

Properties of a Newly Developed Carbon-Aluminum Nanocomposite

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ABSTRACT

A novel thermal management nanocomposite material (CarbAl™ composite) has been developed by means of high-pressure impregnation process. CarbAl™ composite comprises a porous carbonaceous matrix, dispersed aluminum component and a tailored amount of Si additive. CarbAl™ composite presents the unique microstructure, low thermal expansion, high thermal conductivity and excellent thermal diffusivity. Its thermal diffusivity is 2.5 – 3 times higher than that of Cu and Al. CarbAl™ composite has promising application prospects in high-power, high-speed electronic fields.

Keywords: Thermal management material, carbon-aluminum nanocomposite, thermal diffusivity, impregnation, interface control

1 INTRODUCTION

Thermal management technologies are important to everyday life. Most devices or systems that consume energy require some sort of thermodynamics manipulation. In the BCC Research May 2008 report, “The Market for Thermal Management Technologies” Analyst Andrew McWilliams notes that, “As pressure continues to achieve higher levels of device integration while reducing cost, size, and complexity, the issue of managing heat and power dissipation has become very significant.” He calls “The development of the thermal management industry...one of the most interesting aspects of rapid innovation taking place in the high tech industry.” Advances in the development of high power and high performance electronic devices demand innovative approaches for heat transfer materials.

While aluminum and copper and their alloys are still widely used as primary materials for thermal management applications, the outstanding thermal and mechanical properties of diamond and other carbon allotropes drive considerable interest in the development of novel thermal transfer materials based on nanostructured forms of carbon. These carbon materials are superior over Al and Cu in two critical characteristics – their thermal conductivity, k , and density, ρ . Worldwide development effort of nanocarbon-based heat sink materials started over a decade ago after the discovery of carbon nanotubes (CNT) and prediction of their thermal conductivity properties. Today, these novel

forms of carbon include single wall and multi-wall CNTs, carbon fibers, carbon flakes and diamond [1 – 3].

Through recent innovations in nanotechnology and material sciences, significant advances in carbon metal composite material have been achieved. In this study, we present a unique carbon-based metal nanocomposite comprised of 80% carbonaceous matrix and a dispersed metal component of 20% aluminum material --- CarbAl™ composite, which is a sophisticated composite with low thermal expansion, high thermal conductivity and excellent thermal diffusivity.

2 EXPERIMENT

CarbAl™ composite is manufactured using a proprietary process. Briefly, carbonaceous matrix is produced by means of extruding and sintering a graphite/pitch mixture. Commercially available graphite particles are mixed with a pitch and placed in a high temperature press. The material is heated and pressed to create a porous graphitic carbon backbone. During this process, most of pitch is carbonized into graphitic nanocrystallites. After processing the carbonaceous matrix, CarbAl™ composite is synthesized by the high-pressure impregnation method as shown in Figure 1, injecting molten aluminum into matrix using a pressure of approximately 500Kg/cm² to infuse the metal within the

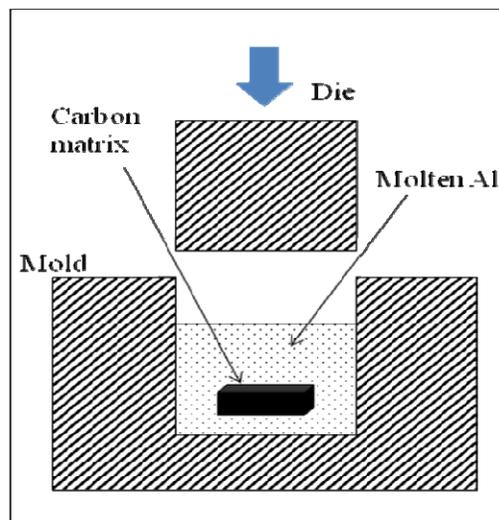


Figure1: Schematic diagram of injection of molten metal into carbon matrix.

porous carbon structure.

The similar process can also create other metals' composite materials depending on the application and desired performance. In each case, the thermal conduction pathways are primarily due to the carbon backbone with the metal providing mechanical support. In the present study we focus our efforts on investigation of carbon-aluminum nanocomposite (CarbAl™ composite). The thermal properties are investigated by laser flash measurement way (LFA-502). The material composition and microstructure are evaluated by Raman spectroscopy, scan electron microscopy (SEM), and x-ray diffraction (XRD) methods.

3 RESULTS AND DISCUSSION

Different to the conventional thermal management composites are metal matrix composites (MMC), CarbAl™ composite presents a unique structural character --- nanostructured carbon filled with aluminum and Si additive. The final form consists of 80% carbonaceous matrix of which most of pores are filled by aluminum plus a small amount of Si additive. Figure 2 is a typical photograph of a CarbAl™ composite sample (60 x 60 x 15 mm). The black contrast metric is carbon, in which the domains in white contrast are aluminum filling areas.

