Enabling Materials for High Temperature Power Electronics

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Overview

Timeline

- Start – FY13Q4
- End – FY16
- 85% complete

Budget

- Total project funding
  - DOE share – 100%
  - DOE VTO's Propulsion Materials (PM) & Electric Drive Technologies (EDT) Programs - 75% and 25%, respectively
- Funding received in FY15: $175k (combined)
- Funding for FY16: $225k (combined)

Barriers

- Reduce cost of Electric Drive System from $30/kW in 2012 to $8/kW by 2022 (1.4 kW/kg, 4 kW/l, and 94% efficiency)
- Reliability and lifetime of power electronic (PE) modules and electric motors (EM) degrade rapidly with increased temperature
- PEs and EMs need improved thermal management for higher temps

Partners/Collaborations

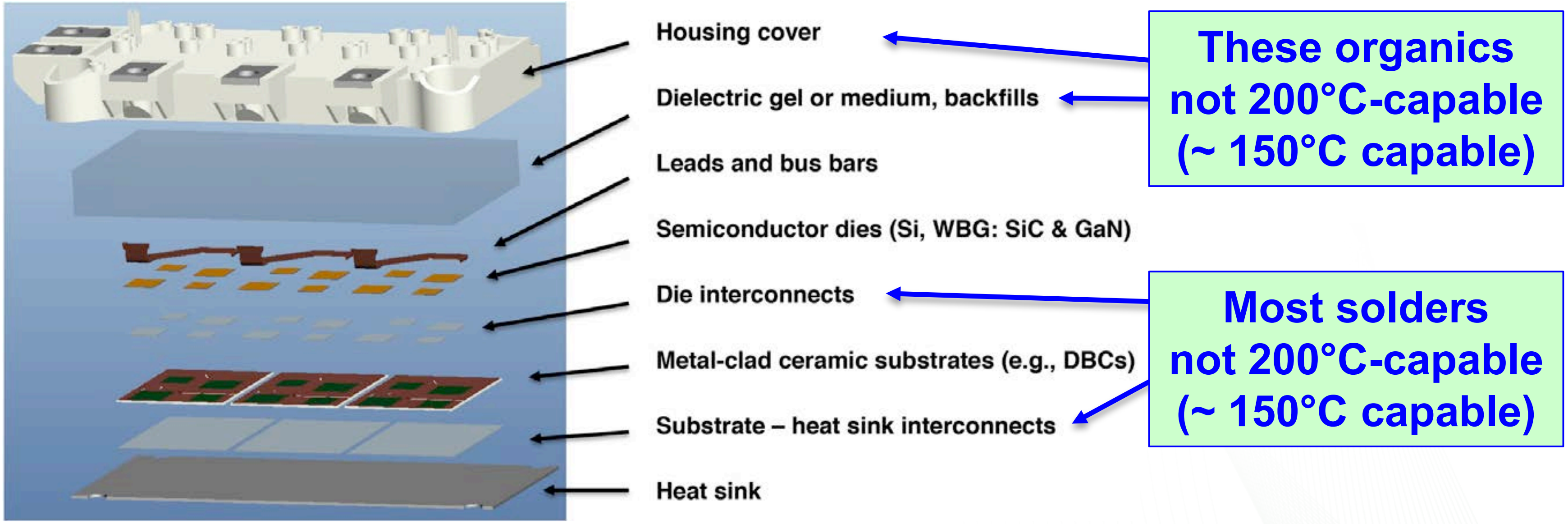
- Alfred University
- General Metal Finishing
- Indium Corporation
- Lord Corporation
- Mount Union University
- NREL
- Rogers Corporation

Project Objective and Relevance (1 of 3):
Address High-Temperature Incapability in PEs

Contemporary PE devices cannot operate at 200°C because:

- **Conventional interconnect materials (solder) in non-equilibrium at 200°C**
- **Most organics/polymers not stable for long times above ~ 175°C**

Example of a single-sided PE device



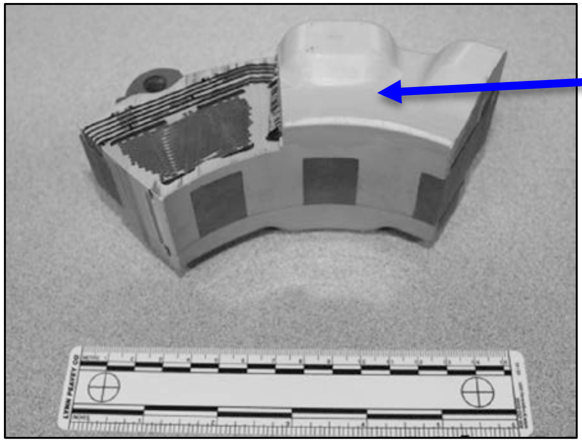
Goal: develop material technologies that enable a 200°C-capable, low-cost, and reliable electronic package with at least 15-year-life

Project Objective and Relevance (2 of 3):
Address Low Heat Transfer Performance in EMs

Contemporary EMs have marginal heat transfer because:

- **Encapsulants and potting compounds have low thermal conductivity (TC)**
- **Thermal transfer between constituents is poor**

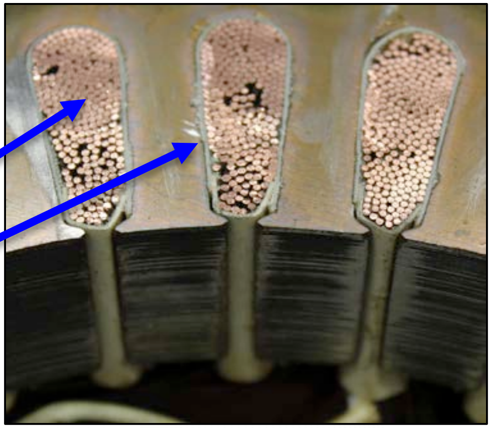
Sectioned Electric Alternator



Encapsulant has low TC

Poor heat transfer within windings and at slot-liner laminate-winding interfaces

Sectioned Windings in Slot Liners



Goal: develop material technologies that enable more rapid overall thermal transfer <u>out</u> of the EM copper windings

