

# Potential for diamond fibres and diamond fibre composites

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*The manufacture of solid diamond fibres by chemical vapour deposition onto various wire and ceramic cores and the production of hollow diamond fibres by removal of the cores is described. The values for Young's modulus of diamond fibres and diamond fibre-Ti alloy metal matrix composites calculated via the rule of mixtures are predicted to be substantially higher than for the corresponding values for the commercial SiC fibre products. It is concluded that chemical vapour deposition diamond fibres offer, for the first time, the possibility of exploiting the properties of diamond in engineering structures.* MST/3007

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## Introduction

Over the last 30 years the structure and properties of natural diamond gemstones and synthetic diamond grit (produced under high temperatures and pressures) have been studied extensively and the unique combination of properties possessed by this form of carbon has long been recognised.<sup>1,2</sup> The diagrams constructed by Ashby<sup>3</sup> provide an excellent comparison of the relative strength and stiffness of natural diamond and other engineering materials (Figs. 1a and 1b). They show that diamond combines a relatively low density with a strength greater than that of any other structural material. Although a substantial market has developed for particulate diamond composites for cutting tools and wear resistant coatings, the strength and stiffness of diamond has remained of academic interest only to structural engineers.

Intensive research in the former USSR, the USA, and Japan led in the early 1980s to several routes for the continuous low temperature chemical vapour deposition (CVD) of diamond thin films. Today it is possible to produce large areas of high quality poly- and single crystal

diamond films (10 cm diameter and 425  $\mu\text{m}$  thick<sup>4</sup>) and freestanding shapes up to 600  $\mu\text{m}$  thick.<sup>5,6</sup> Some of the properties and applications of CVD diamond coatings are summarised in Table 1. It should be noted that the combination of high thermal conductivity and low coefficient of thermal expansion gives diamond excellent thermal shock resistance, which would be maximised in freestanding shapes. A multibillion dollar market is predicted for CVD diamond by the year 2000 (Refs. 7, 8) and this is supported by the explosive growth in research activity, publications, and patents on this material.

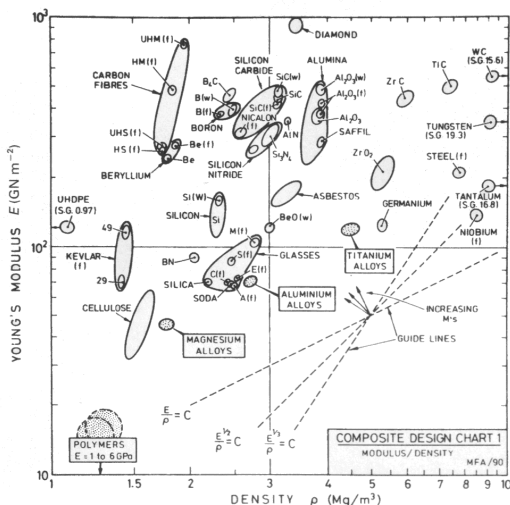
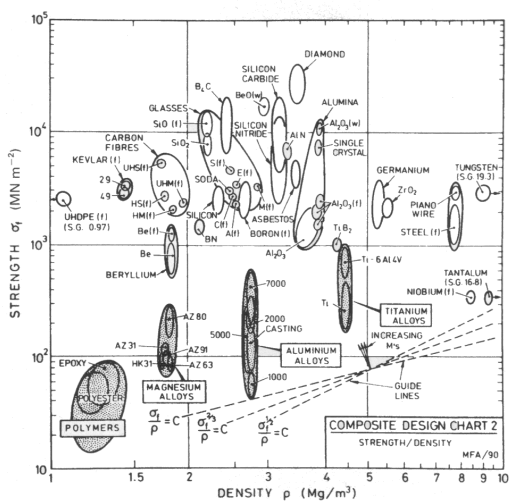
The production of diamond fibres was first reported in 1991<sup>9</sup> and diamond fibre composites were considered in several papers in 1993.<sup>10-13</sup> The development of this new fibre is therefore in its infancy, but its potential is already becoming apparent. A recent review<sup>14</sup> has dealt with diamond fibre manufacture, potential fibre modulus, and the factors affecting fibre cost. It was concluded that diamond fibres offer for the first time the possibility of exploiting the properties of diamond on a large scale via continuous or discontinuous diamond fibre composites. This paper describes the laboratory scale manufacture of these fibres and compares the predicted Young's modulus values of diamond fibres and diamond fibre-Ti alloy metal matrix composites (MMCs) with the equivalent commercial SiC fibre products.

