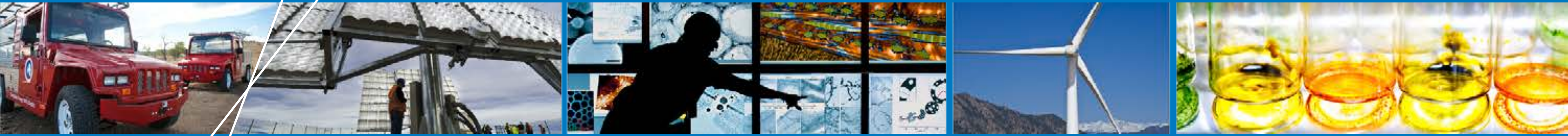
Performance and Reliability of Interface Materials for Automotive Power Electronics



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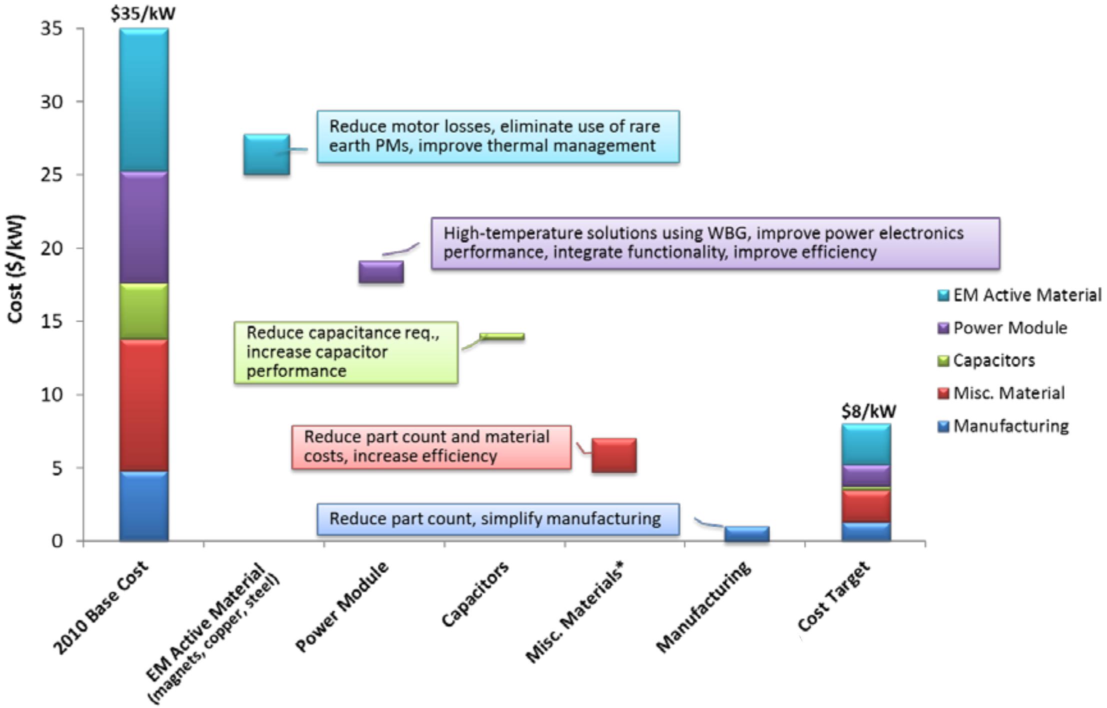
Outline

- Background
- State-of-the-art of interface materials/interfaces
- Non-bonded thermal interface materials (TIMs)
    - Thermal resistance
- Bonded interface materials (BIMs)
    - Thermal resistance
- Reliability of bonded interfaces (accelerated testing)
- Modeling of BIMs
- Summary

Importance of Thermal Management and Reliability

- Excessive temperature degrades the performance, life, and reliability of power electronics and electric motors.
- Advanced thermal management technologies enable
  - keeping temperature within limits
  - higher power densities
  - lower cost materials, configurations and system.
- Improve lifetime/reliability as well as develop new predictive lifetime models.



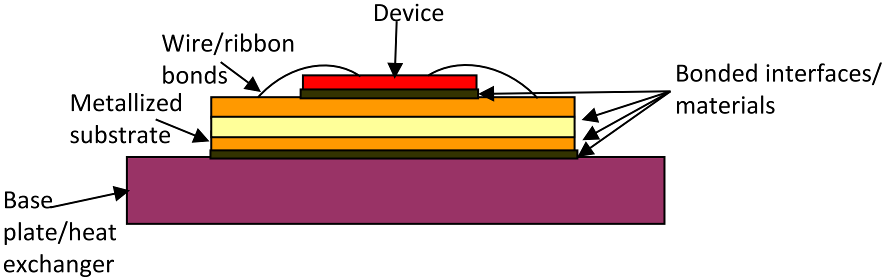
* Inverter: cold plate, drive boards, thermal interface material, bus bar, current sensors, housing, control board, etc.
Motor: bearings, housing, sensors, wire varnish and insulation, potting materials, shaft, etc.

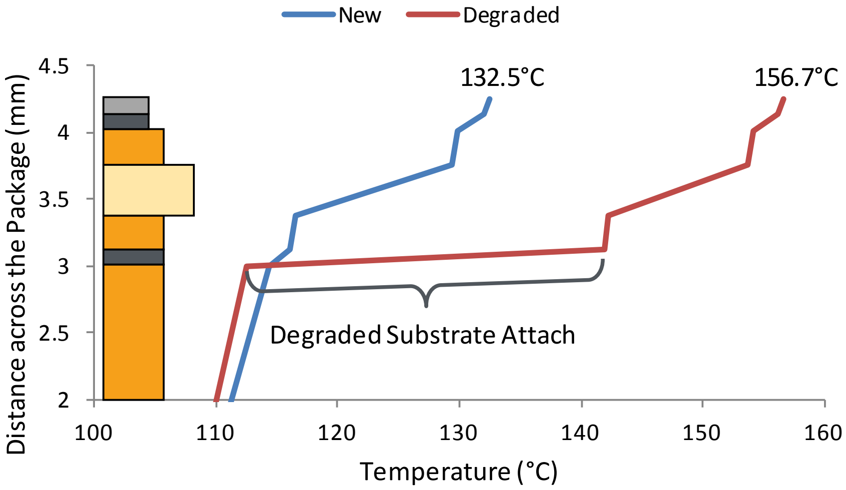
Courtesy: Oak Ridge National Laboratory (ORNL)

Reduce cost, improve reliability

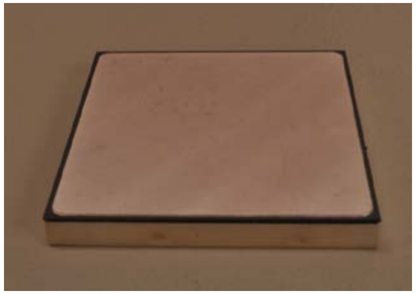
State-of-the-Art of Interfaces/Interface Materials

- Interfaces (especially polymeric interface materials) can pose a major bottleneck to heat removal.
- BIMs, such as solder, degrade at higher temperatures and are prone to thermomechanical failure.
- Need for improved reliability as well as predictive lifetime design tools for lowering cost.
- Important for configurations employing wide bandgap devices.



