NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Reliability of Bonded Interfaces

PI: Douglas DeVoto
National Renewable Energy Laboratory
May 14, 2013

Vehicle Technologies Program
Annual Merit Review
Arlington, Virginia

NREL/PR-5400-58170

Project ID: APE028

Overview

Timeline

Project Start Date: FY10

Project End Date: FY13

Percent Complete: 85%

Barriers and Targets

- Cost
- Weight
- Performance and Lifetime

Budget

Total Project Funding:

DOE Share: $2,300K

Funding Received in FY12: $650K

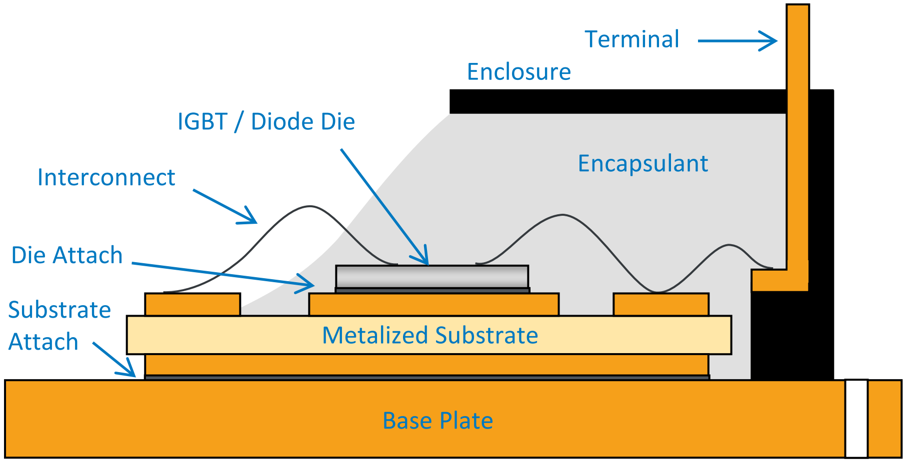
Funding for FY13: $625K

Partners

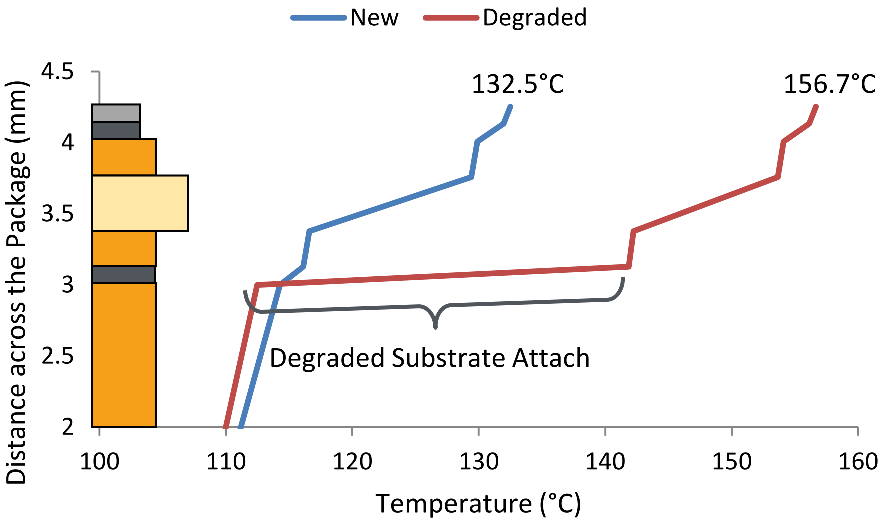
- Interactions / Collaborations
  - General Motors, Btech, Semikron, Heraeus, Kyocera, Virginia Tech, Oak Ridge National Laboratory (ORNL)
- Project Lead
  - National Renewable Energy Laboratory

Relevance

- Excessive temperature degrades the performance, life, and reliability of power electronics components.
- Interfaces can pose a major bottleneck to heat removal.
- Bonded interface materials (BIMs), such as solder, degrade at higher temperatures and are prone to thermomechanical failure.

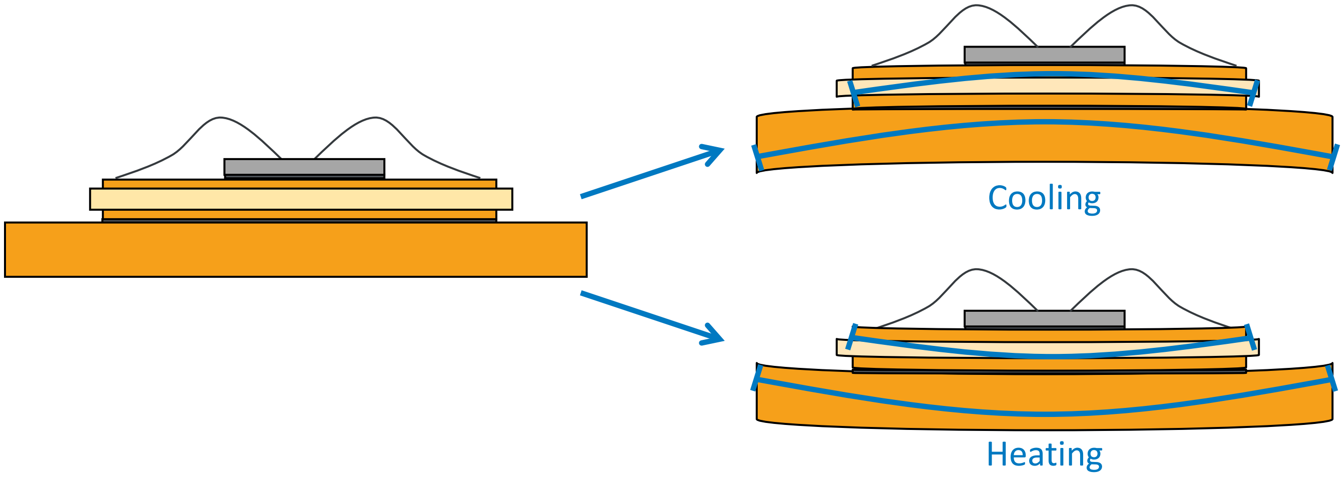


Traditional Power Electronics Package



Relevance

- As operating temperatures increase, the coefficient of thermal expansion (CTE) mismatch between the substrate and the base plate causes defect initiation and propagation in the joining layer.



CTE (ppm/°C)
Silicon: 2.6
AlN: 4.5
Si_3N_4: 3.2
Copper: 16.5
Aluminum: 22.7
Sn63/Pb37 Solder: 24.7

Objectives

- **Overall Objective**
  - Investigate the reliability of emerging BIMs (such as sintered silvers, lead-free solders, and thermoplastics with embedded carbon fibers) for power electronics applications to meet the thermal performance target of 5 mm^2K/W
  - Identify failure modes in emerging BIMs, experimentally characterize their life under known conditions, and develop lifetime estimation models

- **Address Targets**
  - High-performance, reliable, low-cost bonded interfaces enable:
    - Compact, light-weight, low-cost packaging
    - High-temperature coolant and/or air cooling

- **Uniqueness and Impacts**
  - Thermal performance and reliability of emerging sintered materials and thermoplastics for large-area attachments were characterized

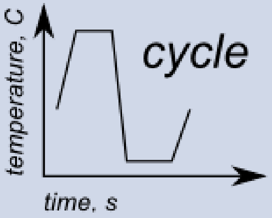
Milestones

Date	Description
October 2012	Completed finite element analysis (FEA) to determine strain energy density in lead-based solder samples with various fillet radius geometries
December 2012	Completed experimental temperature cycling of Btech HM-2 and Semikron sintered silver samples to 2,000 cycles
February 2012	Completed FEA to determine strain energy density in lead-based solder samples under various temperature cycle profiles
June 2013	Complete experimental temperature cycling of lead-based solder samples to 2,000 cycles
July 2013	Complete double lap shear testing of lead-based solder samples and use stress/strain data to revise viscoplastic properties needed for FEA

