Power Electronics Thermal Design with Carbice Nanotubes for Reliability and Cost Saving

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Carbice Nanotube products increase reliability for renewable energy conversion, electric vehicles, data centers, and spacecrafts

Many Industries listed here still lack emission data from a Life Cycle Assessment (LCA) approach, data on reliability impact (which is essential to sustainability) is also not available. The logical impact of Carbice products to reduce environmental footprint for these industries is clear from customer data and experiences, and Carbice will play an active role in establishing the LCA and reliability impact data.

Reliability for Power Electronics:

Increase lifespan and reduce maintenance costs and environmental footprint

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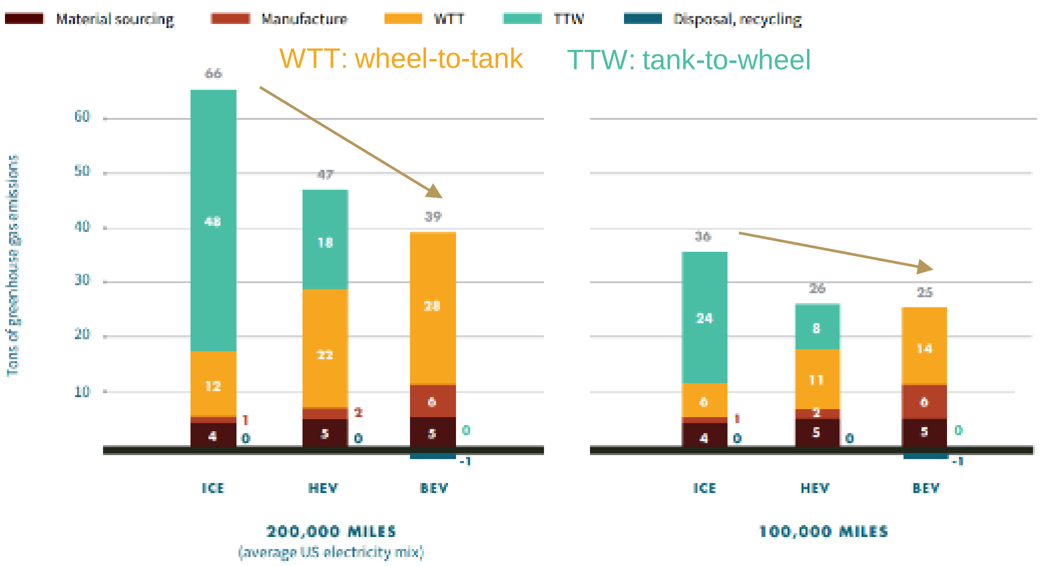
- Power electronics are behind many of the key innovations which will be crucial for the world’s green transition.
- Power electronics are used to convert electricity from one form to another, enabling applications from electric cars to renewable energy systems.
- **Reliability** and **lifespan** of the end products greatly influence their greenhouse gas emission reduction capability
  - example below for the life cycle analysis of Battery Electric Vehicles (BEV), Internal Combustion Engine (ICE) vehicles and Hybrid Electric Vehicles (HEV) showed high sensitivity of vehicle lifespan (lifetime mileage) to GHG emission reduction capability of HEVs and BEVs.

Vehicle Lifespan Sensitivity [1]



- Temperature is a major stressor that destroys power electronic components. And the power device failures is primarily due to temperature cycling. [2]
- Traditional TIMs lose performance over time, causing 20-40% derating of power electronics during promised lifespan. Degradation is caused by temperature cycling.
- **140 million** electric vehicles predicted to be on the road worldwide by 2030 [3]
- **Degradation of power electronic interface results in loss in EV lifetime mileage and GHG emission reduction capability.**

Carbice minimizes degradation of power electronic interfaces and enable the full potential of GHG emission reduction to be reached.

EV’s GHG emission reduction capability **doubles** when mileage increase from 100,000 to 200,000 miles

Source: [1] Life Cycle Analysis Comparison: Electric and Internal Combustion Engine Vehicles – Fuels Institute [2] Blaabjerg et al.: Reliability of Power Electronic Systems for EV/HEV Applications DOI:10.1109/JPROC.2020.3031041 [3] International Energy Agency, US Department of Energy.

