Innovations in Flexible Graphite for Thermal Management Applications

Martin D. Smalc
Research Associate
Topics

- GrafTech International Holdings, Inc.
- eGRAF® Materials and Products
- eGRAF® SPREADERSHIELD™ Applications
  - Displays
  - LED Lighting
  - Smartphones – SS1500
  - Lithium Ion Battery Thermal Management
Business Segments

- **Industrial Materials (IM)**
  - Needle coke
  - Graphite electrodes, refractory materials
  - Key markets include steel and ferroalloys

- **Engineered Solutions (ES)**
  - Engineered synthetic graphite products
  - Flexible graphite products
  - Key markets include solar, electronics, energy and chemical

- $1.3 billion in sales in 2011
- 126 years graphite materials science experience (founded in 1886)
- 3,200 Team Members on 5 continents
GrafTech International - Innovation

Seven **R&D 100 Awards** in the last nine years for revolutionary technologies newly introduced to the market

- 2003 winner for HS-400 heat sinks
- **2004 winner for eGRAF® SPREADERSHIELD™ heat spreaders**
- 2005 winner for Apollo® / Zeus graphite electrodes
- 2006 winner for GRAFOAM® graphite foam
- 2007 winner for GRAFCELL® flow field plates
- 2009 winner for GRAFIXH® flexible heat transfer plates
- **2011 winner for eGRAF® SPREADERSHIELD™ SS1500 heat spreader**
eGRAF® Flexible Graphite Properties

- **Anisotropic Material Properties**
  - Derived from the graphite crystal structure
- **High Thermal Conductivity**
  - 300-1500 W/mK in plane—good heat spreading
  - Spreads heat over a large area
  - Transfers heat to external sink (case, chassis, cold plate, etc.)
  - 3-16 W/mK through thickness
- **Lightweight and Thin**
  - 1.3-2.2 g/cm³ density
  - 17 micron to 1.0 mm thickness
- **Flexible and conformable**
- **Simpler TIM application than paste or grease**
eGRAF® Products Overview

Thermal Interface Materials

- HITHERM™
  - HT-700 Series
  - HT-1200 Series
  - HT-2500 Series

Heat Spreaders

- SPREADERSHIELD™
  - SS300 Series
  - SS400 Series
  - SS500 Series
  - SS600 Series
  - SS1500 Series

- eGRAF® flexible graphite is produced in large rolls in a continuous process
- Rolls can be coated/laminated with adhesives, plastics and metals
- Thickness can be controlled in the range of 20-1000 µm
- Finished rolls are converted into peel and stick die-cut parts in high speed processes
First Spreader Product – Plasma Display Panels

- Flexible graphite heat spreaders for PDPs have been in production since 2003
- 960 mm x 565 mm x 1.5 mm
- Flexible graphite heat spreaders improve performance
  - Reduces image sticking & burn-in
  - Improves brightness uniformity
  - Lowers mechanical stress on chassis
  - Allows for use of low cost stamped steel chassis

Acrylic TIM with Al Sink $T_{\text{max}} = 43.8 \, ^\circ\text{C}$

SS400 Spreader $T_{\text{max}} = 34.3 \, ^\circ\text{C}$
Edge-lit LED/LCD TV’s are less than 25 mm thick

Thermal Objectives
- Display parameters negatively impacted by temperature or temperature gradients
  - Image sticking/ghosting
  - Brightness uniformity
  - Reduced OLED lifetime
- Warping of light guide plates, brightness enhancing filters

Design Constraints
- Edge lit LED light bars create hot spots
- Heat generating components located behind the screen
- Active cooling (fans) highly undesirable
- Super-thin form factor
- Edge-lit designs result in large temperature gradients
**SPREADERSHIELD™ Difference in LCD Displays**

**Without SPREADERSHIELD™ solution**

**Thermal Gradients**
- Thermal gradients gradually develop due to heat sources

**Screen Deformation**
- Heat causes chassis and films to deform

**Brightness Uniformity**
- As components shift, brightness uniformity degrades

**With SPREADERSHIELD™ solution**

**Thermal Gradients**

**Screen Deformation**

**Brightness Uniformity**
**LED Lighting – Directional Light**

- *Warm white LED Directional Light*
  - 12 W input, 600 Lumens
  - Rated lifetime 25,000 hours
  - Finned, cast aluminum reflector acts as a heat sink

- *HiTHERM HT-710A*
  - Bonded to cast housing
  - Larger than LED light engine
  - Combined thermal interface & heat spreader
LED Lighting – Flat Panel Light

- 61 cm x 61 cm LED light panel
  - For drop ceilings
  - 84 LEDs on each of 4 circuit boards

