Overview

- Additive overview
- Tooling applications
- End use part applications
- Tooling for composites
Additive Mfg Sweet Spot

High Complexity, Low Quantity
• Specialty End Use Parts
• Tooling!

Additive Mfg

Conventional Mfg

Complexity

Additive Mfg
Sweet Spot

Quantity

Slide Style Credit to Paul Hauwiller of GDIT
Product Lifecycle Applications

- **Design**
  - Concept Models
  - Access Concept Validation
  - Assembly Simulation

- **Prototype**
  - Prototypes Models

- **Test**
  - Specialized Interface Models
  - Functional Test Models

- **Manufacture**
  - Low Rate Manufacturing Tooling
  - Rate Manufacturing Tooling
  - Specialized Shop Aids
  - Jigs & Fixtures
  - End Use Parts

- **Support**
  - Repair Jigs & Fixtures
  - Repair Shop Aids
  - Repair Tooling
Metal Forming Tools

US Naval Air Systems Command Depots

Hydro Form  Rubber Pad  Stretch Form  Tube Form
Metal Forming
Mold Tools

High Temp Washout Core Molds

Silicone Gasket Mold

Reconfigurable Over Mold
# Injection Molds

<table>
<thead>
<tr>
<th>Part description</th>
<th>Test part</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material injected</td>
<td>PP</td>
</tr>
<tr>
<td>Special features</td>
<td>Living hinge, bosses, press fit</td>
</tr>
</tbody>
</table>
| comments | • 100 parts out of 2 tools  
• Low pressure developed  
• Tools did not fail |

<table>
<thead>
<tr>
<th>Material</th>
<th>PP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Temp [F]</td>
<td>428</td>
</tr>
<tr>
<td>Inj. Pressure [psi]</td>
<td>8700</td>
</tr>
<tr>
<td>Hold Pressure [psi]</td>
<td>4351</td>
</tr>
<tr>
<td>Holding time [s]</td>
<td>8</td>
</tr>
<tr>
<td>cycle time [s]</td>
<td>180</td>
</tr>
<tr>
<td>Comments</td>
<td>Cooling with air pressure</td>
</tr>
<tr>
<td></td>
<td>Cost (US$)</td>
</tr>
<tr>
<td>------------------</td>
<td>------------</td>
</tr>
<tr>
<td><strong>P20 Steel</strong></td>
<td>3400</td>
</tr>
<tr>
<td><strong>Aluminum</strong></td>
<td>1670</td>
</tr>
<tr>
<td><strong>ABS-like</strong></td>
<td>960</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Time saving: 700-1800%
Cost savings:
• 43% over aluminum
• 72% over steel
Trim & Drill Tools

Lockheed Martin Drill Tool

Coordinated Tool Family With Drill Tool
Thermoform Tools

Tool

Trials

Production

Complex Tooling
Assembly Aids
End Use Parts – Light Aircraft

Picture courtesy of RapidPSI

[Images of light aircraft interiors and components]
Unmanned Systems

Pictures courtesy of Draganfly

Pictures courtesy of Leptron

Pictures courtesy of Embry-Riddle

Picture courtesy of NEO S-300 VTOL UAV Swiss UAV GmbH
FDM Composite Tooling

FDM Composite Applications

Patterns
Lay Up / Cure Tools
Consumable Cores
Jigs & Fixtures

Masters
Pre Layup
Consolidation Tools
Low Temp
High Temp
Bonding Fixtures
Intensifiers
Caul Plates
Soluble Cores
Net Shaped Cores
Integrated Interfaces
Trim Tool
Drill Tool
Check Fixture
Coordinated Tool Family

- Application
  - UAV wing box
- Benefits
  - Scaled tool size and qty to meet rate demands
  - Digitally mastered tool family
  - Concurrent tool fabrication

Model Based Definition

Tooling CAD Models

Completed Cover

Female Co-Bond Tool

Trim Tool

Drill Tool

Lay Up Tool

Consumable Core

Co-Bond Tool

Finished Part
Dynamic Flex Test

- 180°C (350°F): Little Margin For Over Temp
- 120°C (250°F): 79%
- 37%
- 32%

Graph showing temperature vs. percent of strength for materials ULTEM 9085, SR100, and ABSM30.
FDM Material Application Map

**FDM Materials**

<table>
<thead>
<tr>
<th>Service Temp</th>
<th>AMB</th>
<th>AMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>80°C</td>
<td>120°C</td>
<td>175°C</td>
</tr>
<tr>
<td>180°F</td>
<td>250°F</td>
<td>350°F</td>
</tr>
</tbody>
</table>

