A NEW CAMX
FOR A NEW TIME

COMBINED STRENGTH. UNSURPASSED INNOVATION

CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

SEPTEMBER 21-24 2020

A VIRTUAL EXPERIENCE

Tooling 101 for Composites Manufacturing

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THE COMPOSITES AND ADVANCED MATERIALS EXPO

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

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APPROACH

- **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

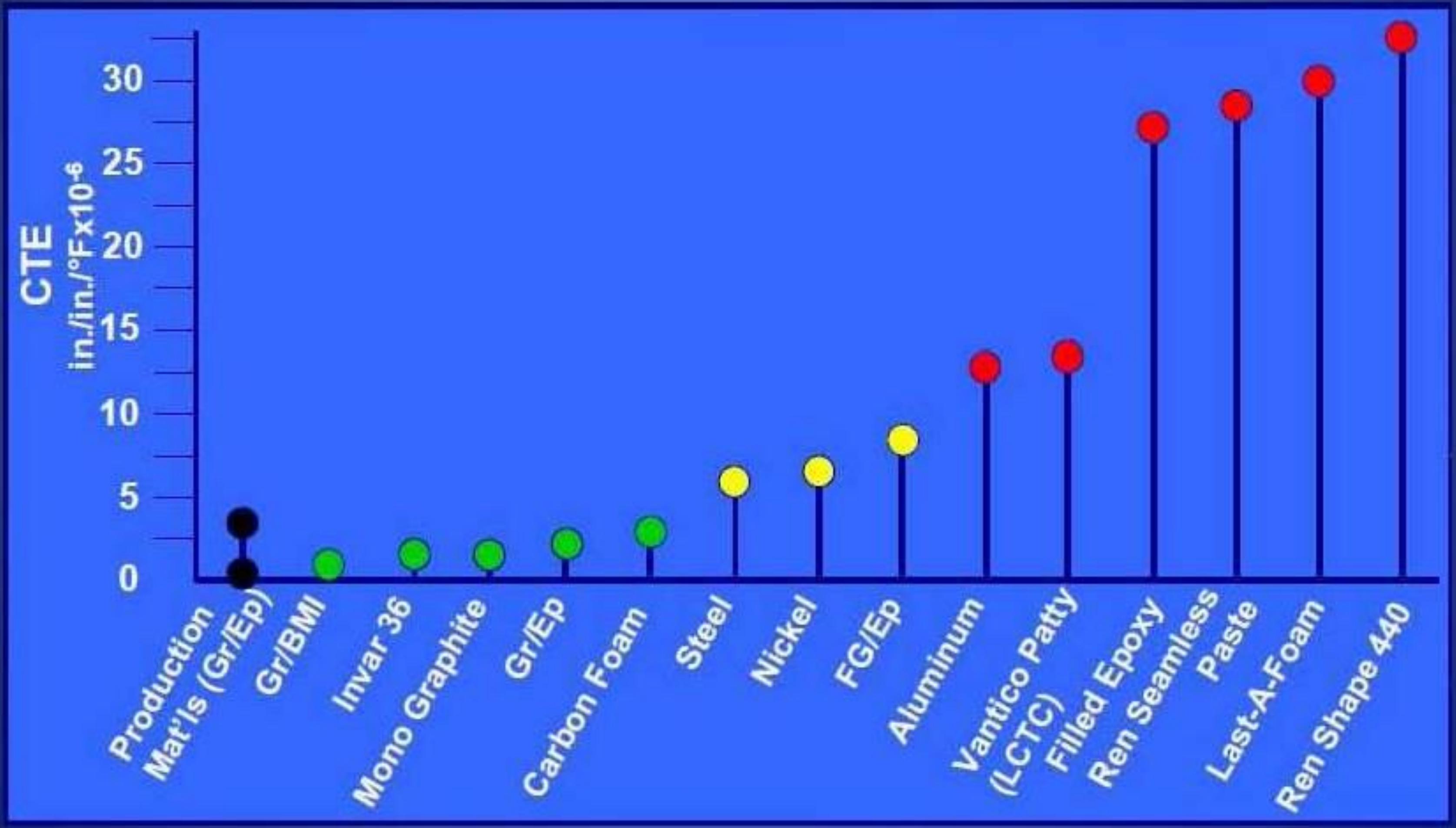
Frequently Used Tooling Materials

- 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

Material	Max Service Temp. (°F)	CTE $X10^{-6}$/ ºF	Density lbs./in.^{3}	Thermal Conductivity Btu./h x ft. x °F
Steel	1500	6.3-7.3	0.29	30
Aluminum	500	12.5-13.5	0.10	104-116
Electroformed Nickel	550	7.4-7.5	0.32	42-45
Invar/Nilo	1500	0.8-2.9	0.29	6-9
Carbon/Epoxy 350°F	350	2.0-5.0	0.058	2-3.5
Carbon/Epoxy RT/350°F	350	2.0-5.0	0.058	2-3.5
Glass/Epoxy 350°F	350	8.0-11.0	0.067	1.8-2.5
Glass/Epoxy RT/350°F	350	8.0-11.0	0.067	1.8-2.5
Monolithic Graphite	800	1.0-2.0	0.060	13-18
Mass Cast Ceramic	1650	0.40-0.45	0.093	0.5
Silicone	550	45-200	0.046	0.1
Isobutyl Rubber	350	≈ 90	0.040	0.1
Fluoroelastomer	450	≈ 80-90	0.065	0.1

CTE Comparison of Tooling Materials



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

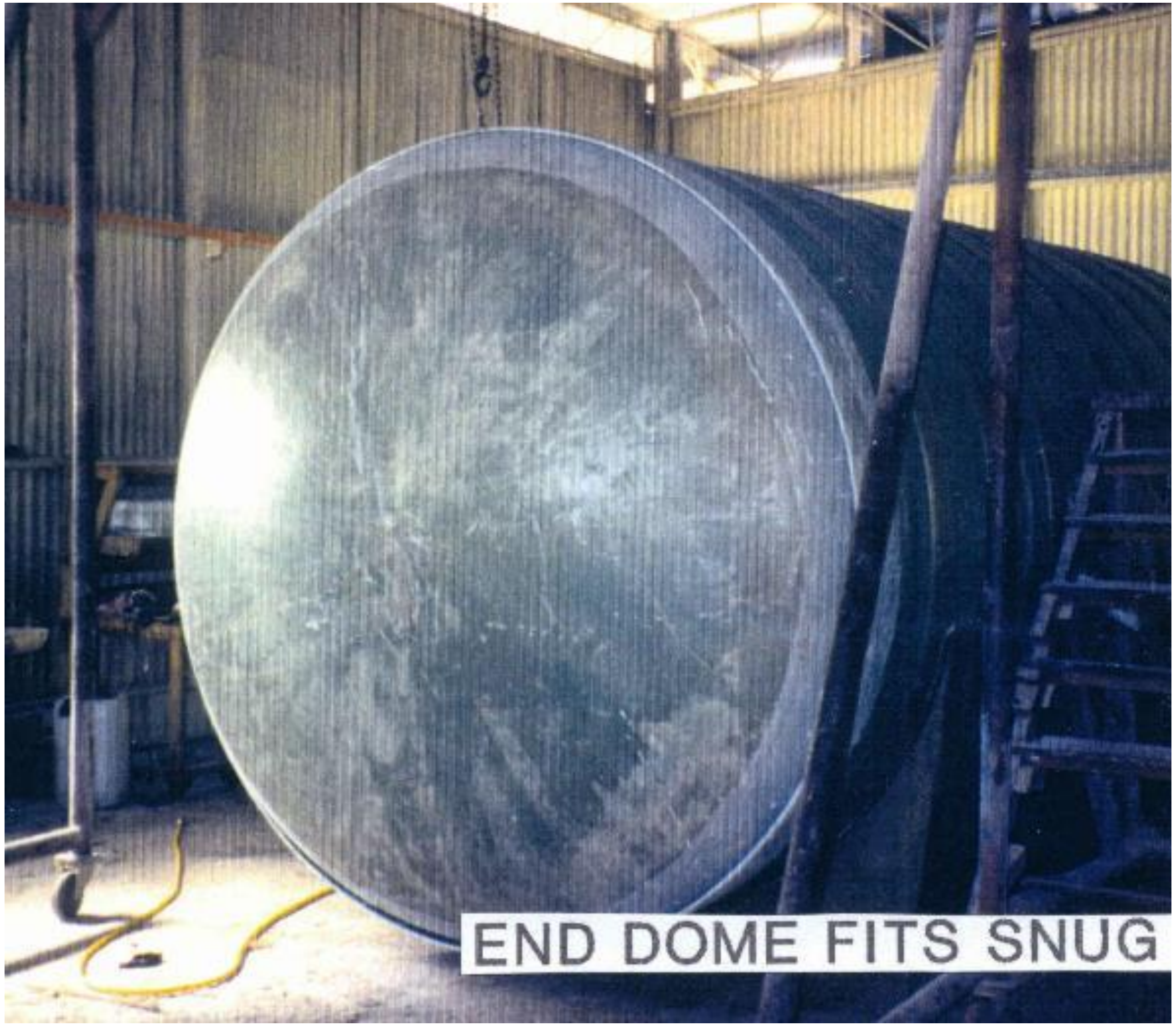
STEEL TOOLING EXAMPLES

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

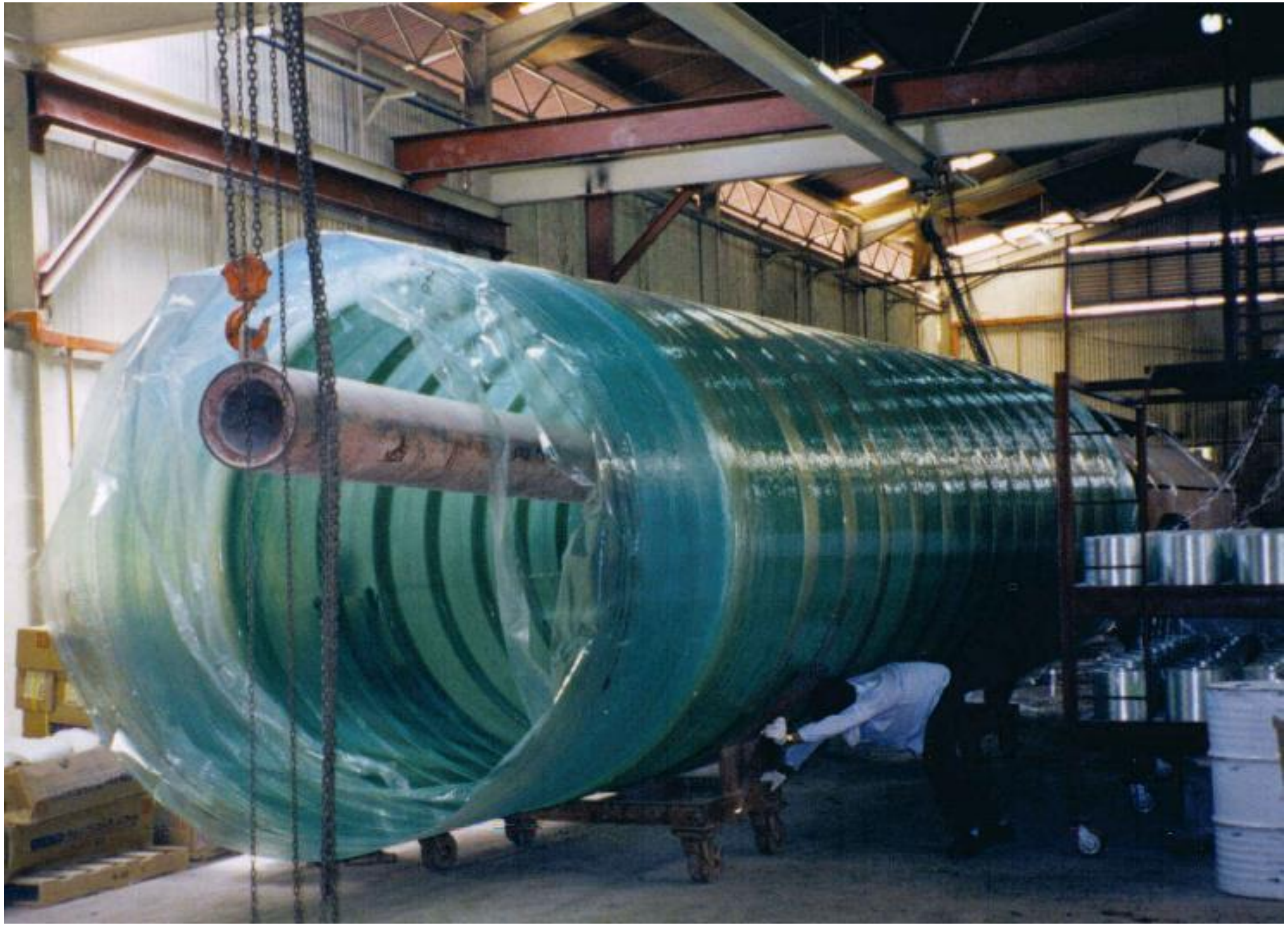
End Dome Installed (but Not Bonded) into UST Main Cylinder Body



Collapsible Steel Mandrel (Full Geometry)

Steel Mandrel <u>Now Collapsed</u> …

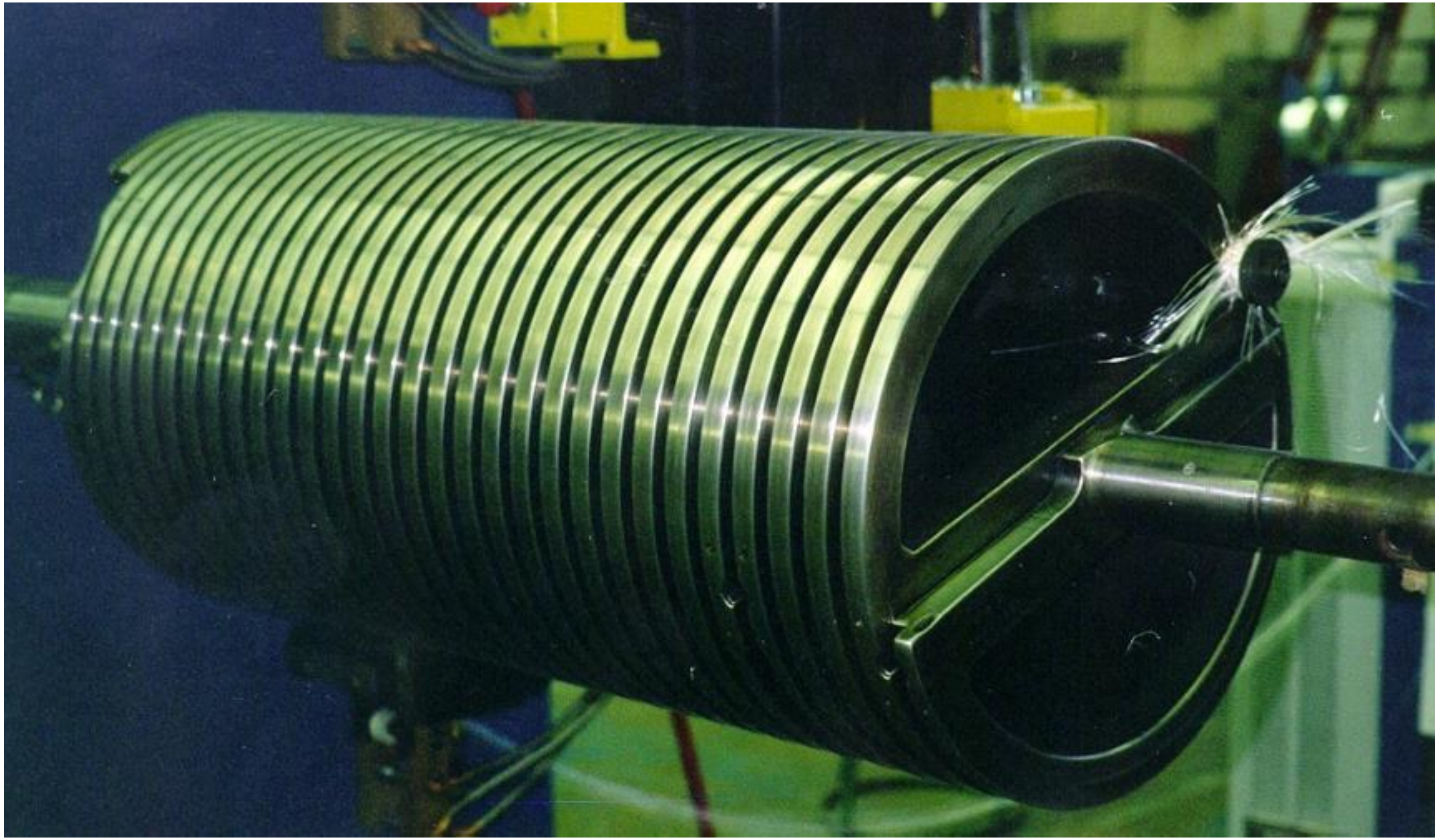
End View of UST Being Removed from Mandrel



