Power Electronics Materials and Bonded Interfaces – Reliability and Lifetime

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National Renewable Energy Laboratory
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DOE Vehicle Technologies Program
2020 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT219

Overview

Timeline

- Project start date: 10/01/2018
- Project end date: 09/30/2023
- Percent complete: 50%

Budget

- Total project funding: $350K
  - DOE share: $175K
- Funding for FY 2019: $175K
- Funding for FY 2020: $175K

Barriers

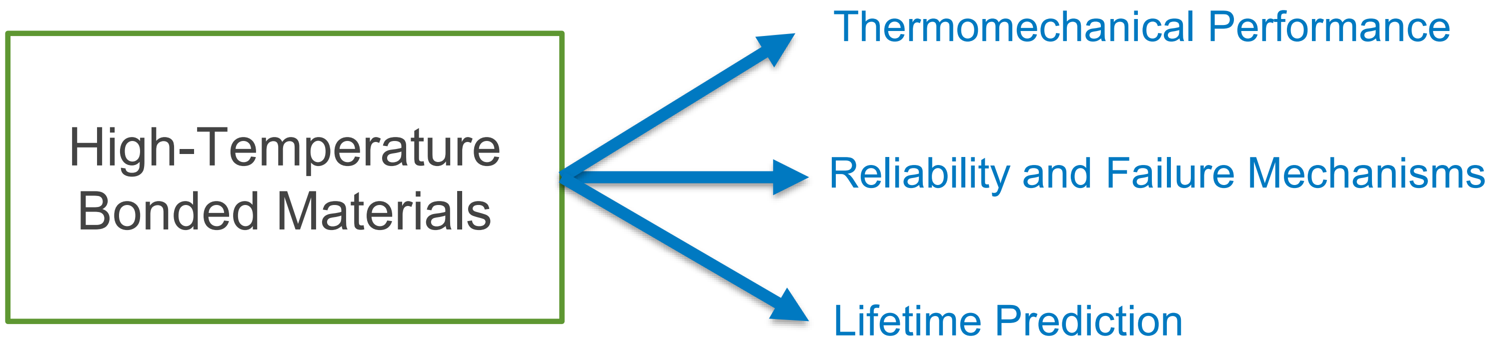
- Cost
- Size and Weight
- Performance, Reliability, and Lifetime

Partners

- Interactions/collaborations
  - Virginia Polytechnic Institute and State University (Prof. G. Q. Lu)
  - Georgia Institute of Technology (Prof. Samuel Graham)
  - Oak Ridge National Laboratory (ORNL)
  - Ames Laboratory
- Project lead
  - National Renewable Energy Laboratory (NREL)

Relevance – Materials for High-Temperature Power Electronics

- Wide-bandgap devices such as silicon carbide and gallium nitride enable low-cost, lightweight, and power-dense automotive power electronics; however, these technologies are currently limited by power electronic packaging.
- It is critical that the packaging design and materials withstand the high-temperature operational environment introduced by the wide-bandgap devices; bonded interfaces must be reliable under extreme thermal stress conditions.
- The main objective of this project is to evaluate the reliability and study the failure mechanisms of bonded interface materials for high-temperature power electronic applications.



Milestones

Description	End Date	Status
Demonstrate viability of coefficient of thermal expansion (CTE)-mismatched round coupons for reliability evaluation of high-temperature bonded interface materials. If the proposed sample design leads to quick failure of the interface material, then redesign the sample structure based on modeling.	10/31/2019	Met
Conduct accelerated thermal cycling on CTE-mismatched samples incorporating bonded interfaces/interface materials.	06/30/2020	Ongoing
Develop a preliminary microstructural model of high-temperature interface materials that simulates fatigue crack initiation and propagation.	09/30/2020	Ongoing

Overall Approach

Bonded Material

Experimental

- Sample synthesis/bonding
- Mechanical Characterization
- Reliability Evaluation – Thermal Cycling
- Failure Mechanisms

Modeling

- Finite Element Analysis
- Strain Energy Density
- J-Integral
- Crack Propagation Model (XFEM)

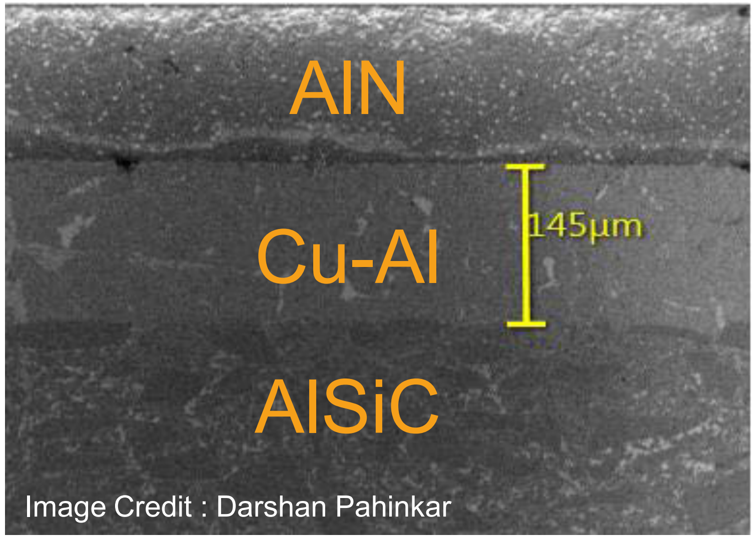
Lifetime Prediction

XFEM – Extended Finite Element Method

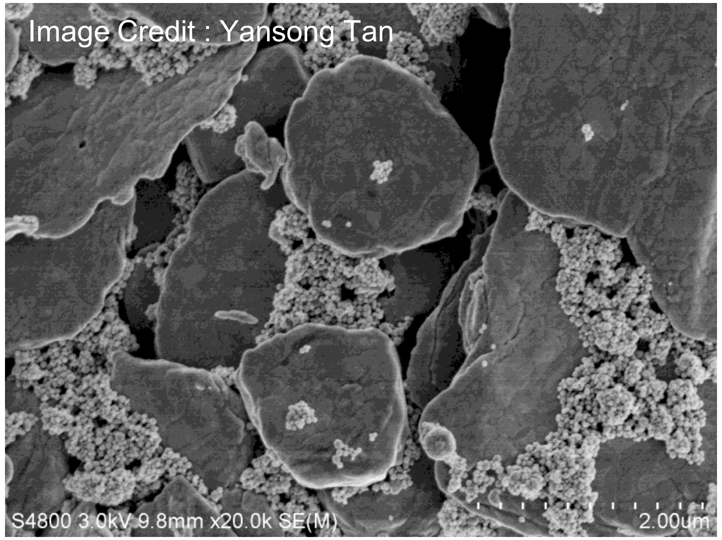
Approach – Materials

High-Temperature Bonded Material

- Georgia Tech
  - Cu/Al, Cu/Sn
- Virginia Tech
  - Sintered Silver
    - Pressureless
    - Low Pressure-Assisted
      - 3 MPa
      - 10 MPa
- NREL
  - Sintered Silver (industry)
    - Pressureless