Table 1 CVD diamond properties and current future applications

Properties	Applications
Hardest known material	Coatings for cutting tools
Highest known Young's modulus at room temperature	Abrasive or erosion resistant coatings
High stress wave velocity	Coatings for bearings
Low coefficient of friction	Materials requiring high thermal shock resistance
High thermal conductivity (highest known at room temperature)	Freestanding speaker diaphragms
Low specific heat	Thermal spreaders for high power electronic devices and thermal management systems
Low thermal expansion	Sensors for severe environments
Thermally stable	<i>In vivo</i> material
Oxidises in air above $\sim 600^\circ\text{C}$	High temperature, high speed power devices
Onset of graphitisation in vacuum $\sim 1700^\circ\text{C}$	Thermistors
Resistant to chemical attack	Window and lens material
High transparency to infrared, visible, and ultraviolet light, X-ray and microwave radiation	Thermal imaging
Resistant to radiation damage	Electro-optical devices
High threshold for laser damage	Diamond fibre composites
Electrical insulator	
High band gap semiconductor and luminescent material when doped	
Low dielectric constant	
High electron and hole mobility	
Large refractive index	

## Manufacture of diamond fibres by chemical vapour deposition

Diamond fibres have been made in microwave plasma enhanced CVD reactors and in hot filament reactors (Figs. 2a and 2b) and the deposition conditions are identical to those used for planar substrates.<sup>15-17</sup> Short lengths of metal wire or non-metallic fibre have been coated with CVD diamond in a hot filament reactor using a  $\text{CH}_4/\text{H}_2$  ratio of 1:100, a flow rate of 200  $\text{cm}^3 \text{min}^{-1}$  (STP), a pressure of 30 Torr and a filament temperature of  $\sim 2000^\circ\text{C}$ .<sup>11,12</sup> The substrates have been lightly loaded to keep them straight and positioned vertically a few millimetres from a single coiled filament. Very uniform coatings on small diameter fibres ( $< 200 \mu\text{m}$ ) can be produced at deposition rates of about 0.5–1.0  $\mu\text{m h}^{-1}$  placed outside the filament or on larger diameter fibres placed centrally and coaxially within a filament. Deposition onto 100  $\mu\text{m}$  diameter SiC fibres has been carried out in a microwave reactor at 2.45 GHz excitation, with a total flow rate of 200–250  $\text{cm}^3 \text{min}^{-1}$  (STP) at 50–90 Torr pressure.<sup>10</sup> To avoid excessive heating of the fibres the applied power level was maintained within

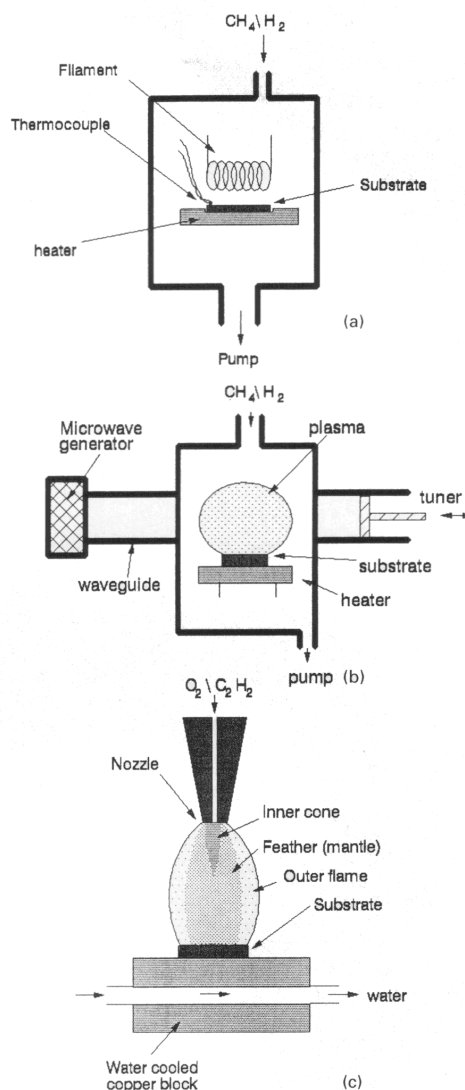


1 Design chart for light strong composites based upon strength v. density (top); light stiff composites based upon Young's modulus v. density (bottom) (From Ref. 3)

500–1000 W. Substrate temperatures in the range 900–1000°C produce good quality diamond films, but with well developed (111) and (100) growth facets on the surface.

Schematic diagrams are shown in Fig. 3 of cross-sections of solid diamond fibres with one core, characteristic of small diameter multifilament fibres and wires, and two cores, characteristic of monofilament SiC fibres. Some examples of diamond fibres produced using various core materials are shown in Fig. 4. A thick 200 μm W wire which has a 22 μm thick CVD diamond coating (Fig. 4a) has a much lower volume fraction of diamond and hence lower effective Young's modulus than a thinner W wire which has a 10 μm thick diamond coating (Fig. 4b). The columnar grains, growth facets, and surface roughness are apparent in Figs. 4b and 4c.