Project Objective and Relevance (3 of 3):
Summarizing This Project's Two Parallel Efforts

Power Electronics (PEs)

- ✓ 200°C – capable materials
- ✓ Materials and engineering:
  - Sintered-Ag interconnects
    - Process improvement
    - Geometrical limitations
    - Other constituents
  - Higher TC encapsulants
- ✓ NREL collaboration for portion of effort (DeVoto and Paret)

Leveraged

Electric Motors (EMs)

- ✓ Improve thermal transfer
- ✓ Materials and engineering:
  - Higher TC dielectrics
    - Encapsulants
    - Potting compounds
  - Phase-change materials
- ✓ Improve intra-winding TC and interfacial heat transfer
- ✓ NREL collaboration for portion of effort (Bennion and Cousineau)

Milestones

Date	Milestones and Go/No-Go Decisions	Status
FY15	Go/No-Go. DuPont's perflouropolymer candidate matrix for high-temperature-capable, thermally conductive dielectric composites? [No-Go; needed substantially more R&D to work for that particular material system]	✓
FY15	<u>Milestone</u>: Complete processing of direct bonded copper (DBC) substrate sandwiches and coefficient of thermal expansion (CTE) - mismatched disk specimens.	✓
Jun 2016	<u>Milestone</u>: Complete thermal property measurements of electric motor copper windings with thermally-conductive, high-temperature-capable potting compound.	On track
Sep 2016	<u>Milestone</u>: Submit Annual Report.	On track

Go/No-Go Decisions in FY16: None - project ending in FY16

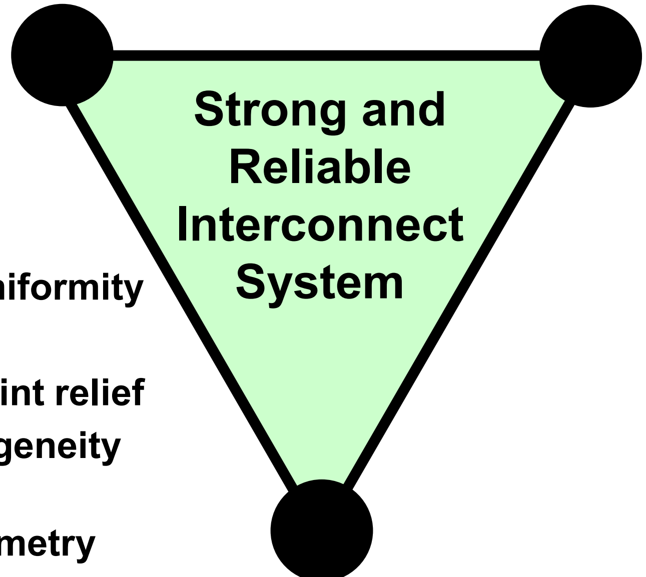
Approach/Strategy - PEs (1 of 3)

Interconnect Strength and Reliability are Functions of Many Parameters

Sintered Silver

- Pressure
- Temperature
- Time
- Print thickness and uniformity
- Processing cadence
- Strain or expansion joint relief
- Microstructural homogeneity and isotropy
- Elastic property asymmetry

Cohesive strength contribution



Plating

- Thickness
- Cleanliness
- O, C, and S contamination
- Promote metallurgical bond

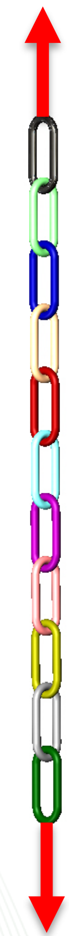
Chemical component of adhesive strength

Die, Substrate, or Baseplate

- Surface finish & topography
- CTE (mismatch)
- Size/area

Mechanical component of adhesive strength

But the “system” is only as good as its weakest link ...

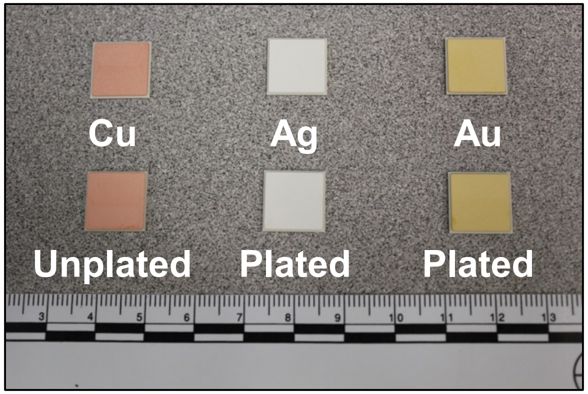


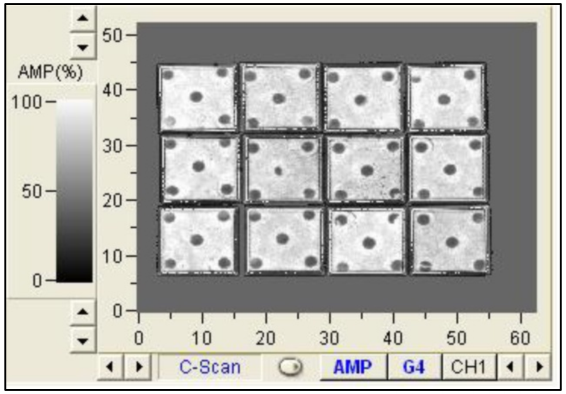
An interconnect system is so much more than just the sintered-silver; therefore, the entire system warrants attention

Approach/Strategy - PEs (2 of 3)

Some Factors Under Exploration at ORNL in FY16

- **Printing method (stencil vs. screen)**
- **Paste drying method, time, and temperature**
- **Choice of plating material and their characteristics**
- **Coefficient of thermal expansion mismatches**