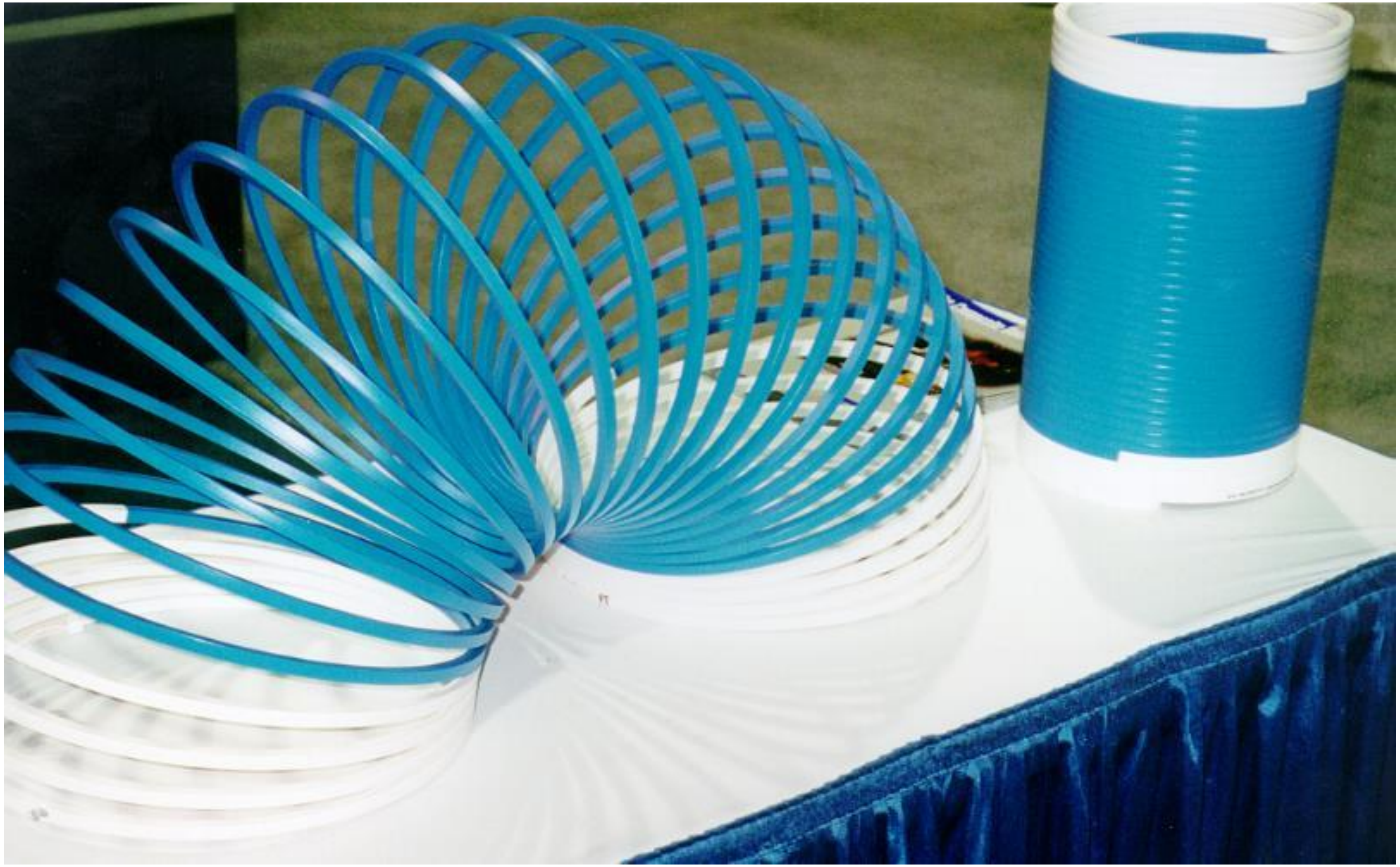
Filament Wound UST Extracted from Steel Mandrel

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 Molds and Mandrels for Aerospace

Photo courtesy of Process Fab, Inc.

Steel Tool face cut from single billet

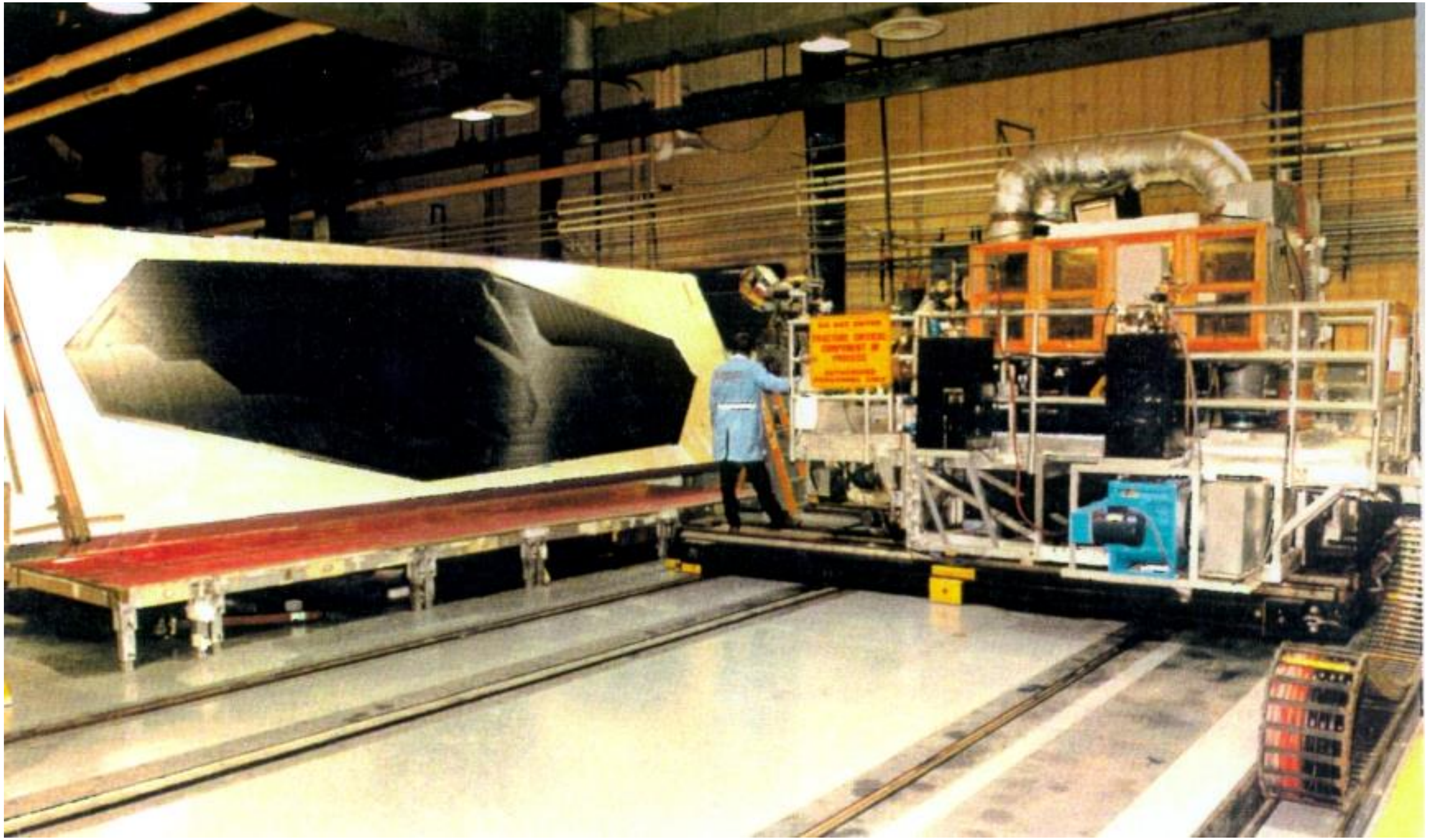
Fiber Placement Mandrel

AFP Composites Simplify and Speed Manufacturing (Boeing 787 Barrel Section)

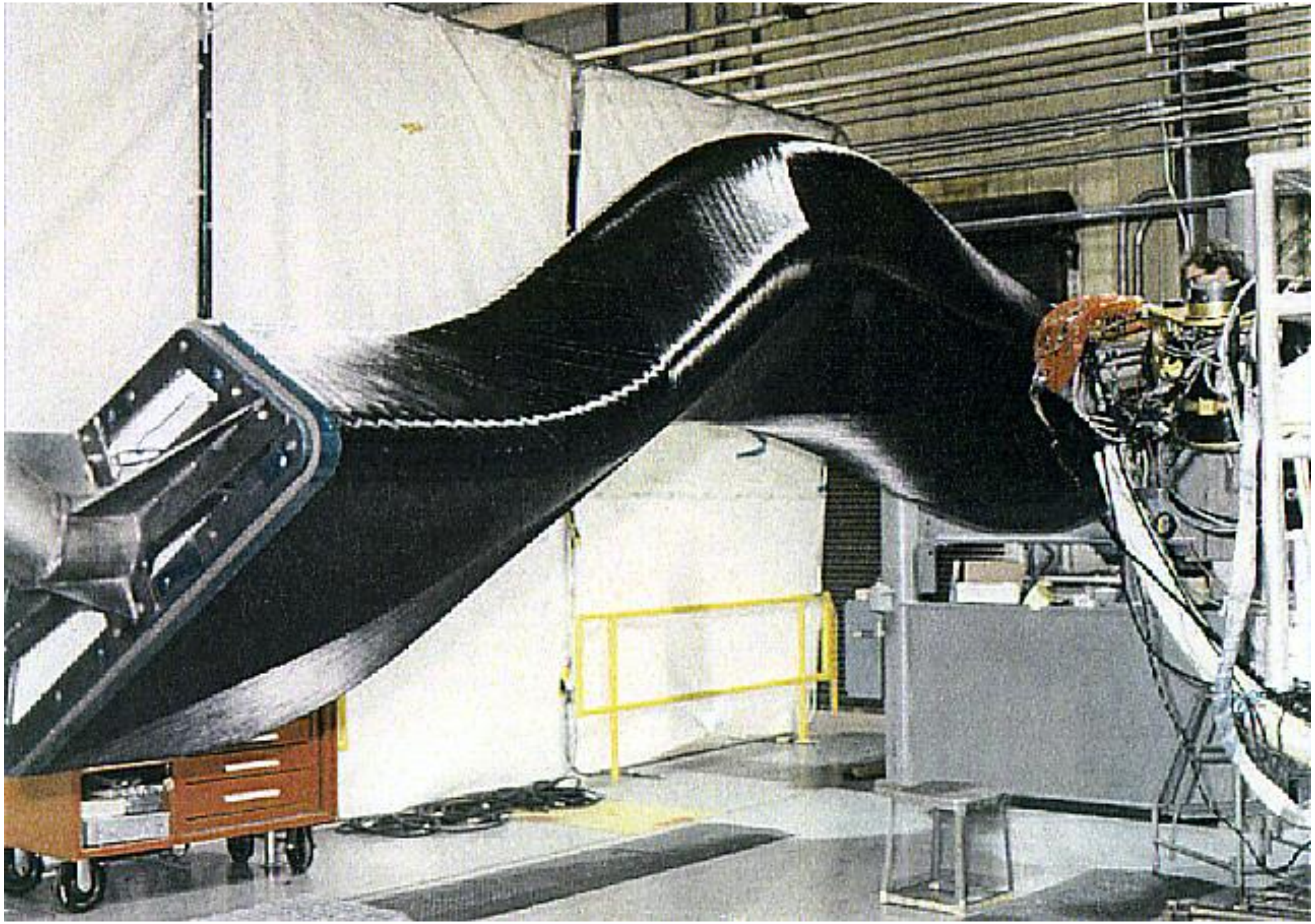
One Piece Barrel Section
(Boeing 787)

V-22 Aft Section Fiber Placement

AFP of Aircraft Stabilizer Section



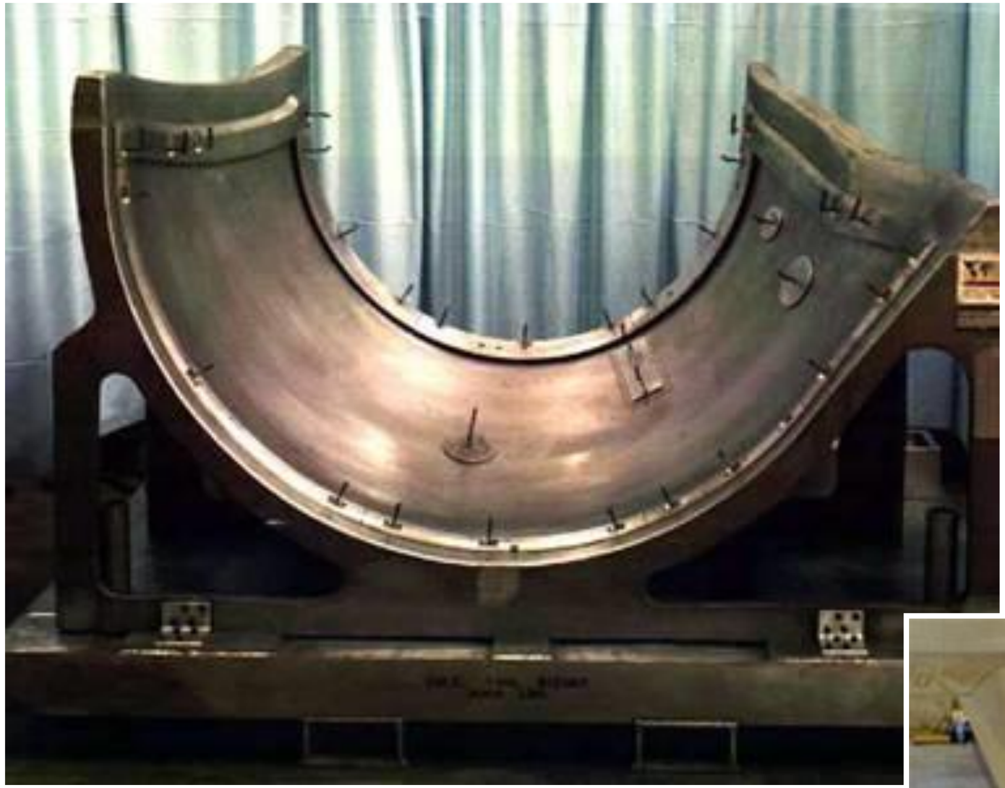
F-22 Inlet Duct (Complex Internal Tooling)



