Carbon and Insulation Materials Technology Group
Metals and Ceramics Division

CRADA Final Report
For CRADA ORNL-99-0563

Characterization of ORNL's High Thermal Conductivity Graphite Foam

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ABSTRACT

The recent development of light-weight foams has led to novel light-weight high-strength carbon based materials and structures. These materials exhibit very high specific strengths and low thermal conductivities. Likewise, the novel development of a very high thermal conductivity graphite foam will lead to novel "out-of-the-box" solutions for thermal management problems. With a thermal conductivity equivalent to aluminum 6061 and $1/5^{th}$ the weight, this material is an enabling technology for thermal management problems ranging from heat sinks to radiators and satellite panels to aircraft heat exchangers. The ability to be machined into a heat sink resembling a metallic heat sink, have comparable thermal conductivities to metallic heat sinks, yet be $1/5^{th}$ the weight is a significant advance to thermal management. However, the foam is not as rugged as the metallic heat sinks in its foamed and graphitized state. Therefore, the material must be rigidized to improve its durability under high demands applications, such as military vehicles. Therefore, this program focuses on several techniques previously conceived to rigidize the foam: carbon CVI, metalization (plating), and polymer coating. These techniques were all explored with success and should lead to improved heat sinks.

PROGRAM OBJECTIVES

One objective of this CRADA was to gain an understanding of the behavior of ORNL's graphite foam as a potential heat sink. However, since there are questions about the ruggedness of the foam in military applications, the ability to rigidize the foam is of paramount importance. Therefore, the objective of this program was to develop and characterize methods to improve the stiffness and durability of the foam so it can maintain shape and functionality under high demand applications.

BENEFITS TO THE FUNDING DOE OFFICE'S MISSION

This was a 100% Funds-in CRADA and, therefore, no DOE funds were spent.

BACKGROUND

The purpose of this Cooperative Research and Development Agreement (CRADA) between Lockheed Martin Energy Research Corporation (Contractor), and General Dynamics, Land Systems, (Participant), is to develop a thermal management heat sink for electronic boxes utilizing the Oak Ridge National Laboratory's (ORNL's) high thermal conductivity carbon foam. The Contractor and the Participant are hereinafter referred to as the "Parties."

Contemporary advanced structural composites exploit the extraordinary mechanical properties of graphite fiber by creating a disconnected network of graphitic filaments held together by an appropriate matrix binder. Recently, the extraordinary thermal properties of graphite fiber have been exploited in a similar manner for thermal management applications. However, like the mechanical properties, the high thermal conductivity of the resultant composites is limited to the direction of the fibers. In most composites [typically 1- or 2- D(imensional)] this results in very high in-plane thermal conductivities and relatively low thermal conductivities in the out-of-plane (through thickness) direction. This is due to the fact that in the out-of-plane direction, the matrix is the dominant phase for heat transfer. Even when carbon is the matrix, it typically does not develop the unique orientation found along the axis of carbon fibers. This, combined with the tortuous path of heat transfer around voids, fibers, and matrix cracks, results in low out-of-plane composite thermal conductivity. Unfortunately, this can be a limiting factor in many applications ranging from wing leading edges in aircraft, to electronic packaging, to heat exchangers.

Carbon foam derived from a pitch precursor, on the other hand, can be considered as an interconnected network of graphitic ligaments and, thus, should exhibit material properties more nearly isotropic. Hence, foams represent a potential reinforcing phase for structural composite materials and a possible cheaper alternative to carbon fibers. But, more importantly, because of the continuous graphitic network, foam-based composites will display higher out-of-plane thermal conductivities than typical 1-D or 2-D carbon fiber reinforced composites.

A new, less time consuming process for fabricating pitch-based graphitic foams without the traditional blowing and stabilization steps has been developed at ORNL and is the focus of this research. It is believed that this new foam will be less expensive and easier to fabricate than traditional foams since the time consuming oxidative stabilization step has been obviated. Potentially, it should lead to a significant reduction in the cost of carbon-based thermal management and structural materials (i.e. foam reinforced plastics and foam core composites).

One objective of this CRADA is to produce finned heat sinks utilizing the foam and either metallic plating or CVI partial densification to improve the mechanical properties of ORNL's Grafoam™. The Contractor will produce the foam heat sinks and supply them to the Participant for metallic plating. The Contractor will also perform CVI partial densification to improve the mechanical reliability of the heat sink. Another objective of this CRADA is to demonstrate that polymer impregnated foams will exhibit high thermal conductivities and mechanical properties suitable to replace aluminum structural members, thereby reducing weight. The last objective of the CRADA is to provide suitable information to the Participant for determining if the foam is applicable to its many thermal management applications.

