RESIN INFILTRATED MULTI-FUNCTIONAL CARBON FOAM

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ABSTRACT

The demand in industry for lighter materials has facilitated the approval of composites for construction in many industries. This acceptance continues to grow and to find new applications. Now with even higher demands in performance, industry is turning to more advanced material systems. These systems are using materials such as carbon composites. Unfortunately, carbon composites are not compatible with most metals and composite materials because of their low coefficient of thermal expansion. Carbon foam, though, is very compatible with carbon composites and offers solutions for integration for these advanced material systems.

The market for finished carbon composites continues to grow and is projected by many to be close to $10.0 billion by 2010. The growth is a reflection of the increasing demand for this advanced material. The ability to utilize this novel material in new structures will be critically important and is especially complicated when there is a required transition to a metal or other non-carbon material. This paper will show how carbon foam can be integrated with carbon composites and other materials to provide an advanced material solution for the designers of the future.

KEY WORDS: Materials-Core/Foam/Syntactic Foam, Resin Infusion/Vacuum Infusion Processing, Carbon Fiber Composites

1. INTRODUCTION

Continuous research on carbon foam is expanding at a fast pace at Touchstone Research Laboratory, Ltd. One of the study focuses is the compatibility of carbon foam with the other materials, especially with carbon composites. Touchstone's carbon foam, CFOAM®, is versatile and compatible with carbon composites from multiple perspectives. The compatibility between CFOAM and carbon composites results in more varieties of CFOAM composite materials for a broad range of future industry applications.

The advantageous material properties of carbon composites in structural, thermal, electrical and chemical areas create a rapid expansion of their commercial market. It has been projected that the market size of carbon composites is to reach $10.0 billion by 2010[1]. Carbon composite materials, however, are not compatible with many other composites nor with most metals primarily because carbon composites materials have very low thermal expansion rate (CTE), generally less than that of Invar™. A close-to-zero CTE is also possible for very high modulus carbon composites. In the meantime, aluminum, as a widely used lightweight metal, can have CTE more than 20ppm/°C. Most metals and other composites expand their dimensions at least several times more than carbon composites. The mismatch in CTE, along with other problems like galvanic corrosion, seriously limits the design options when an integrated materials solution is desirable for technical or economical reasons.

Carbon foam is one of the few materials among those with low CTE that is compatible with carbon composites. CFOAM, a commercially available advanced structural carbon foam, is an emerging material that matches with carbon composites.

CFOAM possesses extraordinary and unique properties beyond low CTE for industry users. The following existing properties define CFOAM as a multi-functional versatile material[2]:

1. From a mechanical strength point of view, CFOAM has high compressive strength and weight ratio. Its compressive strength is in the range of 850 psi to 10,000 psi, and it has an energy-absorbing capability. Fatigue test results also show that CFOAM has very long fatigue life, and it doesn't fatigue after two million cycles at a load above 90% of its ultimate strength with residual tensile strength unchanged.

2. A non-combustible material, CFOAM is very stable especially in sea-water environment. CFOAM can be easily coated to prevent any oxidations occurring at very high temperature.

3. An important and unique characteristic of CFOAM is that most of its properties, including density, thermal conductivity, electric resistivity, etc., can be controlled and altered based on the requirements of the end users. A lightweight material, CFOAM normally has about 10% of the density of aluminum. The density of CFOAM products can vary from 12lb/ft^3, 17lb/ft^3, 25lb/ft^3 to 65lb/ft^3. Its thermal conductivity ranges from 0.5W/m-K to 50W/m-K, i.e., changing from thermally insulating to thermally conducting. CFOAM has excellent thermal shock resistance as a result of its low CTE. The electrical resistivity of CFOAM can be altered from $4.0\times10^{-3}\Omega$ to $4.0\times10^{6}\Omega$, which means that it can be produced as an electric conductor or an electric insulator. CFOAM also presents favorable electromagnetic properties as an absorbing material of electromagnetic waves from radio frequency range to very high frequency.

