A NEW CAMX FOR A NEW TIME

COMBINED STRENGTH. UNSURPASSED INNOVATION

CAMEX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

SEPTEMBER 21-24 2020
A VIRTUAL EXPERIENCE
Tooling 101 for Composites Manufacturing

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SAMPE Global Technical Director
President, BTG Composites, Inc.
August 19, 2020
The Market Areas

Aerospace
- Commercial Aircraft
  - Business Aircraft
  - General Aviation Aircraft
- Military Fixed-Wing
- Rotorcraft (Helicopters)
- Jet Engines
- Space & Launch Vehicles
- Missiles & Munitions
- Carbon-Carbon
- Others

Industrial
- Automotive
- Energy Systems
- General Engineering
- Infrastructure
- Friction materials
- Rollers
- Medical
- Compounds
  - Tooling (across all areas)
- Others

Consumer
- Sports & Recreation
  - Golf
  - Tennis
  - Fishing
  - Racquets
  - Bicycles
  - Winter Sports
  - Spring Sports
  - Archery
  - Hockey
  - Others
- Marine
- Amusement Structures
- Others
The Market Areas

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APPRAOCH

• Provide you with an overview of tooling:
  • Highlight critical “tool material properties”
  • Various “traditional materials”
  • Tooling support structures
  • New and innovative materials
  • Tooling for molding processes
  • Tooling design & process considerations

• Numerous examples ... and many applications
TOOLING MATERIALS & THEIR PROPERTIES
Frequently Used Tooling Materials

• Metals:
  ▪ Aluminum
  ▪ Stainless Steel & P20 Steel
  ▪ Nickel (Electro-Formed Nickel)
  ▪ Invar 36 & Invar 42

• Composites:
  ▪ Glass Fiber Reinforced Plastic (GFRP)
  ▪ Carbon Fiber Reinforced Plastic (CFRP)

• Other Material Options – Numerous
## PROPERTIES OF TYPICAL TOOLING MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th>Max Service Temp. (°F)</th>
<th>CTE X10^-6/°F</th>
<th>Density lbs./in.³</th>
<th>Thermal Conductivity Btu./h x ft. x °F</th>
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<tbody>
<tr>
<td>Steel</td>
<td>1500</td>
<td>6.3-7.3</td>
<td>0.29</td>
<td>30</td>
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<tr>
<td>Aluminum</td>
<td>500</td>
<td>12.5-13.5</td>
<td>0.10</td>
<td>104-116</td>
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<td>Electroformed Nickel</td>
<td>550</td>
<td>7.4-7.5</td>
<td>0.32</td>
<td>42-45</td>
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<tr>
<td>Invar/Nilo</td>
<td>1500</td>
<td>0.8-2.9</td>
<td>0.29</td>
<td>6-9</td>
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<tr>
<td>Carbon/Epoxy 350°F</td>
<td>350</td>
<td>2.0-5.0</td>
<td>0.058</td>
<td>2-3.5</td>
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<tr>
<td>Carbon/Epoxy RT/350°F</td>
<td>350</td>
<td>2.0-5.0</td>
<td>0.058</td>
<td>2-3.5</td>
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<tr>
<td>Glass/Epoxy 350°F</td>
<td>350</td>
<td>8.0-11.0</td>
<td>0.067</td>
<td>1.8-2.5</td>
</tr>
<tr>
<td>Glass/Epoxy RT/350°F</td>
<td>350</td>
<td>8.0-11.0</td>
<td>0.067</td>
<td>1.8-2.5</td>
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<tr>
<td>Monolithic Graphite</td>
<td>800</td>
<td>1.0-2.0</td>
<td>0.060</td>
<td>13-18</td>
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<td>Mass Cast Ceramic</td>
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<td>0.40-0.45</td>
<td>0.093</td>
<td>0.5</td>
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<tr>
<td>Silicone</td>
<td>550</td>
<td>45-200</td>
<td>0.046</td>
<td>0.1</td>
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<tr>
<td>Isobutyl Rubber</td>
<td>350</td>
<td>≈ 90</td>
<td>0.040</td>
<td>0.1</td>
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<tr>
<td>Fluoroelastomer</td>
<td>450</td>
<td>≈ 80-90</td>
<td>0.065</td>
<td>0.1</td>
</tr>
</tbody>
</table>
CTE Comparison of Tooling Materials