Statistically significant testing for evaluation of mechanical response

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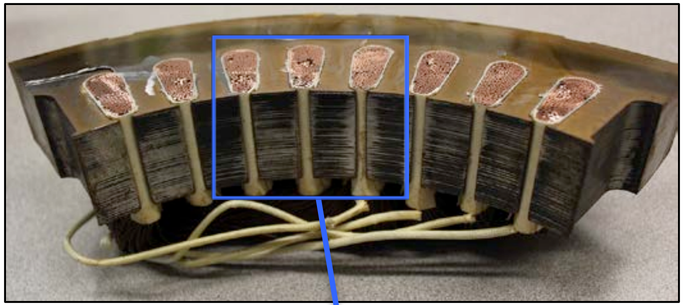
Approach/Strategy – EMs (3 of 3)

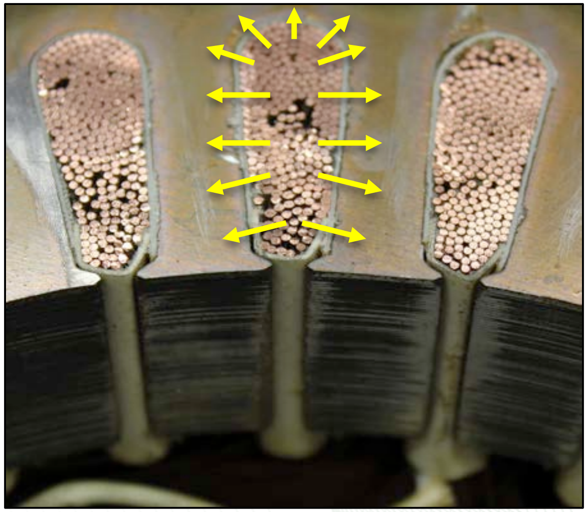
Of Interest: Heat Transfer from Copper Windings into Steel Laminates

- **Motive: Improve understanding of perpendicular thermal transfer within EM copper windings**
- **Use different TC tests to capture transient and steady-state thermal responses**
  - **Fabricate copper wound coupons for transversely isotropic TC measurement**
  - **Develop model to account for variability, wire concentration and packing, varnish, etc.**
- **Representative volume element (RVE)**
- **NREL collaboration for portion of project**

Make surrogate test coupons to better understand this thermal transfer

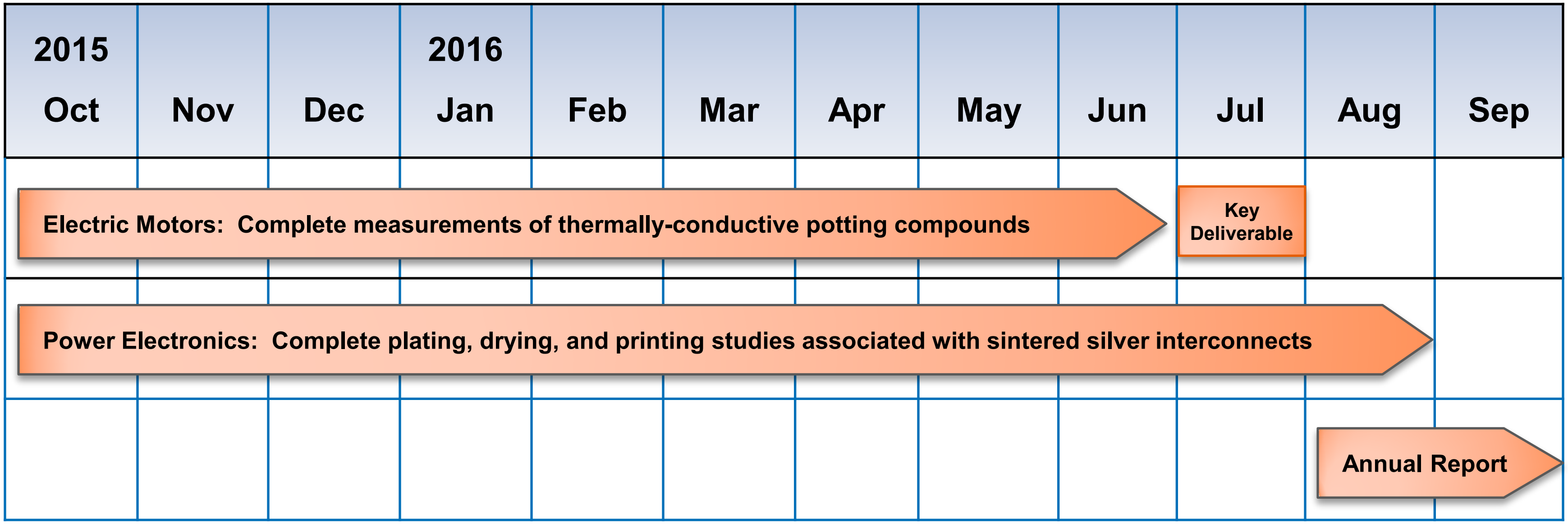
Heat Transfer from Copper Windings into Adjacent Laminates





Wereszczak, Wang, Bennion, Cousineau, Wiles, and Burress, "Anisotropic Thermal Response of Packed Copper Wire," in preparation, (2016).