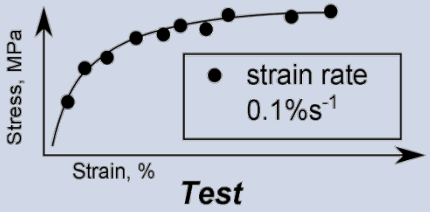
Approach

Sample Synthesis

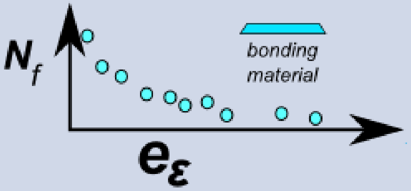
Thermal Testing/ Characterization

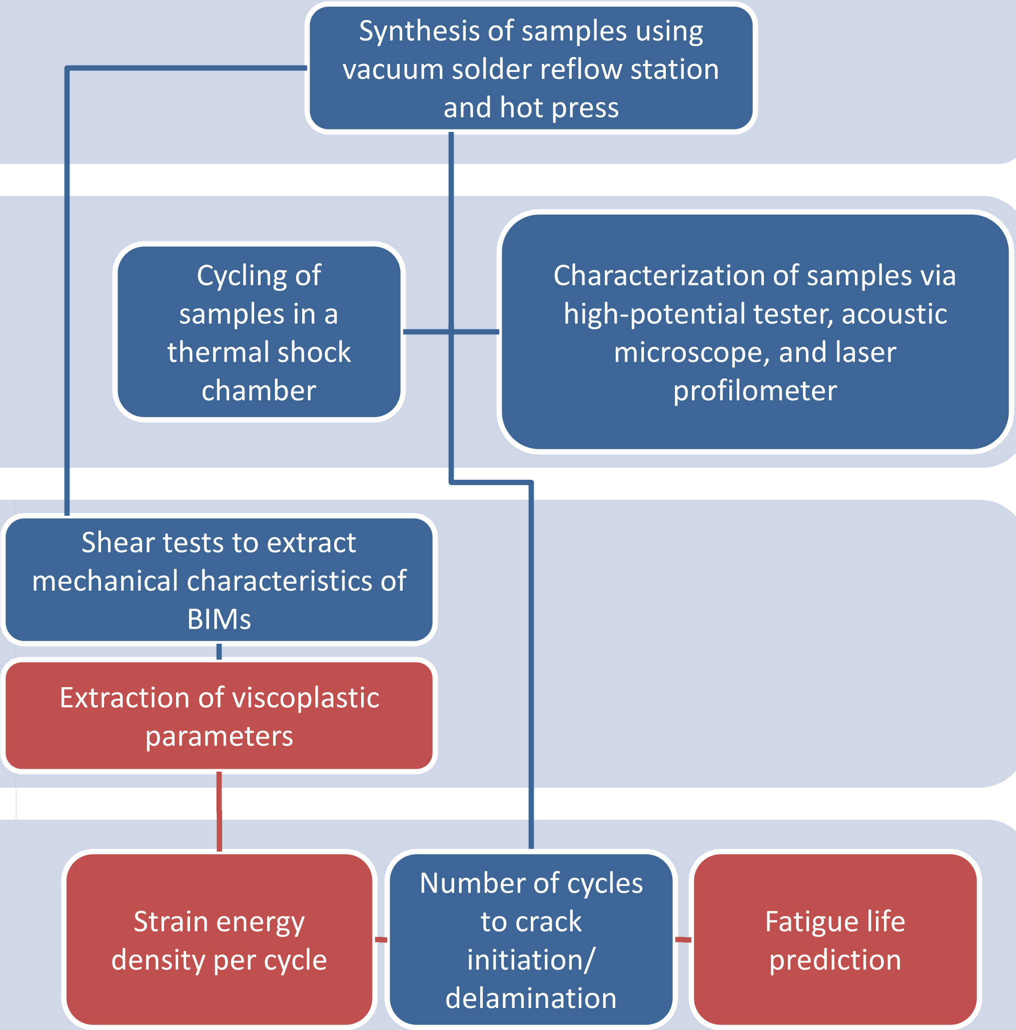


BIM Mechanical Characterization



Reliability Calculation





Synthesis of samples using vacuum solder reflow station and hot press

Cycling of samples in a thermal shock chamber

Characterization of samples via high-potential tester, acoustic microscope, and laser profilometer

Shear tests to extract mechanical characteristics of BIMs

Extraction of viscoplastic parameters

Strain energy density per cycle

Number of cycles to crack initiation/ delamination

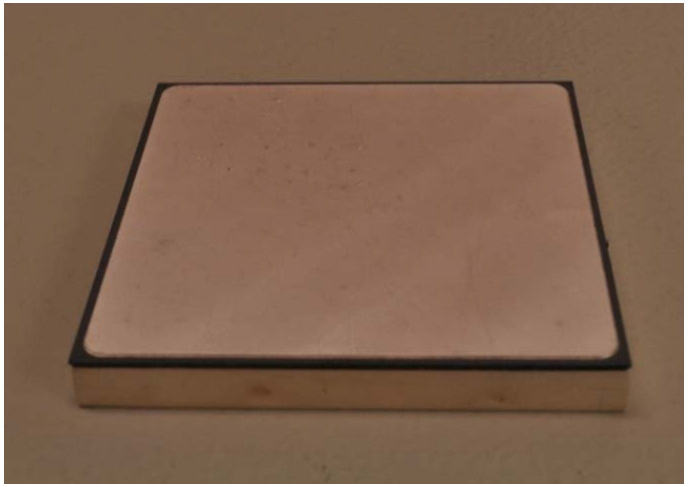
Fatigue life prediction

Experimental Approach

Modeling Approach - FEA/Calculations

Sample Assembly

- Five samples of each BIM were synthesized for testing and included:
  - Silver plating on the substrate and copper base plate
  - Substrate based on a Si_3N_4 active metal bonding process
  - An interface between 50.8-mm x 50.8-mm footprint
- Samples followed manufacturer-specified reflow profiles, and bonds were inspected for quality