- Production Mats (GriEp)
- G1/BMI
- Invar-36
- Mono Graphite
- GriEp
- Carbon Foam
- Steel
- Nickel
- FG/Ep
- Aluminum
- VanTico Patty (LCTC)
- Filled Epoxy
- Ren Seamless Paste
- Last-A-Foam
- Ron Shape 440
METAL TOOLING TECHNOLOGY – EXAMPLES
Manufacturing of Large NC-Machined Steel Bond Tool

Steel Plates and Eggcrate Substructure

Welding Faceplate Sections

NC Machining Faceplate Contour

Completed Tool
STEEL TOOLING EXAMPLES
2.5m Steel Mould for End Domes to Underground Storage Tank (UST)
Fiber and Resin Wet Out inside **Steel Tool** for Dome Structure
End Dome Section Prior to Trimming
End Dome Installed (but Not Bonded) into UST Main Cylinder Body
Collapsible Steel Mandrel (Full Geometry)
Steel Mandrel Now Collapsed ...
End View of UST Being Removed from Mandrel
Filament Wound UST Extracted from Steel Mandrel
Steel, Tapered Mandrel for Rocket Motor Case for Space Launch
Steel Tooling for Boeing 767 Door Spring
Boeing 767 Main Door Composites
Torsional Spring
Steel Tool face cut from single billet

Steel Molds and Mandrels for Aerospace

Photo courtesy of Process Fab, Inc.
Fiber Placement Mandrel
AFP Composites Simplify and Speed Manufacturing (Boeing 787 Barrel Section)
One Piece Barrel Section
(Boeing 787)
V-22 Aft Section Fiber Placement
AFP of Aircraft Stabilizer Section
F-22 Inlet Duct (Complex Internal Tooling)
TP Fiber Placed Tooling by Robotic System
ALUMINUM TOOLING EXAMPLES
Aluminum Molds and Fixtures
Aluminum Molds & Bond Fixtures

Complex shapes warrant careful CTE Calculations
Aluminum Fiber Placement Mandrel
Robotic Fiber Placement Over Metal Mandrel
INVAR TOOLING EXAMPLES
Invar Layup Mold
Basic Invar Tool Construction

- Plate stock
- Plasma cut headers
- Bump-form facesheet
- Assemble/weld
- Machine surface
- Hand finish
- Finished tool
Invar Layup Mold
Invar Fiber Placement Mandrel

Photo courtesy of Fives Manufacturing

A-350 Empennage Section 19 Mandrel
Invar Tooling Cost Breakdown

**HIGHEST FACTORS:**
- Material cost (Invar 36, 42) – 30%
- Machining & Forming cost – 38%

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- **Material** 30%
- **Machining** 19%
- **Weld** 14%
- **Hand Finish** 1%
- **Tool Making** 9%
- **Forming** 5%
- **Cutting** 2%
- **Heat Treat** 1%
- **Tool Des.** 9%
- **N/C Prog.** 5%
- **Engr/Planning** 2%
- **Inspect** 3%

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NICKEL TOOLING EXAMPLES
Nickel Plating Fabrication Process Steps

Electroforming (Plating) Process

Nickel Vapor Deposition (NVD) Process

Source: CVD Mfg., Inc.