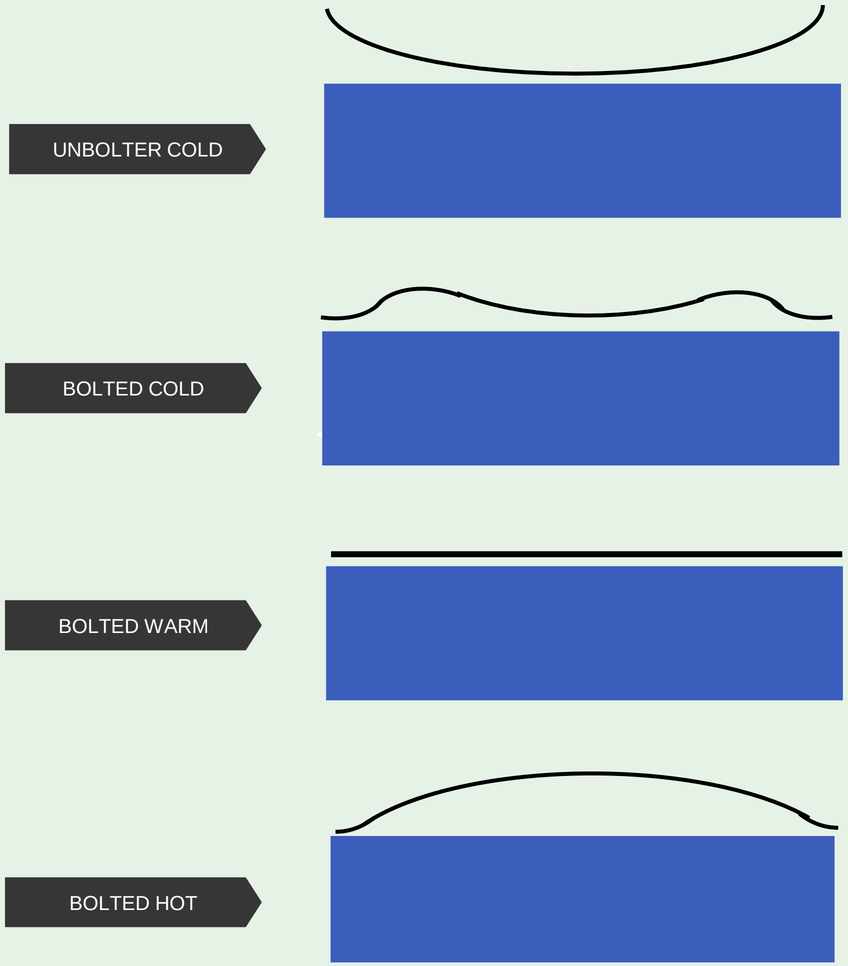
The Scientific Origin of these Problems is at the *Interfaces*

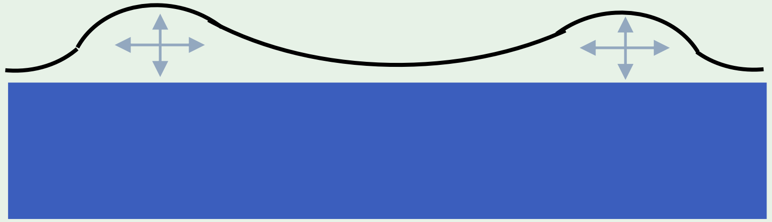
- Engineers have never been able to accurately predict the performance of interfaces under thermal and mechanical stress.
- The mechanics of any interface are non-linear and deform irreversibly under stress.
- All traditional materials deform irreversibly in an interface.
- THE BUSINESS COST IS that engineers are forced to use expensive, inaccurate trial and error and de-rating performance to design interface materials into products.
- ADDITIONAL BUSINESS COST IS high maintenance cost, and frequent unplanned down time and loss of system performance.
- There is NO STANDARD for reliable thermal interface performance in Power Modules!

Problem at the interface – dynamic thermal interface

DYNAMIC THERMAL INTERFACE

Thermal expansion mismatch causes dynamic deformation at the interface during thermal cycling.





The oscillation interface curvature during thermal cycling causes traditional TIMs to “pump out” of, or to “dewet” from (lose thermal contact with) the interface as the pressure distribution traverses the cross section.

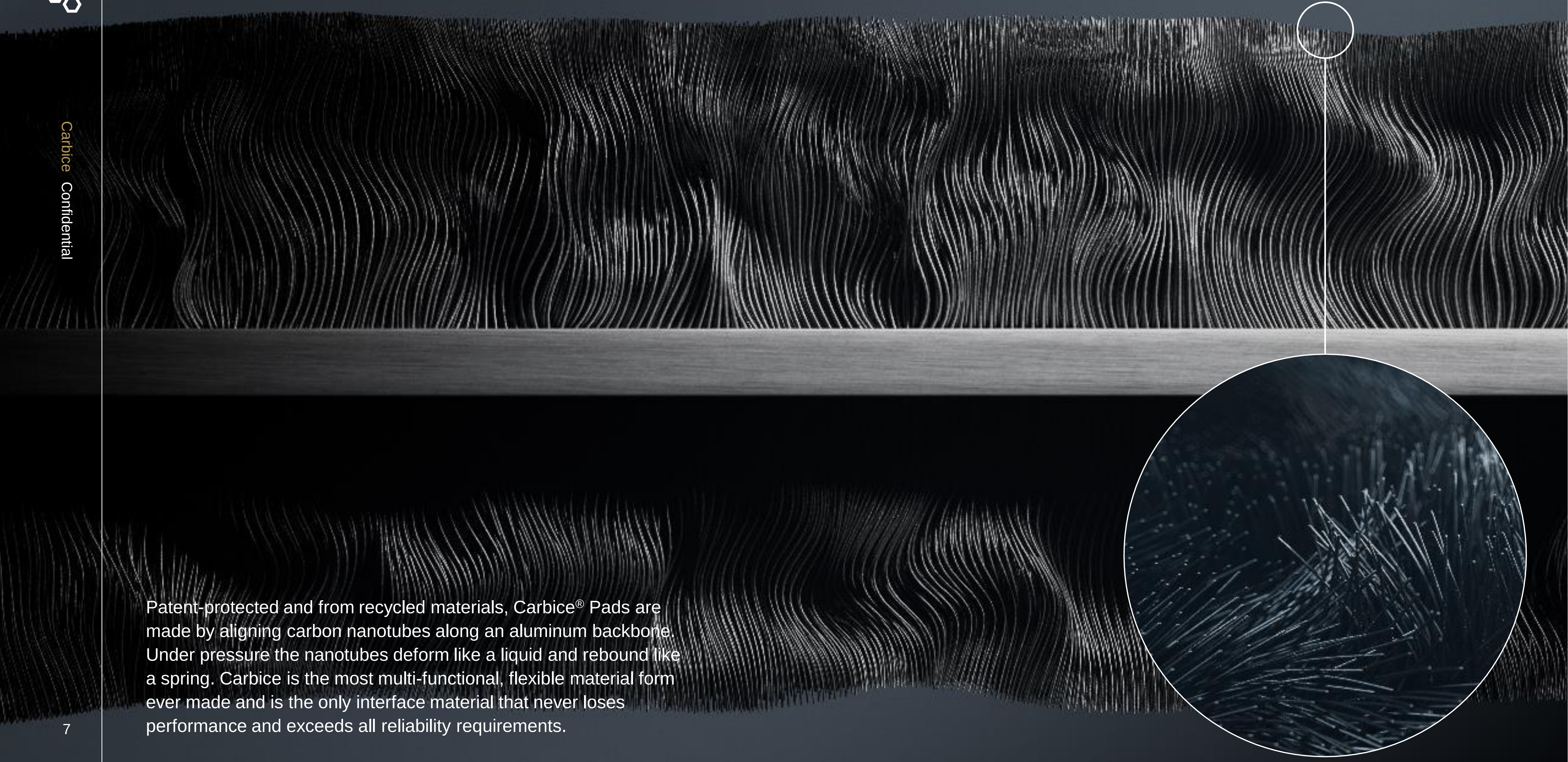
Severed by thermal shocks experienced during power on and off switch, scheduled maintenance, and other intensive power-density swinging events during operation (such as running customer algorithm on a cloud server).