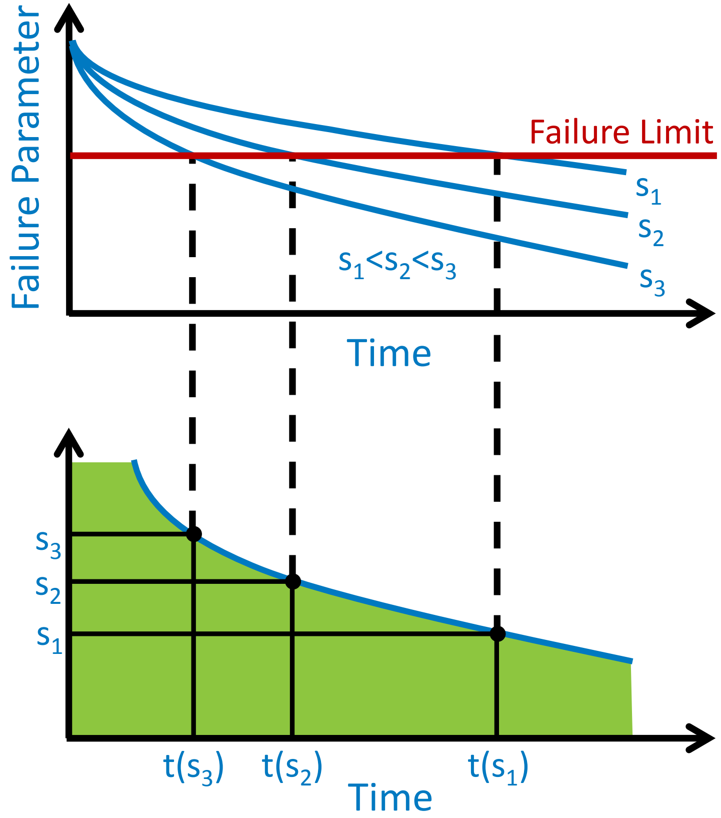
Credit: Douglas DeVoto, NREL

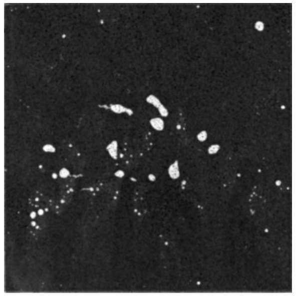
Sample Assembly

Bond Material Type	Name	Comments
Solder	Kester Sn63Pb37	Baseline (lead-based solder)
Sintered Silver	Semikron	Based on Semikron synthesis process
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers

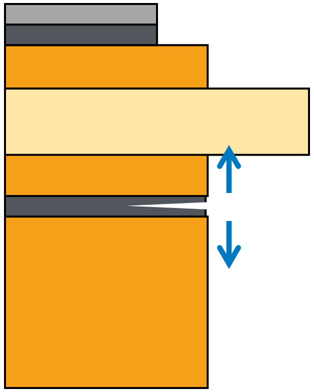
Temperature Cycling

- Cycle Profile
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Failure Mechanisms
  - BIM: voids and cohesive or adhesive/interfacial fractures
  - Substrate: Cu-to-Si_3N_4 delamination and Si_3N_4 cracking

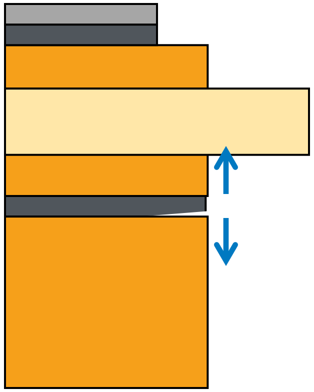




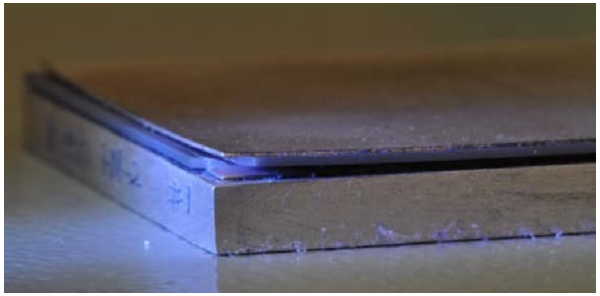
Voids



Cohesive Fracture



Adhesive/Interfacial Fracture



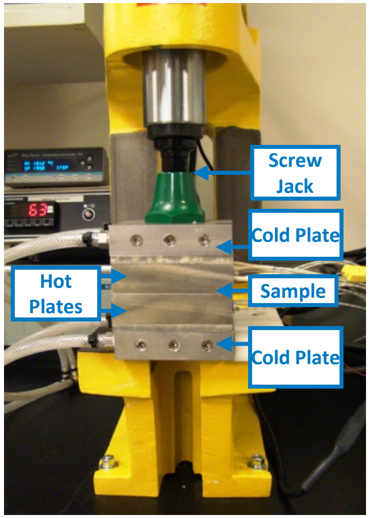
Substrate Delamination and Cracking

Credit: Douglas DeVoto, NREL (all photos)

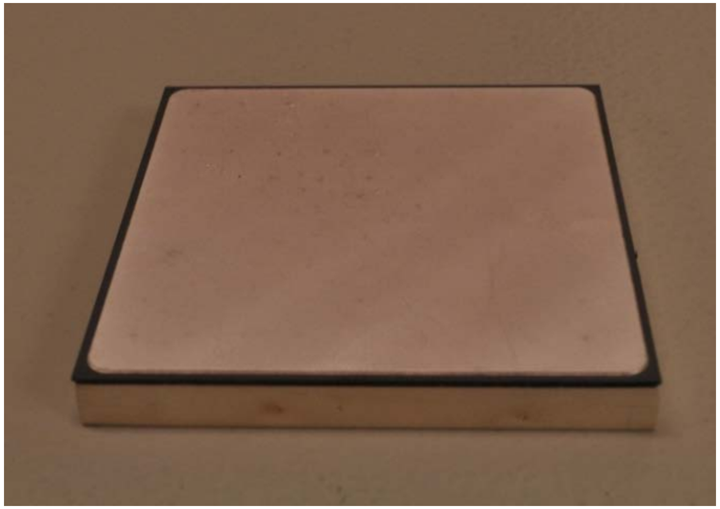
Thermoplastic Evaluation

Btech HM-2 (Carbon Fibers within Polymer Matrix)

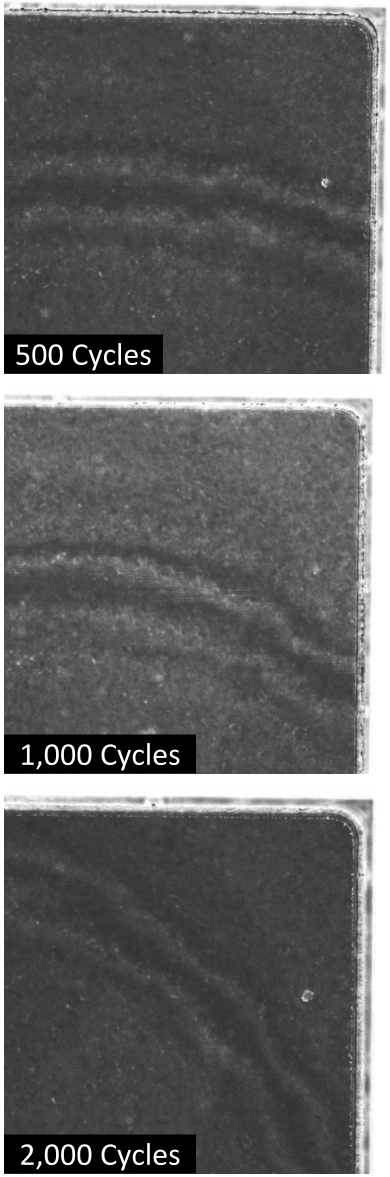
- Bonding
  - HM-2 was cut to the base plate dimensions
  - The sample assembly was placed in the hot press and raised to 195°C
  - 1 MPa (150 psi) of pressure was applied
  - Bond line thickness was measured to be 88.9 µm
- Reliability Results
  - After 2,000 cycles, the bonded interface remained defect-free



