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
2023 Annual Merit Review and Peer Evaluation Meeting

Project ID # ELT219

Overview

Timeline

- Project start date: October 1, 2018
- Project end date: September 30, 2024
- Percent complete: 85%

Barriers

- Cost
- Size and weight
- Reliability and lifetime

Budget

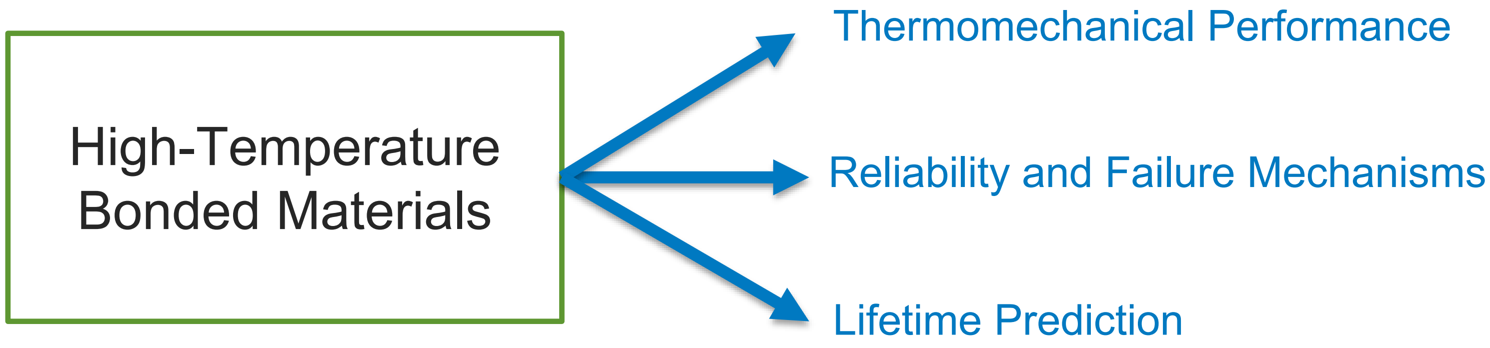
- Total project funding: $850,000
    - DOE share: $850,000
- Funding for FY 2022: $175,000
- Funding for FY 2023: $150,000

Partners

- Georgia Institute of Technology
- Institute of Innovative Mobility (IIMo), Germany

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 electronics 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 electronics applications.


High-Temperature Bonded Materials

Thermomechanical Performance

Reliability and Failure Mechanisms

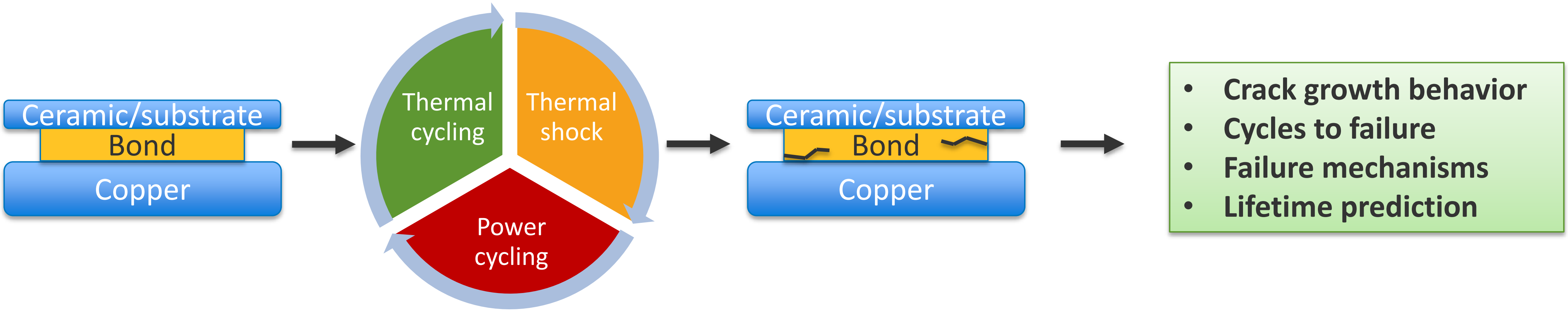
Lifetime Prediction

Milestones

- Conduct the reliability evaluation of polymeric bonded materials and sintered copper under high-temperature thermal cycling (due 6/30/2023).
    - Both polymeric materials (HM-3 and HM-4) and sintered copper are currently undergoing thermal cycling experiments at NREL.

Approach – Bonded Interfaces

- Reliability evaluation of bonded interfaces:
  - Synthesize coefficient of thermal expansion (CTE)-mismatched prototype samples with bonded interfaces and subject them to accelerated experiments.
  - Monitor the bond performance through periodic scanning acoustic microscope (SAM) imaging.
  - Cross-section the samples and obtain scanning electron microscope (SEM) images to investigate the failure mechanisms within the bond.



