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DIAMOND AND RELATED MATERIALS

Laser cutting of diamond fibres and diamond fibre/titanium metal matrix composites

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Abstract

Continuous diamond fibres were produced by chemical vapour deposition of diamond onto tungsten wire. The fibres were embedded in Ti–6Al–4V alloy to produce a diamond fibre reinforced composite. The diamond fibre reinforced titanium alloy composite contained a high volume fraction of fibres uniformly spaced at a distance of about 50–100 μm. Both the fibres and the composite material were extremely difficult to cut without damage by conventional mechanical methods. The use of an Nd-YAG laser to cut these materials is described.

Keywords: Diamond; Fibre; Laser; Composite

1. Introduction

The strength, hardness and elastic modulus values for natural or synthetic diamond grit are greater than those of any other material [1]. Recently, CVD diamond coatings on wires and fibres have led to the manufacture of continuous diamond fibres [2,3]. With small diameter cores (approximately 20 μm) and thick diamond coatings (approximately 50 μm), diamond volume fractions as high as 97% have been obtained (Fig. 1). The reported tensile modulus of CVD diamond fibres is approximately 900 GPa [2,3], which is over a factor of two greater than the modulus of commercial CVD SiC monofilament fibres ($E = 400$ GPa). These fibres may therefore be used to reinforce metallic and non-metallic composites. The manufacture and microstructure of a diamond fibre reinforced Ti alloy composite are described.

The exceptional hardness and stiffness of diamond, associated with a relatively low strain to fracture, make it very difficult to cut the fibres or to machine the composites without damage using conventional tools. The cutting and machining operations have therefore become a critical area of activity in the processing of these materials. Laser machining and ablation have been applied to CVD diamond films [4,5], and this paper describes the effect of laser ablation on diamond fibres and a diamond fibre reinforced Ti alloy composite.

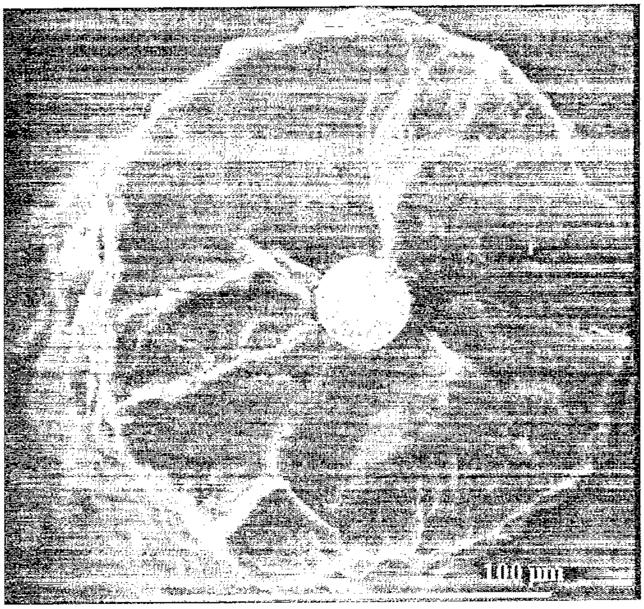

Fig. 1. Image of a high modulus, tungsten-cored diamond fibre.

2. Experimental technique

The monofilament diamond fibres were made by CVD onto 20–125 μm W wire in a standard hot filament reactor using typical deposition conditions of 1% methane in hydrogen, a gas flow rate of 200 sccm, a Ta filament temperature of 2000 °C and a gas pressure of

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20 Torr [3]. 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 $\mu m\ h^{-1}$.

A pulsed (10 Hz) Nd-YAG laser, equipped with unstable resonator or "filled-in beam" optics, was used for the cutting experiments. The parameters to be varied included the wavelength (1064 nm and 355 nm), pulse energy, duration of exposure to radiation and focusing (using spherical lenses of varying focal length and a cylindrical lens to produce a line (rather than a spot) focus across the fibre). All laser processing was carried out in air. The diamond fibres were sputter coated with Ti prior to consolidation as shown in Fig. 2. Composites were produced by stacking the aligned fibres within a block of Ti alloy and hot vacuum pressing in a die at about 900 °C for 1 h. The sputtered Ti coating ensured a uniform fibre spacing and determined the fibre volume fraction, whilst preventing fibre–fibre contact, as described elsewhere [6].