Hot Press



Sample Assembly

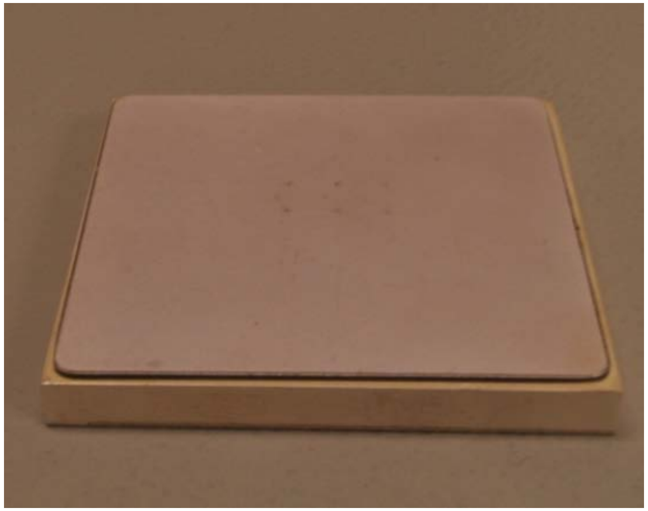


Credit: Douglas DeVoto, NREL (all photos)

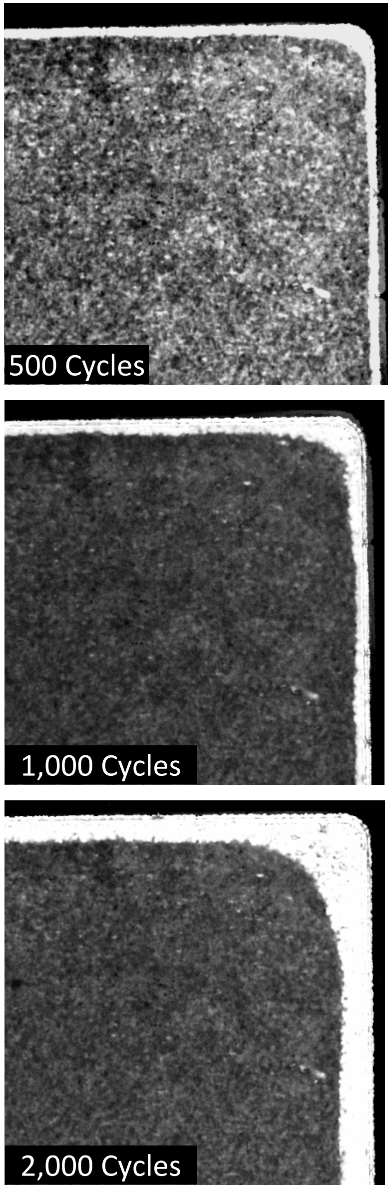
Sintered Silver Evaluation

Semikron Sintered Silver

- Bonding
  - Si_3N_4 edges were ground off to match the metallization layer
  - The sample assembly was placed in a hot press and raised to its processing temperature; then pressure was applied
  - Compression testing of substrates at ORNL showed cracking of substrates required between 30 MPa to 50 MPa of pressure
- Reliability Results
  - Uniform bonds were obtained
  - Cohesive fracture initiated at bonding perimeter



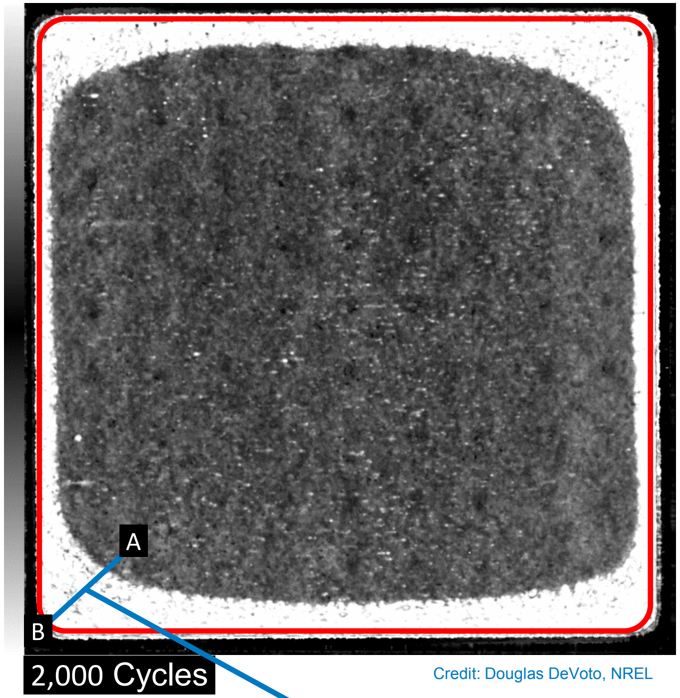
Sample Assembly



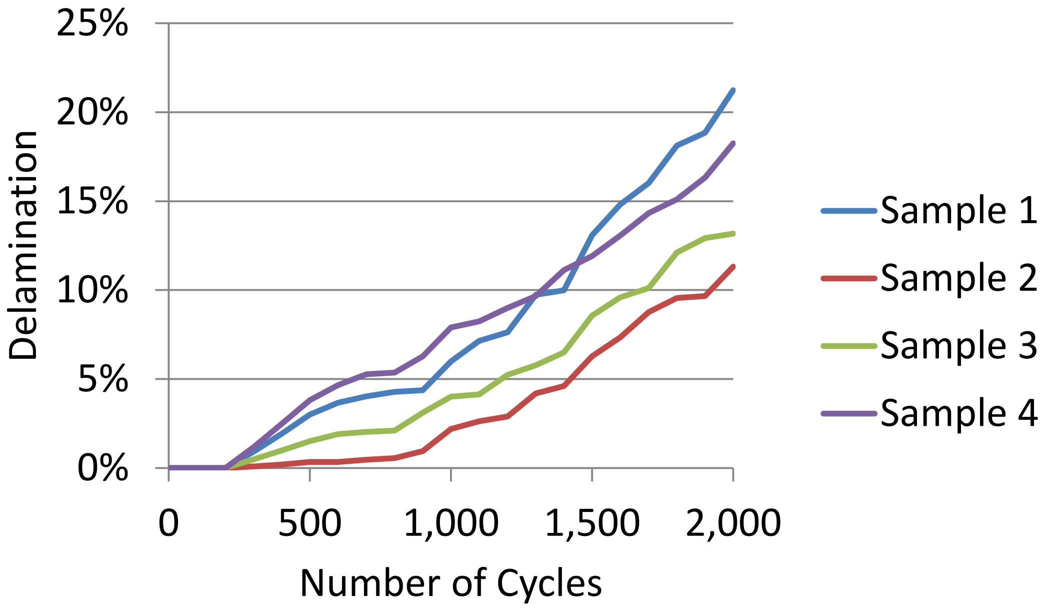
Credit: Douglas DeVoto, NREL (all photos)

