Materials Issues for Developing a Reliability Methodology

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Critical Materials Issues for Developing a Reliability Methodology

Experiments needed to characterize solder joint behavior

What is the set of experiments needed to completely characterize solder joint behavior as input into reliability modeling ?

Strengths and weaknesses in existing techniques

What improvements are necessary?

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Critical Materials Issues for Developing a Reliability Methodology

- Materials Aspects of Solders
  - Physical/Mechanical Metallurgy Characterization
- Materials Test Aspects
  - Accelerated Test $\stackrel{?}{=}$ Use Environment

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Purpose of Reliability Testing and Evaluation

Predict the performance of components for the “use environment” through an accelerated test methodology

- Minimum number of tests in the shortest time
- Accelerated factor correlation must be known
- Desire validated models to predict behavior to minimize testing

Materials behavior determines performance. Can accelerated tests give “true” materials response?

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Materials Aspects: Metals

Metals used in packaging include:

- Die level interconnects (Al-Si-Cu, Cu)
- Solder interconnects (Sn-Pb, Pb-free)
- Leadframe materials (Cu, Alloy 42)

Reliability issues with metals in packaging primarily involve interconnects, and most often the solder joints

Polymer issues

- Adhesion, thermal degradation, delamination, etc.
- Not discussed here, but take into account...

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Materials Aspects: Pb-free Solders

- Environmental legislation and market opportunities have resulted in Pb-free solder development
  - Sn-rich solders
    - Board-level interconnect: Sn-Ag-Cu, Sn-Ag-Bi, Sn-Ag-Cu-Ge, Sn-Ag-Cu-Sb, Sn-Zn, Sn-Cu (wave soldering)
    - Flip chip interconnect: Sn-Cu
    - Die attach: Sn-Sb
  - Higher process temperatures may degrade package materials
  - Different physical and mechanical behavior than Sn-Pb
    - Different reaction kinetics and products with bond pads
    - Greater strength
    - Slower creep
      - Damage into components possible
    - Different TMF behavior

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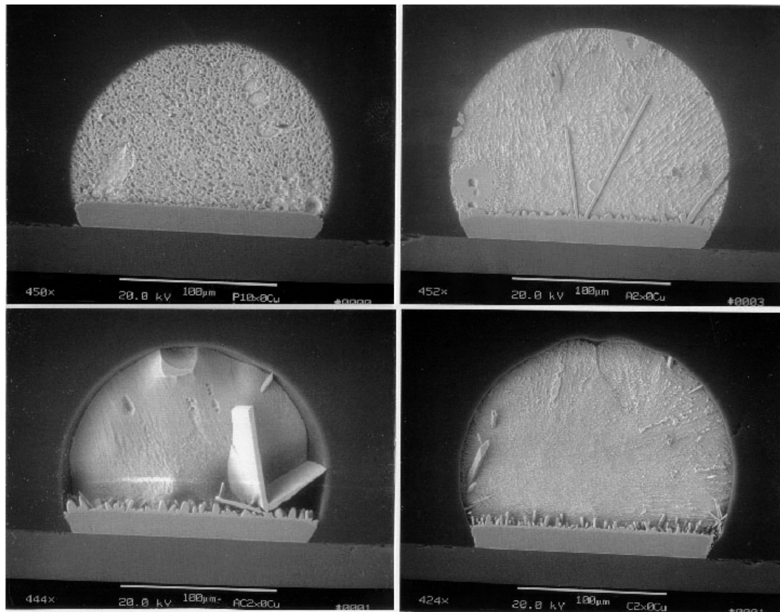
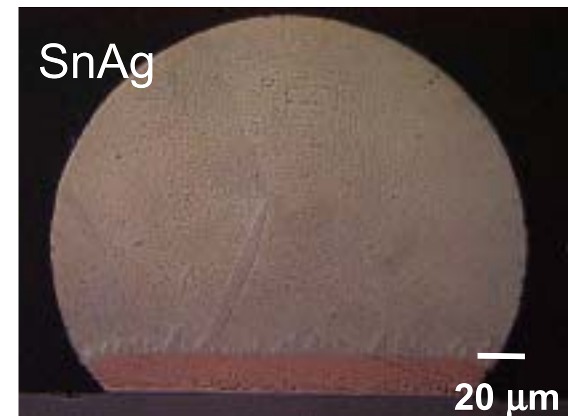
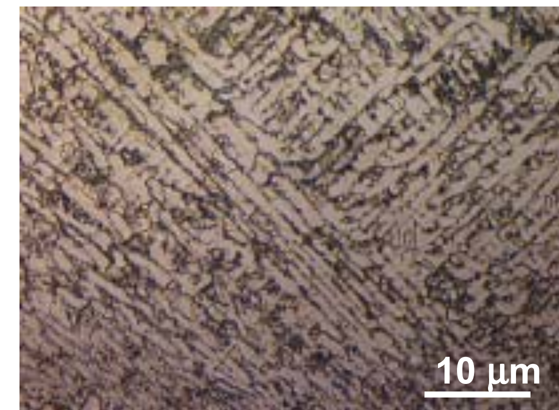
Microstructural Characterization

- Microstructural techniques must be consistent
- Clearly define microstructural features







Etching procedure for Pb-free*
Microstructure: 10%hydrochloric acid+90%methonol for a few seconds
IMC surface: 4 parts glycerol+1 part acetic acid+1part nitric acid at 80°C