Ceramic/substrate
Bond
Copper

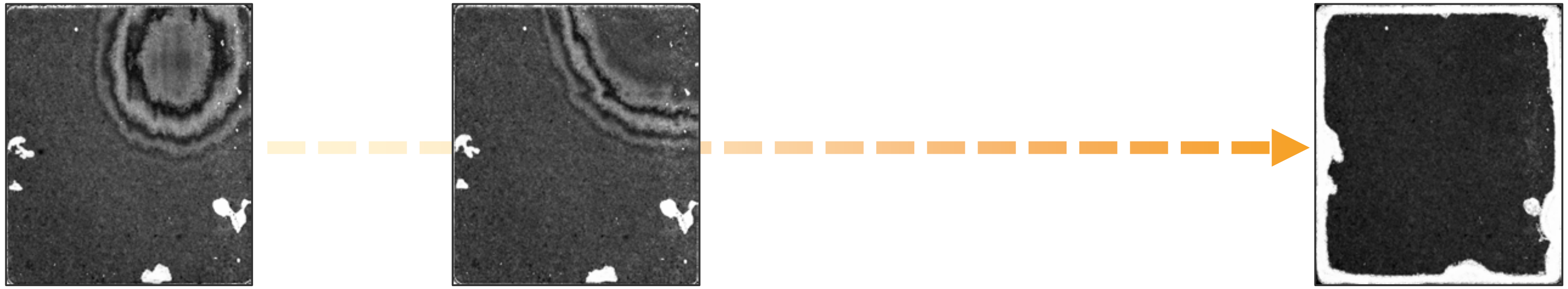
Thermal cycling
Thermal shock
Power cycling

Ceramic/substrate
Bond
Copper

- **Crack growth behavior**
- **Cycles to failure**
- **Failure mechanisms**
- **Lifetime prediction**

Approach –Time-Series Forecasting

- Lifetime prediction model based on time-series forecasting:
  - Conduct a time-series analysis of the crack growth rate of the bonded interfaces under thermal cycling
  - Compare the performance of statistical and machine-learning models in predicting the crack growth trend at later stages of thermal cycling.



Training Data

Forecasting/Prediction

0 cycles

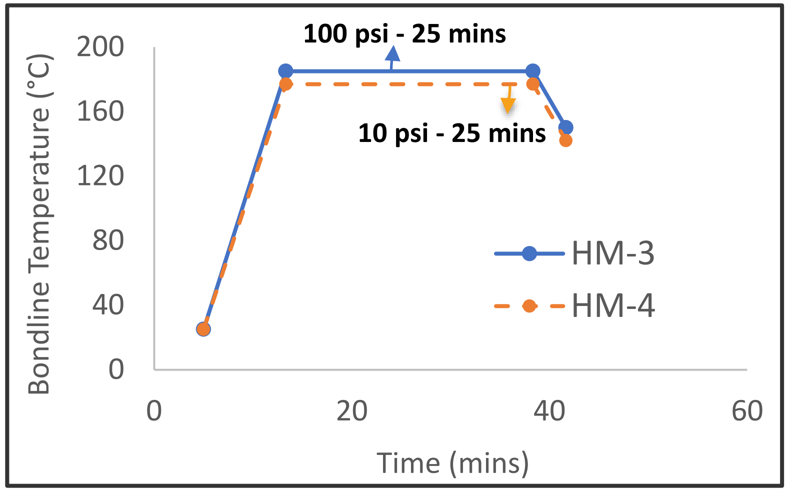
100 cycles

N cycles

Technical Accomplishments and Progress – Synthesis of Bonded Interfaces With Polymeric Materials

- Fabricated a total of 28 samples at NREL with HM-3 and HM-4 as the bonded interface.
  - Sample configuration consists of 1 x 1-inch Cu blocks attached to AlN ceramic layers
  - HM-3 and HM-4 consist of carbon microfibers embedded in a thermoplastic and thermoset polymer, respectively.

