CASE STUDIES OF LARGE CARBON FOAM TOOLING

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ABSTRACT

A new carbon foam tooling system has been developed that results in a low-cost, high-strength material that has been proving attractive for creation of tooling for composite parts. Composites are stronger, lighter, and less subject to corrosion and fatigue than materials that are currently used for fabrication of advanced structures. Tools to manufacture these composite parts must be rigid, durable and able to offer a coefficient of thermal expansion (CTE) closely matching that of the composites. Current technology makes it difficult to match the CTE of a composite part in the curing cycle with anything other than a carbon composite or a nickel iron alloy such as Invar®.

Fabrication of metallic tooling requires many expensive stages of long duration with a large infrastructure investment. Carbon fiber reinforced polymer resin composite tooling has a shorter lead-time but limited production use because of durability concerns. Coal-based carbon foam material has a compatible CTE and strong durability that make it an attractive alternative for use in tooling. The use of coal-based carbon foam in tooling for carbon composites is advantageous because of its low cost, light weight, machinability, vacuum integrity, and compatibility with a wide range of curing processes. Large-scale tooling case studies will be presented detailing carbon foam's potential for tooling applications.

KEY WORDS: Carbon Fiber Composites, Molds/Mold Making/Mold Design, Tools/Tooling Materials/Tooling Technology

1. INTRODUCTION

Construction of aircraft, spacecraft, missile surfaces, automobiles, and other structures is rapidly moving to carbon fiber-reinforced thermoset and thermoplastic resins, resulting in higher strength-to-weight ratio and less subjection to corrosion and fatigue. Tooling is critically important as tools must be low-cost, rigid and durable and offer a CTE that matches that of the composite part. Long lead times and material availability are also growing concerns with alloy-based tools.

Touchstone Research Laboratory, Ltd. (Touchstone) has developed a tooling system using a coal-based carbon foam (CFOAM®) that obviates many of the concerns associated with alloy-based tools (Figure 1).

Figure 1. Coal-based carbon foam tooling.

2. CARBON FOAMS

Materials engineers today can select foams made from a wide variety of materials including organic polymers, metals, and ceramics. These foams find widespread use over other material forms based on specific criteria required for the application, such as density, insulating value, selective absorbing properties, or air/liquid flow. Recently, much attention has been focused on carbon and graphite foams due to the unique properties that carbon can offer such as chemical inertness, use at ultra high temperatures, low CTE, and electrical/thermal conductivity. Carbon foams generally fall into two categories – graphitic or non-graphitic. The graphitic carbon foams offer high thermal and electrical conductivity but considerably lower mechanical strength. The non-graphitic carbon foams are generally stronger, act as thermal insulators, and cost far less to manufacture. To a large extent, the type of carbon foam produced is highly dependent on the precursor material, which may be coal, petroleum or coal tar pitches, highly refined synthetic pitches, or organic resins.

The earliest carbon foams were simply carbonized organic foams or sponges and are currently used as substrates for producing other ceramic or metal foams. Materials are deposited onto the skeleton of these reticulated or "glassy" carbon materials, and the carbon is subsequently removed by heat treatment in an oxidizing atmosphere. These carbon forms tend to be very weak and have limited use beyond the applications mentioned.

Graphitic foams typically are produced from petroleum, coal tar, or synthetic pitches due the ability of these precursors to be converted to the highly ordered graphitic crystal structure during the manufacturing process. Carbon foams produced directly from coals or organic resins generally have crystal structures that are highly amorphous and, thus, will not form the graphitic structure. Depending on the application, graphitic or carbon foams may be selected due to their vastly different properties. Although the highly graphitic foams offer unique properties such as high thermal and electrical conductivity and low density, they are currently not produced competitively either on a cost or volume basis. As such, these foams are currently best suited for low-volume, high-end applications such as heat exchangers and thermal management [1].