Cu-Al bond – SEM image



Hybrid-silver – SEM image

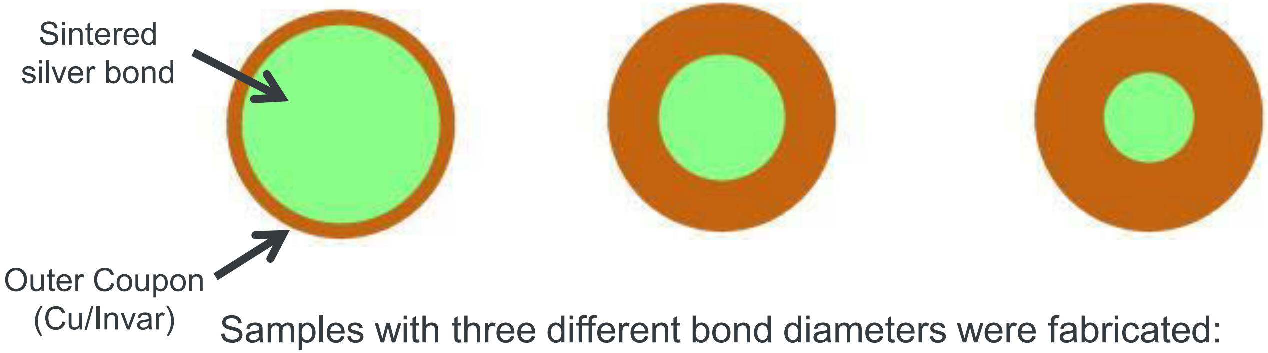
Cu: Copper
Al: Aluminum
Sn: Tin
AlN: Aluminum Nitride
AlSiC: Aluminum Silicon-Carbide

SEM – Scanning Electron Microscope

Approach – Reliability Evaluation

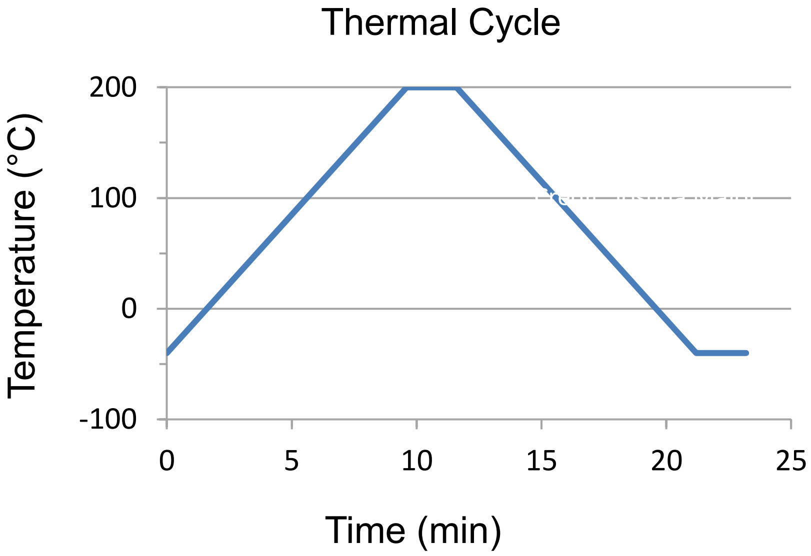
ϕ1-inch Copper and Invar Coupons: non-plated (top), plated with 4-µm-thick silver (bottom)

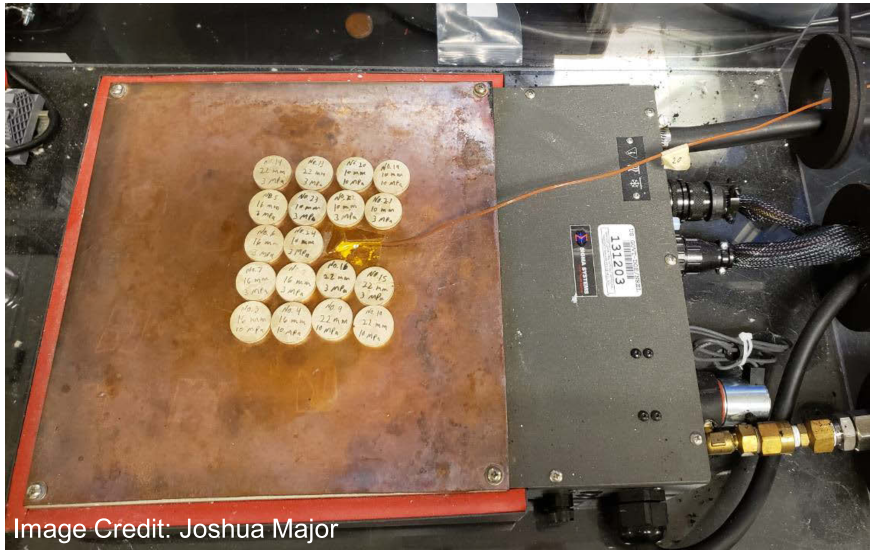
Sample Structure



Samples with three different bond diameters were fabricated: 22 mm (left), 16 mm (center), and 10 mm (right)