This happens naturally during normal operation but needs to be simulated in a test environment.

“Pump out”, “crack”, and “dewet” accelerates incompatibility and contamination of traditional TIM materials in liquid immersion cooling environment.

Traditional TIMs “pump out”, “crack” or “dewet”, introducing unpredictable failure modes during cycling.

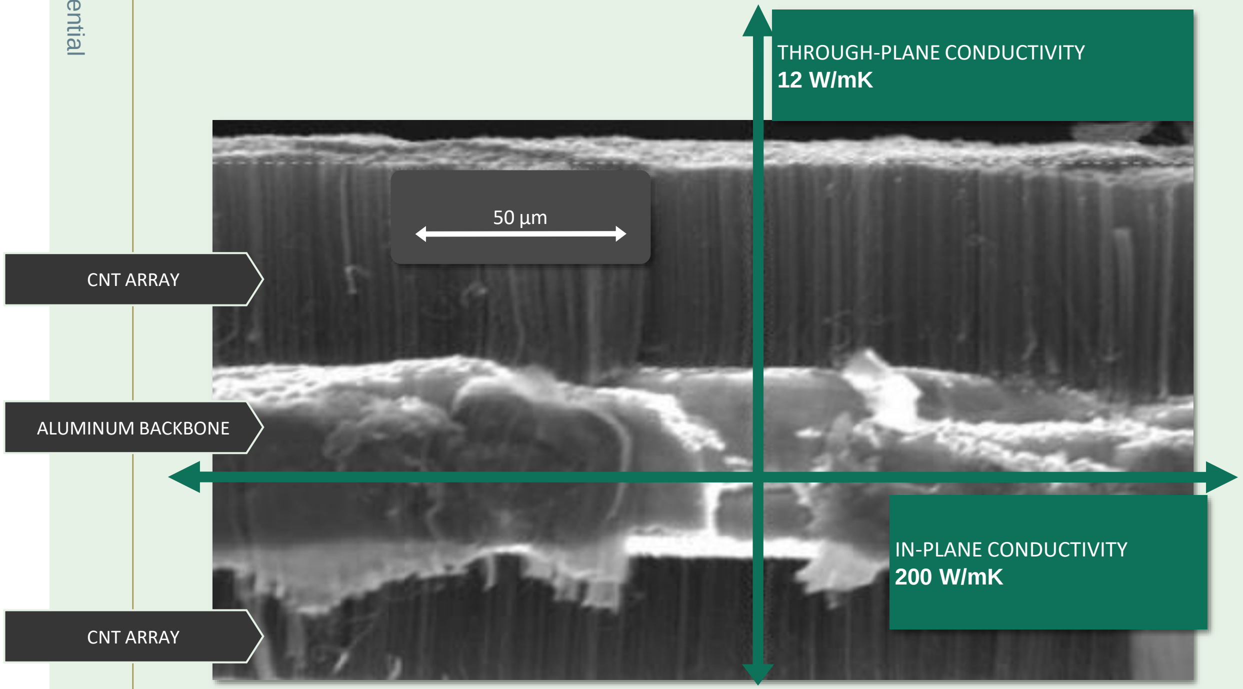
Carbice® Nanotube Technology



Patent-protected and from recycled materials, Carbice® Pads are made by aligning carbon nanotubes along an aluminum backbone. Under pressure the nanotubes deform like a liquid and rebound like a spring. Carbice is the most multi-functional, flexible material form ever made and is the only interface material that never loses performance and exceeds all reliability requirements.