Carbon foams made from less expensive precursor materials such as coal or similarly novel materials are currently made on a larger scale and are now competitively priced in such applications as composite core materials, fire and thermal protection, composite tooling, electromagnetic shielding, and radar absorption. The coal-based carbon foam is open cell, porous carbon with interconnected pores (Figure 2). Competing materials may be poly (vinyl chloride) [PVC], various honeycombs such as phenolic resin or polypropylene, and various metals and ceramics. In each of these applications, critical characteristics such as weight, mechanical properties, ability to pass fire or smoke toxicity (FST) tests, or CTE may be used to determine that one material is better suited than another. The properties of coal-based carbon foam are summarized in Table 1. Table 2 compares two densities of coal-based carbon foam, 20 and 25 lb/cu ft (.32 and .40 Mg/m^3).

Figure 2. Coal-based carbon foam microstructure.

Table 1. Summary of coal-based carbon form properties.

Corrosion	Unlike metals, coal-based carbon foam does not corrode in a salt-water atmosphere, has a very low galvanic activity, and has been tested in a salt fog chamber according to ASTM B 117. The results show no change in physical properties after a 3,072-hour exposure to salt fog.
Mold Growth	ASTM D 3273, Standard Test Method for Resistance to Growth of Mold on the Surface of Interior Coatings in an Environmental Chamber, was recently completed. The results show that coal-based carbon foam does not support mold growth, and the ASTM rating for mold growth after a four-week exposure is zero.
Fire, Smoke & Toxicity (FS&T)	Coal-based carbon foam has been tested for ISO 1182 Non-Combustible, ASTM E 162 Low Flame Spread, and ASTM E1354 Cone Calorimeter. Coal-based carbon foam passed ISO 1182, ASTM E 162 fire testing. It received the highest rating possible, with a flame spread index of one.
Mechanical	Coal-based carbon foam has high mechanical strength with foams ranging in compressive strengths from 1.38 MPa at a density of .19 Mg/m^3 to 138 MPa at a density of 1.6 Mg/m^3.
Fatigue	Coal-based carbon foam shows no degradation in its residual tensile strength after undergoing 2,000,000 cycles at 90% of its ultimate strength.
Porosity	The volume is measured using a well defined and controlled method by the Helium Pycnometry technique. The porosity is determined by taking the ratio of the bulk density and the true density. The results indicate coal-based carbon foam 20 has a porosity of 85% (85% air, 15% Carbon).
Coefficient of Thermal Expansion	The coefficient of thermal expansion (CTE) is done in accordance with ASTM E 288. The average CTE was 5.0 ppm/^oC.
Water Absorption	The water absorption of coal-based carbon foam is being measured in accordance with ASTM C272 – Test Method B, “Elevated Temperature Humidity.” Three specimens were tested in a chamber at 71^oC and 90% relative humidity for 30 days, and the mass change was recorded. Coal-based carbon foam 20 gained only 0.5% mass due to the elevated temperature/humidity environment.
Thermal Conductivity	The thermal conductivity measurements were conducted using a Guarded Hotplate method per ASTM E1225. The thermal conductivity of coal-based carbon foam at 25^oC is approximately 0.25 w/mK.

Table 2. Typical coal-based carbon foam data sheet.

Property	Test Method	Touchstone CFOAM®		Unit
		20	25	
Nominal Density	ASTM D1622	.32	.40	Mg/m^3
Compressive Strength	ASTM C 365	>8.3	>15	MPa
Compressive Modulus	ASTM C 365	620	830	MPa
Tensile Strength	ASTM C 297	>2.2	>3.5	MPa
Tensile Modulus	ASTM C 297	500	830	MPa
Shear Strength	Torsional Shear	>1.7	>2.1	MPa
CTE	ASTM E 228	*5.0*	*5.0*	*ppm/°C*
Thermal Conductivity	ASTM E 1225	*.25 to 25*		*w/mK*
Maximum Operational Use Temperature		600 Air 3000 Inert		°C
Electrical Resistivity	ASTM D 4496	*1E-02 to 1E+07*		*ohm-cm*
Fire Resistance	ASTM E 1354 ASTM E 1515 MIL-STD-1623	Results indicate coal-based carbon foam will pass all key fire tests including: radiant panel, smoke generation, toxicity, cone calorimeter, fire resistance, and room corner tests.		

3. CARBON FOAM TOOLING

As a carbon foam-based composite tooling product, coal-based carbon foams have a tremendous advantage over other materials in that they have very high compressive strengths and low CTE, light weight, and ease in machining.