TP Fiber Placed Tooling by Robotic System

ALUMINUM TOOLING EXAMPLES

Aluminum Molds and Fixtures

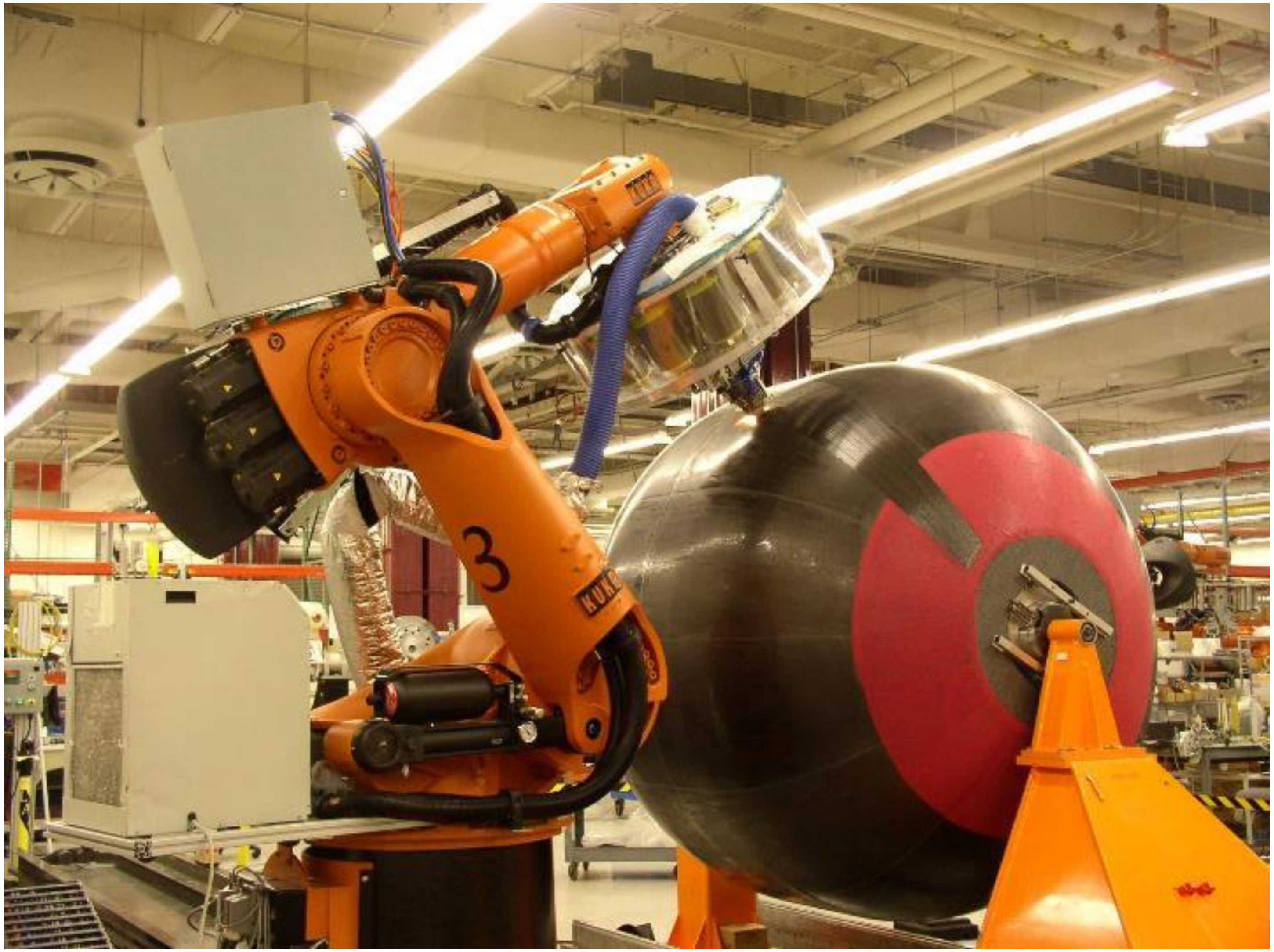


Aluminum Molds & Bond Fixtures

Complex shapes warrant careful CTE Calculations

Aluminum Fiber Placement Mandrel

Robotic Fiber Placement Over Metal Mandrel



INVAR TOOLING EXAMPLES

Invar Layup Mold

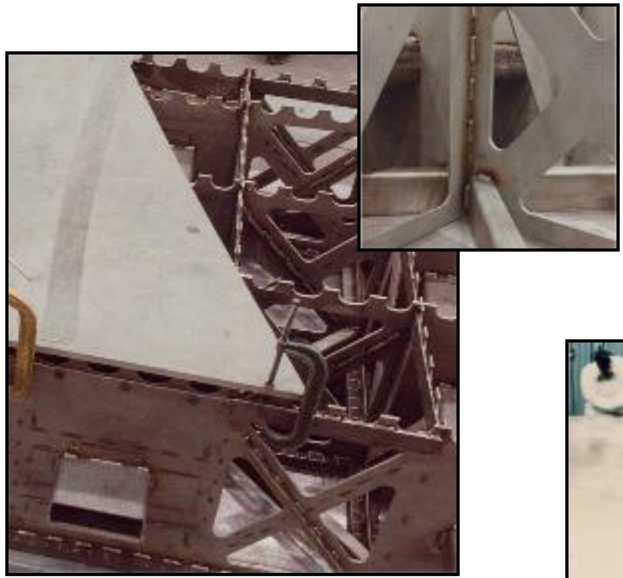
Basic Invar Tool Construction

Plate stock

Plasma cut headers

Machine surface

Bump-form facesheet



Assemble/weld

Hand finish

Finished tool

Invar Layup Mold

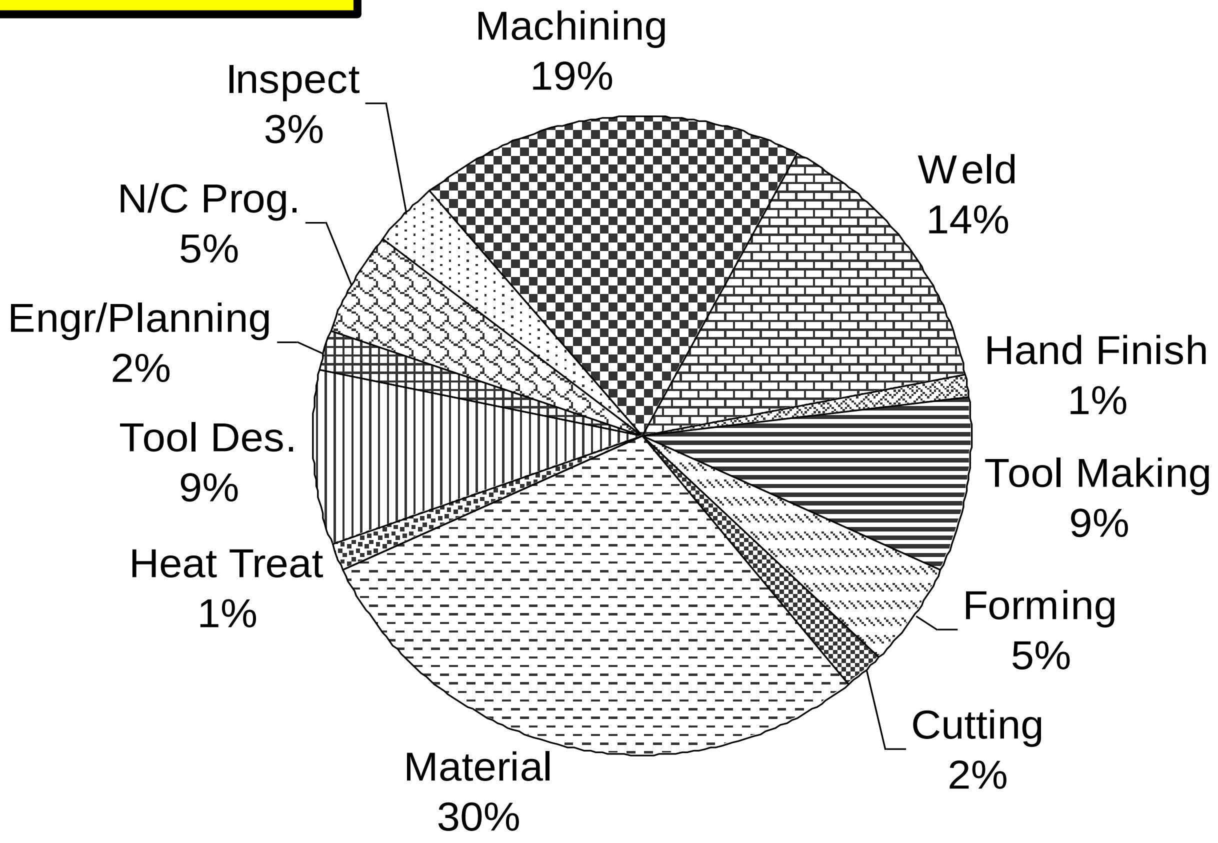
Invar Fiber Placement Mandrel

Photo courtesy of Fives Manufacturing

A-350 Empennage Section 19 Mandrel

Invar Tooling Cost Breakdown

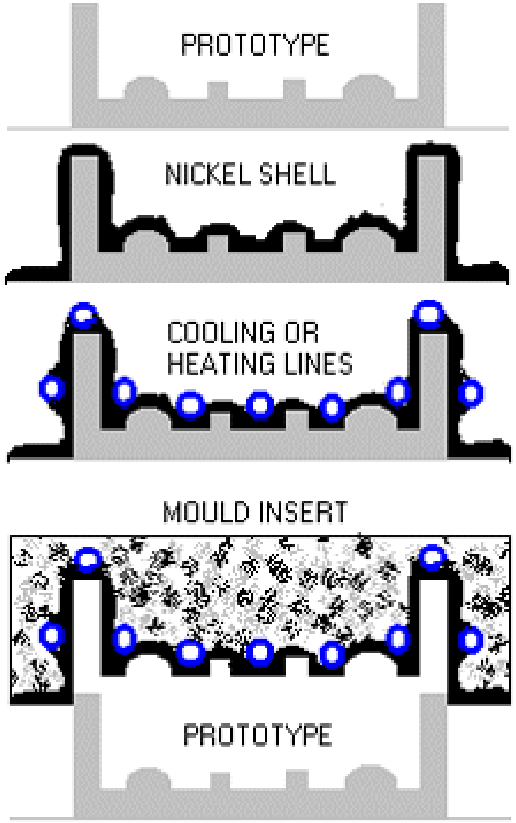
HIGHEST FACTORS:
- **Material cost (Invar 36, 42) – 30%**
- **Machining & Forming cost – 38%**



NICKEL TOOLING EXAMPLES

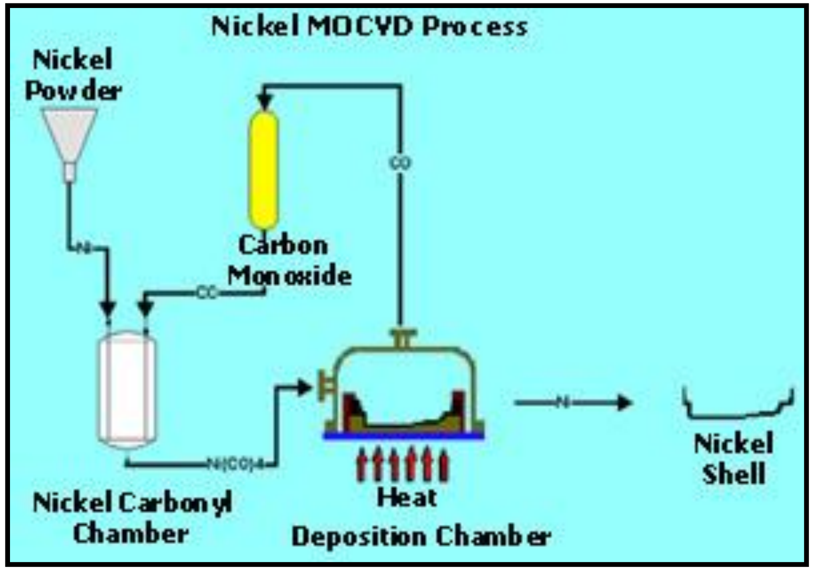
Nickel Plating Fabrication Process Steps

Electroforming (Plating) Process



Source: Metalon, Inc.

Nickel Vapor Deposition (NVD) Process



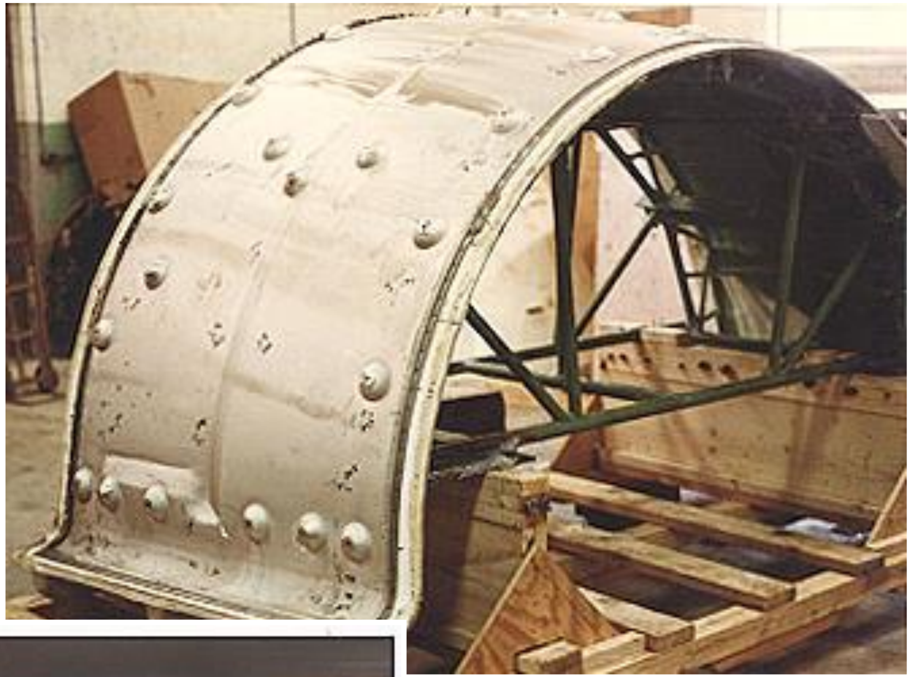
Source: CVD Mfg., Inc.

Metalon, Inc http://www.metalontech.com/tools.ihtml
Mafix, Inc. http://www.mafixinc.com/nickel.htm
CVD Manufacturing, Inc. 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

Image courtesy of Weber Mfg and Plasan Carbon Composites

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

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

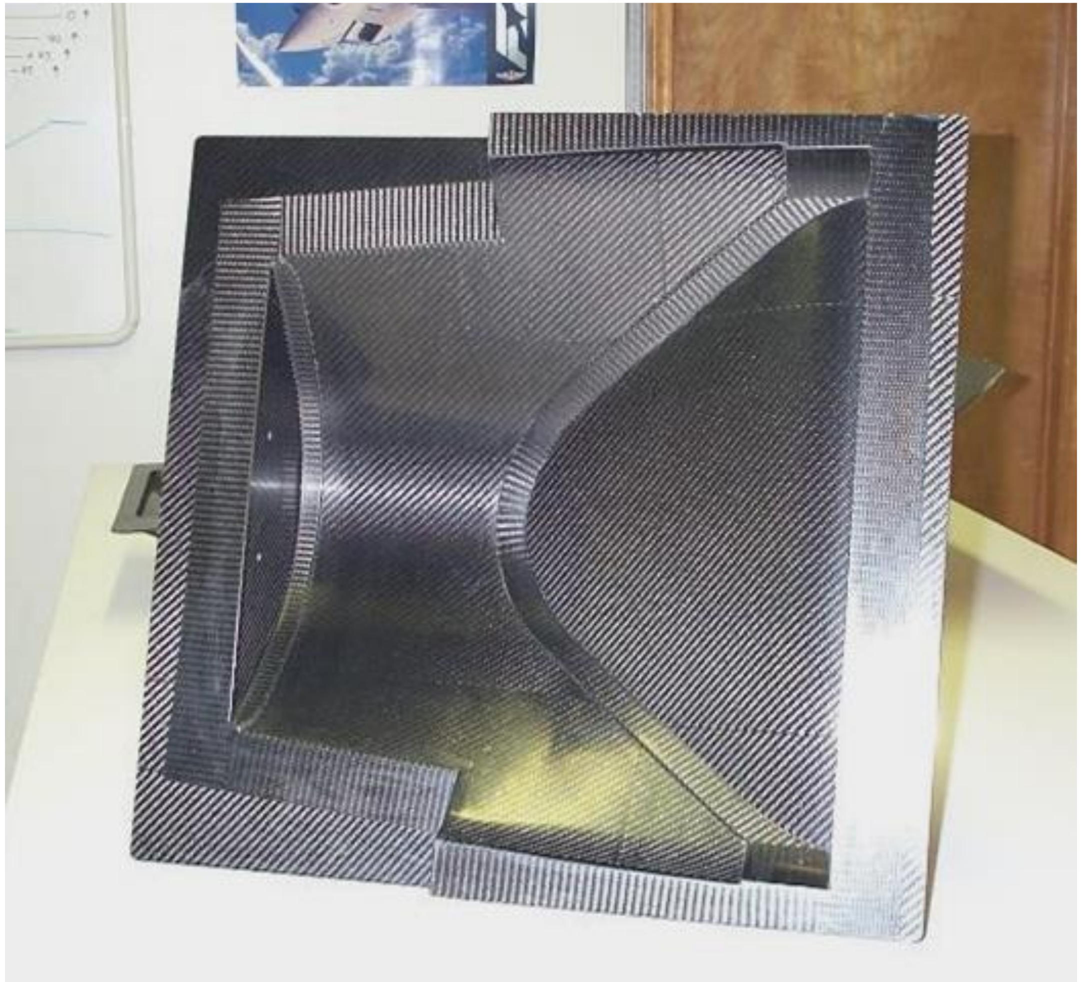
LPG = Liquified Propane Gas

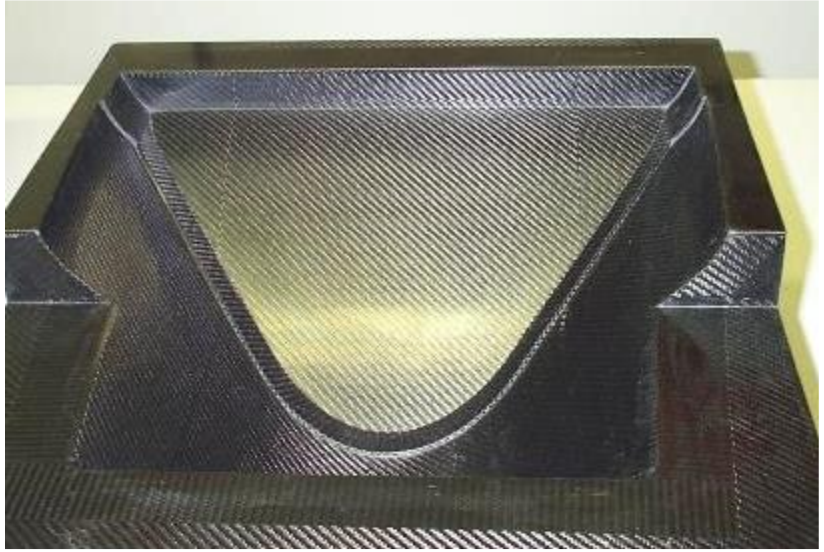
Five (5) LPG Tanks Wound on Plastic Liner Tools