Bonding setup



Synthesis profiles

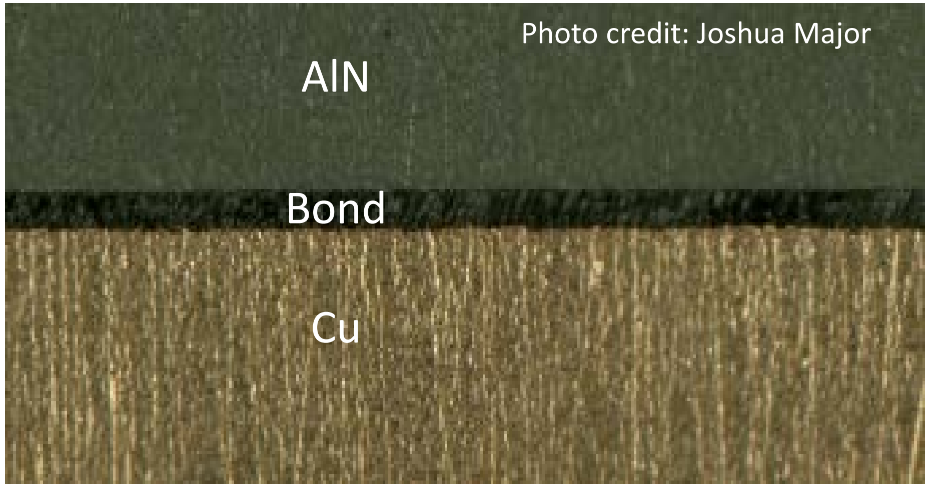
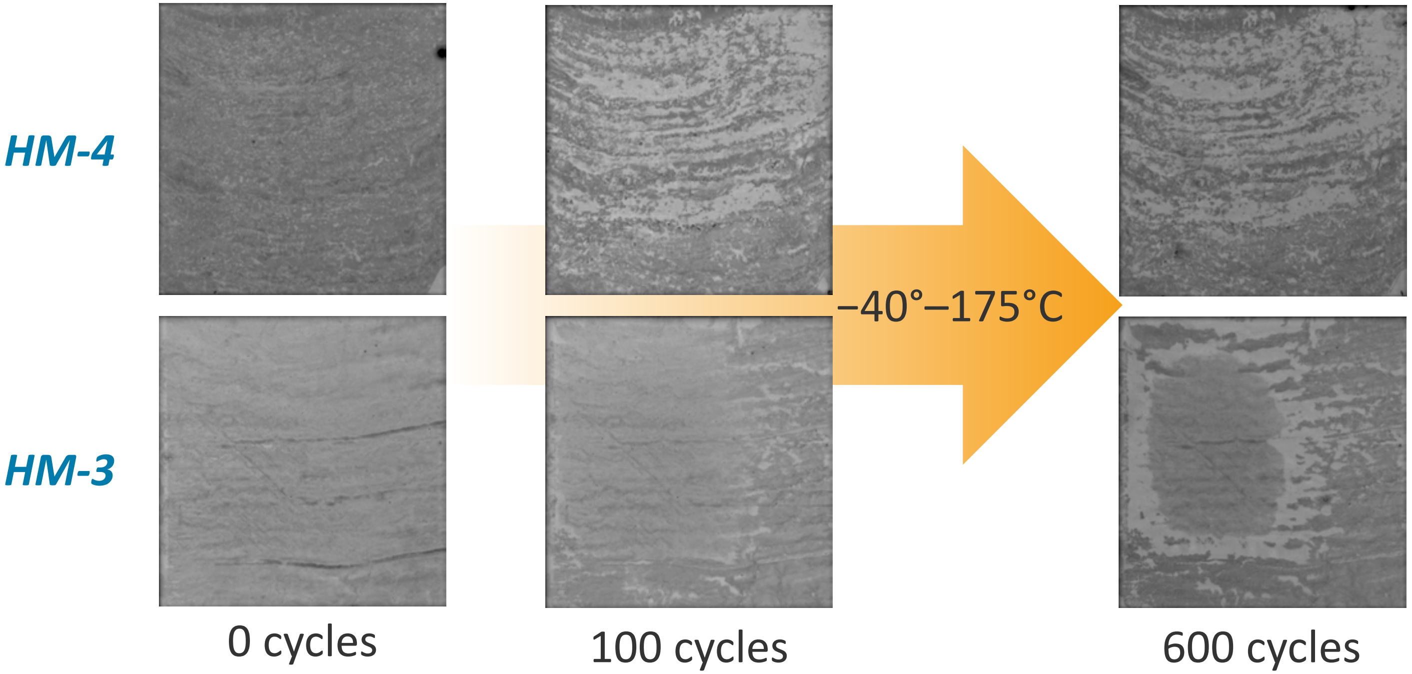


