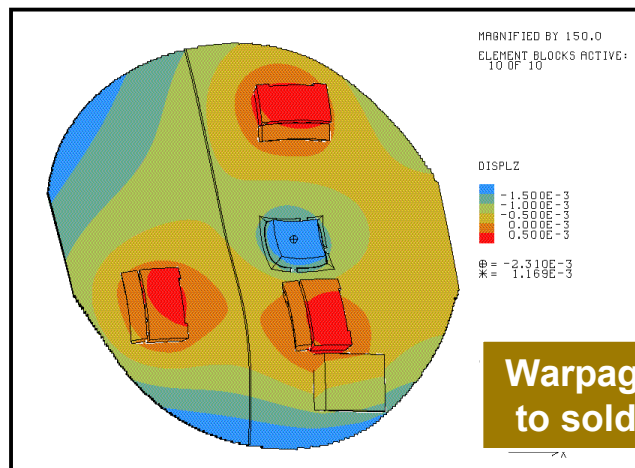
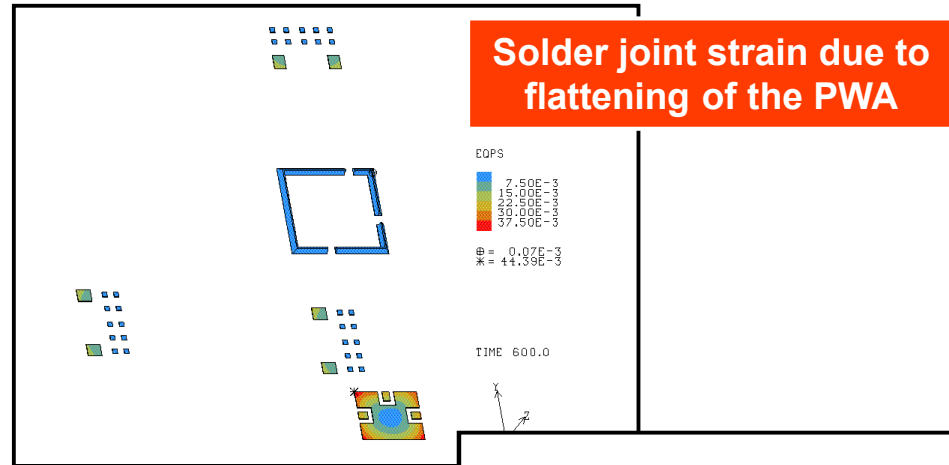
- ◆ Voids of 0 – 16 vol.% content do not affect reliability.

Reliability – Solder Joint Fatigue

- ◆ Computational model can readily address the effects of **sequential environments** on solder joint reliability.

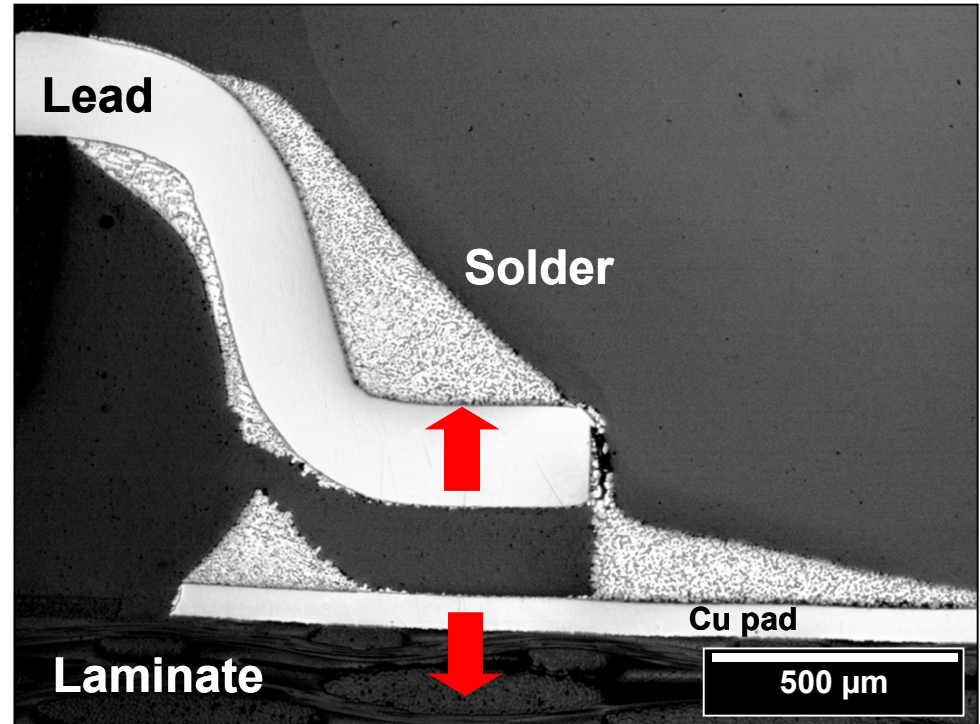
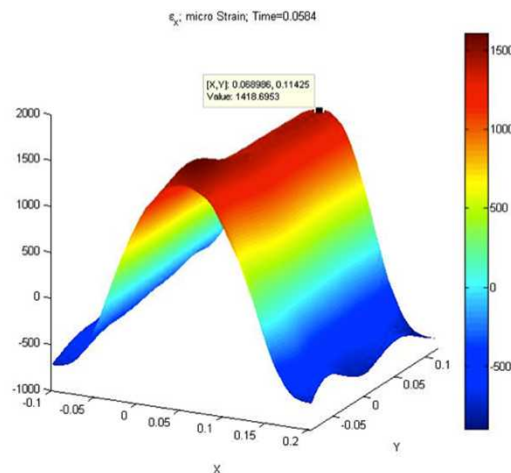
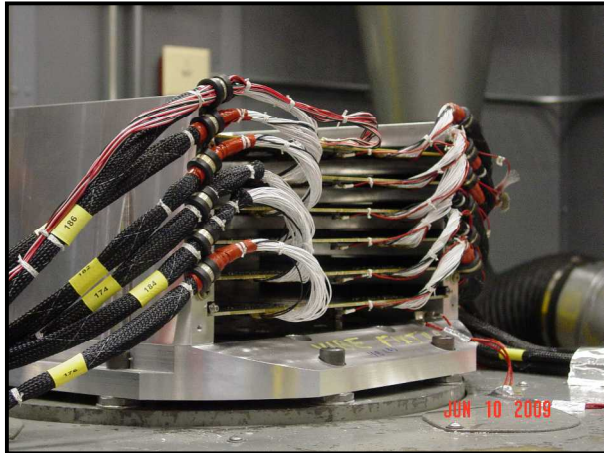