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

Photo courtesy of Abaris Training

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

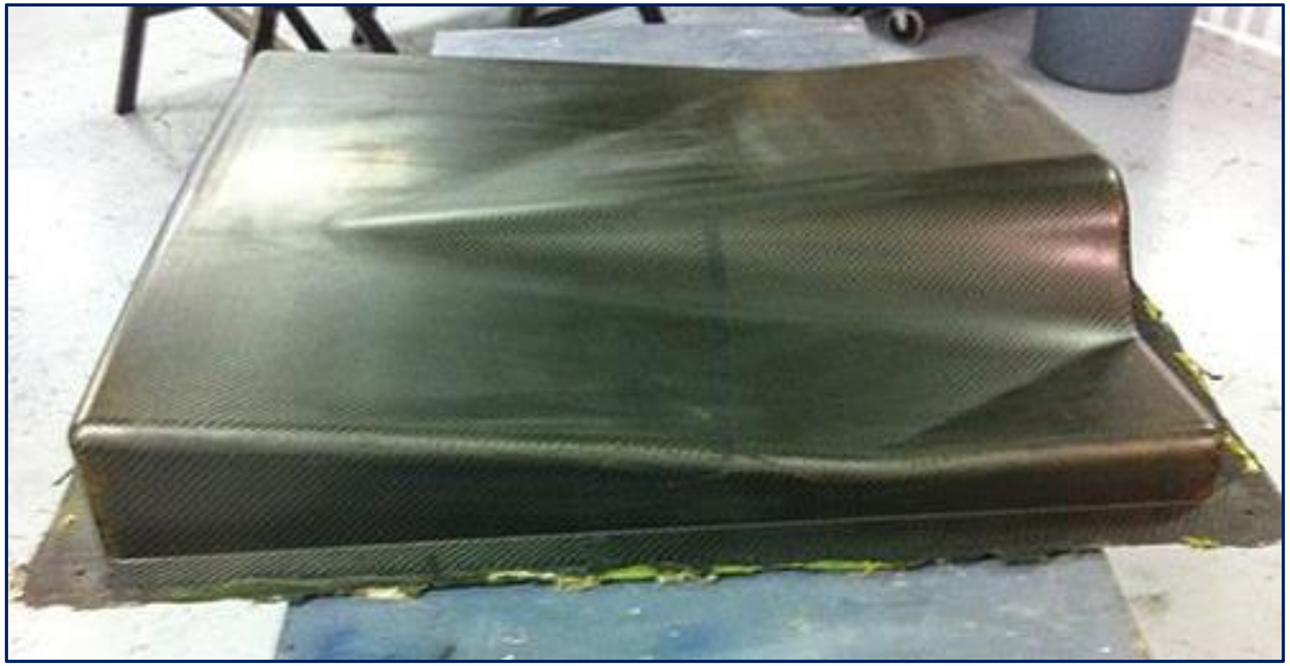
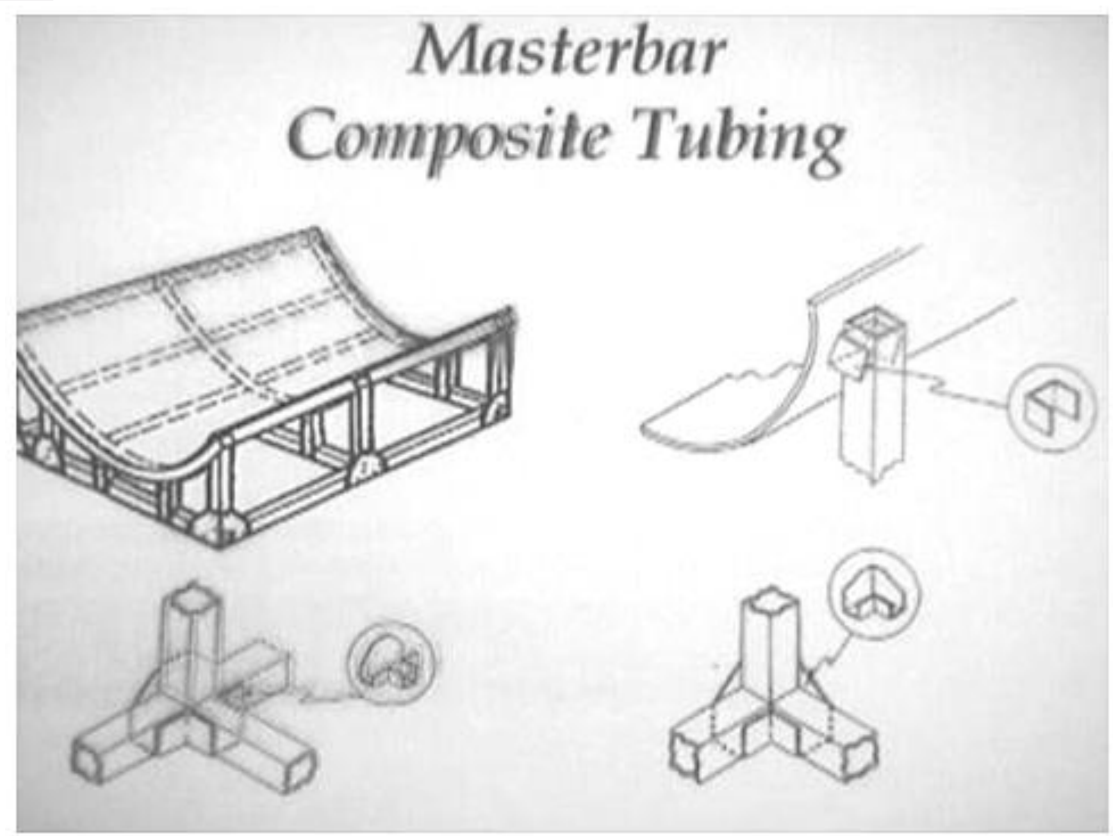


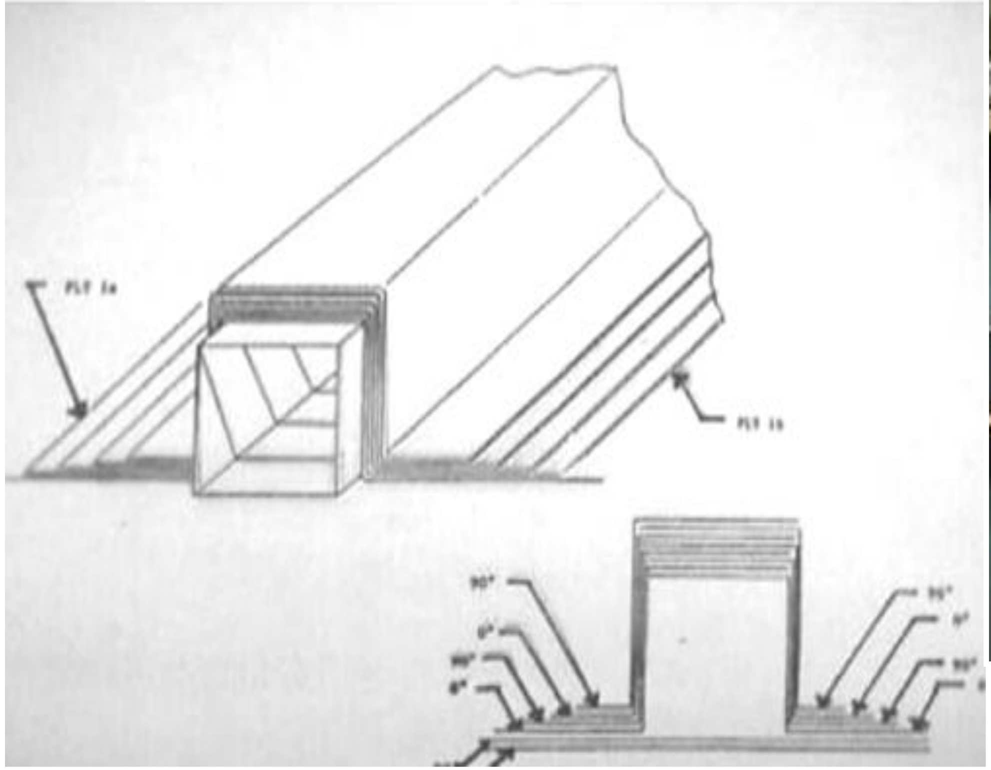
Photo courtesy of Airtech International

Carbon fiber-benzoxazine tool designed with self supporting features

Composite Tubular Structure



Integrally-Stiffened Tool Laminate



CFRP Laminate Layup Mold

Photo courtesy of Coast Composites-Ascent Aerospace co.

<u>Advantages:</u>

- o Lightweight
- o Heats/cools rapidly
- o Low CTE

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

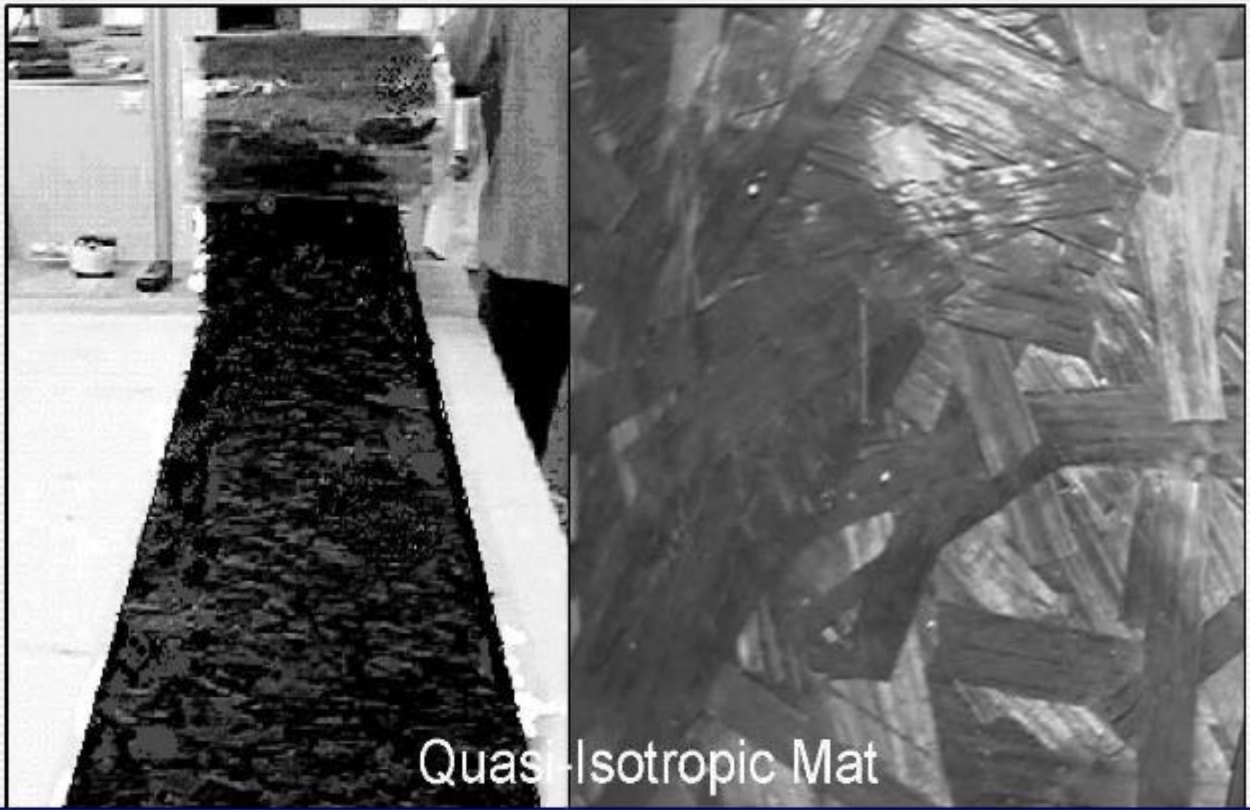
BMI Carbon Fiber "Duratool"

BMI = Bismaleimide resin system

Hexcel Random Fiber BMI "HexTool"

HexTool

HexTool Material (Roll)

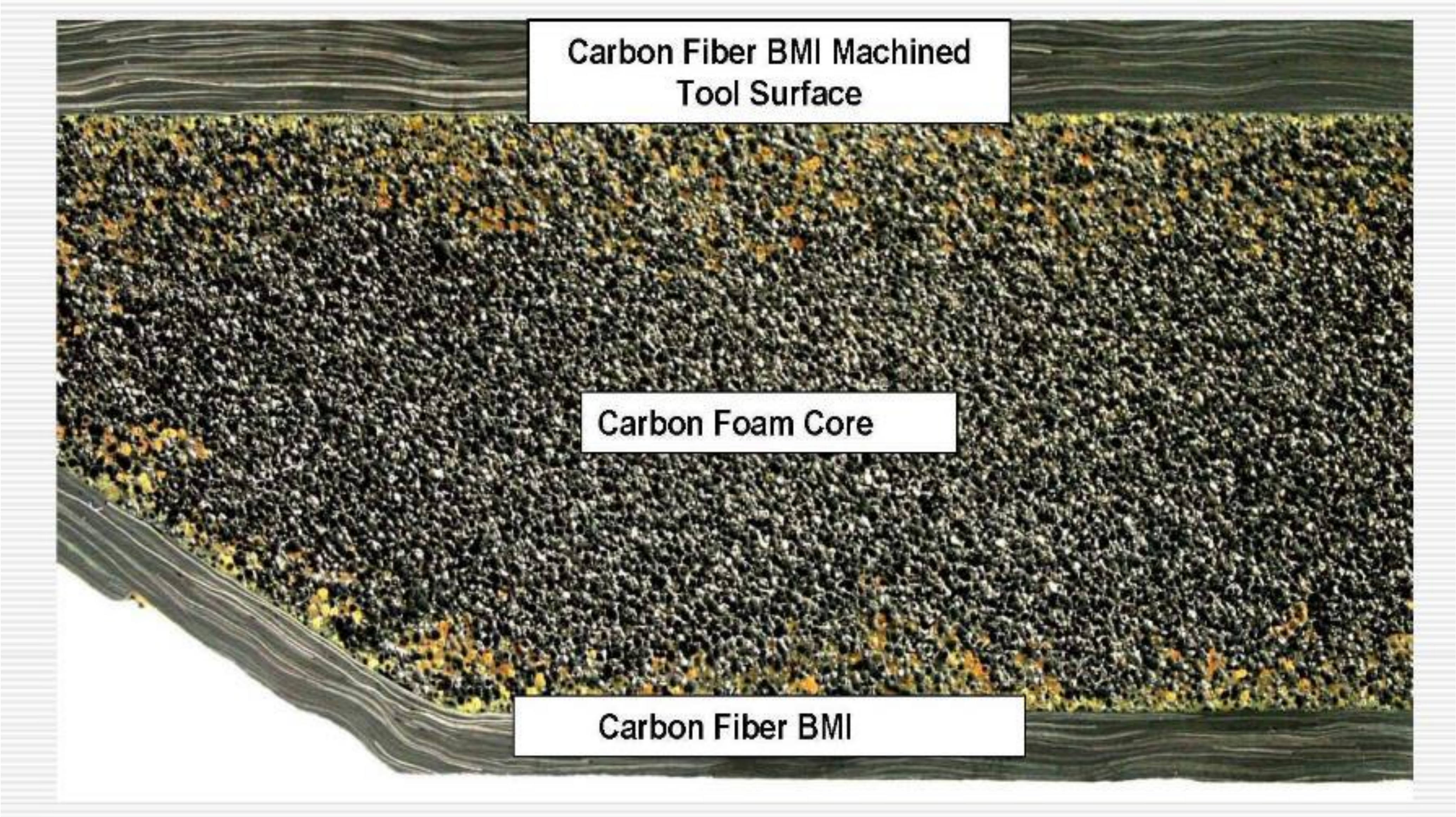


2"x 1/3" "chips" (50mm x 8mm)

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



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

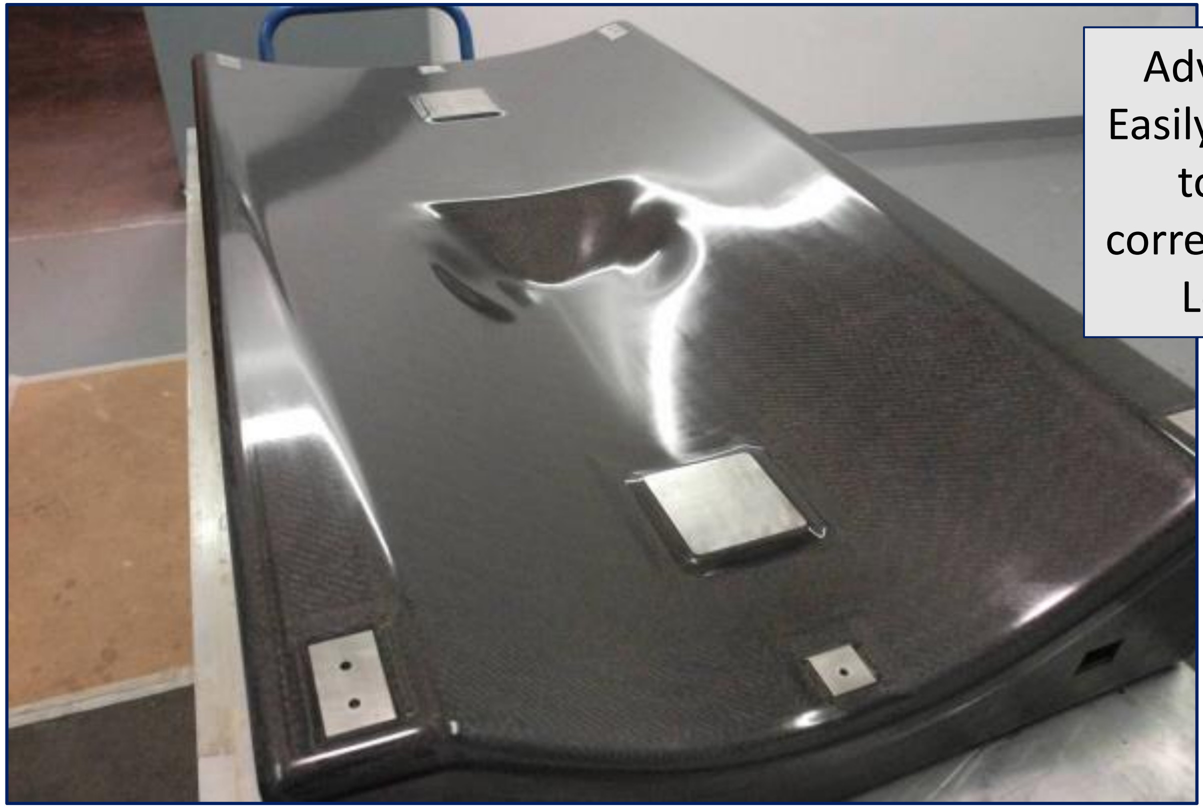
Finish-cut offset surface prior to prepreg