3. Results

3.1. Laser cutting of diamond fibres

Fibres cut mechanically showed cracks in the W core and cracking and spalling of the diamond coating (Fig. 3(a)). This damage was absent in a fibre cut with an Nd-YAG laser operating at a wavelength of 355 nm (Fig. 3(b)). The cut surface was planar and very smooth across both the diamond and the core (Fig. 3(c)). A film of condensed tungsten was deposited around the ablated W core and onto the fibre surface, e.g. at A in Fig. 3(b). A comparison of the Raman spectra from the treated and untreated regions (Figs. 4(a) and 4(b)) indicated that graphitization had occurred on the irradiated surface to a depth of less than 1 μm. UV (355 nm) radiation was one or more orders of magnitude more efficient than the IR fundamental wavelength at ablating both the CVD diamond and the W core. At this UV wavelength there is a threshold laser intensity (estimated at

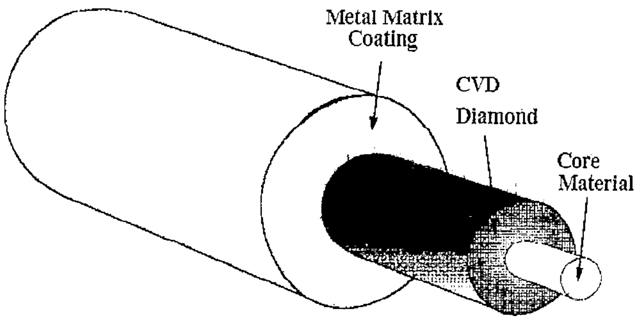
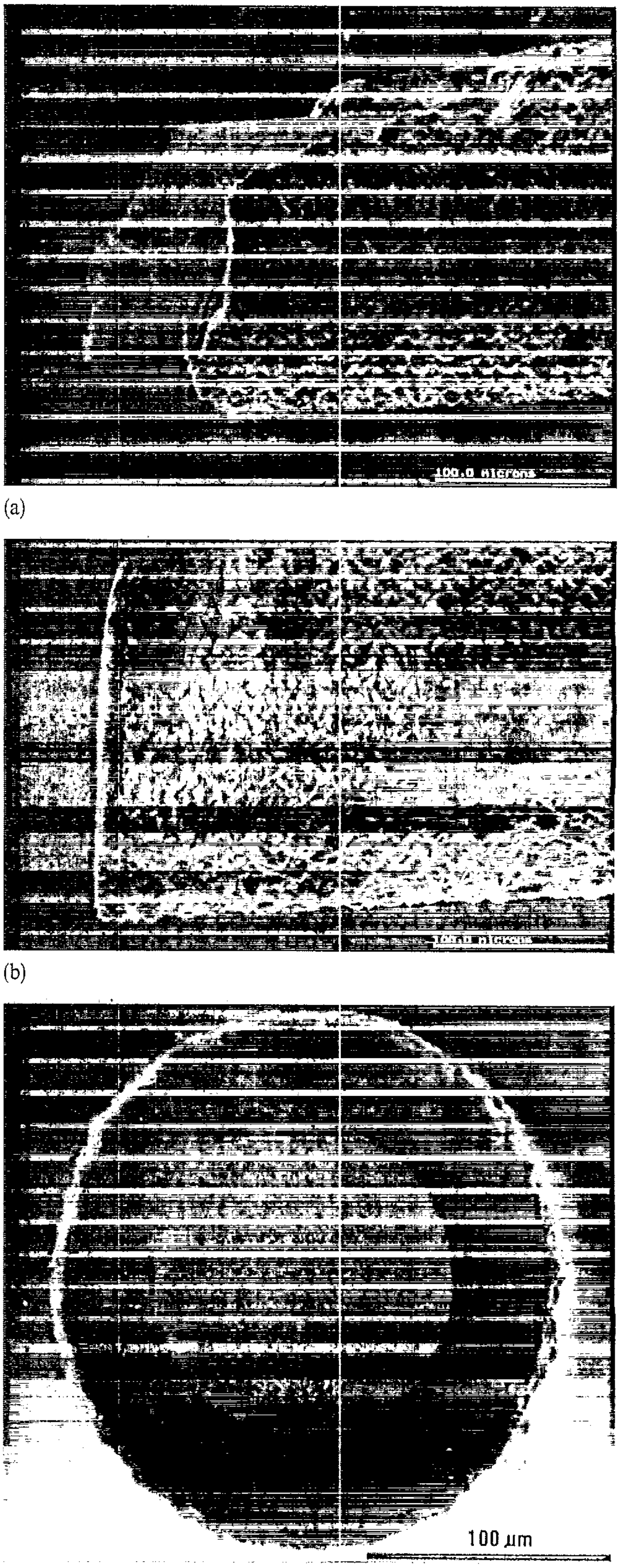


Fig. 2. Schematic diagram of sputter-coated composite diamond fibre prior to consolidation.



(a)

(b)

(c)

Fig. 3. (a) Side view of a mechanically cut, tungsten-cored diamond fibre showing cracking and spalling of diamond coat. (b) Side view of laser cut fibre. A shows an area of tungsten deposition. (c) End view of laser cut fibre showing smoothness of cut diamond surface.

