Thermoplastic Joining Materials Guidance for Aircraft Design and Certification

Process Development & Scaling Studies

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Thermoplastic Joining Materials Guidance for Aircraft Design and Certification

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Industry

ALTAIR
BRANSON
Ambrell
Program Overview

Thermoplastic Bonding

Thermoplastic Welding

Process Development

Performance Evaluation
Background

- Aircraft manufacturing processes will be required to undergo significant technology advancements to increase production rates.
- Thermoplastic material systems are being considered so that
  - Faster cycle time and manufacturing processes
  - Reversible process; thermoplastic materials can be melted and remolded without affecting the polymer’s physical properties.
- Due to this capability, non-traditional joining approaches such as fusion bonding (welding) can be implemented in order to significantly reduce weight and cost over mechanical fastening and adhesive bonding.

The primary goal of this task is to establish best practices for joining thermoplastic composite materials in order to reduce assembly time and cost of next generation structural components. Process specifications and guidance materials are being developed to demonstrate joining techniques at scale.
Thermoplastic Bonding: Contamination Study Results

- Atmospheric plasma treatment (APT) shows resulted in the strongest bond.
- However, when contaminants are present, laser ablation is the most effective decontamination process.
- Mavcoat specimens decontaminated with the APT process did not survive machining.
Effects Surface Preparation - Addition of Laser Ablation + CO₂ Cleaning


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U.S. Department of Transportation
Federal Aviation Administration

May 2023
Final Report

GIC (5%/Max) [kJ/m²] COV [%]

- APT Energetic
- D1 (25.5 J/cm²)
- D2 (50.5 J/cm²)
- UV Laser
- D3 (100.5 J/cm²)

EA9394

FM300-2M

UV Laser Ablation
99% Adh., 1% Coh.

Energetic (OPT)
50% Adh., 50% Coh.

Energetic (APT)
30% Adh., 70% Coh.

Laser Ablation
99% Adh., 1% Coh.

Dust (HS & GB)
100% Adhesion

Degrease
100% Adhesion

Total Surface Free Energy [mN/m]

0.0 0.5 1.0 1.5 2.0 3.0 3.5 4.0 4.5 5.0 5.5 6.0

Apparent Shear Strength [kN/m]

100% Adhesion

40% Adhesion

0% Adhesion

50% Cohesion

0% Cohesion

50% Adhesion

100% Cohesion

EA 9394
Program Overview

Thermoplastic Bonding

Thermoplastic Welding

Process Development

Performance Evaluation
• Coil Design Analysis using 2D static model
  • Coil geometry and design will influence the shape and
density of generated magnetic field, which in turn
influences how the work piece is heated
  • FE model was employed to study the induced thermal
distribution across the weld interface to design the
NIAR induction coil
Induction Welding Model Application

- Material properties analysis and anisotropy electrical characterization model for simulation inputs
  - Heating efficiency knockdown at the inter-ply region need to accounted in characterizing

![Image of thermal analysis and experiment setup]

Infrared camera

Data point location consider for a quasi-isotropic laminate for reverse calculation.

DoE analysis on the UD material properties

Experiment Data Feed In

<table>
<thead>
<tr>
<th>Characterization</th>
<th>Solver</th>
<th>Goal</th>
<th>Anisotropic EER</th>
<th>Reaching bounds</th>
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<tr>
<td>Characterization.f2hst</td>
<td>- Write input</td>
<td>Goal 1</td>
<td>(RHO_X, RHO_Y, RHO_Z)</td>
<td>Yes</td>
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<tr>
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<td>- FE input</td>
<td>Goal 2</td>
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<td>Goal 3</td>
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<tr>
<td>Goal 4</td>
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</tbody>
</table>

![Graphs showing experimental data and correlation analysis]

Correlation

- A
- B
Program Overview

Thermoplastic Bonding

Thermoplastic Welding

Process Development

Performance Evaluation
### Comparison of Weld Single lap Shear Strength (1” OL)

