



Carbon foams for thermal management

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Abstract

A unique process for the fabrication of high-thermal-conductivity carbon foam was developed at Oak Ridge National Laboratory (ORNL). This process does not require the traditional blowing and stabilization steps and therefore is less costly. The resulting foam can have density values of between 0.2 and 0.6 g/cc and can develop a bulk thermal conductivity of between 40 and 180 W/m K. Because of its low density, its high thermal conductivity, its relatively high surface area, and its open-celled structure, the ORNL carbon foam is an ideal material for thermal management applications. Initial studies have shown the overall heat transfer coefficients of carbon foam-based heat sinks to be up to two orders of magnitude greater than those of conventional heat sinks.

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1. Introduction

Carbon foams were first developed in the late 1960s by Walter Ford [1]. These initial carbon foams were made by the pyrolysis of a thermosetting polymer foam to obtain a carbonaceous skeleton or reticulated vitreous carbon (RVC) foam. RVC foams are attractive for many aerospace and industrial applications, including thermal insulation, impact absorption, catalyst support, and metal and gas filtration. They are thermally stable, low in weight and density, and chemically pure; they have low thermal expansion, resist thermal stress and shock, and are relatively inexpensive. RVC foams are used as substrates and overcoated via a chemical vapor deposition process to fabricate foams of alternating compositions. Among the materials that can be deposited are refractory metals (e.g. niobium, tantalum, tungsten, and rhenium) and their ceramic compounds (e.g. the oxides, nitrides, carbides, borides and silicides) [2]. Other applications for RVCs include porous electrodes, high-temperature insulation, filters and demisters, storage batteries, scaffolds, and acoustic control [3]. Fig. 1 is a photomicrograph of a typical RVC foam.

A new generation of carbon foams emerged in the 1990s as research focused on the production of carbon foams

from alternative precursors such as pitches and coal. Researchers from the US Air Force Materials Laboratory developed a production process by applying a ‘blowing’ technique to mesophase pitches to form a carbon foam. The foam is then oxidatively stabilized prior to carbonization and graphitization. These foams were developed

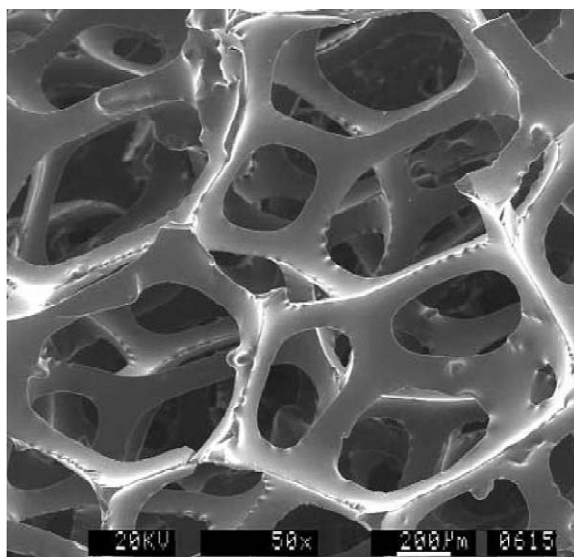


Fig. 1. Typical RVC foam produced by ERG.

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primarily to replace expensive 3-D woven fiber preforms in polymer composites and honeycomb materials. This process was licensed to MER Corporation. A research group at West Virginia University developed a method to use coal as a precursor for high-strength foams with excellent thermal insulation properties and high strength [4]. This process was licensed to Touchstone Research Group.

More recently, a process that does not require the blowing and stabilization steps was developed at Oak Ridge National Laboratory (ORNL). The foam obtained with this process is of graphitic nature and has excellent thermal properties (bulk thermal conductivities of up to 180 W/m K) [5]. This is the first repeatable foam with bulk thermal conductivities of greater than 50 W/m K, and the process was licensed to Poco Graphite under the trade name PocoFoam™.