4. CFOAM is relatively inexpensive and highly producible. Unlike pitch-based foam, CFOAM is formed from an inexpensive precursor with a controlled process; therefore, it is very competitive in terms of affordable product price. Touchstone can readily supply large CFOAM panels up to 24"x48" in mass production quantities.

5. CFOAM is an ideal material to form a single material solution or integrated material solutions for market needs. CFOAM not only has a variety of applications of its own in defense, aerospace and other industries; but, very importantly, it also has compatibilities with other carbon composites materials in terms of a matching CTE, easy bonding, non-corrosiveness, etc. CFOAM can be machined easily through cutting, sanding, milling or

turning with all conventional equipment and tools. It can be machined into almost any geometric shape, complex or simple.

CFOAM is continuously being developed to aim at new applications and to meet new challenges. One of the new developments is to infiltrate CFOAM with different resins to form a carbon foam matrix composite.

The microstructure of CFOAM and its compatibility with carbon composites make CFOAM an ideal matrix material. CFOAM is almost always an open-cell foam with pore sizes in the range of a few microns to a few hundred microns. The ligaments of the pores are capable of bearing structural load. Based on these advantages, vacuum-assisted infiltration technology is being used for the first time to infuse different grades of CFOAM with a wide variety of resins.

Resin-infiltrated CFOAM can gain significant material advantages. After the infiltration process CFOAM's existing material properties are fully transferred and greatly strengthened. With 80% porosity in CFOAM, there is considerable potential for further adjustment of its properties to make CFOAM even more versatile.

2. MATRIX COMPOSITES

The drive behind the new development of a carbon foam matrix composite is to further utilize the compatibility of CFOAM with carbon composites to form advanced composite material solutions.

One of the general applications of infiltrating CFOAM with resins is to increase its mechanical strength for selective reinforcement. Due to the aforementioned open-cell structure, porosity and other properties, CFOAM is an ideal matrix material for the resin infiltration process, similar to resin transfer molding (RTM) for composite fiber performs. RTM is a commonly used process in which resin is injected into fiber preforms enclosed in heated mold cavities.

It has to be pointed out that CFOAM is an ideal material for infiltration. Unlike fibers, CFOAM is a structural material. It does not show obvious deformation under vacuum pressure while almost all fibers are normally non-load bearing material by themselves and would have deformation or displacement under vacuum pressure. For example, fibers tend to have a compaction behavior during vacuum assisted resin transfer. Compaction may cause uneven distribution of fiber reinforcement. The load-bearing feature of CFOAM, its open-cell structure as well as its relatively uniform pore sizes enable resins to penetrate through evenly with compaction during infiltration, curing or heat treat processes. Infiltrated CFOAM, therefore, yields a finished product having great uniformity with a wide variety of resins.

Another advantage of using CFOAM as the matrix for infiltration is to prevent or eliminate certain limitations of common infiltration methods. These limitations include distortion, cracks, shrinkage and corner spring-in, etc. Composite parts made out of infiltrated CFOAM have almost zero distortion under stress or temperature. CFOAM is a rigid carbon foam with very low Poisson's ratio much lower than 0.1. Stresses from external loads, internal pre-stresses or residual stresses do not distort the part shape. Furthermore, CFOAM has very low CTE so the part will not distort with temperature variations.

Infiltrated CFOAM greatly reduces the risk of crack formation and growth compared with other composites. While cracks can form in resin-infiltrated composites due to thermal stress during post-cure when heat is applied, cracks normally do not form in infiltrated CFOAM. Since the resin reinforces the strong but thin ligaments of CFOAM throughout the infiltrated part, CFOAM ligaments are exposed to a very low risk to have localized buckling, which is often the cause of structural failure in bare carbon foam. In the case of localized micro-size cracks in the resin contained inside a pore, the propagation of the cracks is interrupted by the ligament walls; so in most cases the size of a crack in the resin is limited by the pore size, and the crack doesn't grow as quickly as that in many monolithic materials. As a result the overall strength of CFOAM does not show observable changes when micro cracks appear in the resin.

