Comparison of Invar and Composite Tooling Materials for Precision Composite Part Manufacture

Presented at:

SAMPE Brazil

October 2015
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My Background

• M.S. Materials Engineering – Univ of Utah

• Have held various technical and management roles at Goodrich Aerospace, Hercules Aerospace (now ATK), and Zoltek Carbon Fibers

• Today President and COO of Ascent Tooling Group, the largest aerospace tooling business in the world
  – Coast Composites, LLC
  – Odyssey Industries, LLC
  – Global Tooling Systems, LLC
What constitutes a good mold?

1. **Dimensionally accurate**
   - At room temperature and at cure temperature

2. **Vacuum tight bagging surface**

3. **Thermally stable over time & repeated cycles**
   - Dimensions don’t change
   - Vacuum integrity doesn’t degrade
   - Surface finish doesn’t degrade

4. **Durable through required production quantity + buffer**
Aircraft Part Tolerances

- Trend towards determinant assembly (DA) is driving part tolerances
  - Typical profile tolerances ~1.5 mm
  - Positional tolerances for DA holes ~ 0.5 mm
- Tool tolerances are typically 25% to 50% of part tolerances

Stringers located on sub-assembly fixture

Skin positioned to stringers via DA

DA Locating Feature

Thermal expansion differences between tool and part must be considered to achieve desired tolerances
Coefficient of Thermal Expansion

Chart: sme.org, credit Dave Dickson
Tools made from Invar or Composite materials are best choice for elevated cure temperature composite parts.
Production Tool Choices - Invar or Composite – which one should I select?

Selection considerations
- Number of parts to make
- Manufacturing process
- Program risk
- Schedule limitations
- Cost limitations
- Infrastructure and equipment constraints
Tool Life Considerations

• How many parts do you need to make?
  – Prototype/R&D tool
  – Limited run
  – Long-term production run

• How long will program run?

• Anticipated design changes?
  – Minor, reconfigure existing tool
  – Major, make new tool

CFRP tools can be locally reconfigured by adding material to existing laminate
Qualifiers – Composite Tool Life Dependencies

• **Resin**
  – BMI is more thermally stable, less microcracking & dimensional change

• **Manufacturing process**
  – Ply consolidation during layup
  – Ply consolidation during cure
  – Machining techniques

• **Shop practice**
  – Trimming plys on tool surface
  – Demolding practices
  – Exposure to temperatures above Tg
  – Cleaning solvents & practices
  – Proper storage – avoid UV and moisture

Shop practices that shorten tool life:

- Cutting on tool surface:
- Demolding with metal wedges:
- Composite tool exposed to moisture:
Durability and Ease of Repair

• Typical types of tool damage
  – Knife cuts, scratches, nicks
  – Dents from impact damage
  – Delaminations due to damage, over-temp, UV exposure, or moisture exposure

<table>
<thead>
<tr>
<th>Invar</th>
<th>CFRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Durable</td>
<td>Medium durability</td>
</tr>
<tr>
<td>Straightforward to repair with conventional metalworking practices</td>
<td>Major defects difficult to repair</td>
</tr>
<tr>
<td>Vacuum leaks can be fixed with weld</td>
<td>Vacuum leaks need material removal and replacement</td>
</tr>
</tbody>
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Manufacturing Times

Relative Lead Time for Low CTE Tools

- **CFRP Infusion**: Low-cost foam master
- **CFRP Epoxy**: High-density foam master
- **CFRP BMI**: Invar or graphite master
- **Invar**:

Legend:
- Master
- Deliverable Tool
Tool Weight Considerations

- **Movement and handling**
  - Rotational mass on AFP machine
  - Push cart / forklift / crane / AGV

- **Thermal mass**

<table>
<thead>
<tr>
<th></th>
<th>CFRP</th>
<th>Invar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightest tool</td>
<td>Moderate weight</td>
<td></td>
</tr>
<tr>
<td>Least thermal mass</td>
<td>Moderate thermal mass</td>
<td></td>
</tr>
<tr>
<td>Shortest cycle*</td>
<td>Longer thermal cycle*</td>
<td></td>
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CFRP BMI was used for this tool due to weight and rotational force considerations on AFP machine.

*Thermal cycle time often limited by cure profile and not tool
Cost – Initial and Rate Tooling

Life of program cost can be higher for composite tools because of limited life.
## Choosing Between Low CTE Tooling Materials

<table>
<thead>
<tr>
<th>Low CTE Layup Tool Materials</th>
<th>Tool Life (thermal cycles)</th>
<th>Weight</th>
<th>Durability</th>
<th>Initial Cost</th>
<th>Rate Tool Cost</th>
<th>Ease to Reconfigure</th>
<th>Ease to Repair</th>
<th>Tool Technology Legacy</th>
<th>Years in Service</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invar</td>
<td>@ 350F</td>
<td>*</td>
<td>***</td>
<td>***</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>CFRP BMI</td>
<td>Up to 500</td>
<td>***</td>
<td>**</td>
<td>*</td>
<td>**</td>
<td>**</td>
<td>*</td>
<td>***</td>
<td>10</td>
</tr>
<tr>
<td>CFRP Epoxy (autoclave cure)</td>
<td>Up to 100</td>
<td>***</td>
<td>*</td>
<td>**</td>
<td>***</td>
<td>**</td>
<td>*</td>
<td></td>
<td>20</td>
</tr>
<tr>
<td>CFRP Epoxy (infused)</td>
<td>Up to 20</td>
<td>***</td>
<td>*</td>
<td>***</td>
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<td>**</td>
<td>*</td>
<td></td>
<td>10</td>
</tr>
</tbody>
</table>

- Lighter
- Heavier
- More Durable
- Less Durable
- Lower Cost
- Higher Cost
- Easy
- Difficult
Summary

• Low CTE layup tooling is critical to the manufacture of precision composite aircraft parts
  – Invar is still the gold standard for production aerospace molds based upon 25 years of manufacturing and use experience
    • First choice for production layup tooling if no weight constraints
    • Least long-term risk (durable, easily repaired)
  – Composite materials and processes are improving and have a growing place for layup molds
    • BMI and benzoxazine tooling offer improved long term durability and higher temperature capability than traditional epoxy resins
    • Solves weight and infrastructure constraint challenges
Acknowledgements

- Mike Fox – Composite Tool Manager, Coast Composites, LLC
- Dan Brennan – Mfg Engineer, Coast Composites, LLC
- Don Sowers – Design Manager, Coast Composites, LLC
- Ken Page – Design Manager, Odyssey Industries, LLC
- Mark Media – VP Engineering, Global Tooling Systems, LLC
- Bob Mitchell – Technical Director, Ascent Tooling Group
- Colin Birtles – Technical Director, Ascent Tooling Group
APPENDIX
Abstract

Composite aerostructures depend on precision cure tooling to satisfy dimensional requirements, repeatability in manufacture, and part fit-up. Low CTE (coefficient of thermal expansion) materials that are closely matched to that of the composite material used for the part are the key to achieving these goals. Today, invar and composite materials are commonly used for tooling applications because their CTE is closely matched to the composite part.

This paper will contrast tooling made from invar and composite materials and discuss reasons for selection of one versus the other.