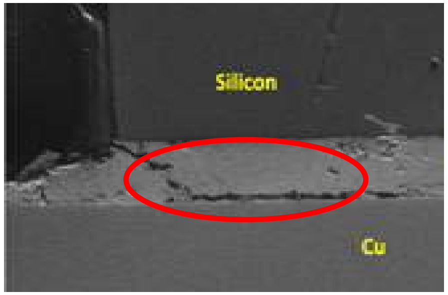


Bonded Interface

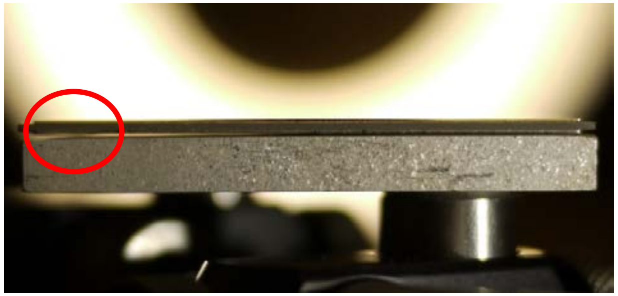


Voiding

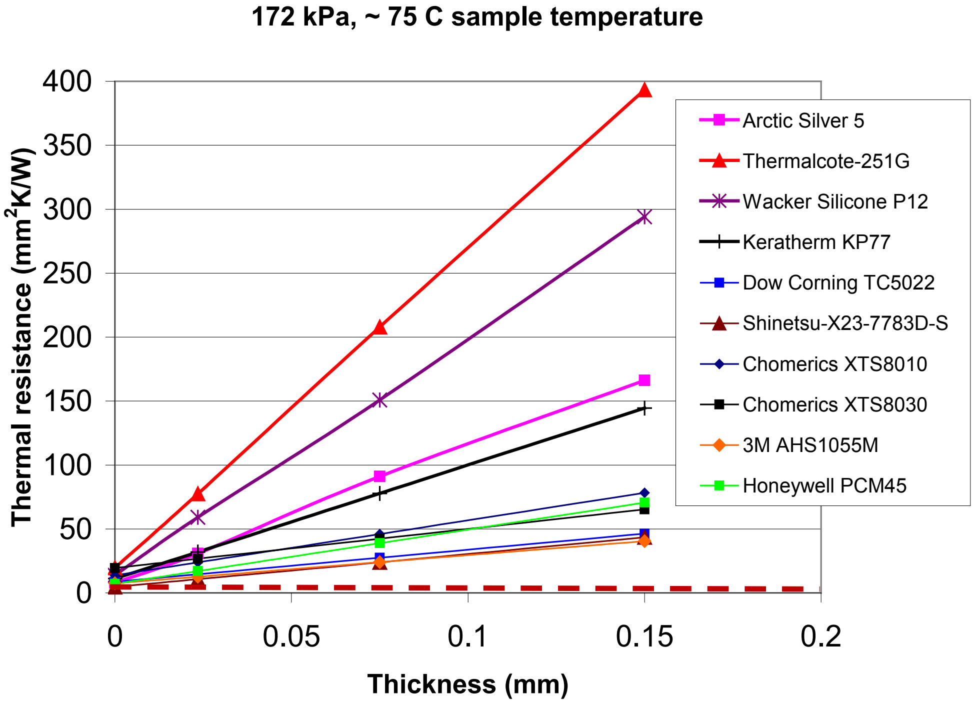
Cracking

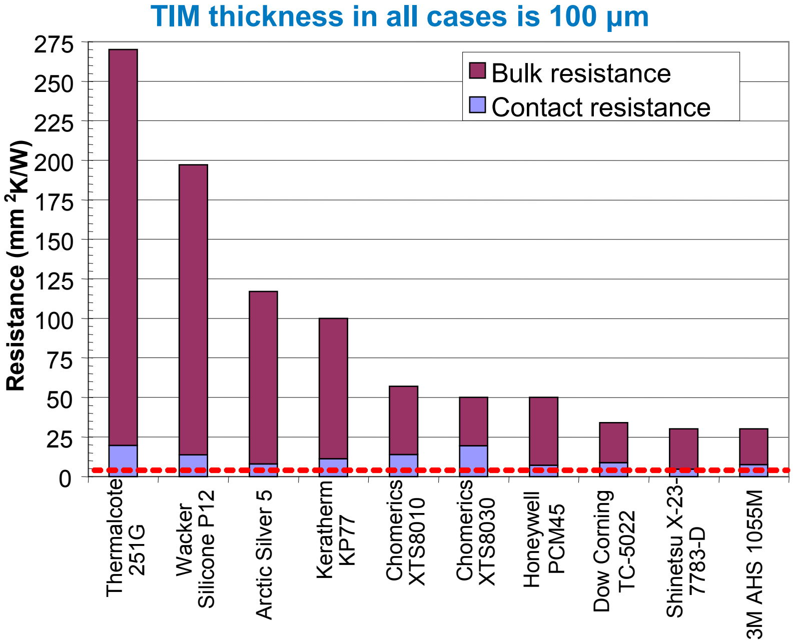


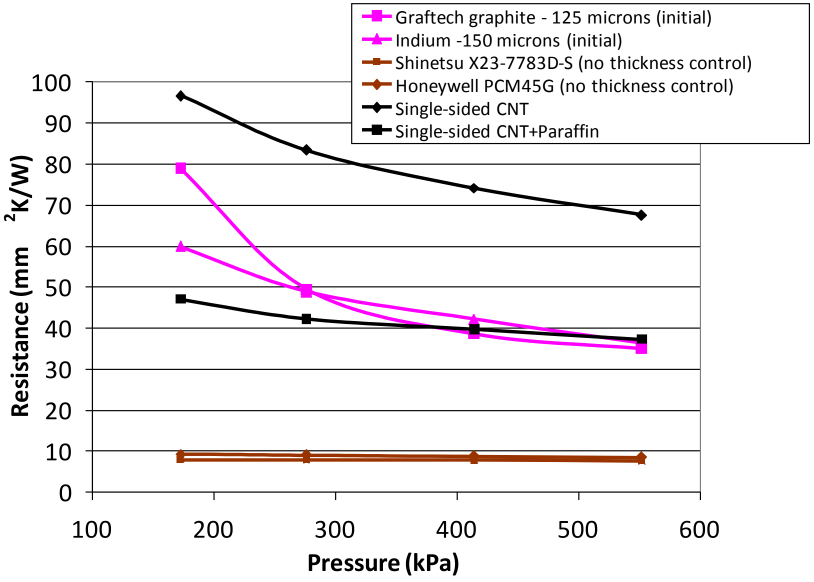
Delamination



Thermal resistance of various non-bonded TIMs

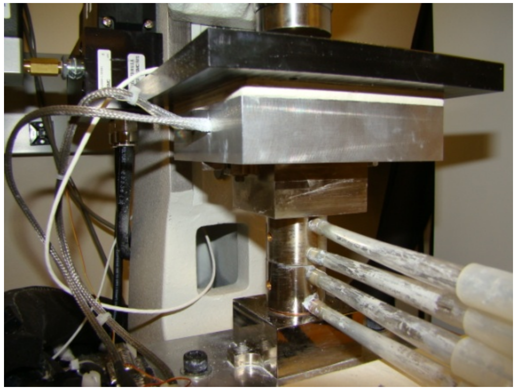






- Red dashed line in the two figures above is the target thermal resistance (**3 to 5 mm^{2}K/W**).
- Most non-bonded TIMs do not come close to meeting thermal specification of 3 to 5 mm^{2}K/W at approximately **100-µm** bond line thickness.

Thermal Resistance of Sintered Silver and Solder



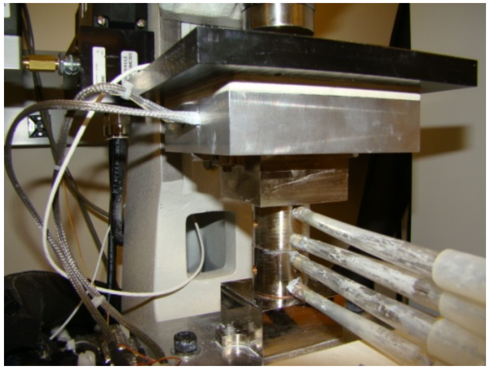
ASTM test fixture

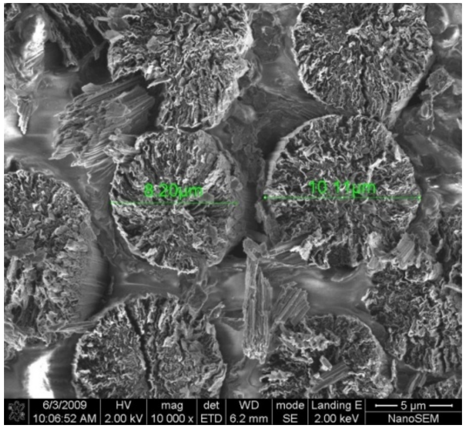
