ELSEVIER

Diamond and Related Materials 4 (1995) 848–851

DIAMOND AND RELATED MATERIALS

Potential high-strength high thermal conductivity metal-matrix composites based on diamond fibres

P.G. Partridge [a], G. Lu [b], P. May [c], J.W. Steeds [b]

[a] *Interface Analysis Centre, University of Bristol, Bristol, UK*
[b] *Department of Physics, University of Bristol, Bristol, UK*
[c] *School of Chemistry, University of Bristol, Bristol, UK*

Abstract

Thermal conductivity data reported for chemical vapour deposited (CVD) diamond films have been used to calculate the effective thermal conductivity of continuous diamond-fibre-reinforced metal-matrix composites. It is concluded that the very high thermal conductivity values (about 2000 W $m^{-1} K^{-1}$) reported for CVD diamond may be difficult to achieve in practical composites. However, the combination of properties such as thermal conductivity, elastic modulus and density predicted for diamond-fibre composites are far superior to those offered by alternative materials. With hollow fibres the ability to combine conductive and convective cooling increases the design options in thermal management systems.

Keywords: Polycrystalline diamond films; Thermal conductivity; Fibres; Composites

1. Introduction

There are an increasing number of applications that require a material with high thermal conductivity (TC) as well as high strength and minimum weight. Aerospace applications include heat exchangers in hypersonic vehicles operating at 520–930 °C, cooling fins in space power systems operating up to 780 °C [1] and multichip modules in electronics, where severe thermal management problems are associated with the high power densities [2,3]. Metallic thermal conductors such as high-purity copper and low-density aluminium and magnesium have relatively low strengths, and any solute-strengthening additions severely reduce their conductivity. This has led to the development of graphite-fibre-reinforced copper composites with a combination of thermal conductivity, strength and lower density [1], but these may be limited by galvanic corrosion. CVD diamond may possess a unique combination of properties, with high values for TC, elastic modulus and electrical resistivity and low density. In this paper the potential for thermal conductors based upon diamond-fibre-reinforced composites is considered.

2. Continuous diamond fibres

Diamond fibres can be made by CVD on to metallic wires or non-metallic fibres [4,5]. Provided the core diameter is small compared with the fibre diameter the fibre properties depend primarily on the diamond properties. In the present paper calculations have been made for continuous solid diamond fibres containing a 20 μm diameter tungsten wire core (Fig. 1(a)) and for hollow fibres. Two types of hollow fibre are possible. One type can be made by etching out metallic or ceramic cores, since diamond is resistant to attack by most reagents. This leads to a very smooth diamond core surface (Fig. 1(b)), since the diamond replicates the smooth wire or ceramic core surface. The etching process is slow, and long fibres with small-diameter cores may be difficult to obtain by this method. An alternative type of hollow fibre is made by diamond deposition on to helical tungsten wire coils (Fig. 1(c)) [6]. Long hollow fibres and a variety of core diameters (from about 50 μm upwards) have been made by this method. This core surface is rougher than for the etched core. Hollow cores can lead to a reduction in composite density and may provide channels for gases or liquids for convection cooling.

3. Effective thermal conductivity of CVD diamond films

The local TC of CVD diamond films increases with increasing thickness t [7,8]. For $t < 300$ μm, TC is greater