Since the diamond deposition temperature in the hot filament process is lower than that for CVD of SiC, a wider range of fibre core materials can be considered for CVD diamond.<sup>14</sup> For example diamond has been deposited on non-metallic fibres such as SiC, alumina, silica, and Cu

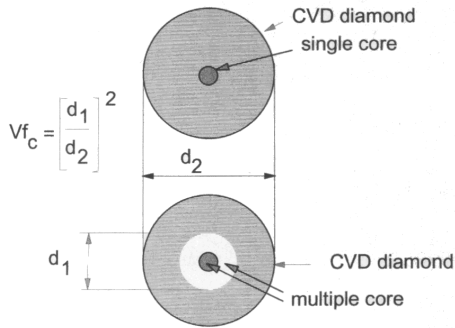


hot filament (a) and microwave plasma (b) techniques use low pressures (~30 Torr) and hydrogen-hydrocarbon process gas mixtures, oxyacetylene torch method (c) operates at atmospheric pressure and can produce high growth rates over small areas

2 CVD diamond deposition techniques

coated C fibre, on carbide forming W, Mo, and Ti wires, and on Cu. In the reactive gas mixture present during diamond CVD copper is not affected, SiC is slightly etched, and C fibre and silica more severely attacked. Carbon fibre has been coated with diamond after pre-coating with copper. The high solid solubility of carbon in Ti alloys, Ni alloys, and ferrous materials may delay diamond nucleation on the bare metals. Subsequent formation of carbide phases may cause cracks in the diamond coating, as shown for coated Ti wire in Fig. 5a. A hollow silica fibre coated with diamond became brittle and cracked (Fig. 5b). The non-metals and W have adequate strength at the deposition temperature, but creep problems may arise with very thin Ti and Cu wires.

A critical part of CVD diamond processing is the initial nucleation of the diamond film. The area density of



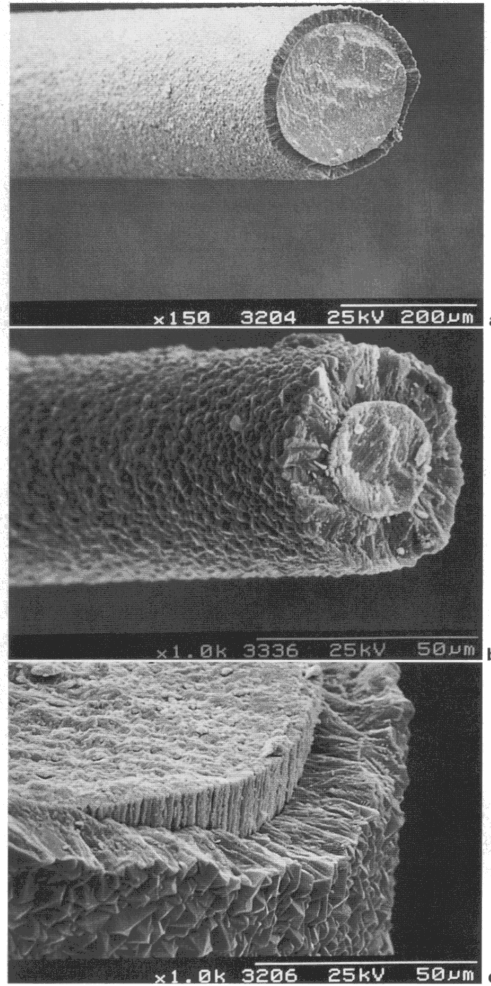
3 CVD diamond fibre with single core and multiple cores

diamond nuclei depends on the substrate material, substrate surface, interface reactions, and deposition conditions. Surface abrasion with diamond grit is the most common method of promoting diamond nucleation on planar substrates. Diamond nucleation along the scratch lines on a W wire is shown in Fig. 6; surface coverage then appears to proceed by sideways growth. Tungsten wires appear to be particularly amenable to diamond nucleation, possibly because during production surface scratches are produced by drawing through diamond dies. Since scratching is impracticable for thin fibres, alternative methods must be developed. The area density of diamond nuclei is greater on substrates that form carbides and can be increased via changes in the substrate temperature during deposition. The initial grain size of CVD deposits is about 1 μm, but depends on the diamond nucleation density. The columnar grains characteristic of CVD and the surface roughness tend to increase in size with increase in thickness of deposit.<sup>18</sup>

The reported length of diamond fibres to date are of the order of 100 mm only, with a maximum diamond coating thickness of ~20 μm. However, CVD diamond can contain hydrogen and the effect of such hydrogen on composite matrixes must be considered.<sup>17</sup>

Table 2 Properties of natural and CVD diamond<sup>1</sup>

Property	Natural diamond	CVD diamond
Relative density ρ	3.51	3.5
Fracture strength, σ <sub>f</sub> , GN m <sup>-2</sup>	~3.5	0.5–1.4 (in tension)
Young's modulus E, GN m <sup>-2</sup>	1050	700–1079
Hardness, GN m <sup>-2</sup>	55–113	31–90
Fracture toughness, K <sub>IC</sub> MN m <sup>-3/2</sup>	3.4–5.0	K <sub>C</sub> ~6
Poisson's ratio ν	0.07	0.07
Coefficient of thermal expansion × 10 <sup>-6</sup> °C <sup>-1</sup>	0.8	0.8–1.05
Thermal conductivity λ, W m <sup>-1</sup> K <sup>-1</sup>	600–2200	300 μm thick 2400 5 μm thick 1000
Specific heat C <sub>v</sub> , C <sub>p</sub> , J mol <sup>-1</sup>	6.2	...
Specific heat capacity, J K <sup>-1</sup> kg <sup>-1</sup>	525	510
Electrical resistivity, Ωm		
high	> 10 <sup>14</sup>	10 <sup>14</sup>
low	0.1–10	B doped 10
Surface roughness, μm	...	1–4
Sound velocity, m s <sup>-1</sup>	10 285	16 200 (Ti = 4900) (Ref. 13)
Coefficient of friction	0.02–0.1	0.15–0.52
Radiation absorption coefficients	Low over ultraviolet, visible, and infrared	Within factor 2–3 of Type IIA diamond
Hall mobility, cm <sup>2</sup> V <sup>-1</sup> s <sup>-1</sup>	325	3–10
Dielectric constant	5.7	5.7