Mafix, Inc. [http://www.mafixinc.com/nickel.htm](http://www.mafixinc.com/nickel.htm)
CVD Manufacturing, Inc. [http://www.nvd.com/process.html](http://www.nvd.com/process.html)
Electro-Formed Nickel Preform Mold

Nickel tooling provides durable surface for preforms for class “A” finish automotive parts
Electro-Formed Nickel Mold
Electro-Formed Nickel Canoe Mold

Note: High-polished surface quality of nickel mold
EF Nickel Mold for Corvette Roof

Advantages:
- Durable for high rate production
- Heated tooling design provides for OoA capabilities

Nickel can be highly polished providing for class “A” surface finish

Photo’s courtesy http://www.nickelelectroform.com/
Image courtesy of Weber Mfg and Plasan Carbon Composites
TITANIUM TOOLING EXAMPLES
Titanium Shell Liner (Drill Riser Interior)
Titanium Shell Liner (Extremely Long)
PLASTIC TOOLING EXAMPLES
HDPE Plastic Tank Liners for LPG Tanks

HDPE = High Density PolyEthylene plastic liner

LPG = Liquified Propane Gas
Five (5) LPG Tanks Wound on Plastic Liner Tools
End Product – LPG Tanks for Homes
COMPOSITE TOOLING EXAMPLES
CFRP Mold-Complex Shape

CFRP = Carbon Fiber Reinforced Plastic
Preferred CFRP Small Composite Layup Mold Designs
Self Supporting Tool Laminate Designs

Integration of bathtub flanges and return flanges in primary tool laminate design eliminate the need for substructure in smaller size molds.

Carbon fiber-benzoxazine tool designed with self supporting features.
Composite Tubular Structure

Masterbar Composite Tubing
Integrally-Stiffened Tool Laminate
CFRP Laminate Layup Mold

Note rolled laminate edges (flanges) and minimal custom CFRP substructure with torsion resistant cross-grid design.

Advantages:
- Lightweight
- Heats/cools rapidly
- Low CTE

Photo courtesy of Coast Composites-Ascent Aerospace co.
BMI Carbon Fiber “Duratool”

BMI = Bismaleimide resin system
HexTool utilizes 12K+ UD (carbon/BMI) prepreg, avoids the need to use 3K and 6K
C-17 Tailcone (Mandrel & Final Part)
Integrated Composite System (ICS) with “C-Foam” Interior

Carbon Fiber BMI Machined Tool Surface

Carbon Foam Core

Carbon Fiber BMI
Machining of C-Foam Understructure

Prepreg carbon fiber reinforced epoxy or BMI is used to cover the C-Foam, cured, then machined to tool surface.

Rough-cut surface

Finish-cut offset surface prior to prepreg

Photos courtesy of Touchstone Research Lab, Ltd
Machined CFRP/Carbon Foam Mold

Internal Mold Line (IML) Beaded Stringer tool
CFRP/C-Foam Production Mold

Advantages:
- Easily machined to net or corrected shape
- Low CTE

Finished carbon foam-carbon prepreg machined mold surface prepared with sealer and release agent

Photo courtesy of Touchstone Research Lab, Ltd
“C-FOAM” Structural Foam

- Spherical pores
- Open porosity
- Interconnected pores
C-FOAM Production Tooling

Note uniform cross-section thickness
MASTER MODEL TOOLING ASPECTS
CNC Machined Tooling Board Model

Tooling board assembly:
Planks are bonded together as need to near net shape prior to machining

Machining F-35 Nacelle Master Model
Templates were hand cut and filed from photo-sensitive aluminum stock transferred from master Mylar's on a light table.

Conventional station templates rigged to framework, caged, and splined using epoxy resin paste or gypsum based tooling plaster.
Legacy Marine Plug Fabrication

Plywood or pressed-board frames with batten wood cover
CNC Machined Tooling Block Model

Note the adhesive lines between the planks in the machined model have a difference in CTE.

Machined block surfaces must be sealed and released prior to use.