Fig. 2 compares the steps of the carbon foam production processes developed at the Air Force Materials Laboratory and at ORNL. The number of processing steps is significantly reduced in the ORNL process. Fig. 3 compares the structure of the foam produced by the blowing process and that of the graphitic carbon foam developed at ORNL. The foam produced by the ORNL process develops highly aligned graphitic ligaments, responsible for the high thermal conductivity of the carbon foam. Table 1 lists typical properties of a variety of carbon foams available.

2. Applications in power electronics cooling

In recent decades, many improvements in electronic components, such as higher-power computer chips and power converters, generate significantly more heat and require more efficient devices for dissipating that heat. Many techniques have been explored to improve the efficiencies of heat transfer devices, such as microchannels, heat pipes, and other exotic designs. One design utilizes metal foams with great efficiency to enhance heat transfer by dramatically increasing the surface area available for heat transfer. These metal foams have been successfully used as heat exchangers for airborne equipment, compact heat sinks for power electronics, heat shields, and air-cooled condenser towers and regenerators.

Because of its lightweight, high thermal conductivity, and high surface area, ORNL's carbon foam is being evaluated as a heat sink material for cooling of power electronics. A test rig, shown schematically in Fig. 4, was designed for the measurements. It consisted of a block of carbon foam (2×2×1.25 inch) brazed to a metal plate and a heater mounted on the other side of the plate (the heater having the same footprint area as the carbon foam block). The carbon foam was then placed into an insulated nylon channel, where an o-ring and four c-clamps were used to ensure a tight seal between the base plate and the channel. Cooling air or water was then forced through the channel

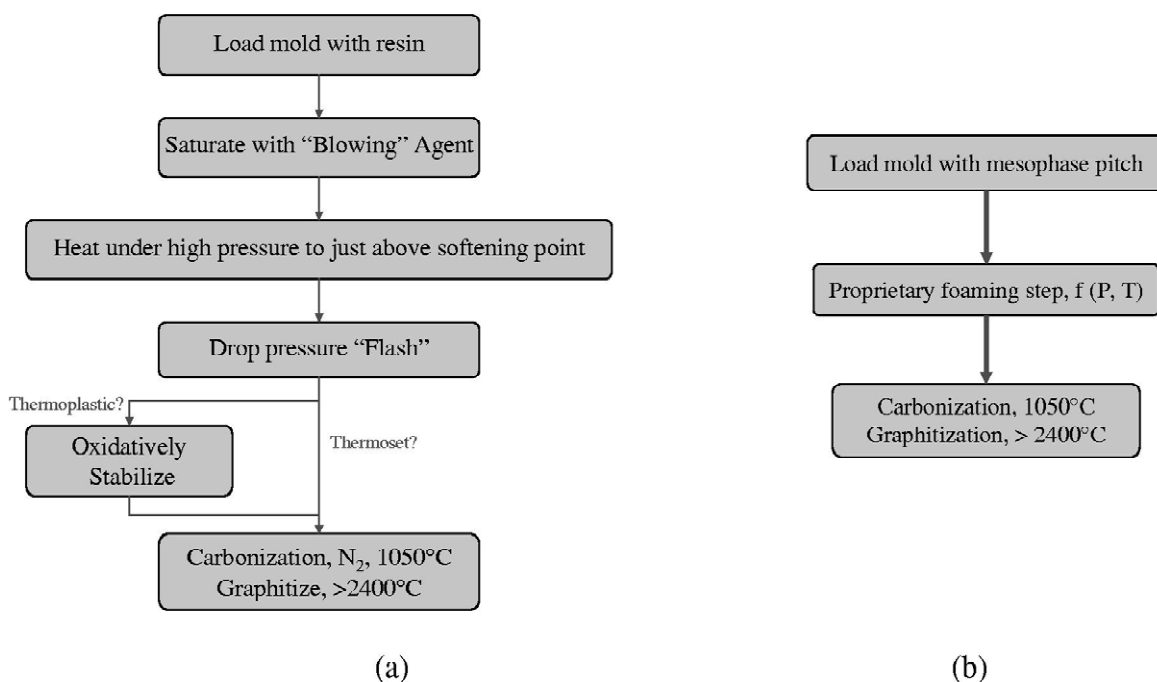


Fig. 2. Comparison of (a) the traditional 'blowing' technique for the production of carbon foams and (b) the process developed at ORNL.