* Developed at UCLA under Prof. K.-N. Tu

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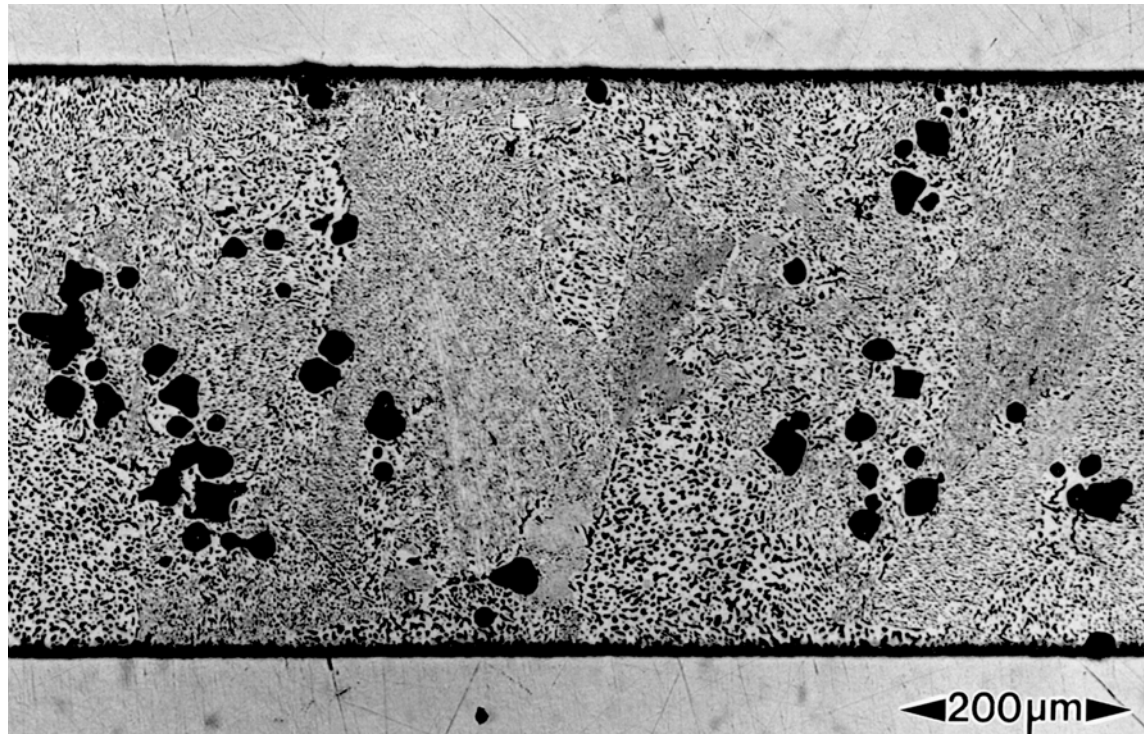
Microstructural Characterization

- Sn-Pb solder has a eutectic microstructure
  - Two-phase mixture of Sn-rich and Pb-rich grains
  - Colony structure dominates mechanical properties
    - Colonies separated by coarsened regions
  - Structure coarsens at temperature and under strain



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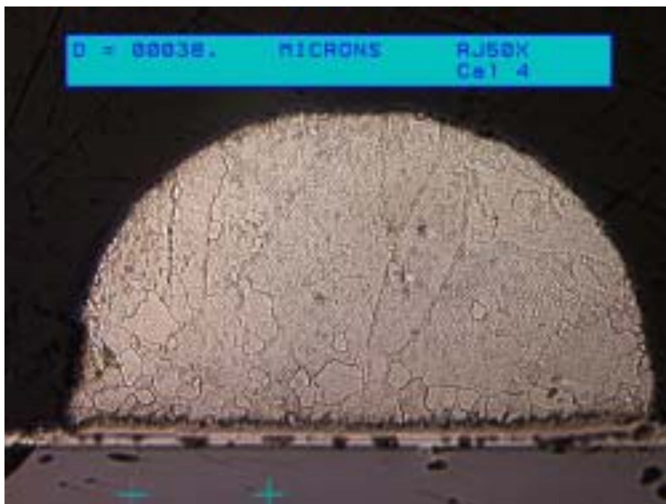
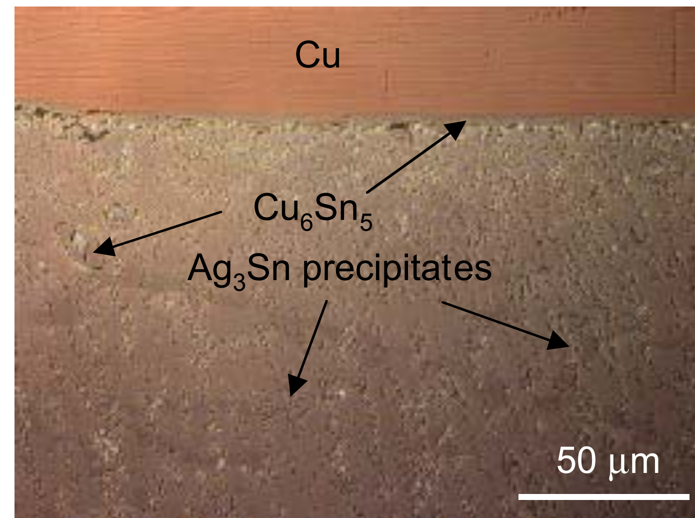
Materials Aspects: Pb-free Solders

- Microstructure of Pb-free solders
  - Sn-rich matrix with Sn-grains
  - Sn-Cu or Sn-Ni intermetallics at the interface and in the bulk of the solder
  - Less potential for microstructural evolution than Sn-Pb solders

SnCu



SnAgCu



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Whisker formation with Pb-free solders

- Whisker formation is known to occur in pure Sn
- Some evidence exists that in Sn-rich Pb-free solders whiskers may also form
- Accelerated testing for whisker formation is a “black art”
- No publicized acceleration test
- Testing needed...