- SPREADERSHIELD SS400 heat spreader covers each circuit board for thermal management
Thermal Issues for Smartphones

Cool Heat Source
LED backlights

SHIELD Heat
From reaching **LCD** or **OLED display**

COOL Heat Source
“Flash” LED

SHIELD Heat
From reaching user through battery cover

SHIELD Heat
From reaching Li-ion battery and causing premature cell failure

COOL Heat Source
Power amplifiers and tuners

SHIELD Heat
From reaching keypad

Uniquely challenging thermal environment in SmartPhones
Heat Spreaders for Smartphones

- Test setup simulating a Smartphone chipset contacting an ABS Smartphone case
  - ABS plastic case, 70 mm x 50 mm
  - 8 mm diameter heat source
  - Natural convection cooling

Bare ABS Case
- A 0.8 W heat source generates a 90°C hot-spot on the outside of the case

ABS case with 110µm thick SS400 (400 W/mK) graphite heat spreader contacting the heat source
- Power increases to 3.0 W
- Hot-spot temperature 26°C lower
Thermal architects think in terms of a few microns thickness!

SS1500 - 17 to 45 microns thick

Thermal performance comparison
1. SPREADERSHIELD SS1500
   - 1500 W/mK In-plane thermal conductivity
   - 3.4 W/mK Thru-thickness thermal conductivity
   - 30 μm thickness

2. Copper foil
   - 388 W/mK Isotropic thermal conductivity
   - 30 μm thickness

Thermal performance of SS1500 at 30 μm is similar to that of SS400 at 110 μm

Copper spreader has an unacceptable hot spot on the case above the heat source
Smartphone Case Study

- Typical Smartphone
  - Size 111mm x 47.5mm x 11mm
  - Weight 100 g
  - LCD transmissive display with resistive touch input
  - Grid keypad
  - Lithium Ion battery
  - Available worldwide

- Thermal management using SPREADERSHIELD solutions
Heat Spreading on Front Cover

- SS1500 – 25 micron thick heat spreader above chipset
  - Spreads heat from chipset into magnesium chassis
  - Shields heat from keypad
Heat Spreading on Back Cover

- SS600 – 0.127 mm heat spreader on back cover
  - Stainless steel back cover is kept at a very uniform low temperature

MEPTEC 2012
“The Heat is On”
Thermal management enhances the battery’s Performance, Durability and Safety

Thermal management becomes increasingly critical as battery packs become larger and more powerful
  – Over Temperature
    • High battery cell operating temperatures lead to irreversible material degradation
  – Thermal Imbalance
    • High battery pack thermal gradients lead to cell voltage imbalances and decrease pack life

Improved thermal solutions are needed to meet power density, energy density and lifetime goals
Thermal Management Needs: Temperature Reduction

- Li-Ion packs operated at high discharge rates can rapidly reach maximum operating temperatures
  - 0.38 kW drill battery pack discharging in 4½ minutes
Battery Thermal Management Approaches

- Industry has responded to battery thermal management challenges with a wide range of approaches…

- These systems typically use heavy aluminum components to transport heat away from the cells
Benefits of a Graphite Thermal Solution

- Aluminum reference design:
  - 200 Prismatic pouch cells
  - Water cooled cold plates
  - Aluminum heat spreaders between each cell and connected to cold plates

- SPREADERSHIELD design:
  - Replace aluminum heat spreaders with SS600 with the same thermal performance

<table>
<thead>
<tr>
<th>For Identical Thermal Performance</th>
<th>Aluminum</th>
<th>SS600</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Spreader</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thermal Conductivity (W/m-K)</td>
<td>200</td>
<td>600</td>
</tr>
<tr>
<td>Thickness (mm)</td>
<td>1</td>
<td>0.3</td>
</tr>
<tr>
<td>Mass of Spreader (g)</td>
<td>104</td>
<td>22</td>
</tr>
<tr>
<td>Total Spreader Thickness (mm)</td>
<td>220</td>
<td>66</td>
</tr>
<tr>
<td>Weight of Spreaders (kg)</td>
<td>23</td>
<td>5</td>
</tr>
</tbody>
</table>

Similar results will apply to pack designs that use different formats, arrangements, and sizes of cells
eBike Battery / Prismatic Pouch Cells

- A commercially available electric bicycle (eBike) battery
  - 0.30 kW battery pack uses twenty 3.7 V lithium polymer pouch cells
  - No cooling solution

- Discharge through a hub motor attached to a bicycle wheel
  - Mechanical resistance unit mimics wind-loading as a function of speed
  - Battery pack can propel the bike at 22 mph for 1 hour
Heat Spreaders with Integrated Heat Sink Fins