EXPERIMENTAL

The objective of this CRADA was to develop a rigidization method for heat sinks utilized in military applications. Therefore, several blocks of foam were acquired from Poco Graphite and machined into heat sinks (dimensions specified by Participant and slightly modified by the Contractor to accommodate the structure of the foam). One of the samples was rigidized with carbon utilizing a standard isothermal CVI technique at ORNL. The CVI furnace conditions were as listed below:

- 1160°C
- 0.8 slpm methane flow
- 12 torr absolute pressure
- 24 hour cycle

The samples were sent to the Participant for plating by various metals to rigidize the foam for military specifications.

A small-scale sample was machined into a finned heat sink and coated with a dilute solution (5 or 10%) of phenolic resin in ethanol. The sample was then dried and cured at 150°C to solidify the phenolic resin. The objective was to rigidize the foam without the need for high temperature processing.

EXPERIMENTAL RESULTS

Machining

It was determined that the designs for the standard aluminum heat sink could not be duplicated exactly by machining in the foam due to the brittle structure of the foam. However, with Participant agreement, it was determined that the fine details in the aluminum heat sink were merely an artifact that the heat sink was cast and not machined. These details did not need to be duplicated and, therefore, were removed from the drawing. The only significant difference was that the base thickness of the heat sink was doubled (from 2 to 4 mm) to improve the sinks stiffness. However, this was at the sacrifice of the height of the fins. A machined sample is illustrated in Figure 1.

Figure 1. Foam heat sink after machining.

Carbon CVI Rigidization

The CVI process was successful in adding approximately 5% of mass to the system to improve the rigidity of the fins.   The foam did not rub off at the touch of a finger or hand and appeared to be stiffer than the raw foam. A sample is illustrated in Figure 2.

Figure 2. Foam heat sink after CVI.

Polymer Coating

The process of coating with dilute phenolic resin resulted in approximately 6% mass gain with the first coating cycle. This appeared to be adequate as the foam was sufficiently protected from flaking and incidental damage (i.e., it did not rub off when touched with a finger). This small sample is illustrated in Figure 3. However, it is unclear what the effect of the phenolic resin coating has on thermal conductivity and the overall heat transfer coefficient.