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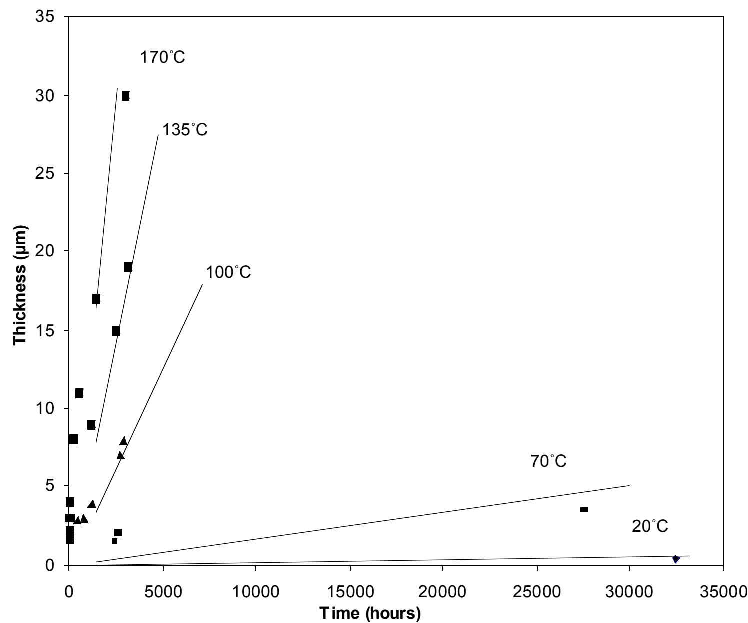
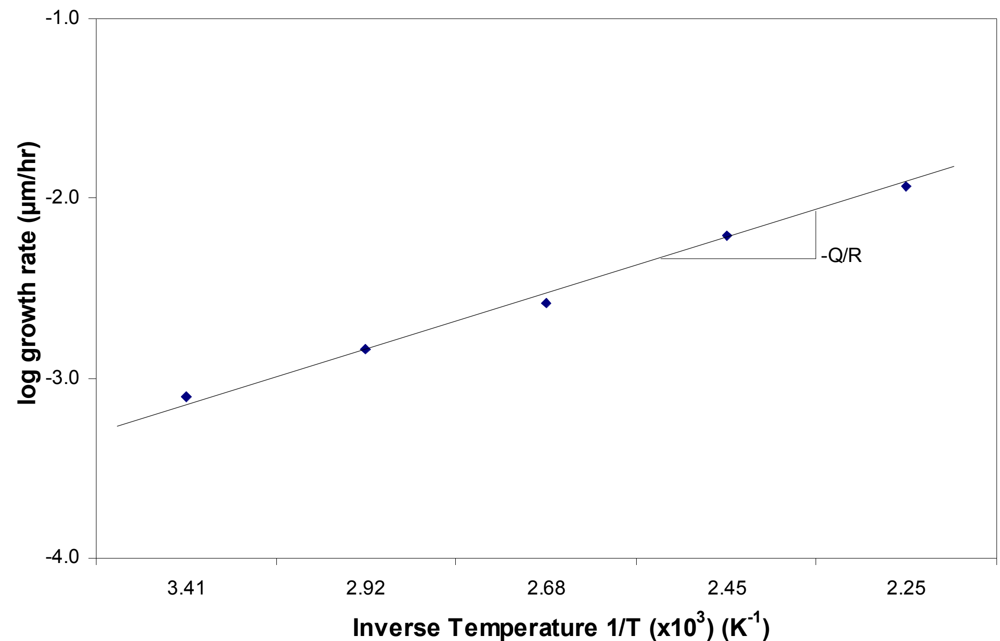
Materials Aspects: Intermetallic Growth

- Solder reacts with metallization to form an interfacial intermetallic
  - Typically Sn-based
- The intermetallic grows with time at temperature
  - During reflow and in the solid state
- Growth can be empirically measured through careful metallography
  - Fit to an Arrhenius equation ($x=Ae^{-Q/RT}$)





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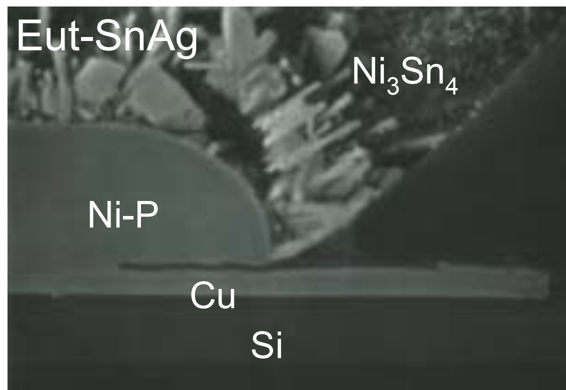
Materials Aspects: Intermetallic Growth

- Growth can be difficult to measure with the convoluted IM surface
  - A consistent measurement methodology must be used
  - Spalling must be taken into account



Ni_3Sn_4 spall off the Ni metallization into Sn-3.5Ag solder

- Becomes a reliability issue when
  - Solder consumes metallization layer
  - Brittle intermetallic becomes a significant fraction of joint thickness

