NREL
NATIONAL RENEWABLE ENERGY LABORATORY

Thermal Performance and Reliability of Bonded Interfaces for Power Electronics Packaging Applications

ASTR 2011 Workshop

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Outline

- Program Overview
- Background and Objectives
- Experimental Approach and Results
- Modeling Approach and Results
- Summary and Future Direction

Advanced Power Electronics and Electric Motors (APEEM)
Research Targets, Challenges, and Research Areas

Reduce Dependence on Oil

Via Electrification of Vehicle Drives

Requirements: 55 kW peak for 18 sec; 30 kW continuous; 15-year life

Technical Targets

Year	Traction Drive System				Power Electronics			Motors		
	($/kW)	(kW/kg)	(kW/l)	Efficiency	($/kW)	(kW/kg)	(kW/l)	($/kW)	(kW/kg)	(kW/l)
2010	19	1.06	2.6	>90%	7.9	10.8	8.7	11.1	1.2	3.7
2015	12	1.2	3.5	>93%	5	12	12	7	1.3	5
2020	8	1.4	4	>94%	3.3	14.1	13.4	4.7	1.6	5.7

(Traction Drive System = Power Electronics + Motors)

Challenges

Research Areas

Traction Drive System
- Benchmarking technologies
- Innovative system designs

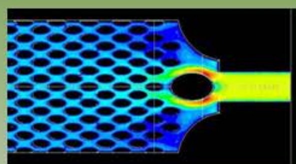
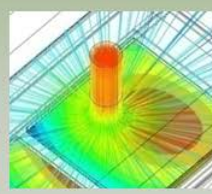
Power Electronics
- Innovative topologies
- Temperature-tolerant devices
- Packaging
- Capacitors
- Vehicle charging

Electric Machines
- Permanent magnet (PM) motors
- Magnetic materials
- High-performance non-PM motors
- New materials

PEEM Thermal Management
- Thermal system integration
- Heat transfer technologies
- Thermal stress and reliability

NREL APEEM Research Focus Areas

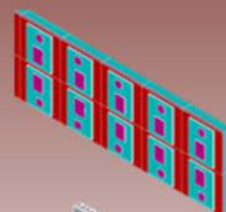
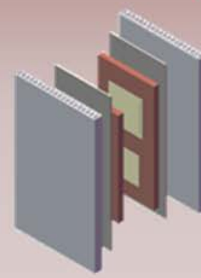
Advanced Heat Transfer

Credit: Ken Kelly, NREL

Enable increased power density at lower cost

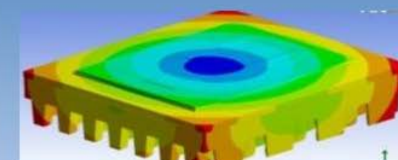
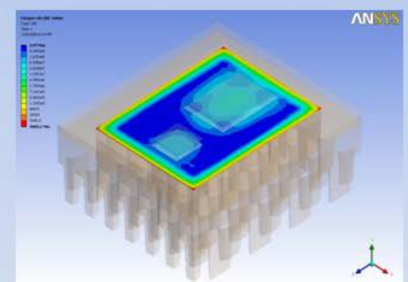
Thermal Systems Integration


Credit: Mark Mihalic, NREL

Achieve technology integration at a lower system cost

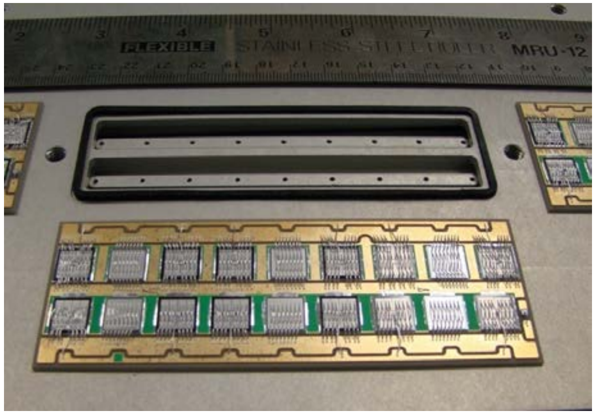
Thermal Stress and Reliability

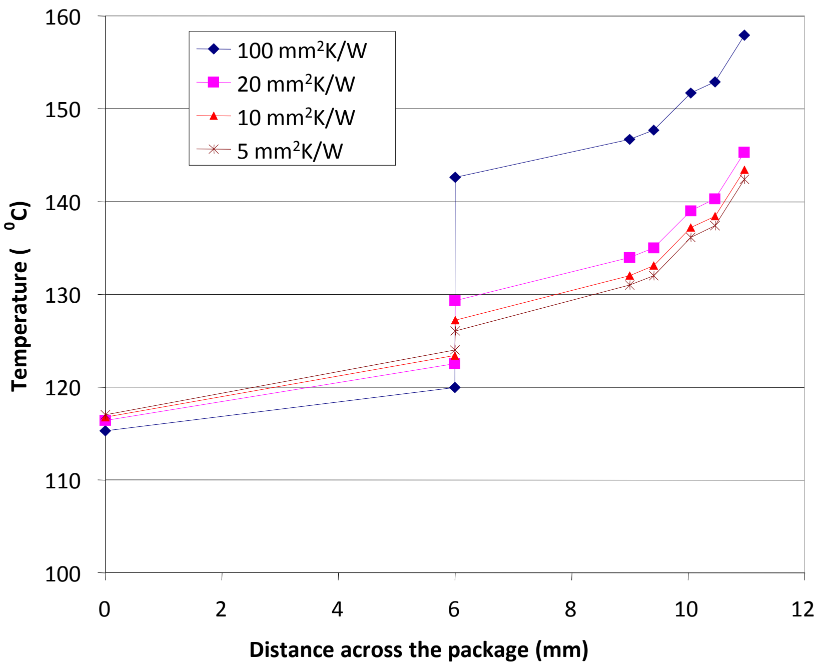
Improve reliability of new technologies

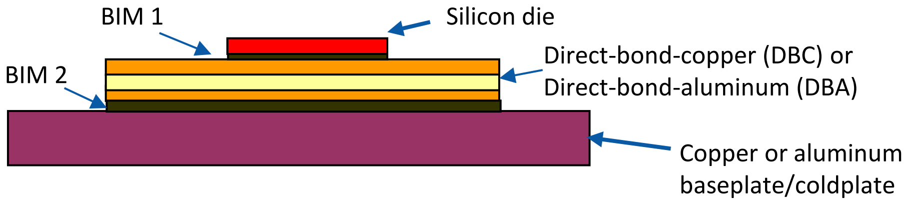
Background

- Power electronics are essential in an electric vehicle drive train for controlling the output of the electric motor
- Excessive temperature (>150°C for silicon [Si] devices) can degrade the performance, life, and reliability of power electronics components
- Interfaces in the package can pose a major bottleneck to heat removal
- Conventional thermal interface materials (TIMs) do not meet thermal performance and reliability targets—the industry trend is towards bonded interface materials (BIMs)
- Bonded interfaces, such as solder, degrade at higher temperatures and are prone to thermomechanical failure under large temperature cycling.