Approach FY16 Timeline

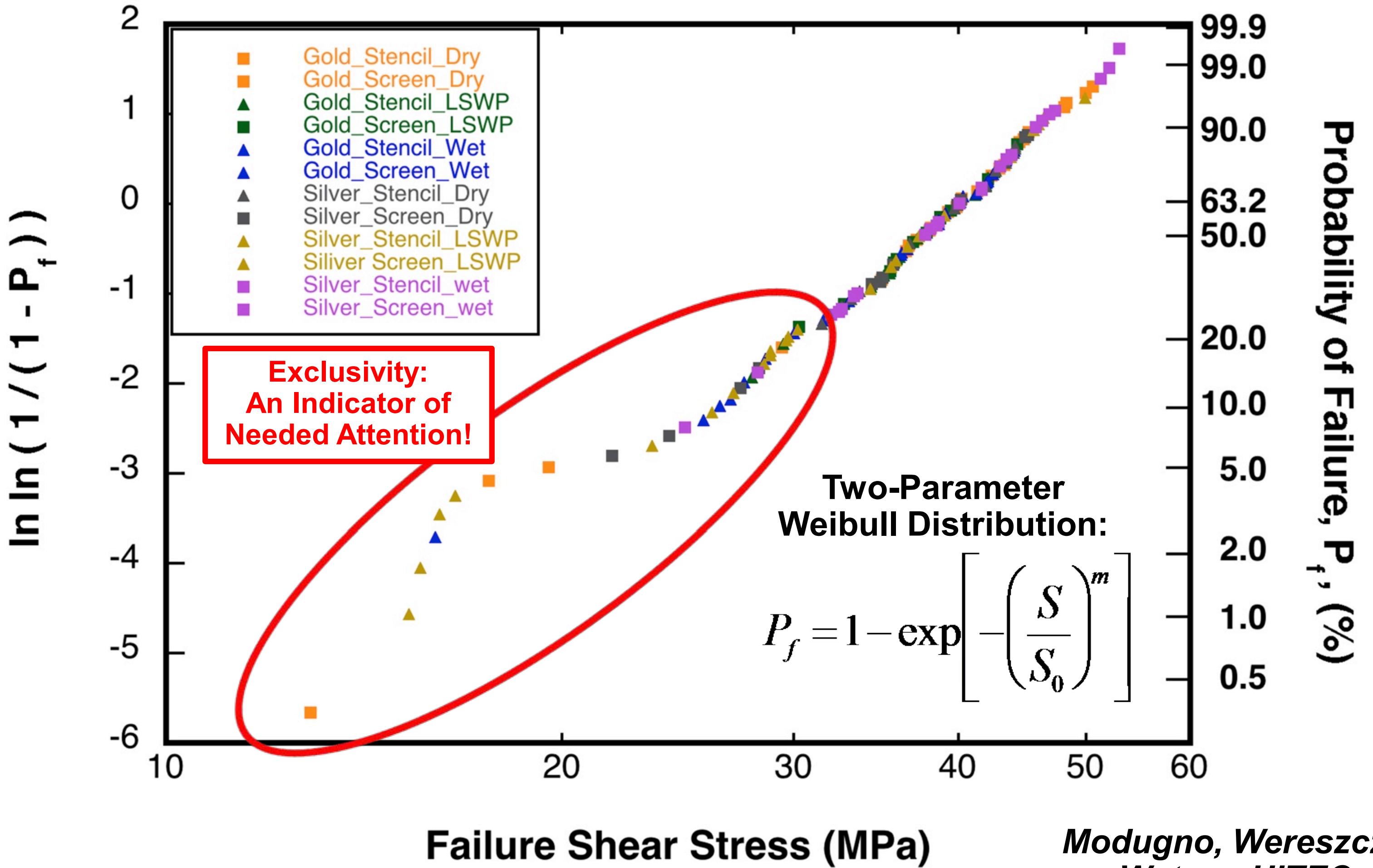


Go No/Go Decision Point: None - project ending in FY16

Key Deliverable: Complete thermal property measurements of electric motor copper windings with thermally-conductive, high-temperature-capable potting compound.

Technical Accomplishments – PEs (1 of 8)

Several Independent Parameters Combined Here (> 100 Tests)



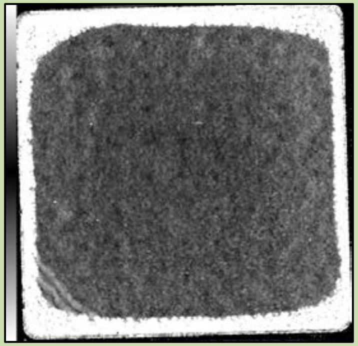
Modugno, Wereszczak, and Waters, HiTEC, 2016

If "properly" processed (FSS > ~ 30 MPa), then the failure stress of a sintered-silver interconnect system is arguably independent of the choice of plating (Au vs Ag), pre-drying or no-drying, and printing method (screen vs. stencil).

Technical Accomplishments – PEs (2 of 8)

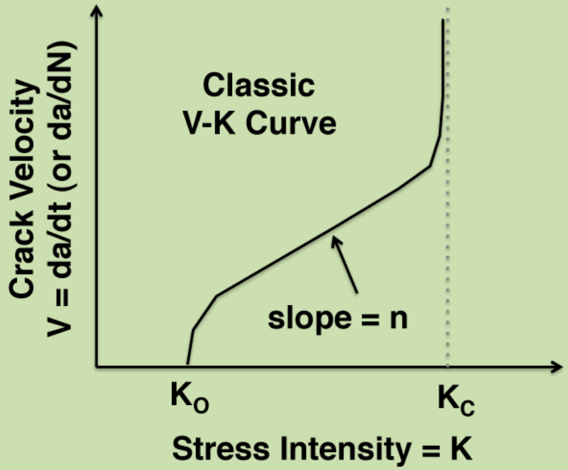
Extending Analysis to Thermal Cycling (via Collaboration with NREL)

Example of delamination ingress



Source: DeVoto and Paret, NREL

ORNL-advocated fatigue analysis pursued using fracture mechanics



But:

Corners complicate delamination interpretation; a circle is a better shape for fundamental understanding & analysis …