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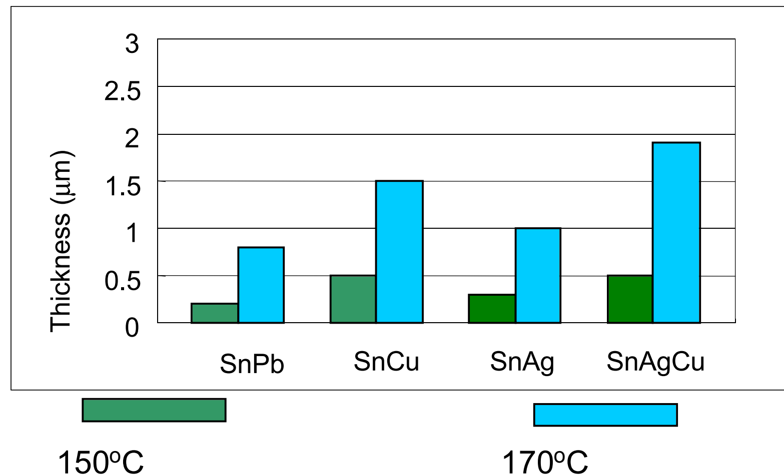
Materials Aspects: Metallization Consumption by IMC Growth

Ni metallization

Initial condition: 2 reflows

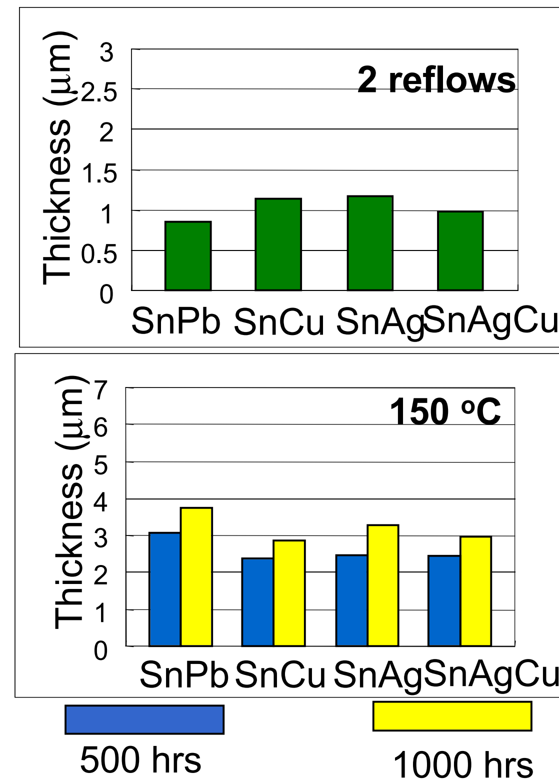
Annealing time: 1000 hrs



150ºC

170ºC

Cu metallization



- **Cu Consumption in liquid state: lead-free solder > SnPb solder**
  in solid state: lead-free solder < SnPb solder

The interfacial intermetallics change morphology and growth rate depending upon the solder alloy.

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Solder Joint Fracture Toughness

- Solder joints must withstand shock conditions
- Measure of shock resistance must be determined
- "Weak link" in solder joint believed to be the interfacial intermetallics
- Test techniques have been developed
  - Fracture Toughness Test (Modified Compact Tension Sample)
  - Nano-hardness testing
    - Determines strength and can measure fracture susceptibility

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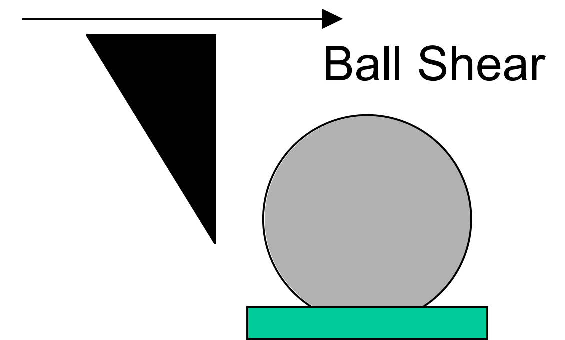
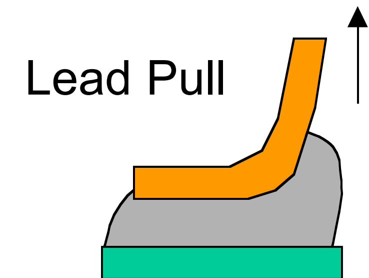
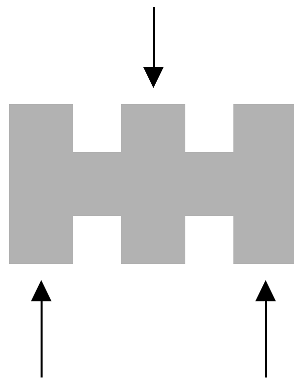
Solder Joint Strength

The strength of the solder is required for:

- Determining creep test parameters
- Inclusion into computation simulations
- A number of measurement techniques exist including
  - Bump/ball shear testing
  - Component or lead pull in tension or shear
  - Bulk solder testing (compression/tension/shear)
- Regardless of test, microstructure must be characterized