Photos courtesy of Touchstone Research Lab, Ltd

Machined CFRP/Carbon Foam Mold

Internal Mold Line (IML) Beaded Stringer tool

CFRP/C-Foam Production Mold



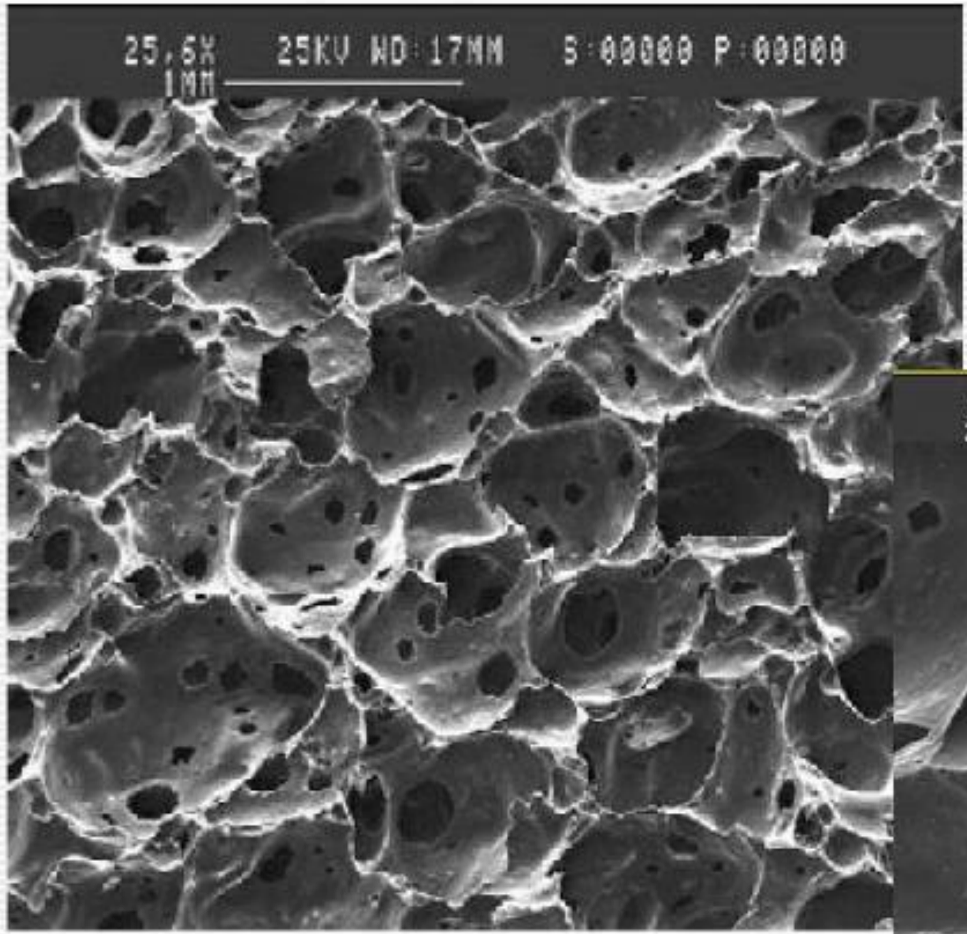
Advantages:
Easily machined to net or corrected shape
Low CTE

Photo courtesy of Touchstone Research Lab, Ltd

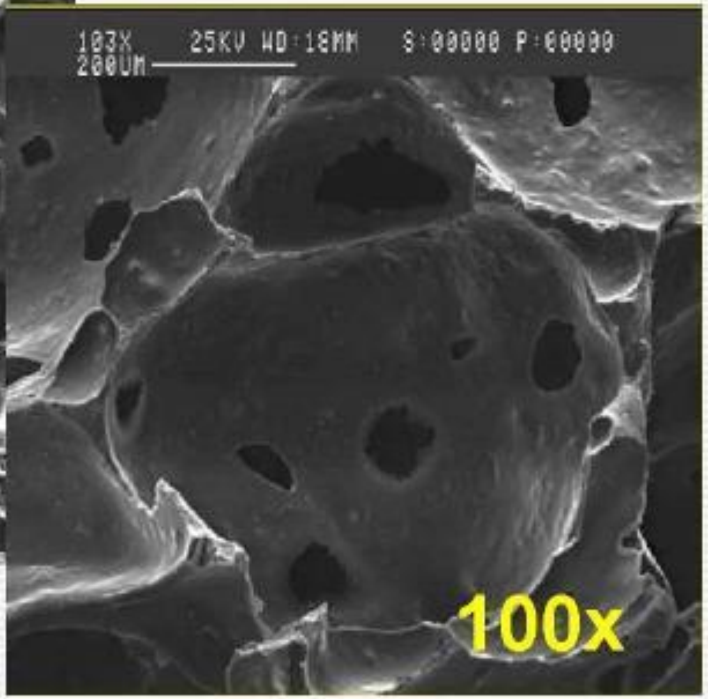
Finished carbon foam-carbon prepreg machined mold surface prepared with sealer and release agent

“C-FOAM” Structural Foam

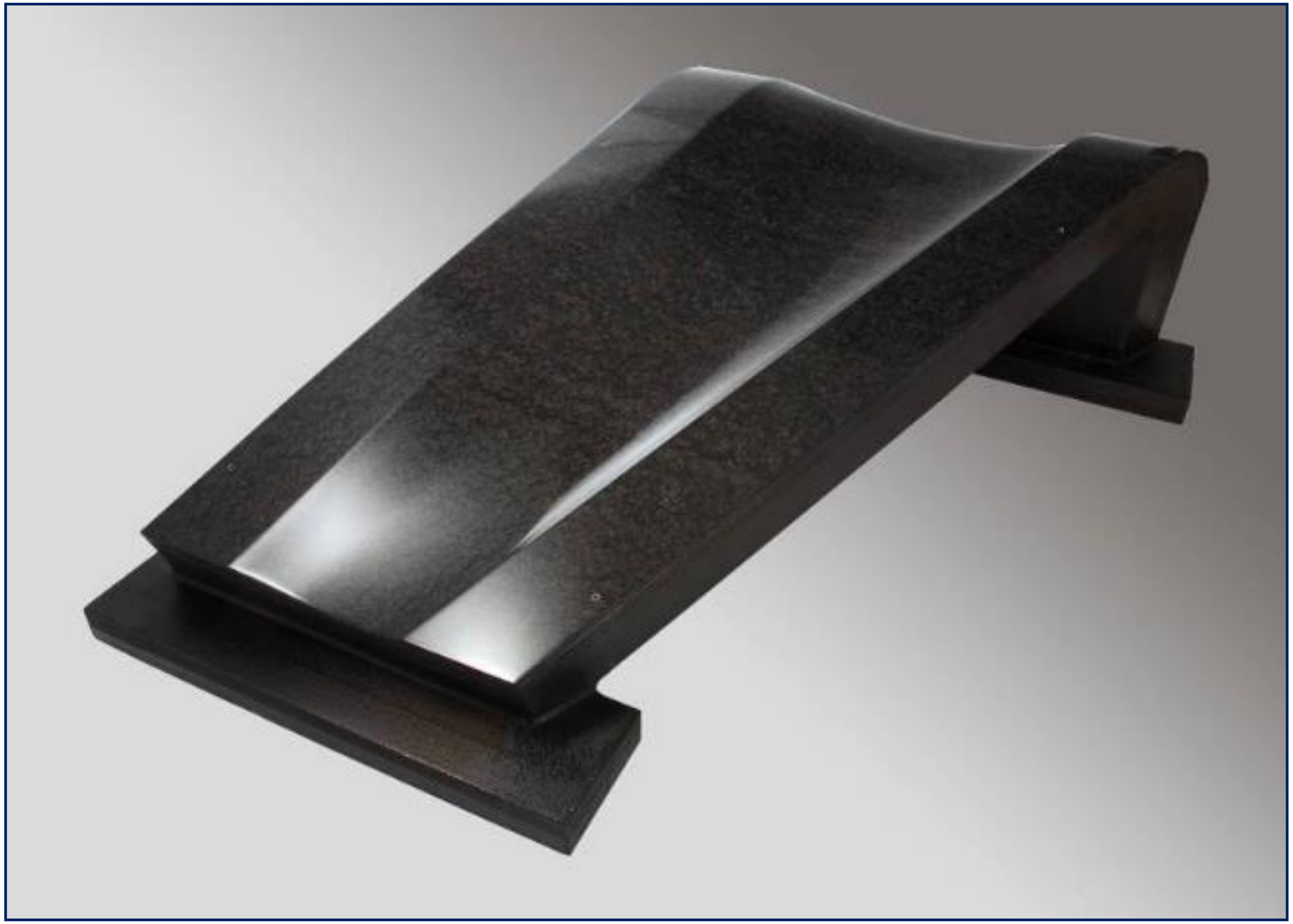
- Spherical pores
- Open porosity
- Interconnected pores



CFOAM®17



C-FOAM Production Tooling



Note uniform cross-section thickness

MASTER MODEL TOOLING ASPECTS

CNC Machined Tooling Board Model

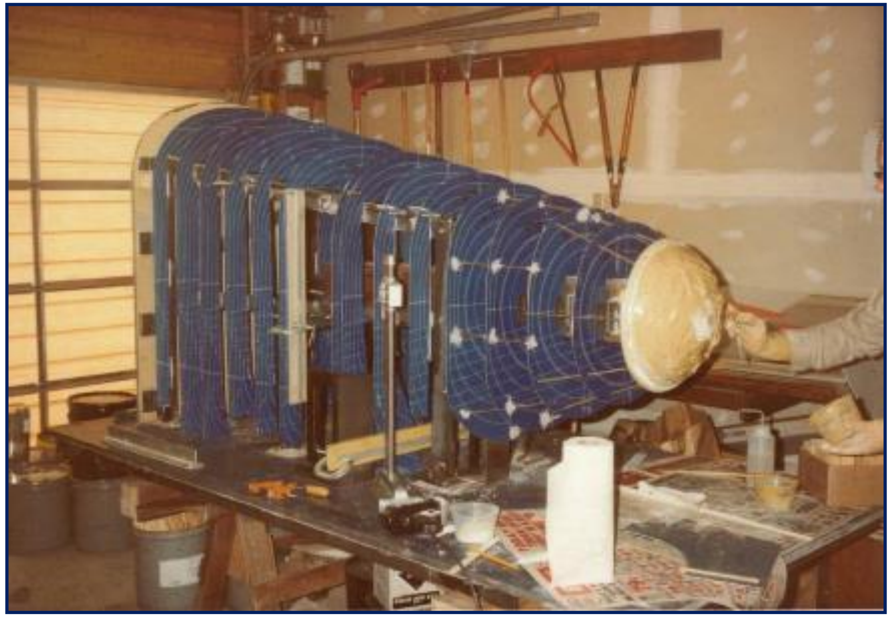
Photo courtesy of Coastal Enterprises

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

Photo courtesy of Process Fab, Inc.

Machining F-35 Nacelle Master Model

Legacy Master Model Fabrication:
Rigged-Template/Splined 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

Photo courtesy of General Plastics Manufacturing Co.

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

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

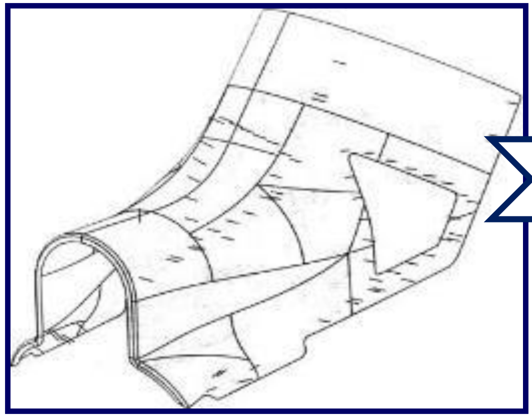
Ceramic Tooling Block Master

(Low CTE Master Model Material)

Photo courtesy of Compotool

Ceramic tooling block comes in medium and high density versions and services ≥ 500°F (260°C)

Example: Master Model-Tool Family


CAD Part-File

CAD Tool Design & Fab

Photos courtesy of Composite Solutions Corporation


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

RUBBER & ELASTOMER, BAGGING TOOLING

Reusable Vacuum Bags (RVB)

Large Reusable Silicone Rubber Vacuum Bag

TOOLING SUPPORT STRUCTURES FOR MANUFACTURING

Modern Composite Eggcrate Design

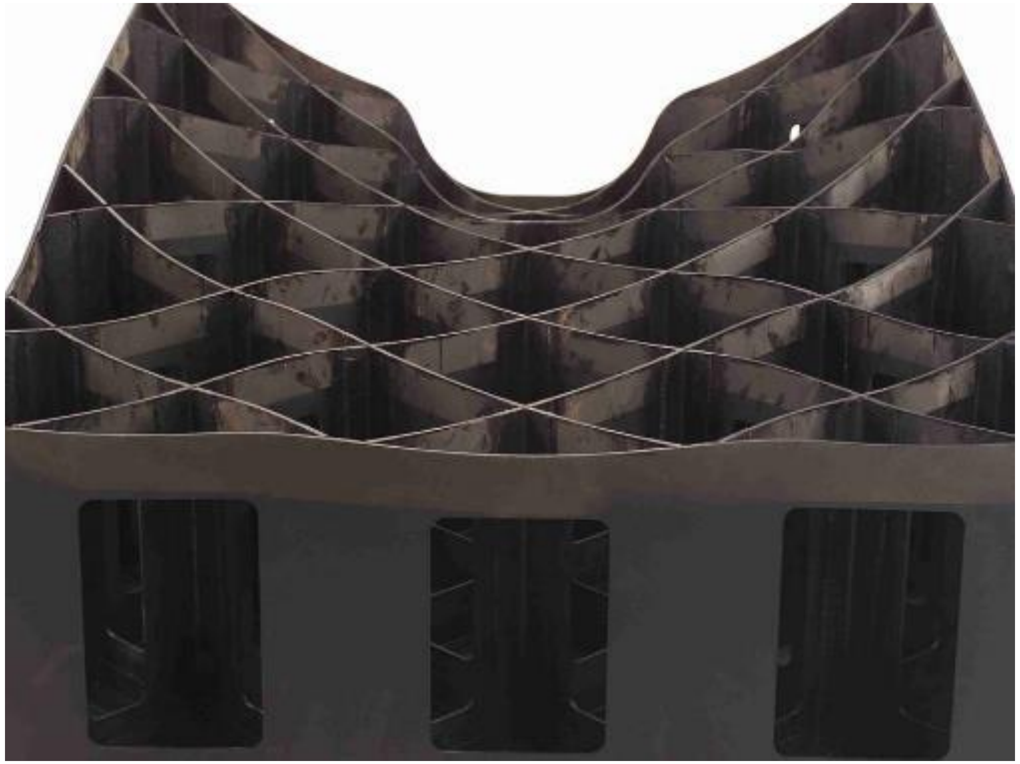
Uses same material for substructure as for tool face to eliminate CTE mismatch

Photo courtesy of Janicki Manufacturing

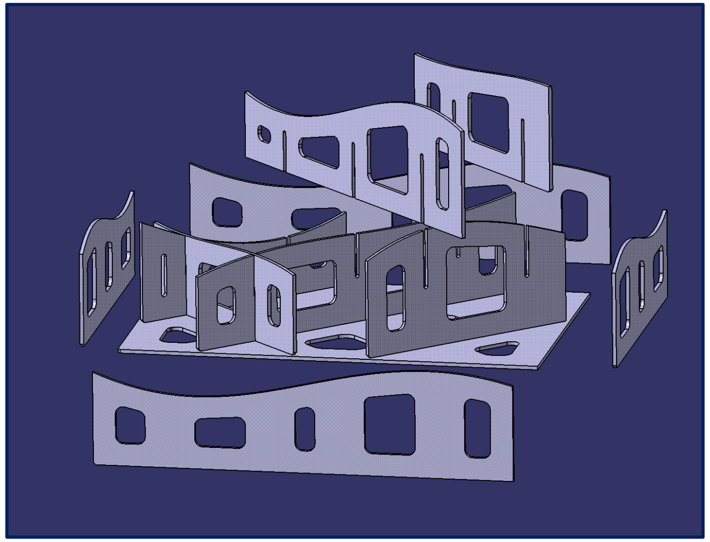
Note torsion box design below

Photo courtesy Coast Composites/Ascent

Truss/Torsion Eggcrate Design



Photo/images courtesy of Burnham Composite Structures

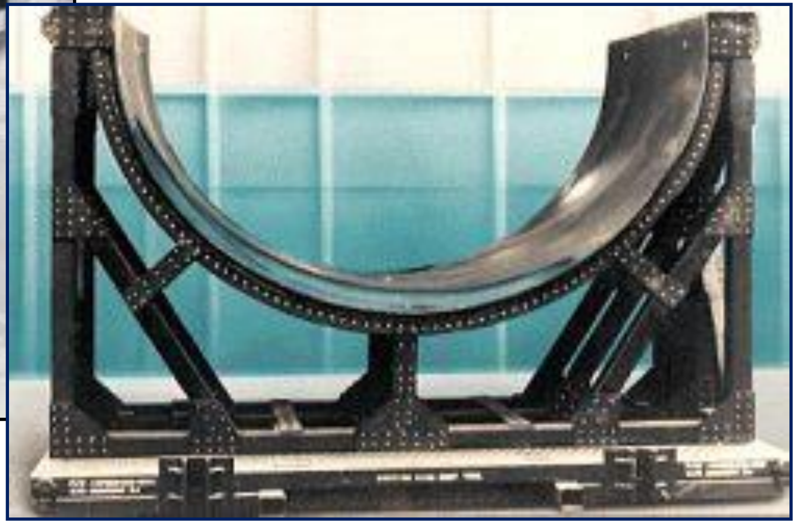


Burnham fabricates "Ready-to Assemble" Cut Kits. Kits are Waterjet cut to desired dimensions as specified by customer's supplied CAD data and / or drawings.