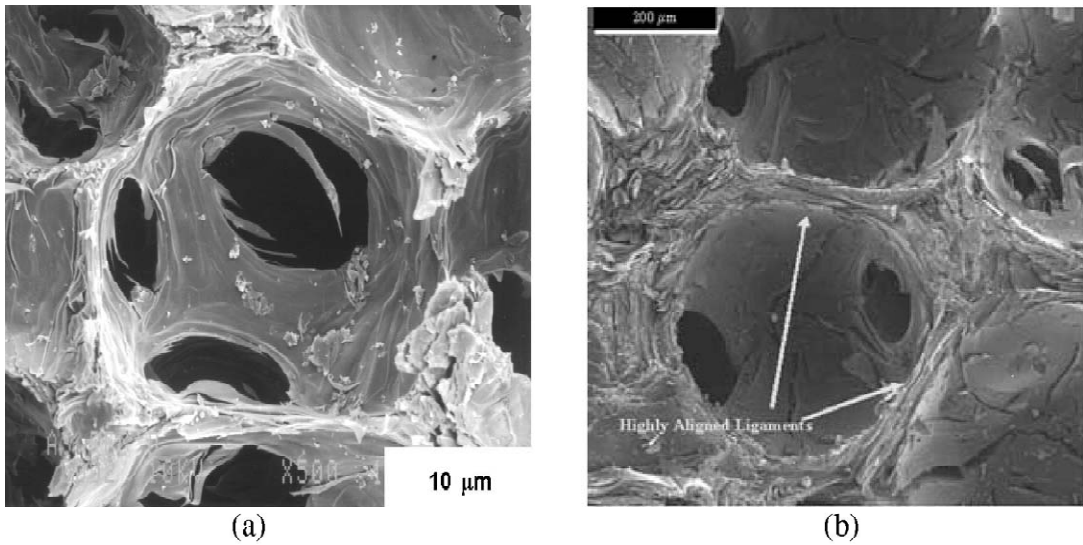


Fig. 3. (a) Carbon foam produced by the ‘blowing’ process, and (b) mesophase pitch-based carbon foam produced at ORNL.

Table 1
Summary of typical properties of a variety of carbon foams

Property	Ultramet's RVC [2]	ERG's RVC [3]	Touchstone [6]	MER [7]	ORNL ^a
Density (g/cc)	0.042	N/a	0.16–0.50	0.016–0.62	0.25–0.65
CTE (ppm/°C)	1.15–1.65	1.2–1.8	6.2	N/a	2.0
Compression strength (MPa)	0.763	0.28–0.48	15.2–20.7	1.7–7.0	1.0–3.5
Tensile strength (MPa)	0.810	0.17–0.35	1.14–6.90	N/a	0.7–1.6
Thermal conductivity (W/m K)	0.085	N/a	0.40–17.50	0.05–210	0.3–180

^a Data obtained at ORNL.

to remove heat from the foam block. The gaps between the foam and the channel walls were very small, ensuring that the fluid traveled through the pores of the carbon foam.