Bulk Shear Test

Bulk Tension/Compression

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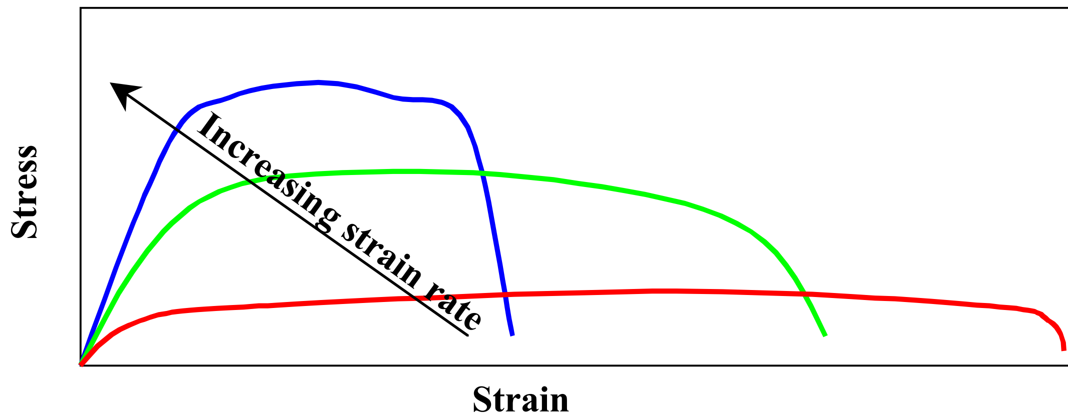
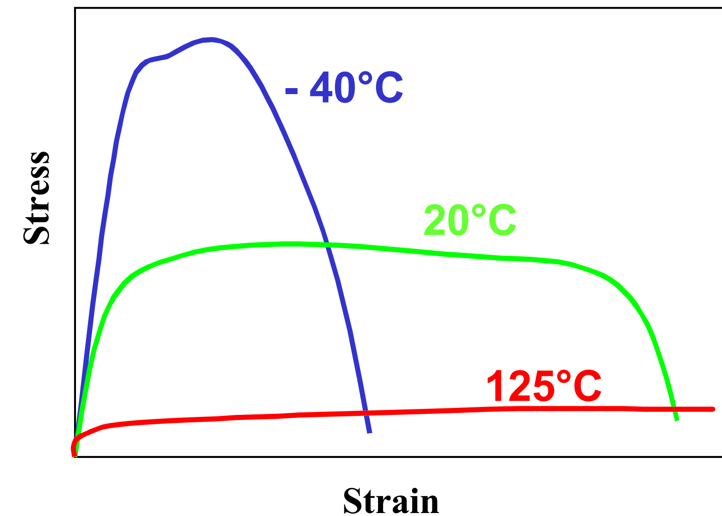
Solder Joint Strength

- Strain Rate Sensitivity
  - Solder has a high degree of sensitivity to changes is strain rate
  - Can impart damage to parts that is a test artifact
  - More critical in lower strength materials





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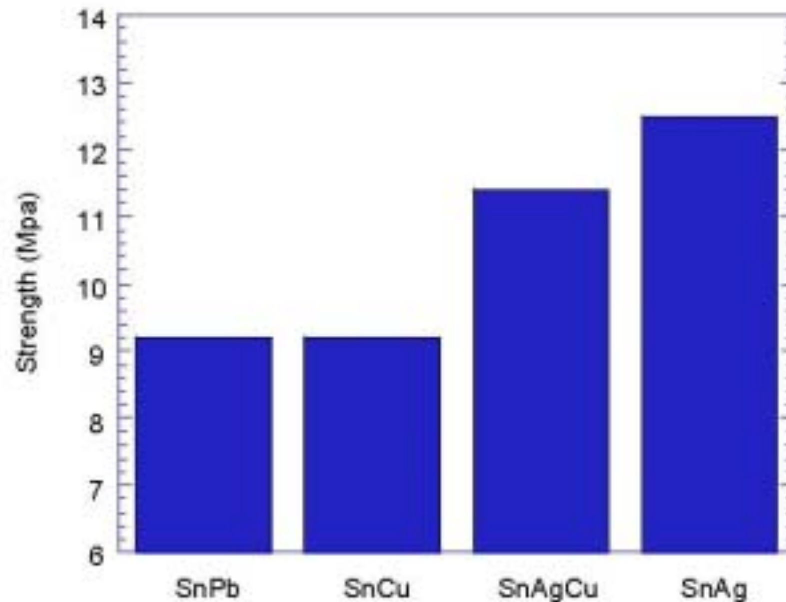
Solder Bump Shear Strength



All failures in solder away from interface

Cu-Sn and Sn-Pb have comparable shear strengths

Lower strength desired:

- Minimize potential impact to Si/package
- Damage limited to solder

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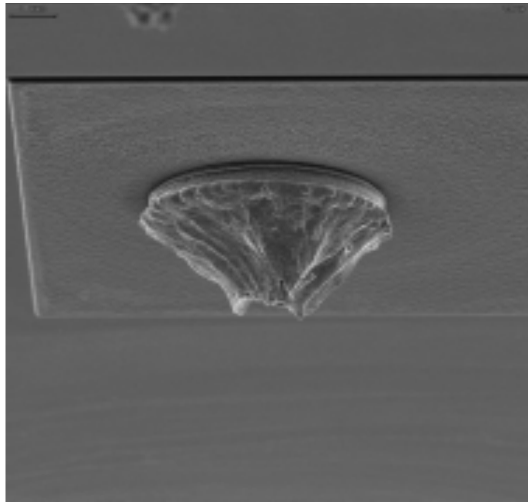
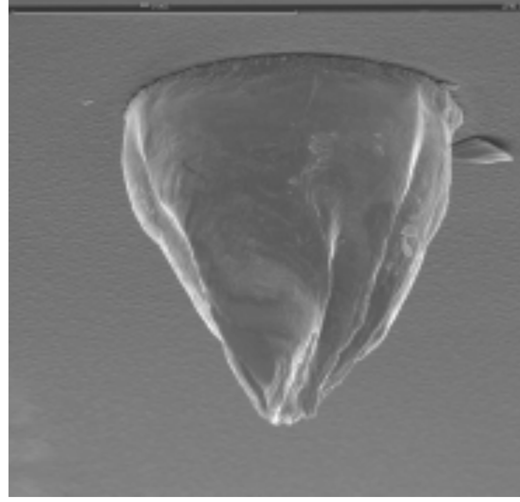
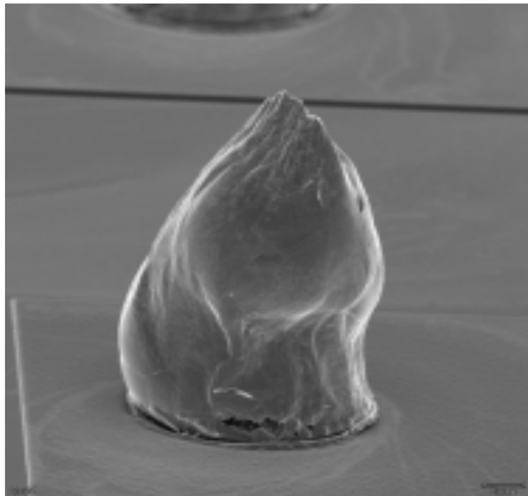
Failure Mode of Solder Joints Must be Characterized