Printed wiring assembly (PWA)



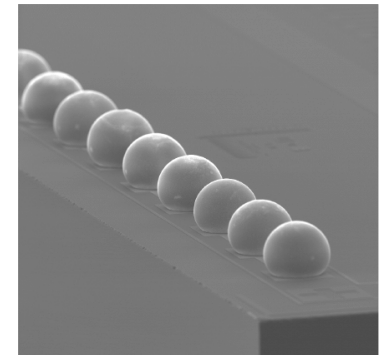
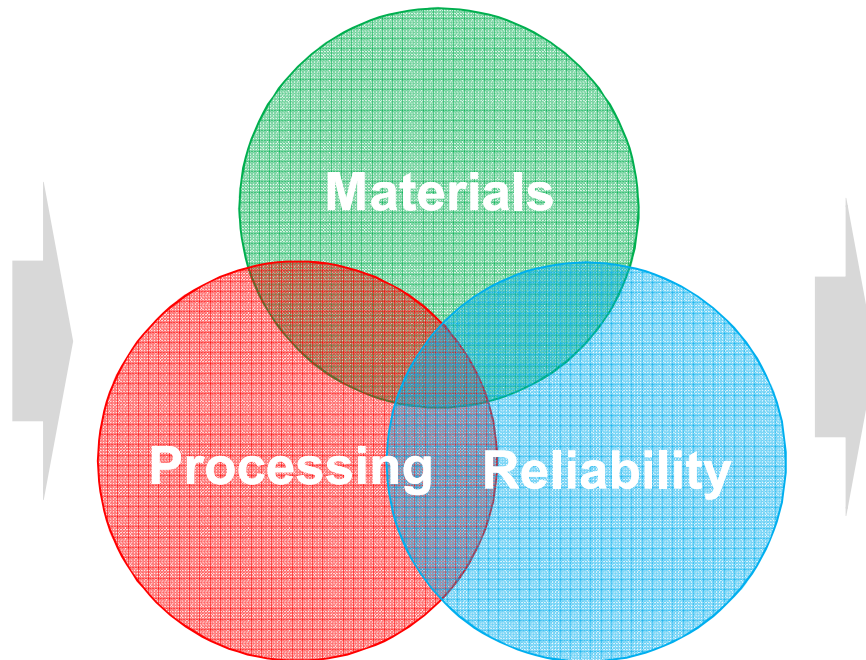
Reliability – Solder Joint Fatigue

- ◆ Vibration performance (high-cycle fatigue) has not received as much attention for solder interconnections.



The physical and mechanical metallurgy of high-cycle fatigue is not well-understood.

Summary



Acknowledgements

- ◆ A.C. Kilgo
- ◆ B.M. McKenzie
- ◆ R.L. Grant
- ◆ M.K. Neilsen
- ◆ A.D. Romig (ret.)
- ◆ M.J. Cieslak (ret.)
- ◆ J.A. Rejent (ret.)
- ◆ J.M. Grazier (ret.)
- ◆ P.L. Hlava (ret.)
- ◆ W.L. Buttry (ret.)
- ◆ G.L. Zender (ret.)
- ◆ W.O. Wallace (dec.)