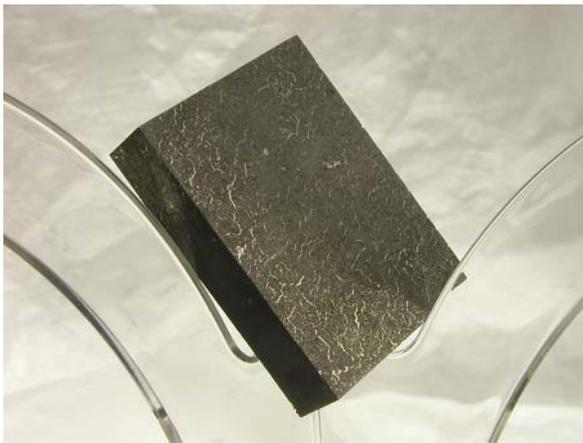


Figure 2: A photograph of a CarbAl™ composite sample.

CarbAl™ composite shows the greatest performance and cost effectiveness through the use of aluminum. Table 1 shows a comparison of CarbAl™ composite to some common thermal management materials. From Table 1 we can see that besides its low thermal coefficient of thermal expansion (CTE), CarbAl™ composite has a thermal diffusivity of 2.55 cm²/sec, which is about 2.5 – 3 times higher than that of Cu or Al.

In general, a substance's thermal diffusivity is an important factor contributing to fast heat transfer and rapid temperature equilibrium. Thermal diffusivity can be represented as follows:

Constant	units	SiC Matrix		Aluminum	Copper	CarbAl™
		Al-SiC(55)	Al-SiC(70)	Al1060H12	C1020	Al-C400
Thermal diffusivity	cm ² /sec	-	0.88	0.84	1.1	2.55
Thermal conductivity	W/mK	240	270	203	390	425
Coefficient of thermal expansion	1/K	10*10 ⁻⁶	7*10 ⁻⁶	24*10 ⁻⁶	17*10 ⁻⁶	7*10 ⁻⁶
Electric resistivity	μΩ•cm	3.0	4.0	2.8	1.7	4.0
Specific Heat	J/gK	1.0	1.0	1.0	0.5	0.75
Specific Gravity	g/cm ³	2.9	3.0	2.7	8.9	2.3
Bending strength	MPa	350	380	80	350	40
Young's Modulus	GPa	200	265	70	119	12

Table 1: Performance comparison of CarbAl™ composite to other heat exchanger materials.

$$\alpha = k / (C_p * \rho) \quad (1)$$

whereby: α is the thermal diffusivity (cm²/s); k is the thermal conductivity (W/mK); C_p is the specific heat capacity (J/gK); and ρ is the material density (g/cm³).

The heat equation is the function of thermal diffusivity:

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \quad (2)$$

where t is time.

The 1-dimensional Green's function for heat equation is defined as follows:

$$G(x, t) = \frac{1}{\sqrt{4\pi\alpha t}} e^{-\frac{x^2}{4\alpha t}} \quad (3)$$

that is the temperature field evolutionary response for a δ -function initial temperature at $x=0$.

A normalized temperature – time curve plotted according to equation (3) shows that a high thermal diffusivity will allow rapid diffusion of heat from the point of creation to a dissipative heat sink (Figure 3). In other words, a material with high thermal diffusivity can rapidly adjust the temperature to that of its surroundings, preventing overheating.

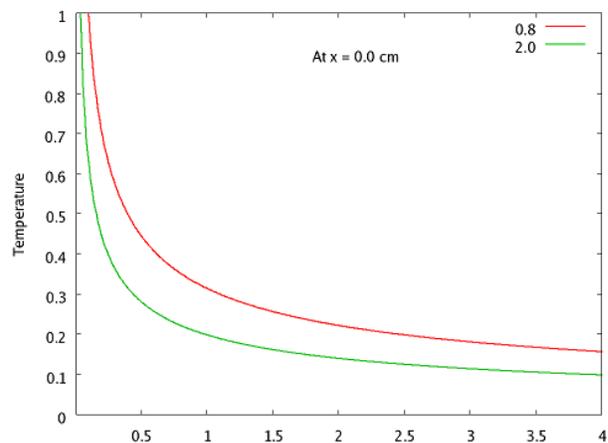


Figure 3: Normalized temperature-time curve at a hot-spot site.

This point is especially important for high-power, high-speed electronic devices or systems, where high thermal diffusivity materials are strongly required to modulate temperature and eliminate “hot spots” since temperature dramatically impacts device lifetime.