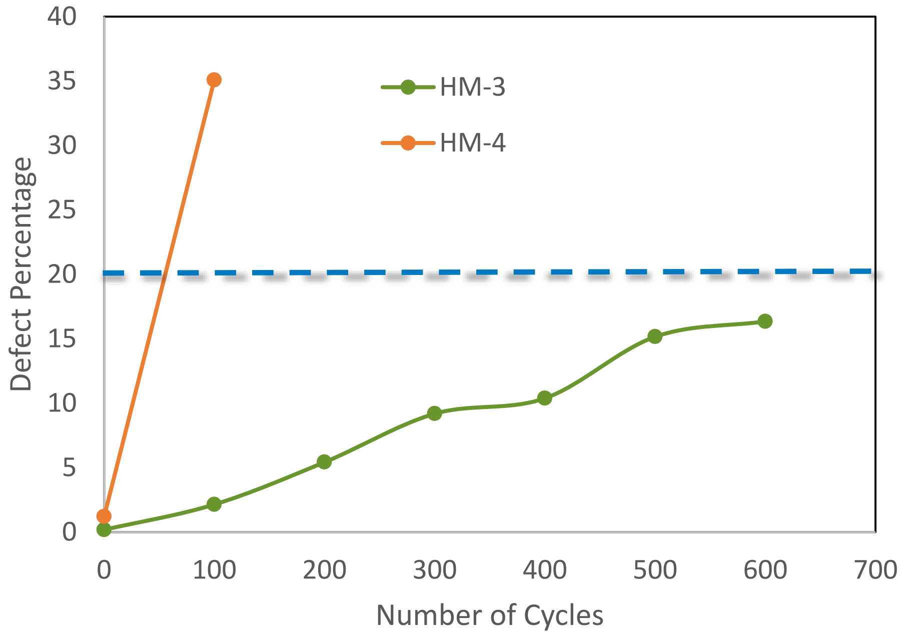
Photo credit: Joshua Major

Cross-sectional image

Technical Accomplishments and Progress – Reliability of Polymeric Materials

- Under thermal cycling (-40°C – 175°C, 5°C/min ramp, 10-min dwell), both HM-3 and HM-4 displayed patterns in the C-SAM images, which likely indicate delamination in the first 100 cycles.
- HM-4 passed the failure criterion (20%)* within the first 100 cycles.
- Additional accelerated experiments on these materials with different thermal profiles will be conducted.

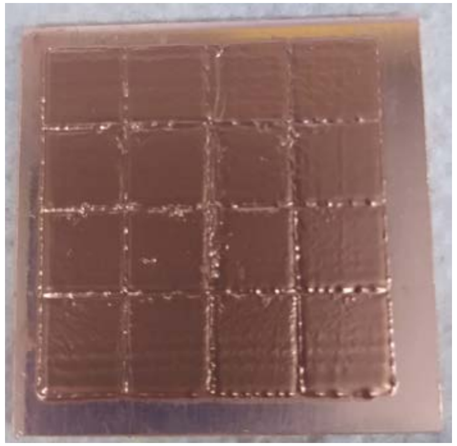




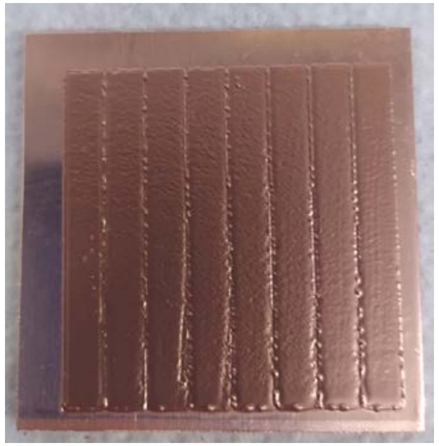
- *The defect percentages estimated from C-SAM images are highly sensitive to the pixel threshold value.*
- *C-SAM - C-mode scanning acoustic microscope*

Technical Accomplishments and Progress – Synthesis of Sintered Copper Samples

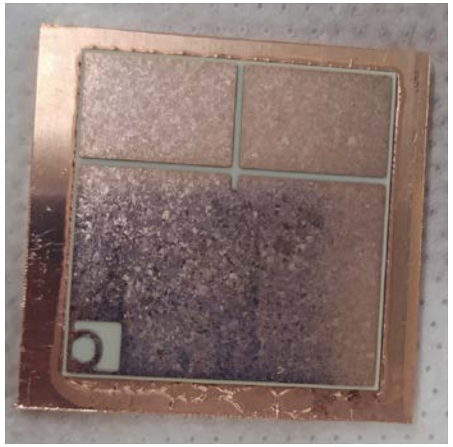
- 24 sintered copper samples were fabricated at IIMo and sent to NREL for accelerated experiments.
    - Out of the 24 samples, 12 were bonded using a grid stencil, and the remaining in a stripe pattern.
    - The sample configuration consists of Cu baseplates (50 x 50 mm; 3–5 mm thick) bonded to AMB substrates with Si_3N_4 as the ceramic.
- Synthesis profile:
    - Pre-drying stage – 15 min at 100°C (N_2 atmosphere)
    - Sintering – 5 min at 275°C and 20 MPa bonding pressure (N_2 atmosphere).