To achieve the advantages of infiltrated CFOAM, the recommended processes are vacuum pressure assisted infiltration, vacuum and positive pressure assisted infiltration and iso-pressure impregnation. Before considering the details of CFOAM infiltration, it is necessary to review other matrix composite materials.

Other than carbon composites the most commonly used matrix composites are ceramic matrix composites, metal matrix composites and polymer matrix composites. Ceramic matrix composites (CMCs) are made by reinforcing ceramic phases with a ceramic matrix. There are discontinuous and continuous reinforcements with the latter more suited for large structures. CMCs have superior properties, but their cost could compete with high alloy steels. It is predicted that the price of CMCs can possibly be reduced to $200-$400/lb from current $1000/lb. Also, special tools are normally required to machine CMC parts due to their high strength; therefore, the cost of finished parts may be pushed even higher [3].

Metal matrix composites (MMCs), consisting of metallic matrices reinforced with ceramic particles or fibres for higher strength and stiffness, lower thermal expansion and improve high temperature properties and wear resistance. Long-fiber materials show the most significant property gains, but they are the most expensive to produce. So the applications are limited to aerospace and defense industries that can bear the associated material costs. It is also possible to infiltrate molten metals into ceramic foams for improved strength and to increase creep resistance, but high-temperature infiltrations involve special equipment to handle since most metals melt at least at a few hundred degrees Centigrade.

Polymer matrix composites (PMCs) have higher specific tensile strength and stiffness properties than other composites, are more advanced in terms of fabrication technology development, and have lower raw material and fabrication costs. PMCs often have anisotropic characteristics with high strength and stiffness parallel to the fibers and much lower strength and stiffness perpendicular to the fibers.

Carbon foam matrix composites or infiltrated CFOAM shows advantages compared with the aforementioned matrix composites. First of all, infiltrated CFOAM is cost competitive.

Touchstone selects the inexpensive, room temperature vacuum assisted resin infiltration process along with conventional heat treatment for after cure. No special equipment is needed for this inexpensive process of producing CFOAM from its inexpensive precursor. The second advantage is the significant improvement in material properties of infiltrated CFOAM. For example, the structural strength of phenolic resin-infiltrated CFOAM is almost an order of magnitude higher compared to basic CFOAM, and the particle erosion resistance is much higher than most high-grade graphite materials. Full resin infiltration enables the infiltrated CFOAM to be more isotropic with the option of a partial infiltration for selective reinforcement. In the situation of complex geometry, CFOAM can be easily pre-machined to the exact shape of the finished part before resin infiltration to avoid difficult machining. This pre-machining can also lower the cost by using a smaller amount of resin and having less infiltration time.

3. PROCESS OF INFILTRATED CARBON FOAM

Touchstone developed the vacuum assisted resin infiltration process to infiltrate its CFOAM with different types of resins for a wide range of applications. The level of cost of this process is comparable to or less than the inexpensive vacuum assisted resin transfer mold (VARTM).

The CFOAM infiltration process involves several steps. The first step is to determine the infiltration inlet and the vacuum outlet on the part to be infiltrated. From a part made of bare CFOAM sealed inside a vacuum bag, the pressure at the resin reservoir is set to the atmospheric pressure. A manifold is attached to the resin reservoir to equalize the resin infiltration pressure for uniform infiltration. A vacuum pressure is applied at the vacuum side of the part pulling resin to flow from the reservoir through the CFOAM part. The resin flow front position can be monitored through the transparent vacuum bag for the purpose of research. **Figure 1** shows the schematic of resin infiltration and **Figure 2** the picture of the apparatus for infiltration.

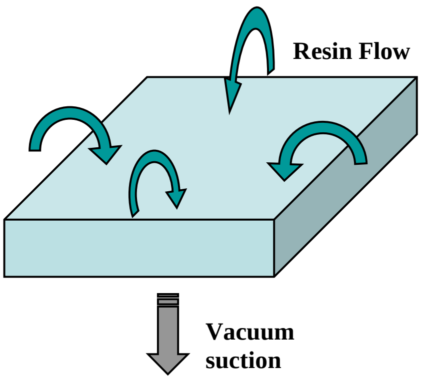

Figure 1. Schematic of resin infiltration through a CFOAM block.