- **ABS**
  - Low Temp Tools
  - Low Temp Consumable Cores
  - Master Patterns

- **SR30/SR100/S1**
  - SR30 Soluble Cores
  - SR100 Soluble Cores
  - ULTEM S1 Break Out Cores

- **PC**
  - Low Temp Cure Tools & Consumable Cores
  - Master Patterns
  - Trim & Drill Tools

- **ULTEM 9085**
  - Med Temp Cure Tools & Consumable Cores
  - High Strength Trim & Drill Tools
  - Caution above 150°C/300°F

- **PPSF**
  - High Temp Tools & Consumable Cores

- **ABS Master & Tooling Composites**
  - High Temp CTE Matched Tools

- **ABS Master & Nevada Composites**
  - High Temp CTE Matched Tools
  - High Temp CTE Matched Soluble Cores

**Notes**

- ABS:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

- PC:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

- ULTEM 9085:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

- PPSF:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

- ABS Master & Tooling Composites:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

- ABS Master & Nevada Composites:
  - Service Temp: 80°C, 120°C, 175°C
  - AMB: 180°F, 250°F, 350°F

**Temperatures in °C/°F**

- ABS: 150°C/300°F Max
- ULTEM 9085: 200°C (400°F) Max
- ABS Master & Tooling Composites: 371°C (700°F)
Soluble Cores

- **Dissolve FDM soluble core**
  - WaterWorks bath solution
  - Heated tank ~ 140°F (60°C)
  - Agitation & circulation recommended
  - Rinse composite part
  - Duration is dependent on geometry

- **Compatible with most epoxy resins**
  - WaterWorks has been demonstrated to attack some polyester resins
  - Tests to confirm resin compatibility are recommended
Break Out Cores

ULTEM S1 CORE

- ULTEM S1 core compromised with acetone after cure
- ULTEM S1 becomes brittle
- Core is broken into pieces for removal

Cured Part

Finished Part
Large Hybrid Cores

• Mandrel Specifications
  – Hybrid mandrel
    • Aluminum main shaft
      • ~ 6’ (15.2cm) long x 9” (22.9cm) dia
    • FDM soluble core ends
      • 24” (61cm) diameter x 12” (30.5cm) tall
  – 12 lb normal load for tow winding
  – 200°F (121°C) Cure

• Lessons Learned
  – Washout process is a design driver
  – Part rotation during cure evens out loads during cure cycle
Hybrid Break Out Core

- Aluminum/ULTEM-S1 Hybrid
  - Reusable aluminum sections
  - ULTEM-S1 trapped section
  - Build time minutes
  - Minimal costs
  - Size mitigated CTE mismatch
Automotive Applications

SR-100 Soluble Tool Material
• Produce 250°F cured composite parts
• 80 psi pressure
• Supports complex geometries
Thin Skin Tooling

- **Design**
  - Ultem material
  - 6mm thick
  - 5hrs build time
  - Tool surfaced with epoxy
  - Vibratory polished hands off for 1 hr

- **Use**
  - Released surface
  - Lay up part
  - Envelop bagging balances forces
  - Cured at 250F, 80 psi
  - Caution: geometry sensitive
Larger Scale Tooling

Lockheed Martin Layup Tool

Boeing FDM C-channel Mandrel
Hybrid Assemblies

• First Robotics Team #3824
  – Hardin Valley Academy
  – RoHawktics
  – Sponsored by ORNL Manufacturing Demonstration Facility (MDF)

• Hybrid Assembly
  – FDM Fittings
  – Pultruded Rods
  – Filament winding

• Benefits
  – Additive is great at relatively smaller more complex
  – Carbon fiber is great at long, simple, light weight, high strength structures
  – Combining provides strengths of both technologies
First Robotic Team #3824

- Application
  - Robot Chassis
  - Stiff/light weight
- Solution
  - FDM light weight end pieces with critical interfaces
  - Pultruded carbon rods for spanners
  - Filament wound for bonding and strength/stiffness
- Results

<table>
<thead>
<tr>
<th>Part</th>
<th>Length</th>
<th>AM Only</th>
<th>Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fab Time</td>
<td>Weight</td>
</tr>
<tr>
<td>Long Beam</td>
<td>54&quot;</td>
<td>90 hrs</td>
<td>14.64 lbs</td>
</tr>
<tr>
<td>Short Beam</td>
<td>21&quot;</td>
<td>24 hrs</td>
<td>7.44 lbs</td>
</tr>
</tbody>
</table>
Summary