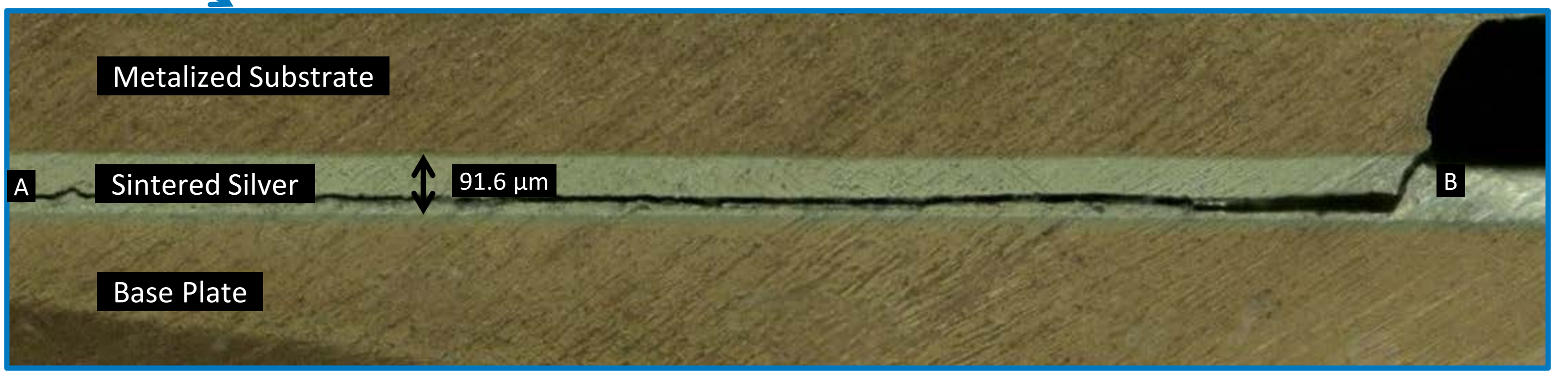
Sintered Silver Evaluation

- After 2,000 cycles, perimeter fracturing reached 11% to 21%



Credit: Douglas DeVoto, NREL



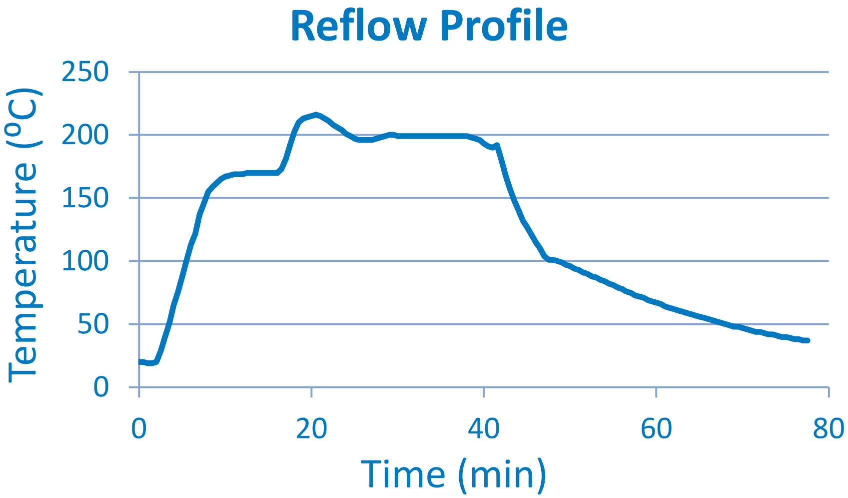


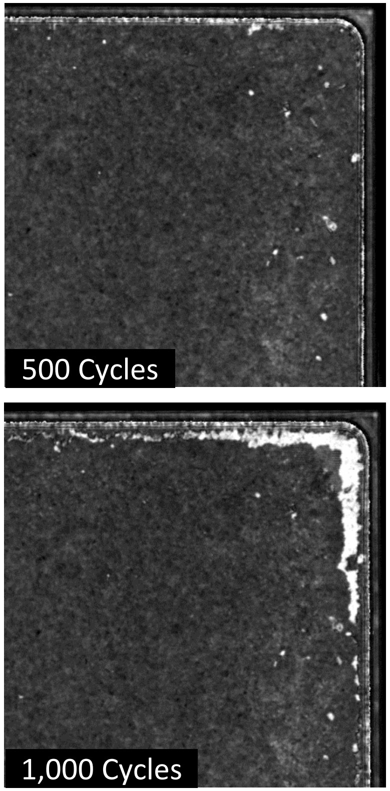
Credit: Paul Paret, NREL

Solder Evaluation

Lead-based (Sn63Pb37) Solder

- Bonding
  - Manual stencil was used to apply a 127-µm-thick solder layer to the substrate and base plate surfaces
  - The assembled sample was placed in a vacuum solder reflow oven and raised to its processing temperature
- Reliability Results
  - Bonds with voiding under 2% were obtained
  - Cohesive fracture initiated at bonding perimeter

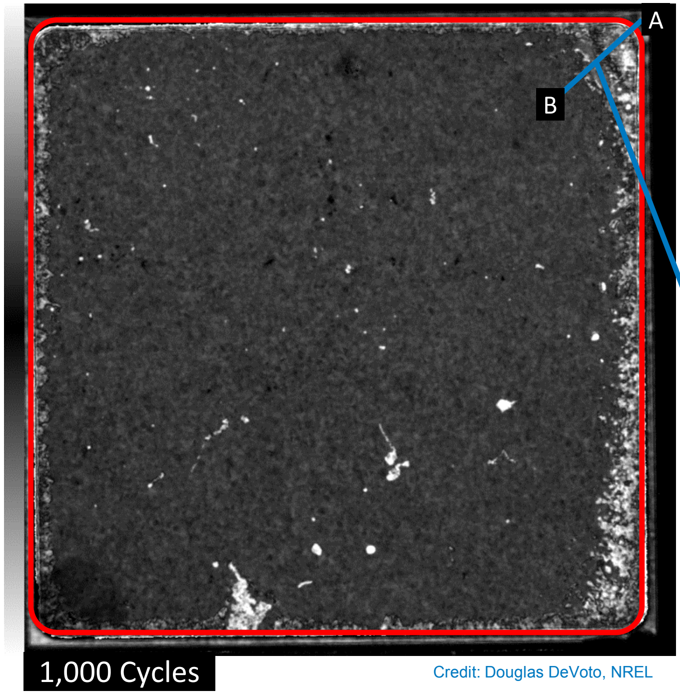




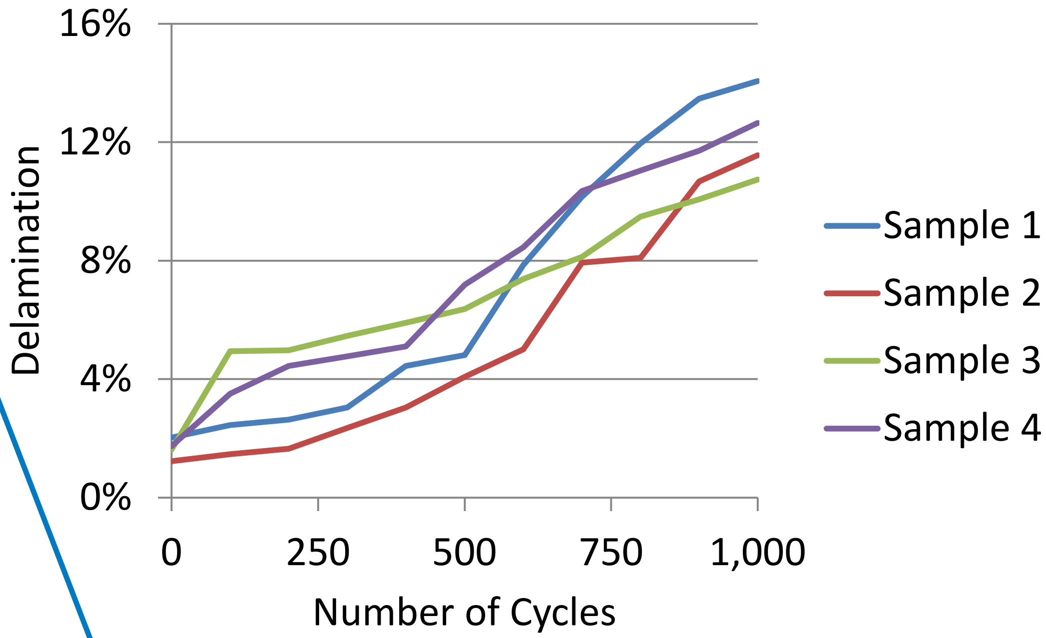
Credit: Douglas DeVoto, NREL (all photos)