Industry trend is to provide torsion stability and minimize depth of substructure

Composite Tubular/Truss Structures

Source: Leading Edge Aerospace



Source: Burnham Composites

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

Composite LM w/Aluminum Frame

Courtesy of the Advanced Composite Group, LTD (Cytec)

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

Invar Tube Frame Substructure

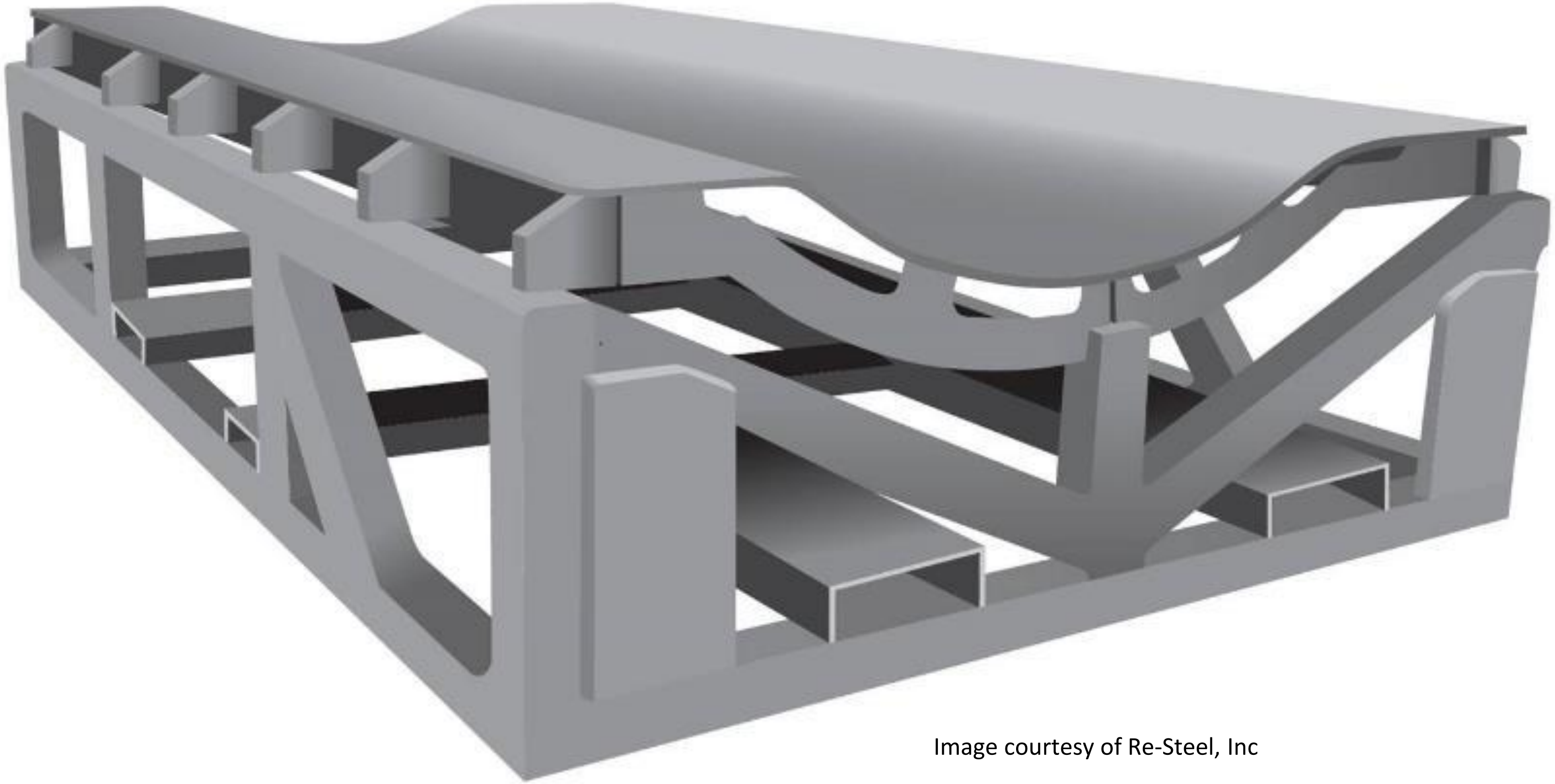
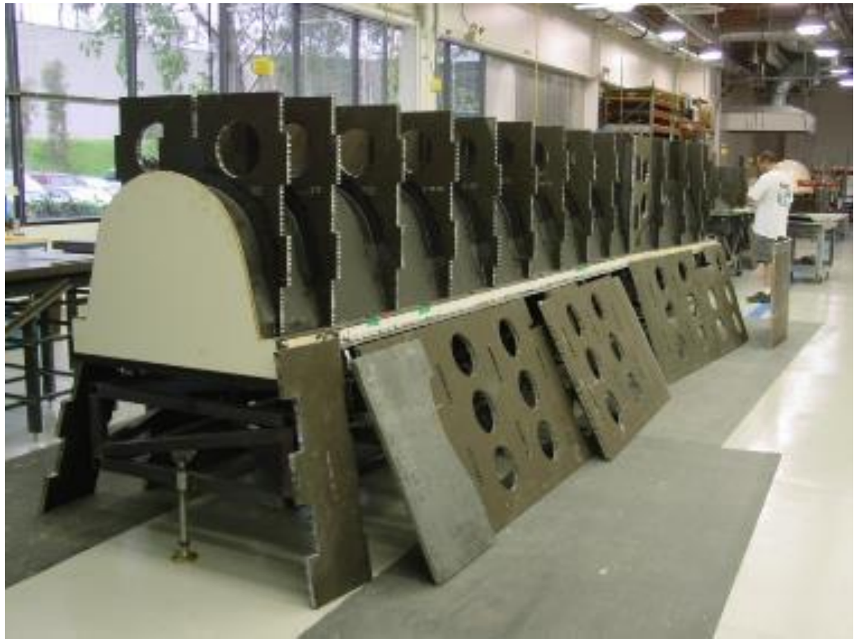


Image courtesy of Re-Steel, Inc

Compare weight to conventional Invar eggcrate design

Conventional Egg-crate Design

Note: Air circulation and lightening holes cutout in the honeycomb sandwich egg crate structure

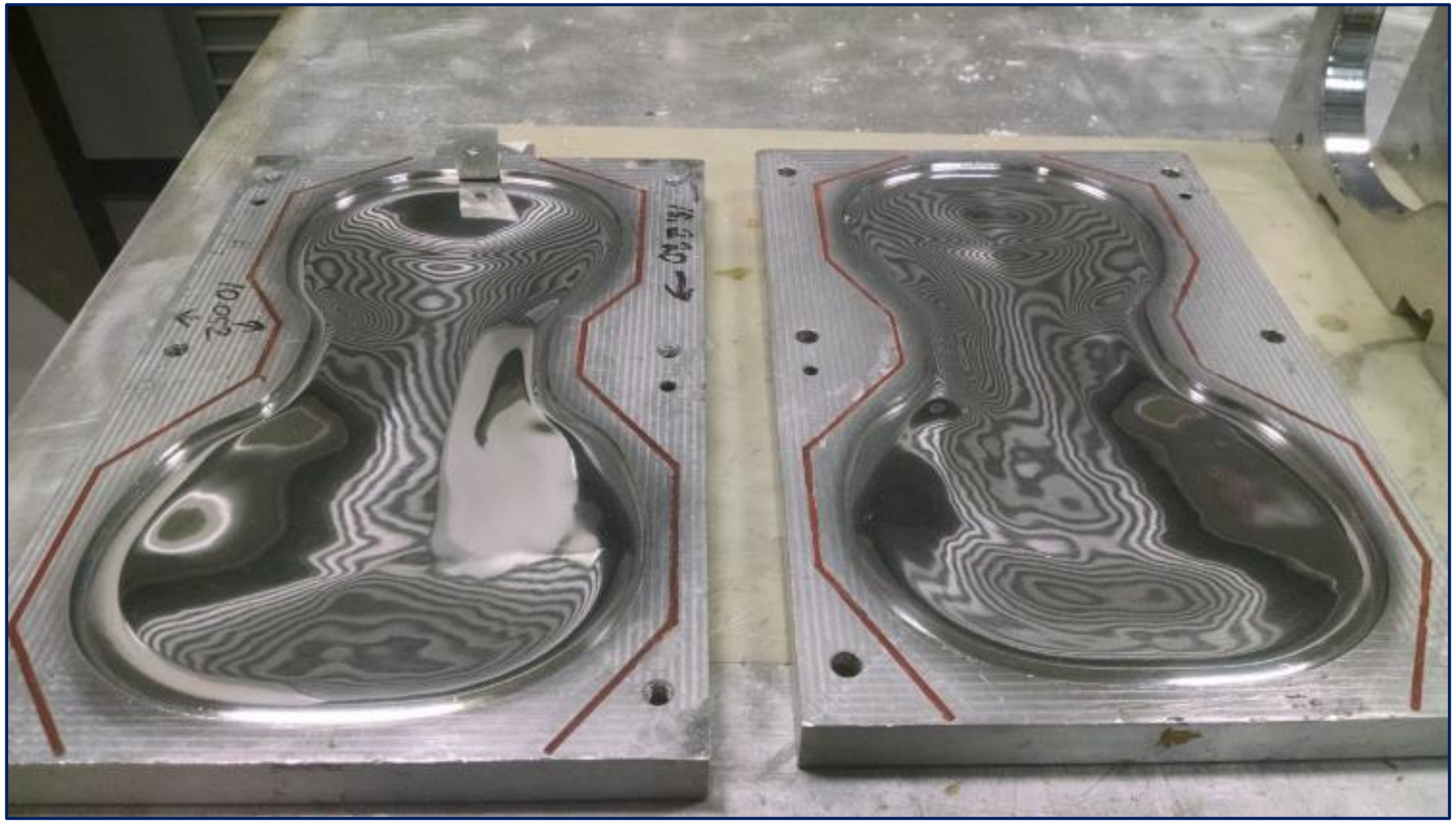


Composite Tool ʷ/Aluminum Frame

Low-Cost Spar & Stringer Molds

MISCELLANEOUS TOOLING TECHNOLOGIES

Aluminum Clamshell Mold for Violin



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

Machined aluminum clamshell molds for violin body

Invar Layup Mold

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

Photo courtesy of Coast Composites-Ascent Aerospace

Machined Monolithic Graphite Molds

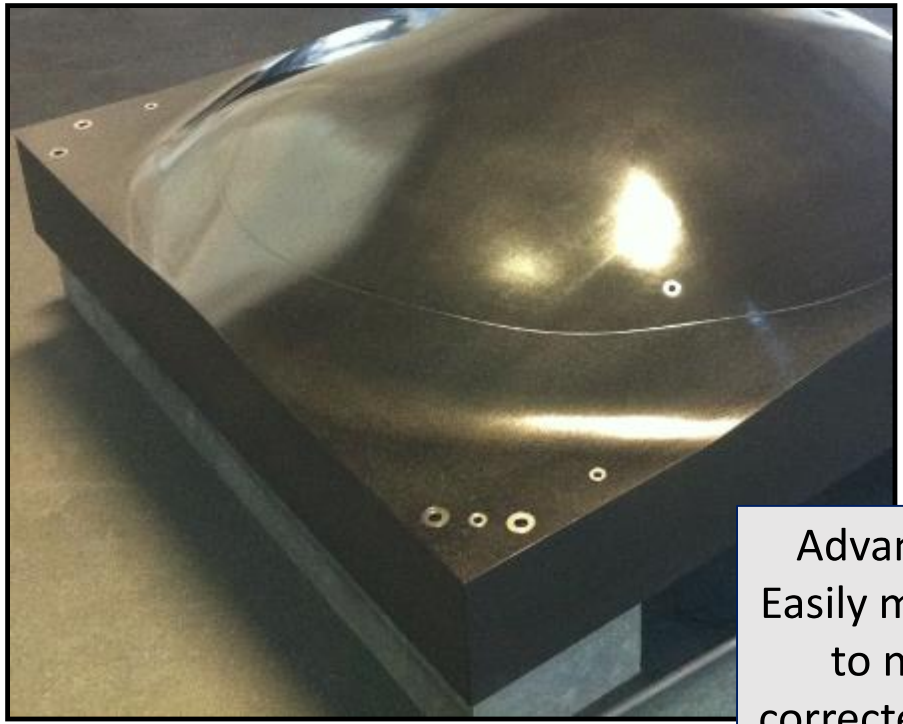


Photo courtesy of Electro Tech Machining

Advantages:
Easily machined to net or corrected shape
<u>Very</u> <u>Low</u> CTE

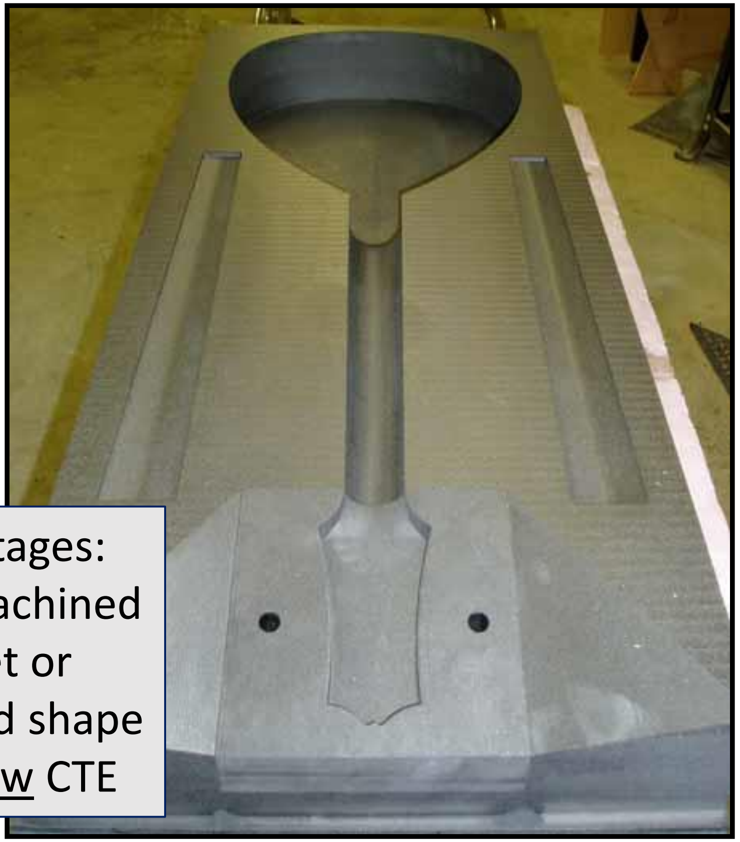


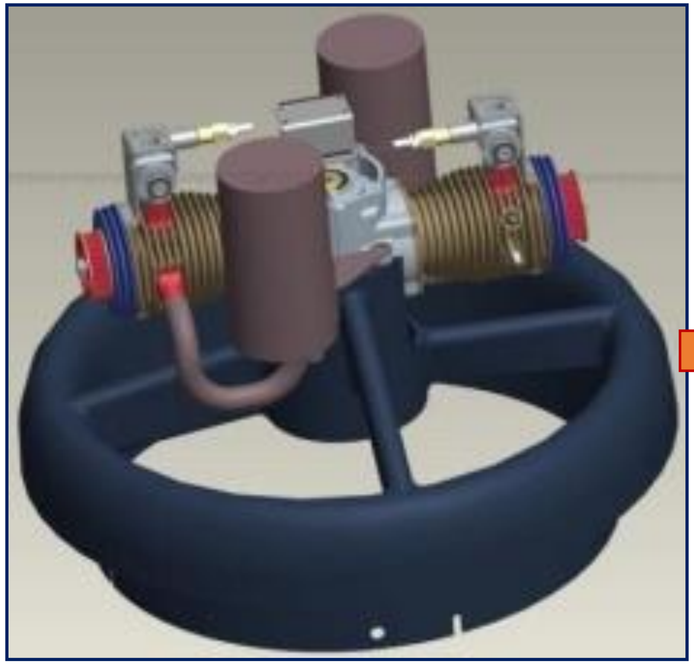
Photo courtesy of Turnpoint Design

True "Graphite" tooling

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

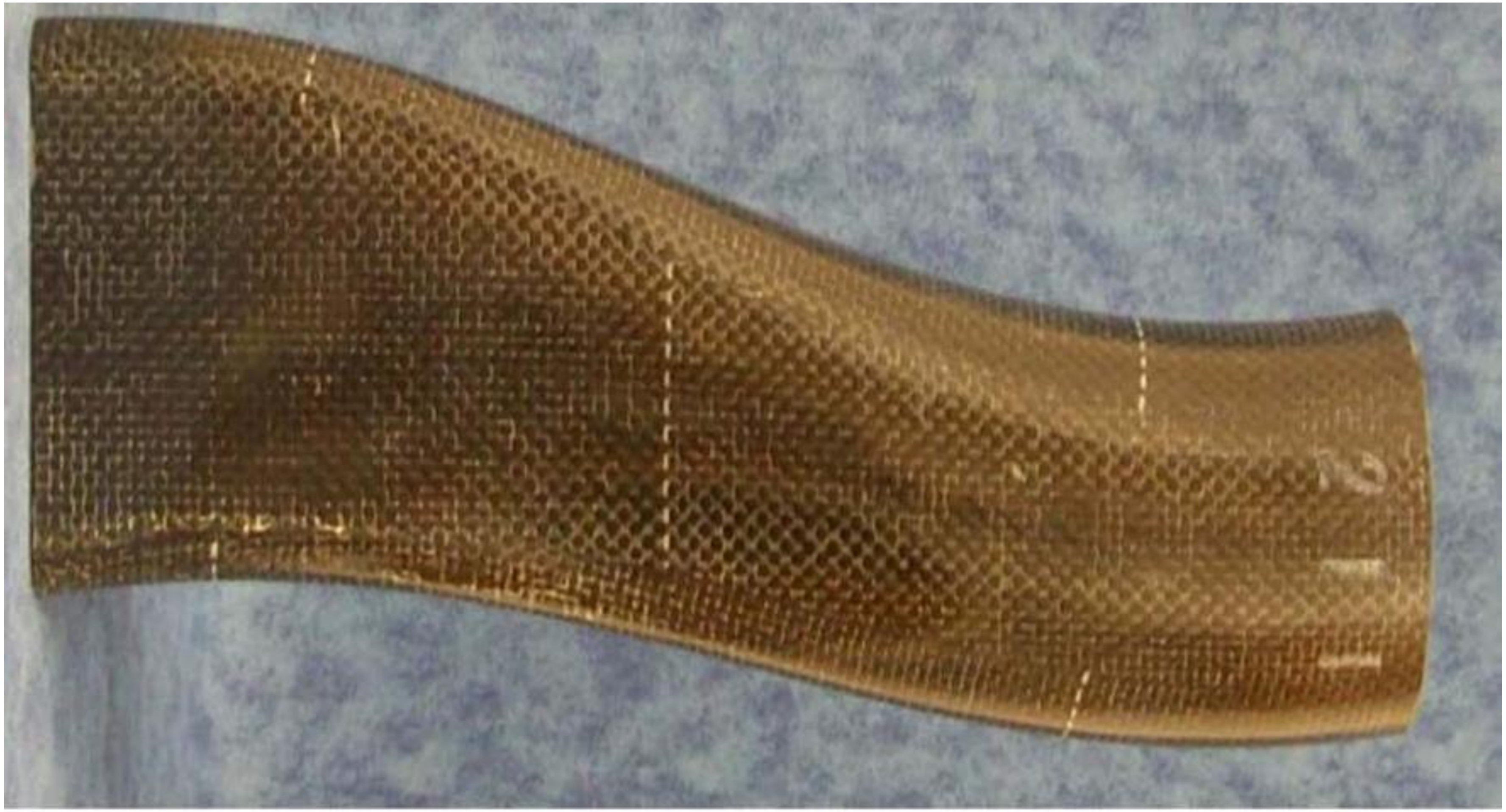
Photos courtesy of Ibis Cycles

3D Printed Washout Mandrels

Courtesy of Stratasys

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

Complex Curvature Composite



"S"-Shape Demo

Heated above activation temperature and air pressure applied

Composite Lay-up

Smart mandrels™

Finished Part Cured and mandrel removed

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

75M Wind Blade Tooling (Infusion)