• Additive has a growing role in manufacturing
• Stratasys provides solutions over product life cycle
• Enabling a wide spectrum of tooling options
• Performance materials enable end use parts
• Real solutions for composite tooling
• R&D efforts expand validated applications
John Dobstetter
Stratasys DDM Group
Business Development Manager
John.dobstetter@stratasys.com
732-495-4027 o
612-963-2395 c
Back Up Slides
Thin Skin Tooling

• Tool
  – Thickness 8mm (0.31”)
  – Material PPSF

• Lay Up
  – Aramid fiber, 108g/m^2
  – 180C epoxy resin

• Results
  – Final tolerance: ±0.25 (0.010”) on 350mm (12”)
  – No spring back effect on “C” shape”
Aerospace Application

• Application
  – Inlet duct, size = 0.6m x 0.6m x 0.9m (2’x2’x3’)
  – Trapped geometry

• Solution
  – 180°C OoA composite system
  – 2 hr 130°C (266°F) initial cure
  – 2 hr freestanding 180°C (356°C) post cure
  – ULTEM S1 break out core

• Results
  – Tool build time < 8 days
  – Reduced tool lead time to < 14 days
  – Tool maintained less than +/-1 mm (0.040”) accuracy

Project worked with NGC under AFRL Call 6 Program
Break Out Core Application

Tool Preparation

Out of Autoclave Composite Layup

Debulking

Envelope Bagging

Cured Composite Structure

Tool Break Out
# Injection Molds

<table>
<thead>
<tr>
<th>Industry</th>
<th>Automotive</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part description</td>
<td>Steering wheel connector</td>
</tr>
<tr>
<td>Material injected</td>
<td>Wax, HDPE</td>
</tr>
<tr>
<td>Special features</td>
<td>Highly complex. Thin walls</td>
</tr>
<tr>
<td>comments</td>
<td>10 parts molded, long cycle time</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>HDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Temp [F]</td>
<td>365</td>
</tr>
<tr>
<td>Inj. Pressure [psi]</td>
<td>8700</td>
</tr>
<tr>
<td>Hold Pressure [psi]</td>
<td>4351</td>
</tr>
<tr>
<td>cycle time [s]</td>
<td>360</td>
</tr>
<tr>
<td>Clamping force [kN]</td>
<td>300</td>
</tr>
</tbody>
</table>
# Injection Molds

<table>
<thead>
<tr>
<th>Industry</th>
<th>Consumer goods</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part description</td>
<td>Ice cream spoons</td>
</tr>
<tr>
<td>Material injected</td>
<td>PP</td>
</tr>
<tr>
<td>Special features</td>
<td>6 cavity mold</td>
</tr>
<tr>
<td>comments</td>
<td>Injected in different colors</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Material</th>
<th>Cost (US$)</th>
<th>Turnaround (days)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>P20 Steel</td>
<td>3200</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>Aluminum</td>
<td>1400</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>ABS-like</td>
<td>785</td>
<td>7 hr. (1 day)</td>
<td>Connex 260 Consumption: 400gr RGD535 480gr RGD515 100gr support</td>
</tr>
</tbody>
</table>

**Time saving:** 3000%

**Cost savings:**
- 44% over aluminum
- 75% over steel
<table>
<thead>
<tr>
<th>Item/ Material Group</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Materials</td>
<td>PP, PE, PS, ABS, TPE..</td>
<td>• PP +GF, PA, POM, PC+ABS, PVC...</td>
<td>• PA+GF, PC, POM+GF...</td>
<td>• PC+GF, PPO, PPS..</td>
</tr>
<tr>
<td>Geometry</td>
<td>• Accuracy up to 0.1mm</td>
<td>• Thin walls down to 0.5mm</td>
<td>• Pins down to 0.8mm</td>
<td></td>
</tr>
<tr>
<td>Size</td>
<td>• Insert/ Mold up to 500<em>400</em>200mm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of parts</td>
<td>~100</td>
<td>• ~30</td>
<td>• ~15</td>
<td>• ~5</td>
</tr>
<tr>
<td>Process</td>
<td>• According to Rapid Molds IM guidelines</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tool Design</td>
<td>• According to Rapid Molds IM guidelines</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Answers to FAQ are mostly found in this table
## Part 1 – Injection parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>PP+GF</th>
<th>PA+GF</th>
<th>POM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nozzle Temp [C]</td>
<td>195</td>
<td>285</td>
<td>195</td>
</tr>
<tr>
<td>Inj. Pressure [bar]</td>
<td>200</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Hold Pressure [bar]</td>
<td>200-400</td>
<td>200-400</td>
<td>200-400</td>
</tr>
<tr>
<td>cycle time [s]</td>
<td>110</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>Clamping force [kN]</td>
<td>400</td>
<td>400</td>
<td>400</td>
</tr>
</tbody>
</table>
Additive Manufacturing Evolution