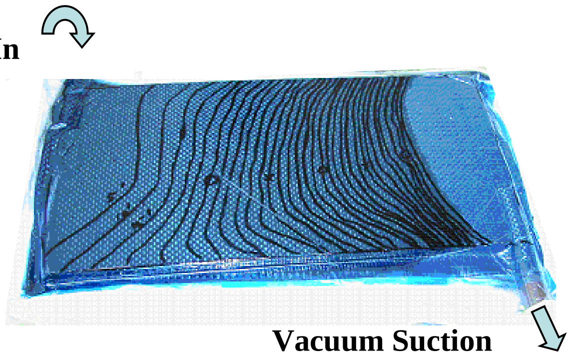

Figure 2. Infiltration apparatus.
Resin flow front at different times is marked starting from the left.

Infiltration time and the infiltration uniformity are important factors for a successful process. The speed of infiltration is related to the resin viscosity and the part geometry, mainly the maximum thickness in the flow direction. Touchstone's infiltration process is designed to best use the microstructure characteristic of CFOAM porosity to reduce infiltration time. The relatively even distribution of CFOAM pores enables the resin to be channeled in all directions for uniform infiltration without much difficulty.

The most critical and difficult task in the process is removing volatiles and air bubbles from resin during infiltration and in post-cure. Product-specific methods have been tested and applied to successfully produce the fully infiltrated finished part.

The resins that can be used in this room temperature infiltration can be epoxy, phenolic, graphite resin or any other resins that have comparable viscosity. The same process is viable for metal infiltration after minor modifications. Liquid or powder additives can be added to the resins as long as the viscosity stays at a manageable level. For example, certain fire retardants can be added into the resins to increase their fire resistance.

It is interesting to see that a full infiltration or a partial infiltration can be accomplished with the same process by controlling the time of infiltration, selecting the location of the infiltration inlet and regulating the vacuum pressure. While full infiltration is desired in most cases, a partial infiltration can be useful for surface densification and selective reinforcement at certain locations of the part.

The infiltration process can be associated with an automated adhesion process. CFOAM infiltration can be completed at the same time with adhesion of the carbon fiber, carbon fiber face sheets, or other composite face sheets. For large parts the resin adhesive bond formed with infiltration has better uniformity and quality than hand lay-up. For example, if a carbon fiber face sheet is placed at the surface of a CFOAM panel before infiltration, there will be a small gap in between the CFOAM panel and the face sheet. This small gap, minimized in size by vacuum pressure, is going to guide resin seepage flow front through it and will remain filled at the end of the process. Once the resin solidifies, the face sheet is bonded to CFOAM by the resin with a full infiltration on the CFOAM panel at the same time. Benefiting from the uniform vacuum pressure, the resin is applied to the face sheet uniformly. Furthermore, the resin on the face sheet is connected with the resin in CFOAM pores on the surface to result in better bonding between the foam and the face sheet. The same benefit is applicable to the situation of bonding fibers to CFOAM. **Figure 3(a)** shows the schematic of the combined infiltration and adhesion process. **Figure 3(b)** is a finished CF17 panel bonded to a carbon fiber face sheet and infiltrated with high phenolic for high temperature application.

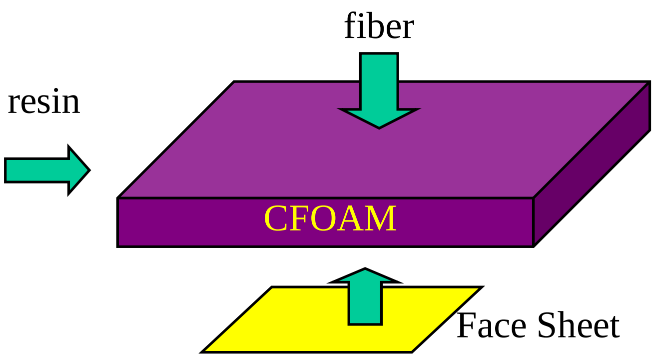

Figure 3(a). Schematic of combined adhesion and infiltration process.