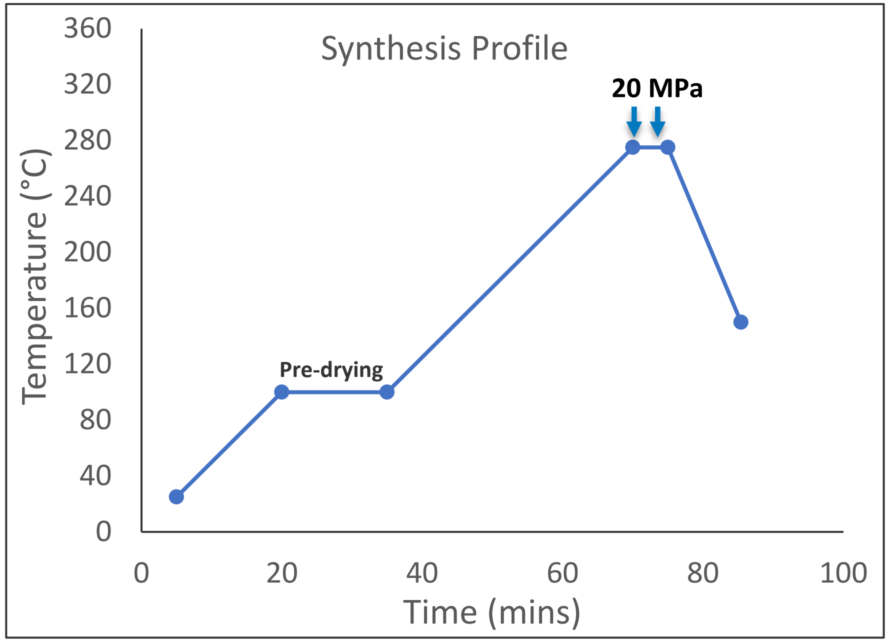
Grid pattern



Stripe pattern



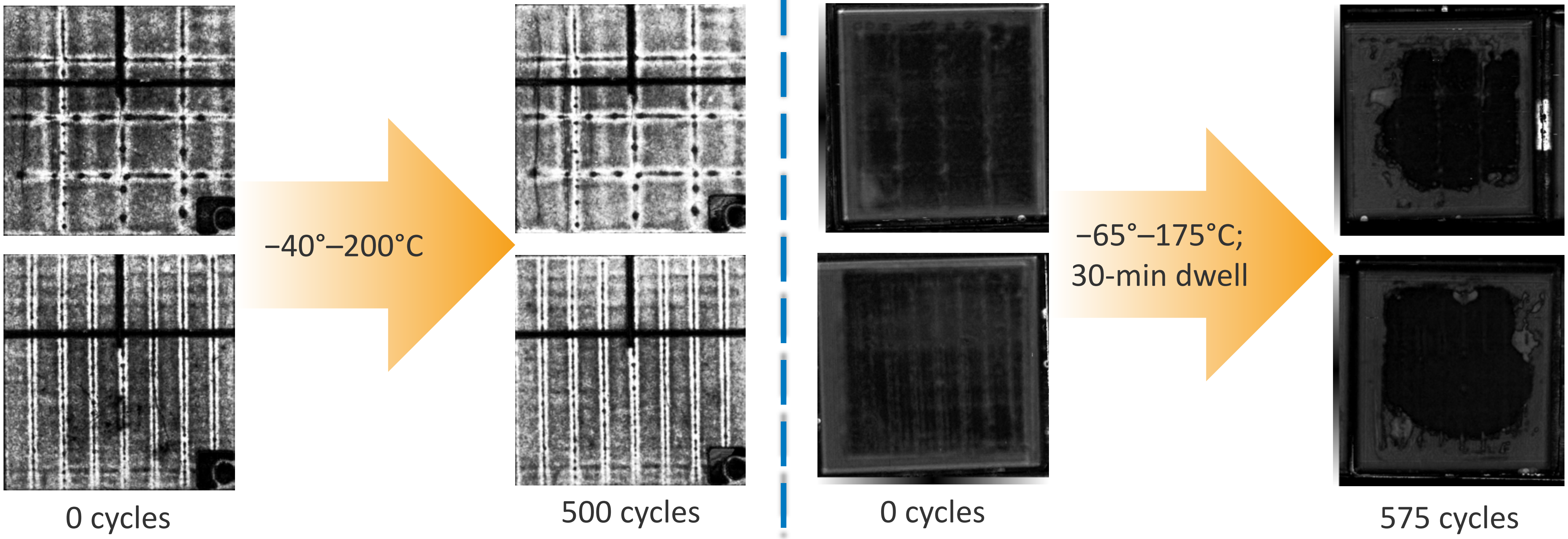
Bonded sample



- *AMB – active metal bonding/brazing*
- *Si_3N_4 – silicon nitridde*

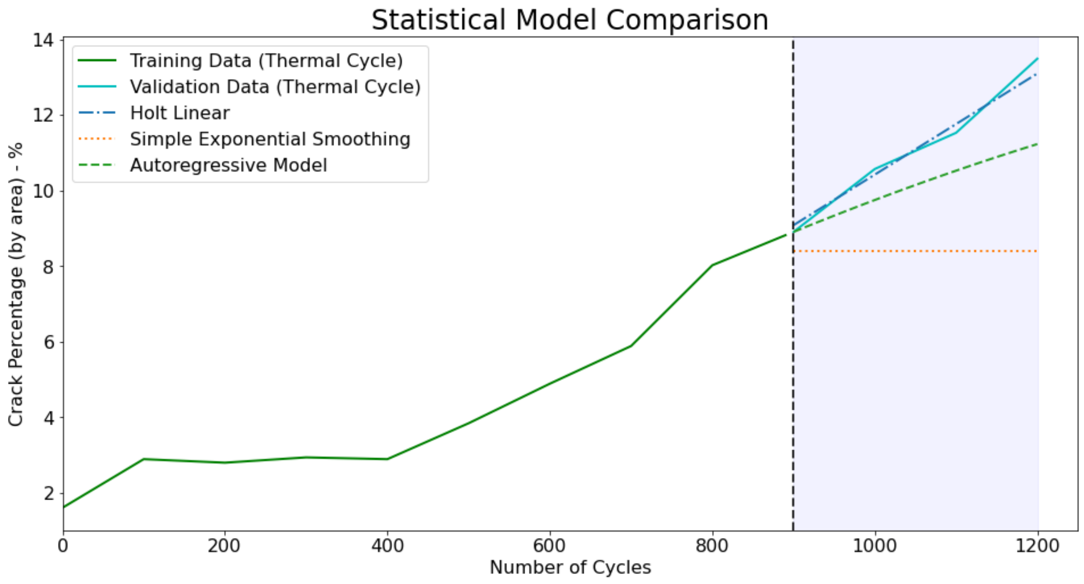
Technical Accomplishments and Progress – Reliability of Sintered Copper

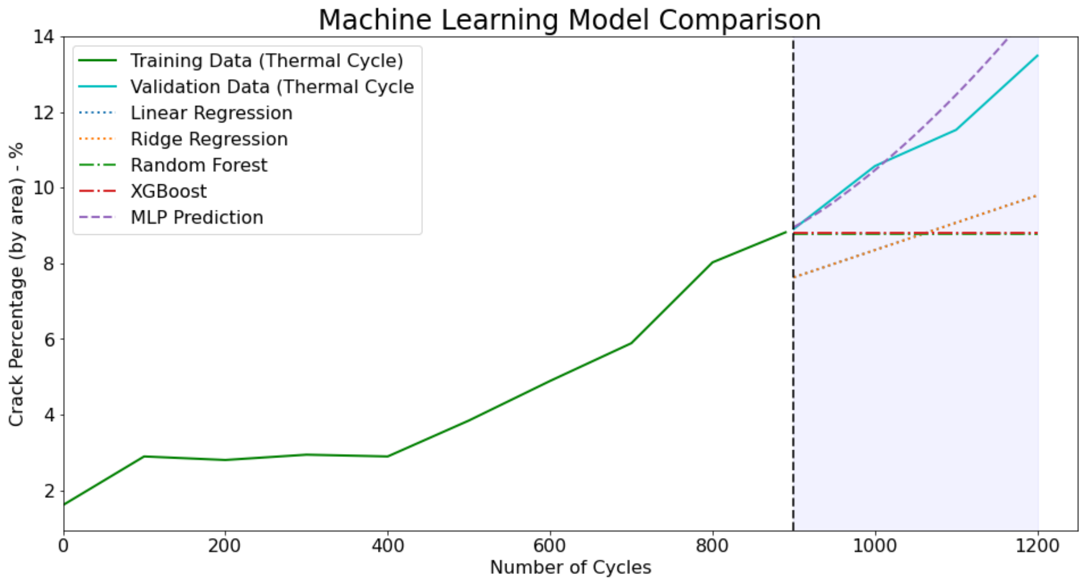
- Initial defect percentages* were estimated to be in the range of 10%–15% and 5%–8% for the grid-patterned and stripe-patterned samples, respectively.
- No discernible signs of cracking were observed under a thermal shock profile of −40°C to 200°C.
- However, samples reached failure under a thermal cycling profile of −65°C to 175°C (30-min dwell). This thermal cycling experiment was conducted at IIMo.