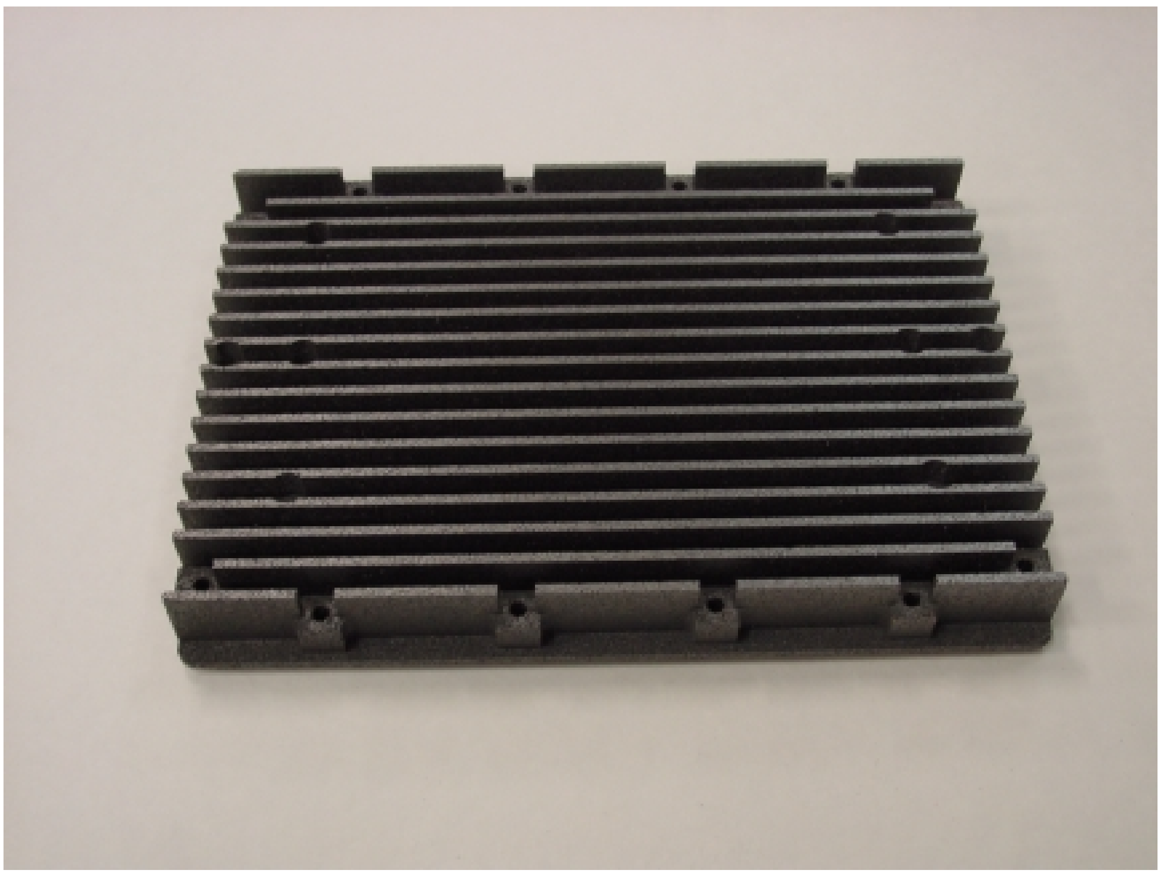

Figure 3. Heat sink coated with one cycle of diluted phenolic resin.

Metalization

After processing and machining at ORNL, three heat sinks were shipped to the Participant for metalization (plating). The preliminary tests on small samples of foam were very promising. Therefore, the other samples were sent for plating at an external company. The first plated heat sink returned with no problems discovered by the plating company. This is illustrated in Figure 4. At the time of writing, no thermal testing had been completed by the Participant.

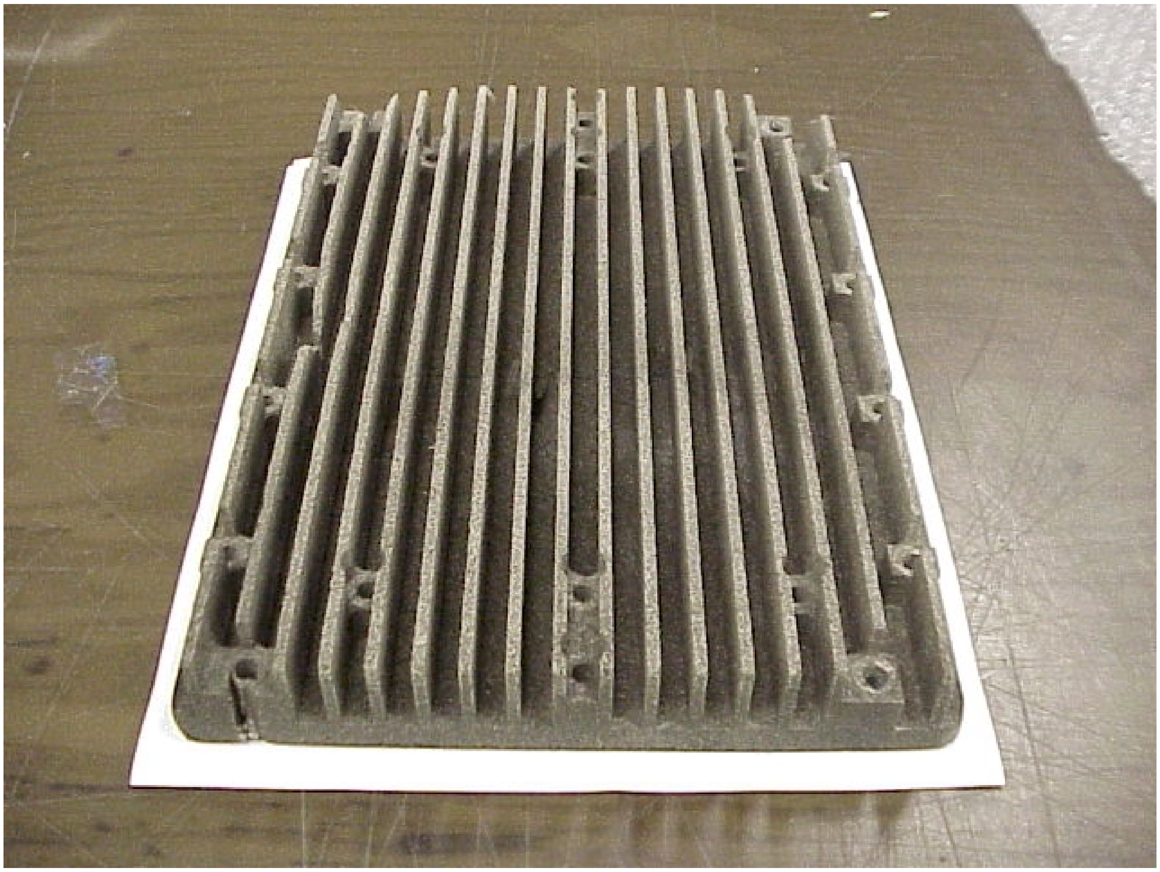

Figure 4. Metalized (plated) foam heat sink.

