Exit Presentation: Infrared Thermography on Graphite/Epoxy

By
Kayla Comeaux
Agenda

• Personal Information
• Project
  – Objectives
  – Flat bottom hole simulation
  – Flat bottom hole experiment
  – Thin delamination simulation
• Summary
  – Skills acquired
  – Future work
  – Experiences at JSC
  – After Graduation
  – Acknowledgments
Personal Information

- Hometown: Friendswood, Texas
- University: Southwestern University
- Major: Mathematics
- Minor: Physics, Economics
- Pi Mu Epsilon, Chi Alpha Sigma, Pi Theta Kappa
- Soccer, Lacrosse, Choir, Tutoring
- MUST Intern
Project Objectives

• Simulate Flash Thermography on Graphite/Epoxy Flat Bottom hole Specimen and thin void specimens.

• Obtain Flash Thermography data on Graphite/Epoxy flat bottom hole specimens

• Compare experimental results with simulation results

• Compare Flat Bottom Hole Simulation with Thin Void Simulation to create a graph to determine size of IR Thermography detected defects
Composite Dimensions

Diagram showing composite dimensions with various measurements and annotations.
Composite Dimensions
Composite Dimensions
Creating Flat Bottom Hole Simulation

• Simulation requirements
  – Uniform thickness
  – Defects completely inside composite

• Pixel size
  – Circular defects to square defects
  – Width in terms of pixels

<table>
<thead>
<tr>
<th>Thermal Properties of Composite</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Density</td>
<td>1150(kg/m³)</td>
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<tr>
<th>Thermal Properties of air</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>1.20(kg/m³)</td>
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<tr>
<td>Heat Capacity</td>
<td>1005(J/kg/K)</td>
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<tr>
<td>Conductivity: Z axis</td>
<td>0.026(W/m/K)</td>
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<tr>
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<td>0.026(W/m/K)</td>
</tr>
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<td>Conductivity: Y axis</td>
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</tbody>
</table>

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<table>
<thead>
<tr>
<th>Specimen</th>
<th></th>
<th>Layers</th>
<th></th>
<th>Heat Source</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Length, $L_{x}$, [m]</td>
<td>0.1115</td>
<td>Conductivity, $K_{x}$, [W/(m.°C)]</td>
<td>0.023557</td>
<td>Source in space</td>
<td>Exponential</td>
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<tr>
<td>Width, $L_{y}$, [m]</td>
<td>0.064</td>
<td>Conductivity, $K_{y}$, [W/(m.°C)]</td>
<td>0.023557</td>
<td>Max heat pulse, $Q$, [W/m²]</td>
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<td>Heat exchange coef. front surface, $h_{F}$, [W/(m².°C)]</td>
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<td>Conductivity, $K_{z}$, [W/(m.°C)]</td>
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<td>Heat exchange coef. rear surface, $h_{R}$, [W/(m².°C)]</td>
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<td>Heat capacity, $C$, [J/(kg.K)]</td>
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<td>Steps along X</td>
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<td>Density, $r$, [kg/m³]</td>
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<td>Coef. of spatial distribution in X, [1/m²]</td>
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<td>Steps along Y</td>
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<td>Coef. of spatial distribution in Y, [1/m²]</td>
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<td>Number of layers, $i$</td>
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<td>Number of defects</td>
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<tr>
<td>Length of each step in X, [m]</td>
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<td>Thickness of each step in Z, [in]*</td>
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<td>Output</td>
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<td>Total thickness, $L_{Z}$, [in]*</td>
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<td>Output time step, [s]</td>
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<td>Timing</td>
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<tr>
<td>Type</td>
<td>Square Pulse</td>
<td>Heat time, $\tau_{hp}$, [s]</td>
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<td>End time, [s]</td>
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<td>Time step, [s]</td>
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</table>
## Simulation Dimensions: Column 1