Photo courtesy of General Plastics Manufacturing Co.
Ceramic Tooling Block Master
(Low CTE Master Model Material)

Ceramic tooling block comes in medium and high density versions and services ≥ 500°F (260°C)
Example: Master Model-Tool Family

- CAD Part-File
- Machined Master Model
- CFRP Layup Mold from MM
- Final Kevlar/Epoxy Part made from the Layup Mold
- Trimmed & Drilled in TDF
- Trim & Drill Fixture (TDF) from MM

Photos courtesy of Composite Solutions Corporation

CAD Tool Design & Fab
RUBBER & ELASTOMER, BAGGING TOOLING
Reusable Vacuum Bags (RVB)
Large Reusable Silicone Rubber Vacuum Bag
TOOLING SUPPORT STRUCTURES FOR MANUFACTURING
Modern Composite Eggcrate Design

Uses same material for substructure as for tool face to eliminate CTE mismatch.

Note torsion box design below.

Photo courtesy of Janicki Manufacturing.

Photo courtesy Coast Composites/Ascent.
Truss/Torsion Eggcrate Design

Burnham fabricates "Ready-to Assemble" Cut Kits. Kits are Waterjet cut to desired dimensions as specified by customer's supplied CAD data and / or drawings.

Industry trend is to provide torsion stability and minimize depth of substructure
Composite Tubular/Truss Structures

Square tubes, angles, columns and gussets that can be cut to size, bonded and fastened together to provide a cradle structure

Source: Leading Edge Aerospace

Source: Burnham Composites
Composite LM w/Aluminum Frame

Note in-plane pad-to-frame features allowing for “free-floating” tool laminate to prevent effect of CTE mismatch. Utilizes galvanic (glass) barrier between CF and aluminum.

Composite LM rests in aluminum cradle/workstand.

Courtesy of the Advanced Composite Group, LTD (Cytec)
Invar Tube Frame Substructure

Compare weight to conventional Invar eggcrate design

Image courtesy of Re-Steel, Inc
Conventional Egg-crate Design

**Note:** Air circulation and lightening holes cutout in the honeycomb sandwich egg crate structure
Composite Tool w/Aluminum Frame
Low-Cost Spar & Stringer Molds
MISCELLANEOUS TOOLING TECHNOLOGIES
Aluminum Clamshell Mold for Violin

Machined aluminum clamshell molds for violin body

Courtesy of Zach Wing, Ph.D - Advanced Ceramics Manufacturing
Invar Layup Mold

Advantages:
- Durable and long-lasting production capabilities
- Low CTE

Photo courtesy of Coast Composites-Ascent Aerospace
Machined Monolithic Graphite Molds

Advantages:
- Easily machined to net or corrected shape
- Very Low CTE

True “Graphite” tooling

Photo courtesy of Electro Tech Machining

Photo courtesy of Turnpoint Design
Ceramic Washout Mandrels

Ceramic washout mandrels manufactured in FDM split molds manufactured by Stratasys.
Ceramic Washout Materials Using Additive Manufacturing

From CAD File... To 3D printed mandrel made from RapidCore product from ACM

Advanced Ceramics Manufacturing (ACM)
Silicone Rubber Bladder for CFRP Frame

Layup on inflatable silicone bladder prior to installation into clamshell mold for processing at 220°F and 150 psi internal pressure

Photos courtesy of Ibis Cycles
3D Printed Washout Mandrels

Mandrels are washed out after the part is cured using a detergent solution

Courtesy of Stratasys
Complex Curvature Composite

“S”-Shape Demo
Manufacturing Trials

Representative Duct

- 8552/196 PW Prepreg
- Cure Cycle
  - 4 °F/min Ramp to 250 °F
  - 4 hour soak at 250 °F

SMP Bladder Mandrel
Inflating SMP Mandrel
Mold Release Mandrel
Prepreg Lay-up
Curing Composite
Infusion Tooling – Wind Blades
Wind Blade Tooling and Structures

48.5m blade tip mold
Courtesy GE

Portion of 60m spar cap infusion mold Courtesy DowAksa

Large shear web mold
Courtesy GE
OTHER INNOVATIVE TOOLING
MANDRELS & FORMS ...
Large Number of Tooling Mandrel Materials Acceptable

• Inflatable (air bags, rubber mandrels)
• Disposable, Expendable or Removable:
  • Plaster (break out, washout later)
  • Sand or salt (washout later)
  • Glass
  • Plastic, thermoplastic
  • Meltable alloy materials
  • Wax materials
  • Foam and cork materials,
  • Wood and Balsa wood
  • “Shape-memory” materials
  • Additive manufacturing (AM) / 3D Printing
Tooling Options (continued ...)