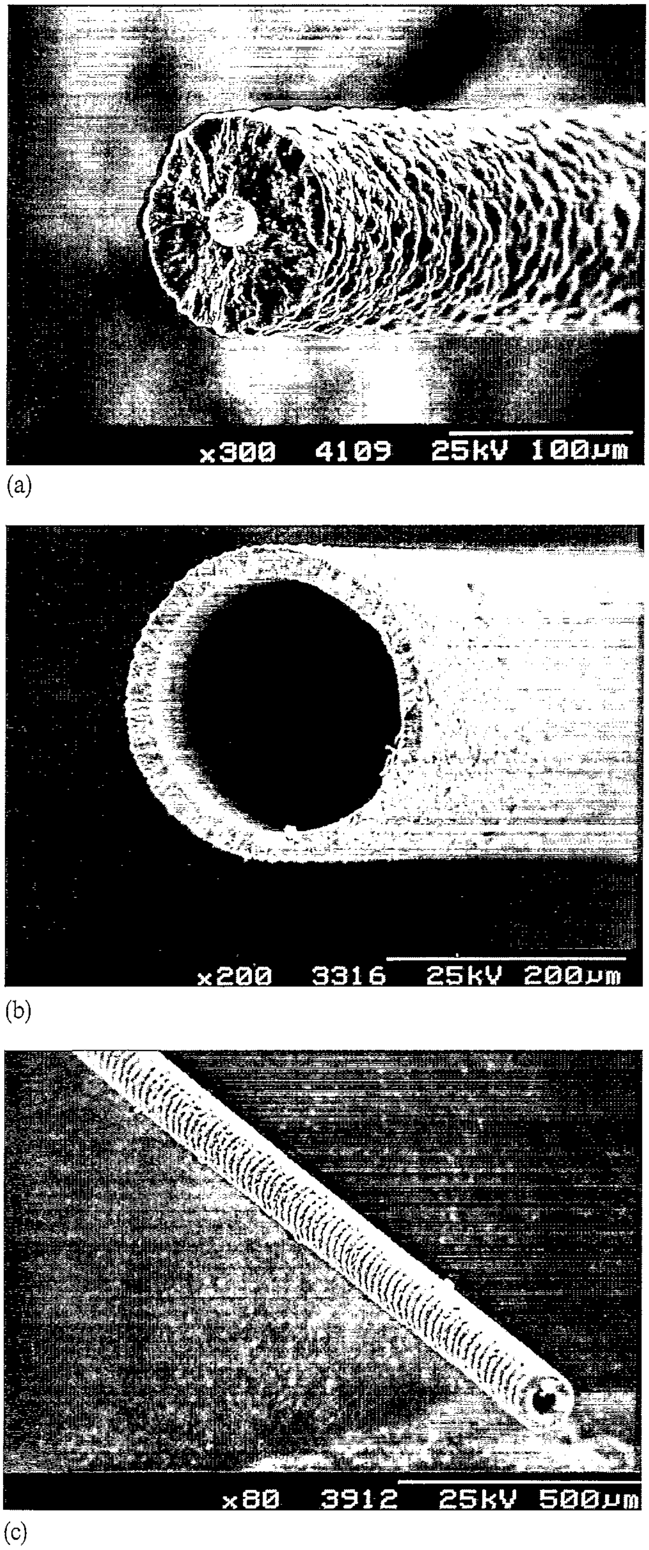

Fig. 1. Diamond fibres: (a) solid fibre with tungsten wire core; (b) hollow fibre produced by etching out core; (c) hollow fibre produced using tungsten wire coil.

in a direction parallel to the long axis of the columnar diamond grains (normal to the substrate) than in directions normal to this direction. The diamond films on fibres can be considered to be composed of thin concentric layers of different TC or thermal resistance [8]. The effective TC of a diamond film can then be obtained from the rule of mixtures (ROM), with heat flow in the radial "series" direction (λ_R) given by the lower boundary value and heat flow in the longitudinal "parallel" direction (λ_L) given by the upper boundary value. Based upon the data obtained by Graebner and co-workers [7,8], the effective TC of diamond films up to 300 μm are plotted in Fig. 2 for the principle fibre directions. For thin diamond layers the TC values are slightly lower for coatings containing a tungsten helix, because the helix introduces an initial layer of lower TC. For $t=300$ μm or above, TC values in both the R and L directions are greater than 1800 W m^{-1} K^{-1}, and the effect of the helix on TC is negligible.

4. Thermal conductivity and stiffness of diamond-fibre/metal-matrix composites

In this paper the effects of thermal resistances at core–diamond or diamond–matrix interfaces and of thermal expansion mismatch are not considered. The TC values for composites will depend on the volume fraction of diamond, which is proportional to the fibre diamond film thickness and the number of fibres (fibre volume fraction). With the possibility of different hollow core diameters, a wide range of composites properties are possible.

Composites requiring both strength and toughness as well as TC will be limited to small-diameter fibres (less than 200 μm) and to fibre volume fractions of about 0.5, typical values for commercial metal-matrix composites [9]. For example, a hollow fibre of diameter $d_2=205$ μm and a core diameter $d_1=65$ μm would have a diamond film thickness of $t=70$ μm. This film would give an effective fibre wall thermal conductivity of $\lambda_L=796$ W

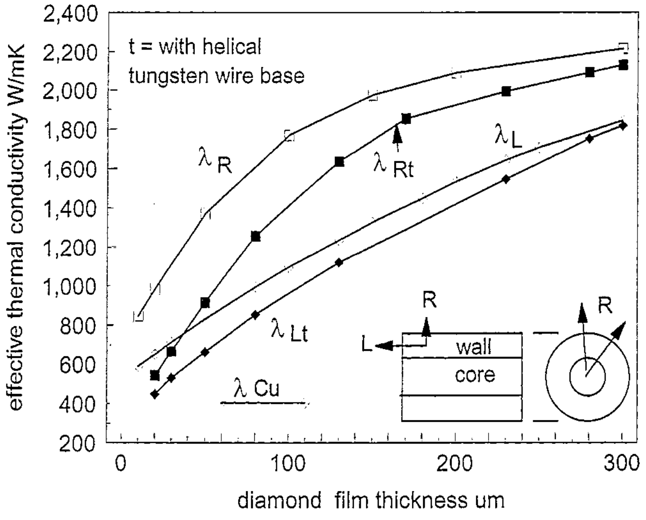

Fig. 2. Effective diamond film thermal conductivity versus diamond film thickness. λ_{Lt}, λ_{Rt}, for helical wire core; λCu = thermal conductivity of copper.