#### TC1225 / T700GC

<table>
<thead>
<tr>
<th>Category</th>
<th>Average Apparent Shear Strength [ksi]</th>
<th>COV [%]</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASC- BL- AC- TC1225</td>
<td>5.54</td>
<td>11.30</td>
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<tr>
<td>MASC- IW- TC1225</td>
<td>5.03</td>
<td>2.51</td>
<td>-9.24%</td>
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<tr>
<td>MASC- UW- TC1225</td>
<td>4.73</td>
<td>18.70</td>
<td>-14.65%</td>
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<tr>
<td>MASC- RW- TC1225</td>
<td>5.04</td>
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<td>-9.12%</td>
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<tr>
<td>MASC- RW- CFHE</td>
<td>4.93</td>
<td>1.68</td>
<td>-11.13%</td>
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</table>

#### APC / AS4D

<table>
<thead>
<tr>
<th>Category</th>
<th>Average Apparent Shear Strength [ksi]</th>
<th>COV [%]</th>
<th>% Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MASC- BL- AC- APC</td>
<td>5.64</td>
<td>3.03</td>
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<tr>
<td>MASC- IW- APC</td>
<td>5.65</td>
<td>2.99</td>
<td>0.06%</td>
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<td>MASC- UW- APC</td>
<td>5.26</td>
<td>5.58</td>
<td>-6.75%</td>
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<td>MASC- RW- APC</td>
<td>4.98</td>
<td>1.98</td>
<td>-11.82%</td>
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<tr>
<td>MASC- RW- CFHE</td>
<td>4.67</td>
<td>5.63</td>
<td>-17.26%</td>
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</tbody>
</table>
Resistance Welding: Temperature & Pressure Dependance (0.5” OL)

TC1225 / T700GC

Initial Assessment Ranges (large range) Evaluated with 45/45 interface

Finalized Range (smaller operational range) Evaluated with QI 0/0 interface

Stainless-Steel Heating Element

<table>
<thead>
<tr>
<th>Temperature &amp; Pressure Contribution</th>
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<tbody>
<tr>
<td>[0.5” Overlap, 45/45 Ply Interface, TC1225 / T700GC]</td>
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</table>

Carbon-Fiber Heating Element

<table>
<thead>
<tr>
<th>Temperature &amp; Pressure Contribution</th>
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<tbody>
<tr>
<td>[0.5” Overlap, 0/0 Ply Interface, TC1225 / T700GC]</td>
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</table>
Process Parameter Trend (Pressure & Temperature) – APC / AS4D
Induction Welding (1.0” OL)

Evaluated on QI 0/0 interface
OVERLAP LENGTH = 1.0”
Process Parameter Trend (Pressure & Amplitude) – TC1225 / T700GC
Ultrasonic Welding (1.0” OL)

Evaluated on QI 0/0 interface
OVERLAP LENGTH = 1.0”
Best Case Grouping from Pressure/Temp/Amplitude Study & Initial Static Dataset

**All 0/0 Interface**

**BEST Process Parameter Combination (Pressure/Temp./Amplitude)**

TP Welding Configurations: Best Process-Specific Results
[TC1225/T700GC & APC/AS4D]
0/0 Laminate Interface

**All 45/45 Interface**

**BEST Process Parameter Combination (Pressure/Temp./Amplitude)**

TP Welding Configurations: Best Process-Specific Results
[TC1225/T700GC & APC/AS4D]
45/45 Laminate Interface
Single Lap-Shear Fatigue Testing

- **Substrate Material (TC1225):**
  - QI45: [45/0/-45/90]_{2S}
  - QI0: [0/-45/90/45]_{2S}
  - CP0: [0/90]_{4S}

- **Adhesive Bond:**
  - Adhesive: FM300-2M (0.06 psf)
  - Surface Preparation: Atmospheric Plasma Treatment
  - 250°F at 40-psi

**Fatigue life increased by a factor of 2 when changing interface ply from 45° to 0°**

**Adhesive bonded specimens performed slightly better than welds with fiberglass insulation**

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress (psi)</td>
<td>1000</td>
<td>2000</td>
<td>3000</td>
<td>4000</td>
</tr>
<tr>
<td>RW-CP0</td>
<td>2,768 cycles</td>
<td>QI45 (48gsm FG) (1-3)</td>
<td>2,768 cycles</td>
<td>QI45 Adhesive Bond (1-3) 6,015 cycles</td>
</tr>
<tr>
<td>RW-QI0</td>
<td>QI45 (48gsm FG) (1-3) 42,127 cycles</td>
<td>QI45 (1-3) 42,127 cycles</td>
<td>QI0 (1-3) 83,941 cycles</td>
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<tr>
<td>RW-QI45</td>
<td>174,962 cycles</td>
<td>CP0 (1-3) 174,962 cycles</td>
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</tr>
<tr>
<td>RW-QI45-FG</td>
<td>100% AWI 10% S1 50% Coh 40% Adh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AB-FM300-2M</td>
<td>100% AWI 10% S1 50% Coh 40% Adh</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Static Strength Summary**
RW Substrate & HE Surface Preparation Considerations