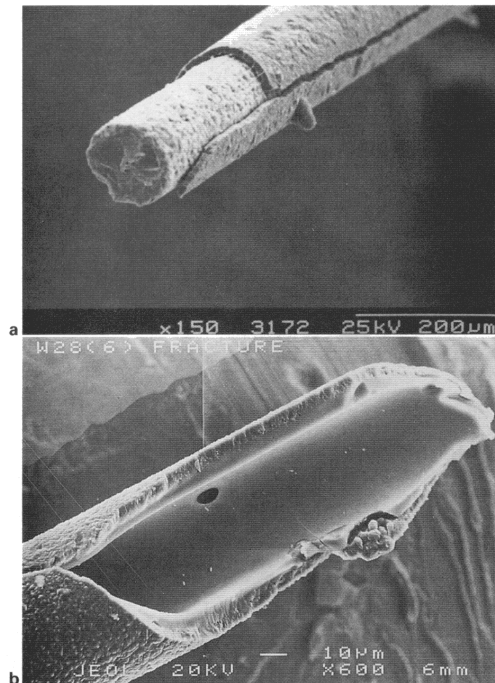
a 200 μm diameter W wire core, 22 μm thick diamond coatings to give V<sub>f,d</sub> = 0.33, predicted E = 537 GN m<sup>-2</sup>, ρ = 14.1, E/ρ = 38 GN m<sup>-2</sup>; b 25 μm diameter W wire core, 10 μm thick diamond coating to give V<sub>f,d</sub> = 0.69, predicted E = 727 GN m<sup>-2</sup>, ρ = 8.4, E/ρ = 86 GN m<sup>-2</sup>; c as for b showing good contact between W fibre and diamond coating, columnar grain microstructure, and faceted surface of diamond

4 Solid CVD diamond fibres produced at Bristol University

Properties of natural diamond and chemical vapour deposition diamond thin films

Some properties of natural and CVD diamond are given in Table 2. Strength data for natural diamond are obtained indirectly via compression or hardness measurements and are dependent on the value of Poisson's ratio.<sup>1,19</sup> Stress wave and crack growth velocities are greater in diamond than in any other material;<sup>1</sup> the former makes diamond attractive for speaker diaphragms.<sup>5</sup>

Certain properties of CVD diamond can approach or equal the value for natural diamond e.g. Young's modulus, thermal conductivity, and radiation absorption, but all are dependent on deposition conditions and on microstructure.<sup>15,20</sup> In experiments on a microwave plasma



5 Diamond coating *a* on Ti wire (crack in diamond caused by interface reaction) and *b* on hollow silica fibre (cracked fibre caused by interface reaction)

deposited diamond film on silicon, Seino and Nagai<sup>21</sup> were the first to determine the temperature dependence of Young's modulus for CVD diamond up to 800°C. At room temperature the modulus of the film was 891 GN m<sup>-2</sup>, approximately 17% less than that of bulk diamond (1050 GN m<sup>-2</sup>), but twice the modulus of CVD β-SiC<sup>22</sup> over this temperature range (Fig. 7). Some diamond films have been reported with much higher values of Young's modulus<sup>2,22,24</sup> and biaxial modulus values of 1180 GN m<sup>-2</sup> for randomly oriented films and 1220 GN m<sup>-2</sup> for (110) textured films have been obtained.<sup>19</sup> The Young's modulus and specific modulus of some fibres and metals are compared with diamond in Table 3.

High elastic properties are more easily achieved in thin CVD diamond films than high tensile fracture strength. Fracture in CVD diamond is dominated by transgranular cleavage on (111) planes;<sup>1</sup> since these are also the growth planes the preference for cleavage in these planes may be due to growth defects.<sup>1</sup> Few measured tensile strength values have been reported as distinct from strength values deduced from hardness,<sup>25</sup> compression tests,<sup>19</sup> or diaphragm

bulge tests.<sup>24,26</sup> The reported tensile fracture strengths of ~0.7–1.4 GN m<sup>-2</sup> (Refs. 1, 2, 9) are lower by approximately a factor of 3 than values predicted for natural diamond; this has been attributed to surface cracks of 2–10 µm in the CVD diamond film. The columnar grain boundaries show a surprising resistance to fracture under tensile stress normal to the grain growth direction. This may be caused by crack blunting in amorphous layers at the grain boundaries and by the presence of high residual stresses, as suggested by Brown.<sup>2</sup> Fracture toughness at ~6 MN m<sup>-3/2</sup> (Refs. 24, 27) appears to be slightly greater than for natural diamond.