Credit: Mark Mihalic, NREL





Objectives

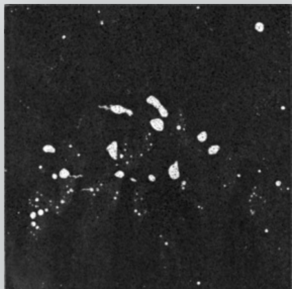
- **Overall Objective**
  - Investigate thermal performance and reliability of novel bonded interface materials (such as sintered silver and thermoplastics with embedded carbon fibers) for power electronics applications to meet the following specific objectives:
    - Thermal resistance of 5 mm^2K/W
    - Thermal resistance maintenance of 5 mm^2K/W after 2,000 thermal cycles from -40°C to 150°C.

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

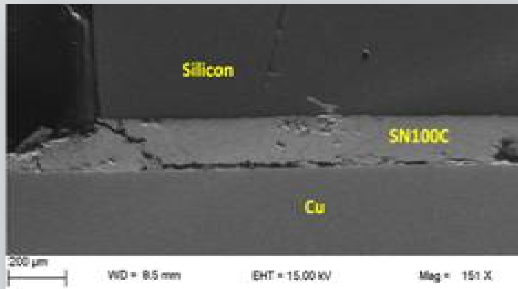
Failure Mechanisms

Bonded Interface Materials

Voids



Cohesive Fracture

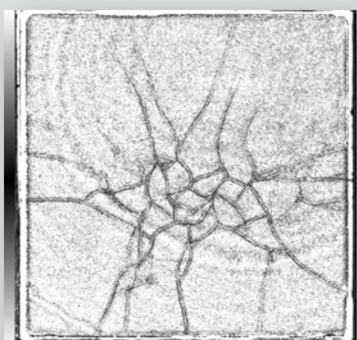


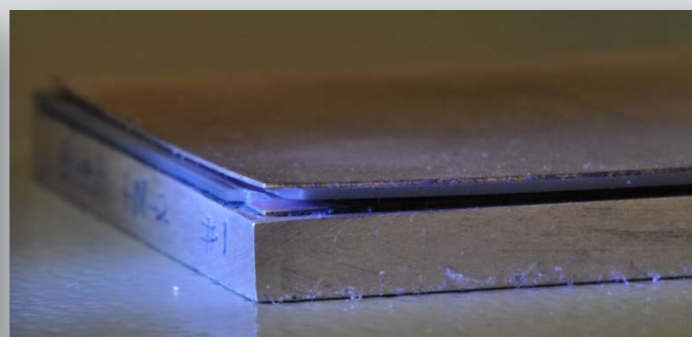
Credit: G.Q. Lu, Virginia Tech

Adhesive Fracture

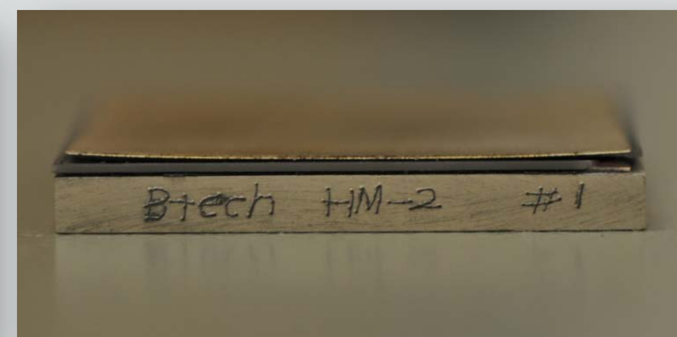
Direct-Bond-Copper (DBC)

Aluminum Nitride (AlN) Cracks





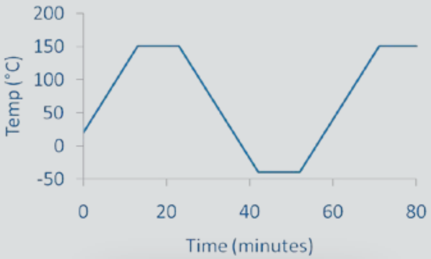
Copper (Cu) to AlN Delamination



Credit: Doug DeVoto, NREL (all remaining photos)

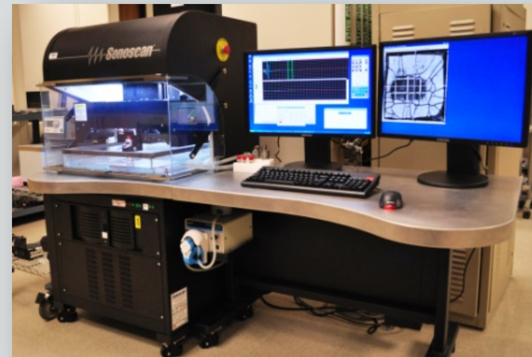
NREL Reliability Capabilities

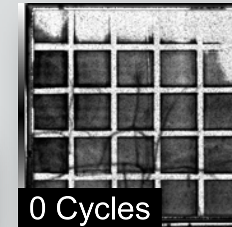
Thermal Cycling

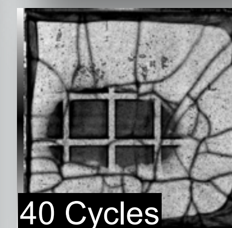


Ceramic Electrical Failure (High-potential [hi-pot] tester)

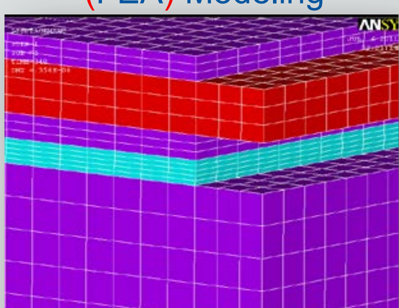
Non-Destructive Imaging (C-mode scanning acoustic microscope [C-SAM])



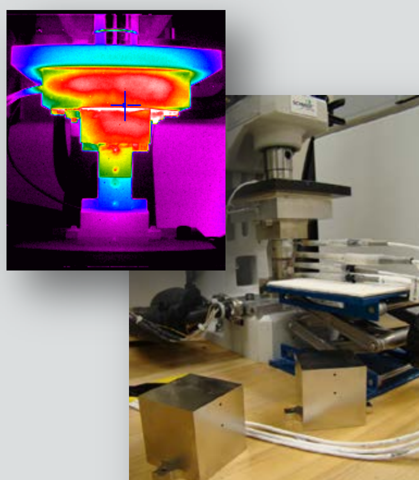




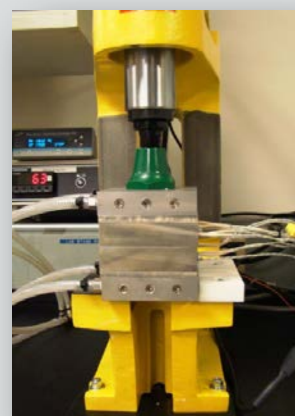
Finite Element Analysis (FEA) Modeling



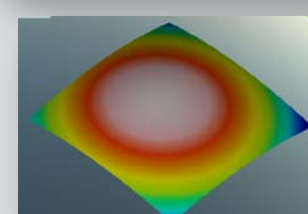
Thermal Resistance (ASTM stand)