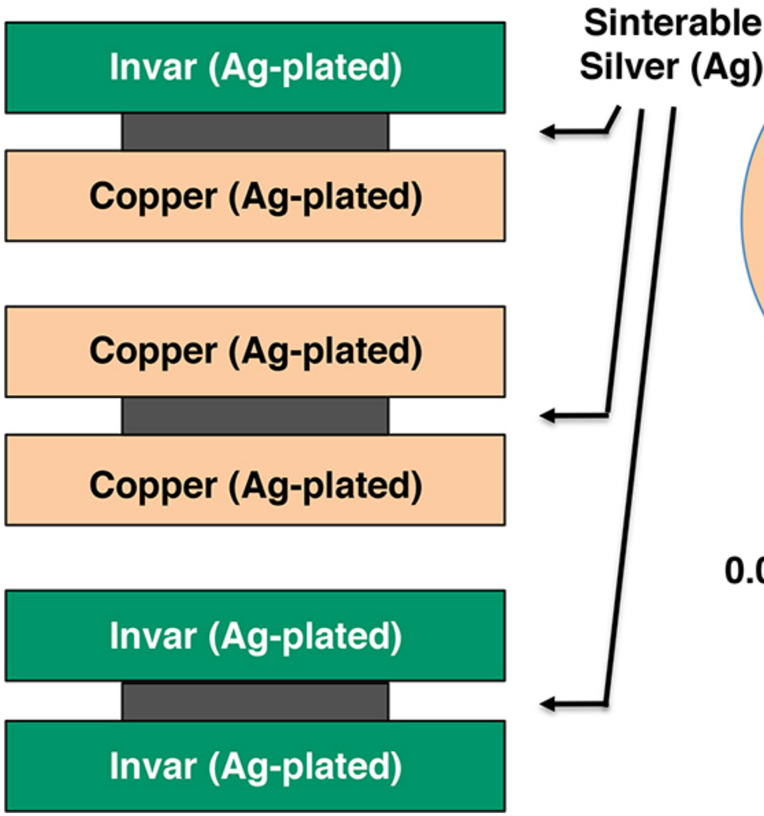
Interpret this phenomenon using fracture mechanics and fatigue analyses and other ORNL efforts to try to ultimately prevent its onset

Wereszczak, Modugno, Waters, DeVoto, and Paret, HiTEC, 2016

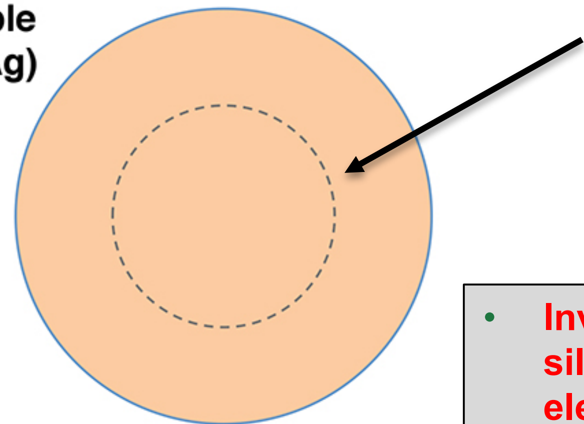
Technical Accomplishments – PEs (3 of 8)

Residual Stress and Onset of Delamination

Side View



Top View



Pad Diameters:
10 mm
18 mm
22 mm

25.4 mm dia disks &
2 mm thickness
0.050 mm bond thickness

- **Invar: simulates low CTE of silicon and substrates in electronic devices**
- **Thermal cycle (at NREL) & track delamination response**

Nominal Properties:

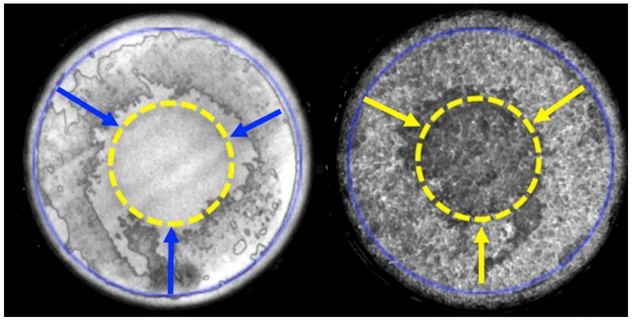
Material	CTE (ppm/°C)	E (GPa)
Copper	17	115
Sintered Ag	20	15-60
Invar	1.3 - 2.7	145

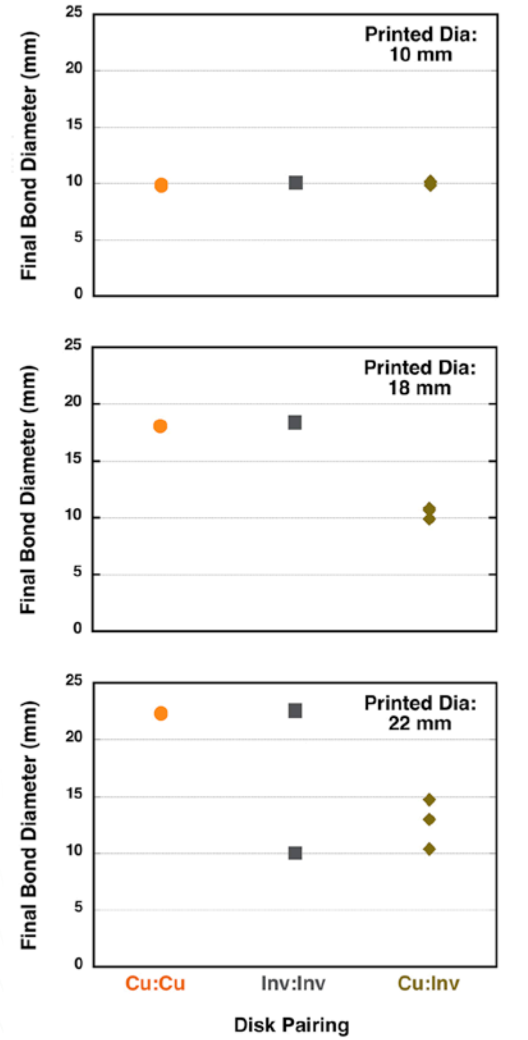
Purposely varying the CTE-mismatch-induced residual stress

Wereszczak, Modugno, Waters, DeVoto, and Paret, HiTEC, 2016

Technical Accomplishments – PEs (4 of 8)