After the testing block was assembled, power was added to the heaters and the voltage and current were measured to find the exact power output of the heater. The heater dissipated heat into the metal plate and hence into the foam block, which acted as a heat sink. The inlet and outlet bulk fluid temperatures were measured, along with the temperature of the base plate of the heater. Pressure taps were also mounted on both sides of the carbon foam block to measure the pressure drop of the system. The overall heat transfer coefficient was then calculated using the following relation:

$$h = \frac{Q}{A\Delta T_{LM}} \tag{1}$$

where h is the heat transfer coefficient (W/m² K), Q is the

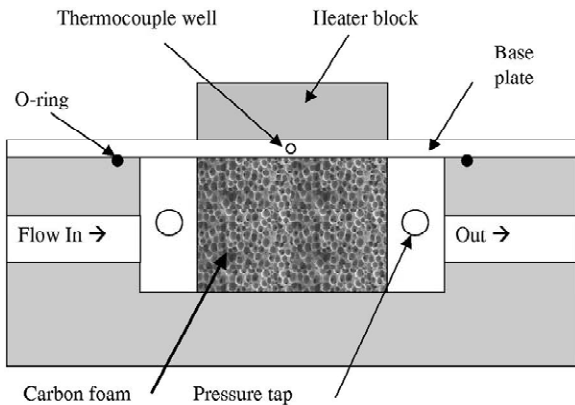


Fig. 4. Schematic of heat sink test configuration.

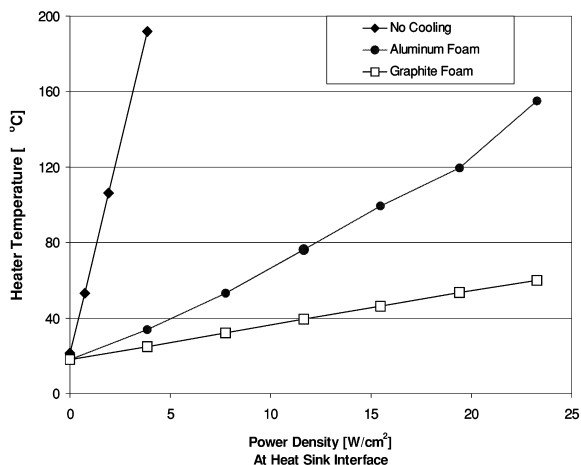


Fig. 5. Heater temperature vs. power density for aluminum and carbon foam (fluid flow 0.75 gpm water).

heater power dissipation (W), A is the heater and foam footprint area (m²) and ΔT_{LM} is the log mean temperature difference (K).

Initial tests using water as the cooling fluid were performed on blocks of carbon and of aluminum foam. The temperature of the heater versus the heater power density for a variety of configurations is plotted in Fig. 5. The figure clearly demonstrates that carbon foam dissipates more heat than aluminum foam. Another significant difference in the materials is shown as the nonlinearity in the profile for the aluminum foam. It is a result of the low thermal diffusivity of the aluminum foam. After a change in the power level of the heaters, the aluminum foam heat sink took more than 20 min to reach an apparent steady state condition, while the carbon foam heat sink reached steady state in approximately 2 min. Very high heat transfer coefficients (~2600 W/m² K) were calculated for the carbon foam heat sinks compared with those of aluminum foam heat sinks (~250 W/m² K); however, the pressure

Table 2

Comparison of air-cooled heat transfer coefficients obtained for graphite foam and aluminum foam

Geometry	Air cool (15cfm-172 inch/s)			
	Aluminium		Carbon foam	
	Heat transfer coeff. h (W/m ² K)	$\Delta P/L$ (p.s.i./inch)	Heat transfer coeff. h (W/m ² K)	$\Delta P/L$ (p.s.i./inch)
Finned 	70	<0.05	1000	<0.05
Pin-finned 	550	<0.05	1500	0.05
Blind-holes (pin fin negative) 	–	–	2000	1
Blind-holes (parallel to air flow) 	–	–	3100	0.35
Corrugated 	–	–	4100	0.1
Solid foam 	250	<0.05	2600	2

drop of this system was fairly high compared with that of the aluminum foam.

