# THROUGH-THICKNESS HEATING OF LAYERED STACK OF CARBON REINFORCED PREPREGS

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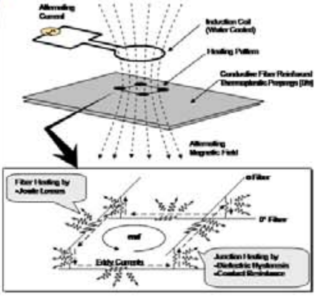
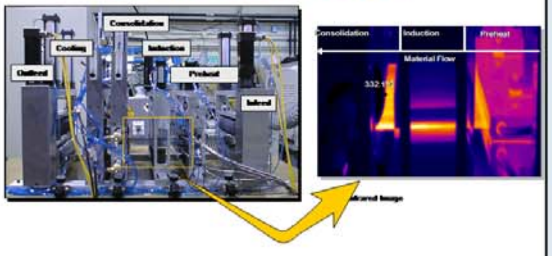
## PROCESS OVERVIEW



- Conductive Loops Formation at Prepreg Interfaces
  - Non-zero Orientation Angles Required
- Heating Locations and the Mechanisms
  - Carbon fibers: Joule Heating
  - Fiber Junctions: Dielectric or Contact Resistance
- Layered Stack of Unconsolidated Prepregs
  - Contact Resistance Heating Dominance
  - Parameters: Fiber resistance, Contact Resistance

- Process Advantage
  - Heating/Consolidation of Multiple Prepregs
    - Volumetric Heating in Thickness Direction
  - Internal Heat Generation
    - No External Heat Sources and
    - No Magnetic Field Susceptors
      Ex.) metal mesh, ferromagnetic particles

## APPLICATION: RAIL (RAPID AUTOMATED INDUCTION LAMINATION) PROCESS DEVELOPED BY UD-CCM

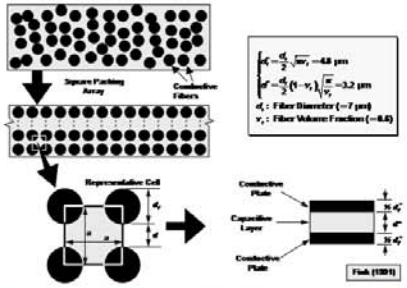


- 8-Ply Laminator (AS4/PEI Prepreg)
- Processing Speed: 1.5-3.7 m/min
- Heating Rate: 10-100 °C/sec
- Issue: High Likelihood of Non-uniform Heat Generation Profiles in Thickness Direction due to Heating only at the Prepreg Interfaces
- Objective: Achieve Uniform Through-Thickness Temperature Field

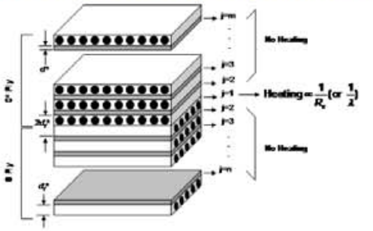
## MODELING: PREPREG MICROSTRUCTURE

**Assumptions**

- Square Packing Array Assumption
  For Cross-Section of Prepreg
- Conductive Plates and Capacitive Layers
  - Conductive Plates: Heat Source for Contact Resistance Heating
  - Capacitive Layers: Electric Insulators between Conductive Plates for Contact Resistance Heating
  - 16 Conductive Plates and 16 Capacitive Layers for a AS4/PEI Prepreg



## MODELING: PREPREG MICROSTRUCTURE



**Assumptions**

- Layered stack of unconsolidated prepregs
  - Heating: only at prepreg interfaces having non-zero orientation angles
  - Contact resistance heating dominance
  - L: contact resistance between single fibers at the interface

## MODELING: HEAT GENERATION/TRANSFER

$$\rho C_p \frac{\partial T}{\partial t} = k_z \frac{\partial^2 T}{\partial z^2} + g(z)$$

- 1-Dimensional Heat Transfer
  - Through-Thickness Heating
  - Transient (Unsteady State)
  - Heat Source Term

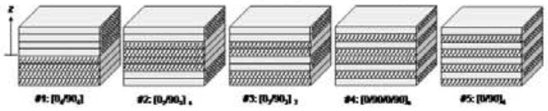
- Boundary Conditions
  - Adiabatic ($h = 0$)
  - Natural Convection ($h = 10$ W/(m²K))
  - Fixed Surface Temperature ($T_s = T_r$)