Table 1
Predicted properties for diamond fibre composites with Cu, Al and Mg matrices

Property	Copper		Aluminium		Magnesium	
	Matrix	Composite	Matrix	Composite	Matrix	Composite
Relative density, ρ	8.96	6.06	2.7	2.93	1.74	2.45
Thermal conductivity (W m^{-1} K^{-1})						
λ radial	403	640	238	557	157	517
λ longitudinal		559		477		437
λ/ρ radial	45	105	88	190	90	211
longitudinal		92		163		178
Modulus, E (GPa)	130	506	70	476	45	463
E/ρ	14.5	83.5	26	162	26	189

Composite with 50 vol.% fraction fibre, fibre with $d_2=205$ μm, hollow core $d_1=65$ μm (10% vol. fraction), diamond coating thickness $t=70$ μm.

m^{-1} K^{-1} and $\lambda_R=1152$ W m^{-1} K^{-1}. A composite containing 0.5 volume fraction of this fibre in a copper, aluminium or magnesium matrix would have an outstanding combination of thermal conductivity, stiffness, and low density compared with the matrix alone, as shown in Table 1.

When high thermal conductivity is a priority, the wall thickness may be kept constant at $t=300$ μm to give a constant wall thermal conductivity of $\lambda_L=1817$ W m^{-1} K^{-1} and $\lambda_R=2129$ W m^{-1} K^{-1}. The fibre diameter and core volume fraction will then increase with increase in fibre core diameter, as shown in Fig. 3 for fibres up to 1 mm diameter. Consider a solid diamond fibre with a 20 μm diameter tungsten core (fibre diameter 620 μm). A monolayer of these fibres embedded in copper with a 1 μm surface layer of copper would produce a thin foil 0.622 mm thick. With a maximum theoretical fibre packing density of about 0.78, the composite effective properties would be $\lambda_L=1526$ W m^{-1} K^{-1} and $\lambda_R=1816$ W m^{-1} K^{-1}, $\rho=4.7$, $E=796$ GPa. Note that this type of fibre with a hollow core could only have about 12% core volume fraction for a relatively large (about 1 mm) diameter fibre (Fig. 3), equivalent to about 9% core volume in a composite.

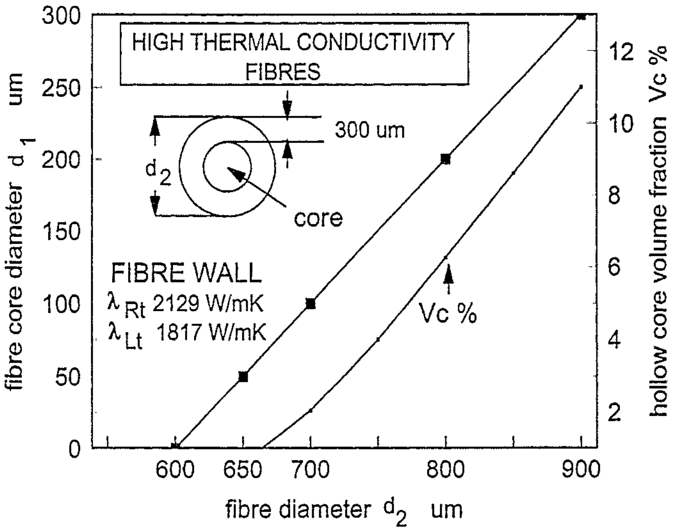

Fig. 3. Fibre hollow core diameter d_1 versus fibre diameter d_2, for high thermal conductivity fibres with a constant diamond film thickness of 300 μm and constant fibre wall thermal conductivity. V_c is volume fraction of hollow core in fibre.

5. Conduction and convection cooling

Hollow diamond fibres offer not only lower-density composites [4], but the possibility of convection cooling by passing gases or liquids through the diamond fibre cores. Such cores can be very small, enabling convection cooling of thin sections. However, for a given fibre diameter, a larger core diameter leads to thinner diamond films and lower TC. A compromise might be to keep a core volume fraction of 0.5 and vary the diamond film thickness t and fibre diameter d_2 to suit the composite section thickness, as shown in Fig. 4. For $d_2=0.998$ mm and $t=146$ μm, the fibre wall effective TC would be $\lambda_L=1193$ W m^{-1} K^{-1} and $\lambda_R=1727$ W m^{-1} K^{-1}. If this fibre was embedded in a 1 mm thick foil with a packing density of 0.78, the effective foil material properties would be $\lambda_L=1019$ W m^{-1} K^{-1} and $\lambda_R=1228$ W m^{-1} K^{-1} and the composite properties would be $E=411$ GPa, $\rho=3.34$ with 39% hollow core volume fraction. For a large area foil $L_1=L_2=100$ mm (Fig. 5), containing the above monolayer of continuous fibres 100 mm long, the surface area of the fibre cores would be about 222 cm^2 compared with the foil face area of 100 cm^2. Doubling the foil thickness would double the core area without change in the foil face area. The high stiffness of the foils also suggests the possibility of through-thickness edge cooling of extended