Sample Synthesis (Hot press)



Sample Deformation (Laser profilometer)



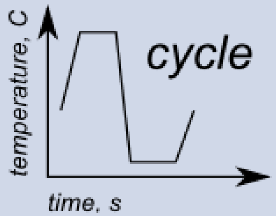
Credit: Doug DeVoto, NREL (all photos)

Approach

Sample Synthesis

Synthesis of samples using stencil printer and hot press

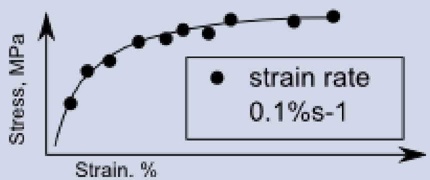
Thermal Testing/ Characterization



Cycling of samples in a thermal shock chamber

Characterization of samples via steady-state thermal resistance tester, hipot tester, C-SAM, and X-ray imaging

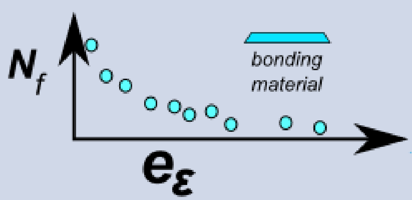
BIM Mechanical Characterization



Shear tests to extract mechanical characteristics of BIMs

Extraction of Anand model parameters

Reliability Calculation



Strain energy density per cycle

Number of cycles to crack initiation/ delamination

Fatigue life prediction

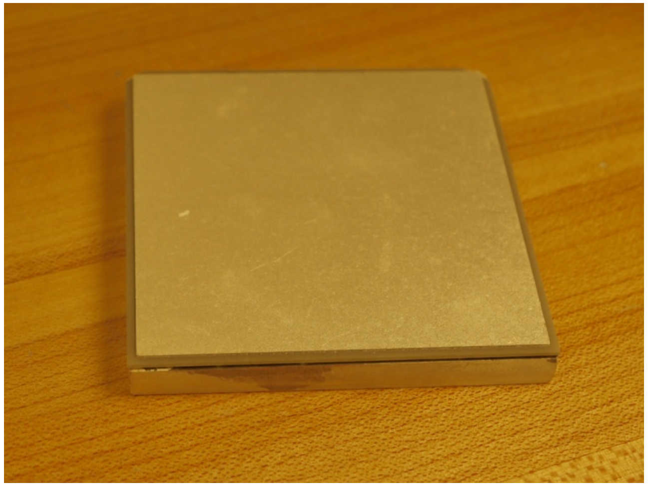
Experimental Approach

Numerical Approach - FEA/Calculations

Sample Assembly

- Five samples of each BIM (between DBC/copper baseplate) were synthesized for testing and included:
  - Silver coating on the DBC and baseplate
  - DBC base on an AlN substrate
  - An interface between 50.8 mm x 50.8 mm footprint
- Samples followed manufacturer-specified reflow profiles, and bonds were inspected for quality.

DBC/Base Plate Assembly

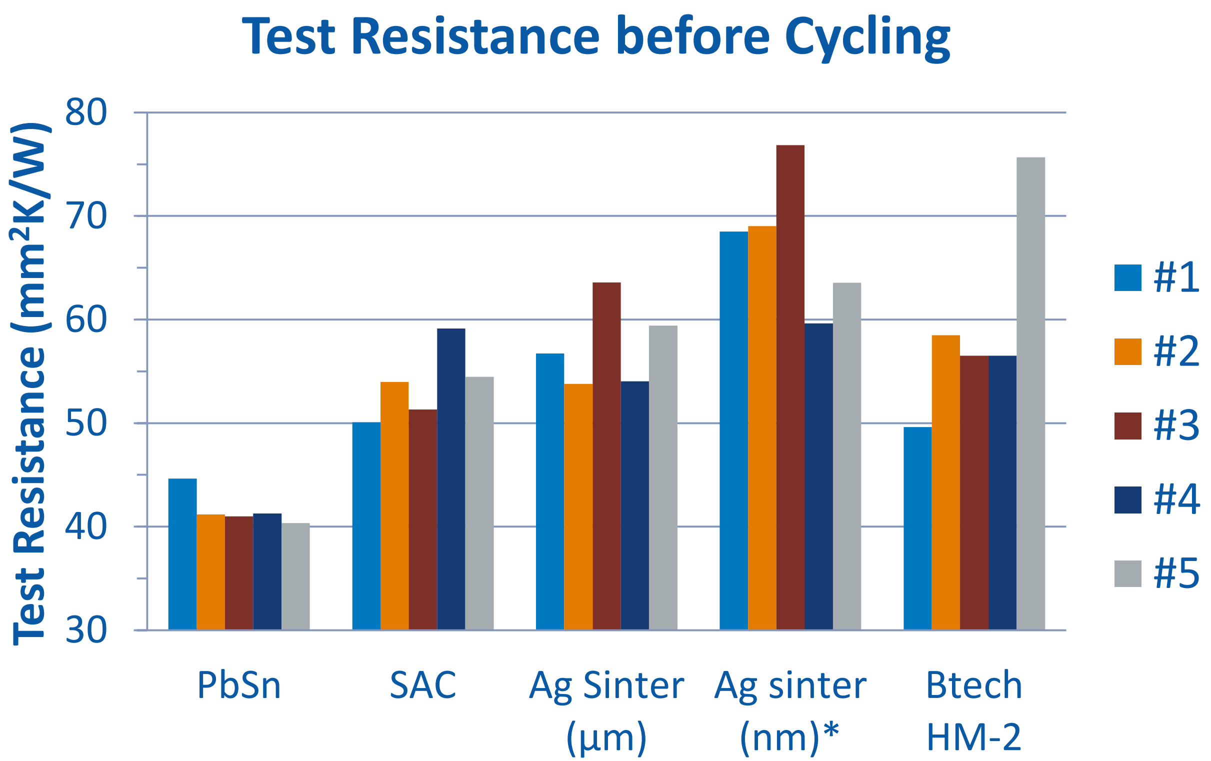


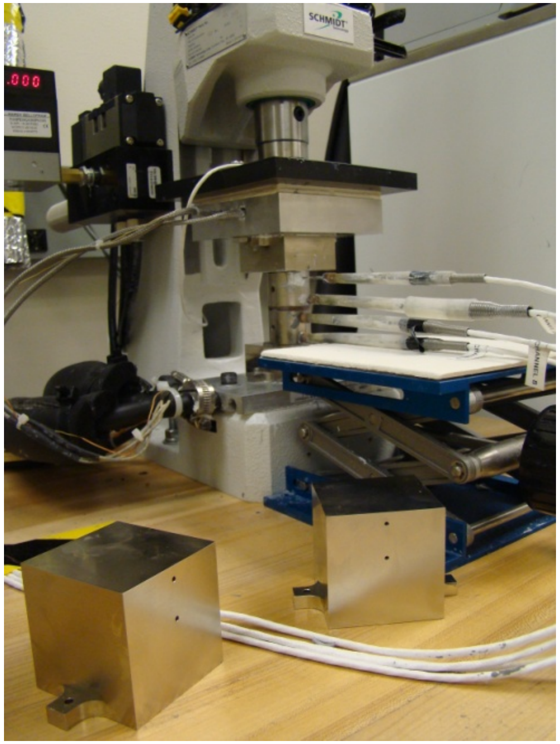
Credit: Doug DeVoto, NREL

Solder	Sn63Pb37	Baseline (lead-based solder)
Solder	SAC305	Lead-free solder
Sintered silver	Heraeus C1075A	Based on micron-size silver particles
Sintered silver	nanoTach®	Based on nanoscale silver particles
Adhesive	Btech HM-2	Thermoplastic (polyamide) film with embedded carbon fibers