Interpreting Sustained Interconnect Print Size





- **The sustained "Rorschach-like" bond size illustrates the potential of the ”interconnect system"**
- **Size is a convoluted function of many parameters:**
  - **Residual stress; both magnitude and orientation**
  - **Plating materials and processing**
  - **Sintered-Ag processing conditions**
  - **Ag paste cohesive strength**
  - **Adhesive strengths of all the various interlayers**
  - **Cleanliness of all the surfaces**

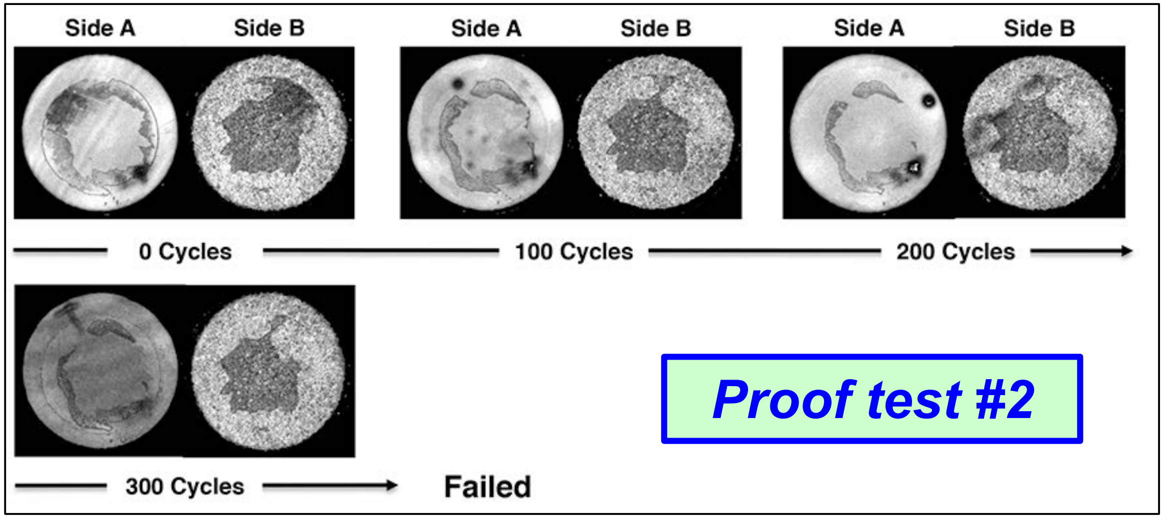
Proof test #1

Delamination (immediately after processing) did not occur for the smallest-sized print-pad diameter

Wereszczak, Modugno, Waters, DeVoto, and Paret, HiTEC, 2016

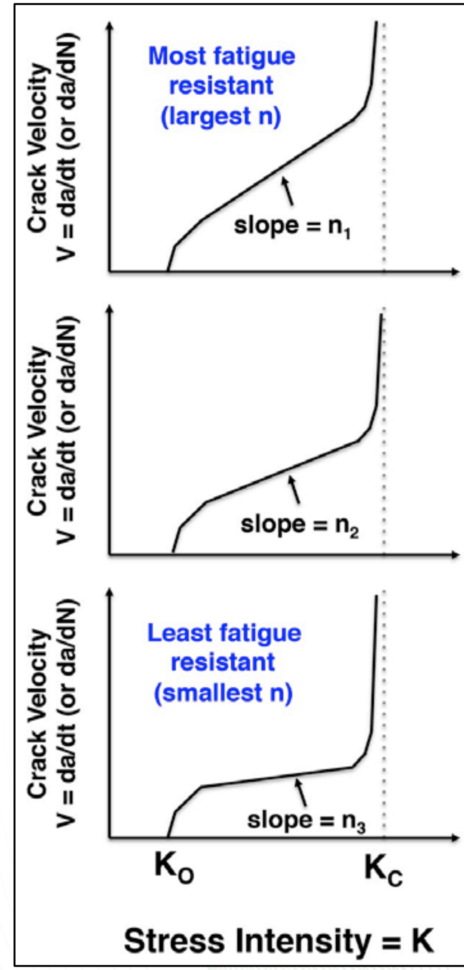
Technical Accomplishments – PEs (5 of 8)

Failure Occurred in < 400 Cycles in the Copper-Invar Couples; Cu-Cu and Invar-Invar Couples Did Not Fail (i.e., Ran Out)



Trapezoidal waveform:
± 5°C/min ramps, 170°C with 5 min dwell, -40°C with 15 min dwell

No obvious damage progression prior to failure; suggests a relatively high-valued fatigue exponent, n