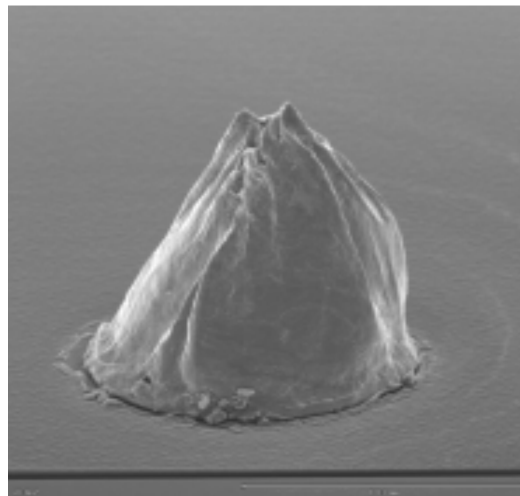
SnCu/Cu UBM

SnCu/Ni UBM









- Failure is in solder
- "Taffy pull" indicates good ductility

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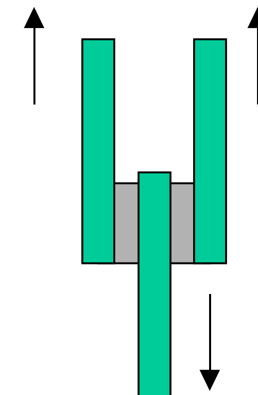
Solder Joint Creep Behavior

The creep behavior of the solder is required for:

- Developing the constitutive behavior of interconnects
- Inclusion into computation simulations
- Creep measurement techniques include
  - Bulk shear/compression/tension tests
  - Lap shear testing (double/single)
  - Indentation testing (compression)
- Regardless of test, microstructure must be characterized



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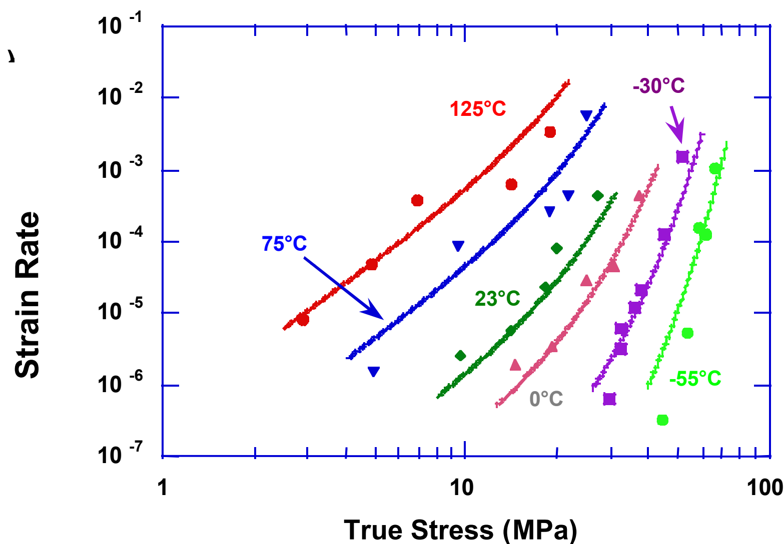
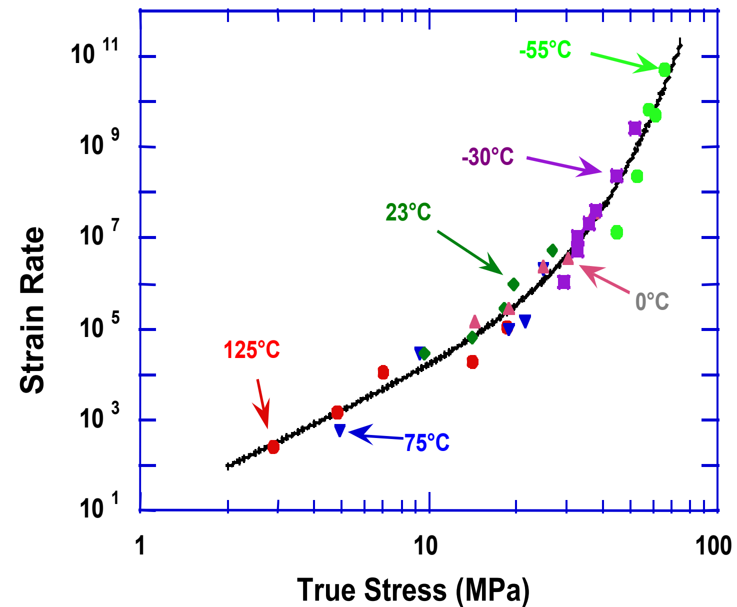
Materials Aspects: Reliability Testing for Solders

- Creep rate sensitivity
  - Solder deforms with time at temperature under stress
    - Viscoplasticity
  - Shortening time under stress/strain can change creep damage mechanism





Eutectic Sn-Pb creep mechanism changes over temperature, does Pb-free?

