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DIAMOND AND RELATED MATERIALS

Diamond fibre metal matrix composites

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Abstract

Solid and hollow diamond fibres have been manufactured by chemical vapour deposition (CVD) on to tungsten wires and coils. The fibres were coated with metal matrices by sputter deposition. The matrices were Cu, Al, and Ti-alloy. The coated fibres were then consolidated by hot pressing to metal–matrix composites. The properties of the composites are compared with current composites. Copper and aluminium composites have potential for high stiffness thermal conductors, and Al and Ti-alloy are attractive light-weight high stiffness materials for aerospace applications. In combination with hollow fibres, lower density and higher compressive stiffness are expected. © 1997 Elsevier Science S.A.

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1. Introduction

The extreme properties of diamond have recently been exploited by growing CVD diamond coatings on wires and fibres leading to the manufacture of continuous diamond fibres [1]. The use of small diameter cores (~ 20 μm) and thick diamond coatings (~ 50 μm) has given diamond volume fractions as high as 97% [2]. Nicholson et al. [3] reported that such fibres had a tensile modulus of ~ 900 GPa (cf. 400 GPa for commercial monofilament SiC fibres) and hence were suitable for reinforcement of metallic and non-metallic composites. The manufacture and microstructure of several diamond fibre-reinforced metal–matrix composites is described.

The use of hollow fibres provides a method for increasing the specific stiffness of a composite. A method of manufacture for hollow diamond fibre composites and some initial results are presented.

2. Experimental technique

2.1. Diamond fibre production

The monofilament diamond fibres were made by CVD on to 20–125-μm tungsten wire in a standard hot filament reactor using typical deposition conditions of 1% methane in hydrogen, 200 sccm gas flow rate, Ta filament temperature of 2150°C and 20 Torr gas pressure [1]. The fibre temperature during deposition was about 900°C. The fibre cores were abraded with 1–3-μm diamond powder prior to deposition to enhance the diamond nucleation. The diamond growth rate was about 0.5–1 μm h^{-1}. The fibres were created in nominal 100-mm lengths.

2.2. Diamond fibre MMC production

The diamond fibres were sputter coated with the matrix metal (Ti-alloy, Cu or Al) and then laser cut into lengths of ~ 1 cm [2] for the creation of the composite test pieces. A schematic diagram of a coated fibre prior to consolidation is shown in Fig. 1. Composites were produced by stacking the aligned fibres within a V-notched block of matrix material and hot vacuum pressing in a die at about 900°C for 1 h. The sputtered matrix coating ensured a uniform fibre spacing and determined the fibre volume fraction, whilst preventing direct diamond/diamond contact, as described elsewhere [4].

The resulting composite pieces were sectioned using a diamond saw to remove the excess matrix, and an excimer laser to cross-section the diamond fibres [2]. The section surfaces were then cleaned up by gently

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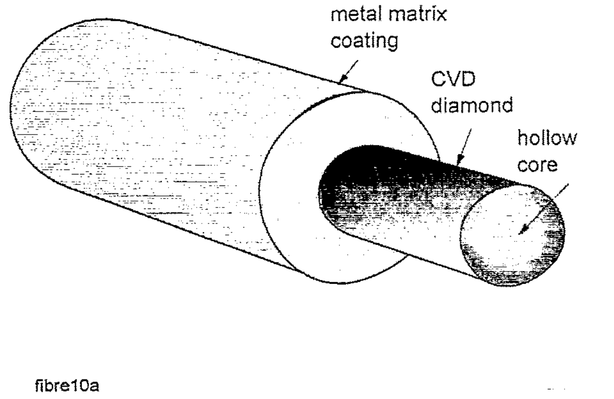

Fig. 1. A schematic diagram of a coated fibre prior to consolidation.

polishing with 1-μm diamond paste to remove the laser cutting detritus. Conventional polishing with a coarser diamond grit was found to leave the diamond fibres protruding above the matrix material.