• Metal mandrels (several options):
  • Collapsible metal shell structures
  • Monolithic single shell (push off end)
  • Net metal mandrel

• Composite mandrels

• Plastic liner systems
Plaster ‘Washout” Tooling

• Plaster sometimes used for complex structures
• Chain or rope embedded within plaster for easier removal later
• Withstands 250-350F (121-177C) cures
• BUT – messy and very dusty – often required several layering steps
Washout ‘Sand’ Mandrel

- Washout `sand’ mandrel
- Fine, rounded sand plus:
  - Water
  - PVA
  - Isopropyl Alcohol
- Cured at temperature
- Machine shape
- Water washout
Inflatable Rubber Mandrel

- Rubber or elastomeric mandrel with EPDM rubber
- Reinforced with embedded **Aramid** fibers
- Cured, machined to shape
- Inflated and held under pressure during cure
Braid Used Extensively in RTM for Sporting Goods Tooling Bladders

• Carbon fibre 2D braided preforms
• High performance bicycle swing arm:
  ▪ Primary braided legs
  ▪ Cross-over part (over thermoplastic hollow core)
• RTM resin infusion (DOW Tactix 123)
• Low viscosity resin
Technology Assessment: Consumer Marketplace

Bladder Molding (Baseball Bats)
MOLD TOOLING EXAMPLES
VARIOUS “RTM-TYPE” TOOLING
Multi-Piece Aluminum RTM Die

North Coast Tool & Mold display at SAMPE conference includes reconfigurable inserts to support multiple parts numbers

Advantages:
- Easily machined to net or corrected shape
- Close tolerance
- Net molded parts
Completed RTM Part w/o Covers

40-50 Pieces of Tooling Required
Multi-Piece *SQRTM Tooling
*Same Qualified Resin Transfer Molding process

All black-anodized aluminum tooling
Aluminum RTM Mold \(^{\text{W}}\)/Internal Bladder

Advantages:
- Easily machined to net or corrected shape
- High heat transfer
- Bladder provides internal pressure

Aluminum has lower density than steel but very high CTE-
Best for small parts cured at elevated temps

Image courtesy of Swarf Cycles
SUMMARY

• **Tooling for composites --- Art Supported By Science !**

• Many methods for producing tools !

• Very process and applications – driven

• Always several solutions for the same part

• Prototyping vs. production tooling – often very different

• Tooling properties cover wide range of properties:
  • Mechanical (strength, stiffness)
  • Thermal (expansion/contraction and upper limits)
  • Physical (dimension control, durability)

• **There is no substitute for experience ...**
ACKNOWLEDGEMENTS

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• Coast Composites/Ascent Aerospace
• Composites One
• Engineering Technology (Entec)
• Janicki Tooling
• Northrop Grumman Corporation
• Radius Engineering, Inc.
• SAMPE Proceedings, Conferences and Workshops
• Spencer Composites Corporation
• Spintech LLC
• Stratasys, Inc.
• Touchstone Research Laboratory
• Others noted on various slides
QUESTIONS ???

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Tooling Slide Addendum
(not covered in virtual presentation)

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FOR A NEW TIME

COMBINED STRENGTH, UNSURPASSED INNOVATION

CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

SEPTEMBER 2020
A VIRTUAL EXPERIENCE
TOOLING MATERIALS – STEEL

• Pros:
  • Traditionally used for autoclave processing
  • Cheap material that is durable (many cycles – over 1500 in autoclave)
  • Cast-able, weld-able and bendable to shape
  • Wide temperature range (low to very high)

• Cons:
  • Steel is heavy and slow to heat & cool
  • Relatively high thermal expansion
  • Fails in welds typically (but repairable)
TOOLING MATERIALS – ALUMINUM