** The defect percentages estimated from C-SAM images are highly sensitive to the pixel threshold value.*

Technical Accomplishments and Progress – Time-Series Forecasting Framework

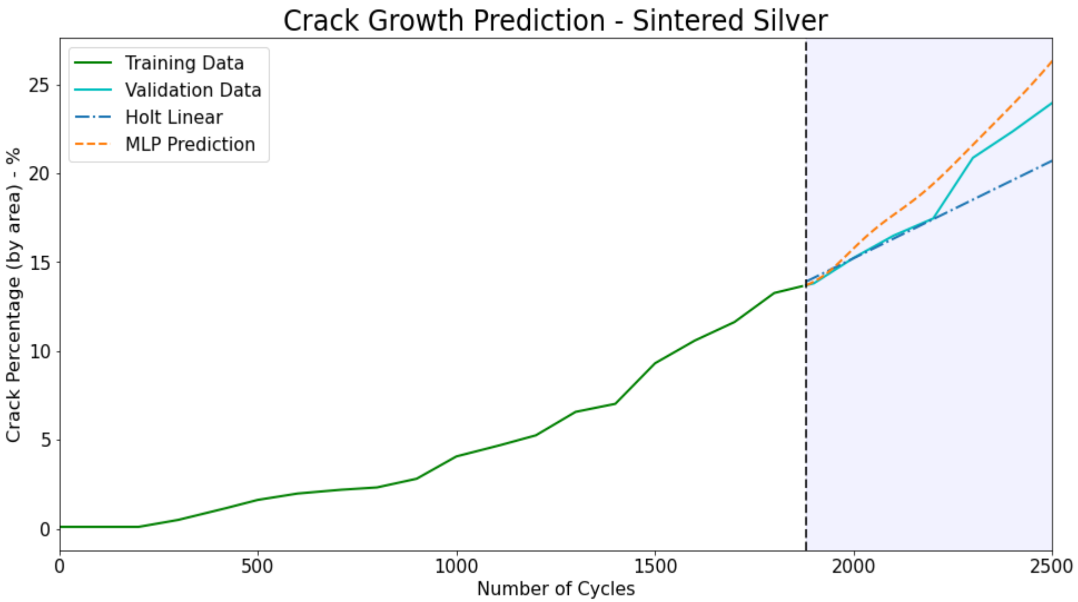


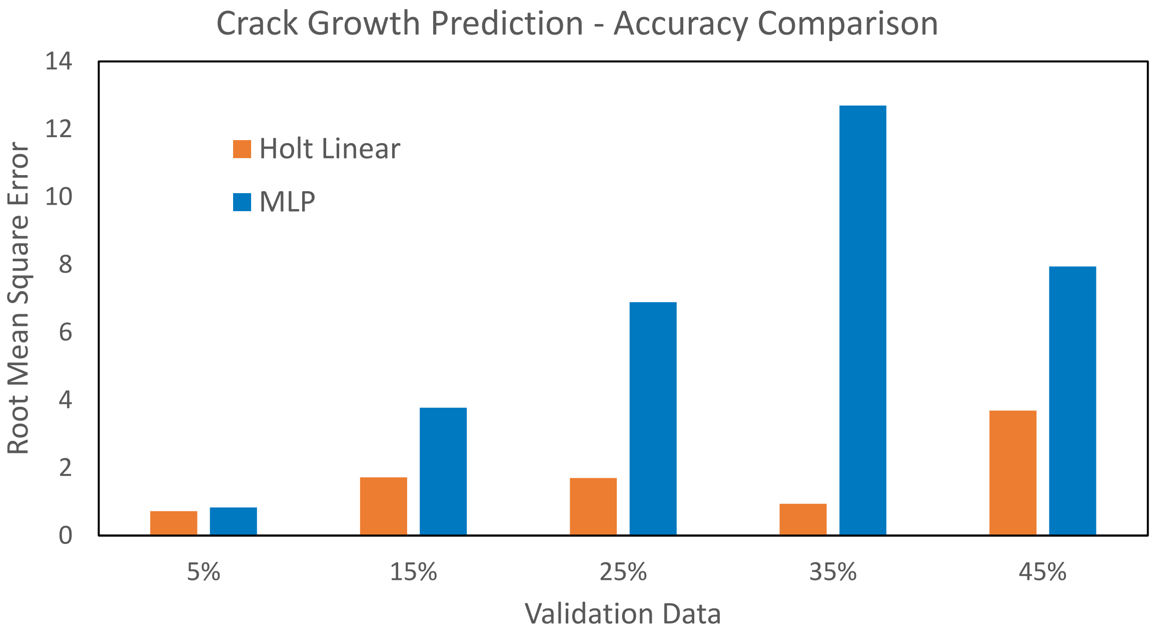


- A few different statistical and machine-learning models were compared to investigate their accuracy in predicting the crack growth rate of bonded interfaces (eutectic lead solder in this case).
- Among the statistical models, Holt linear resulted in the highest accuracy (RMS error = 0.15), while multilayer perceptron (neural network)-based approach (RMS error ≈ 2) slightly outperformed the supervised machine-learning models.
- Both random forest and XGBoost captured the trend in the training data well but were found to be unsuitable for predictions.
- These results confirm the superior time-series prediction capability of statistical models over machine-learning techniques.