Thermal Resistance Measurements

- Each sample was tested for thermal resistance before the temperature cycling was initiated
- Resistance values included package resistance and two layers of 25µm Dow TC 5022 interfacing between a sample and the test stand blocks.



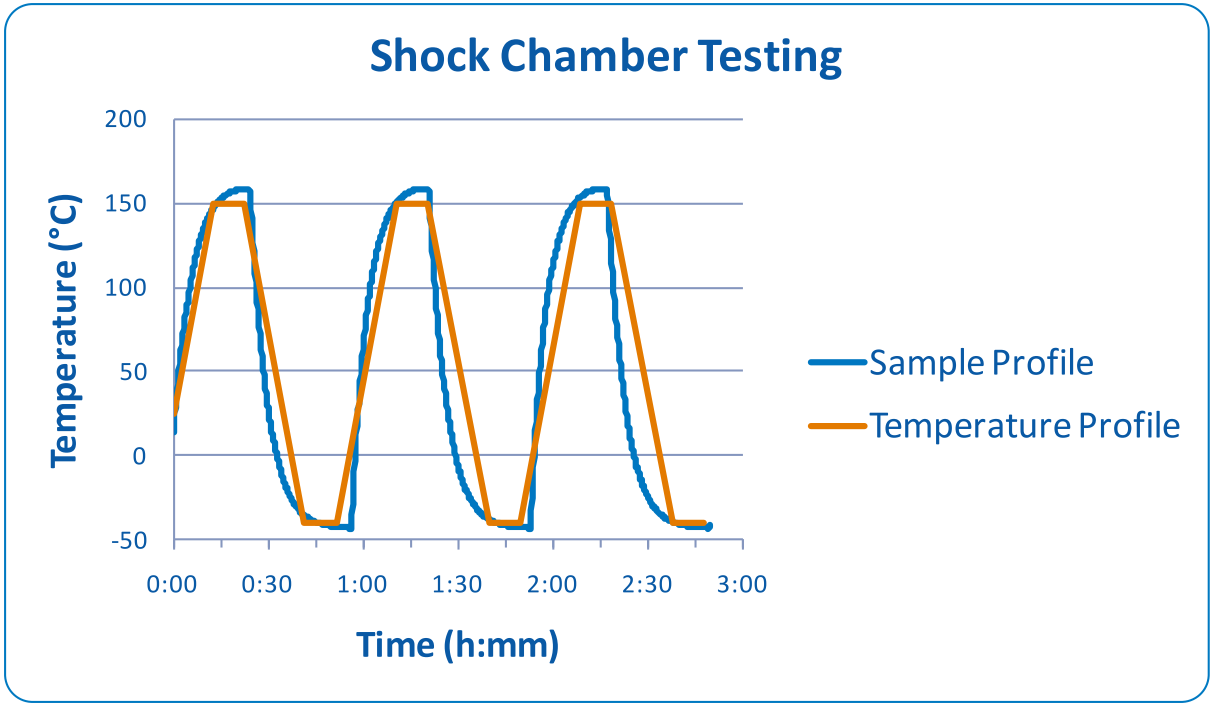


Credit: Doug DeVoto, NREL

*DBC of samples 2 and 5 delaminated from baseplate after ASTM test.

Thermal Cycling

- Cycle Profile
  - Thermal extremes from -40°C to 150°C
  - Ramp rate of 10°C/minute, with a dwell/soak time of 10 minutes
  - Adherence to JEDEC Standard 22-A104D for temperature cycling.



Shock Chamber

Credit: Doug DeVoto, NREL

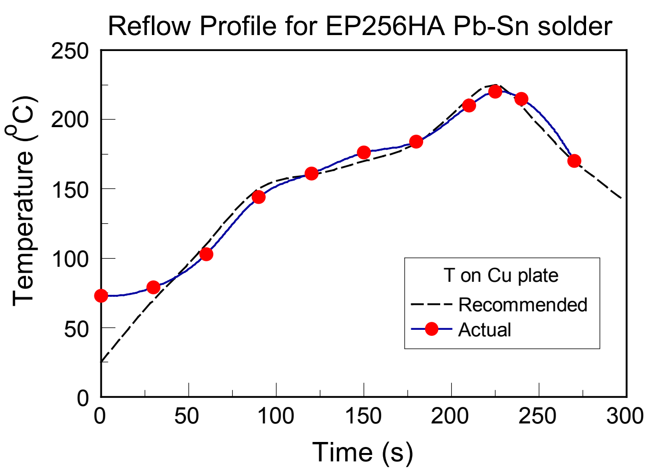
Bonded Interface Materials Testing

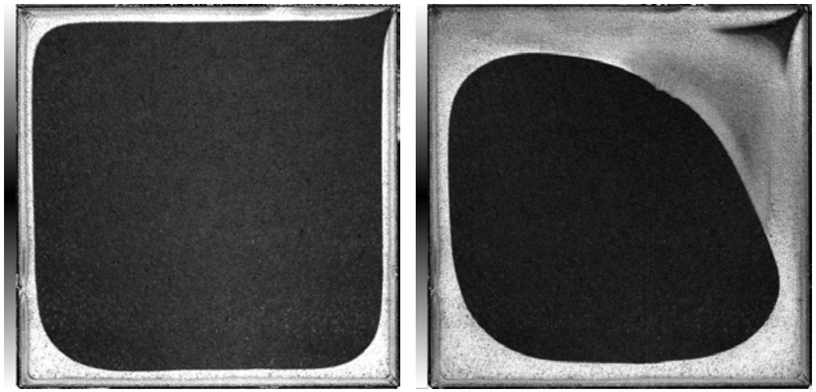
- Failure Mechanisms:
  - BIM, including voids and adhesive/cohesive fractures
  - DBC, including Cu-to-AlN delamination and AlN cracks.