• Pros:
  • Much lighter than steel
  • Easier to machine than steel
  • Frequently “hard anodized” against surface damage

• Cons:
  • Difficult to make tight, leakproof castings and welds
  • Has much higher thermal expansion (mismatch with parts)
  • Susceptible to scratches, nicks (softer material)
  • Limited temperature range and number of cycles in autoclave
TOOLING MATERIALS (INVAR, NICKEL)

• Pros:
  • Both have very low thermal expansion
  • Much better thermal match with carbon fiber composites
  • Can be cast, machined and welded
  • Introduced in 1990’s for composites

• Cons:
  • Very expensive and slow heat-up rates of tool and composite part
  • More difficult to machine than steel
TOOLING MATERIALS (COMPOSITES)

• Pros:
  • Polymer composites (Epoxy, BMI, etc.) used successfully over their specific temperature limits
  • Best thermal expansion match with composites
  • Relatively light vs. all metal tooling
  • Great heat-up rates in an autoclave
TOOLING MATERIALS (COMPOSITES) – Continued

• Cons:
  • Requires a “master/mandrel” for lay-up of material
  • Surfaces can more easily be scratched or damaged
  • **Negative experience with multiple autoclave cycles over time**
  • Moisture absorption can be concern:
    • Must be slowly dried after long term storage in oven
    • Autoclave can cause blisters and delamination if moisture not removed beforehand
## COMPARISON OF THERMAL AND PHYSICAL PROPERTIES

<table>
<thead>
<tr>
<th>Material</th>
<th>Specific Gravity</th>
<th>Specific Heat (Btu/lb./°F)</th>
<th>Thermal Mass (Btu/lb./°F)</th>
<th>Thermal Conductivity Coefficient (Btu/ft²/hr/°F/in)</th>
<th>Coefficient of Thermal Expansion (CTE) (10^-6 in/in/°F)</th>
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</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>2.70</td>
<td>0.23</td>
<td>0.62</td>
<td>1395</td>
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<td>Stainless Steel</td>
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<td>0.12</td>
<td>0.96</td>
<td>113</td>
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<td>EF-Nickel</td>
<td>8.90</td>
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<td>0.89</td>
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<td>GFRP</td>
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<td>0.30</td>
<td>0.54-0.60</td>
<td>22-30</td>
<td>8.0-9.0</td>
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<tr>
<td>CFRP</td>
<td>1.50-1.60</td>
<td>0.30</td>
<td>0.45- 0.48</td>
<td>24-42</td>
<td>0.0-6.0</td>
</tr>
</tbody>
</table>
Material Thermal Properties (CTE)

• Coefficient of Thermal Expansion (CTE)

  • Coefficient of thermal expansion defined as fractional change in length per unit rise in temperature.
  • Example: μin/in/°F or μm/m/°C
  • All materials have this tendency
  • It is a primary concern when selecting material to make molds and fixtures that see a change in temperature in service.
Case FOR Metal Tooling

• Metal tooling is more damage-tolerant
  ▪ Composites are more fragile
  ▪ Composites have lower surface hardness

• Metal tooling maintains vacuum/pressure integrity
  ▪ Composites tend to micro-crack
  ▪ Composites tend to leak over time through multiple thermal/pressure cycles

• Metal tooling can be made adjustable
  ▪ Composite materials are not ductile
  ▪ Composites cannot be forced to new shapes after initial cure process
Case AGAINST Metal Tooling

• Metal tooling is **heavy**
  • Requires heavy duty transportation equipment

• Metal tooling **requires surface machining**
  • Long lead-time normal for larger tools
  • Manufacturing identical units may not be easily achievable

• Metal tooling has a **higher thermal mass**
  • Has a higher thermal mass than composites tooling – thus heats and cools at a much slower rate than composites
Case FOR Composite Tooling

• Composites are lightweight, easy to transport

• Composites has better thermal expansion
  • Better dimensional accuracy
  • Less stress on the post-processed part