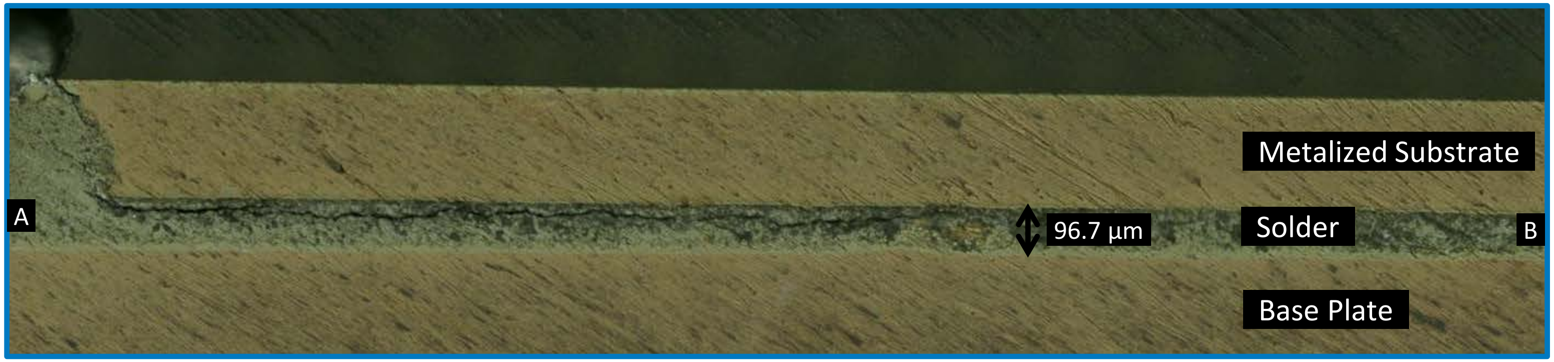
Solder Evaluation

- After 1,000 cycles, perimeter fracturing reached 11% to 14%



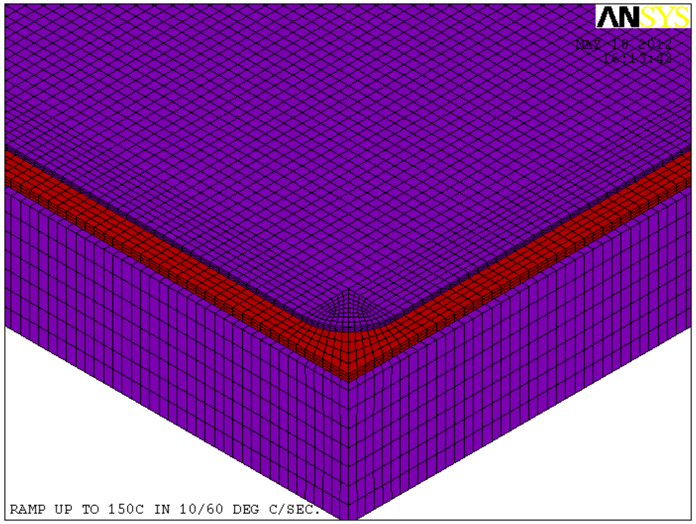
Credit: Douglas DeVoto, NREL



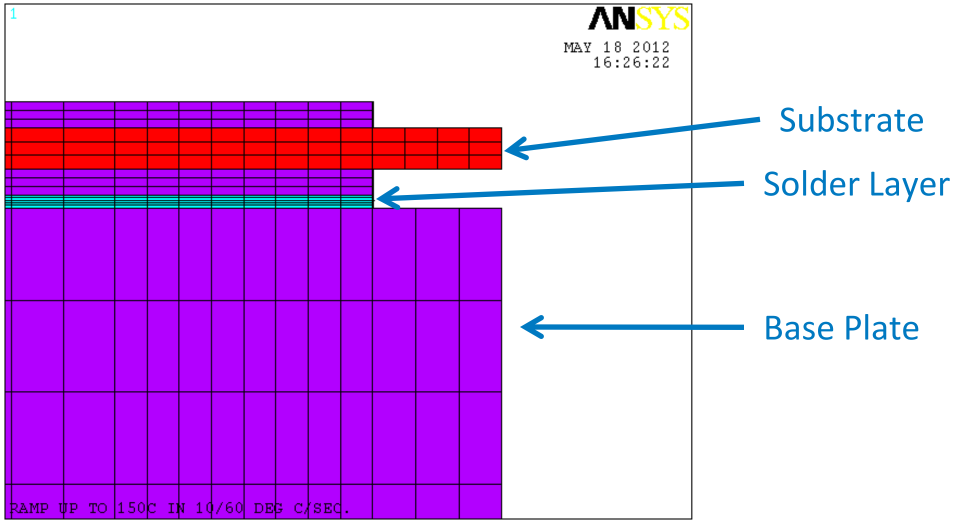


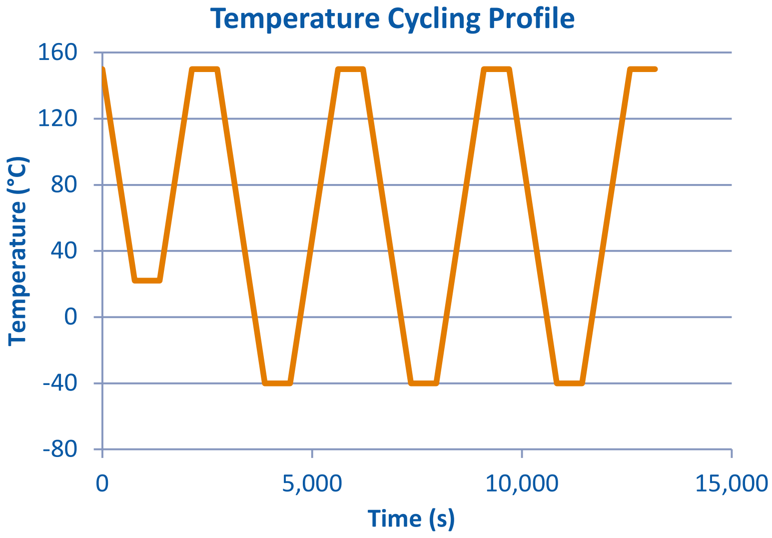
Credit: Paul Paret, NREL

BIM Finite Element Modeling



Quarter Symmetry Model



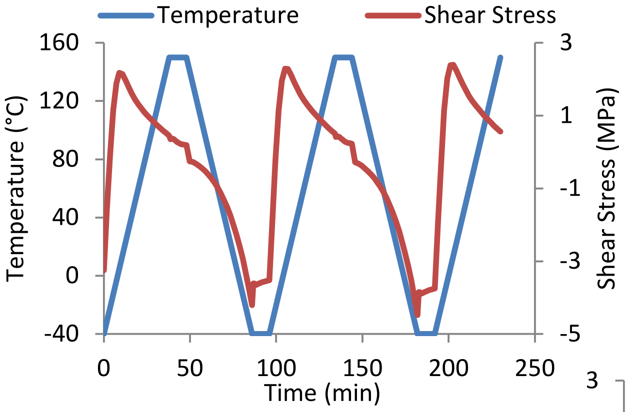


- Temperature cycling parameters:
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Viscoplastic material model applied to solder layer
- Temperature-dependent elastic material properties incorporated for base plate and substrate