**Material and Process Parameters**

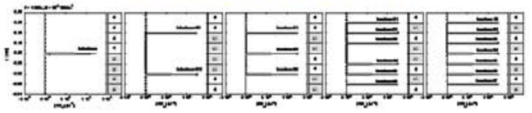
| | |
|---|---|
| Electrical resistivity of carbon fiber | $\rho_f = 1530$ μΩ cm |
| Dielectric constant of PEI | $\kappa = 3.5$ (room temperature) |
| Loss factor of PEI | $\tan \delta = 0.0016$ |
| Induction frequency | $f = 1$ MHz |
| Contact resistance | $\lambda = 1.25 \times 10^{6} - 1.25 \times 10^{7}$ Ω |
| Volumetric heat capacity of AS4/PEI | $\rho C_p = 2 \times 10^{6}$ J/(m³ °C) |
| Thermal conductivity of AS4/PEI (z-dir) | $k_z = 0.28$ |

## MODELING: HEAT GENERATION/TRANSFER

**Selected Stacking Sequences (8 Plies)**



**Through-Thickness Heat Source Profiles**



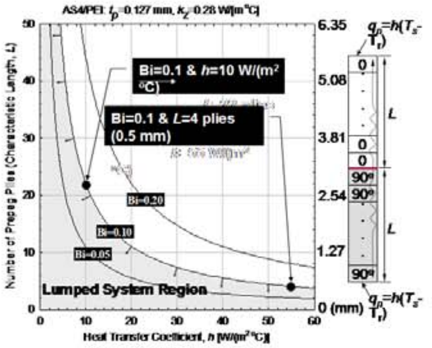
## RESULTS – BIOT NUMBER

**Stacking: Heating only at the Center of the Stack (*N* number of 0° Plies and *N* number of 90° Plies, Symmetric)**

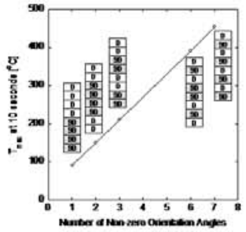
**Parameters: Boundary Condition and Number of Prepreg Plies**

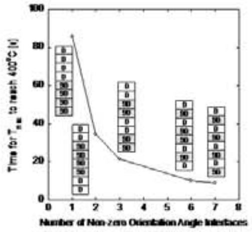
**Contour Plot of Biot Number**

- Determination of Maximum Heat Transfer Coefficient for Lumped System Approach (Uniform Through-thickness Heating)
- Determination of Maximum Number of Prepreg Plies for Uniform Through-thickness Heating
- More Complicated Stacking Sequences
  - Shorter Characteristic Length for Heat Diffusion
  - Lower Biot Number for More Uniform Heating



## RESULTS: STACKING SEQUENCE EFFECTS





**Benefit of Stacking Sequence Change**

- Augmented heating and more uniform temperature field

**Maximum Temperature (10 seconds, Adiabatic)**

- Simple linear increment due to additional heating locations
  Augmented heating intensity in thickness direction
- Possible control of internal heat generation profile to obtain more uniform temperature field in thickness direction

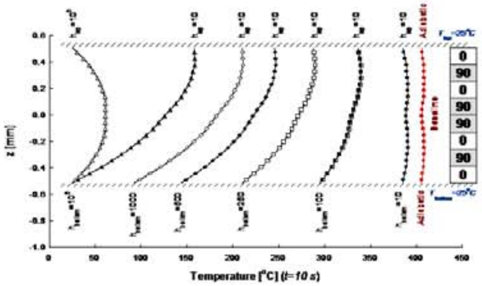
**Time for Temperature (400°C, Adiabatic)**

- Reduced time to reach melting/consolidation temperature of PEI

## RESULTS: BOUNDARY CONDITIONS EFFECTS

**Through-Thickness Temperature Field (10 seconds) with Asymmetric Boundary Conditions In Equipment**

- Non-uniformity in through-thickness temperature field nevertheless in spite of low Biot Number
- Importance of processing equipment design considering boundary conditions



## FUTURE WORK

**Strategies for Uniform Temperature Field**

**Given stacking sequence for desired mechanical properties**

- Possible non-uniformity of temperature
- Boundary condition adjustment for temperature uniformity (ex. Heated tool surface, forced convection)
- Control of induction power and other processing parameters to maintain or increase processing speed and heating rate

**Fixed boundary conditions in processing equipment**

- Possible non-uniformity of temperature
- Stacking sequence change adjustment for uniform temperature
- Control of induction power and other processing parameters to maintain or increase processing speed and heating rate

**Experimental Validation of Heating Mechanism and Model**

- Heating rate and temperature measurement in short time scale to neglect lateral heat diffusion
- Consideration angle-ply [0/θ, θ< 90°] change of contact resistance value with angle and contact area between fibers at the interface

**3-Dimensional Heat Transfer Analysis**

- To consider lateral (in-plane) heat diffusion
- To establish generalized design tool for induction lamination
- Coil design for uniform in-plane heating patterns

## ACKNOWLEDGEMENTS

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