THIS IS WHAT CARBICE PAD IS MADE OF

A new class/allotrope of carbon: A carbon nanotube (CNT) forest bonded covalently to an aluminum core.



Thermal Properties

- Conductivity
  - Carbice CNTs maintain their ballistic conduction, even under compression: heat is transferred along the CNT even when non-linear.
  - Aluminum core delivers optimal heat spreading.
- Resistance
  - The length of each nanoscopic CNT adjusts to the peaks and valleys of the contact surface, ensuring best-in-class Thermal Contact Resistance.

Chemical Properties

- Carbice CNTs are non-reactive and non-corrosive.
- Carbice Pad can withstand temperatures up to 660℃ in vacuum, at which point the Al core will melt.
- Carbice CNTs are hydrophobic. Even ice won’t form on Carbice CNTs.

Mechanical Properties

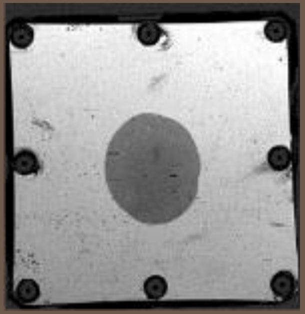
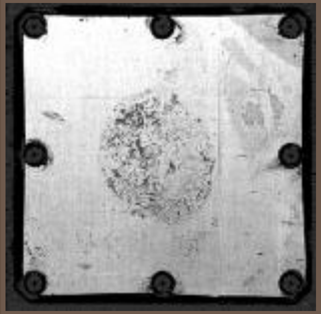
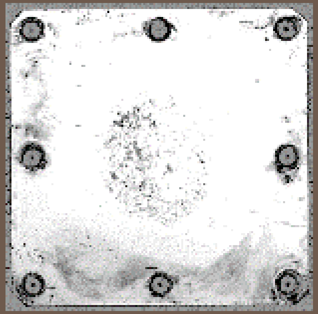
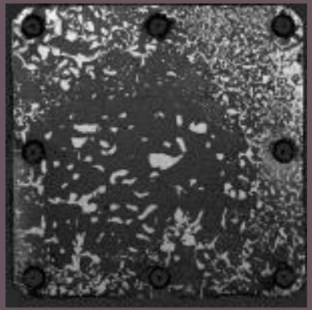
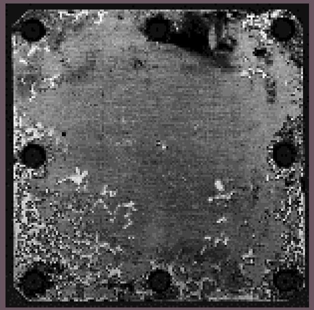
- CNTs are the strongest materials in terms of tensile strength and elasticity.
- Carbice CNT’s arrays are soft and flexible under radial pressure.
- When compressed Carbice CNT arrays buckle and absorb kinetic energy, dampening shock and vibration. But their spring-like mechanics let them recover 100% once released.

Electrical Properties

- CNTs are inherently conductive.
- However, Carbice can be either conductive or non-conductive with the addition of proven, customizable surfacing.

RELIABILITY: Performance Study On Bolted Joint:
ICE PAD vs. GREASE vs. PCM (-55ºC to 110ºC Thermal Cycling)

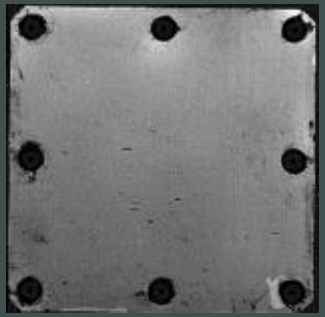
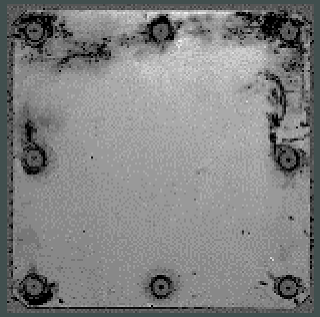
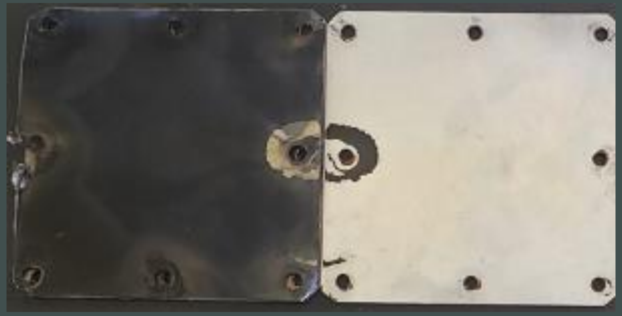
Industry leading TIM reliability

	Initial Install	50 cycles	2000 cycles	Inspection after disassembly	
Shin-Etsu Grease X23-7783D					After only ~50 cycles Grease is completely dried out.
Honeywell PCM PTM7900					Air voids migrate around interface with PCM.