• Composites have low thermal mass
  • Heats and cools faster than metals

• Composites have more efficient heat transfer
  • Carbon fiber with: Epoxy, Cyanate Ester, or BMI tooling

• Easier to duplicate multiple, identical units from master or permanent pattern
Case AGAINST Composite Tooling

• Composites lack decent design standards, M & P procedures resulting in variable quality of tools
  • Very few high quality vendors available
  • Wide range in quality and workmanship

• Composites easily damaged and less durable than metal tooling in production

• Composites prone to lose vacuum and pressure integrity prematurely compared to metal tooling
  • Multiple thermal cycles tend to micro-crack matrix resin, eventually causing vacuum/pressure leaks
“RTM-TYPE” TOOLING CONSIDERATIONS
RTM Tooling Considerations

• Tooling is **THE** Most Important Factor in successful RTM

• Matched metal tooling – number 1 rule!

• Both surfaces controlled can produce 0.005-inch/0.15-mm tolerances easily

• Great for complex shapes

• But – requires complex assembled tooling

• Other considerations:
  • Must be gated and vented properly
  • Must seal and hold good vacuum/pressures
  • Must not deflect in a press, open or leak from resin pressures to 35-40 bar
RTM Tooling – Mandrels, Design

• Major mandrel issue is CTE and removal
• All internal mandrels need to be “hard located” (e.g. mold pins) and not allowed to float/move
• Have tooling design and fabricated by an experienced RTM tooling house:
  • They know what they are doing and have the experience
  • May cost more but will save a lot in the long run ...
RTM Tooling – Heating

• Heated tooling – far better than running heated platens
• Oil or water heating better than electric heaters:
  • Can aid in cooling down
  • Faster cycle times
• But – keep oil/water away from dry preforms
• Design tools for ease of handling (metal molds are always “heavy”)


RTM Tooling – Heating Options

• No heat (**SLOW**)
  • Roll loaded mold into an oven or autoclave (convection)
  • Use heated press platens to provide heat (conduction)
  • Or – resin cure generates its own heat ...

• Integrated heating (**FASTER**)
  • Much faster heating, and, cooling control
  • **Hot oil preferred**
  • **Hot water another option**
  • Both provide cool-down controls
  • Electric cartridge heating (no cool-down option) – poor choice
RTM Tooling

• **Steel tooling (P20) whenever possible**
• Inlet and vent ports – always **off** the part whenever possible
• Allow at least 0.125-inch/3.18-mm for trim area
• Part removal from tool is THE major source of part rejection (so, design in method of removal)
Multi-Cavity RTM Part

40-50 Pieces of Tooling Required
“LITE (or LIGHT) RTM” TOOLING
GFRP Light-RTM Mold Set

Advantages:
Lower cost than RTM tooling
2-sided tool surface quality

Uses reusable “flimsy” GFRP upper mold piece with integrated resin & vacuum ports/channels
Typical Light-RTM Mold Cross-Section

Concentric resin flow from center toward outer periphery allows for good air/gas movement during processing
GFRP/Elastomer Light-RTM Mold Set

Uses Sprayomer™ a Bio-based reusable vacuum bag for LTRM infusion

Advantages:
- Conforms well to complex configuration
- Provides good compaction

Photo courtesy of John Burn-UK
Lite RTM Tooling Systems

Epoxy System for Glass Fiber Reinforced Truck roofs and Wind Deflectors – RTM Technology

RTM mold and truck roof while demolding, source: Fritzmeier Composite.
Light-RTM Infusion in Process

Example of LRTM process and vac/resin plumbing requirements
Tooting Accuracy – RTM vs. LRTM

- RTM tooling accuracy is +/- 0.002-inch at best – (+/- 0.05-mm)
- LRTM (Lite RTM) tooling accuracy is +/- 0.025-inch at best – (+/- 0.65-mm)
- LRTM tool accuracy governed by fiber pack and vacuum level – often unpredictable
- RTM tool set accuracy controlled by design (very predictable)
- Can usually “net mold” with RTM
- Lite RTM going to require edge trimming
VIP (Vacuum Infusion Processing) TOOLING
Vacuum Infusion Process (VIP) Mold