Samples	Thickness (µm)	Resistance (mm^2K/W)
Silvered Cu-Cu sintered interface	**20**	**5.8**
	27	**8.0**
	64	**5.4**
Cu-Cu soldered interface (SN100C)	**80**	**1.0**
	150	**4.8**
	200	**3.7**

- The thermal resistance tests were performed using the NREL ASTM TIM apparatus
  - Average sample temperature ~ 65°C, pressure is 276 kPa (40 psi).
- The silvered Cu-Cu sintered interface showed promising thermal performance.
- Results hinted at some problems with the bonding of the silvered Al-Al interface.
- The initial thermal results for a lead-free solder (SN100C) interface were promising.
- Bonded interface resistance in the range of 1 to 5 mm^2K/W is possible.

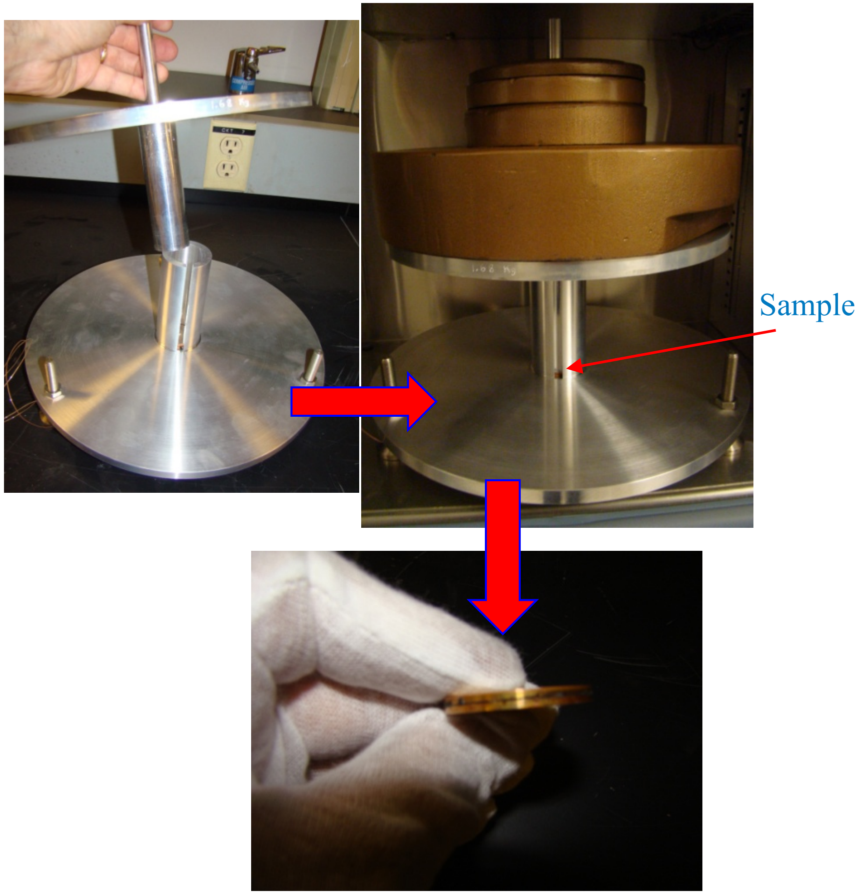
Thermal Resistance of Thermoplastics with Embedded Fibers