<table>
<thead>
<tr>
<th>Thermal Properties of Defects</th>
<th>Defect A</th>
<th>Defect B</th>
<th>Defect C</th>
<th>Defect D</th>
<th>End of Part</th>
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<tbody>
<tr>
<td>Conductivity, $K_x$, [W/(m.$\circ$C)]</td>
<td>0.026</td>
<td>0.026</td>
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<tr>
<td>Conductivity, $K_y$, [W/(m.$\circ$C)]</td>
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<tr>
<td>Conductivity, $K_z$, [W/(m.$\circ$C)]</td>
<td>0.026</td>
<td>0.026</td>
<td>0.026</td>
<td>0.026</td>
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<tr>
<td>Heat capacity, $C$, [J/kg.$\circ$K]</td>
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<td>1005</td>
<td>1005</td>
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<td></td>
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<tr>
<td>Density, $r$, [kg/m$^3$]</td>
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<td>1.20</td>
<td>1.20</td>
<td>1.20</td>
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<tr>
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<td>5.500E-03</td>
<td>5.500E-03</td>
<td>5.500E-03</td>
<td>5.500E-03</td>
<td></td>
</tr>
<tr>
<td>X initial point, [m]</td>
<td>2.950E-02</td>
<td>5.000E-02</td>
<td>7.050E-02</td>
<td>9.100E-02</td>
<td>1.115E-01</td>
</tr>
<tr>
<td>Width, $L_y$, [m]</td>
<td>5.500E-03</td>
<td>5.500E-03</td>
<td>5.500E-03</td>
<td>5.500E-03</td>
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</tr>
<tr>
<td>Y initial point, [m]</td>
<td>2.950E-02</td>
<td>2.950E-02</td>
<td>2.950E-02</td>
<td>2.950E-02</td>
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<tr>
<td>Thickness, $L_z$, [m]</td>
<td>6.096E-04</td>
<td>7.620E-04</td>
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<tr>
<td>Z initial point, [m]</td>
<td>5.080E-04</td>
<td>3.556E-04</td>
<td>3.556E-04</td>
<td>3.556E-04</td>
<td></td>
</tr>
</tbody>
</table>
Flat Bottom Hole Simulation: Column 1

- Simulation size

Front view:

Top view:

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Data from Flat Bottom Hole Simulation: Column 1

Infrared Thermography Simulation of 0.044 Inch Thick Graphite/Epoxy Composite

Center of Defect D
Center of Defect C
Center of Defect B
Center of defect A

Min 2.241 K
Max 2.751 K

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Simulation Results: Temperature v. Time Image

- Shows the difference in temperature.
- Blue curve is reference point.
- $X, Y$: Coordinates defect’s center on simulation.

<table>
<thead>
<tr>
<th>Num</th>
<th>$x$</th>
<th>$y$</th>
<th>Color</th>
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</thead>
<tbody>
<tr>
<td>y 1</td>
<td>106</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>y 2</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>y 3</td>
<td>65</td>
<td>65</td>
<td>-</td>
</tr>
<tr>
<td>y 4</td>
<td>147</td>
<td>65</td>
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<tr>
<td>y 5</td>
<td>188</td>
<td>65</td>
<td>-</td>
</tr>
</tbody>
</table>

Number of output time steps (Output time step 0.010000s)
Normalizing Data and Graphing

- Collect data from Temperature v. Time graph
- Convert text file to excel spreadsheet
- Normalized contrast:
  \[
  \frac{(T_i - T_{i0}) - (T_r - T_{r0})}{(T_i - T_{i0}) + (T_r - T_{r0})}
  \]
  \(T = \) Temperature for simulation, Pixel intensity for experimental IR data

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Experimental Set-up

- IR Camera
- Reflector
- Glass shield
- Hood
- Test object
- Stand-off
- Work bench
- Opening in back face of hood
- Flash lamp

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Framed of Infrared Thermography Evaluation

Defects A-D in Columns 1-3
Experimental Data

- Reference point
- Point of Interest
- Different sizes

Image Window: Flat Bottom Hole

Defect B2
Simple Contrast

- Finding maximum simple contrast
- Saving data as text file
- Transporting data to Excel
- Creating Normalized contrast
Calculating and Graphing Normalized Contrast

- Average pre-flash temperatures for both reference point and point of interest
- Use averages as initial temperature

