Introduction to Aluminum and Magnesium Annealed Pyrolytic Graphite (k-Core)

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San Jose, CA
Cooling Requirements

• High capability semiconductor devices generate large amounts of waste heat
  – Typical Aircraft Versa Module Europa (VME) board produces 250 watts over a 15.24 cm. by 22.86 cm. area
  – High power aircraft electronics can produce 500 watts in 0.16 cm².

• Keep operating temperatures below 125°C
Conduction Cooling

• Aluminum substrates provide the baseline
• Low Cost
• Processing well-understood

**BUT**

• Limited by low thermal conductivity
  – 180 to 240 W/m-K
• Copper has better conductivity, but is HEAVY
Annealed Pyrolytic Graphite (APG)

**Thermal Conductivity (W/mK)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity x (W/mK)</th>
<th>Conductivity y (W/mK)</th>
<th>Conductivity z (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>APG</td>
<td>1800</td>
<td>1600</td>
<td>1200</td>
</tr>
<tr>
<td>UHM Pitch Fiber</td>
<td>1600</td>
<td>1400</td>
<td>1000</td>
</tr>
<tr>
<td>Copper</td>
<td>1000</td>
<td>800</td>
<td>600</td>
</tr>
<tr>
<td>Aluminum</td>
<td>500</td>
<td>400</td>
<td>200</td>
</tr>
</tbody>
</table>

**Mechanical Properties**

<table>
<thead>
<tr>
<th>Material</th>
<th>Modulus (GPa)</th>
<th>Poisson's Ratio</th>
<th>Shear Modulus (GPa)</th>
<th>CTE (PPM/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed Pyrolytic Graphite (APG)</td>
<td>11 GPa</td>
<td>0.3</td>
<td>6.6</td>
<td>6.6</td>
</tr>
</tbody>
</table>

**Thermal, 25 °C**

<table>
<thead>
<tr>
<th>Conductivity (W/mK)</th>
<th>Diffusivity (cm²/K)</th>
<th>Specific Heat (W/gK)</th>
<th>Density (g/cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>k1</td>
<td>v1</td>
<td>Cp</td>
<td>d</td>
</tr>
<tr>
<td>k2</td>
<td>v2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>k3</td>
<td>v3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1700.0</td>
<td>1071.5</td>
<td>0.702</td>
<td>2.26</td>
</tr>
</tbody>
</table>

**Specific Heat (W/gK)**

<table>
<thead>
<tr>
<th>Material</th>
<th>Cp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annealed Pyrolytic Graphite (APG)</td>
<td>0.702</td>
</tr>
</tbody>
</table>
**APG Description**

### As Deposited Pyrolytic Graphite (PG), Mosaic Spread 40 to 50 Deg

- $k_{ab} = 300. \text{ W/m-K}$
- $k_c = 3.0 \text{ W/m-K}$
- $E_{ab} = 34 \text{ GPa}$
- $E_c = 11 \text{ GPa}$
- CTE$_{ab} = 0.5 \times 10^{-6} \text{ °C}^{-1}$
- CTE$_c = 20. \times 10^{-6} \text{ °C}^{-1}$
- Tensile Strength$_{ab} = 100 \text{ MPa}$
- Tensile Strength$_c = 1.03 \text{ MPa}$

### Annealed Pyrolytic Graphite (APG), Mosaic Spread 5 to 10 Deg

- $k_{ab} = 1700. \text{ W/m-K}$
- $k_c = 10. \text{ W/m-K}$
- $E_{ab} = 103 \text{ GPa}$
- $E_c = 34 \text{ GPa}$
- CTE$_{ab} = -1.0 \times 10^{-6} \text{ °C}^{-1}$
- CTE$_c = 25. \times 10^{-6} \text{ °C}^{-1}$
- Tensile Strength$_{ab} = ---$
- Tensile Strength$_c = ---$ksi

### Highly Oriented Pyrolytic Graphite (HOPG), Mosaic Spread < 2 Deg

- $k_{ab} = 2000. \text{ W/mK}$
- $k_c = 10. \text{ W/mK}$
- $E_{ab} = 145. \text{ GPa}$
- $E_c = 21 \text{ GPa}$
- CTE$_{ab} = -1.0 \times 10^{-6} \text{ °C}^{-1}$
- CTE$_c = 25. \times 10^{-6} \text{ °C}^{-1}$
- Tensile Strength$_{ab} = ---$
- Tensile Strength$_c = ---$
Annealed Pyrolytic Graphite (APG)

- Thermal Conductivity
  - 1700 W/m-k
  - Al is ~ 200

- Density
  - 2.1 g/cc
  - Al is 2.7 g/cc

- Fragile
- Hygroscopic
k-Core® Material Concept

- Patented Encapsulated APG material system – 3x the conductivity (k) of copper with the mass of aluminum
- Annealed pyrolytic graphite provides a high k path
- Encapsulant sets the CTE and structural properties
- Encapsulant material selected to satisfy requirements

Annealed Pyrolytic Graphite (APG) $k_{xx}=k_{yy}=1700 \text{ W/mK}$

No Shear transfer at Interface

Encapsulant

U.S. Patent #5296310
Production Electronics Modules

Finished part appearance

X-Ray image
Typical Performance Comparison

- **SEM E Avionics Application**
  - Dissipating 100 W Per Side
  - Design Goal - Use COTS Electronic Parts
    - Junction Temperatures Below 85°C
- **Baseline Material**
  - 6061-T6 Aluminum