Prototypes
- Affordability
- Tough materials
- Minimal build constraints

Functional Prototypes
- Tougher materials
- Bigger build sizes

Tooling
- Engineered Materials
- Engineered Solutions
- Lower Risk Adoption

End Use Parts
- Design Rules
- Industry Experience
- Industry Standards
- Proven Material Properties
Aero – Interior Applications

ULTEM 9085 Flame, Smoke, & Toxicity rated

Enables commercial aerospace interior applications
Fused Deposition Modeling

- Additive Manufacturing Process
- Thermal Plastic Materials
- Lights Out Fabrication

Process CAD File → Manufacture → Completed Part
FDM Process
FDM Process

Filament Fed Liquefier

Layered Deposition of Model & Support Material

Layer By Layer Deposition Until Desired Part is Realized

Once Build is Complete Model & Support are Separated

Source of images – Solid Concept YouTube Video http://youtu.be/oujzQvz79ig
# FDM Material Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>SR30</th>
<th>SR100</th>
<th>ULTEM S1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tg</strong> (°F)</td>
<td>212</td>
<td>271</td>
<td>365</td>
</tr>
<tr>
<td><strong>Tg</strong> (°C)</td>
<td>100</td>
<td>133</td>
<td>185</td>
</tr>
<tr>
<td><strong>CTE (ASTM E228)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95°F-212°F</td>
<td>[E-5 in/(in°F)]</td>
<td>6.5</td>
<td>5.5</td>
</tr>
<tr>
<td>35°C-100°C</td>
<td>[E-6 m/(m°C)]</td>
<td>115.53</td>
<td>100</td>
</tr>
<tr>
<td><strong>CTE (ASTM E228)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>212°F-266°F</td>
<td>[E-5 in/(in°F)]</td>
<td>Not Applicable</td>
<td>10.4</td>
</tr>
<tr>
<td>100°C-130°C</td>
<td>[E-6 m/(m°C)]</td>
<td>Not Applicable</td>
<td>195</td>
</tr>
<tr>
<td><strong>CTE (ASTM E228)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>95°F-330°F</td>
<td>[E-5 in/(in°F)]</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
<tr>
<td>35°C-165°C</td>
<td>[E-6 m/(m°C)]</td>
<td>Not Applicable</td>
<td>Not Applicable</td>
</tr>
</tbody>
</table>
## ULTEM S1 Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Room Temp</th>
<th>High Temp</th>
<th>% Diff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Temp (°F)</td>
<td>70</td>
<td>350</td>
<td></td>
</tr>
<tr>
<td>Test Temp (°C)</td>
<td>32</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>Tensile Strength (ASTM E228) (KSI) (MPa)</td>
<td>7.97</td>
<td>3.81</td>
<td>48%</td>
</tr>
<tr>
<td>Tensile Strength (ASTM E228) (MPa)</td>
<td>54.95</td>
<td>26.27</td>
<td></td>
</tr>
<tr>
<td>Tensile Modulus (ASTM E228) (KSI) (MPa)</td>
<td>336</td>
<td>305</td>
<td>91%</td>
</tr>
<tr>
<td>Tensile Modulus (ASTM E228) (MPa)</td>
<td>2317</td>
<td>2103</td>
<td></td>
</tr>
<tr>
<td>Compressive Strength (ASTM E228) (KSI) (MPa)</td>
<td>6.97</td>
<td>3.39</td>
<td>49%</td>
</tr>
<tr>
<td>Compressive Strength (ASTM E228) (MPa)</td>
<td>48.06</td>
<td>23.37</td>
<td></td>
</tr>
<tr>
<td>Compressive Modulus (ASTM E228) (KSI) (MPa)</td>
<td>98</td>
<td>72</td>
<td>73%</td>
</tr>
<tr>
<td>Compressive Modulus (ASTM E228) (MPa)</td>
<td>676</td>
<td>496</td>
<td></td>
</tr>
</tbody>
</table>

*PRELIMINARY TEST DATA
Flat Build Orientation Only
Initial Material Tuning*
FDM Core Material Summary