Thermoplastics with embedded carbon fibers





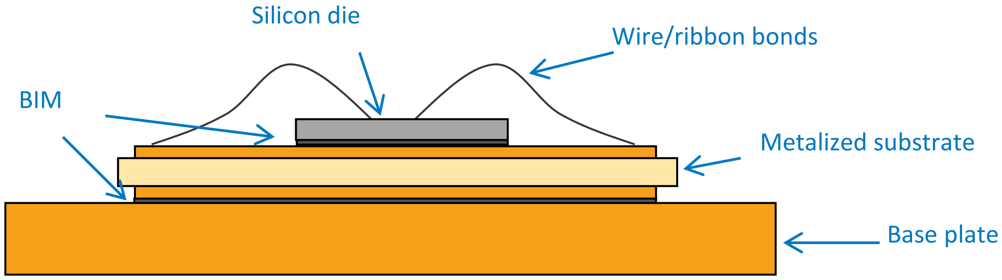
Sequence of bonding steps



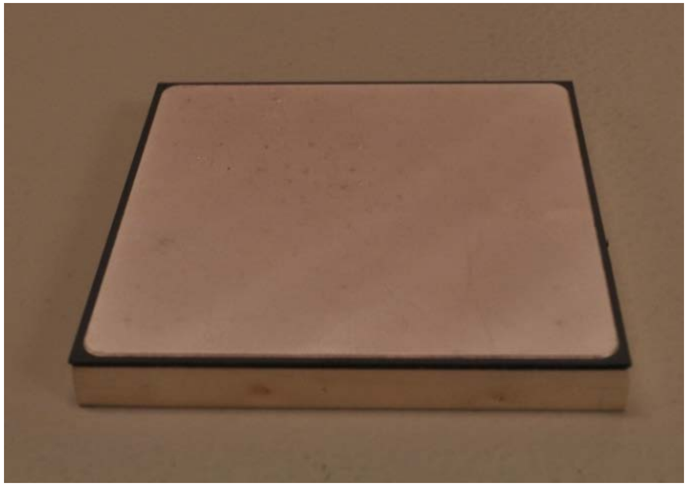
- Thermoplastic films (provided by Btech) bonded between 31.8-mm-diameter copper disks.
- Promising thermal results (8 mm^{2}K/W for 100-µm bondline thickness).
- Continuing work at NREL to further decrease contact resistance to approach target thermal performance, as well as characterize reliability.

Reliability of Bonded Interfaces

- Investigate the reliability of emerging BIMs to meet the thermal performance target of 3 to 5 mm^{2}K/W.
- Identify failure modes in emerging BIMs.
- Experimentally characterize their life under known conditions.
- Develop lifetime estimation models.



Traditional Power Electronics Package

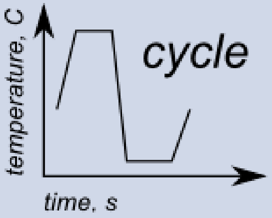


Sample Assembly

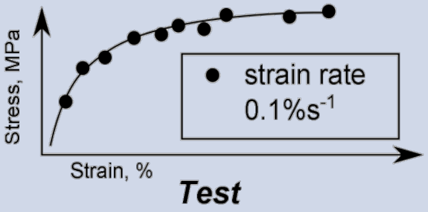
Approach

Sample Synthesis

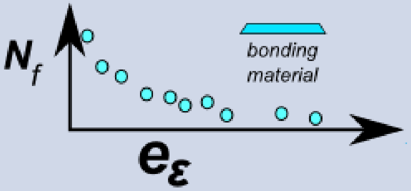
Thermal Testing/ Characterization

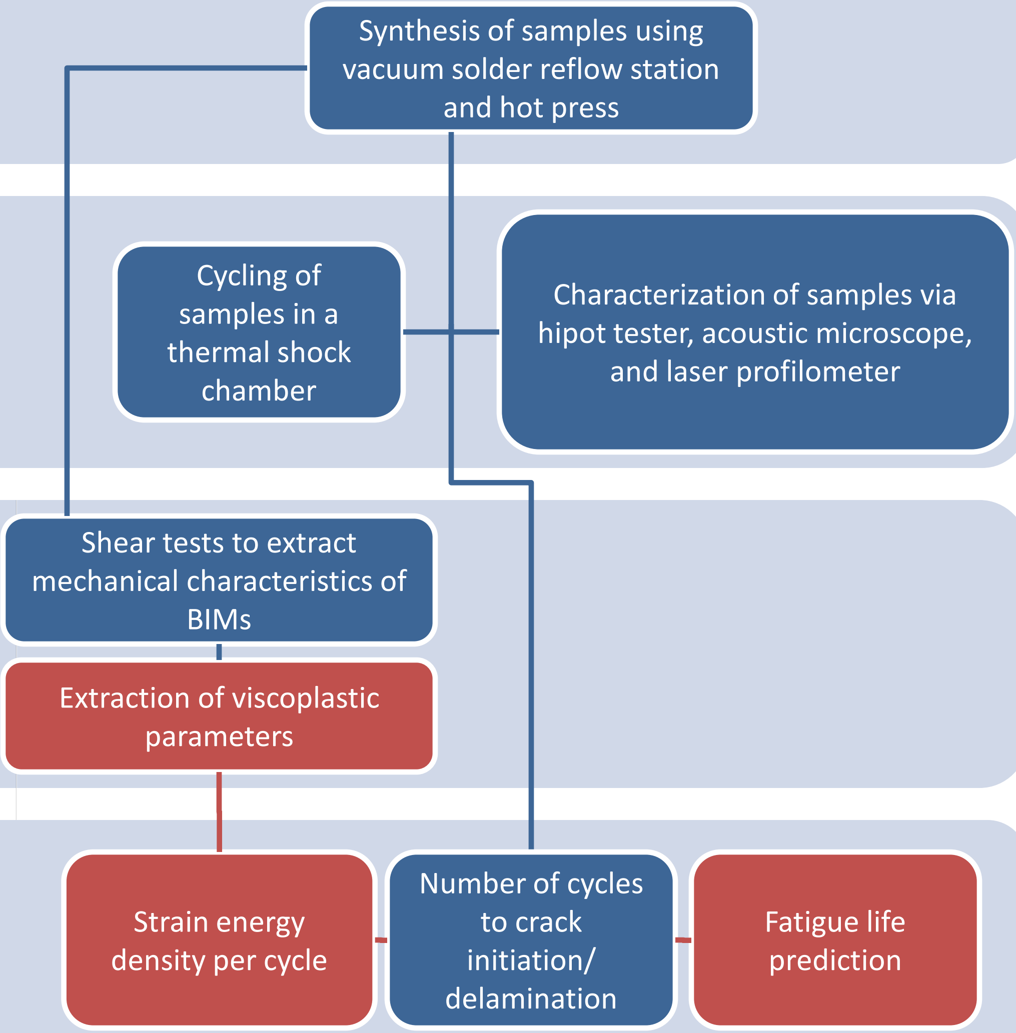


BIM Mechanical Characterization



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 hipot 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