<table>
<thead>
<tr>
<th>Time</th>
<th>Reference Point</th>
<th>Point of Interest</th>
<th>Reference Point*</th>
<th>Point of Interest*</th>
<th>Normalized Contrast</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.15</td>
<td>7240</td>
<td>7249</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>-0.133</td>
<td>7241</td>
<td>7253</td>
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<td></td>
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<tr>
<td>-0.117</td>
<td>7240</td>
<td>7249</td>
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<tr>
<td>-0.1</td>
<td>7240</td>
<td>7249</td>
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<td></td>
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</tr>
<tr>
<td>-0.083</td>
<td>7239</td>
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<tr>
<td>-0.067</td>
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<tr>
<td>-0.05</td>
<td>7239</td>
<td>7247</td>
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<tr>
<td>-0.033</td>
<td>7241</td>
<td>7255</td>
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<td>-0.017</td>
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<td>7250</td>
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<td></td>
<td>7239.889</td>
<td>7250.778</td>
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</tbody>
</table>
Comparison and Correction of Simulation

- The Normalized contrast for the original simulation and experimental data
- Analysis
- Peak Contrast
- Peak Time
- Correction of simulation data to more accurately portray experimental data
Correction of Simulation

• Diffusivity: \( \alpha = \kappa / (\rho \times C) \)

• Change properties of material
  – Change Specific Heat
  – Change in Conductivity
  – Could change Density

• Final Decision

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<th>Final Values</th>
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<td>3.85(W/m/K)</td>
</tr>
</tbody>
</table>

Simulation Data: Defect B1

Heat Capacity times 0.05

-0.12 -0.1 -0.08 -0.06 -0.04 -0.02 0 0.02 0.04 0.06 0.08
0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2 0.22 0.24 0.26 0.28 0.3

Normalized Contrast

Time (s)
Corrected Simulation

- Corrected simulation
- Comparison between original simulation, corrected simulation, and experimental data
Sources of Differences

• Simulation contrast is based on temperature versus time. Experimental contrast is based on pixel intensity versus time.

• Experimental Flash vs. Simulation Flash
  – Experimental flash envelope has a sharp rise and slow decay
  – Simulation flash is a square pulse

• Experimental factors
  – Experimental data is more sensitive to pixel size. Get smaller pixel intensity for a larger pixel
  – Uneven flash causes some lateral heat flow
  – Part has a surface texture causing lateral heat flow

• Emissivity
  – The specimen emissivity was measured to be 0.9 and provides lower (< 5%) experimental contrast

• Simulation inaccuracies (model approximations, boundary condition approximations, no lateral heat flow)
Creating Thin Delaminations

• Change depths of the defects, but leave the initial points unchanged.

• Input data into ThermoCalc-6L

• Run simulation

Flat Bottom Hole Simulation:

Thin Delamination Simulation:
Collecting Data

• Same as for the flat bottom hole simulation
  – Collect data from Temperature v. Time graph for each defect
  – Convert the text file to excel spreadsheet compatible
  – Generate normalized contrast graph
Comparison of Simulations

• Comparing flat bottom hole simulation to thin delamination simulation

• Compare and graph the peak contrast ratio and peak time ratio
  – Thin delamination/Flat bottom hole
Peak Contrast Ratio and Peak Time Ratio

Graphite/Epoxy Composite

y = -8.9195x^2 + 18.262x - 8.3551

Peak Contrast/Peak Time

-.5 mil thickness
2 mil thickness
6 mil thickness
10 mil thickness
20 mil thickness
70.4 mil thickness

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Future Work

• Make controlled impacts to make thin delaminations
• Evaluate delaminations with Infrared Thermography
• Evaluate delaminations with Ultrasonic Techniques
• Section the specimen at delaminations
• Determine actual size of delaminations
• Compare actual results with simulated results
• Determine accuracy of the simulation
Skills Acquired

• Learned Thermodynamics
  – Theory and application
    • IR temperature measurement
• Infrared Thermography NDE
  – Simulation
  – IR Experimental data acquisition and analysis
• Eddy Current
• Ultrasonic Testing
• Time management
• Work hours
• Technical paper
After Graduation

- Capestone Project
- Graduation 5/2011
- Intern at JSC
- Co-op 2011-2016
- Graduate School 2011-2016
- Work for NASA
- Professor of Mathematics

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JSC- ES4, MUST Intern Program
Acknowledgements

• Parents and Family
• Mentors: Ajay Koshti & David Stanley
• Ovidio Olveras, Eddie Pompa, Norman Ruffino, Rodrigo Devivar, John Figert, Budd Castner, Mike Kocurek, Denise Plantier, Erica Worthy, Joseph Prather
• MUST Point of Contact: Cornelius Johnson
Thank You