MLP – multilayer perceptron

Technical Accomplishments and Progress – Time-Series Forecasting of Crack Growth in Sintered Silver





- The time-series forecasting framework was also applied to sintered silver thermal cycling data. This sintered silver from Semikron comprises a micron-sized particle formulation.
- Holt linear performs better than machine-learning techniques in the case of sintered silver as well.
- Even with a relatively low training data size (55%), the Holt linear model predicts the crack growth rate with >95% accuracy.

Responses to Previous Year Reviewers’ Comments

- This project was not reviewed in FY 2022.

Collaboration and Coordination

- Institute of Innovative Mobility: technical partner in the research of sintered copper
- Georgia Tech: technical partner on the synthesis of transient liquid phase Cu/Al bonds, Cu–graphene metallization
- Oak Ridge National Laboratory, Ames National Laboratory, and Sandia National Laboratories: technical guidance.

Remaining Challenges and Barriers

- The reliability of sintered copper as a die-attach needs to be investigated at junction temperatures exceeding 175°C.

- Additional synthesis process optimization is required to reduce the initial void fraction of sintered copper to acceptable levels (<5%).

- Thermomechanical modeling of sintered copper and polymeric materials is a challenge due to the nonexistence of constitutive models.

Proposed Future Research

- Conduct accelerated thermal cycling of polymeric materials under different temperature profiles: −40° to 200°C, −40° to 150°C.

- Cross-section sintered copper, HM-3, and HM-4 samples and investigate the failure mechanisms using SEM imaging.

- Conduct power cycling experiments on sintered copper samples with silicon carbide devices.

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 electronics 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
  - Initiated the reliability evaluation study on sintered copper and polymeric material-based bonded interfaces. Additional experiments will reveal insights into the degradation mechanisms in these materials.
  - Compared the performance of different statistical and machine-learning models in predicting the crack growth rate of bonded interfaces. This framework uses only experimental cycling data and serves as a lifetime prediction model.
- Collaborations
  - Institute of Innovative Mobility, Germany
  - Georgia Tech
  - Oak Ridge National Laboratory
  - Ames National Laboratory
  - Sandia National Laboratory.

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Thank You

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Publications and Presentations

- Publications
  - P. Paret, J. Major, D. DeVoto, S. Narumanchi, C. Ding and G. -Q. Lu. 2022. “Reliability and Lifetime Prediction Model of Sintered Silver Under High-Temperature Cycling.” *IEEE Journal of Emerging and Selected Topics in Power Electronics* 10 (5): 5181–5191.
  - C. Imediegwu, S. Graham, D. G. Pahinkar, S. Narumanchi, P. Paret, and J. Major. 2022. “Interdiffusion and formation of intermetallic compounds in high-temperature power electronics substrate joints fabricated by transient liquid phase bonding.” *Microelectronics Reliability* 137: 114788.
  - P. Paret. 2022. “Power Electronic Materials and Bonded Interfaces – Reliability and Lifetime.” In *FY22 EDT Annual Progress Report*.

- Presentations
  - P. Paret. 2022. “Bonded Interfaces for High-Temperature Power Electronics Packages.” 2022 IEEE ITHERM, San Diego, CA.
  - P. Paret. 2022. “Power Electronic Materials and Bonded Interfaces – Reliability and Lifetime.” 2022 DOE VTO Annual Merit Review, Washington, D.C.

Critical Assumptions and Issues

- Achieving a high-quality initial bond (defect fraction <5%) is challenging with high-temperature bonded interface materials.
  - Synthesis trials should cover a lot of variations to identify the most promising solution.

- Ascertaining accurate defect information through nondestructive bond evaluation techniques is difficult.
  - C-SAM images of certain samples can be noisy (low signal-to-noise ratio).
  - In situ characterization techniques need to be investigated; however, these techniques should be able to withstand the high-temperature operating conditions.

- Constitutive models of sintered copper and polymeric materials do not exist; deformation kinetics of these materials cannot be captured through simulations.
  - Generating stress-strain data of materials through experiments can address this knowledge gap.