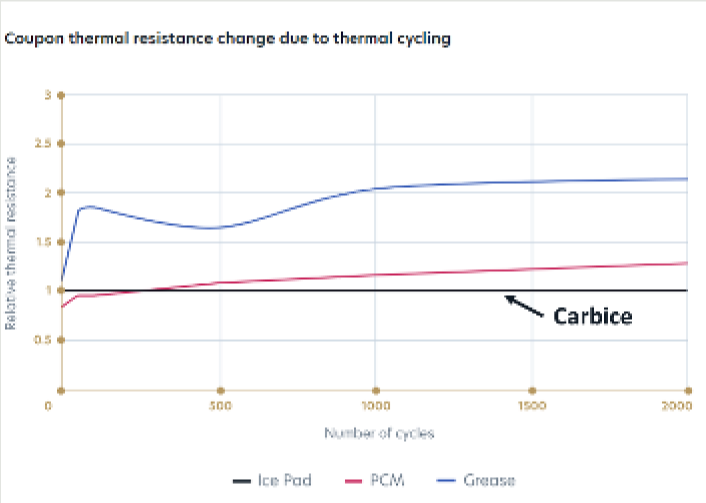
Non-destructive imaging (CSAM) of assembled interfaces

PERFORMANCE STUDY ON BOLTED JOINT:
ICE PAD vs. GREASE vs. PCM (-55ºC to 110ºC Thermal Cycling)

Industry leading TIM reliability

	Initial Install	50 cycles	2000 cycles	Inspection after disassembly
CARBICE ICE PAD IP150				

Carbice Ice Pad maintains consistent contact and performance.



"If your data sheet numbers actually deliver, that would be a game changer."

They do:

After 2000 cycles Carbice Ice Pad outperforms Grease **by 2.6x** and PCM **by 1.4x**.

Unlike conventional TIMs, we maintain our specs over time & cycling.

INDUSTRY LEADING RELIABILITY FOR THE INDUSTRY'S TOUGHEST APPLICATIONS!

Accelerated Stress Testing 85 °C/ 85% Relative Humidity Aging (Based on JESD22-A101 Guidance)

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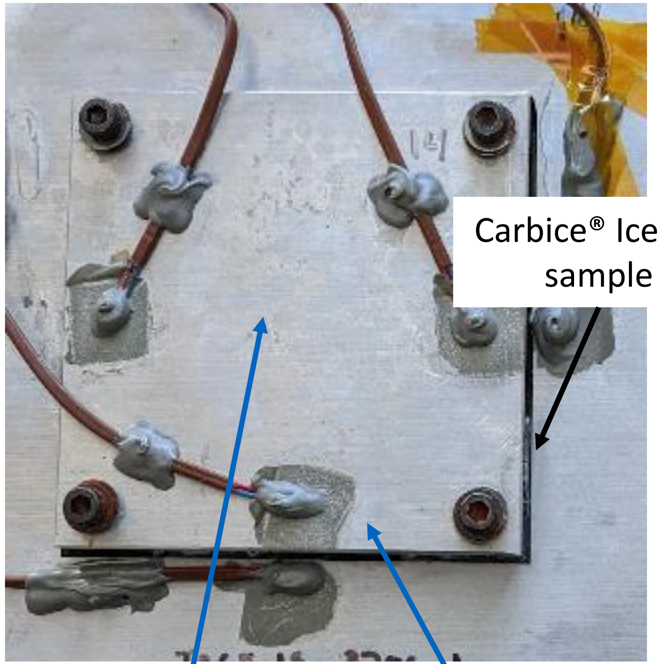


Carbice® Ice Pad sample

Aluminum bolted joint w/85 mm x 85 mm top plate

Heater block attaches to top plate during testing

<u>Test Apparatus</u>

- 85 mm x 80 aluminum bolted joint
- Flanges bolted at 9.2 in-lb (100 psi average interface pressure)
- Top plate heated via cartridge heater, base plate cooled via direct contact with water block
- Thermal resistance measured at initial assembly and after exposure to elevated temperature and humidity conditions

<u>Exposure conditions</u>

- **85 °C/85%** relative humidity **1,000 hours**
- After exposure:
  - Thermal resistance re-measured
  - Torque values checked for bolt torque loss
  - Visual inspection for signs of corrosion
  - Target criteria: <5% increase in thermal resistance after exposure

HAST Testing: 85 °C/85% RH Results:

✓No bolt torque loss observed on test interfaces after exposure

✓No significant loss of performance observed after exposure testing

✓Ice Pad Samples improved on average 9% after exposure:

Carbice® Ice Pad solutions often improve performance over time as the nanostructures wet the interface