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

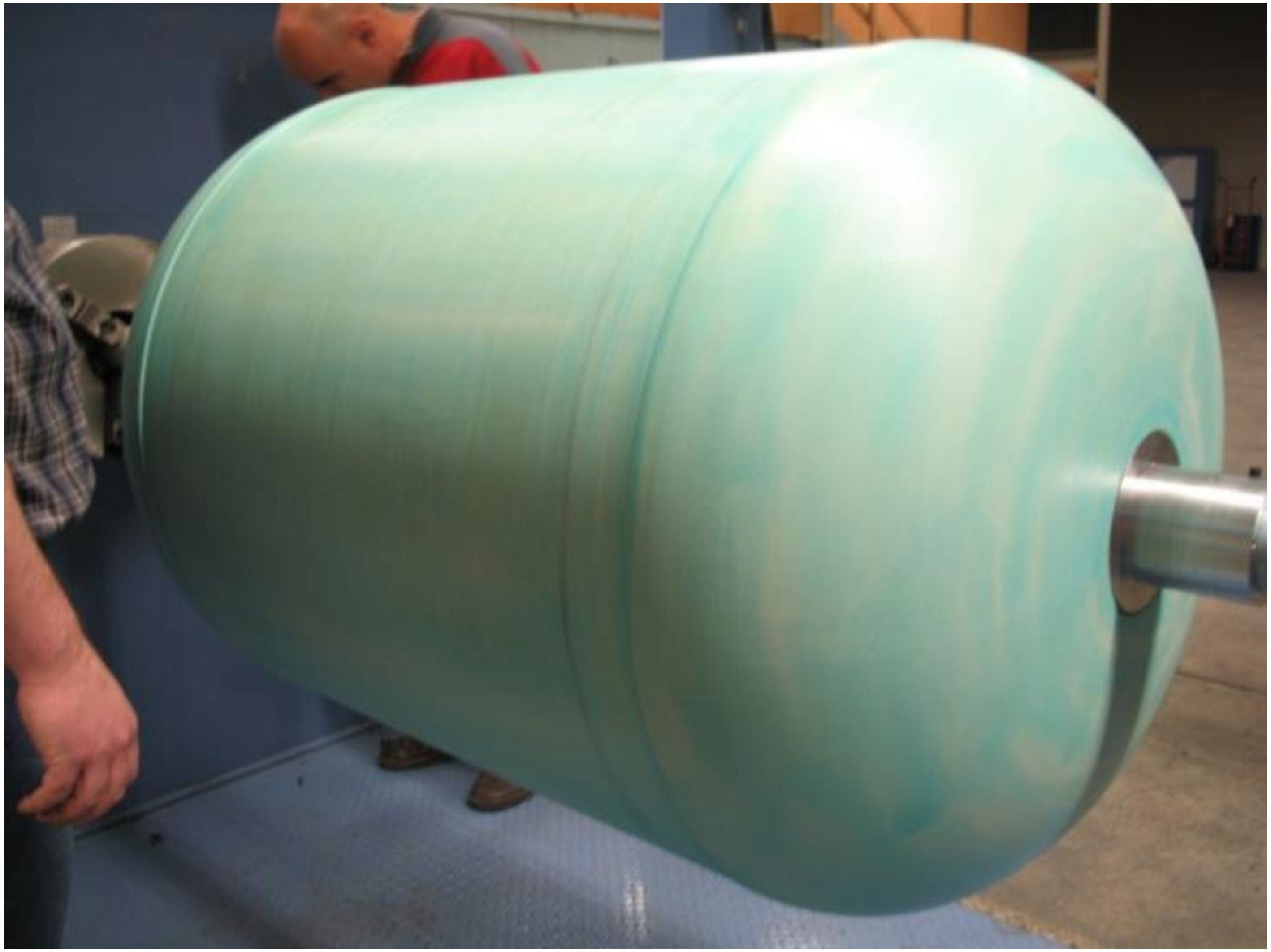
Plaster `Washout” Tooling

- 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

Foam Mandrel



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

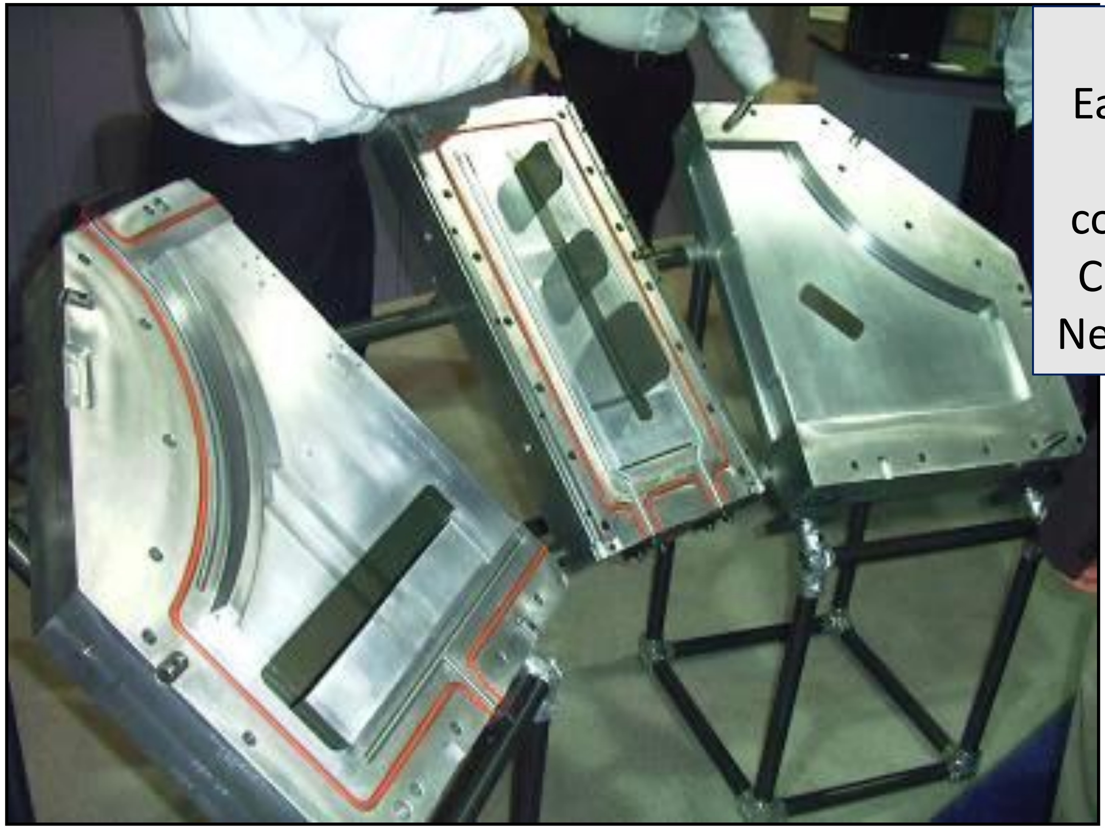
Technology Assessment: *Consumer Marketplace*

Bladder Molding (Baseball Bats)

MOLD TOOLING EXAMPLES

VARIOUS “RTM-TYPE” TOOLING

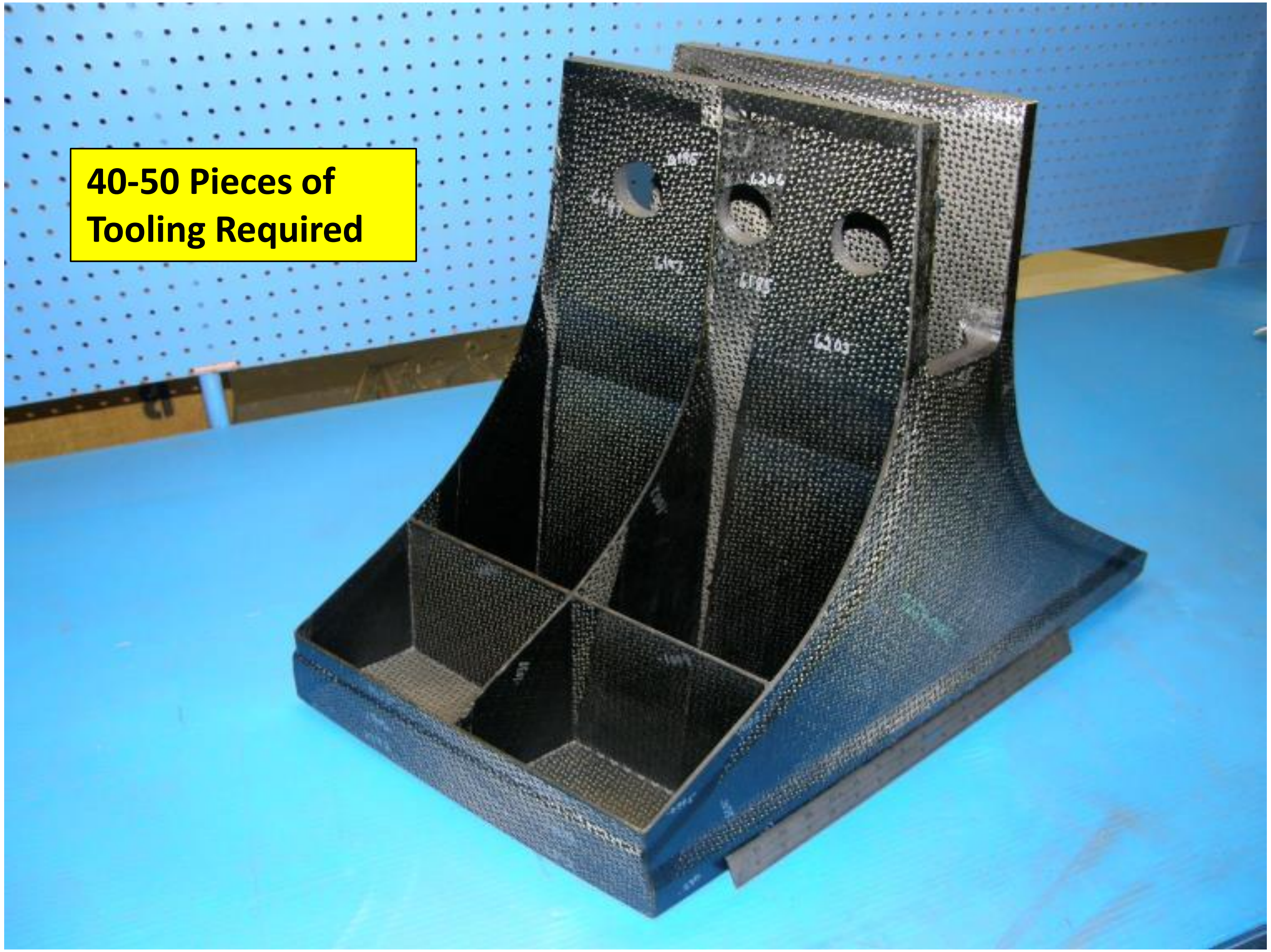
Multi-Piece Aluminum RTM Die



Advantages:
Easily machined to net or corrected shape
Close tolerance
Net molded parts

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

Completed RTM Part w/o Covers



Multi-Piece *SQRTM Tooling
*Same Qualified Resin Transfer Molding process

All black-anodized aluminum tooling

Aluminum RTM Mold ^{W}/Internal Bladder

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

Image courtesy of Swarf Cycles

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

SUMMARY

- **Tooling for composites --- <u>Art Supported By Science !</u>**
- Many methods for producing tools !
- Very process and applications – driven
- Always <u>several</u> 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 <u>no substitute for experience …</u>**

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- 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)

A NEW CAMX
FOR A NEW TIME

COMBINED STRENGTH. UNSURPASSED INNOVATION

CAMX
THE COMPOSITES AND ADVANCED MATERIALS EXPO

SEPTEMBER 2020
A VIRTUAL EXPERIENCE

TOOLING MATERIALS & THEIR PROPERTIES

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:
  - <u>Much lighter than steel</u>
  - <u>Easier to machine than steel</u>
  - Frequently “hard anodized” against surface damage
- Cons:
  - Difficult to make tight, leakproof castings and welds
  - Has <u>much higher thermal expansion</u> (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
  - <u>Negative experience with multiple autoclave cycles over time</u>
  - 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

Material	Specific Gravity	Specific Heat (Btu/lb./°F)	Thermal Mass (Btu/lb./°F)	Thermal Conductivity Coefficient (Btu/ft^2/hr/°F/in)	Coefficient of Thermal Expansion (CTE) (10^{-6} in/in/°F)
Aluminum	2.70	0.23	0.62	1395	12.9
Stainless Steel	8.02	0.12	0.96	113	9.6
EF-Nickel	8.90	0.10	0.89	500	7.4
Invar 36	8.11	0.12	0.97	72.6	0.8
GFRP	1.80-1.90	0.30	0.54-0.60	22-30	8.0-9.0
CFRP	1.50-1.60	0.30	0.45- 0.48	24-42	0.0-6.0

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: $\mu in/in/^{\circ}F$ or $\mu m/m/^{\circ}C$
  - 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
- <u>Matched metal tooling – number 1 rule !</u>
- Both surfaces controlled can produce 0.005-inch/0.15-mm tolerances easily
- <u>Great for complex shapes</u>
- 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")

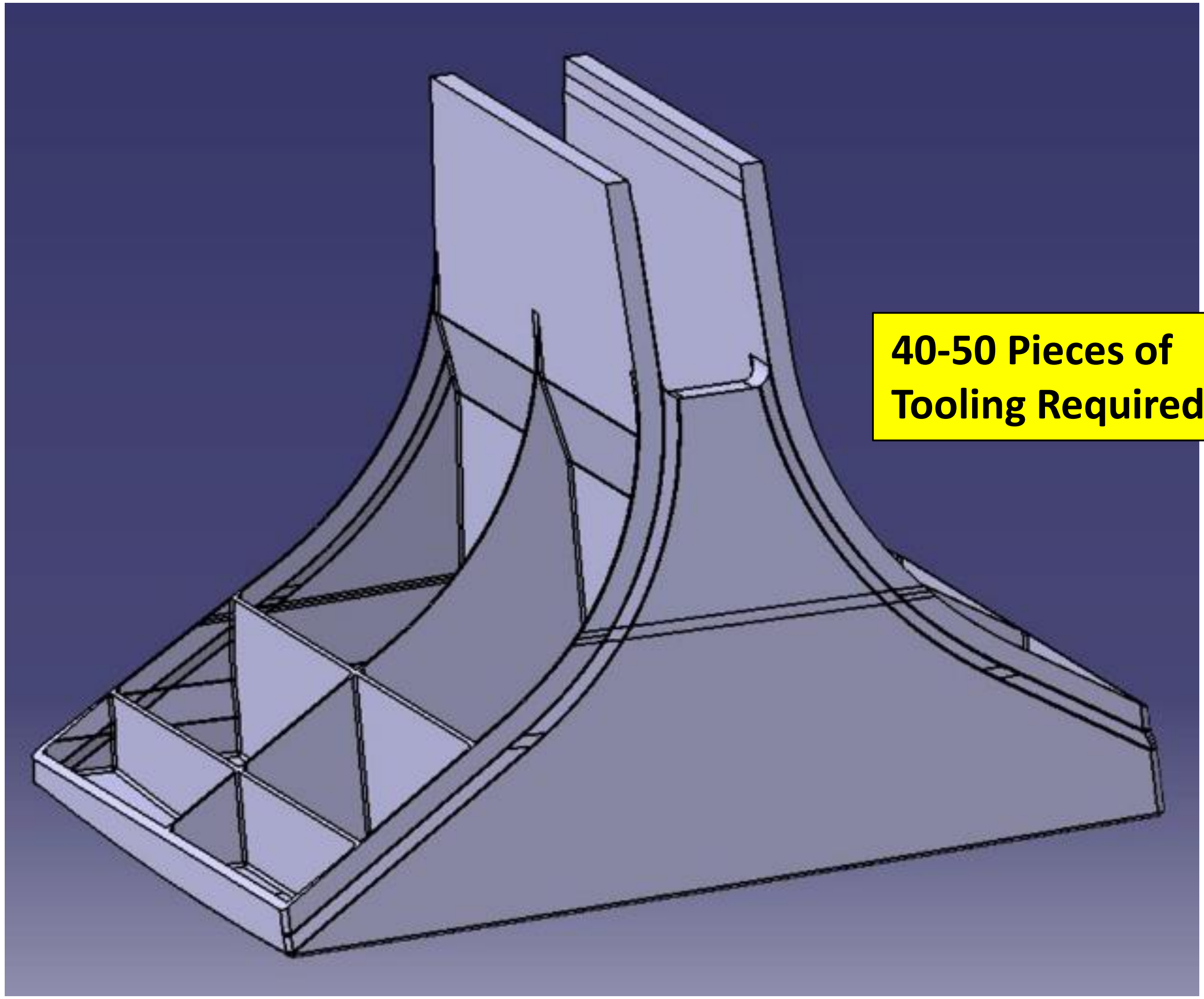
RTM Tooling – Heating Options

- 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
  - <u>Hot oil preferred</u>
  - <u>Hot water another option</u>
  - Both provide cool-down controls
  - Electric cartridge heating (no cool-down option) – poor choice