Accelerated Thermal Cycling

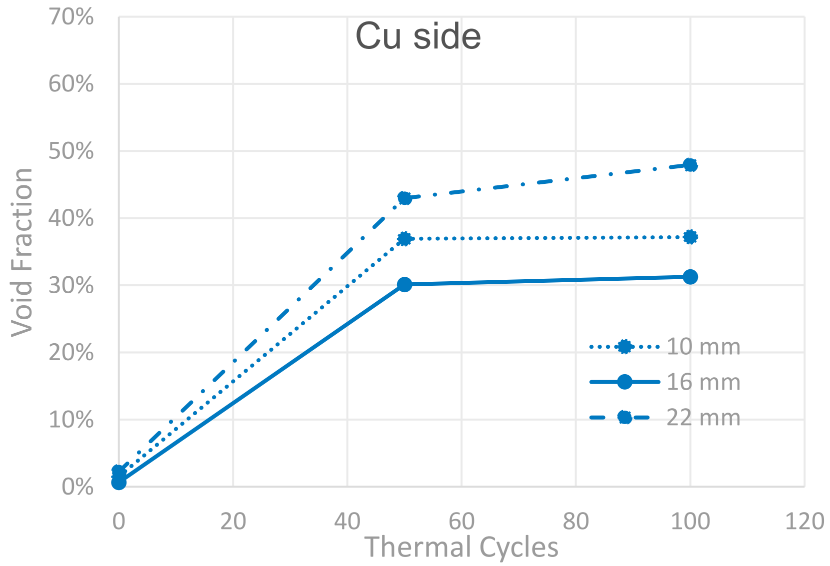


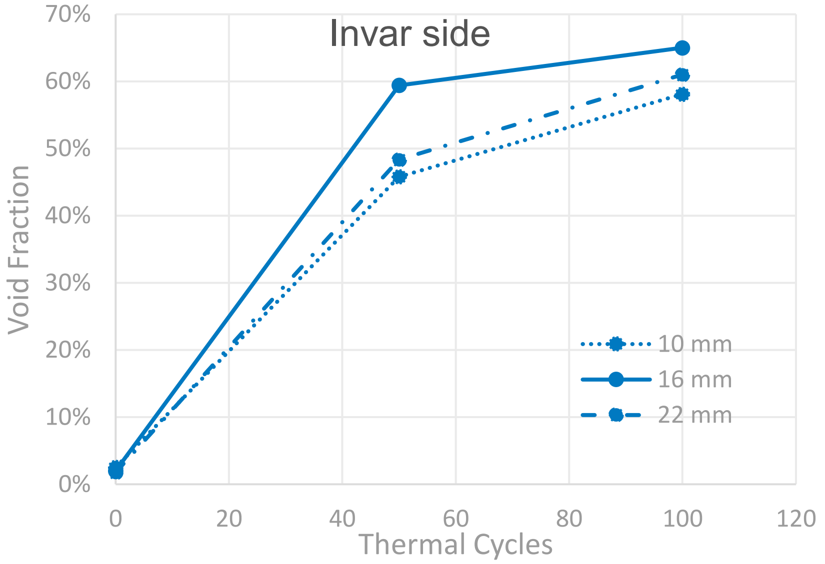


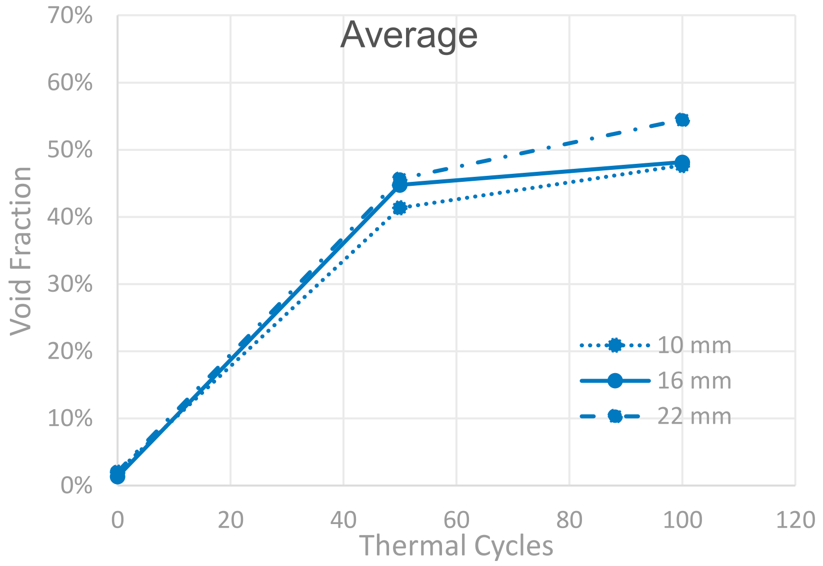
Samples placed on thermal platform for thermal cycling, C-SAM images of these samples are taken periodically

C-SAM – C-Mode Scanning Acoustic Microscope
ϕ - Diameter

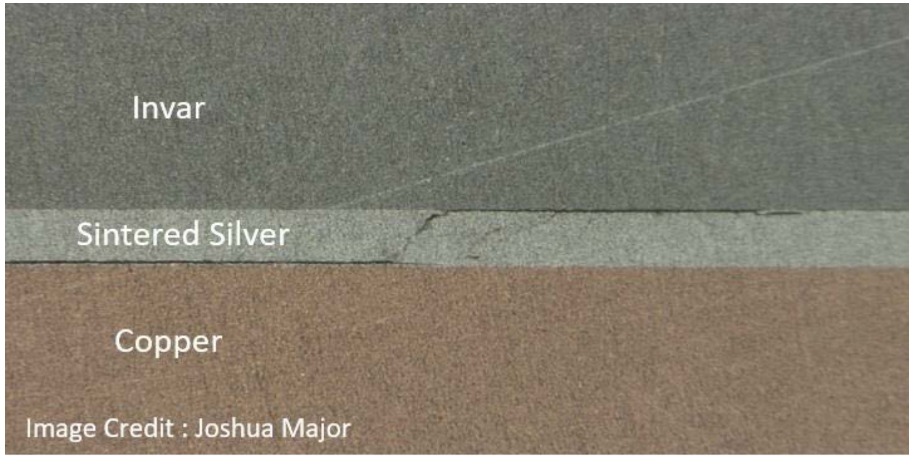
Technical Accomplishments and Progress: Reliability of Sintered Silver – 3 MPa Sintering Pressure