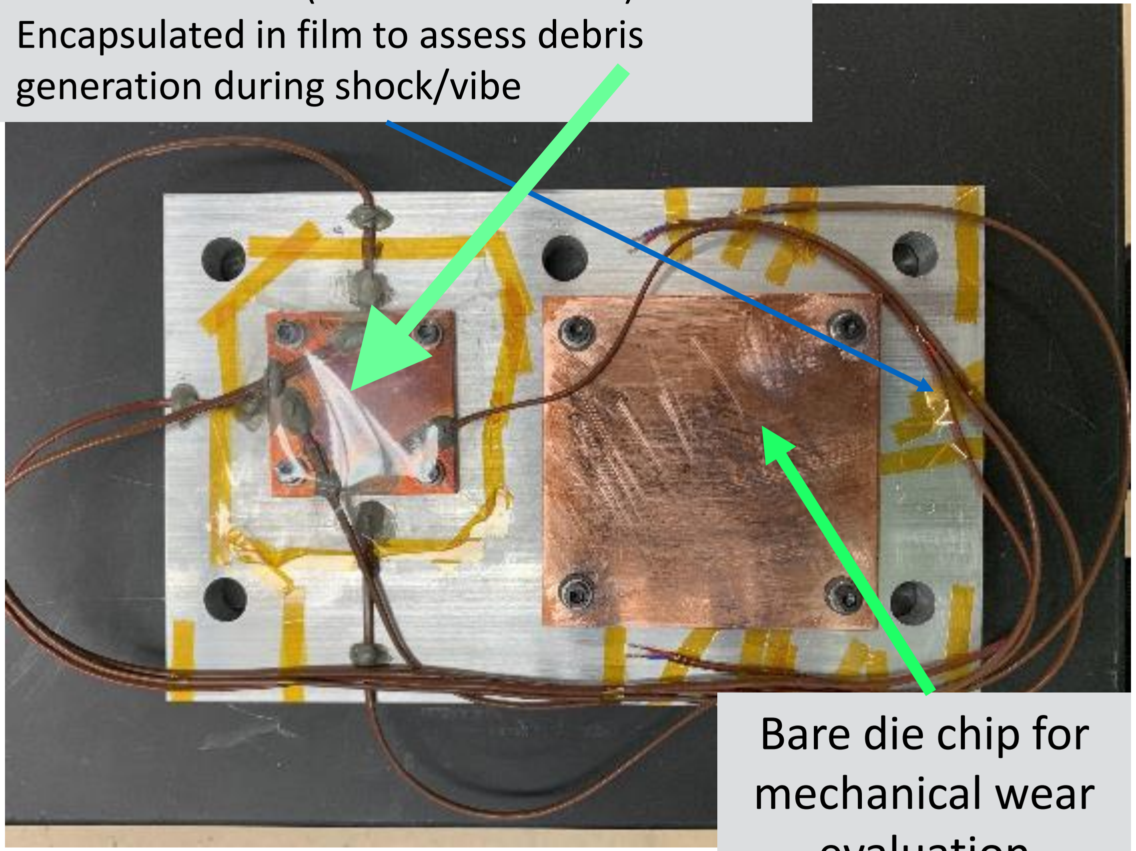
✓No visual indication of corrosion inside interface

Carbice® Solutions can meet the challenging requirements of EV Powertrain Applications

Carbice® Reliability

Shock and vibration… Can handle the toughest environments

- Bolted joint (50 mm x 50 mm) for thermal characterization (heater not shown)
- Encapsulated in film to assess debris generation during shock/vibe



Bare die chip for mechanical wear evaluation

- Carbice® Ice Pad subjected to MIL-STD-810 elevated shock and vibration levels to simulate entire service life
- Vibration levels applied sequentially along each of the three orthogonal axes for 2 design cases
- Operational Shock: One hundred 10G, 16ms, ½-sine shocks were applied along each axis and direction for a total of 600 shocks.
- Thermal performance characterized before and after test

Shock and Vibration Results:

✓No debris present after test

✓Mechanical wear/impact passed: Silicon die in bolted joint in like new condition after test and tear down

✓No significant change in thermal performance after test

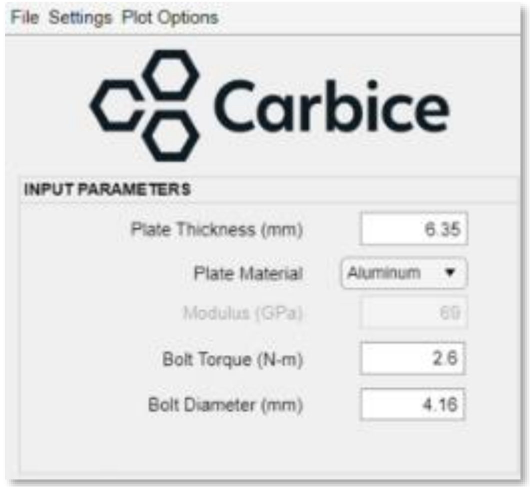
Carbice® Solutions can meet the challenging requirements of EV Powertrain Applications

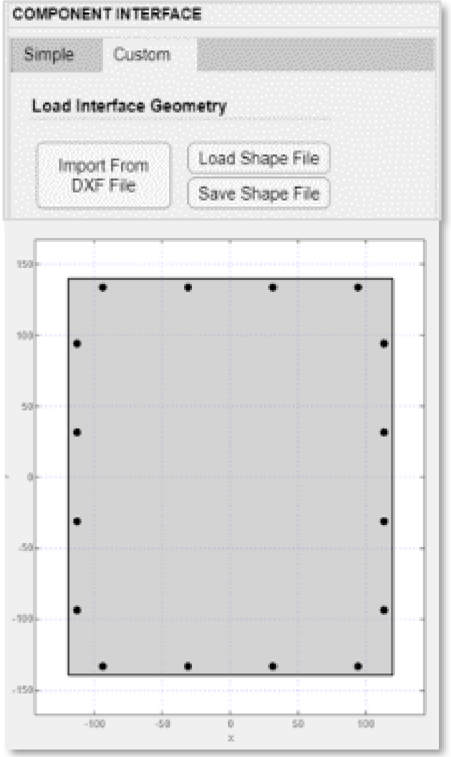
Reliable CNT Mechanics Enables Predictive Interface Design