Current technology makes it difficult to match the CTE of a composite part in the curing cycle with anything other than a carbon composite or a nickel iron alloy such as Invar®. As seen in Figure 3, coal-based carbon foam has very uniform thermal expansion when compared with Invar 36 and 42, enabling post-curing of the composite parts on the tool with high-temperature resins.

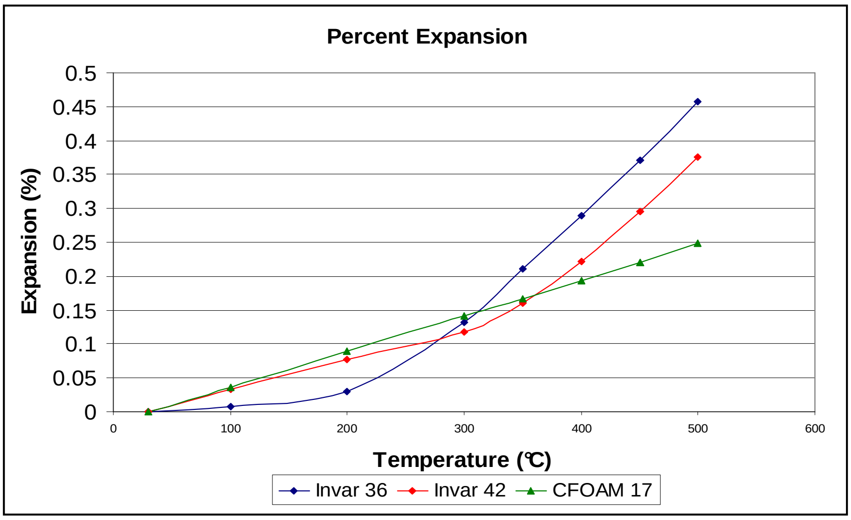

Figure 3. Coal.-based carbon foam CTE vs. Invar 36 & 42.

A comprehensive benefit analysis comparing the use of coal-based carbon foam versus Invar, aluminum and steel tools was performed. The analyses confirmed that the use of coal-based carbon foam is a suitable alternative to the current method and also provides several significant benefits:

- Lower CTE closely matches the composite part
- Lower fabrication costs
- Lightweight tooling
- Tooling easier to modify/repair
- Improved performance durability
- Cycle time reduction due to lower mass energy requirements in autoclave cure

Important process methods, prototype and production tooling methods critical for manufacturing of carbon foam composite tooling have been developed. Tool performance was tested and evaluated. Important developments were made in tooling surface coatings including continuous and chopped fiber with high-temperature resins. Coal-based carbon foam composite tools are currently in service today and are successfully being used at commercial composite lay-up production facilities. Figure 4 shows a chopped fiber surface bonded to coal-based carbon foam. It is important to get resin penetration into the pores of the foam, and it is easily done because of the open porosity in the carbon foam. The open cell (porous microstructure) of coal-based carbon foam allows for maximum penetration of the resin into the carbon foam, yielding a very robust adhesion of the carbon fiber to the substrate.

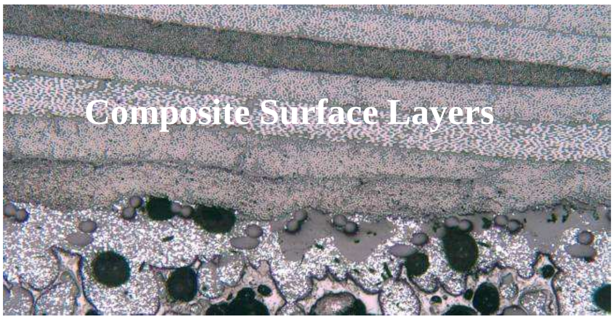

Figure 4. Coal-based carbon form SEM image.

4. RAPID PROTOTYPE/SHORT PRODUCTION RUN TOOLING

Spiral design philosophy is driving the defense industry to shorter manufacturing cycles and evolutionary design changes. Additionally, the demand for accurate, rapid and functional prototype parts is growing. Unfortunately, typical long lead times and costliness of composite tooling place constraints on the number of prototypes produced and on the design changes with a product life cycle. Utilizing coal-based carbon foam as an inexpensive, rapidly producible tooling system allows greater design freedom with lower impact to program costs. Also, coal-based carbon foam tooling offers unique advantages to rework selective areas of an existing tool to meet design changes.