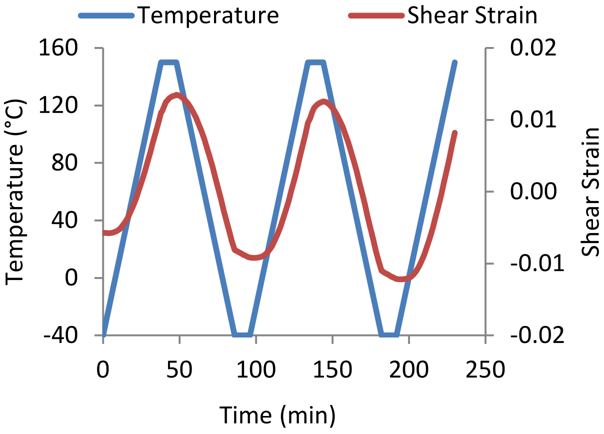
BIM Finite Element Modeling

- Stress-strain hysteresis loops help to understand the inelastic behavior of the solder interface
- Energy stored in the solder interface region due to deformation during thermal loading is referred to as the strain energy density

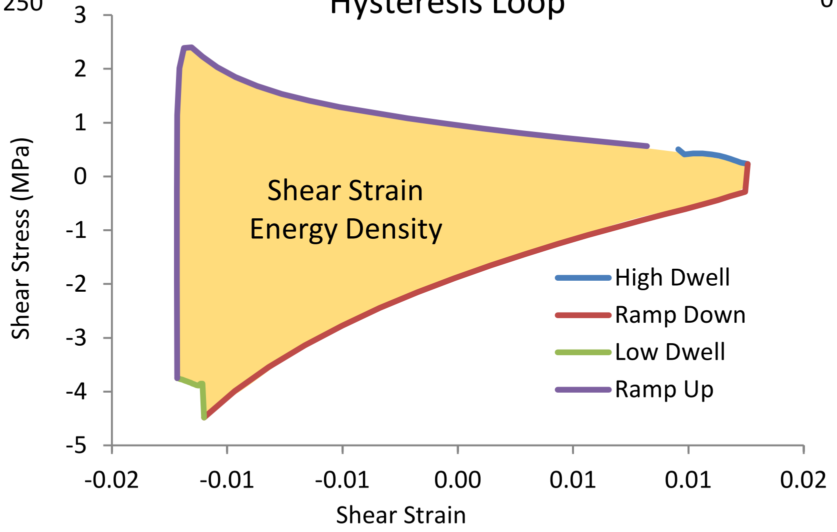
Temperature and Shear Stress versus Time



Temperature and Shear Strain versus Time

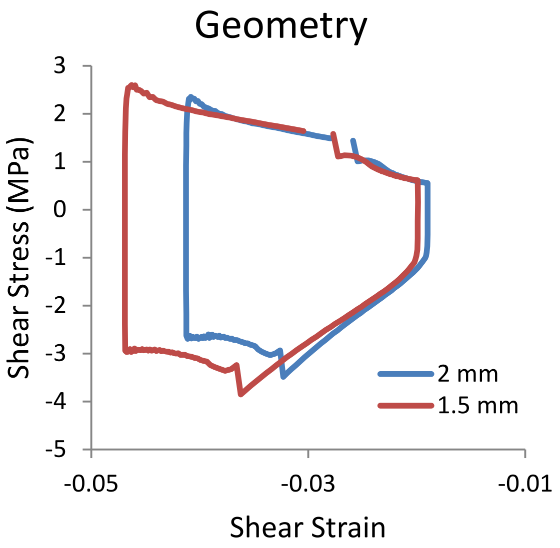


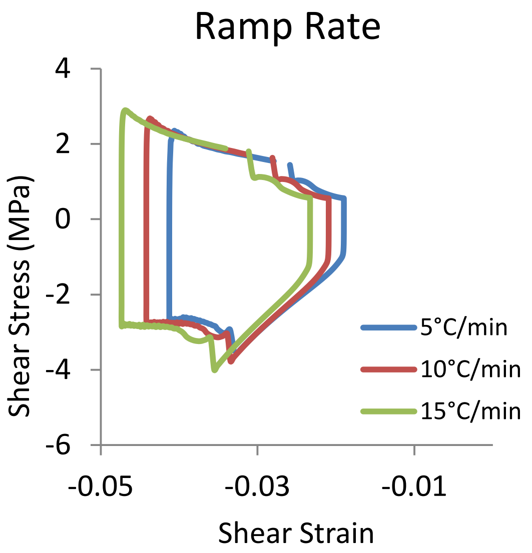
Hysteresis Loop

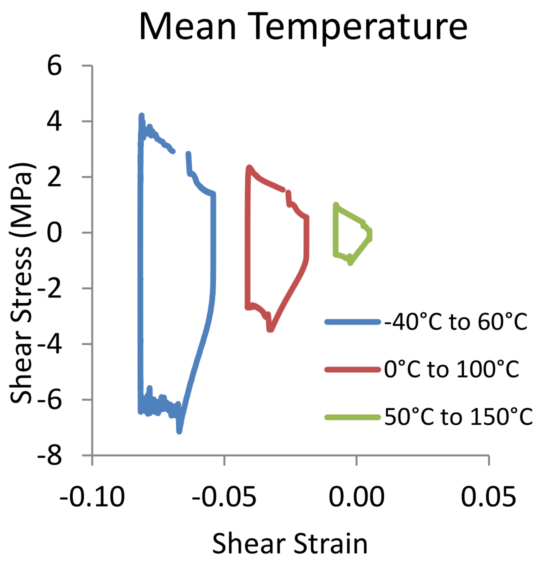


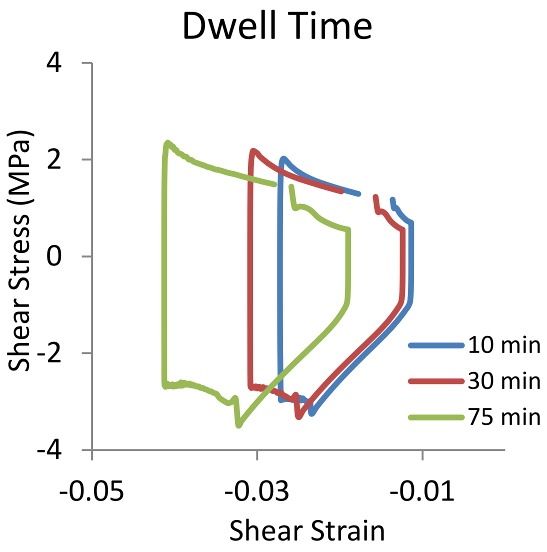
BIM Finite Element Modeling

- Hysteresis loops for variations in package geometry, dwell time, and ramp rate were explored
  - Geometry: 1.5 mm and 2 mm fillet radius
  - Ramp rate: 5°C/min, 10°C/min, and 15°C/min
  - Mean temperature: 50°C, 10°C, and 100°C
  - Dwell time: 10 min, 30 min, and 75 min
- Strain energy density value will be compared to experimental fracture rate to obtain a cycles-to-failure correlation for lead-based solder









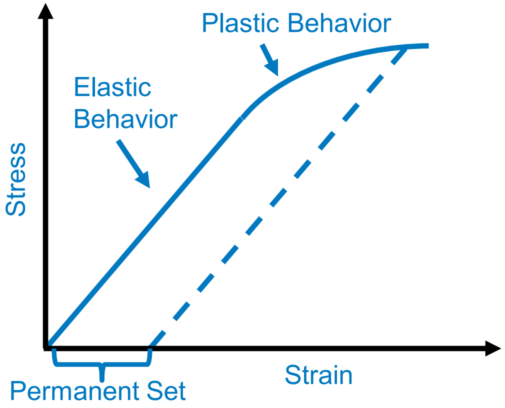
BIM Mechanical Characterization

- Strain prediction of solder material is dependent on stress, temperature, and time
  - A high enough stress will cause the material to plastically deform
  - Solder has a tendency to creep (time-dependent plasticity) at room temperature; this increases as operating (absolute) temperature approaches the melting temperature
- Viscoplasticity models combine plasticity and creep deformations into one equation to properly define solder in FEA
- Sample testing using a double-lap shear test fixture at various strain rates and temperatures generates the needed data to characterize the viscoplastic nature of solder