Figure 3(b). Finished Part by combined infiltration and adhesion process (1/4" CF17 panel infiltrated with phenolic resin and bonded with carbon fiber sheets at all four sides).

4. MATERIAL ADVANTAGES AND APPLICATIONS OF INFILTRATED CFOAM

Mechanical tests show significant improvement in mechanical properties of infiltrated CFOAM. **Figure 4** shows a sample of CF17 infiltrated with phenolic and **Figure 5(a) and 5(b)** the compression test results of CF17 infiltrated with phenolic and epoxy. A microscopic image is shown in **Figure 6**.

Figure 4. CF17 infiltrated with phenolic resin.

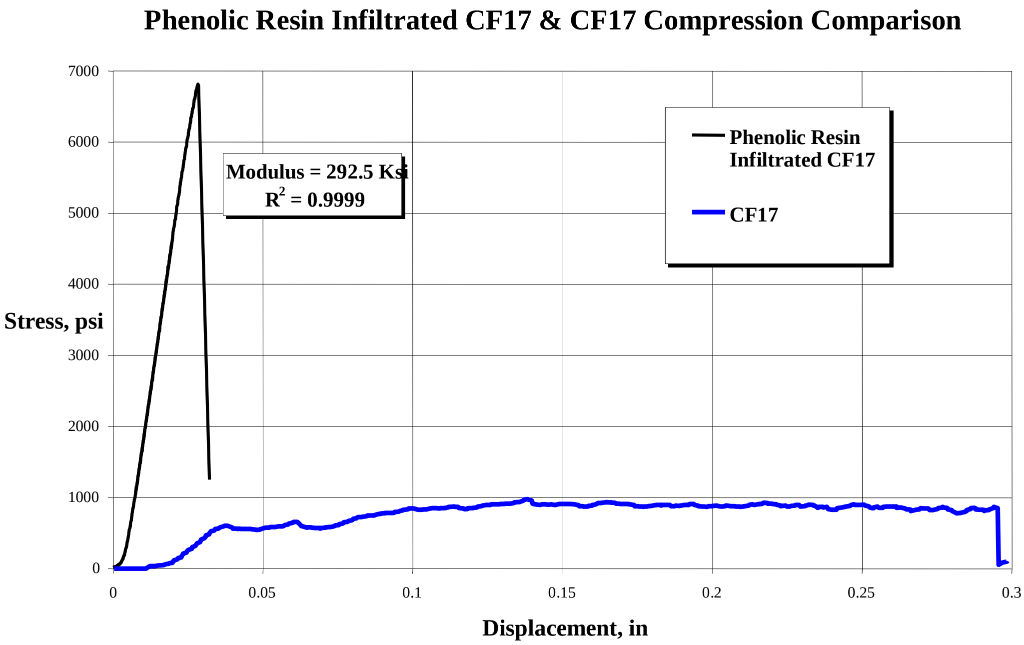

Figure 5(a). Compression test of CF17 infiltrated with phenolic resin.