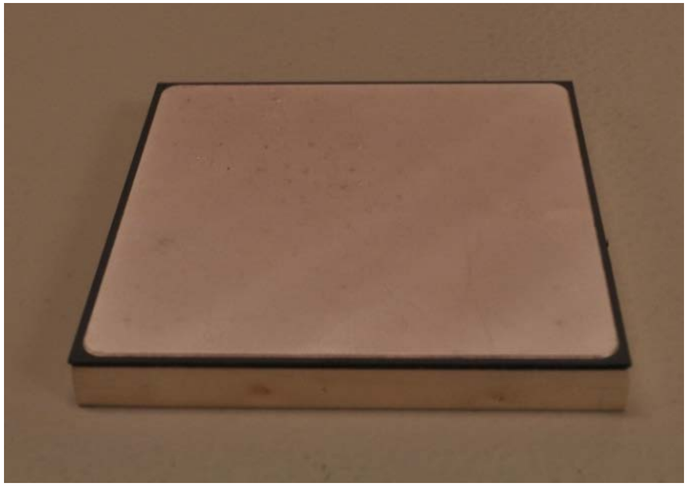
Fatigue life prediction

Experimental Approach

Modeling Approach – Finite Element Analysis/Calculations

Approach – Sample Assembly

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

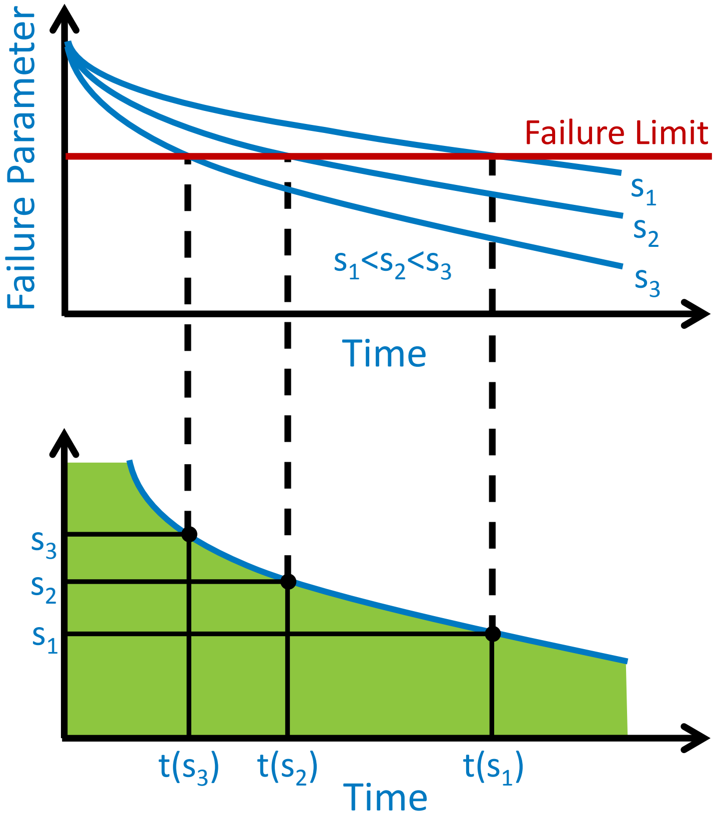


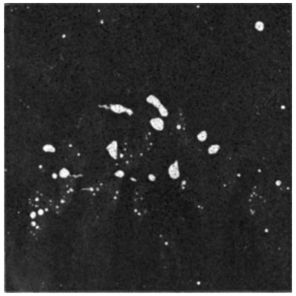
Sample Assembly

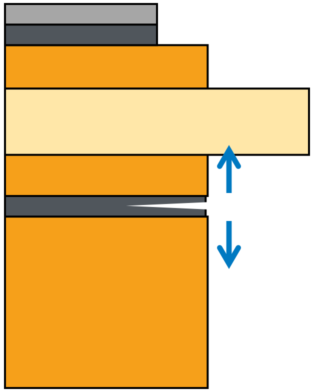
Bond Material Type	Name	Comments
Solder	Kester Sn63Pb37	Baseline (lead-based solder)
Sintered Silver	Semikron	Based on Semikron synthesis process
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers

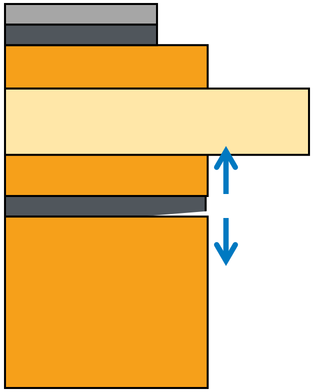
Approach – Temperature Cycling

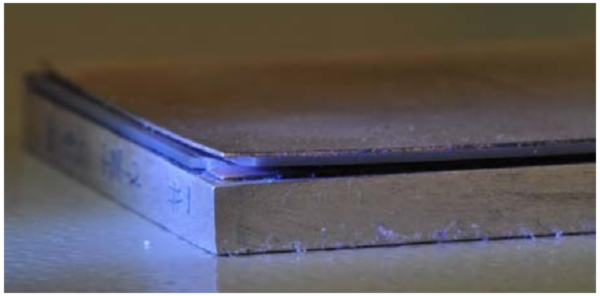
- Cycle Profile
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Failure Mechanisms
  - BIM: voids and cohesive or adhesive/interfacial fractures
  - Substrate: Cu-to-Si_3N_4 delamination and Si_3N_4 cracking