**Predicted modulus of diamond fibres**

Comprehensive reviews of commerial fibres have been presented by Harris<sup>28</sup> and Cooke<sup>29</sup> and the manufacture of continuous fibre reinforced composites has been reviewed by Partridge and Ward-Close.<sup>30</sup> The slow deposition rates for CVD diamond suggest that thin diamond deposits on small diameter cores will be more cost effective for diamond fibres. It is therefore worthwhile comparing the predicted density and Young's modulus of diamond fibres containing different cores and volume fractions of diamond.

From the rule of mixtures (ROM) equation for the upper bound values,<sup>3,31</sup> the density ρ is given by

$$\rho_f = Vf_c \rho_c + Vf_d \rho_d \dots \dots \dots (1)$$

where f, c, and d refer to the properties of the fibre, fibre core, and CVD diamond coating, respectively, and Vf refers to the corresponding volume fraction in the fibre cross-section. The upper bound values for Young's modulus E in the longitudinal fibre direction are also given by the ROM if the core and coating deform to the same strain.<sup>3,31</sup> If d<sub>1</sub> and d<sub>2</sub> are the core and fibre diameters, respectively, (Fig. 4), the Vf values are determined by the diameter ratio k where

$$k = d_1/d_2 \dots \dots \dots (2a)$$

$$Vf_c = (d_1/d_2)^2 = k^2 \dots \dots \dots (2b)$$

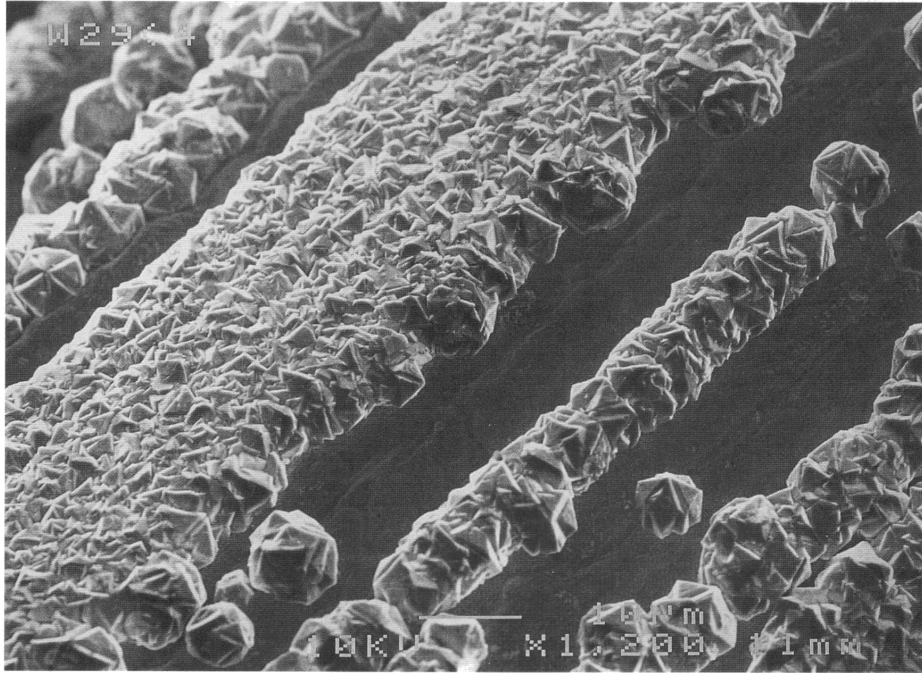
$$Vf_d = 1 - k^2 \dots \dots \dots (2c)$$

**SOLID DIAMOND FIBRES**

Values for ρ and E for solid diamond fibres with various cores and for hollow diamond fibres have been calculated using ROM taking the measured value for CVD diamond of E = 891 GN m<sup>-2</sup> (Ref. 32). Comparisons have been made with commerial SiC fibres, which are supplied in two sizes, 100 or 140 µm with W wire and C fibre cores, respectively. The effect of 10 µm C fibre and 20 µm W, Ti, and quartz cores on the predicted Young's modulus of diamond fibres is shown in Fig. 8a. With the C fibre core the modulus is insensitive to coating thickness for fibre diameters in the range 50–150 µm, but with the 20 µm

**Table 3 Specific stiffness and thermal conductivity data**

Material	Relative density ρ	Young's modulus E, GN m <sup>-2</sup>	Specific modulus E/ρ, GN m <sup>-2</sup>	Thermal conductivity λ, W m <sup>-1</sup> K <sup>-1</sup>	Specific thermal conductivity λ/ρ, W m <sup>-1</sup> K <sup>-1</sup>
Natural diamond	3.51	1050	299	600–2200	171–626
CVD diamond	3.5	891	255	1000–2000	286–571
CVD SiC (BP)	3.4	400	117	110	32
C fibre pitch P100	2.15	700	326	600	279
Silica	2.21	74	34	11	5
Tungsten	19.3	411	21	177	9.2
Copper	8.96	130	15	403	45
Aluminium	2.7	70	26	238	88
Ti-6Al-4V (IMI 318)	4.42	110	25	5.8	1.3



6 Nucleation of diamond along scratches on W wire, courtesy Q. S. Chia

diameter core modulus values are sensitive to fibre diameter below about 100 μm. Note the significant increase in fibre modulus for all diamond fibre cores compared with the values for commercial SiC fibres. Of much greater significance is the effect of the core on the fibre specific modulus  $E/\rho$ , shown in Fig. 8b. For fibre diameters less than about 50 μm the high density of W reduces  $E/\rho$  for the diamond fibres to values below those for commercial SiC fibres. It is therefore necessary to ensure the ratio of diamond coating thickness/W wire core diameter is large enough to compete with the lower density C fibre, SiC and quartz cores. The stability of diamond/core and diamond fibre/metal matrix interfaces has yet to be studied.