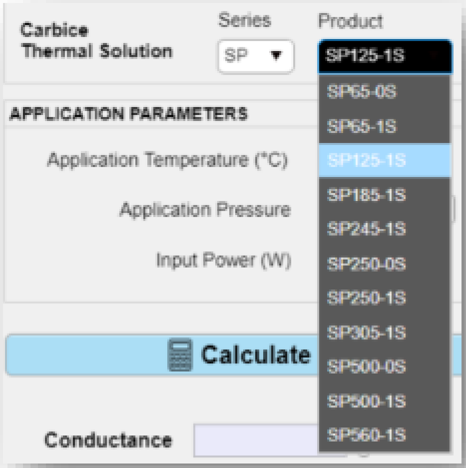
Carbice® SIM is a suite of predictive modeling tools for fast and accurate analysis of thermal and structural performance of Carbice in real interfaces.

- Thermal design is one of the only parts of the build process that relies on trial and error
- Mechanical- thermal co-design minimizes inefficiencies and ***creates the possibility for new optimization***
- Understanding real world thermal performance early in the design cycle ***saves testing time and money***.

We utilize several Computational Models developed in-house







Deflection-Contact Predictions

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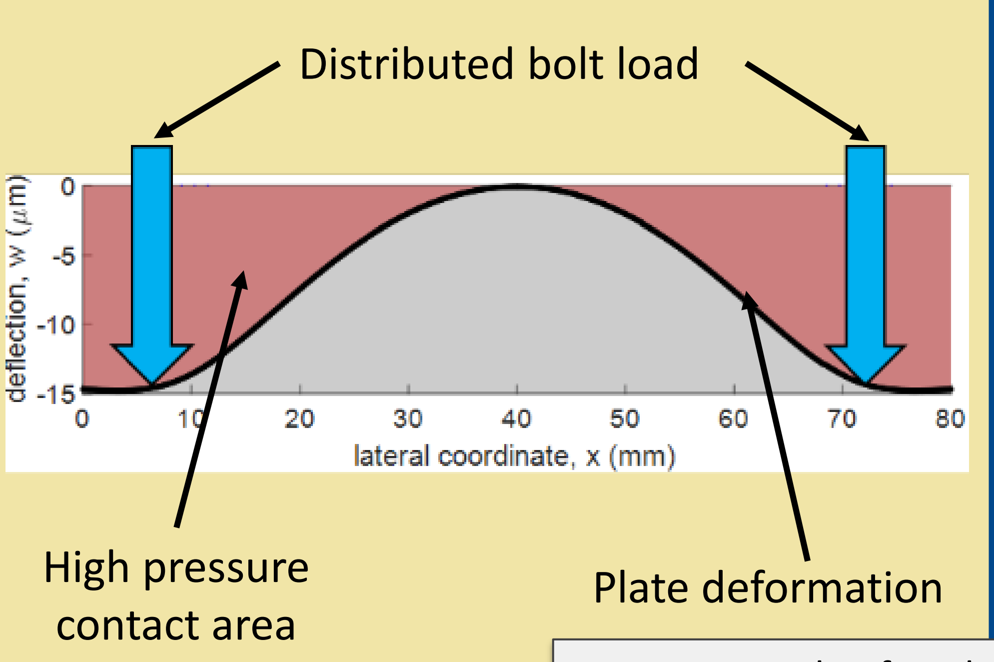
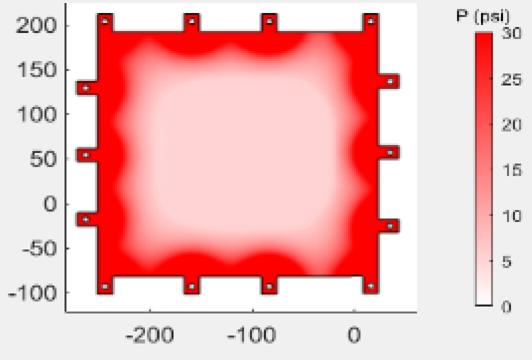
Example: Cross Section of an 80 mm plate