Voids

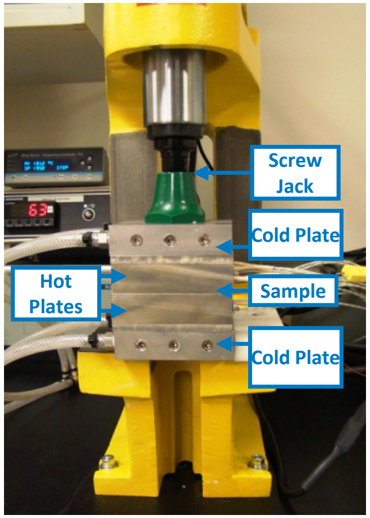

Cohesive Fracture


Adhesive/Interfacial Fracture

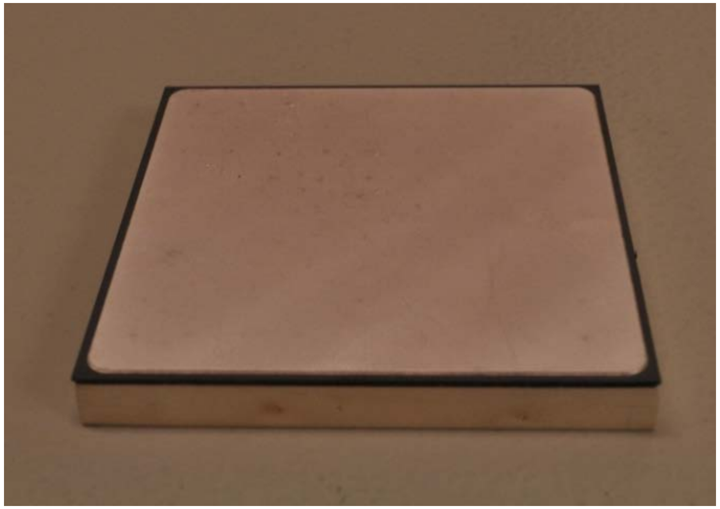

Substrate Delamination and Cracking

Reliability of Thermoplastic-based BIM

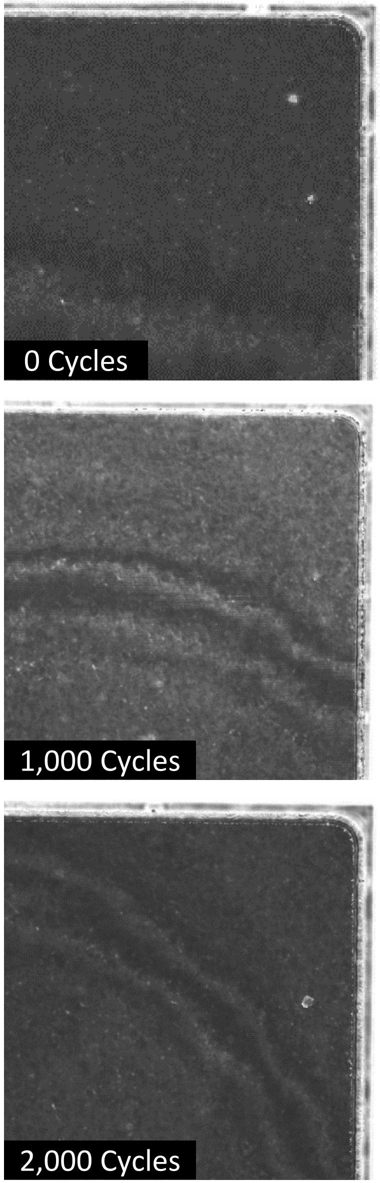
- Btech HM-2 (Carbon fibers within polyamide matrix)
  - Bonding
    - HM-2 was cut to the base plate dimensions
    - The sample assembly was placed in the hot press and raised to 195°C
    - 1 MPa (150 psi) of pressure was applied
  - Reliability Results
    - After 2,000 cycles, the bonded interface remained defect-free



Hot Press

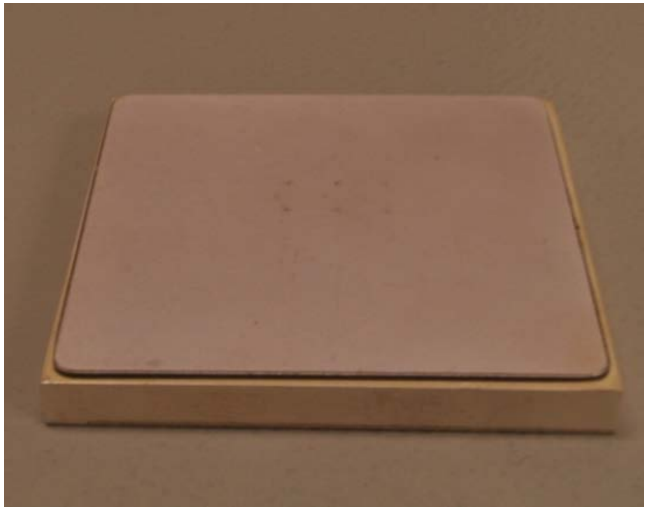


Sample Assembly

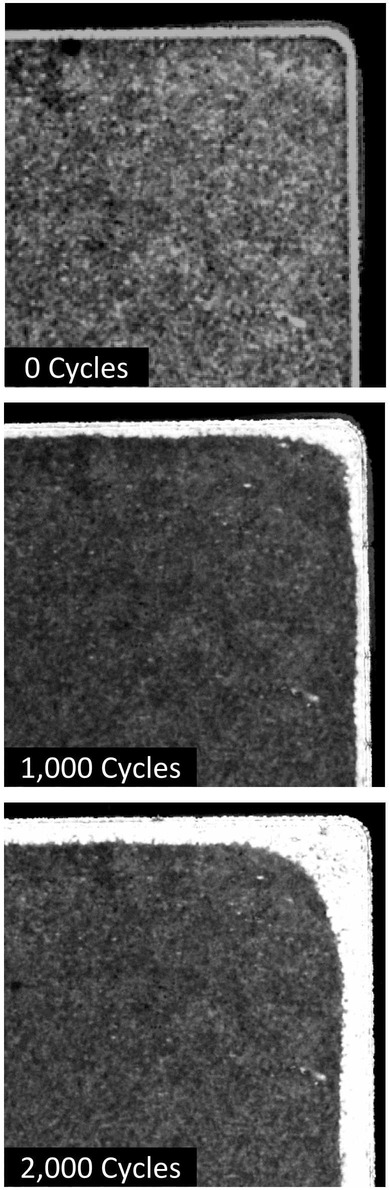


Reliability of Sintered Silver-based BIM

- 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.
    - Adhesive fracture has initiated at the bonding perimeter.