Material	0 cycles	20 cycles	40 cycles	100 cycles	200 cycles
PbSn	2%–10% voiding	-	-	DBC delamination	Additional DBC delamination
Tin-silver-copper (Sn-Ag-Cu or SAC)	19%–33% voiding	Minor DBC delamination	-	Additional DBC delamination	
Silver (Ag) Sinter (µm)	Poor adhesion, AlN cracking	Minor DBC delamination	Additional DBC delamination	Testing ended	
Ag Sinter (nm)	BIM cohesive fracturing in two of five samples	BIM fracturing in three remaining samples	Testing ended		
Btech HM-2	Successful bond	Bond quality maintained	-	Excessive DBC delamination	Testing ended

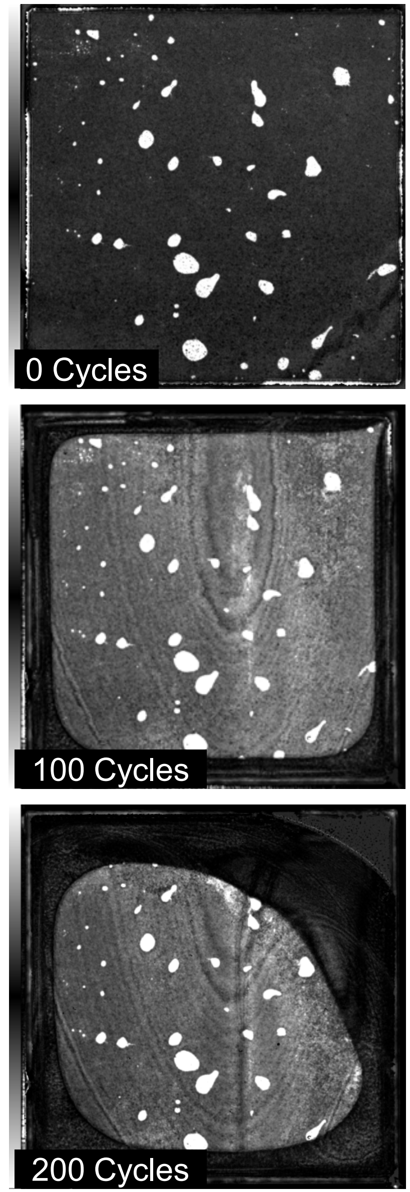
PbSn

- Kester Sn63/Pb37 256HA
  - Printing
    - A 50.8 µm (2-mil) stainless-steel stencil was raised to 101.6 µm (4 mil) with Kapton tape and placed over the baseplate. The stencil pattern has 9 mm x 9 mm square openings with 1 mm separations. The solder material was applied to the top of the stencil and a squeegee was used to ensure uniform application.
  - Reflow
    - The assembled sample passed through a Sikama reflow oven following the recommended profile
  - Initial Results
    - Low percentage of voiding (2%–10%), solder thickness of 50 to 75 µm
  - Cycling Results
    - Two samples show large liftoff of the top Cu layer, with the remaining three samples revealing minor liftoff.





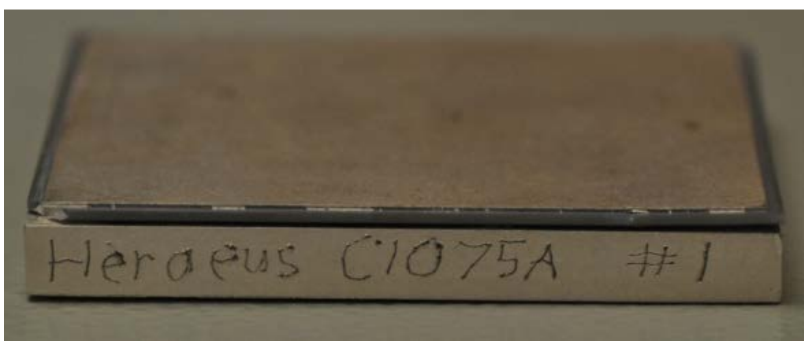
The top Cu layer delaminating from AlN is shown after 100 cycles (left) and 200 cycles (right).

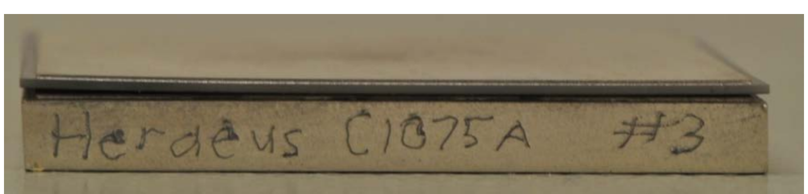


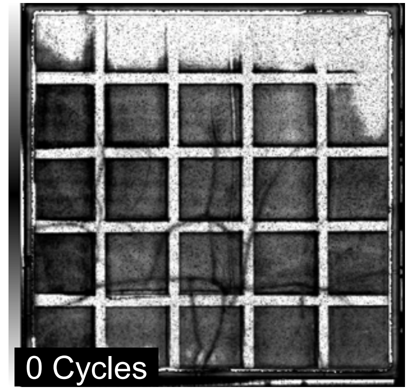
Credit: Doug DeVoto, NREL (all photos)

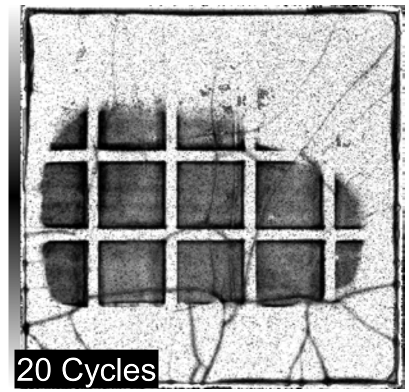
Ag Sinter (μm)

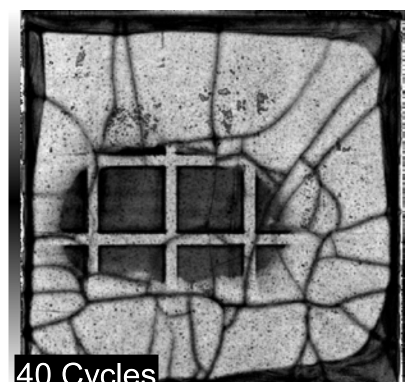
- Heraeus C1075A (silver conductor paste)
  - Printing
    - Two layers of paste were applied with a 50.8 μm stencil, and each layer was dried after application at 80°C for 30 minutes
  - Sintering
    - Binder was burned off for 2 hours at 250°C, and then the assembly was heated to 280°C and underwent 30 MPa of pressure for 30 minutes
  - Initial Results
    - High-bonding temperatures caused cracking within the AIN layer and poor adhesion at the edges was revealed in the C-SAM images
  - Cycling Results
    - Together, top Cu and AIN warp and delaminate from the lower Cu layer. Cycling of samples will not continue.