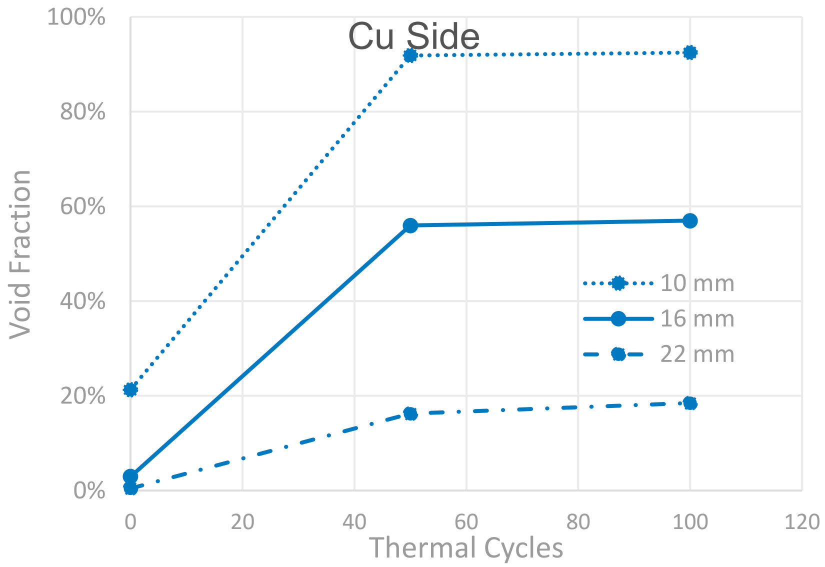
- Most of the samples exhibited very good initial bond quality—void fraction was calculated to be less than 2%.
- The rapid failure of these samples factored out any correlation between sample design variables (bond diameter) and reliability.
- Sample evaluations were first performed after 50 cycles but it likely that samples failed* in 20 or 30 cycles.
- Cross-sectional images reveal the failure mechanisms to be mostly adhesive in nature with near-vertical cohesive cracks in between.

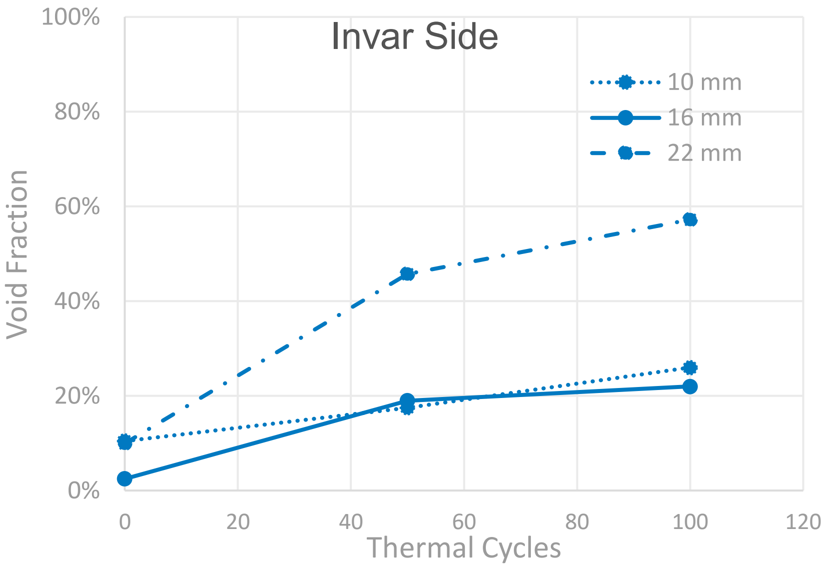


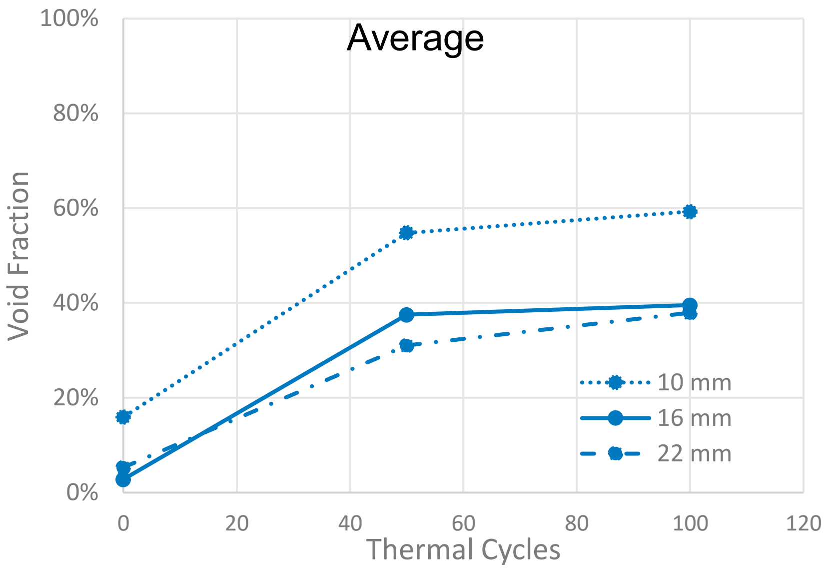
Cross-sectional image of cracks formed in sintered silver bond under thermal cycling: sintering pressure – 3 MPa; bond diameter – 16 mm

Failure – 20% void fraction; void fraction on the y-axes here includes the initial voids and the cracks formed under thermal cycling.