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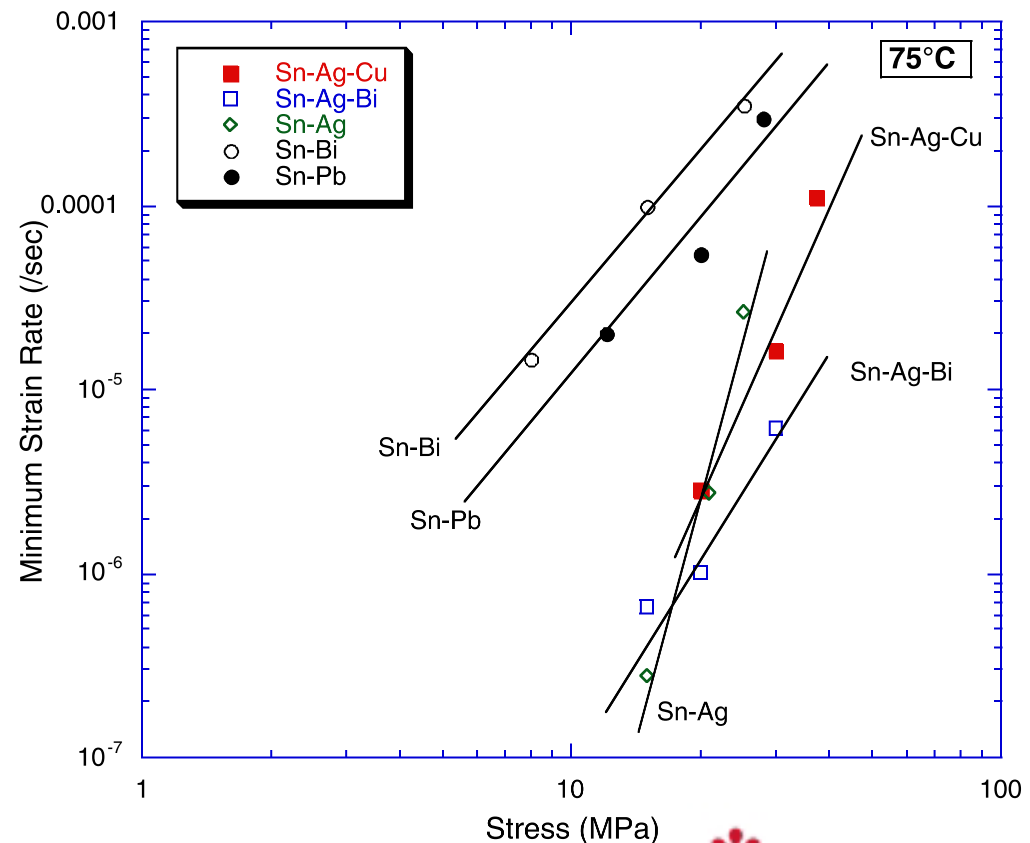
Solder Joint Creep Behavior

Accepted creep behavior and constitutive relations are needed

$$d\gamma/dt = A\sigma^n e^{-Q/RT}$$

$$d\gamma/dt = A\sinh(\alpha\sigma)^n e^{-Q/RT}$$

- Sn-Ag based solders have a much slower creep rate than Sn-Pb
- Some relations exist in the literature, more are needed



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Solder Thermomechanical Fatigue Behavior

The thermomechanical fatigue behavior of the solder is required for:

- Understanding behavior of solder joints under use conditions
- Validation of computational models
- Creep measurement techniques include
    - Bulk shear/compression/tension tests
        - Microstructure differences?
    - Lap shear testing (double/single)
        - Difficult test to perform
    - Component cycling
        - “Unknown” strains
- Regardless of test, microstructure must be characterized

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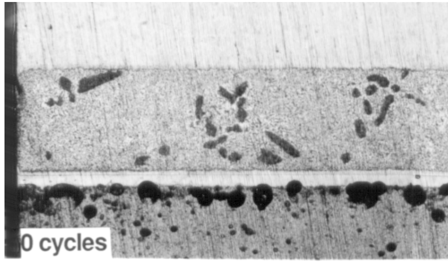
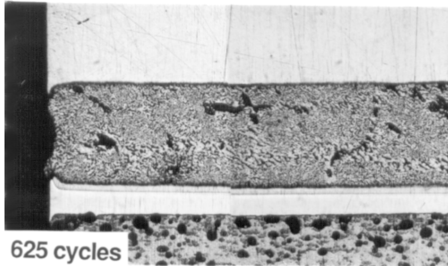
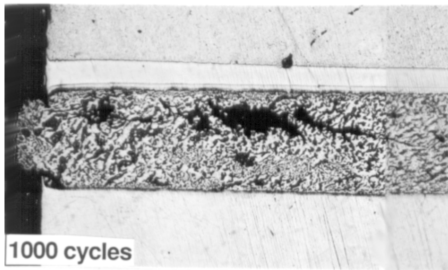
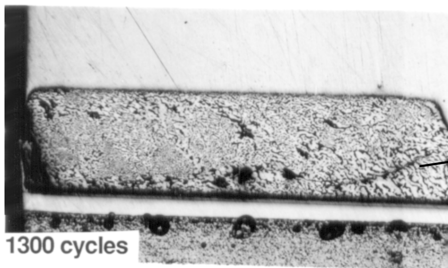