RTM Tooling

- **<u>Steel tooling (P20) whenever possible</u>**
- Inlet and vent ports – always <u>off</u> 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

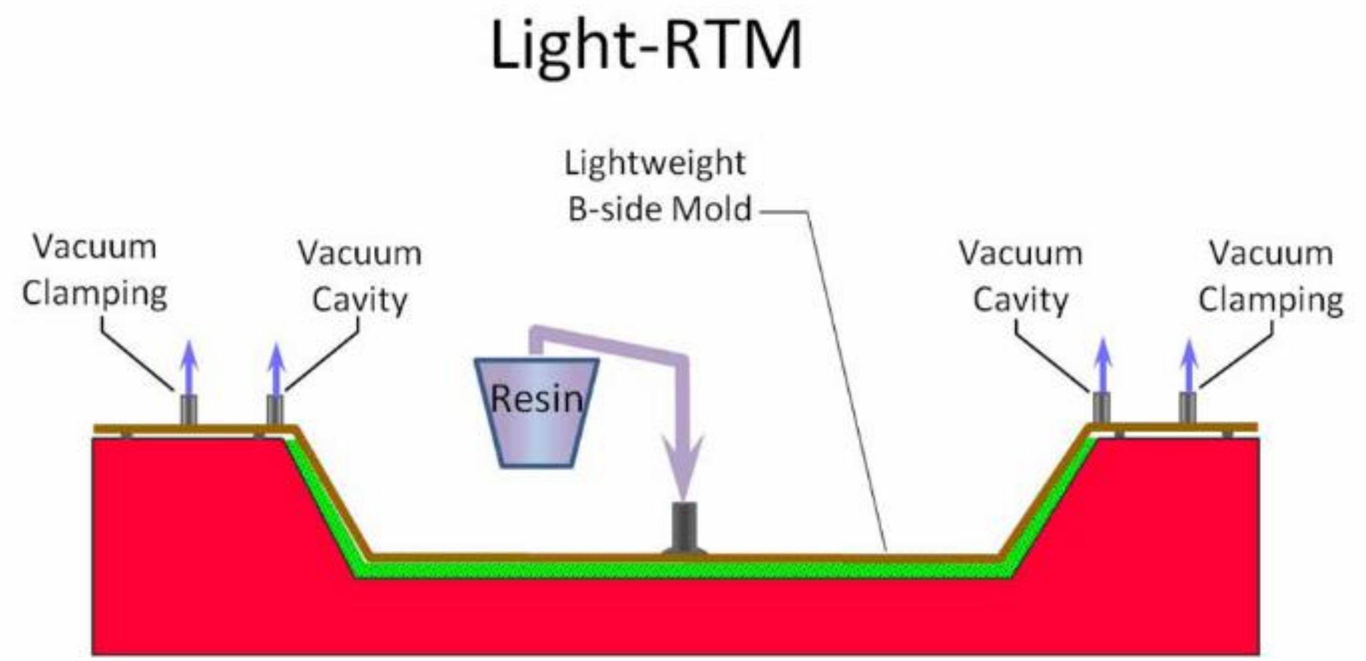
“LITE (or LIGHT) RTM” TOOLING

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

Advantages:
Conforms well to complex configuration
Provides good compaction

Photo courtesy of John Burn-UK

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

Lite RTM Tooling Systems

MOMENTIVE

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

Tooling 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 – <u>often unpredictable</u>
- RTM tool set accuracy controlled by design (<u>very predictable</u>)
- **<u>Can usually "net mold" with RTM</u>**
- Lite RTM going to require edge trimming

VIP (Vacuum Infusion Processing) TOOLING

Vacuum Infusion Process (VIP) Mold

Note: Resin reservoir is below mold height

Photo courtesy of JHM Technologies, Inc

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

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

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

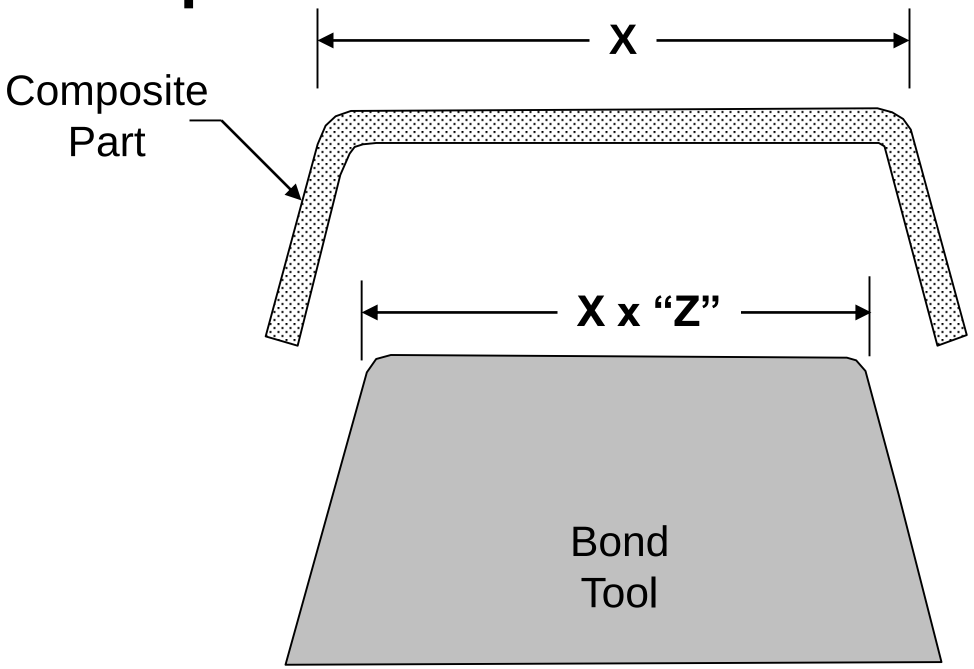
- Stable at Use Temperature (Usually 350°F) OR HIGHER
- Withstand Loads of 100 psi
- Smooth Finish in Part Area
- Acceptable to Parting Agent
- Have Expansion Factor Compensation
- Wear Resistant to Scraping
- Resistant to Solvent Cleaning
- Machinable or Capable of Lamination
- Locate and Support All 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 ca be handled by:
  - Cooling tool at room temperature
  - Allowing for expansion in tool design (often proprietary)

Thermal Expansion Correction Factors for Tooling



X = Engineering Part Dimension
"Z" = Correction Factor

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

Where:

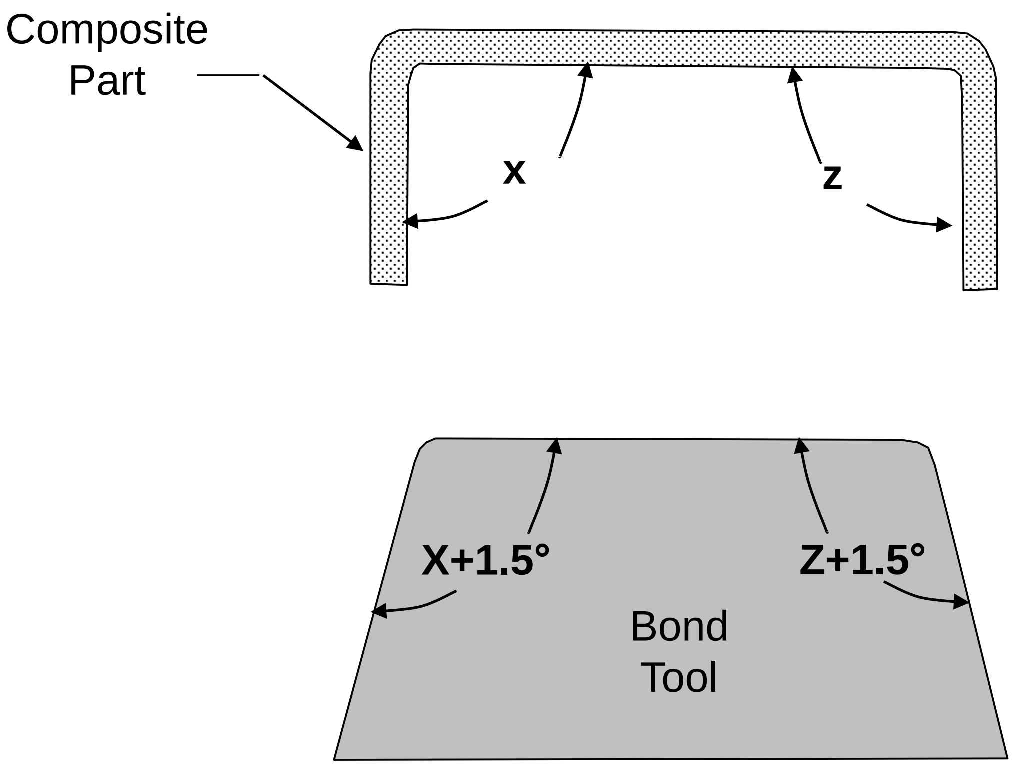
CTE_P = Coefficient of Thermal Expansion of Part
CTE_T = Coefficient of Thermal Expansion of Tool
T_{Gel} = Temperature of Resin Gelation
T_{RT} = Room Temperature

SPRING-IN / SPRING-OUT ISSUES

SPRING-IN & SPRING-OUT OPTIONS

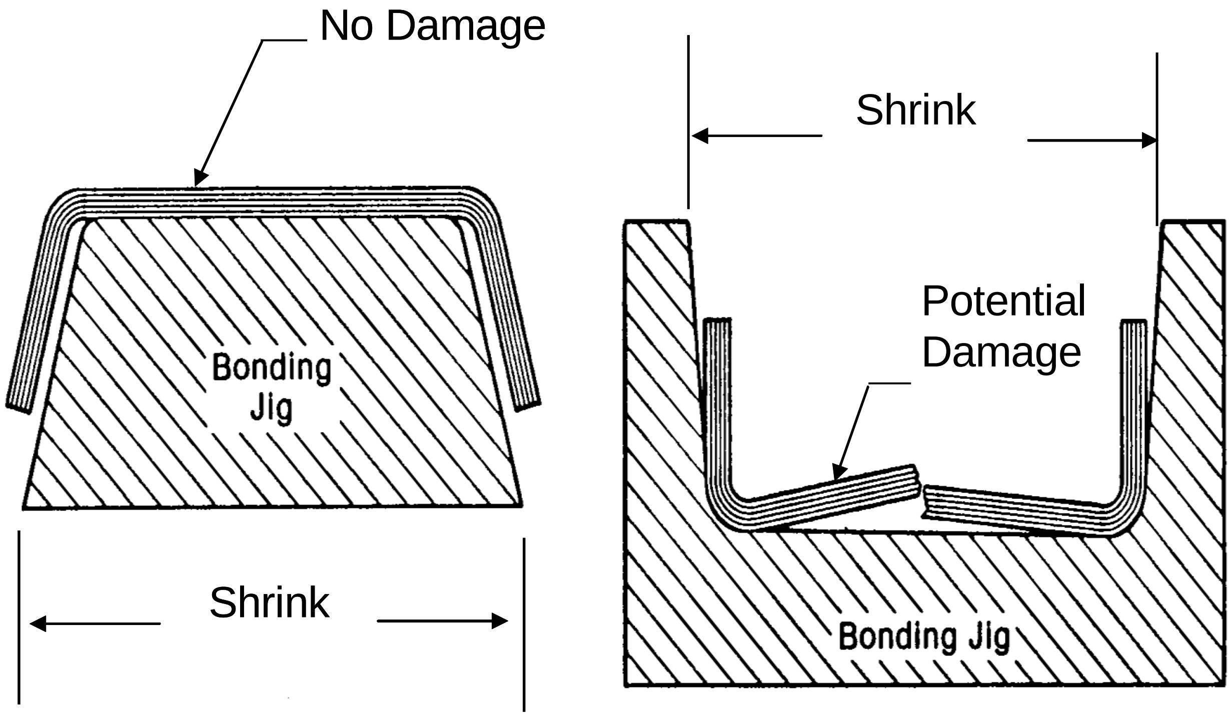
- “Angled tooling geometries” must compensate for part-tooling thermal expansion:
  - Depends on part lamination, configuration, and properties
  - Composites tend to “spring-in” – contract during cure shrinkage
  - Metals tend to “spring-back” – so often must be “over-formed” at room temperature
- Analysis (typically Finite Element Analysis – FEA) can handle this during tool design

Spring-In Correction Factors



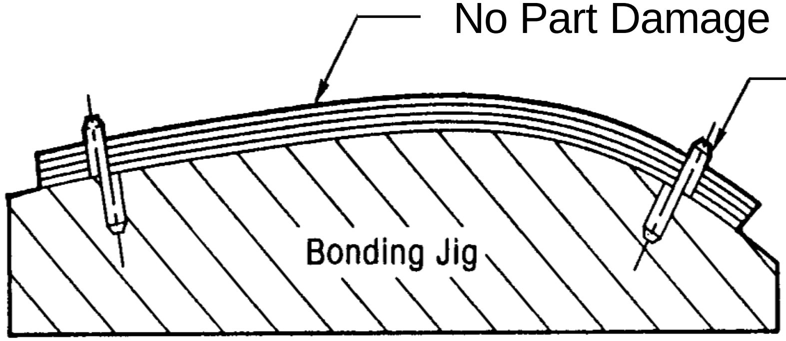
Note: 1.5º shown. Typical values range from 0-5º depending on tool material used.

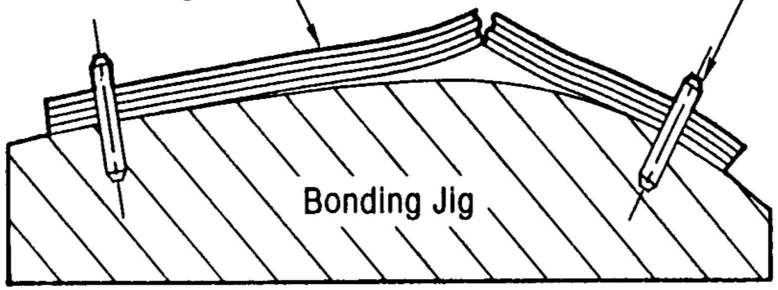
Potential Effects of Tool Shrinkage on Part Quality



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.

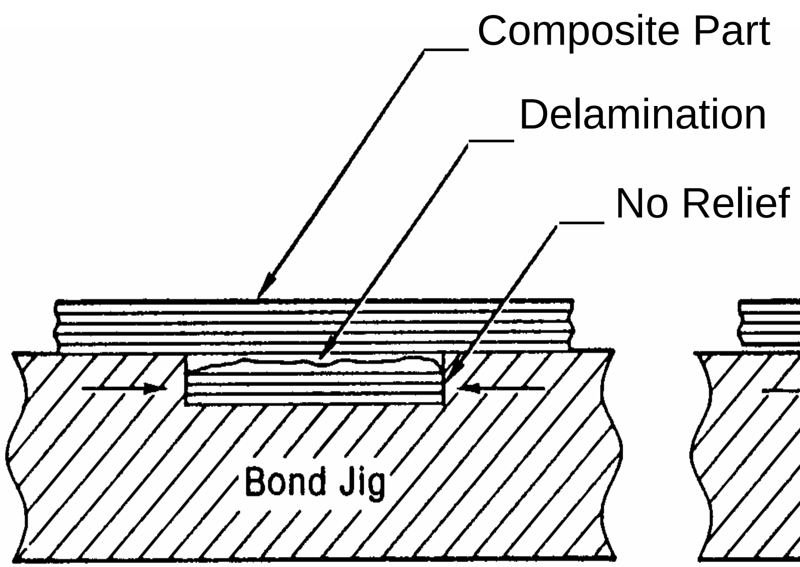
Shear Pins Used to Eliminate Tool Shrinkage Damage

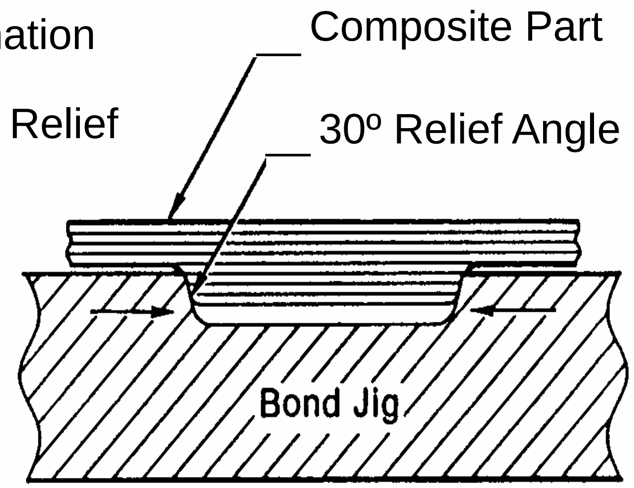




Teflon shear pins are often used to prevent damage. It is possible to hard pin a tooling detail at one, or possibly two locations, on the bond tool, but the detail must be allowed to freely contract separate from the bond tool on cooling.

Draft Used to Prevent Tool Shrinkage Damage





Cool-Down Shrinkage of Bond Tool Can Cause Delamination Of Plies During Removal of Part

Cool-Down Shrinkage of Bond Tool Causes Part to Lift Up From Bond Tool Avoiding 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.