Wereszczak, Modugno, Waters, DeVoto, and Paret, HiTEC, 2016

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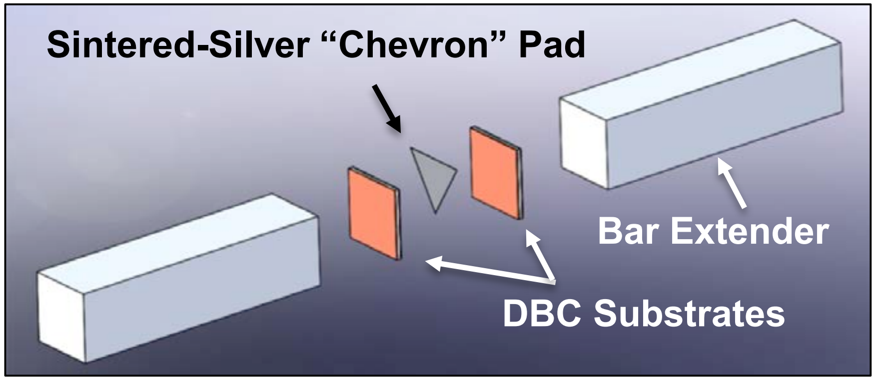
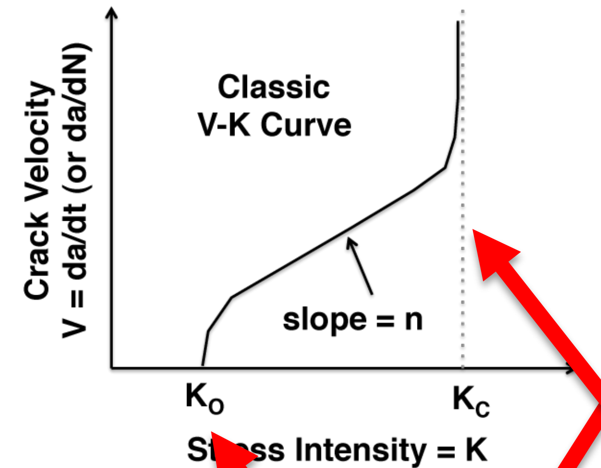
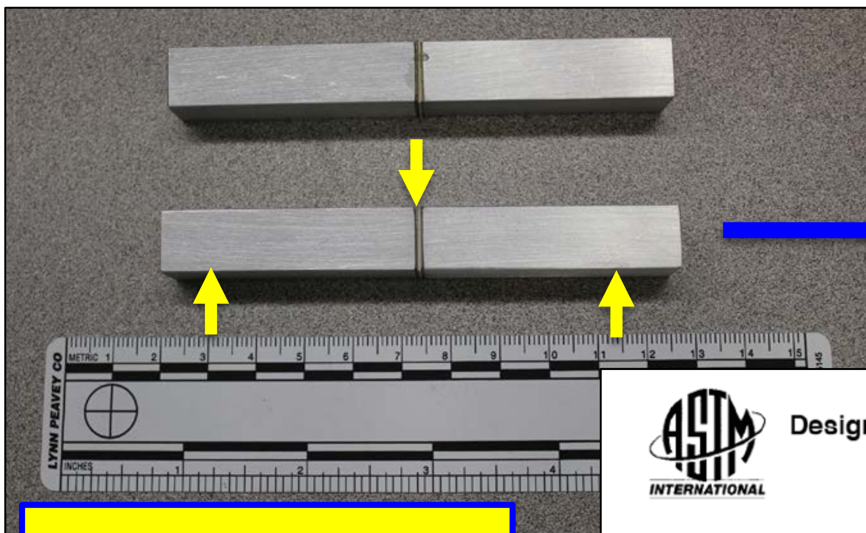
Technical Accomplishments – PEs (6 of 8)

Fracture Mechanics Tests Under Development at ORNL: K_o and K_{Ic}



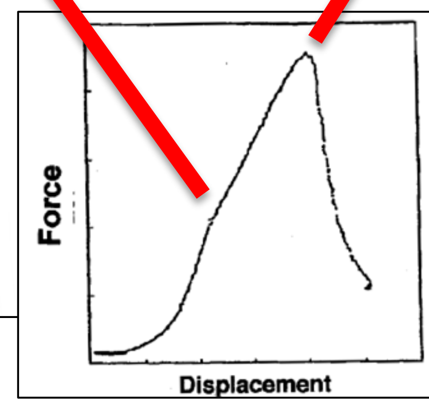


Examples of Fabricated Specimens



Test in 3-Pt Bending

& Produced Response



Designation: C 1421 – 01a

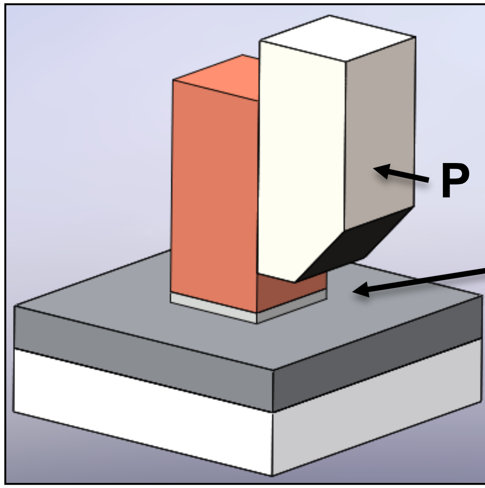
Standard Test Methods for
Determination of Fracture Toughness of Advanced Ceramics at Ambient Temperature[1]

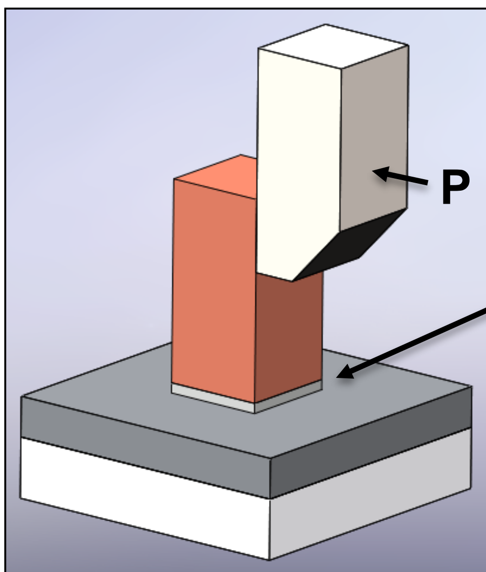
Goal: quantify the conditions of delamination onset

Wereszczak, Modugno, and Waters, 2016

Technical Accomplishments – PEs (7 of 8)

Cantilever Testing Under Development at ORNL: Shear + Tension



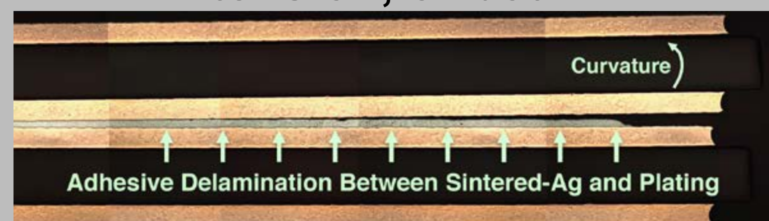


Wereszczak, Modugno, Jadaan, Waters, and Sharp, 2016

Of interest? The Interconnect.