2.3. *Hollow fibre composites*

Metal–matrix composites have been made using hollow fibres constructed by the coil method [5]. With this method, fine tungsten wires (20-μm diameter) were wound around a wire former (typically 200-μm diameter stainless steel) to a length of ~1 cm. Next, the coils were removed from their former. One trailing end of each coil was inserted into a fine copper tube (OD 0.5 mm, ID 0.22 mm) which was pinched flat to grip the wire. Each copper tube was bent into a hook shape and the resulting assembly hung from a frame in the CVD reactor. The coils were hung vertically to avoid bending.

After diamond coating, the coils were removed from the hooks and threaded onto a thin wire, on which they were supported during sputter coating with matrix material. The rest of the procedure used was identical to the production of solid fibre composites (see Section 2.2.

3. Results

3.1. *Solid diamond fibre metal–matrix composites*

Fig. 2 shows a back-scattered electron image of a laser-cut section of diamond fibres in a Ti–6Al–4V alloy matrix. The fibres had 125-μm diameter tungsten cores (bright in figure) coated with 40 μm of diamond (dark in figure). Fig. 3 shows a Raman image of the 1332 cm^{-1} diamond emission from the same composite (rotated through approximately 30°). The bright spot between the fibres is a pore containing grinding paste residue.

Fig. 4 shows a back-scattered electron image of ten similar diamond fibres in a copper matrix.

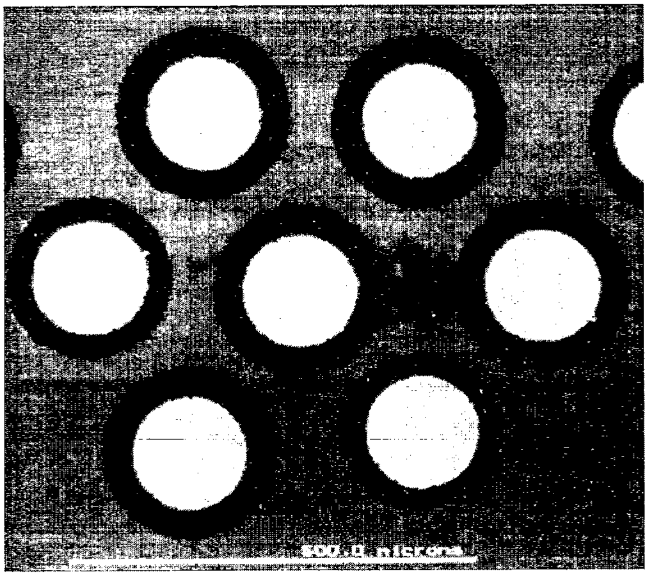

Fig. 2. A back-scattered electron image of a laser-cut section of diamond fibres in a Ti–6Al–4V alloy matrix.

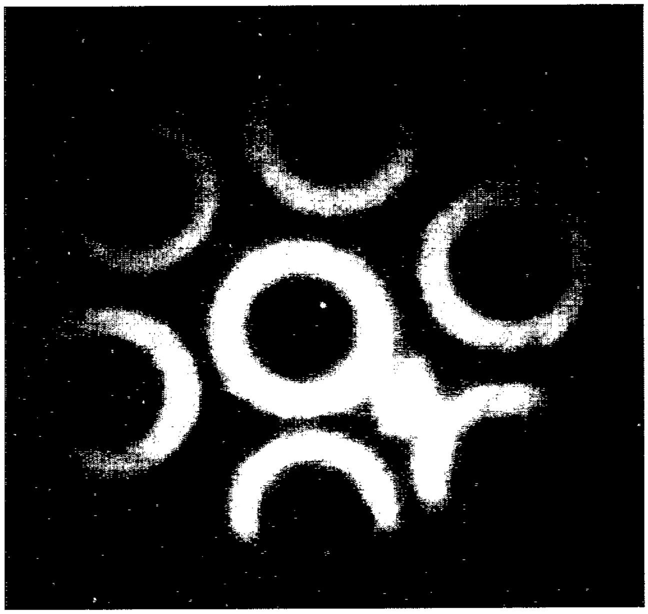

Fig. 3. A Raman image of the 1332-cm^{-1} diamond emission from the same composite (rotated through approximately 30°).