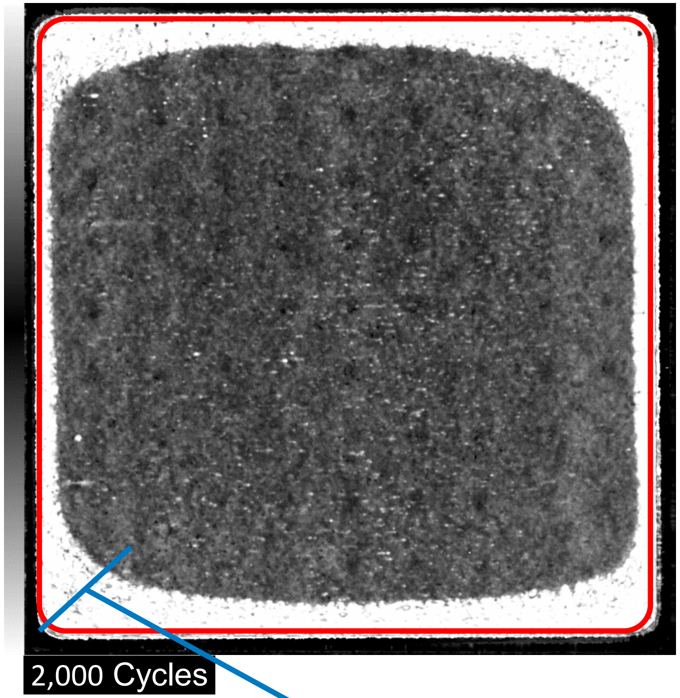


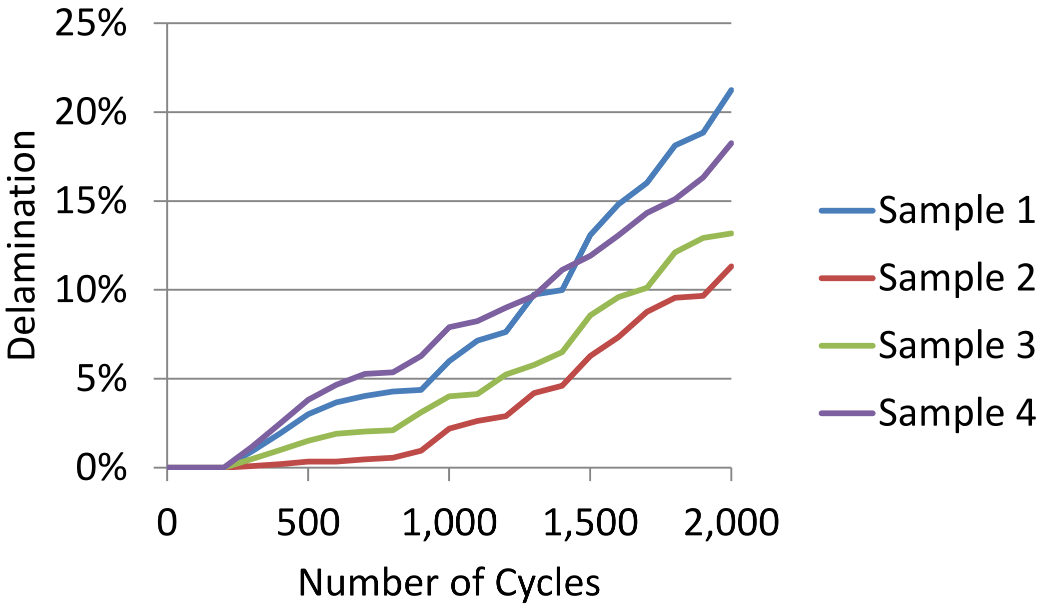
Sample Assembly



Reliability of Sintered Silver-based BIM

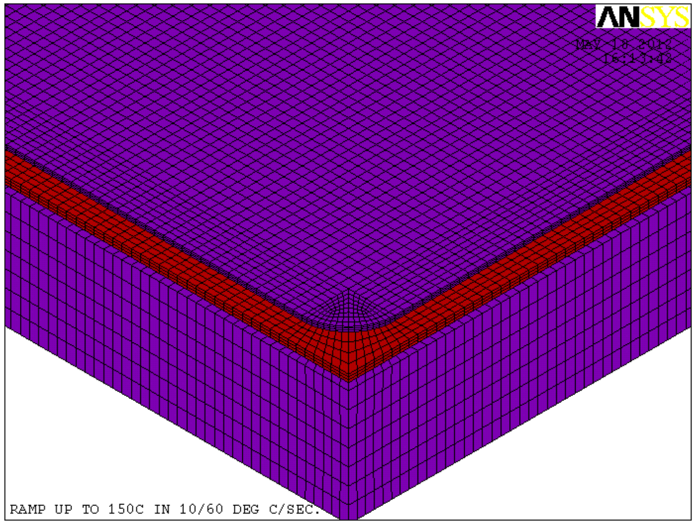
- After 2,000 cycles, perimeter fracturing has reached 11% to 21%.



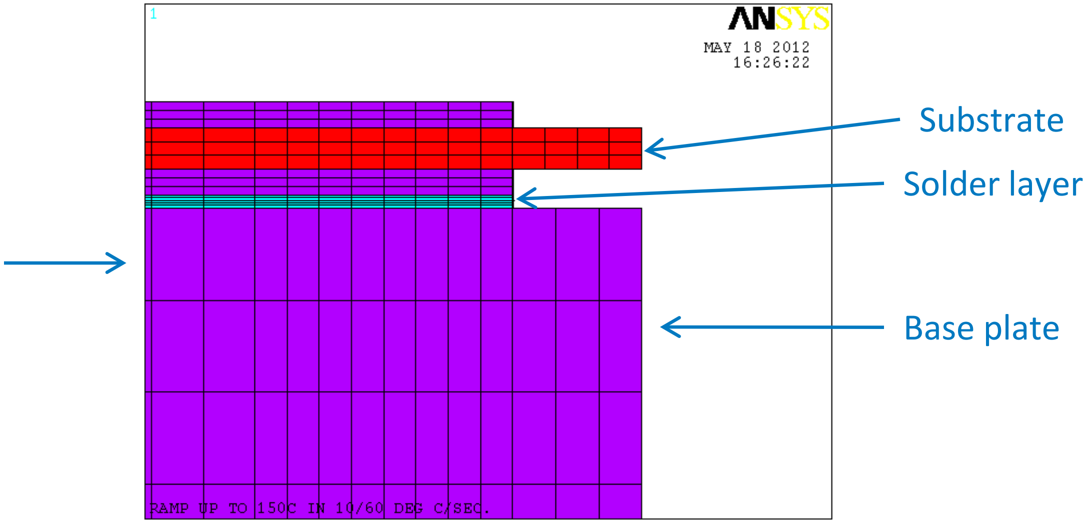


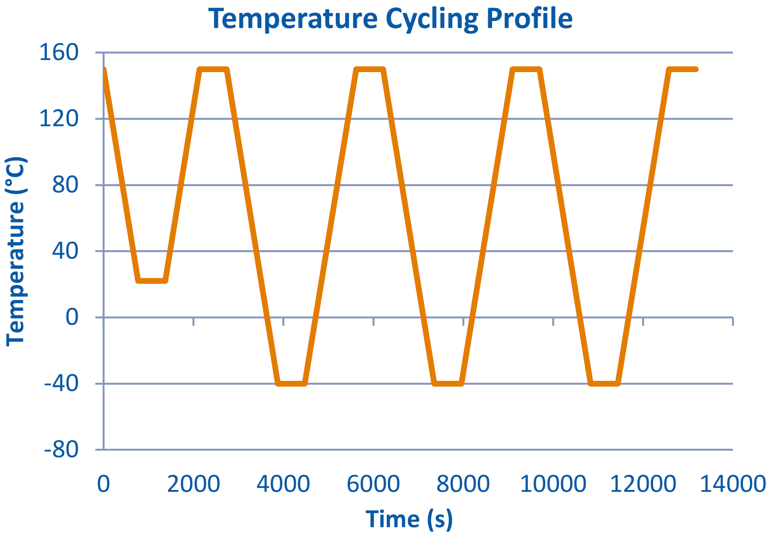
Credit: Paul Paret

BIM Finite Element Modeling (FEM)