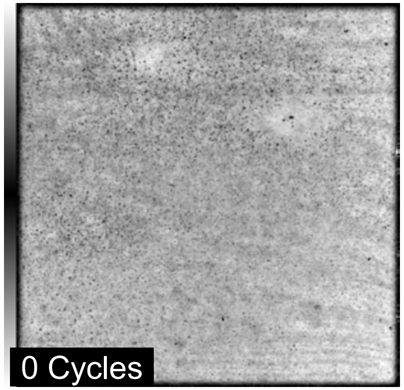


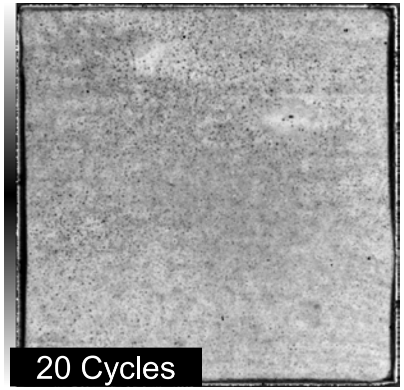


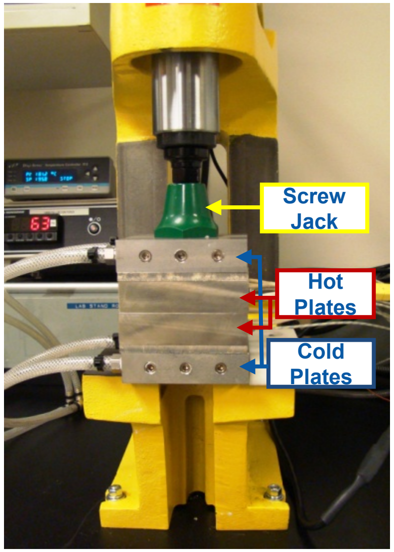
Credit: Doug DeVoto, NREL (all photos)

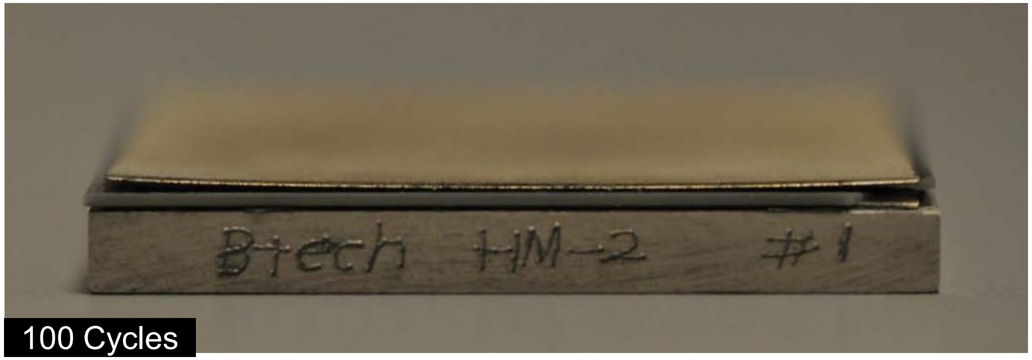
Thermally Conductive Adhesive Film

- Btech HM-2 (Carbon Fibers within Polymer Matrix)
  - Bonding
    - HM-2 was cut to the baseplate dimensions. The sample assembly was placed in the hot press and raised to 190°C, and then 0.689 MPa (100 psi) of pressure was applied.
  - Initial Results
    - C-SAM images showed less contrast with thermoplastics, but uniform bonds were obtained.
  - Cycling Results
    - After 100 cycles, excessive DBC delaminations were present. Delaminations occurred both between the AlN and lower Cu as well as the AlN and top Cu.





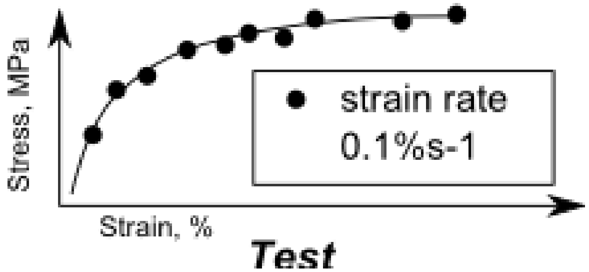




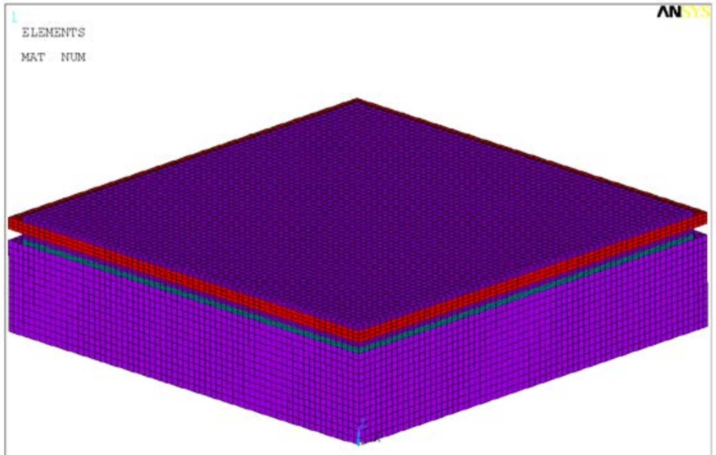
Credit: Doug DeVoto, NREL (all photos)

BIM Mechanical Characterization

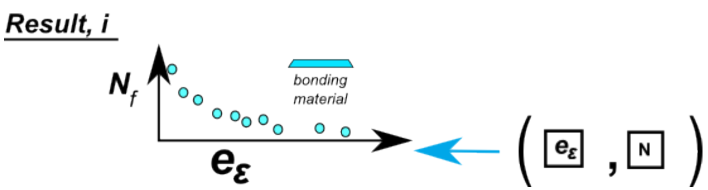
- Shear testing fixture was designed for BIM specimens. The fixture will allow for sample testing at various strain rates and temperatures.
- Script developed to derive Anand viscoplastic parameters from strain rate test data. This will allow the behavior of new solder and sinter materials to be modeled in FEA simulations.
- Template established for performing FEA simulations of the sample geometry to determine the strain energy density per thermal cycle. This will be used as a fatigue-life indicator.