**HOLLOW DIAMOND FIBRES**

Since diamond is resistant to attack by almost all chemicals, it is possible to remove metallic and ceramic fibre cores via etching to produce straight hollow diamond fibres with

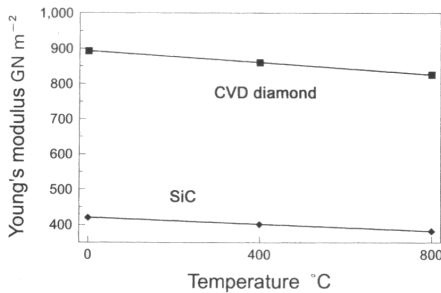
uniform wall thickness (Fig. 9a). Depending on the core and coating thickness, thick and thin walls (Figs. 9b and 9c) and smooth internal surfaces (Fig. 9b) can be obtained. These hollow fibres have potential not only for reducing the weight of composites, but also for providing channels for gases and sensors in smart composites.<sup>33</sup> Since a wide range of hollow core diameters and thickness of fibre wall is possible, a range of effective density  $\rho_f$  and effective modulus  $E_f$  is possible with hollow diamond fibres, depending on the volume fraction of hollow core  $Vf_c = k^2$  where

$$\rho_f = \rho_d(1 - k^2) \dots \dots \dots (3a)$$

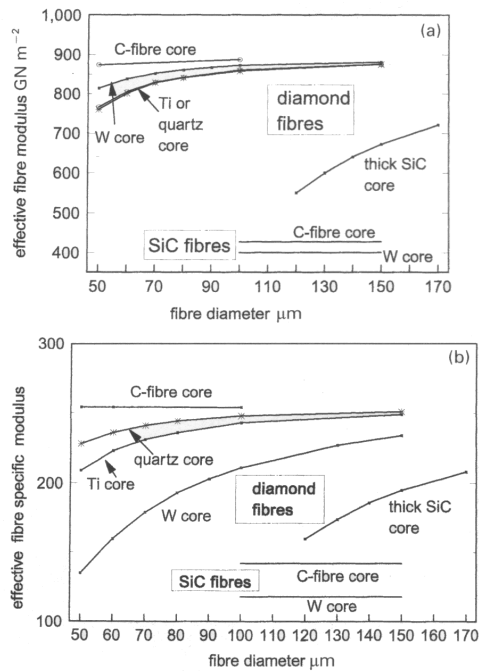
$$E_f = E_d(1 - k^2) \dots \dots \dots (3b)$$

Theoretically,  $Vf_c$  can be selected to produce hollow diamond fibres with effective moduli substantially greater than the values for solid SiC fibres. For a given  $Vf_c$ , the effective hollow fibre modulus is independent of fibre diameter, as shown in Fig. 10a for  $Vf_c = 0.3$  and 0.5. The effective fibre specific modulus  $E_f/\rho_f$  is a constant for hollow fibres and equal to the value for hypothetical monolithic solid diamond fibres. The dramatic effect of a hollow core is apparent when comparisons are made of effective fibre specific modulus for solid and hollow fibres, as shown in Fig. 10b. At a 55%  $Vf_c$ , the hollow diamond fibre modulus  $E_f = 400 \text{ GN m}^{-2}$ , the value for SiC fibre, but the diamond fibre effective density and specific density values become  $\rho_f = 1.58$  and  $E/\rho = 255 \text{ GN m}^{-2}$ , respectively, compared with the corresponding values for SiC fibre of  $\rho = 3.4$  and  $E_f/\rho_f = 118\text{--}142 \text{ GN m}^{-2}$ .

Thin walled hollow fibres may have a further advantage. Under transverse loads the fibre may change shape from a circular to an oval cross-section and provide greater transverse strength than solid fibres.<sup>32,34</sup> It may therefore be possible via mixing these types of hollow fibre with solid fibres, to tailor a composite to have a range of stiffness values or a through thickness stiffness gradient.