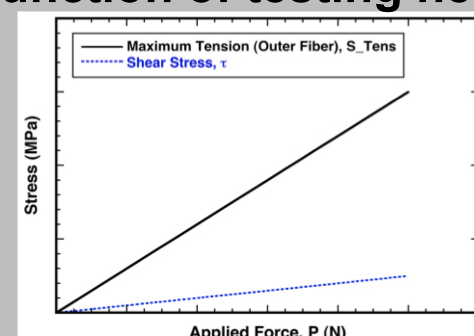
- **Shear + Tension**
- **Ag-sinter-bonding 5x5x10mm Si pillars to DBC substrates for cantilever test method development**

What can cause this delamination? In-plane shear, out-of-plane tension, or both.



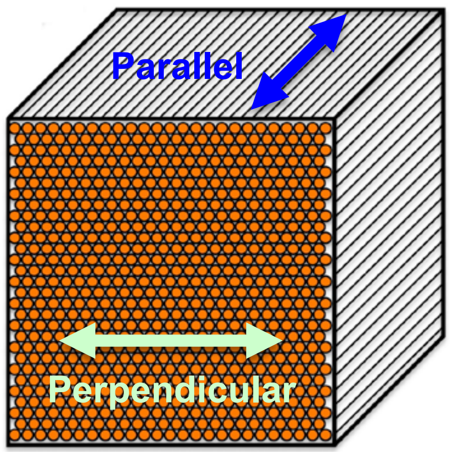
Relevant to: die thickness, double-side bonding, interconnect heterogeneities and property assymetry

Ratio of shear/tension is a function of testing height



Technical Accomplishments – EMs (8 of 8)

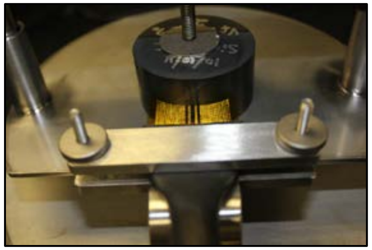
Thermal Conductivity (TC) Anisotropy is Large for Baseline



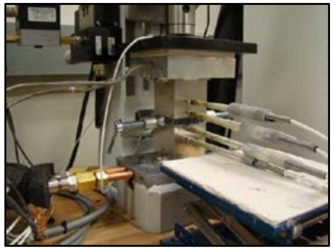
Copper Wound Coupons for TC Measurements

ORNL: Laser Flash

ORNL: Transient Hot Disk



NREL: Transmittance



TC anisotropy with varnish baseline: Parallel ≈ 100x Perpendicular

Wereszczak, Wang, Bennion, Cousineau, Wiles, and Burress, "Anisotropic Thermal Response of Packed Copper Wire," in preparation, (2016).

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Responses to Previous Year Reviewers' Comments

Last Year's Review
(in Propulsion Materials Section)

Question 1: Approach to performing the work–the degree to which technical barriers are addressed, the project is well-designed, feasible, and integrated with other efforts.

Reviewer 1:

This reviewer observed that the Propulsion Materials program is solving a difficult issue in power electronics, as 200°C-capable, low-cost materials would significantly decrease the cost of improved-efficiency power electronics. The reviewer lamented that funding limitations have restricted the investigation of a high-potential solution. If this solution is indeed of significant potential, the reviewer urged that DOE continue the effort fully to assess that option, because leveraging solutions from a parallel approach provides opportunity to solve more than one issue with a developed solution.

Reviewer 2:

Agreeing that this work addresses the overall Electric Drive Technologies (EDT) goals of reduced size, weight and cost, the reviewer believed the PI could have provided a more detailed explanation for the reasoning behind the 200°C target for power electronics (PE) components, as some audience members may not be clear on why that was established. The reviewer further described the work as combining materials and EDT expertise at ORNL and called the parallel efforts with PE and electric motor (EM) materials a reasonable approach, leveraging learnings between efforts. ORNL/ National Renewable Energy Laboratory (NREL) collaboration, the reviewer concluded, takes advantage of core capabilities at both labs.

Collaboration / Interactions

- **Alfred University**: Alternative sinterable Ag processing
- **General Metal Finishing**: Plater
- **Indium Corporation**: Established manufacturer of electronic interconnect materials including sinterable Ag
- **Lord Corporation**: Established manufacturer of encapsulant and potting materials
- **Mount Union University**: Mechanical test development for interconnects
- **National Renewable Energy Laboratory (NREL)**: Thermal cycling testing and non-destructive analysis of interconnects (Devoto and Paret) and materials for electric motors (Bennion and Cousineau)
- **Rogers Corporation**: DBC substrate manufacturer and plating studies

Remaining Challenges and Barriers

- **PEs: Sintered-silver interconnects**
  - **Identifying conditions to avoid onset of delamination**
  - **Limitation of plating adhesive strength**
- **EMs: Can the thermal interfacial losses be overcome to enable improvement of overall thermal transfer characteristics?**

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Proposed Future Work

Remainder of FY16 (project's end):

- **Submit journal article on effect of thermally-conductive filler in copper windings on overall thermal conductivity**
- **Complete mechanical testing and write articles on test methods for (1) K_{I0} – K_{Ic}, and (2) cantilever shear/tension measurements**

Summary

- **Relevance:**
  - Higher-temperature-capable materials, new packaging technologies, improved thermal transfer in EMs, and reliability and efficiency
  - Addresses major materials needs for the EV/HEV sectors
- **Approach/Strategy**: 200° C-capable interconnects and dielectrics for PEs and strategies to improve thermal management of EMs
- **Collaborations:** Industry, university, and national laboratory
- **Accomplishments:**
  - Identifying maximum capabilities of sintered-silver interconnects
  - Thermal conductivity (TC) anisotropy in copper windings and TC increase perpendicular to the wires
- **Future Work – Remainder of FY16:**
  - Identify stress intensity threshold for delamination
  - Complete supportive thermal measurements and modeling of thermal transfer in electric motor constituents