Initial experiments have produced short production-run tooling using coal-based carbon foam as the primary structure and an easily machined ceramic material for the tool surface. Further research is needed to review this combination and other candidate rapid surface materials and to establish parameters to scale-up this technique. Experiments will also be conducted to develop techniques to modify existing coal-based carbon foam tooling to simulate design changes. Rapid prototyping/short production run materials and techniques will be evaluated based on:

- Cost to manufacture
- Time to manufacture
- Tool durability
- Cost and time to modify to meet design changes

5. TOOL LIFE

Tool life is an important consideration when determining the type of tool to be used. Production tools are generally considered to be any tool which can produce more than 100 parts. Prototype tools, on the other hand, are less expensive and have much shorter lead times, so manufacturers of prototype parts and small production lots generally look for non-durable tooling options that have both a short lead time and lower cost. Coal-based carbon foam tooling, however, can meet the needs of those looking for either production or prototype parts.

A key consideration when estimating tool life is surface hardness. Maintaining a good vacuum on the surface is necessary because any cracking or failures in the surface create pressing issues for the tool. Since Invar tools are considered to be durable, Table 3 references Invar as the baseline or standard for a metallic specimen. The composite specimen referenced in the table is the coal-based carbon foam tooling system with a HexTOOL® surface, which is comparable to Invar 36 from a surface hardness perspective. Other tooling prepregs, boards, and even Aluminum 2024 are softer than HexTOOL. The HexTOOL material can be used up to 500 cycles at 205°C service temperature, and test data show it can support 1000 hours at 230°C and 5000 hours at 200°C. HRB in the table below refers to the Rockwell Hardness Scale.

Table 3. Coal-based carbon foam tool hardness.

<table>
<tr><th></th><th colspan="2">Products</th><th>Average HRB Value</th></tr>
<tr><td rowspan="3">Composite Specimen</td><td colspan="2">CFOAM®/HexTOOL®</td><td>83</td></tr>
<tr><td colspan="2">Tooling Prepregs</td><td>23 to 53</td></tr>
<tr><td colspan="2">Tooling Board</td><td>42</td></tr>
<tr><td rowspan="7">Metallic Specimen</td><td rowspan="3">Aluminum Alloy 2024</td><td>Treatment 0</td><td>45</td></tr>
<tr><td>Treatment T4</td><td>75</td></tr>
<tr><td>Treatment T6</td><td>78</td></tr>
<tr><td rowspan="4">Invar™ 36</td><td>Annealed</td><td>70 Max</td></tr>
<tr><td>¼ Hard</td><td>78 to 83</td></tr>
<tr><td>½ hard</td><td>84 to 88</td></tr>
<tr><td>Coil Rolled</td><td>97</td></tr>
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Table 4 and Figure 5 compare the relative costs of coal-based carbon foam prototype tooling to other methods. It can be seen that the cost of coal-based carbon foam, traditional foam, and composite mold tools increases linearly with complexity due to the nature of fabrication. Prototype tooling (Figure 6) refers to coal-based carbon foam tooling which is capable of producing fewer than 20 parts. The cost of aluminum, steel, and Invar tooling becomes progressively more expensive as the complexity and curvature increases. Coal-based, carbon foam-based tools are 12% less expensive than traditional foam-based tools, 35% less expensive than composite tools, 15% to 37% less expensive than aluminum tools, 29% to 47% less expensive than steel tools, and 58% to 62% less expensive than Invar tools.

When compared to the cost of coal-based, carbon-foam production tooling, prototype tooling tracks very closely with steel-based tooling. On the other hand, durable production tooling is capable of producing more than 100 parts (Figure 7). The cost of traditional foam and composite mold tools increases linearly with complexity due to the nature of fabrication. The cost of coal-based carbon foam, aluminum, steel, and Invar tooling becomes progressively more expensive as the complexity and curvature increase. Coal-based, carbon foam-based production tools are typically more expensive than traditional foam, composite, and aluminum tools and are slightly cheaper than steel-based tooling and 50% less expensive than Invar tools.