Example of Gasket Pressure Distribution

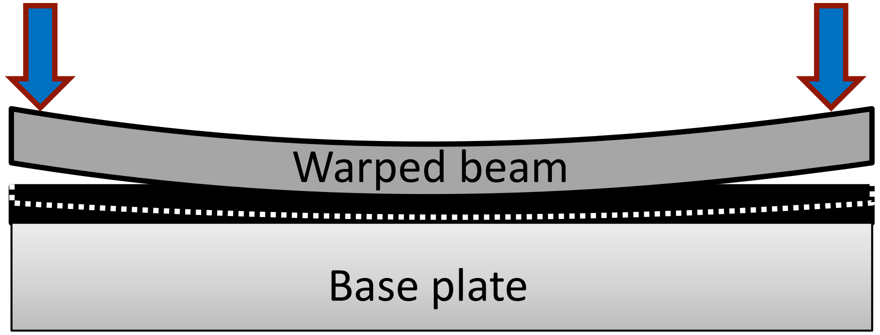


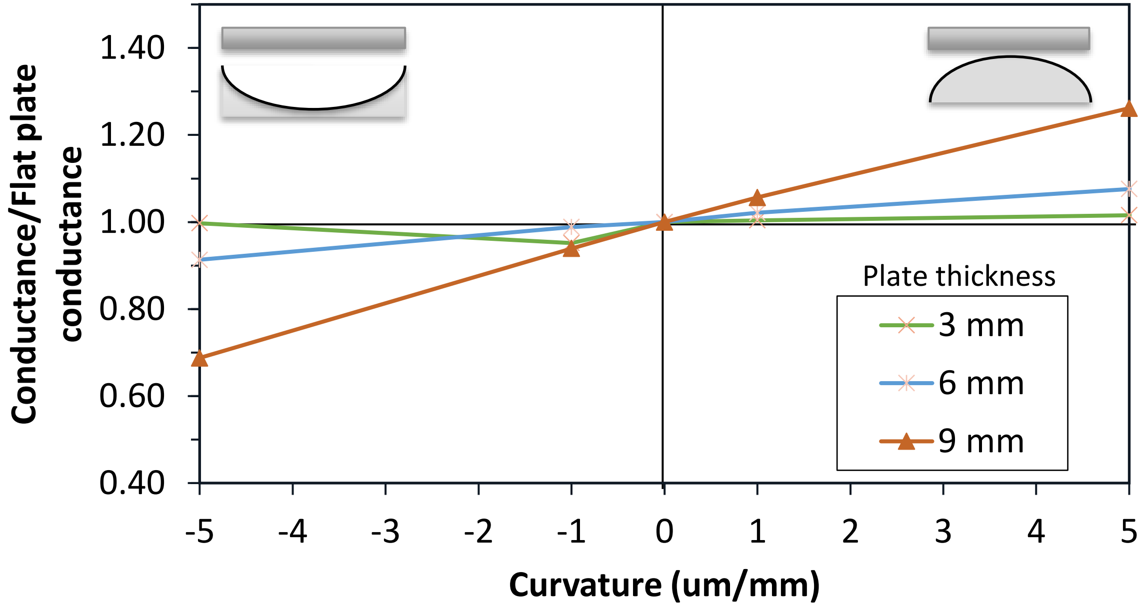
Modeling Approach

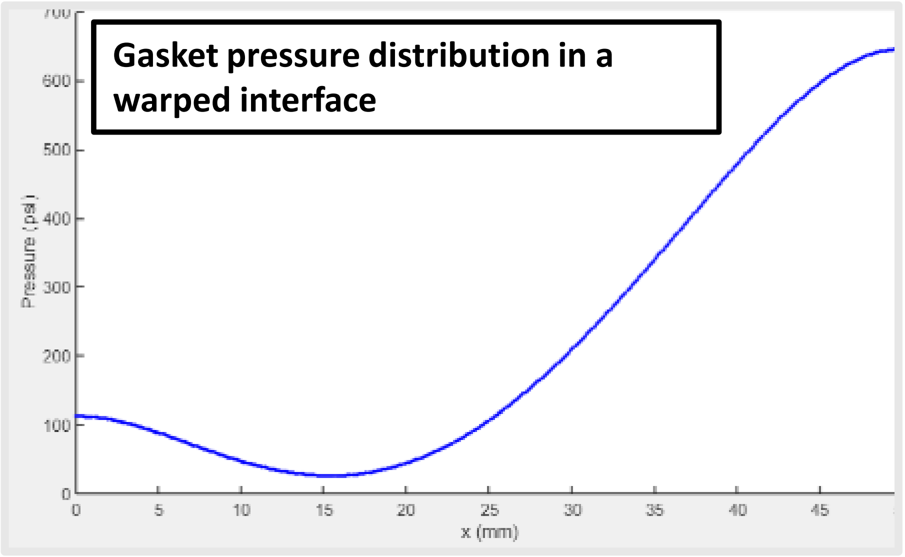
- *Apply* distributed loads to interface at bolt/washer locations
- *Solve* the mechanical structural problem for the resulting plate/ box deflection
- *Identify* overlap between plate deflection and gasket to determine high pressure contact area and contact pressure distribution in interface
- Use interface pressure distribution, combined with pressure-conductance relationships for Carbice® Space Pad to determine conductance distribution across interface
- *Solve* for temperature distribution in box/plate to incorporate spreading effects and power nonuniformity

Curvature and Flatness Tolerances

✓ Carbice® SIM can give predictable conductance for Curved, Wavy, or Warped interfaces







Reliability, Performance, Ease of Assembly, Ease of Maintenance, And Total Cost…

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Conventional TIMs	Carbice
Always requires expensive, time-consuming testing	Predictable impact without testing
A mess to work with and difficult to rework	Easy installation and rework
Performance = low thermal conductivity	Performance = best in class thermal conductivity
Performance degrades rapidly with time and cycling	Long-lasting reliability in any use condition
Expensive manufacturing steps and many hidden costs	Simplifies and reduces manufacturing costs
Generates waste and drives overconsumption of energy	Recycled and lowers energy required to build things

VS

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