Materials Aspects: Microstructural Evolution

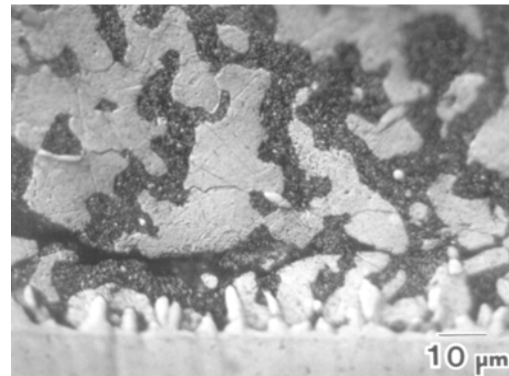


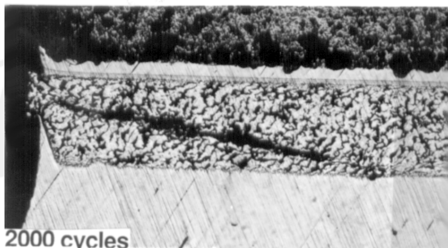
- Under thermal cycling conditions Sn-Pb microstructure evolves
  - Difference in CTE imposes strain
  - Strain accumulates at cell boundaries
  - Cell boundaries coarsen and eventually fail





Crack initiation





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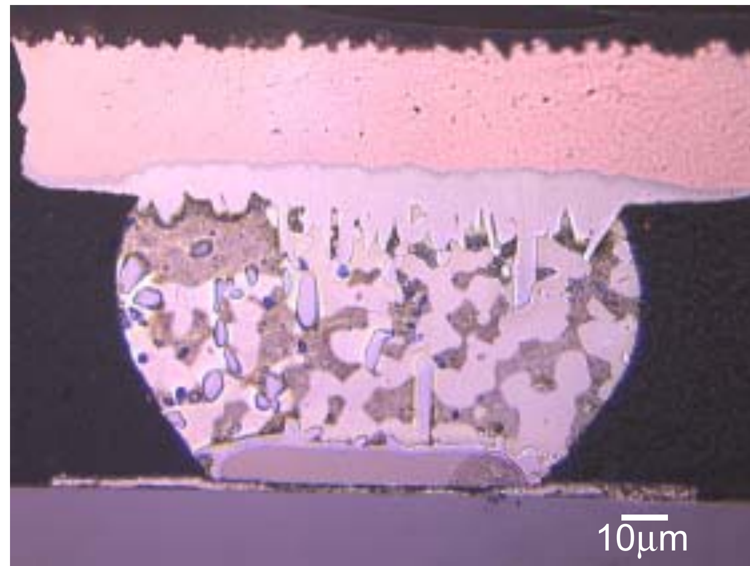
Materials Aspects: Electromigration in Solder

Electromigration becomes important as joints shrink and current density increases

Cross-section of SnPb solder (150°C, 200hrs, no current)



- Sn-Pb solder homogeneously coarsens
  - Weakens the joint
- Interfacial intermetallics coarsen
  - Consume the metallization

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Materials Aspects: Electromigration in Solder

Cross-section of SnPb solder (150°C, 4 ampere, 200hrs)

Substrate

Tin-rich phase

Lead-rich phase

Si die

e^-

e^-

e^-

e^-

10 µm

Migration of Pb-rich phase

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Materials Aspects: Electromigration in Solder

- After electromigration:
  - Significant coarsening of the intermetallic
  - Movement of the intermetallic in the joint
    - Moves with electron flow
  - Migration of the Pb-rich phase with the electron flow
  - Void formation in the solder

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Materials Aspects: Reliability Testing for Solders

- Thermal Cycling
  - Cycling out of temperature range can engage inappropriate damage mechanisms
    - Material response changes with temperature
  - Cycling out of strain range
    - Can accelerate strain range if damage is in plastic range
    - Difficult to perform on components
      - Must increase component size which affects strain orientation
  - Decreasing hold time/Increasing deformation rate
    - Temperature extremes must be sufficiently long to mimic use conditions
    - Deformation rate must be slow enough to have suitable damage mechanisms

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Materials Aspects: Reliability Testing for Solders

- Electromigration testing of solders
  - Temperature and current have a strong effect on microstructure
  - Not known whether current or temperature can be extrapolated
    - Work must be performed to characterize and quantify
      - SRC and UCLA effort underway
  - Very limited data for Pb-free

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Materials Aspects: Materials Modeling

- Computational modeling is a very useful tool to reduce number of required reliability tests
- Only applicable with appropriate input
  - Can input appropriate time/temperature/geometry
  - Require appropriate materials properties to be characterized and quantified
- Model must be validated with experimental results

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Critical Aspects for Characterization of Pb-free Solders

- Intermetallic consumption of base metal and intermetallic growth
- Microstructural evolution of the solder
- Solder alloy strength (on microstructurally significant samples)
- Creep testing (on microstructurally significant samples)
  - Constitutive relation development
- Thermomechanical fatigue behavior
  - Life, failure mode, model validation
- Electromigration behavior for high power applications
- Very limited data available for Pb-free

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Critical Aspects Needed for Pb-free Solders

- Microstructurally based constitutive relations
- Solder joint strength (microstructurally dependant)
- Effect of whiskers and a test to evaluate
- Access to a “validated” data base of microstructurally-based materials properties

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