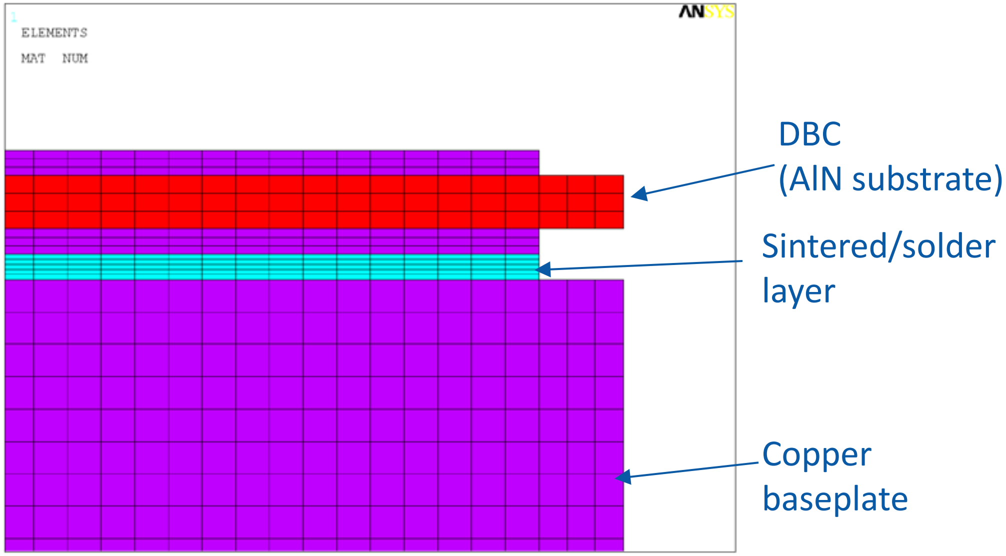
Example Stress-Strain Test Data

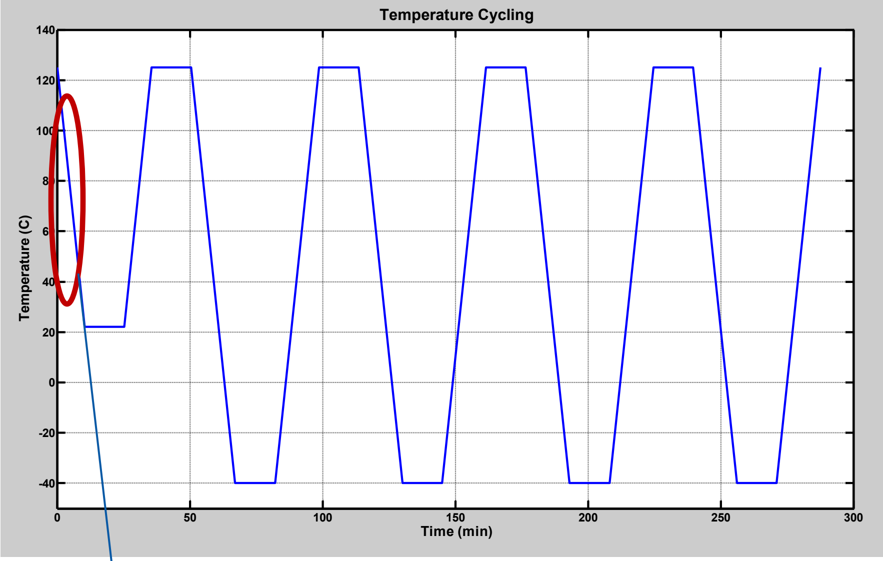


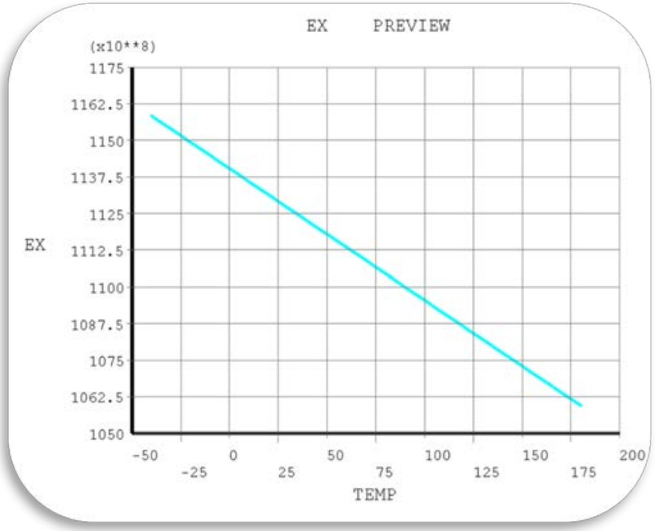
Courtesy: Andreas Vlahinos,
Atmospheric Environment Service (AES)

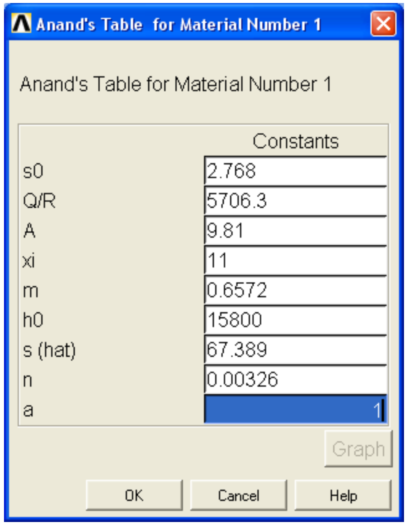


FEA Modeling








Anand's Table for Material Number 1

Anand's Table for Material Number 1

	Constants
s0	2.768
Q/R	5706.3
A	9.81
xi	11
m	0.6572
h0	15800
s (hat)	67.389
n	0.00326
a	1

Graph

OK Cancel Help

Parameters

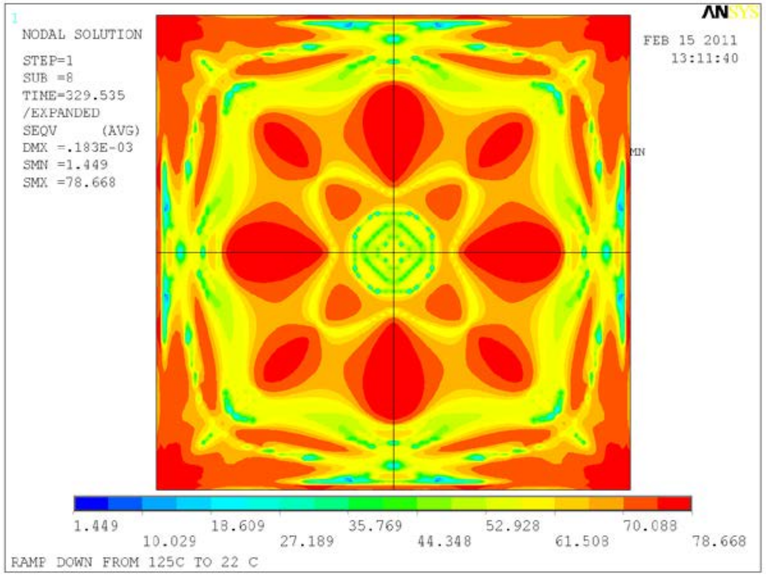
- Reflow temperature = 125°C
- Room temperature = 22°C
- Ramp rate = 10°C/minute

Anand's viscoplastic material model for the solder/sintered material

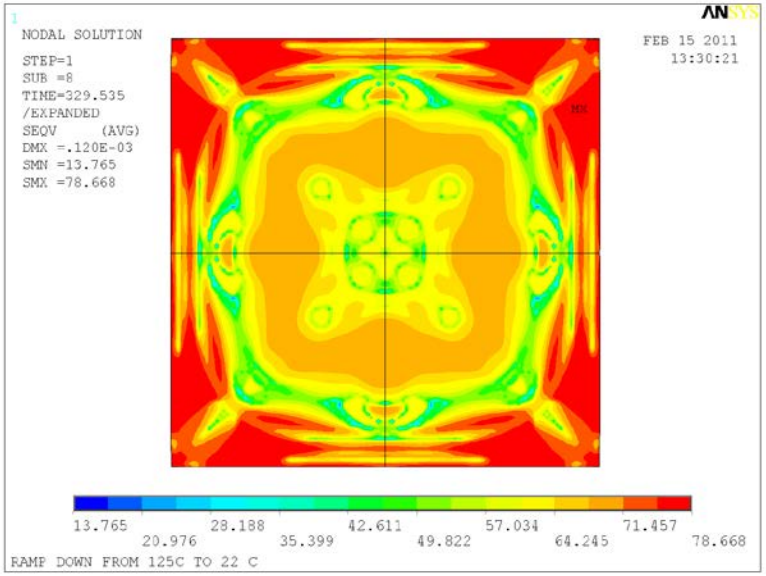
Temperature-dependent material properties for Cu and AlN