Further work was directed to engineering a system in which a high heat transfer coefficient was maintained while the pressure drop was reduced. For this purpose, a number of carbon foam geometries were evaluated to reduce the pressure drop. The first concept was to mimic current finned heat sinks; other designs included pin-finned configurations and blind holes (both perpendicular and parallel to the fluid flow). Table 2 lists the heat transfer coefficients and their corresponding pressure drops for these systems and compares them with those of aluminum foam (where applicable); the cooling medium utilized was air, at a flow-rate of 15 cfm. As is observed in this table, the pressure drop was reduced significantly by modifying the geometry of the heat sink, while the heat transfer coefficients are still considerably better than those obtained with the aluminum.

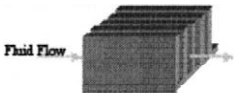
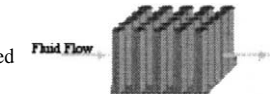
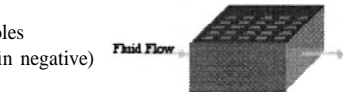



Additional work was performed to compare the results obtained using both water and air as the cooling medium (see Table 3). As is observed, greater heat transfer coefficients are obtained with water as the cooling fluid. However, the values obtained with carbon foam and air are still considerably higher than those obtained with aluminum

heat sinks, indicating that perhaps air could be used with the proper geometries of the foam in some applications. The use of air cooling would dramatically reduce the complexity of the cooling systems used to cool power electronics by eliminating the recycling of the fluid.

3. Conclusions

- ORNL has developed a process for the fabrication of high-conductivity carbon foams. This process does not require the blowing and stabilization steps, thus reducing the manufacturing time, and most important, the cost of the foam.
- ORNL’s carbon foam is an efficient thermal management material. Compared with aluminum-based heat sinks, it was demonstrated that the foam-based heat sink can be used to reduce the volume of the cooling fluid required or potentially eliminate the water cooling system altogether.
- Carbon foam heat sinks respond to transient loads significantly faster than traditional heat sinks. This response time may be crucial for power electronics, as

Table 3
Comparison of air-cooled and water-cooled heat transfer coefficients obtained for carbon foam

Foam geometry	Air cool (15cfm-172 inch/s)		Water cool (0.75 gpm-1.2 inch/s)	
	Heat transfer coeff. <i>h</i> (W/m ² K)	$\Delta P/L$ (p.s.i./inch)	Heat transfer coeff. <i>h</i> (W/m ² K)	$\Delta P/L$ (p.s.i./inch)
Finned 	1000	<0.05	2100	0.5
Pin-finned 	1500	0.05	2500	0.5
Blind-holes (pin fin negative) 	2000	1	4600	0.5
Blind-holes (parallel to air flow) 	3100	0.35	4500	0.5
Corrugated 	4100	0.1	9500	0.033
Solid foam 	2600	2	23 000	2

it could dramatically lower temperatures during peak loads. These peak loads drive the cooling system requirements even though they are experienced for a minimal amount of time during the operational life of a component.

Acknowledgements

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References

- [1] Ford W. Method of making cellular refractory thermal insulating material. US patent 3121050, 1964.
- [2] Ultramet Advanced Materials Solutions. 12173 Montague Street, Pacoima, CA 97331, USA. Ultramet foams datasheet.
- [3] ERG Materials and Aerospace Corporation. 900 Stanford Avenue, Oakland, CA 94608, USA. Reticulated vitreous carbon datasheet.
- [4] Stiller AH, Stansberry PG, Zondlo JW. Method of making a carbon foam material and resultant product. US patent 5888469, 1999.
- [5] Klett JW. Process for making carbon foam. US patent 6033506, 2000.
- [6] Touchstone Research Laboratory, The Millennium Center, Triadelphia, WV 26059, USA. CFoam datasheet.
- [7] Materials and Electrochemical Research Corporation, 7960 South Kolb Road, Tucson, AZ 85706, USA. Carbon/graphite foams datasheet.