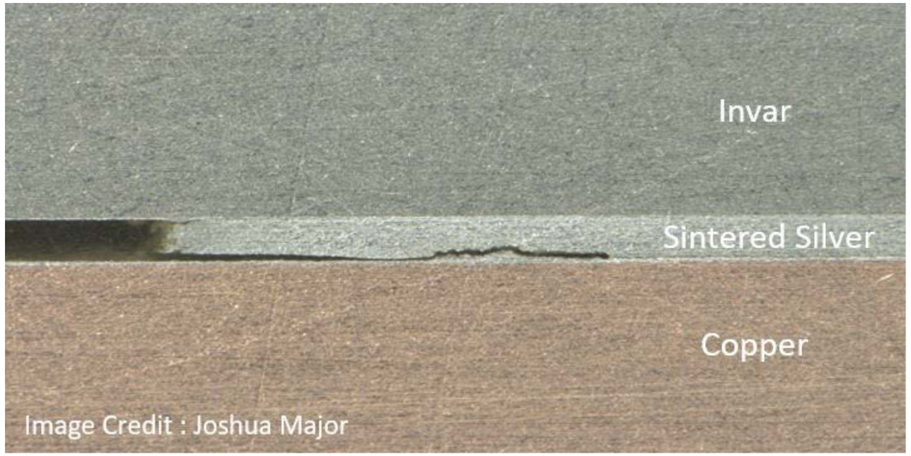
Technical Accomplishments and Progress: Reliability of Sintered Silver – 10 MPa Sintering Pressure







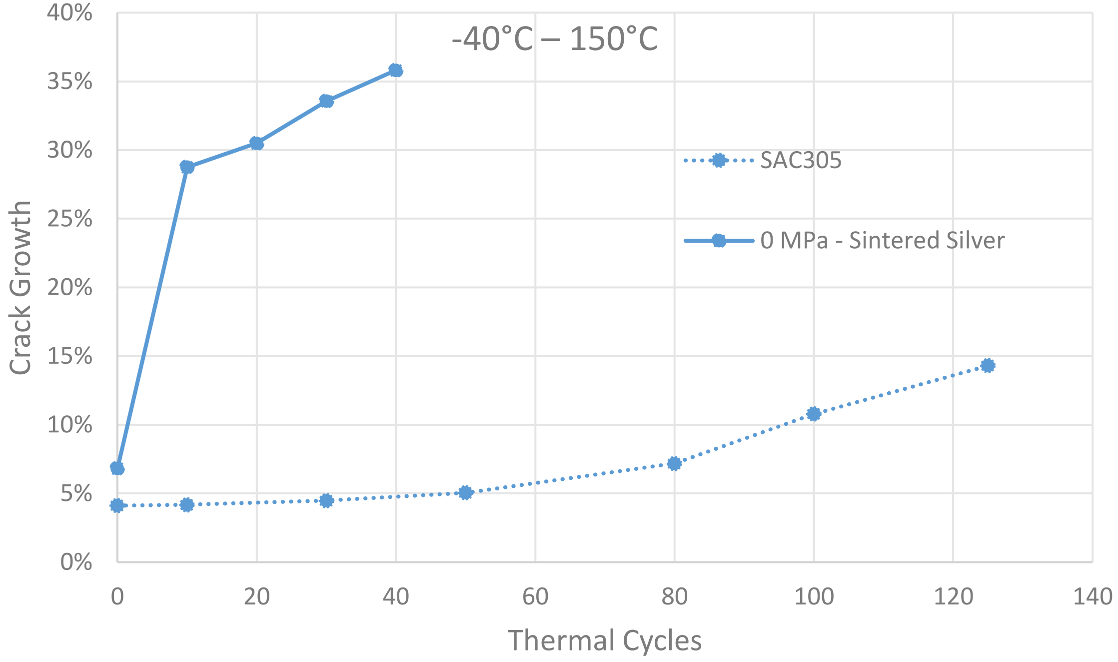
- For the ϕ22-mm and ϕ16-mm samples, the crack growth (average) is lower than the corresponding 3-MPa samples.
- The higher void fraction of ϕ10-mm samples is due to the high initial void fraction on the Cu side.
- A higher sintering pressure (10 MPa) likely led to an increased densification of the sintered silver joint and better adherence to the invar coupons, leading to a slightly better performance.

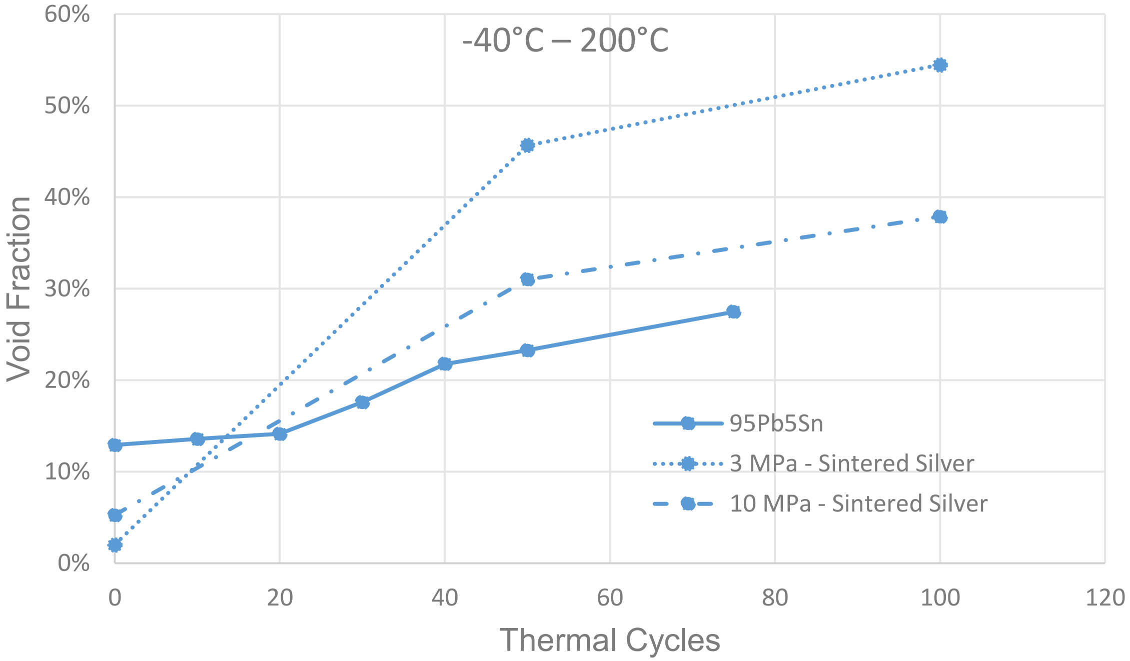


Cross-sectional image of cracks formed in sintered silver bond under thermal cycling: sintering pressure – 10 MPa; bond diameter – 10 mm

