In-Situ Consolidation of Thermoplastic using Automated Fiber Placement

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Background

• Aircraft manufacturing processes will be required to undergo significant technology advancements to increase production rates.

• Recent advances in thermoplastic material heating technologies like laser and pulsed light solutions has enabled the use of thermoplastics in automated fiber placement (AFP) processes.

• Further process optimization via in-situ consolidation eliminates the need for secondary processing, which significantly reduces manufacturing costs and increases production rates.

Main goal of this research task is to develop protocol for *in-situ consolidation* of AFP thermoplastics (ICAT). Protocols will be expanded for using thermoplastics for *in-space manufacturing with multi-robotic tool-less AFP process.*
Thermoplastic Research at NIAR ATLAS

Modeling for Affordable Sustainable Composite (MASC)

- Automated fiber placement (AFP)
  - NCAMP qualifications
  - In-situ consolidation
  - Tool-less manufacturing
- Scalable Composite Robotic Additive Manufacturing (SCRAM)
- Fusion welding
- Over-molding
- Material characterization
- Lightening strike material evaluation
Tool-less Manufacturing In Space
Thermoplastic AFP Post- vs. In-Situ Consolidation

- During automated fiber placement (AFP), thermoplastic tape and substrate are heated using laser and fused together while applying pressure.
- In order to achieve final consolidated ply thickness (CPT) and reduce porosity, post-AFP consolidation in an oven/autoclave is utilized.
- Process cycle (especially the cooling rate) is developed to achieve proper crystallinity to improve interfacial bond strength.

- In-situ consolidation eliminates secondary processes (increase production rate) and decreases cost
# In-situ Consolidation & Secondary Heating (ICASH) Process Development

<table>
<thead>
<tr>
<th></th>
<th>Baseline*</th>
<th>Fairing</th>
<th>Fuselage Panel</th>
<th>Dual-Robot AFP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tool</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Tool Heating</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Curve</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Equipment</td>
<td>AFP+Press</td>
<td>EI-1 (Laserline), EI-2 (VSSL), Coriolis, and Mikrosam</td>
<td>EI-1 (Laserline), EI-2 (VSSL), and Coriolis</td>
<td>Mikrosam</td>
</tr>
</tbody>
</table>

![Quality](image1)

![Consolidation Pressure](image2)

![Speed](image3)
AFP Parameters and Processing
# AFP Material Characterization

<table>
<thead>
<tr>
<th>Material Type</th>
<th>Vendor</th>
<th>Number / Name</th>
<th>Composition</th>
<th>GSM</th>
<th>Slit-Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermoset</td>
<td>Solvay</td>
<td>30202946</td>
<td>IM7/5320-1</td>
<td>145</td>
<td>½”</td>
</tr>
<tr>
<td></td>
<td>Toray</td>
<td>P172EBN-19</td>
<td>T1100G/3960</td>
<td>192</td>
<td>¼”</td>
</tr>
<tr>
<td>Dry Fiber Infusion</td>
<td>Solvay</td>
<td>TX1105</td>
<td>IMS65/EP2400</td>
<td>280</td>
<td>¼”</td>
</tr>
<tr>
<td></td>
<td>Hexcel</td>
<td>HITAPE</td>
<td>IM7/1078-1</td>
<td>280</td>
<td>¼”</td>
</tr>
<tr>
<td>Thermoplastic</td>
<td>Victrex</td>
<td>AE250</td>
<td>IM7/LMPAEK</td>
<td>148</td>
<td>¼”</td>
</tr>
<tr>
<td></td>
<td>Solvay</td>
<td>APC</td>
<td>AS4D/PEKK-FC</td>
<td>145</td>
<td>¼”</td>
</tr>
<tr>
<td></td>
<td>Toray</td>
<td>TC1225</td>
<td>T700/LMPAEK</td>
<td>145</td>
<td>¼”</td>
</tr>
</tbody>
</table>

**Phase 0:** Slit Tape Receiving Inspection & Effects of Defects  
**Phase I:** Material Screening  
**Phase II:** Machine Variability & Alternative Heat Sources  
**Phase III:** Head Configuration (Q8, H8, and ATL)  
**Phase IV:** NCAMP Process Specifications  