Thermal management composites must rely on several factors to achieve good thermal conduction, including: (i) high thermal conductivity of the parent materials, (ii) quality phonon coupling and propagation between each of the parent materials, (iii) and in many cases, creation of interface chemistry between the two parent materials. Carbon – aluminum composites have the potential to achieve excellent thermal conductivity since both aluminum and graphitic carbon have high thermal conductivity values. However, the last two criteria offer much room for improvement.

For the carbon – aluminum composite, a major task is to suppress the interfacial Al_4C_3 phase to achieve high performance. Al_4C_3 is brittle, hygroscopic, and generally known to have a low thermal conductivity. It decreases thermal conduction from carbon to aluminum by impeding phonon propagating across the carbon/aluminum interface. Therefore, suppression of Al_4C_3 significantly benefits materials’ thermal conduction, and meanwhile, benefits materials’ mechanical properties and erosion-resistance.

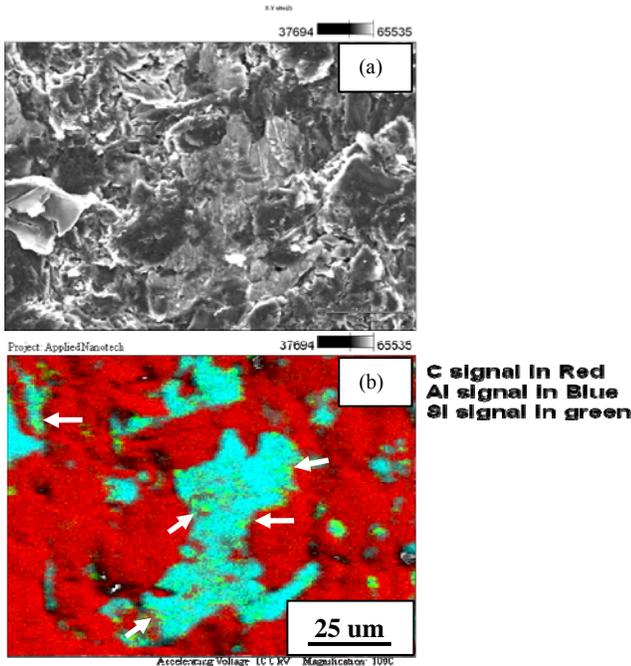
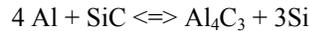


Figure 4: SEM (a) and corresponding EDX (b) data for the CarbAl™ composite. Arrows indicate the presence of Si localized at the interface between the carbon and Al.

In the present study, we control the interface structure and suppress the interfacial Al_4C_3 phase formation by adding the proper amount of Si content into base aluminum metal. The tertiary system comprises aluminum, silicon and carbon. The reaction between these three elements can generate four possible combinations: aluminum silicide

(AlSi), aluminum carbide (Al_4C_3), silicon carbide (SiC) and aluminum silicon carbide (Al_4SiC_4). Aluminum carbide can transfer into silicon carbide by reacting with excess Si through the following reaction:



At optimized Si concentration and impregnation conditions, Si can aggregate in the interface region and suppress Al_4C_3 formation. Figure 4 (a) and (b) shows SEM and EDX data for the CarbAl™ composite. The data show that the composite represents three elements; C, Al and Si. It is noted that the silicon content appears to localize at the interface between the carbon and aluminum as indicated by arrows. The evidence suggests that the trace amount of Si precipitates near the carbon and aluminum interface.

The Raman spectra of the CarbAl™ composite are shown in Figure 5. The data was collected near the interface of the carbon and aluminum in the composite. The peak at 520 cm^{-1} is a crystalline silicon peak. The existence of this peak is consistent with the concentration of Si in the interface region as shown in the SEM/EDX images (Figure 4). Other Raman peaks revealed originate from nanostructured carbon matrix. The sharp G band (1580 cm^{-1}), low D/G ratio, pronounced double phonon peak (2750 cm^{-1}), and advent of D' (1620 cm^{-1}), band indicate the carbonaceous matrix is well graphitized. The D/G ratio between 0.5 and 0.9 means that the carbon possesses high-grade crystallinity and the smallest graphite crystallites are at least larger than 5 nm [4]. Raman data suggest high quality carbonaceous backbone, which is the basis for further fabrication of carbon composite materials with high thermal conductivity. The XRD spectra of CarbAl™ composite are shown in Figure 6, and a summary of the XRD peaks is given in Table 2. The reference data for the