- Heat spreaders 0.5 mm thick between cells with 25 mm high integrated fin

- Initial tests in natural convection
  - Maximum temperature reduced from 41.0°C to 36.8°C
  - Temperature gradient reduced from 3.9°C to 2.9°C

eBike Battery Pack
- As received – no cooling solution

SS400 finned heat spreaders

---

MEPTEC 2012
“The Heat is On”
Graphite Spreader with Fins in Forced Convection

- Battery pack mounted in housing with slotted cover
  - SS400 fins exposed to forced convection air flow

- Laboratory wind tunnel used for forced convection
  - 22 mph air flow matches wheel speed

- Thermal performance
  - Maximum temperature reduced to 25.9°C
  - Temperature gradient reduced to 2.2°C

MEPTEC 2012
“The Heat is On”
Graphite Spreader with External Heat Sink in Forced Convection

- Battery pack mounted in housing with slotted cover
  - SS400 flexible graphite fins cut back in length and folded over curved mandrels built into case
- Two aluminum heat sinks bolted to case
  - Fins match up with each other and are compressed against mandrel and heat sink base
  - Fins transfer heat to base and form weatherproof seal between case and sink

- Wind tunnel tests repeated
- Thermal performance in declines slightly
  - Maximum temperature increases slightly to 26.9°C
  - Temperature gradient increases slightly to 2.9°C
Summary of eBike Heat Spreader Performance

- Temperature Rise vs. Thermal Gradient
- Graphite thermal management solutions improve thermal performance
  - Thermal gradients reduced by 50%
  - Temperature rise reduced by 75%
- Al heat sink with graphite spreader has slightly poorer performance than graphite fin

![Graph showing temperature rise and thermal gradient comparison](image)
Active Cooling of Lithium Ion Batteries

- Liquid cooling is advantageous in high power applications (e.g. PHEV, HEV, EV)
  - Higher heat generation
  - Higher energy density
- Large format cells generate heat across their faces
  - Modest heat flux
- Heat must be conducted to a cold plate or heat sink
  - Higher heat flux density
- Collect heat from a large area and concentrate it at the cold plate or heat sink
- Demonstrate use of flexible graphite heat spreaders combined with liquid cooling on a large format battery cell
Hybrid Thermal Solution

- Liquid cooled tube wraps around 3 sides of the cell perimeter
- Heat spreaders transfer heat from faces of the cell to the liquid coolant tube
- Advantages of this design:
  - Thin, compact, and lightweight
  - Durable and robust
  - Easy to manufacture
  - Potentially low cost

Cell and Tube

Front

Back
Experimental Variables

- **Simulated Pouch Cell Pack**
  - Size of typical automotive cell
  - 14W of heat distributed uniformly across both faces of each cell
  - Decouples testing from Li-ion effects (state of charge, battery degradation)

- **1100 Series Aluminum Heat Spreader**
  - 0.25 mm thick
  - 220 W/mK thermal conductivity
  - PET coating for electrical isolation
  - Acrylic adhesive on to attach to cell and tubing

- **SPREADERSHIELD™ SS500 Graphite Heat Spreader**
  - 0.25 mm thick
  - 500 W/mK thermal conductivity
  - PET coating for electrical isolation
  - Acrylic adhesive to attach to cell and tubing
The SS500 flexible graphite solution provides a 41% improvement in heat transfer coefficient versus aluminum.
References


eGraf® and SPREADERSHIELD™ are trademarks of Advanced Energy Technology Inc. All rights reserved. All other trademarks and registered trademarks are the property of their respective owners.
eGraf® thermal management products, materials, and processes are covered by one or more of the following US patents: 4,961,991; 5,198,063; 5,830,809; 6,245,400; 6,395,199; 6,432,336; 6,482,520; 6,503,626; 6,538,892; 6,673,284; 6,746,768; 6,749,010; 6,758,263; 6,771,502; 6,777,086; 6,841,250; 6,886,249; 6,982,874; 7,108,055; 7,108,917; 7,138,029; 7,150,914; 7,160,619; 7,161,809; 7,166,912; 7,186,309; 7,232,601; 7,276,273; 7,292,441; 7,303,005; 7,303,820; 7,306,847; 7,365,988; 7,385,819; 7,393,587. Other US and foreign patents granted or pending.
Acknowledgments

- Research & Development, Sales, Marketing, Applications Engineering and Manufacturing groups at GrafTech International
- Ohio Department of Development - Third Frontier Grants
- Some work was carried out in collaboration with The Ohio State University Center for Automotive Research

This publication was prepared with financial support from the State of Ohio. The content reflects the views of GrafTech International Holdings, Inc. and does not purport to reflect the views of the State of Ohio.