- As Received
- APT
- 150G Hand Sand
- 80G Grit Blast

**Average Surface Roughness (Sa) [µm]**

- As Received
- APT
- 150G HS
- 80G GB

**COV [%]**

- Degrease
- APT
- GB (80G)
- GB (80G) + APT
- HS (150G)
- HS (150G) + APT

**Apparent Shear Strength [ksi]**

- 0.0
- 1.0
- 2.0
- 3.0
- 4.0
- 5.0
- 6.0
- 7.0
- 8.0
- 9.0
- 10.0

**Height Laser + Optical**

- As Received
- APT
- 150G Hand Sand
- 80G Grit Blast

- 100% AWI
- 10% S1/S2
- 90% AWI
- 100% AWI

**As Received**

- APT
- Hand Sand
- Grit Blast
Mavcoat Contamination Study: Single Lap Shear Strength - 0/0 Interface

This is in progress for all three weld methods with various other contaminants.
Certification of Thermoplastic Joints

- **TP Weldment qualification using** **7PB** test method
- Analytical benchmarking, calibration & validation exercises
- **Sizing study** of 7PB test load application points & effect on **mode-mixity**
Fracture Toughness Mode I (TC1225/T700GC)
Effects due to Fiber Bridging

Mode I Fracture Toughness: TC1225 / T700GC

- Lamina Baseline: 2.10
- Resistance Manufacturer DataSheet: 4.61
- Weld-SSHE Lamina 0/0 interface: 4.47
- Resistance Weld-SSHE Q10 interface: 3.94
- Ultrasonic Weld: 3.94

Load vs. Displacement graph for Q10 and Q145 (2) samples.
7-Point Bend Static Testing

- Graph showing axial force vs. displacement for different conditions.
- Bar chart comparing load (lb) for various samples:
  - TP - Ultrasonic Welded
  - TP - Resistance Welded T700/TC1225
  - TP - Bonded
  - TS - Bonded IM7/5320-1

- Images showing testing equipment and samples.
Thermoplastic Welded Element Level – 7pt Bend Test

Progressive failure monitored during fatigue using video camera + intermittent NDI (UT-PE and XCT)

NDI pre- and post-fatigue on thermoplastic bonded specimen

- Before fatigue @ 0 cycles
- After 100k cycles @ 444lb fatigue max. load
- After 100k cycles @ 800lb fatigue max. load
Tooling for Fuselage Panel Demonstrator
Summary

• Adhesive Bonding
  • Abrasion surface preparation techniques that have been historically used to prepare thermoset composites are insufficient for thermoplastic composites because the surface is not chemically activated in the abrasion process
  • Atmospheric plasma treatment can increase the surface free energy (specifically the polar surface free energy) and chemically activate the substrate to form a strong bond with the adhesive
  • Laser ablation surface preparation require further studies for process development
  • Minimal substrate failures were witnessed with thermoplastic bond failures due to the increase in interlaminar fracture properties associated with thermoplastics over thermosets

• Fusion Welding
  • Controlling and monitoring interfacial temperature, pressure, and time is essential to weld quality and performance
  • Weld certification guidance will be addressed though scaling studies
  • Fatigue data indicated a significant sensitivity to process parameters and interfacial plies
  • Welds do not require the surface of the substrate to be chemically activated, as the polymer near the weld interface is melted (no chemical bonding occurring)
  • Initial surface contaminate studies have demonstrated the robustness of welding, but require further studies to establish guidance
Looking Forward / Future Work

• Benefit to Aviation
  • Generating guidance materials for adhesive bonding and welding reinforced thermoplastic composites
  • Identification of critical processing parameters in adhesive bonding and weld processes to aid in establishing process controls

• Next Steps:
  • Development of laser ablation as a surface preparation method
  • Scaling studies for fuselage panel demonstrator
  • Development of ultrasonic welding gantry for fuselage panel demonstrator
  • Development of guidance materials for joining of thermoplastics