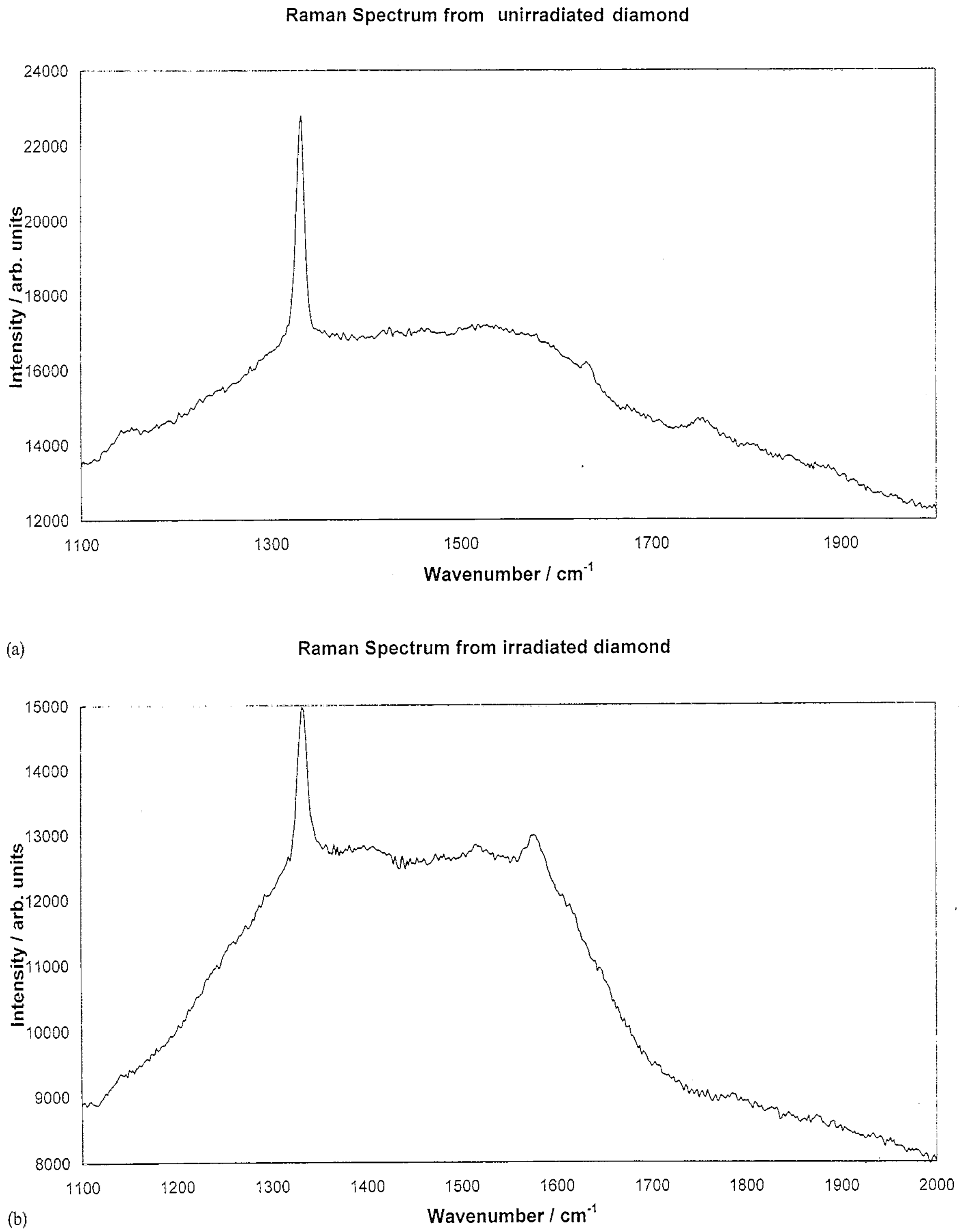


Fig. 4. Raman spectra from unirradiated (a) and irradiated (b) areas of a diamond fibre. Raman spectra sampled from 1 μm^3 volume only.

approximately 2×10^8 W cm^{-2} at 355 nm) below which no material ablation occurred.

3.2. Diamond fibre composite

A polished section through a W wire core diamond fibre/Ti alloy composite is shown in Fig. 5(a). The diamond was about 24 μm thick on 125 μm thick W wire. The uniformity of the fibre spacing produced by this manufacturing route should be noted. Planar polished surfaces were very difficult to obtain on the composites because of the extreme hardness of the CVD diamond (approximately 7000 Knoop). Raman spectra showed that the quality of the diamond was retained during consolidation. No cracks were detected in the diamond; however, carbide phases were formed at the interfaces.