7 Young's modulus of CVD diamond film compared with CVD SiC film in temperature range 0–800°C, based upon the data of Refs. 21 and 22



a predicted  $E$  versus fibre diameter for different diamond cores of C fibre (10  $\mu\text{m}$  diameter), Ti, W, and quartz (20  $\mu\text{m}$ ) compared with commercial monofilament SiC fibres with C fibre core and W core; b predicted  $E/\rho$  versus fibre diameter compared with commercial monofilament SiC fibres

## 8 Solid fibres

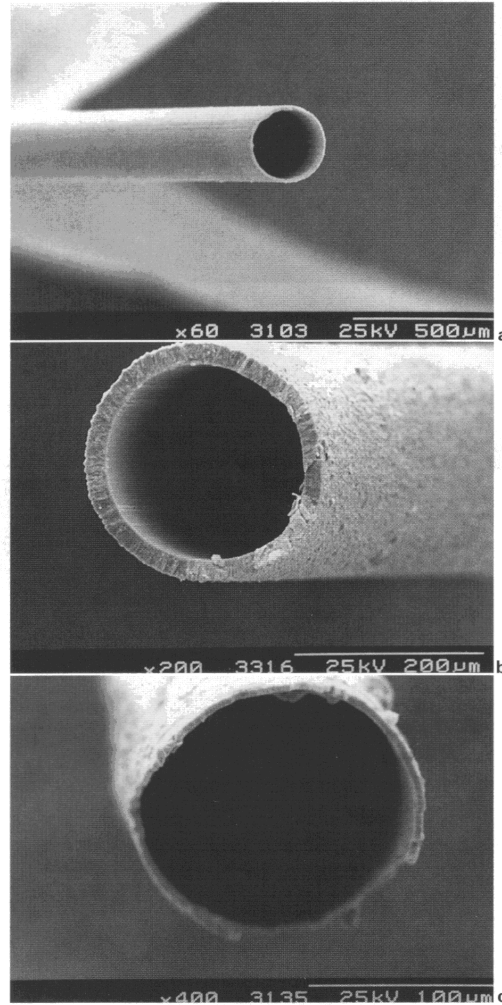
### DISCONTINUOUS FIBRES

Short diamond fibres have also been considered for composites and have several important advantages. The cost of composite manufacture is usually much less for discontinuous fibre than for continuous fibre, the discontinuous fibre composite is more easily formed into complex shapes and when the fibres are randomly distributed the composite properties are more isotropic. Since the removal of cores in long fibres has yet to be demonstrated, short hollow fibres would be more attractive. For the same fibre length, discontinuous diamond fibre composites are expected to be significantly stiffer than the equivalent SiC fibre composites.<sup>35</sup>

### Diamond fibre metal matrix composites

Galvanic corrosion can be a major problem in graphite fibre reinforced MMCs. Since diamond is an electrical insulator, this problem may be avoided with CVD diamond fibres. However fibre/matrix interface coatings may have to be tailored for each matrix.

The literature on interface coatings to control the reaction between SiC fibres and Ti alloys is extensive and some success has been achieved with C rich layers. The composite stiffness values for a continuous diamond fibre/Ti-6Al-4V matrix composite have therefore been calculated using the ROM. For comparison with SiC fibre composites, a 100  $\mu\text{m}$  diameter fibre having a 20  $\mu\text{m}$  diameter W wire core has been used. Taking  $E = 891 \text{ GN m}^{-2}$  for CVD diamond, this fibre would have  $E_f = 872 \text{ GN m}^{-2}$  and  $\rho_f = 4.13$ .<sup>14</sup> The predicted composite properties for a 30% volume fraction of fibres are shown in Table 4 and



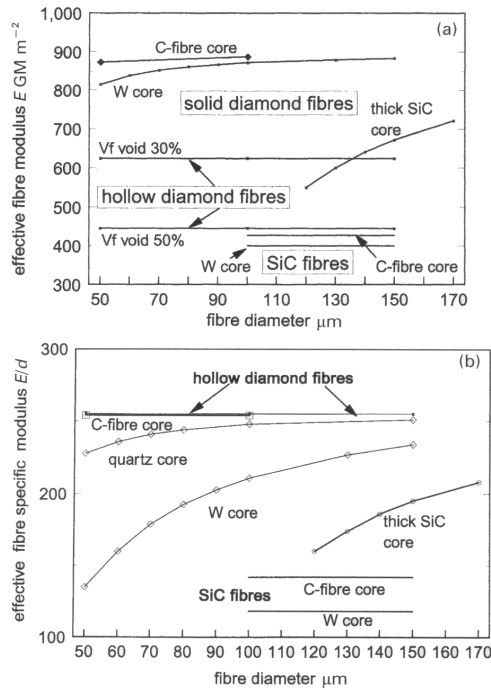
a 200  $\mu\text{m}$  diameter fibre, 22  $\mu\text{m}$  thick wall produced via etching out W fibre core in fibre shown in Fig. 4a,  $V_f = 0.33$ ,  $\rho = 1.15$ ,  $E = 294 \text{ GN m}^{-2}$ ,  $E/\rho = 255 \text{ GN m}^{-2}$ ; b as for a showing smooth internal surface; c diamond fibre with 3.5  $\mu\text{m}$  wall thickness

## 9 Hollow CVD diamond fibres

compared with the matrix properties and the properties of the commercial SiC fibre composite. An increase of 54% in specific stiffness is predicted for the diamond fibre composite compared with the commercial SiC fibre composite.