Table 4. Comparative tooling cost relative to Invar 36.

Tool Curvature	**Coal-based carbon foam - Production Cost/sq ft**	**Coal-based carbon foam - Prototype Cost/sq ft**	**Traditional Foam Cost/sq ft**	**Composite Cost/ sq ft**	**Alum 6061 Cost/ sq ft**	**Steel Cost/ sq ft**	**Invar 36 Cost/ sq ft**
Linear	0.60	0.42	0.48	0.65	0.50	0.60	1.00
3-Axis	0.62	0.41	0.44	0.60	0.52	0.62	1.00
5-Axis	0.79	0.41	0.42	0.34	0.60	0.72	1.00

*Note: Cost based upon vendor referencing materials provided to the company.

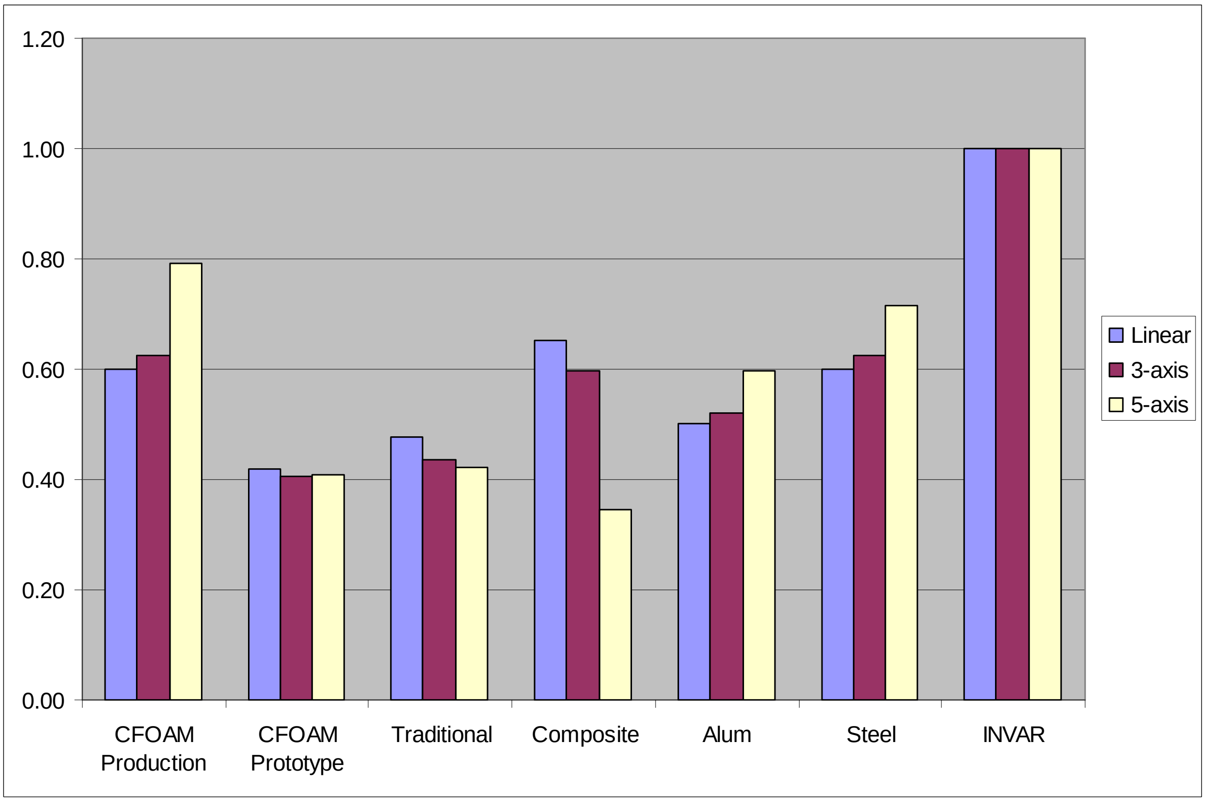


Figure 5. Graph of comparative tooling cost relative to Invar 36.

Figure 6. Coal-based carbon foam - Prototype tooling.