**2021**  
- Machine Variability  
- Equivalency HL ➔ AFP
Thermoplastic Prepreg Tape Quality

- Thermoplastic pre-impregnated tape quality variability assessment
  - TP prepreg tapes are not as evolved as thermoset prepreg tapes
  - Variability associated with TP prepreg tapes affect the AFP process and eventually the **end-product quality**
  - Past studies have shown that TP prepreg tapes can significantly vary in **thickness**, **width**, **porosity content**, and have variable **resin & fiber distributions**
In-Situ Consolidation of Thermoplastics
AFP FEM Efforts: In-situ Consolidation Model

Prediction of residual stress & Through-thickness temperature evolution in a thermoplastic laminate fabricated by in-situ AFP process

Load & Rotation modelled per course

- **ELEM Activate/Deactivate Programmed**

- An Inverse-based Approach for Roller Mat Props. (Hyperelastic Ogden, n = 3)
  - Easy to adopt any Roller type

- Parametric script w/ MARC solver simulates placement of each course/ply
  - PY-based parametric script: Ply mat props, Roller & part geom., Roller velocity, consolidation pressure etc.

- Material Model: Temp. dependent Thermoplastic material model

Roller Mat Prop: An Inverse Approach based Optimization

- Parameter Initialization
  - Initial Values

- MARC Model
  - Contact Area, A_c
  - Max. Contact Pressure, P_c

- Dr. Fabrizio Sunghi

- Experiment
  - Measured Roller Contact Area, A_c
  - Measured Roller Max. Pressure, P_c

- FEA
  - Predicted Contact Area

Material Model (Temperature Dep.)
- Thermo-elastic
- Thermo-Visco-elastic

START

Material Model Definition

Results (Post-Processing)

Experimental Measured Contact Area

**ELEM Activate/Deactivate Programmed**
AFP Curved Panels with Heated Tooling

Established high-fidelity in-situ heating methods.

Achieved excellent quality consolidation on flat and high curvature representative parts.

Established NPT and Tool Temperature trends

- Increased NPT decreases porosity
- Increased tool temperature decreases porosity
- 790°F (420°C) NPT local optima
- Optical analysis -> 0.3% porosity maximum
In-Situ Consolidation Quality: Photomicrographs

**Quality**
- Excellent consolidation quality
- High curvature section shows good interface between layers

**Comparison to alternatives**
- In-Situ CPT - 0.0055 in.
- Oven CPT - 0.0054 in.
- Press CPT - 0.0051 in.
- High curvature section shows good interface between layers

- 8% thicker CPT than press consolidation
- 300 psi for 30 min vs 100 psi for 0.2 seconds
In-situ Consolidation and Secondary Heat

- Improved crystallinity through the thickness.
- Improved surface finish.
- Minimizes Delaminations
**Short Beam Strength**

Interlaminar strength comes from molecular diffusion between plies.

<table>
<thead>
<tr>
<th>Tool Temp: Amb</th>
<th>380°C</th>
<th>400°C</th>
<th>420°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apparent Short Beam Strength (MPa)</td>
<td>32.2</td>
<td>32.6</td>
<td>33.5</td>
</tr>
<tr>
<td>Tool Temp: 140°C</td>
<td>37.6</td>
<td>38.5</td>
<td>40.5</td>
</tr>
<tr>
<td>Tool Temp: 170°C</td>
<td>39.9</td>
<td>41.4</td>
<td>42.5</td>
</tr>
</tbody>
</table>

**Factors Influencing Interlaminar Strength**
- Time above melt
- Pressure
- Consolidation
- Molecular diffusion

**Graphical Representation**

- Time Above Melt
- Pressure
- Cooling rates

**Graph Details**
- Y-axis: Apparent Short Beam Strength (MPa)
- X-axis: Tool Temperatures (380°C, 400°C, 420°C)
- Tool Temperatures: 100°C, 140°C, 170°C
- CoV (%): Variability in strength measurements
In-Process Inspections for Quality Assurance and Process Optimization
In-process AFP Manufacturing Inspection System (IAMIS)
Summary

• Primary AFP parameters are highly coupled and require validated analysis for process optimization.
• ICASH process successfully produced curved fairing panels
  • 0.3% or less porosity
  • Crystallinity above 20% through the thickness

Looking Forward

• Increasing interlaminar strength via variable focus optics and melt control
• Removing the need for heated tooling on large scale parts
• Double curvature complex parts
• Completely tool-less in-situ consolidation
• In-process inspection for dimensional stability
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