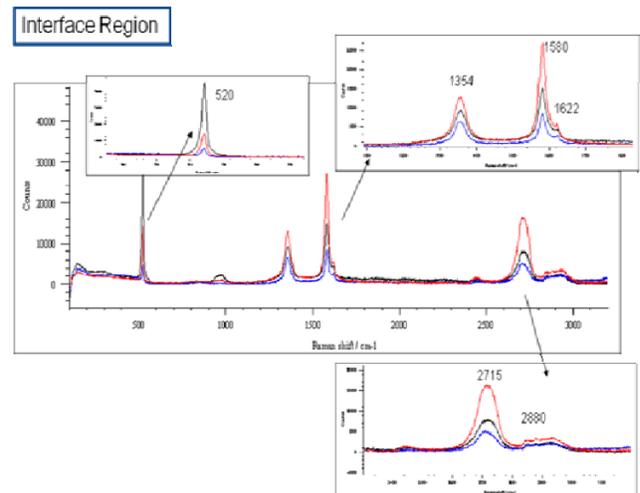


Figure 5: Raman spectra taken from Al/C interface regions of CarbAl™ composite.

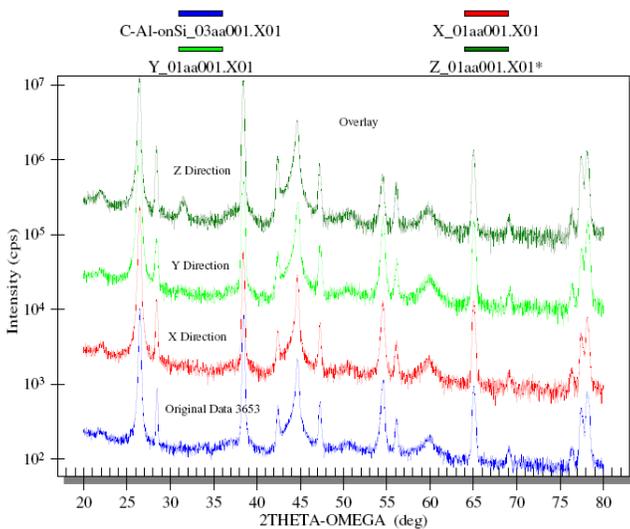


Figure 6: XRD spectra of CarbAl™ composite.

Peak Assignment	XRD Peak Location (2θ-Ω)	
	Measured Location	Reference location
Carbon	26.441	26*
Si	28.38	28*
Al, SiC	38.452	38.3*
SiC, Al ₄ SiC ₄	42.38	42.5*
Al	44.667	44*
Si	47.248	47*
SiC	54.450	54*
Si, Al ₄ SiC ₄	56.037	56*
Al	65.004	65.101
Al	77.38	78.23
*Values as measured from Viala, et al [5].		

Table 2: XRD peak assignments.

XRD peak identification are cited from the paper authored by Viala, et al. [5]. There are several major peaks that are easily identified. These are the carbon peak of 26° and the aluminum peaks at 38°, 65° and 77°. The remaining peaks are due to less abundant phases within the material. Several

of the peaks identified correspond with either silicon carbide or aluminum silicon carbide. There are no peaks associated with aluminum carbide (Al₄C₃), suggesting that aluminum carbide formation has been successfully suppressed at the interface region by addition of Si. The silicon based carbide at the interface may allow enhanced phonon propagating between the two parent materials and increase the thermal conductivity of the overall composite.

4 CONCLUSIONS

CarbAl™ composite presents unique structure and superior thermal properties, offering an effective approach to the world of thermal management. Its superior thermal properties originate from a comprehensive optimization of materials selection, process control and tailoring the interface region between the two main components. A small amount of Si incorporated into the aluminum starting material plays an important role on improving the interface properties. The evidence suggests that Si precipitates near the carbon and aluminum interface, suppressing the Al₄C₃ phase through formation of interfacial silicon based carbides.

REFERENCES

- [1] W. Shih, "Development of Carbon-Carbon Composites for Electronic Thermal Management. Applications". IDA Workshop, May 3–5, 1994.
- [2] M. J. Biercuk, M. C. Llaguno, M. Radosavljevic, J. K. Hyun and A. T. Johnson, *Appl. Phys. Lett.* 80, 2767, 2002.
- [3] K. Jagannadham and Hsin Wang, *J. Appl. Phys.* 91, 1224, 2002.
- [4] S. Kurita, A. Yoshimura, H. Kawamoto, T. Uchida, K. Kojima, M. Tachibana, P. Molina-Morales and H. Nakai, *J. Appl. Phys.* 97, 104320, 2005.
- [5] J. C Viala, P. Fortier and J. Bouix, *J. Mat. Sci.* 25, 1842, 1990.

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