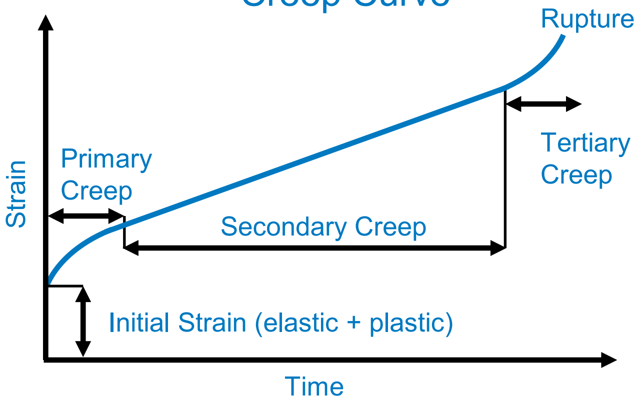
Double-Lap Shear Fixture and Sample

Credit: Douglas DeVoto, NREL

Stress-Strain Curve



Creep Curve



Collaboration and Coordination

- Partners
  - **Btech** (Industry): collaboration on optimizing thermoplastic BIM for large area attachment
  - **General Motors** (Industry): technical guidance
  - **Heraeus** (Industry): collaboration on using low-pressure sintered silver materials before products are commercially available
  - **Kyocera** (Industry): provided insight on Si_3N_4 substrate bonding process and advantages over AlN substrates
  - **ORNL** (Federal): collaboration to determine maximum pressure that Si_3N_4 substrates could withstand
  - **Semikron** (Industry): provided bonded samples to NREL using company's silver sintering process
  - **Virginia Tech** (University): collaboration on synthesis of samples using sintered silver material

Proposed Future Work (FY13)

- Derive viscoplastic parameters for lead-based solder from double-lap shear test experiments
- Expand strain energy density versus cycles-to-failure models to lead-free solders
- Complete 2,000 thermal cycles on lead-based solder samples
- Report on reliability of each BIM under specified accelerated test conditions

Summary

- **DOE Mission Support**
  - BIMs are a key enabling technology for compact, light-weight, low-cost, reliable packaging and for high-temperature coolant and air-cooling technical pathways
- **Approach**
  - Synthesis of various bonds between substrates and base plate, thermal shock/temperature cycling, high-potential test and bond inspection (acoustic microscope), and strain energy density versus cycles-to-failure models
- **Accomplishments**
  - Evaluated a number of bonded interfaces subjected to temperature cycling
    - Lead-based solder, sintered silver, thermoplastic
  - Implemented FEA for solder bonded interface geometries

Summary

- **Collaborations**
  - General Motors, Virginia Tech, ORNL, Btech, Semikron, Heraeus, Kyocera
- **Future Work**
  - Derive viscoplastic parameters for lead-based solder from double-lap shear test experiments
  - Expand strain energy density versus cycles-to-failure models to lead-free solders
  - Complete 2,000 thermal cycles on lead-based solder samples
  - Report on reliability of each BIM under specified accelerated test conditions

Acknowledgments:

Susan Rogers and Steven Boyd,
U.S. Department of Energy

For more information contact:

Principal Investigator
Douglas DeVoto
Douglas.DeVoto@nrel.gov
Phone: (303)-275-4256

Team Members:

Mark Mihalic
Paul Paret

APEEM Task Leader

Sreekant Narumanchi
Sreekant.Narumanchi@nrel.gov
Phone: (303)-275-4062

Reviewer-Only Slides

Responses to Previous Year Reviewers' Comments

- "One evaluator described that the up-front analysis addressed potential failure modes and technical issues to date are understood."
  - It is a primary goal to validate modeling tools by comparing them to likely failure modes (adhesive or cohesive failures) observed through accelerated testing.
- "The other person commented that the collaboration appears adequate or better, especially with industry such as Semikron."
  - Collaboration with many industry partners has leveraged their material and bonding experience to ensured that NREL is testing production quality bonds.
- "One person pointed out that it was hard for them to say much about the future plans, but the research seems well-conceived."
  - At the time of the Annual Merit Review, this project was in its last year and hence no long-term future work goals were presented. Since then, we have submitted the draft of the FY2013 Annual Operating Plan to DOE in which we have proposed a project related to reliability of high-temperature attach materials/interfaces. Future work in the area of bonded interfaces will focus on the failure mechanisms of sintered silver materials/interfaces and other high-temperature attach materials/interfaces under thermal cycling conditions, as well as development of physics-of-failure models.

Publications and Presentations

- **Publications**
  - D. DeVoto, 2012, "Thermal Performance and Reliability of Bonded Interfaces," FY20112 DOE APEEM Annual Report, October 2012.
  - D. DeVoto, 2012, "Thermal Performance and Reliability of Bonded Interfaces," IMAPS Automotive Microelectronics and Packaging, May 2012.
  - S. Narumanchi and D. DeVoto, 2011, "Thermal Performance and Reliability of Bonded Interfaces," FY2011 DOE APEEM Annual Report, October 2011.
- **Presentations**
  - S. Narumanchi, 2013, "Performance and Reliability of Interface Materials for Automotive Power Electronics," Applied Power Electronics Conference, Long Beach, CA, March 2013.
  - D. DeVoto, 2012, "Thermal Performance and Reliability of Bonded Interfaces," Advanced Power Electronics and Electric Motors FY13 Kickoff Meeting, DOE Vehicle Technologies Program, Oak Ridge, TN, November 2012.
  - D. DeVoto, 2012, "Thermal Performance and Reliability of Bonded Interfaces," Presented to the DOE Vehicle Technologies Program Electrical and Electronics Technical Team, Southfield, MI, May, 2012.
  - S. Narumanchi, 2012, "Thermal Performance and Reliability of Bonded Interfaces," SAE World Congress, Detroit, MI, April 2012.
  - D. DeVoto, 2011, "Thermal Performance and Reliability of Large-Area Bonded Interfaces in Power Electronics Packages," ASME International Mechanical Engineering Congress and Exposition, Denver, CO, November 2011.
  - S. Narumanchi, 2011, "Thermal Performance and Reliability of Bonded Interfaces," Advanced Power Electronics and Electric Motors FY12 Kickoff Meeting, DOE Vehicle Technologies Program, Oak Ridge, TN, November 2011.
  - D. DeVoto, 2011, "Thermal Performance and Reliability of Bonded Interfaces for Power Electronics Packaging Applications," Accelerated Stress Testing and Reliability Workshop, San Francisco, CA, September 2011.

Critical Assumptions and Issues

- Large-area bonded interfaces can lead to thermomechanical stresses in the package and consequently cracks, voids and delaminations. For any proposed solution, it is important to address issues related to thermomechanical reliability.
  - The issue of reliability is specifically being addressed in this project.
- Physics-of-failure and degradation mechanisms for several newer bonded interface materials (e.g., silver sintered material) are not well known and have to be addressed.
  - We are addressing these aspects to some extent in this project. The hypothesis is that we are developing generalized (i.e., independent of geometry) strain energy density versus cycles-to-failure relations for specific bonding materials (solders).
- The bonded interface solution will have to be low cost and be easily integrated into the manufacturing process.
  - Arguably, none of the materials and processes considered in this project are particularly high cost or complex from a manufacturing process integration standpoint.