Courtesy: Andreas Vlahinos, AES (all graphics)

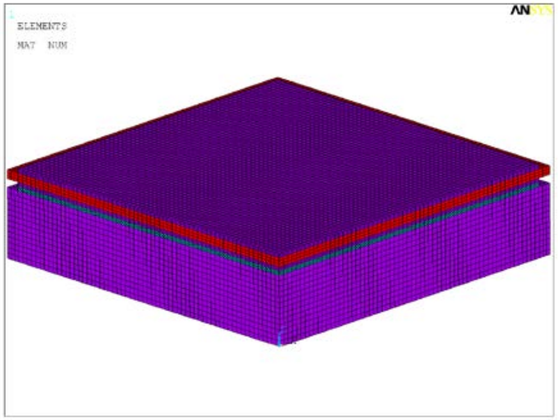
Stress Distribution



Upper/top layer of bonded joint



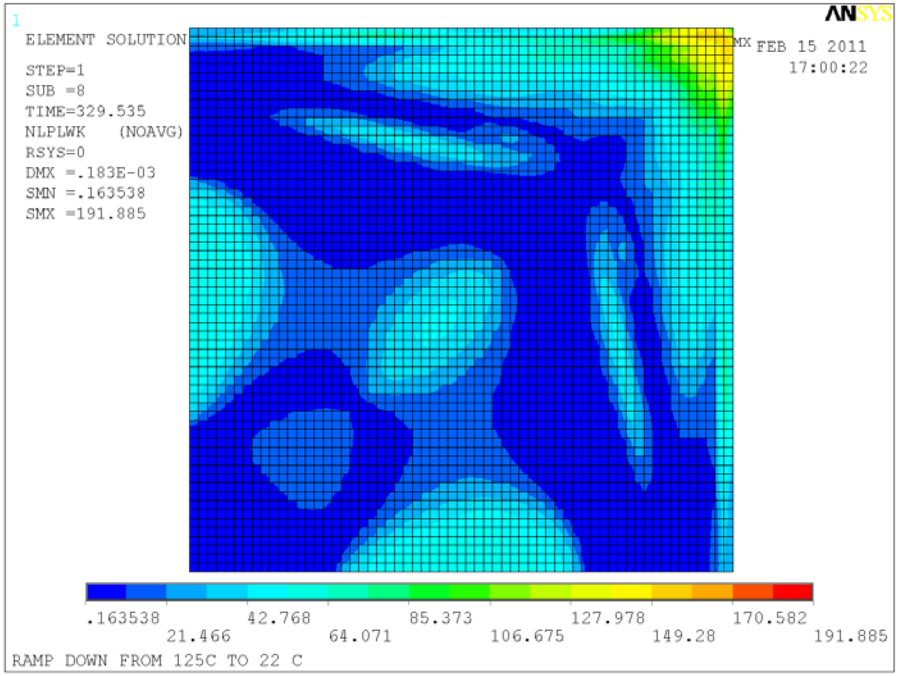
Middle layer of bonded joint



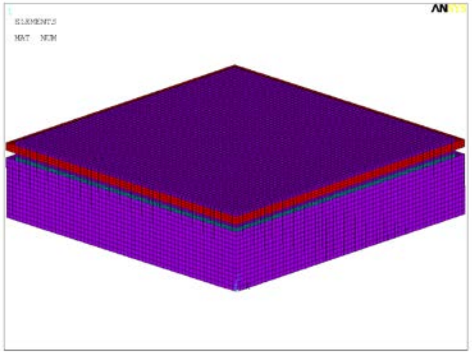
- Equivalent stress distribution in the upper/top and middle layer of the bonded joint
- Stresses are higher in the layer adjoining the DBC and higher in the corner regions.

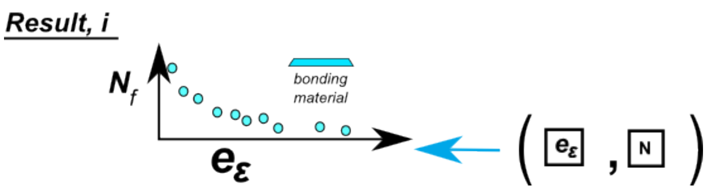
Courtesy: Andreas Vlahinos, AES (all graphics)

Plastic Work Density Distribution



Quarter Symmetry Model





- Plastic work density distribution in the bonded joint region
- Work density higher in the corner regions—failures likely to originate here
- Plastic work density/strain energy density versus cycles-to-failure correlation is the new contribution of this effort.

Courtesy: Andreas Vlahinos, AES (all graphics)

Collaborations

Collaborator	Nature of Interaction/Collaboration
Electrical and Electronics Technical Team, GM, Delphi	• Technical guidance
Oak Ridge National Laboratory	• Packaging
National Institute of Standards and Technology	• Electrothermal modeling of power modules
Virginia Tech	• Synthesis of soldered and sintered joints • X-ray imaging • Provider of nanosilver paste
Btech	• Provider of HM-2 thermoplastic (polyamide) with embedded carbon fibers
Atmospheric Environment Service	• Finite element modeling support

Summary

- **Approach**
  - Synthesis of various joints between DBA/DBC and baseplate (Cu/Al), thermal shock/temperature cycling, thermal resistance measurements, high-potential test and joint inspection (X-ray, C-SAM), and strain energy density versus cycles-to-failure models
- **Current Work**
  - Synthesized a number of bonded interfaces between the DBC/Cu base plate based on different BIM technologies, including lead-based and lead-free solder, sintered silver (micron-size and nanosilver), and thermoplastic
  - Initiated FEA for bonded interface geometries
  - Initiated thermal resistance measurement and quality characterization for the different bonded interfaces prior to thermal shock/cycling.
- **Future Work**
  - For bonded interface between the DBC/Cu baseplate:
    - Refine the bond synthesis process
    - Continue thermal cycling of the bonded samples
    - Characterize thermal resistance and bond quality
    - Characterize BIM to obtain stress-versus-strain mechanical constitutive relationships
    - Perform FEA modeling to infer strain energy density, defect initiation, and propagation
    - Correlate strain energy density to cycles-to-failure.
  - Investigate the thermal performance and reliability of the bonded interfaces between DBA/aluminum as well as alternatives to AlN, such as Si_3N_4.

NATIONAL RENEWABLE ENERGY LABORATORY

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