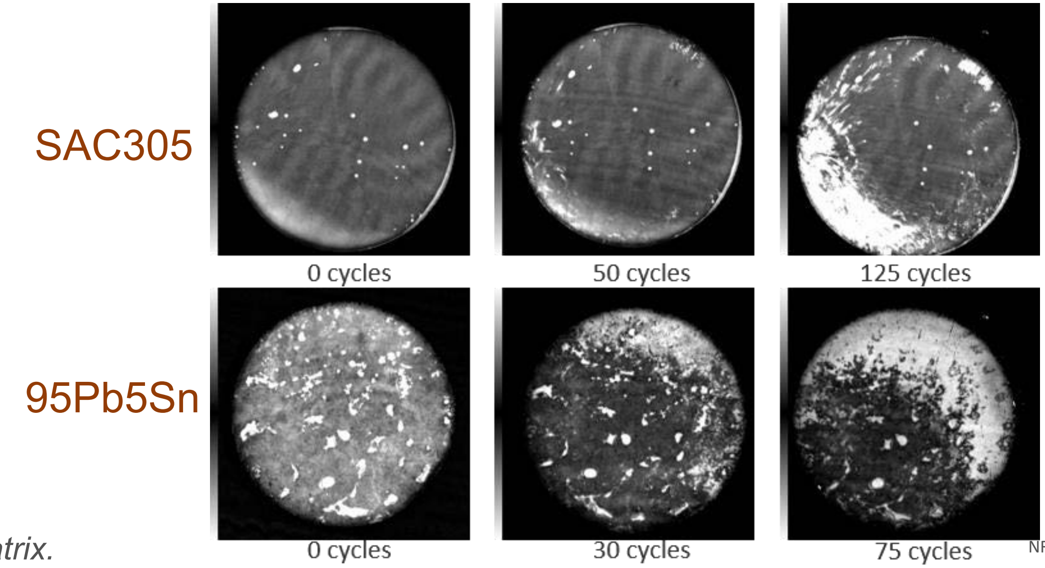
**Failure – 20% void fraction; void fraction on the y-axes here includes the initial voids and the cracks formed under thermal cycling.*

Technical Accomplishments and Progress: Comparison with Solder Joints



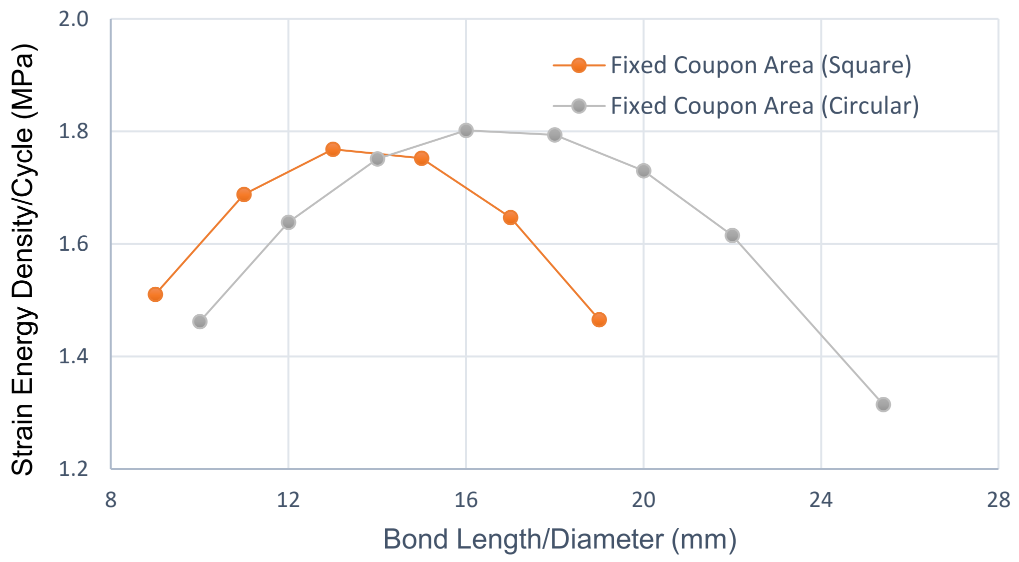


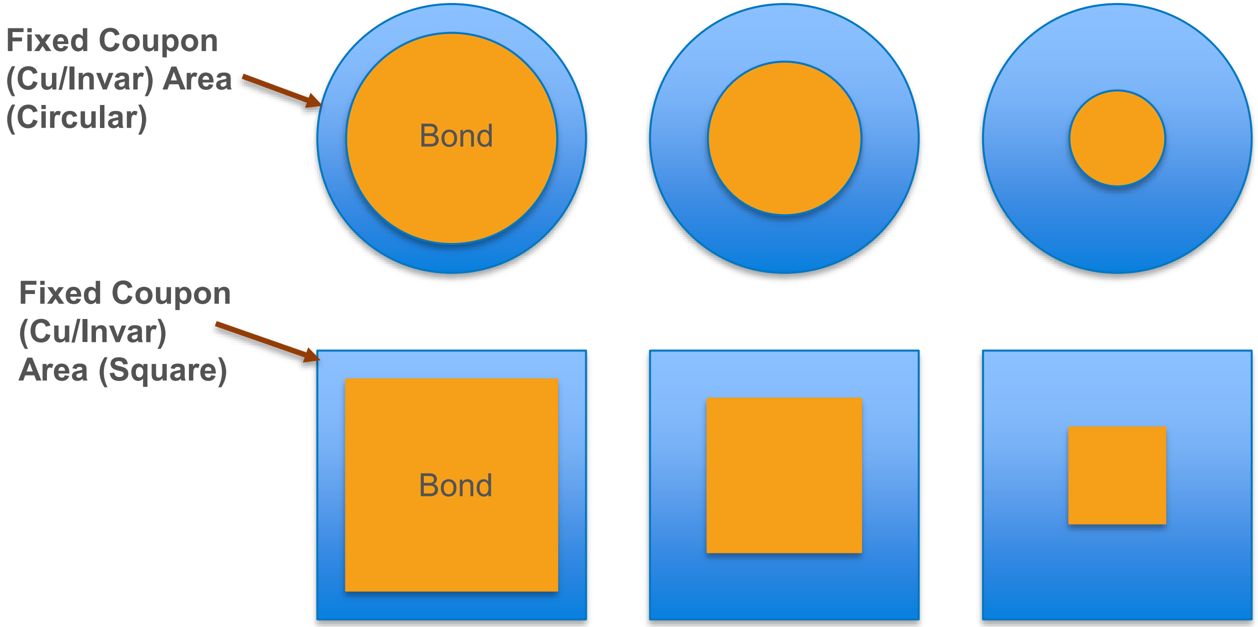
- SAC305 samples were subjected to −40°C to 150°C and 95Pb5Sn samples to −40°C to 200°C, for reference.
- Pressureless sintered silver samples (ϕ10mm) failed in just 10 cycles under −40°C to 150°C.
- For both solders, crack growth is dominant at the Cu side; failure mechanisms are likely to be cohesive in nature given the slow rate of crack growth.
- Despite the higher initial void fraction in 95Pb5Sn sample, crack propagation is slower, indicating higher reliability*.