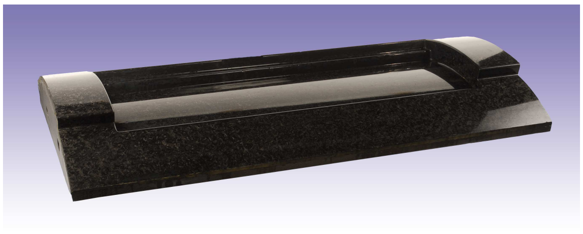
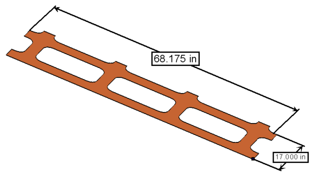
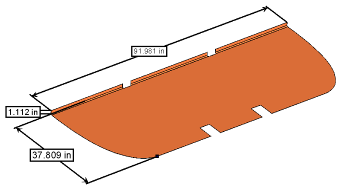
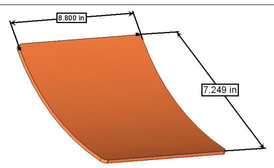
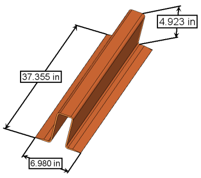
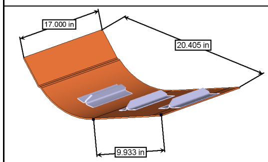
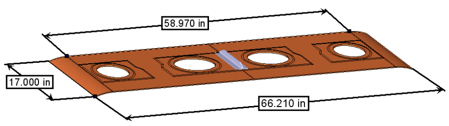
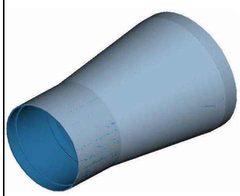


Figure 7. Coal-based carbon foam – Production tooling option.

Determining the complexity of a tool can be challenging. Some of the things to consider include tool tolerances, fixturing for part hold-downs, tooling balls, radius and curvature of tool, size and complexity of the features. Table 5 shows a variety of tools ranging from fairly simple flat geometries to very complex curves with embedded features and compares their costs.

Table 5. Coal-based, carbon-foam production tooling cost relative to Invar 36.

Part Geometry	Classification	Relative cost vs. Invar®
	**Simple** **Complex**	.6
	**Simple** **Complex**	.6
	**Simple** **Complex**	.65
	**Simple** **Complex**	.65
	**Simple** **Complex**	.65
	**Simple** **Complex**	.65
	**Simple** **Complex**	.8

6. FABRICATION TECHNIQUES

Knowing the dimensions for a tool is necessary before work begins and understanding the geometry and dimensional requirements for the tool must also be determined. Once the size is established, coal-based carbon foam blocks are stacked to the desired finished part geometry.

6.1 Block Bonding

Coal-based carbon foam bonding adhesive is used to adhere all of the blocks together in the proper form (Figures 8 and 9). Use of a notched trowel insures that a sufficient amount of adhesive is applied. The adhesive is applied to both the surface and the edges where any of the blocks are in contact. It is important to carefully follow the curing instructions from the adhesive supplier.

Figure 8. Coal-based carbon foam bonding adhesive.

Figure 9. Bonded coal-based carbon foam billets.

6.2 Rough Machining

After the adhesive has cured, the resulting coal-based carbon foam block can be machined into the proper shape (Figure 10). However, this machined product should be undersized from the actual dimensions to allow room for the composite surfacing material. The specific under-cut will vary depending upon the type of surface to be applied. Several different surfacing materials have been developed and tested. Technical support for information on specific surfacing materials can be supplied.

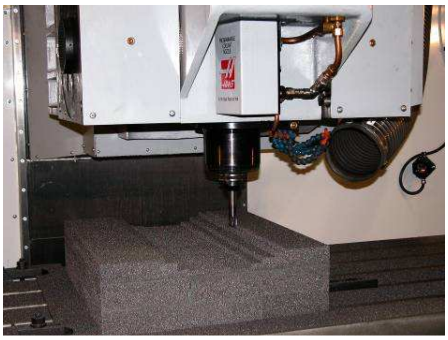


Figure 10. Coal-based carbon foam rough machining.