Two hollow fibres have been considered with hollow core volume fractions  $V_{fc}$  of 0.3 and 0.5. The corresponding values for these fibres are  $E_f = 624 \text{ GN m}^{-2}$  and  $\rho_f = 2.45$  ( $V_{fc} = 0.3$ ) and  $E_f = 447 \text{ GN m}^{-2}$  and  $\rho_f = 1.75$  ( $V_{fc} = 0.5$ ).<sup>14</sup> The composite properties for a 30% volume fraction of fibres are given in Table 4. For the diamond fibre composite an increase in specific stiffness values of 15 and 35% is predicted for  $V_{fc} = 0.5$  and  $V_{fc} = 0.3$ , respectively, compared with the commercial SiC fibre composite.

Diamond composites may also be attractive in thermal management systems. The thermal conductivity  $\lambda$  of various materials is compared with the value for diamond in Table 3. The outstanding properties of CVD diamond are apparent, with values of  $\lambda/\rho$  being 3 to 6 times greater than



a predicted  $E$  versus fibre diameter for hollow diamond fibres with  $V_f$  values of 0.33 and 0.50, compared with solid diamond fibres and commercial SiC fibres; b predicted effective fibre specific modulus ( $E/d$ , where  $d$  is effective fibre density) versus fibre diameter for hollow diamond fibres with  $V_f$  values of 0.33 and 0.50, compared with solid diamond fibres and commercial SiC fibres

10 Hollow diamond fibres

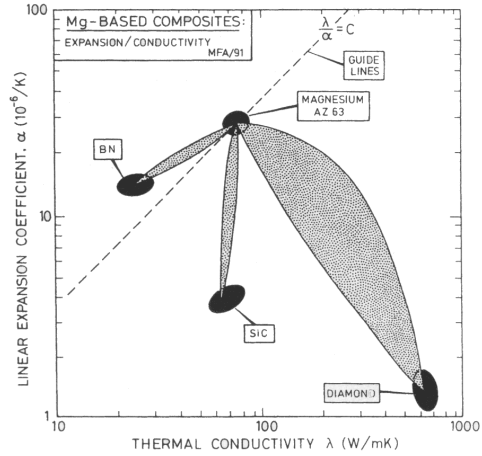
for Cu or Al. Again, an excellent illustration of the potential for exploiting the combination of properties obtainable with metal matrix–diamond composites is given by Ashby’s diagram in Fig. 11.<sup>13</sup> Diamond fibres in an Mg alloy could lead to high thermal conductivity, low thermal distortion, and very high strength/weight ratios, without the risk of galvanic corrosion.

Table 4 Predicted stiffness data for Ti–6Al–4V alloy reinforced with continuous diamond fibres\*

Material	Relative density $\rho$	Young’s modulus $E$ , GN m <sup>-2</sup>	Specific stiffness $E/\rho$ , GN m <sup>-2</sup>	Specific stiffness†
Ti–6Al–4V	4.42	110	24.8	0.49
Commercial metal matrix composite 30 vol.-% SiC fibre (W core) in Ti–6Al–4V matrix	4.05	206	50.9	1.0
30 vol.-% 100 μm diameter solid diamond fibre with 20 μm W core in Ti–6Al–4V matrix	4.33	339	78.2	1.54
30 vol.-% 100 μm diameter hollow diamond fibre with 50 vol.-% hollow core	3.62	211	58.3	1.15
30 vol.-% 100 μm diameter hollow diamond fibre with 30 vol.-% hollow core	3.83	264	68.9	1.35

\* Based on ROM.

† Relative to commercial Ti alloy metal matrix composite.



11 Linear thermal expansion versus thermal conductivity design chart for Mg–AZ63 alloy composites to resist distortion. Large increases in performance are possible for Mg–diamond composites within shaded upper and lower bound envelope between Mg and diamond (From Ref. 3)

Discussion

As might be expected, there are many aspects of diamond fibre and diamond fibre composite technology that require further research. The current hot filament and microwave diamond deposition rates are orders of magnitude slower than the rates for SiC and this is a major factor leading to the much higher predicted costs for CVD diamond fibres compared with alternative mono- or multifilament fibres.<sup>14</sup> There are however high temperature plasma torch processes (Fig. 2c) being studied that can deposit diamond at rates two orders of magnitude greater than those for the hot filament method. The commercial competitiveness of CVD diamond fibres will depend on these future developments and on the unique properties of the diamond fibre.

SiC monofilament fibres have excellent high temperature stability in oxidising and non-oxidising environments even at 1800°C, but in practice it is the reactions that occur at the fibre/matrix interface that limit the service temperature of MMCs, e.g. SiC fibres in a Ti alloy matrix are limited to ~600°C. It is likely that this will also be the maximum service temperature envisaged for diamond fibres without oxidation protection. As with all composites, interface coating will play an important role in the development of composite properties as well as influencing the material costs.

One interesting aspect of the small diameter diamond fibre development is the possible effect on compressive properties. Since the critical buckling load of a fibre in compression increases with the 1st power of the modulus, but with the 4th power of the fibre diameter, thicker fibres are particularly attractive for composites loaded in compression. Thus diamond fibres may be superior to graphite fibres in polymer matrixes.

Conclusions

The unique combination of physical, chemical, and mechanical properties of diamond guarantees diamond fibres and composites based on them will receive increasing attention in the future. It is hoped that this paper will alert potential

users to these new developments in diamond technology and help to generate new applications for these materials over a wide range of disciplines

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