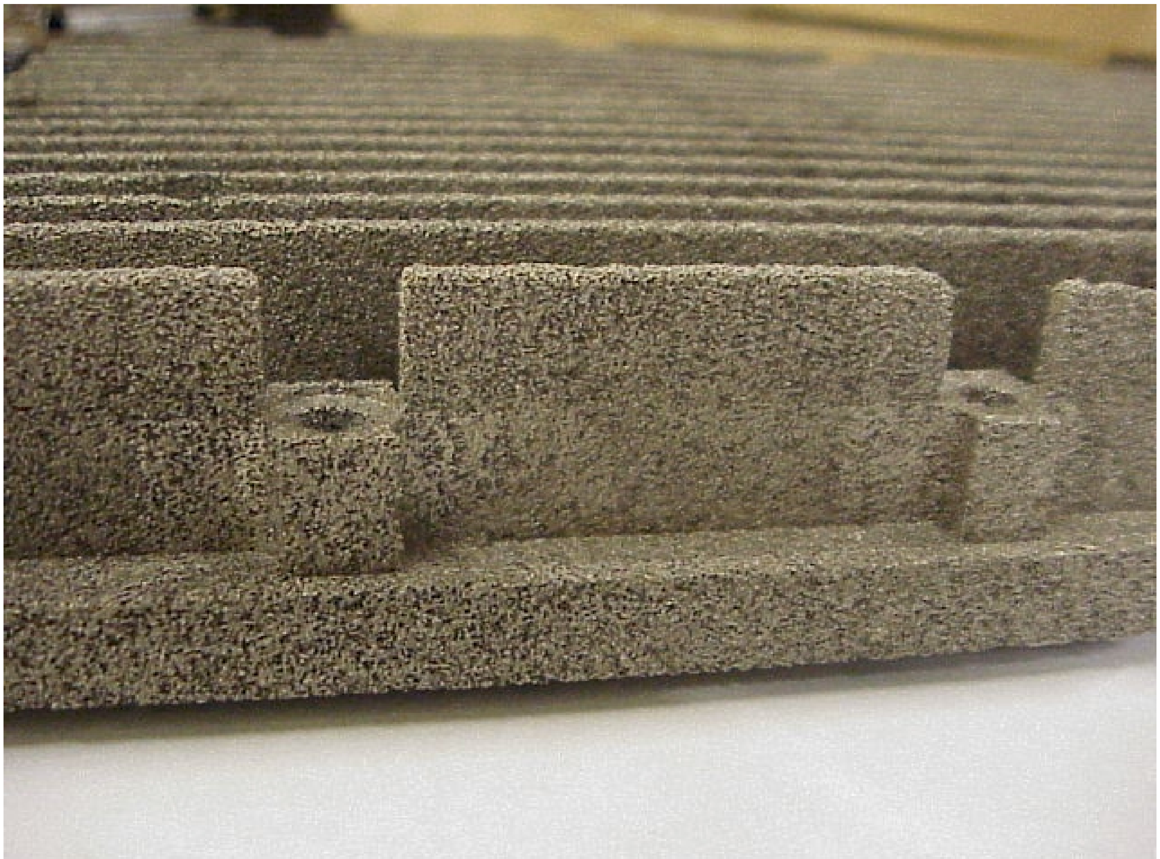

Figure 5. Closeup view of metalized heat sink.

INVENTIONS

None were made.

COMMERCIALIZATION POSSIBILITES

The Participant is interested in marketing this for military applications.

PLANS FOR FUTURE COLLABORATION

The parties plan to collaborate in future work through consulting arrangements and possibly CRADA arrangements.

CONCLUSIONS

Carbon foam heat sinks can be machined with enough details to be fabricated into large heat sinks for electronics applications. These heat sinks can be rigidized by several techniques such as carbon CVI, polymer coating, and metalization by vapor plating techniques. This increase in stiffness may prove to be the enabling step in utilizing the carbon foam in many military and civilian technologies.

ACKNOWLEDGEMENT

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