6.3 Adding Composite

The surface adhesive is applied to the unfinished tool. Polymer matrix composite prepreg surface plies are applied to the rough-machined coal-based carbon foam. Adhesive film cut to size is applied to the bottom of the tool. In this example a bi-directional carbon prepreg is used (Figure 11). The weight of this material varies and should be adjusted as needed. The amount of material will primarily be driven by the durability and handling requirements of the tool. A prepreg is cut to size and applied to the bottom of the tool and is cut slightly larger than the actual measurements to allow for trimming. Each individual piece is trimmed before the next layer is applied.

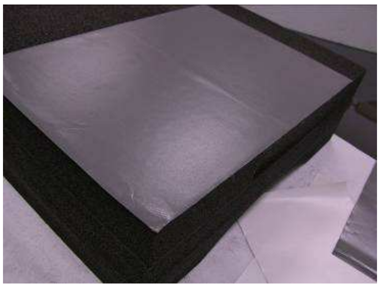


Figure 11. Prepreg applied to bottom.

Once all the pieces are applied to the bottom, then work is begun on the sides of the tool (Figure 12). The adhesive film is applied as before, and the same process is followed until all sides are covered. The tool is flipped over, and the adhesive is applied to the top surface. If the tool has a complex geometry, this process can be done in sections to ensure adequate adhesion. The tool is to be pressed firmly to avoid air pockets behind the adhesive. The tool is then ready for application of the surface material. As with the adhesive, it should be applied in sections per the engineering ply layout.

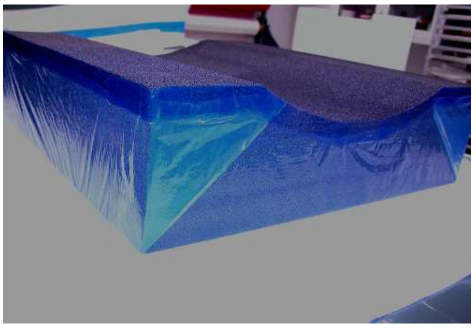


Figure 12. Prepreg applied to the sides.

6.4 Final Preparation and Processing

The tool is ready to be placed into a vacuum bag and autoclave cured. Vacuum bagging of materials and procedures are dependent upon specific resin systems and may also be varied depending upon part geometries.

When the tool is ready to be placed into the autoclave, a vacuum line is attached to the tool inside the autoclave, the door is sealed shut, and the program is set to the manufacturer's surface curing temperatures (Figure 13).

Figure 13. Vacuum bagging.

The tool is removed from the autoclave and the vacuum bag before it is machined to its final dimensions (Figure 14). When the surface machining is complete, a seal coating is applied to the top surface to fill any pinholes or scratches on the surface (Figure 15). In the final step the tool is wet sanded for a polished finish.

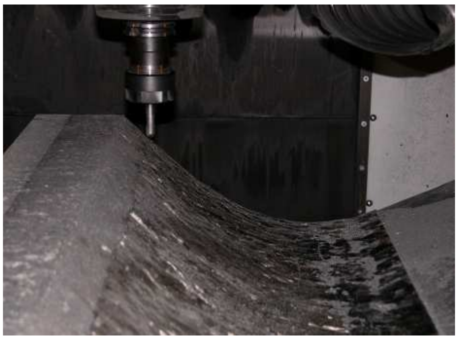


Figure 14. Final machining.

Figure 15. Completed tool.

Lessons learned have been transferred from the small tools to larger-scaled tooling. An example of this process is shown in Figures 16-22.