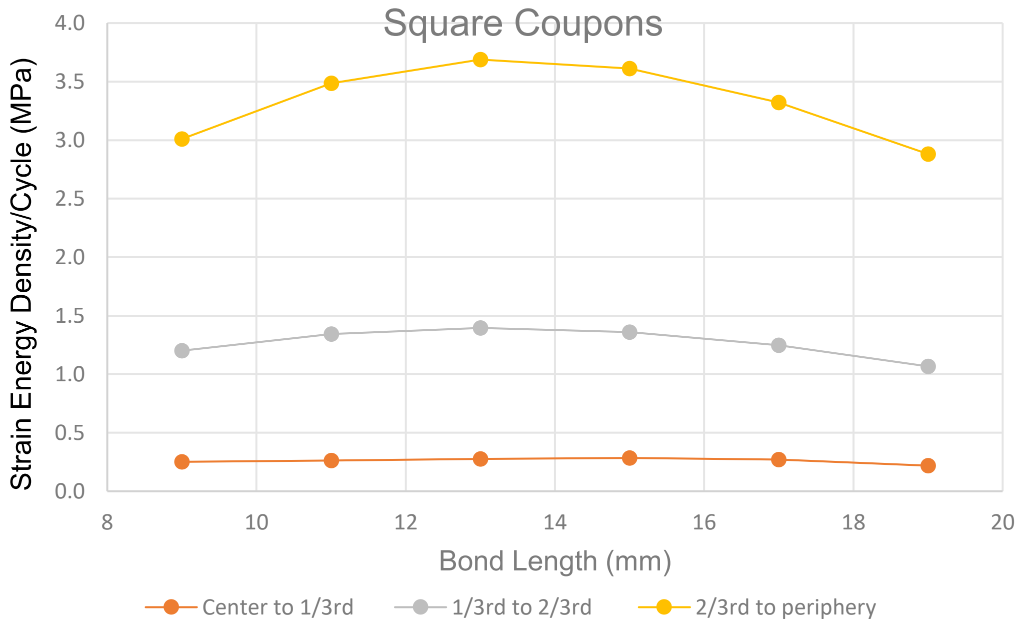


** - Based on results averaged from two 95Pb5Sn samples. More samples will be added to the matrix.*

Technical Accomplishments and Progress: Thermomechanical Modeling – Sintered Silver



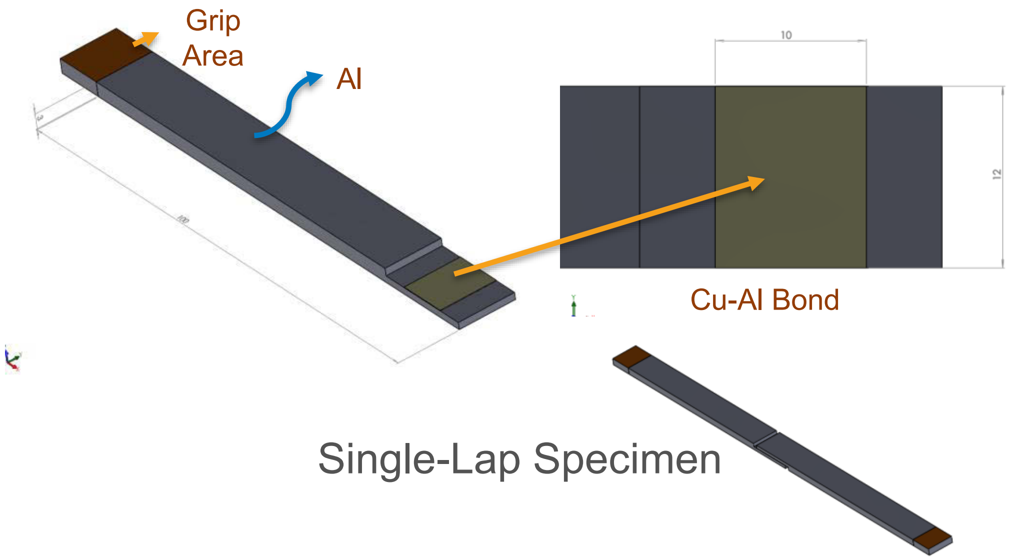




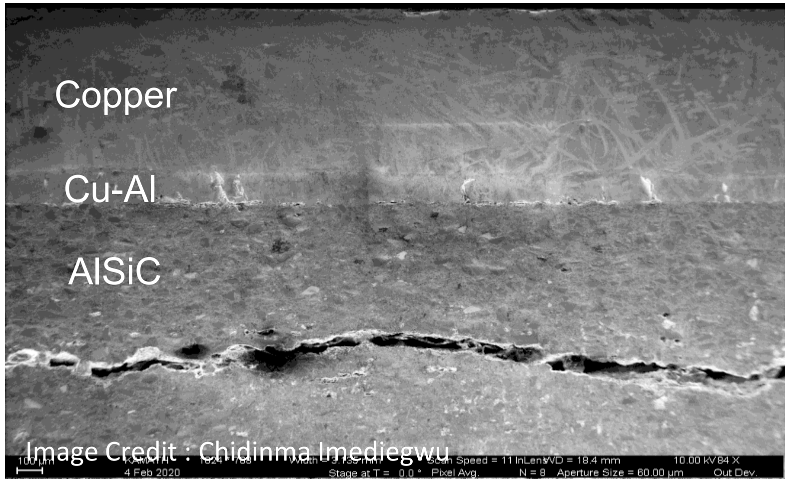
- In both square and circular coupons, strain energy density first increases and then decreases with reduction in bond size.
- Strain energy density is mainly concentrated in the outer regions of a bond.
- For a given coupon size, it is optimal to align the bond dimensions with that of the coupons for maximum reliability.