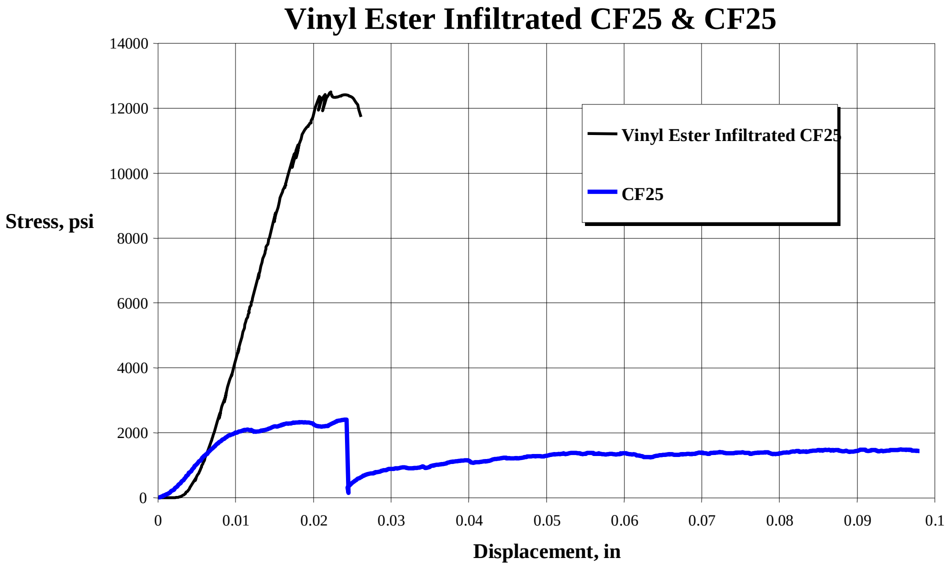

Figure 5(b). Compression test of CF25 infiltrated with vinyl ester resin.

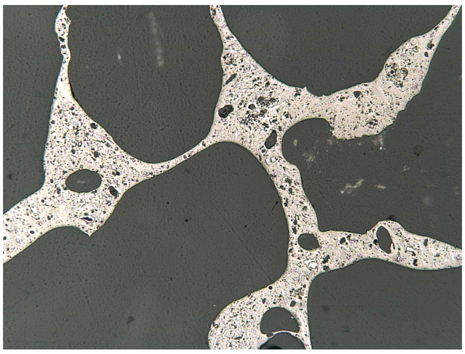

Figure 6. 100X microscopic image of CF17 infiltrated with epoxy resin.

In addition to the material property gains, the following list summarizes the benefits of infiltrated CFOAM.

- Compression strength an order of magnitude higher. For epoxy infiltrated CFOAM, the compressive strength is about 12 times of that of CF17. The compression strength is about 10 times greater compared with bare CF17 if phenolic resin is used.

- Thermal conductivity can be further increased or decreased according to the application. CFOAM itself can be thermally insulting and conducting. Infiltrated CFOAM will make CFOAM more versatile. It is possible to infiltrate CFOAM with conducting metals for enhanced thermal conductivity.

- Ablation material candidate. CFOAM consists of carbon. Combined with high temperature phenolic resin, CFOAM becomes an ablation material similar to the existing ablation materials.
- Increased hardness and abrasion resistance. Surface hardness and abrasion resistance are not normally the advantages of any type of foams; however, phenolic infiltrated CFOAM performs better than high-grade graphite in sand blast test at 60 psi pressure and shows little noticeable recess on the surface.

- Increased durability. Infiltration of CFOAM can be used for the purposes of selective reinforcement, surface densification, stronger bonding and mechanical fastening like tapping.

- Shaping complex geometry of high strength material. Due to the ease of machining of CFOAM, it is very economical to shape the CFOAM matrix first and then infiltrate the CFOAM with the type of resin desired. Minimal amount of final finish may be needed but the low CTE and low Poisson's ratio of CFOAM preserve the final finished part with dimension variations within 5 ppm, the CTE of CFOAM. .

- Low-cost process for large parts. CFOAM infiltration can be used for large components used for tooling, ship and aircrafts.

5. FUTURE DEVELOPMENT OF INFILTRATED CFOAM

The following developments will be pursued at Touchstone in the direction of CFOAM infiltration.

- Tailoring electrical properties of CFOAM

- Further strengthening bonding at resin CFOAM interfaces

- Resin with metal contents

- Ceramic infiltration of CFOAM for high modulus complex parts

- Selectively reinforced CFOAM panel without overall infiltration

- Development of CFOAM panel and CFOAM tool repair kit using infiltration

- Computer Simulation of Infiltrated CFOAM to further unveil the material characteristics of carbon foam from the microstructure point of view.

6. CONCLUSIONS

Resin infiltration of CFOAM is an inexpensive but reliable process to tailor CFOAM properties, selectively reinforce CFOAM structures and bond or fasten CFOAM structures with other structures or materials. It adds another application dimension to the already versatile CFOAM material and it connects CFOAM closely with other materials especially carbon composites materials. The infiltration process introduced in this paper is proven to have reliable quality and is scalable for large parts.

7. ACKNOWLEDGMENT

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