Finite Element Model of SEM E Module

- 100 W Waste Heat (2) Sides
- 40°C @ Rail (2) Places
SEM-E Thermal k-Core™

APG Material
Max Surface Temperature - 59.4°C

Aluminum Baseline
Max Surface Temperature - 152°C
**F35 Joint Strike Fighter Standard Module**

**Aluminum Baseline**
Max Surface Temperature – 59.8°C

**k-Core Material**
Max Surface Temperature – 17.5°C

- Conduction cooled module, F35 standard
- Standard APG configuration with core personalization
- Up to 250 W heat dissipation through core
- Aluminum encapsulation
VME k-Core™ Power Supply

- Conduction cooled VME 1101.2 Format
- 80 W Heat Dissipation through Core
- Aluminum Encapsulation
- In Service

Encapsulated APG
Delta Temp = 18°C
Weight = 204 gm

OFHC Copper
Delta Temp = 24°C
Weight = 731 gm

Carbon Fiber Composite
Delta Temp = 28°C
Weight = 172 gm
k-Core™ Process

- **Materials**
  - Aluminum
  - Graphite

- **Material Prep.**

- **Target Assembly**

- **HIP Bonding**

- **Bonded Target**

- **Machining**

- **Finishing and Assembly**
k-Core Applications Over Temperature

Electronic Packaging

- Cryo Conduction Bar
  - Al/Cu/APG

- Cold Shield Bracket
  - Al/APG

Power Conversion
- Ni/APG Conductors

Power Generation
- BeCu/APG Conductors

Re-entry Carbon-Carbon/APG nose cone
Bi-Metallic k-Core Conduction Bar

K-Core Aluminum with Copper Flange

Bonded and Machined Bi-Metal Bar
k-Core® VME 1101.2 Module
Aluminum Encapsulated APG
Ruggedized Conduction Cooled VME Format (IEEE 1101.2)

Qualified and Fielded

AL/APG Assembly View
Aluminum Encapsulated APG with Copper Vias
DoD Radar Systems

Qualified and Fielded
Magnesium k-Core
## Density Comparison
**Al, Al k-Core, Mg, Mg K-Core**

<table>
<thead>
<tr>
<th>Component Material</th>
<th>Weight % APG</th>
<th>Weight % Encapsulant</th>
<th>Overall Density (gm/cc)</th>
<th>Density Improvement (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 Al</td>
<td>0</td>
<td>100</td>
<td>2.7</td>
<td>Baseline</td>
</tr>
<tr>
<td>Al k-Core</td>
<td>50</td>
<td>50</td>
<td>2.48</td>
<td>8.1</td>
</tr>
<tr>
<td>Mg AZ80A</td>
<td>0</td>
<td>100</td>
<td>1.8</td>
<td>33</td>
</tr>
<tr>
<td>Mg k-Core</td>
<td>50</td>
<td>50</td>
<td>2.03</td>
<td>25</td>
</tr>
</tbody>
</table>
## Thermal Conductivity Comparison

<table>
<thead>
<tr>
<th>Component Material</th>
<th>Volume % APG</th>
<th>Volume % Encapsulant</th>
<th>Thermal Conductivity (W/m-k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061 Al</td>
<td>0</td>
<td>100</td>
<td>170</td>
</tr>
<tr>
<td>Al k-Core</td>
<td>65</td>
<td>35</td>
<td>1071</td>
</tr>
<tr>
<td>Mg k-Core</td>
<td>65</td>
<td>35</td>
<td>1054</td>
</tr>
</tbody>
</table>
Property Overview

• Magnesium k-Core significantly reduces weight
  – 25% weight reduction below Al
  – 10 to 20% weight reduction below Al k-Core
• Thermal conductivity values equivalent to Al k-Core

Conclusion-Mg k-Core saves weight with no thermal management penalty
Prototype Chassis
Completed k-Core, Prototype Magnesium Chassis (Adhesive Bonded-not hardware suitable)
## Prototype Chassis

Data Comparison

<table>
<thead>
<tr>
<th>Chassis Composition</th>
<th>Mass (g)</th>
<th>Mass Reduction (%)</th>
<th>Delta Temp (K)</th>
<th>Temp Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum 6061</td>
<td>1235</td>
<td>Baseline</td>
<td>28.0</td>
<td>Baseline</td>
</tr>
<tr>
<td>Magnesium AZ31B</td>
<td>808</td>
<td>35%</td>
<td>67.0</td>
<td>-139%</td>
</tr>
<tr>
<td>k-Core, Aluminum</td>
<td>1199</td>
<td>3%</td>
<td>17.4</td>
<td>38%</td>
</tr>
<tr>
<td>k-Core, Magnesium</td>
<td>881</td>
<td>29%</td>
<td>16.7</td>
<td>40%</td>
</tr>
</tbody>
</table>
Other Considerations

• Cost Reduction Possibilities
  – Magnesium Forming Technologies such as die casting may prove useful
  – The low density of magnesium compared to aluminum compensates for the higher per pound cost