Large-Scale Tooling

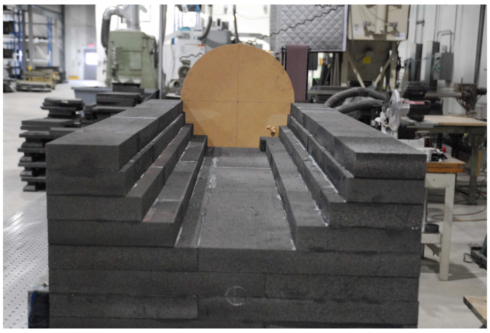
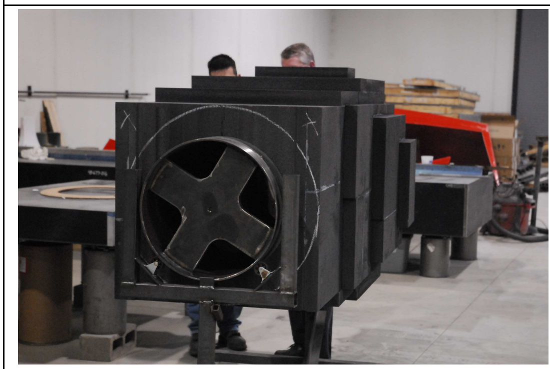
	Figure 16. Coal-based carbon foam blocking and rough lay-up. The carbon foam billets are bonded together with a room-temperature cure adhesive. In this example a round cylinder mandrel will be inserted into the center of the tool as a holding fixture for machining the tool.
	Figure 17. Coal-based carbon foam inside mandrel rough machining. The blocked carbon foam billet is then loaded onto a 5-axis CNC and precision machined to the outside diameter of the inside mandrel.
	Figure 18. Installation of inside tool holding fixture. The two machined halves are now bonded together over the outside of the mandrel. A carbon layer between the steel mandrel and the carbon foam can be seen. This procedure is necessary to allow the tool to be removed from the mandrel after the tool is completed.

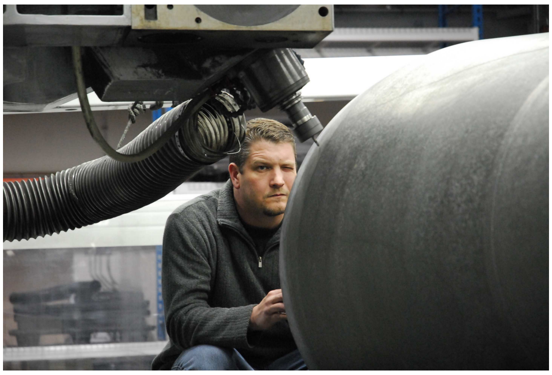
	Figure 19. Installation of thermocouples and chopped carbon surface. Per the customer requirements, this specific tool had thermocouples mounted directly below the surface of the tool. Thermocouples as well as other features are easily integrated into the tool. The outside of the tool has also been machined to the dimension needed just prior to the application of the surfacing material.
	Figure 20. Machining of chopped carbon surface. After the tool has been machined, the carbon fiber is added to the surface and then is precision machined to the final dimension. The steel mandrel is used as the holding and machining fixture on this cylinder/ conical shaped tool.
	Figure 21. Final finishing of tool. After the final machining, the tool is polished and buffed to a smooth finish. In this picture the operators are wet sanding with a diamond grit paper.

	Figure 22. Completed tool. The picture is rotated, but the final product can be seen. One of the concerns with this tool was being able to remove the part because of the small draft angle along the cylinder part of the tool. The tool worked extremely well.

This project was a collaborative effort between Touchstone and San Diego Composites.

7. CONCLUSIONS

Performance requirements and critical characteristics such as manufacturability, tool costs, durability and functionality have been identified and addressed. Based on the results of the work conducted and presented, coal-based carbon foam tooling appears to be an excellent material for the base structure for composite tool construction. Current tooling systems rely primarily on either metallic, composite or graphite tool surfaces. While each of these methods has advantages, they each also carry inherent disadvantages. Metallic surfaces are typically more durable but also require longer lead times and are heavy and expensive. Composite tooling can be fabricated in shorter times but have durability issues and can be costly due to material and machining costs. Graphite tools are stable across a range of operating temperatures but are heavy and require machining and sealing methods in addition to the expense of the raw graphite billets. Coal-based carbon foam prototype and durable tooling options provide tooling customers with cost-effective, rapid, lightweight tooling alternatives. With the aerospace industry going to larger and larger parts, composite tooling needs to be as light as possible to help with handling, fixtures, and processing times. The weight savings associated with coal-based carbon foam tooling is an excellent option when looking at large-scale tooling.

Other benefits include:

- Stable CTE
- Reduced heating
- Easy modifications
- Repair capabilities
- Reduced lead time
- Durability

8. REFERENCES

1. Drew M. Spradling and R. Andrew Guth, “Carbon Foams,” *Advanced Materials & Processes*, Nov. 2003, pp. 29-31.