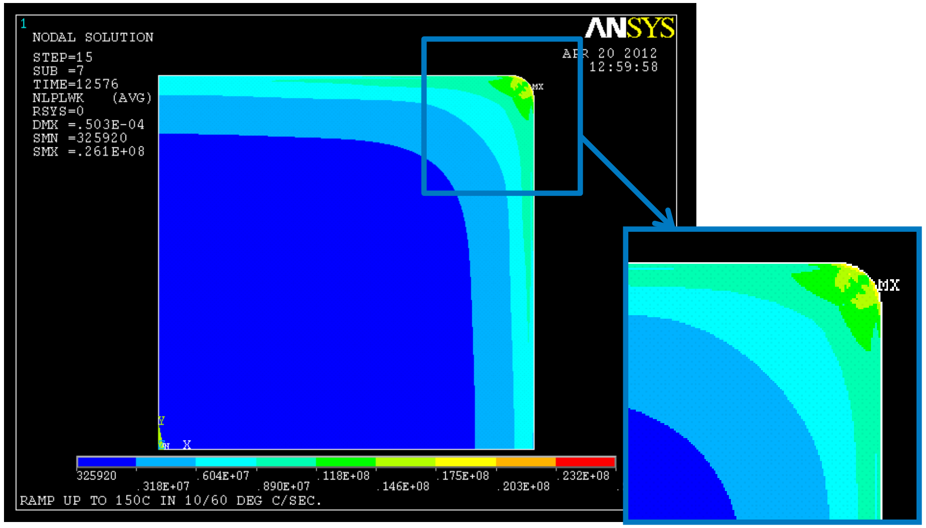
Quarter Symmetry Model



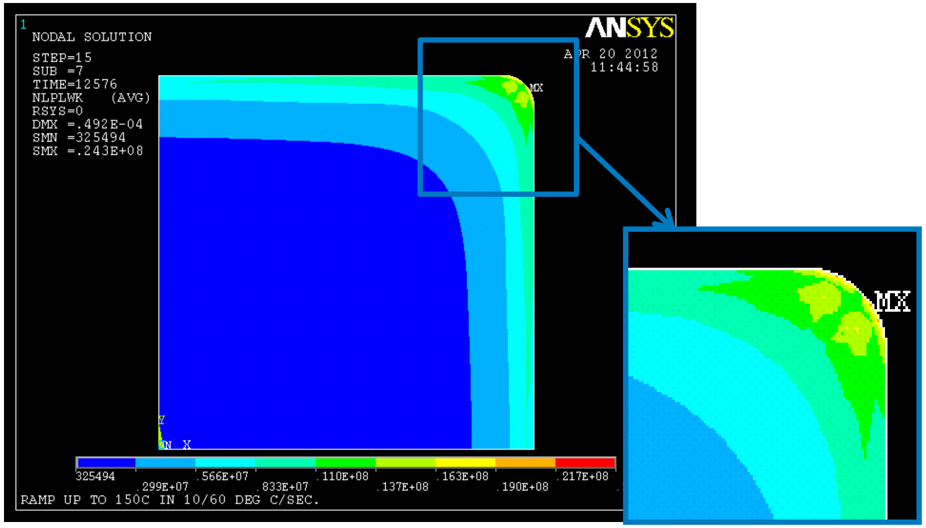


- Temperature cycling parameters:
  - -40°C to 150°C
  - 5°C/minute ramp rate
  - 10 minute dwell/soak time
- Viscoplastic material model applied to solder layer
- Temperature-dependent elastic material properties incorporated for base plate and substrate

BIM FEM

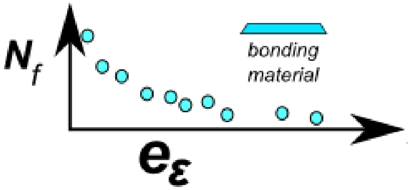


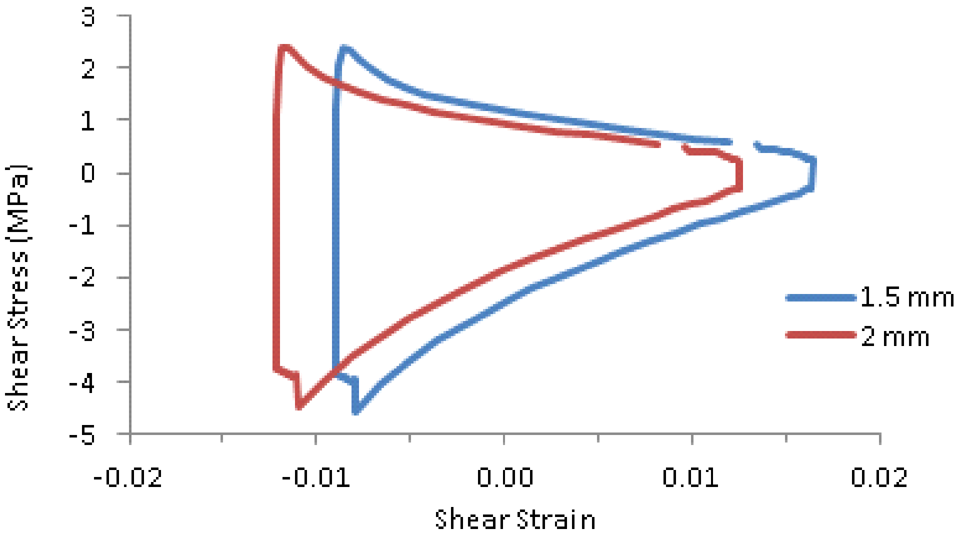
Solder Layer Top Surface (1.5-mm radius)



Solder Layer Top Surface (2-mm radius)

- Strain energy density in the bonded joint region shown to decrease as fillet radius increases (11.3 MPa and 11.2 MPa for 1.5 mm and 2 mm, respectively).
- Strain energy density versus cycles-to-failure correlation to be obtained for lead-based and lead-free solders.





Summary

- TIMs/BIMs are a key enabling technology for compact, light-weight, low-cost, reliable packaging and for high-temperature coolant and air-cooling technical pathways.
- Characterization of thermal performance of TIMs/BIMs
  - 3 to 5 mm^{2}K/W resistance at 100 µm is a difficult target for non-bonded TIMs
  - BIMs can meet this thermal target immediately after bonding – main question is reliability
- Characterization of reliability of BIMs
  - Synthesis of various joints between substrates and base plate, thermal shock/temperature cycling, high-potential test and joint inspection (C-SAM), and strain energy density versus cycles-to-failure models
  - Thermoplastic BIM is very reliable after 2,000 cycles, sintered silver BIM showing some significant edge delamination
- Initiated FEM for solder-bonded interface geometries – ultimate goal is to develop predictive lifetime model for BIM.

Summary

- **Current/Future Work**
  - Complete 2,000 thermal cycles on all selected materials using Si_3N_4-based substrates
  - Report on reliability of each BIM under specified accelerated test conditions
  - Derive viscoplastic parameters for lead-based and lead-free solders from double-lap shear test experiments
  - Develop strain energy density versus cycles-to-failure predictive lifetime model for lead-based solder
  - Expand strain energy density versus cycles-to-failure predictive lifetime model to lead-free solders
  - Improve process for large-area sintered silver-based interface, and eventually develop predictive lifetime model

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