Technical Accomplishments and Progress: Synthesis of Transient Liquid Phase Cu-Al Bonds

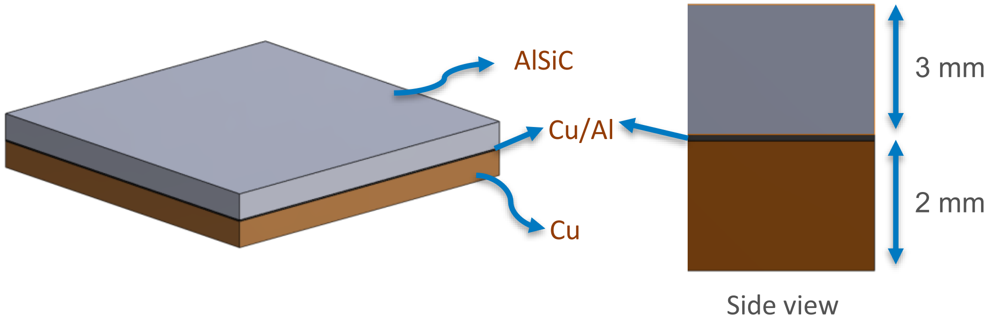
- Mechanical Characterization
  - Single-lap configuration designed for conducting shear strength characterization of the Cu-Al alloy bond.
  - Trial samples were synthesized at Georgia Tech and sent to NREL for evaluation.
- Reliability Evaluation
  - Selected sample configuration: Cu bonded to AlSiC coupons using Cu-Al alloy, footprint is 1-inch x 1-inch.
  - Trial samples synthesized at Georgia Tech exhibited cracking in the AlSiC layer.
  - Currently in the process of synthesis profile optimization to improve bond quality.



Single-Lap Specimen



Cross-sectional image of Cu-AlSiC sample with Cu-Al bond. Cracking in AlSiC layer could be due to excessive Cu migration.



Sample design for reliability evaluation

Responses to Previous Year Reviewers' Comments

The reviewer said the team seems to be collaborating well internally. It is unclear what the interaction with industry (original equipment manufacturer [OEM], Tier 1/Tier 2, and raw material suppliers) is to ensure that solutions being explored are relevant and transferrable.

The conclusions of this project are periodically presented before the Electrical and Electronics Tech Team, which consists of automotive OEMs. Also, information will be disseminated as publications in journals and conferences.

The reviewer said it is important to compare new bonding solutions to a baseline of materials and processes commonly used in the industry today. This should include metrics that incorporate not only reliability and performance of the bonding technology, but also measures of the investment, cost, and processing time.

Most of the current baseline materials used in the industry today are limited to 150°C or at most 175°C. The operational temperature of 200°C is very challenging, and we have compared the reliability of sintered silver with solder joints. Assessing the impact of investment, cost, and processing time are outside the scope of this project.

Collaboration and Coordination

- Virginia Tech: technical partner on the synthesis of sintered silver bonds
- Georgia Tech: technical partner on the synthesis of transient liquid phase Cu/Al bonds
- ORNL: technical guidance
- Ames: technical guidance

Remaining Challenges and Barriers

- Correlation between simulations and experimental results is hard to establish due to the macroscopic nature of modeling and microstructural causes of failure mechanisms in bonded materials.

- While current formulations of sintered silver may work for small area attach (die-attach), novel material compositions and microstructures need to be identified for large area attach layers with sufficient reliability.

- Synthesis profile and parameters of Cu-Al bond need to be optimized to reduce the initial void fraction to acceptable levels (<5%).

Proposed Future Research – FY 2020

- Investigate the effect of sample stiffness on reliability—conduct accelerated thermal cycling on sintered silver samples with 1-mm-thick Cu and Invar coupons. (FY 2020 Milestone)

- Develop a preliminary microstructural crack propagation model—this model will be an advancement over the current macroscale models to simulate and predict the failure mechanisms of sintered silver and other high-temperature bonded interface materials. (FY 2020 Milestone)

- Conduct mechanical characterization of Cu/Al alloy at different strain rates and temperatures—develop a constitutive model that captures the deformation behavior of the Cu/Al alloy.

- Synthesize Cu/Al alloy samples with high bond quality (<5% initial void fraction)—optimize the synthesis profile and investigate Al-Cu/Al-AlSiC structure in addition to the current Cu-Cu/Al-AlSiC configuration.

Any proposed future work is subject to change based on funding levels.

Proposed Future Research – FY 2021

- Conduct accelerated thermal cycling of Cu/Al bond samples under different temperature profiles: −40°C to 200°C, −40°C to 175°C.
- Expand the microstructural crack propagation model to include physics at lower length and timescales and establish microstructure-property relationships to accelerate novel high-temperature material development.
- Investigate the reliability and failure mechanisms of alternate high-temperature materials such as sintered copper and Cu-Sn transient alloys.

Any proposed future work is subject to change based on funding levels.

Summary

- DOE Mission Support
  - Reliability evaluation of bonded materials is a critical research area for enabling low-cost, lightweight, and reliable power electronic packages that can operate at high temperatures.
- Approach
  - Synthesis of high-temperature bond materials, mechanical characterization, reliability evaluation, thermomechanical modeling, and lifetime prediction models.
- Accomplishments
  - Sintered silver may be a promising material for die-attach applications (from literature review), but solder joints perform better than current formulations of sintered silver under −40°C to 200°C thermal cycling.
  - Modeling results, in general, show good correlation with experimental results of sintered silver and solder joints.
  - Preliminary synthesis of samples with Cu-Al bond alloy completed; synthesis profile and sample design will be iterated to improve bond quality.
- Collaborations
  - Virginia Tech
  - Georgia Tech
  - Oak Ridge National Laboratory
  - Ames Laboratory

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Thank You

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