Fig. 5 shows a group of four diamond fibres (50-μm tungsten cores, 75-μm diamond coating) embedded in an Al–Li matrix. The area marked "A" in the figure is a residue of copper-loaded epoxy mounting resin.

3.2. *Hollow diamond fibre metal–matrix composites*

Figs. 6(a) and (b) show optical images of three hollow diamond fibres consolidated into a copper matrix. The differences in appearance arise from lighting; Fig. 6(a) lit from above and Fig. 6(b) additionally from below.

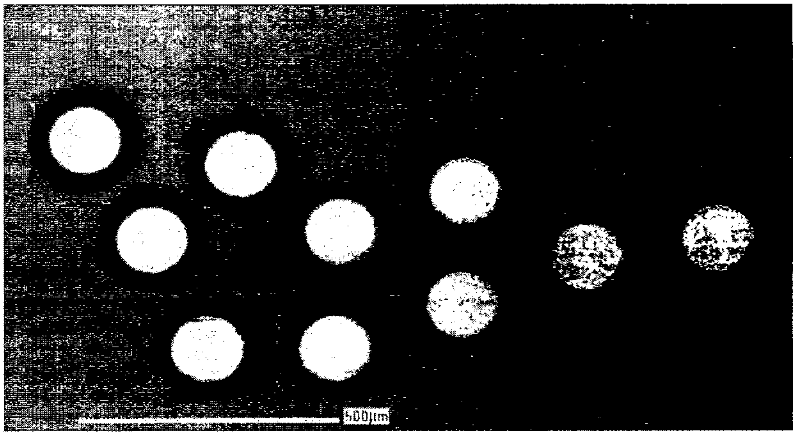

Fig. 4. A back-scattered electron image of ten similar diamond fibres in a copper matrix.

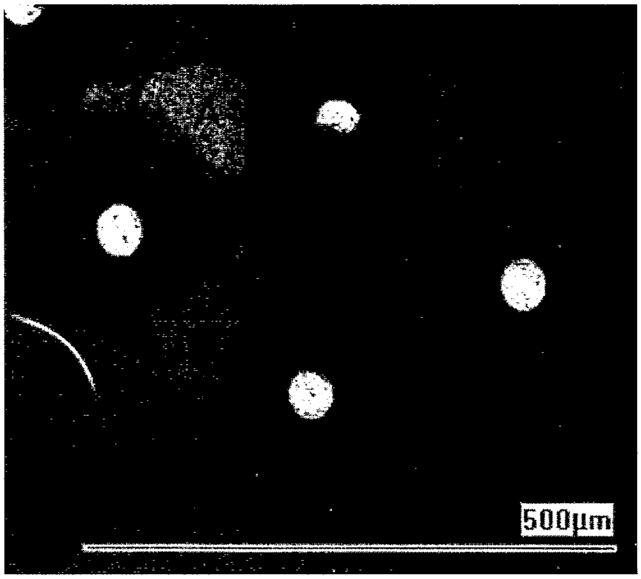

Fig. 5. A group of four diamond fibres (50-μm tungsten cores, 75-μm diamond coating) embedded in an Al–Li matrix.

4. Discussion

For each of the composites shown above (Figs. 2–6) "rule of mixtures" calculations have been carried out (Table 1), to establish the theoretical values of the Young's modulus, E, the relative density, ρ and the thermal conductivity λ, based on the total area shown in each figure. Also, the percentage of diamond and tungsten for each figure is shown.

There is a significant increase in the Young's modulus of all composites over the matrix materials. Note that ideally, the diameter of the tungsten wire should be minimised. The effect of this is shown in the Al–Li composite (40% vol. fraction diamond, 2% tungsten), where substantial increases in the stiffness and thermal conductivity values are shown.

The hollow fibre composite shows a factor of two increase in modulus over copper and nearly double the specific thermal conductivity.

Initial tensile data for an 8% volume fraction of diamond fibre in Ti-6Al-4V alloy has been shown to produce about a 50% increase in Young's modulus (A. Wisbey, private communication).

