Tool Shape Compensation for Composite Laminate Parts and CTE Characterization for Encapsulants

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On behalf of

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1. CTE Characterization for Encapsulants
2. Spring-in Simulation Work Flow
3. Tool Shape Compensation for Radial Stiffeners
4. Additive 3D Simulation Work Flow – Bonding Jig for Radial Stiffeners
CTE Measurements – Experimental Setup

- Liquid nitrogen cooling
- Chilled water jacket
- Liquid nitrogen cooling
- Polyimide film
- Sample
- Glass plates
- Heated stage apparatus
- Temperature controller (-150°C to +350°C)
- LN2 pump
- DIC
- Light source

Analyzed region of interest
# CTE Measurements — Results

**CTE Measurements**

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### Sample Description

<table>
<thead>
<tr>
<th>Sample</th>
<th>Description</th>
<th>CTE ($\mu\varepsilon/°C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SYL3</td>
<td>Sylgard – Neat polymer</td>
<td>$(0.5 \pm 0.2) \times T + (198.4 \pm 9.6)$</td>
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<tr>
<td>SYL4</td>
<td>Sylgard – Radiated with 200 MRad dose</td>
<td>$(0.5 \pm 0.1) \times T + (154.6 \pm 16.2)$</td>
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<tr>
<td>POL3</td>
<td>Polyurethane UR6060 – Neat polymer</td>
<td>$(0.7 \pm 0.2) \times T + (146.4 \pm 2.7)$</td>
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<tr>
<td>POL5</td>
<td>Polyurethane UR6060 – Radiated with 200 MRad dose</td>
<td>$(0.7 \pm 0.1) \times T + (139.3 \pm 2.8)$</td>
</tr>
</tbody>
</table>
**INNER TRACKER STRUCTURE**

- Designed 3 kg composite structure to support ~25 kg* detector and services
- Fabricated prototype service cylinder
- Validated structural simulations

*Specified at time of design. Closer to 40kg in latest.

Stringers connect the TFPX frame structures along each edge of shell

Radial stiffeners at TBPX interface (left) to be redesigned to act as TBPX mount point – will help with TFPX stiffness locally
REINFORCING RADIAL STIFFENERS FABRICATION

- Manufactured L-profile, C-shaped Radial Stiffeners as structural reinforcements
- Frames adhered to shell via post-cure bonding operation
- Need to choose rad-hard adhesive for future

• Radial Stiffeners determine the shape of the service cylinder
**SPRING-IN SIMULATION WORK FLOW**

1. **MODEL SET-UP**
   - Geometry
     - part geometry, nominal tool geometry & ply cut out, assign local material orientation, initial/boundary conditions
     - Set up FE Model

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Composite Layup

Female Mold Tool – Tooling Board
**SPRING-IN SIMULATION WORK FLOW**

Unit: °C

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**2. THERMO-CHEMICAL ANALYSIS**

cure kinetics, heat transfer between ambient & the tool-part assembly, heat generation - chemical cure reaction

Define Cure Conditions

Thermal History & Degree of Cure

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Model Setup

Thermo-Chemical

Flow Compaction

Stress Deformation

Tool Shape Compensation
3. FLOW-COMPACTION ANALYSIS
resin (Darcy) flow relative to elastic porous fiber-bed, pressure load development in resin, change in laminate thickness

4. STRESS-DEFORMATION ANALYSIS
process induced deformations & residual stress, mismatch of thermal-mechanical properties, cure shrinkage & tool part interaction

Material properties are updated at each solution step to account for the progression of cure and the subsequent change in thermal properties.
**Tool Shape Compensation for Radial Stiffeners**

**5. Compensated Tool Shape Generation**

Deformed shape inverted about nominal

Tool Shape used for Thermal Deformation Analysis of the Tooling Material

Material properties (tool)

Compensated Tool Shape

5a. Tooling Board Tool (isotropic material properties)

Visual deformation scaling 20x

- **Original Shape**
- **Deformed Shape**

Spring-in ~1.24mm

340 mm

<table>
<thead>
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<th>U, Magnitude (m)</th>
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</thead>
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<td>+1.235e-03</td>
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<tr>
<td>+1.132e-03</td>
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ADDITIVE 3D SIMULATION WORK FLOW

MATERIAL & MACHINE CHARACTERIZATION
- Tooling material, 3D printer parameters, processing parameters, constituent properties

AM PRINTING PROCESS SIMULATION
- Geometry
  - global orientation, printing history, boundary conditions
- Slicing
  - machine code
- AM System Card
  - temperature, degree of bonding & crystallinity

PERFORMANCE SIMULATION
- Geometry & Slicing
- In-service Deformation
  - cure conditions for laminate part

Compensated Tool Shape

5b. ADDITIVELY MANUFACTURED (AM) TOOL
(anisotropic processing conditions influenced material properties)
CAMRI – PROCESS MONITORING

Video 10X
BONDING JIG FOR RADIAL STIFFENERS
AM PRINTING PROCESS SIMULATION

**Inputs**
- Machine Code
- AM System Card
- Digital Material Card
- Property Prediction
- Material Models
- Global Fiber Orientation
- Boundary Conditions

**Outputs**
- Temperature
- Bonding
- Residual Stress

FEA Process Simulation

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AM PRINTING PROCESS SIMULATION RESULTS

Temperature (K)  Crystallinity  Interlayer Bonding

80x Printing Speed
AM Printing Process Simulation Results

Stress - $\sigma_{11}$ (MPa)

Deformation - $U_x$ (mm)

10x Deformation & 80x Printing Speed
AN INTEGRATED WORKFLOW FOR AM DESIGN

- Geometry
  - CAD
  - Sliced CAD
- EDAM Process Simulation
  - Temperature
  - Polymer Crystallization
  - Residual Stress
- Performance Simulation
  - Creep
  - Shape Change
- Digital Material Card
  - Property Prediction
  - Material Models
COMPOSITE TOOLS FABRICATED WITH CAMRI

- Autoclave tools
- Printed thermoforming tool
- VARTM tool
- Printed compression molding tools
- Printed stamping tools
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