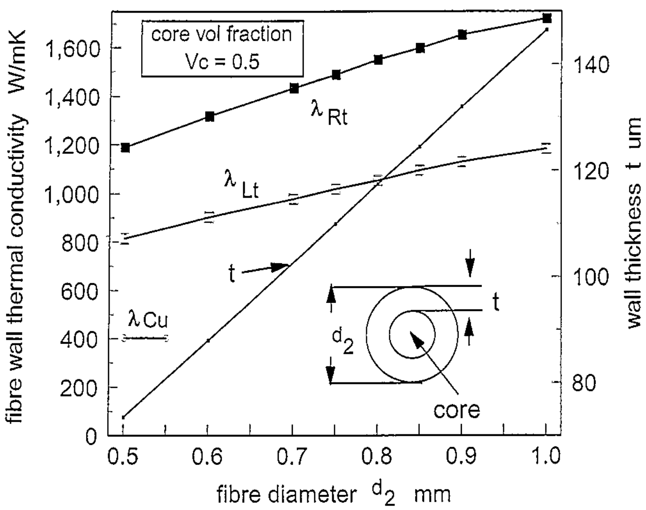

Fig. 4. Fibre wall thermal conductivity vs fibre diameter for fibres with a constant core volume fraction of 0.5. t = diamond wall thickness.

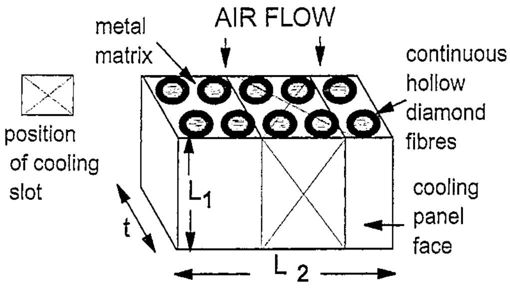

Fig. 5. Diagram showing composite cooling panel with cooled face area $L_1 \times L_2$ and thickness t containing two layers of hollow fibres for convection cooling. Possible cooling slot position shown for monolithic metal panel.

substrate foils in 3D multichip modules with $L_1 = \approx 2$ mm, $L_2 = 100$ mm (Fig. 5). Cooling slots for enhanced cooling [2] would be unnecessary, since the increase in cooling surface area due to a slot would be less than the area lost due to fibre cores.

6. Conclusions

The above analysis indicates that the very high TC values (approx. 2000 W m^{-1} K^{-1}) assumed for CVD diamond [2] may be difficult to achieve in practical composites, because of the TC gradient inherent in CVD diamond films. For tough metallic composites there may be additional limitations imposed by a need for large numbers of small-diameter fibres and a limit on fibre volume fraction. Nevertheless the effective TC, stiffness and density values predicted for diamond-fibre composites are far superior to those offered by alternative materials. The use of hollow fibres to combine conductive and convective cooling will increase the options in the design of thermal management systems.

Acknowledgements

The authors wish to thank M.N.R. Ashfold, C.A. Rego, K.N. Rosser and N.M. Everitt for many helpful discussions and to acknowledge financial support from DTI and DRA(F). © British Crown Copyright 1994/DRA; reproduced with the permission of Her Britannic Majesty's Stationery Office.

References

[1] D.L. Ellis, *Met. Trans., 24A* (1993) 43.
[2] R.C. Eden, *Diamond Relat. Mater., 2* (1993) 1051–1058.
[3] D.R. McCutchan and J.W. Reilly, *Microprocess. Microsyst., 18* (1994) 231.
[4] P.G. Partridge, P. May and M. Ashfold, *Mater. Sci. Technol., 10* (1994) 1777.
[5] M.L. Lake, J.-M. Ting and J.F. Phillips, *Surf. Coat. Technol., 62* (1993) 367.
[6] G. Lu and P.G. Partridge, *J. Mater. Sci.*, in press.
[7] J.E. Graebner, S. Jin, G.W. Kammlott, Y.-H. Wong, J.A. Herb and C.F. Gardinier, *Diamond Relat. Mater., 2* (1993) 1059.
[8] J.E. Graebner, *Diamond Films Technol., 3* (1993) 77.
[9] P.G. Partridge and C.M. Ward-Close, *Int. Mater. Rev., 38* (1993) 1.