Table 1

	% diamond in composite	% tungsten in composite	Young's modulus, E (GPa)	Thermal conductivity, λ ($W\,m^{-1}\,K^{-1}$)	Relative density, ρ	Specific stiffness, ρ/E	Specific thermal conductivity, λ/ρ
42% diamond fibre in Ti (Fig. 2)	25	17	354	285	6.8	52	42
28% diamond fibre in Cu (Fig. 4)	16	12	283	475	9.2	31	52
42% diamond fibre in Al–Li (Fig. 5)	40	2	404	540	3.3	122	164
41% hollow diamond fibre in Cu (Fig. 6)	24	not considered	268	478	6.1	43	78
Ti–6Al–4V alloy			110	5.8	4.4	25	1.3
Copper			130	403	8.92	15	45
Al–Li			78	237	2.53	30	94

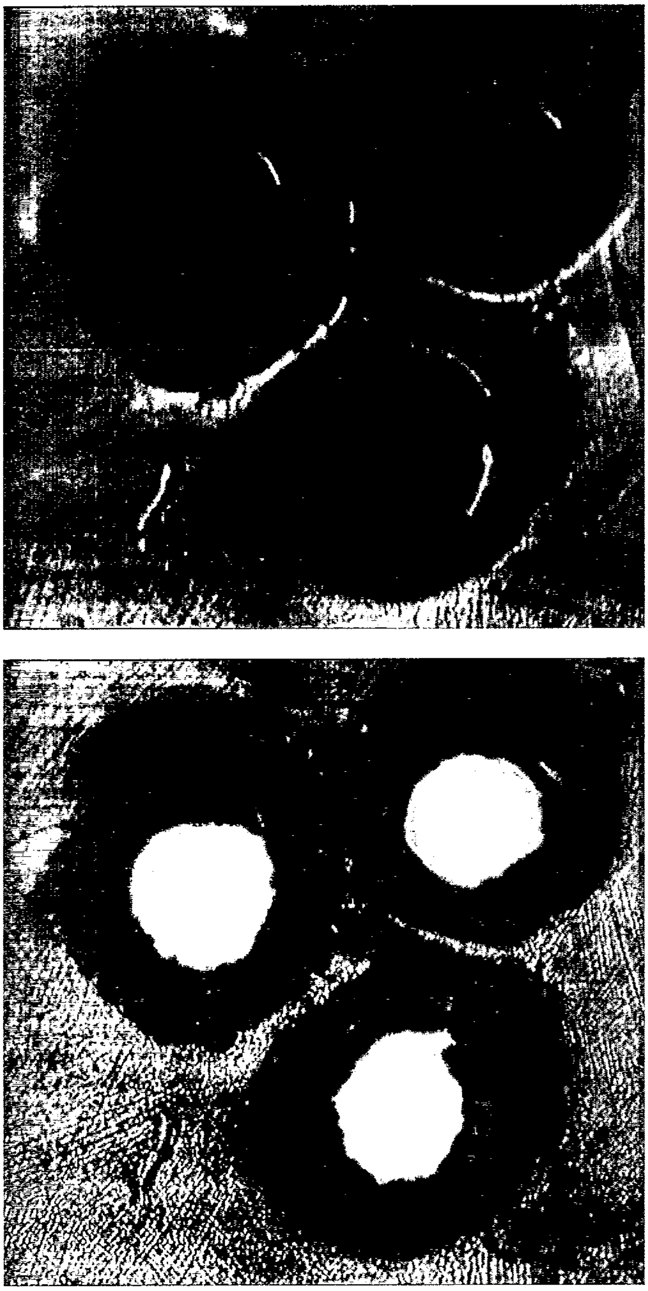

Fig. 6. Different optical images of three hollow diamond fibres consolidated into a copper matrix. The width of both images is 750 μm.

5. Conclusions

The rule of mixture properties of the diamond fibre composites manufactured show large improvements over traditional materials in the stiffness and thermal conductivity values. The potential for saving weight using hollow diamond fibres is particularly attractive. This suggest that diamond fibre composites could have wide spread applications in engineering.

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