Advantages:
- Lower cost than LRTM tooling
- Intimate vacuum bag allows for good compaction and high fiber volume fraction

Note: Resin reservoir is below mold height

Large flange area required to facilitate vacuum & resin plumbing and adequate resin “break zone”
SQRTM TOOLING
Multi-Piece *SQRTM Tooling
*Same qualified resin transfer molding process

Advantages: Uses same qualified liquid resin to provide cavity pressure to further consolidate prepreg materials
Mold one-piece monocoque structures

All black-anodized aluminum tooling with adjacent platen press work cell

Courtesy of Radius Engineering
Assembled SQRTM Tooling Ready for Additional Resin Infusion
HP-RTM TOOLING PROCESS
HP-RTM Mold Tooling for BMW i8
Side-frame Molded Part
TOOLING “DESIGN & PROCESSING” CONSIDERATIONS
CURE TOOLING GENERAL REQUIREMENTS
POTENTIAL REQUIREMENTS FOR COMPOSITE CURE TOOLING

- Stable at Use Temperature (Usually 350°F) OR HIGHER
- Withstand Loads of 100 psi
- Smooth Finish in Part Area
- Acceptable to Parting Agent
- Have Expansion Factor Compensation
- Wear Resistant to Scraping
- Resistant to Solvent Cleaning
- Machinable or Capable of Lamination
- Locate and Support All Components
- Capable of Producing Production Article within Tolerance and Process Specification
- May Require Vacuum Integrity
- Uniform Heat-Up Rate
- Light Weight
- Compatible to Shop Equipment
TOOLING THERMAL MANAGEMENT
THERMAL MANAGEMENT

• Tool heat-up/cool-down:
  • Steel, aluminum expand more than composite part during heating
  • During cooling they contract much more

• Expansion/contraction of tool can cause composite part damage!

• Tooling thermal expansion can be handled by:
  • Cooling tool at room temperature
  • Allowing for expansion in tool design (often proprietary)
Thermal Expansion Correction Factors for Tooling

Thermal Correction = Engineering Dimension \times (CTE_P - CTE_T) \times (T_{Gel} - T_{RT}) \times \text{"Z"}

Where:
- $CTE_P$ = Coefficient of Thermal Expansion of Part
- $CTE_T$ = Coefficient of Thermal Expansion of Tool
- $T_{Gel}$ = Temperature of Resin Gelation
- $T_{RT}$ = Room Temperature

$x = \text{Engineering Part Dimension}$

$\text{"Z"} = \text{Correction Factor}$
SPRING-IN / SPRING-OUT ISSUES
SPRING-IN & SPRING-OUT OPTIONS

• “Angled tooling geometries” must compensate for part-tooling thermal expansion:
  • Depends on part lamination, configuration, and properties
  • Composites tend to “spring-in” – contract during cure shrinkage
  • Metals tend to “spring-back” – so often must be “over-formed” at room temperature

• Analysis (typically Finite Element Analysis – FEA) can handle this during tool design
Spring-In Correction Factors

Note: 1.5° shown. Typical values range from 0-5° depending on tool material used.
Cool-down from cure can cause problems because the tool shrinks or contracts at a faster rate than the part. For a tooling material with a large CTE such as aluminum, the tool can actually bind the part causing ply cracking or delaminations.
Shear Pins Used to Eliminate Tool Shrinkage Damage

Teflon shear pins are often used to prevent damage. It is possible to hard pin a tooling detail at one, or possibly two locations, on the bond tool, but the detail must be allowed to freely contract separate from the bond tool on cooling.
Draft Used to Prevent Tool Shrinkage Damage

Draft is often required in a tool pocket to allow the part to be pushed out from the pocket during cool-down avoiding the possibility of ply cracking.