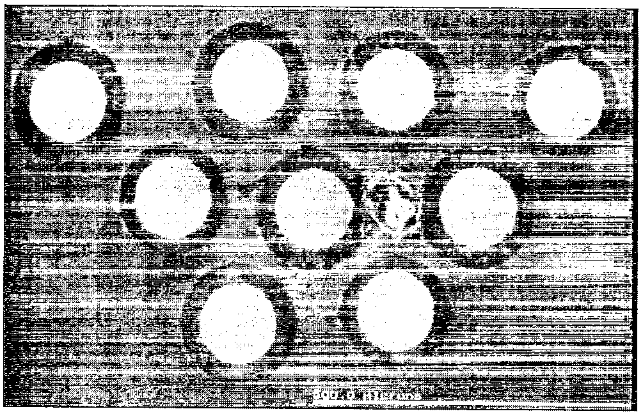
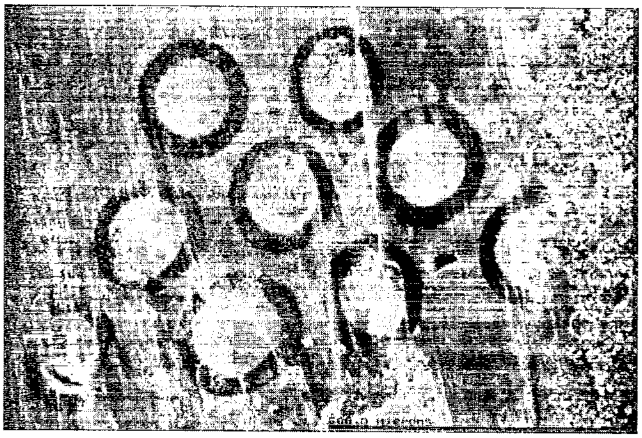
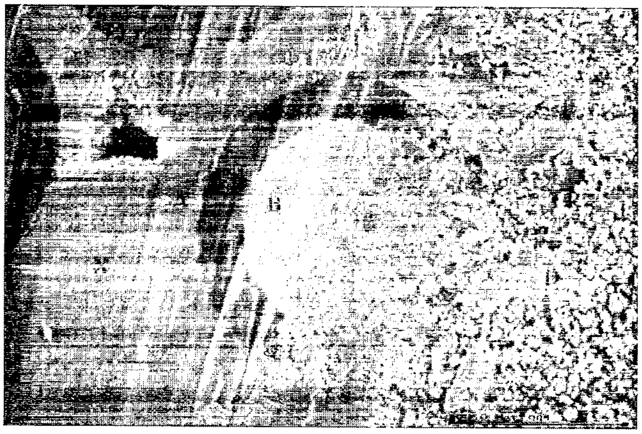


Fig. 5. Mechanically polished section through a Ti alloy/diamond fibre (tungsten core) metal matrix composite.



(a)



(b)

Fig. 6. (a) Other half of composite shown in Fig. 5 after laser cutting. (b) Detail of laser cut composite (a). See text for label explanations.

Auger analysis indicated a WC layer of approximately 2.5 μm and a TiC layer of 1.5 μm. The WC layer thickness was the same as that reported on W wire after diamond coating [7].

3.3. *Laser cutting of diamond fibre reinforced Ti alloy composite*

The surface of a laser cut section through the composite shown in Fig. 5 is illustrated in Fig. 6(a). Fig. 6(b) shows the detail of the laser cut surface. The surface was not planar on a macroscopic scale, but locally it was smooth (e.g. at X) and continuous across the Ti–diamond–W interfaces AB. The smooth surface and lack of surface damage are revealed by the sharp edges around the residual pore present in the Ti alloy matrix at C. The cut areas away from the cutting face became coated with a Ti deposit as shown at D.

4. Discussion and conclusions

Laser processing has a clear advantage over mechanical methods for cutting diamond fibres without damage. It may also be used for profiling or smoothing the fibre surface. Faster cutting rates are expected using the fourth harmonic (266 nm) of an Nd-YAG laser equipped with gaussian optics or with an excimer laser operating at a photon energy above the bandgap of diamond.

The results show that continuous diamond fibres can be incorporated into a reactive metal such as Ti with no degradation of the diamond. A Ti alloy matrix composite with 80% volume fraction of fibres, made with 97% diamond fibres, would have a predicted elastic modulus, based on the rule of mixtures, of approximately 712 GPa. This is about 3.5 times greater than that for commercial Ti alloy/continuous SiC fibre composites (approximately 206 GPa) with about 30% fibre volume fraction. The matrix coated fibre route for composite manufacture [6] allows precise control of the diamond volume fraction and fibre spacing, because these are dictated by the diamond coating and the matrix coating thicknesses respectively in the composite fibre (Fig. 2) which can be accurately controlled.

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