ABS M30
- Pattern/mold for traditional tooling materials
- Pattern/mold for Nevada Composites tool materials

ULTEM S1
- Breakout, embrittled with acetone
- 300°F (150°C), 100psi (6.9 Bar) autoclave
- 350°F (175°C) as a free standing post cure

SR100
- Soluble, WaterWorks bath
- Up to 250°F (120°C), 80psi (5.5 Bar) autoclave

SR30
- Soluble, WaterWorks bath
- Up to 180°F (80°C), 80psi (5.5 Bar) autoclave
High Temp testing of Tensile & Compression Strength indicate 49% of ambient strength at 180°C (350°F)

Good Correlation w/ Dynamic Flex Results!
FDM Core Tool Design

• Design your core
  – Create geometry in CAD
  – Scale for CTE Growth
  – Export STL

• Process in Insight
  – Determine part density
  – Adjust raster air gap
  – Set wall thickness
  – Set “Invert build materials” checkbox
  – Generate tool paths
  – Save and send to FORTUS system
CTE Compensation

- **Part Tolerances**
  - Part tolerance +/-0.030inch

- **CTE Calculations**
  - Unadjusted ToolFeatureGrowth@CT = FeatureLength@RT x ΔTemp x CTEfdm
  - Adjusted ToolFeature@RT = FeatureLength@RT (1+ΔTemp(CTEcomp - CTEfdm))
  - TSFToolScaleFactor = ToolFeature@RT / FeatureLength@RT

**ULTEM Example**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Feature Length @ RoomTemp</th>
<th>Unadjusted Tool Feature Growth @ Cure Temp</th>
<th>Adjusted Tool Feature @ RoomTemp</th>
<th>Tool Scale Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width</td>
<td>1.5</td>
<td>0.015</td>
<td>1.489</td>
<td>99.266%</td>
</tr>
<tr>
<td>Height</td>
<td>3</td>
<td>0.030</td>
<td>2.978</td>
<td>99.266%</td>
</tr>
<tr>
<td>Length</td>
<td>23</td>
<td>0.232</td>
<td>22.831</td>
<td>99.266%</td>
</tr>
</tbody>
</table>
Tool Bagging Method

- **Surface Bagged**
  - Minimizes autoclave pressure loads on tool
  - Requires good surface seal throughout cure cycle
  - Requires additional tool surface to seal bag too

- **Envelop Bagged**
  - Full autoclave pressure applied to tool
  - Does not require a perfectly sealed surface
  - Long skinny tools many need special support at temperature

- **Bagged to Plate**
  - Full autoclave pressure applied to tool
  - Does not require a perfectly sealed surface
  - Plate can reinforce larger tools during cure cycle
Build Orientation

- **Identify Critical Surfaces**
- **Orientate Build**
  - Minimize layer stepping on least critical surfaces
  - Attempt to minimize build costs
Tool Finishing

- **“As Is”**
  - Fastest, minimal cost
  - Unimproved surface
  - Requires surface seal

- **Filled Surface**
  - Most accurate surface
  - Tough surface seal
  - Demonstrated multiple releases
  - Supports surface bagging

- **Sanded Surface**
  - Less accurate
  - Sand to valleys
  - Requires surface seal

- **Teflon Taped**
  - Provides a good surface seal and reliable release surface
  - Geometry dependent

---

<table>
<thead>
<tr>
<th>CAD Model</th>
<th>FDM Software Builds Crowns to CAD Surface</th>
<th>FDM Layered Part</th>
<th>Coated Part</th>
<th>Smoothed to crown [more accurate to CAD model]</th>
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<tbody>
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<td>Sanded Part Smoothed to valley [less accurate to CAD model]</td>
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Finishing Products

- **As Is**
  - Fastest method
  - Requires surface seal to prevent resin leaching
    - Vacuum bag seal
    - Hysol 9396/Zyvax QuickSkin

- **Filled Surface**
  - Most accurate surface
    - Fill and sand back to zebra
  - Demonstrated surface coats
    - Hysol 9394 & EA960F
  - Meets 350F service temp

- **Sanded Surface**
  - Less accurate
    - Sand to valleys
  - 120-220 grit aluminum oxide
  - Requires surface seal to prevent resin leaching
    - Hysol 9396/Zyvax QuickSkin

- **Teflon Taped**
  - Airtech’s “ToolTech” tape
  - Provides a good surface seal
  - Reliable release surface
  - Geometry dependent