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Laser ablation of diamond fibres and a diamond fibre metal matrix composite

G. MEADEN, P. G. PARTRIDGE, M. N. R. ASHFOLD*, E. D. NICHOLSON*
*Interface Analysis Centre, and *School of Chemistry, University of Bristol, Bristol BS8 1TS, UK*
A. WISBEY
Defense Research Agency Farnborough, GU14 6TD, UK

Continuous chemical vapour-deposited diamond-coated fibres with tungsten wire or SiC fibre cores are attractive for reinforcing metals and ceramics. The fibres have been embedded in Ti–6A1–4V alloy to produce a diamond fibre-reinforced composite. Both the fibres and the composite material are extremely difficult to cut without damage by conventional mechanical methods. The use of a Nd–YAG laser to cut these materials is described.

1. Introduction
The strength, hardness and elastic modulus values for natural or synthetic diamond grit are greater than those of any other material [1], and the major market for particulate diamond is in composites for cutting and superabrasive grinding [2]. Chemical vapour deposited (CVD) diamond films retain many of the properties of natural diamond [3] and are also being considered for cutting tools [4]. A recent development has been the manufacture of diamond fibres by microwave plasma-enchanced CVD and hot-filament CVD (HFCVD) on to wires and ceramic fibres [3, 5]. These fibres may be superior to current commercial fibres for reinforcing metallic and ceramic matrix composites. However their exceptional hardness and stiffness, associated with a relatively low strain to fracture, makes 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 has been applied to CVD diamond films [6, 7] and this paper describes the effect of laser ablation on diamond fibres and a diamond fibre-reinforced titanium alloy composite.

2. Experimental procedure
Fibres have been made by chemical vapour deposition of diamond by the hot-filament method on to tungsten wire and Sigma SiC fibre (containing a 15 μm diameter tungsten wire core) [3, 5]. The diamond fibre core diameters were 20–100 μm for the wire and 100 μm for the SiC fibre. The diamond coating thickness was varied to give diamond volume fractions on the fibre of up to about 97%. Aligned continuous diamond fibres were sputter coated with titanium and embedded in Ti–6Al–4V alloy at 900 °C by hot vacuum pressing under superplastic conditions or by hot isostatic pressing to produce a diamond fibre metal matrix composite [8]. The inter-fibre spacing was about 0.25–1.0 times the fibre diameter, leading to a high volume fraction of fibre.

A pulsed (10 Hz) Nd–YAG laser, equipped with unstable resonator or "filled-in beam" optics was used. The parameters varied included wavelength (1064 and 355 nm), pulse energy, the 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. Individual fibres were held vertically and displaced in the vertical direction in steps and irradiated from one side under the various conditions.

3. Results
3.1. Laser cuts in diamond fibres
A low-magnification scanning electron micrograph of a diamond-coated fibre after localized ablations is shown in Fig. 1. The areas of the diamond surface at A were unirradiated and appeared bright due to the enhanced electron emission characteristics of diamond. The irradiated upper surface, B, between the bright bands appeared black. A comparison of the Raman and Auger spectra from the bright and dark regions (Fig. 2) indicated that graphitization had occurred on the irradiated surface to a depth of less than 1 μm. However, it has been reported that after exposure of a similar graphitized diamond surface to a hydrogen plasma, no evidence of graphitization was apparent in a Raman spectrum [9]. It was concluded, therefore, that the diamond had not been significantly affected. This remains to be confirmed in the present work.

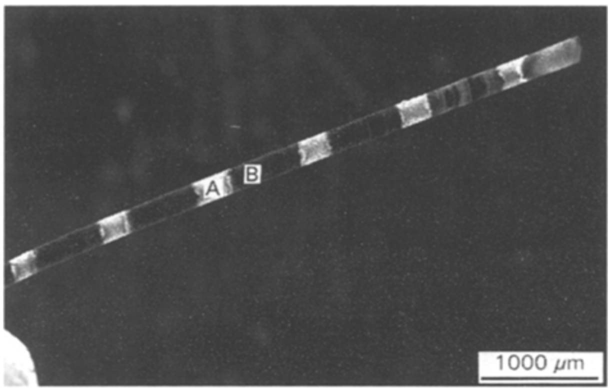

Figure 1 SEM low-magnification secondary electron image of diamond fibre showing a laser irradiated area at B and an unirradiated area at A.

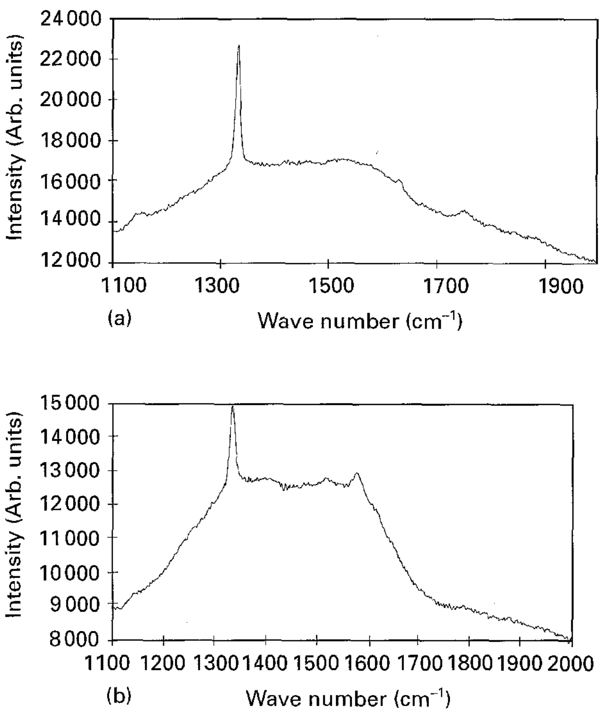

Figure 2 Raman spectra of diamond fibre showing (a) before laser treatment the sharp peak at 1332 cm^{-1} due to diamond, (b) after laser ablation the additional broad peak around 1600 cm^{-1} attributed to graphitic carbon.

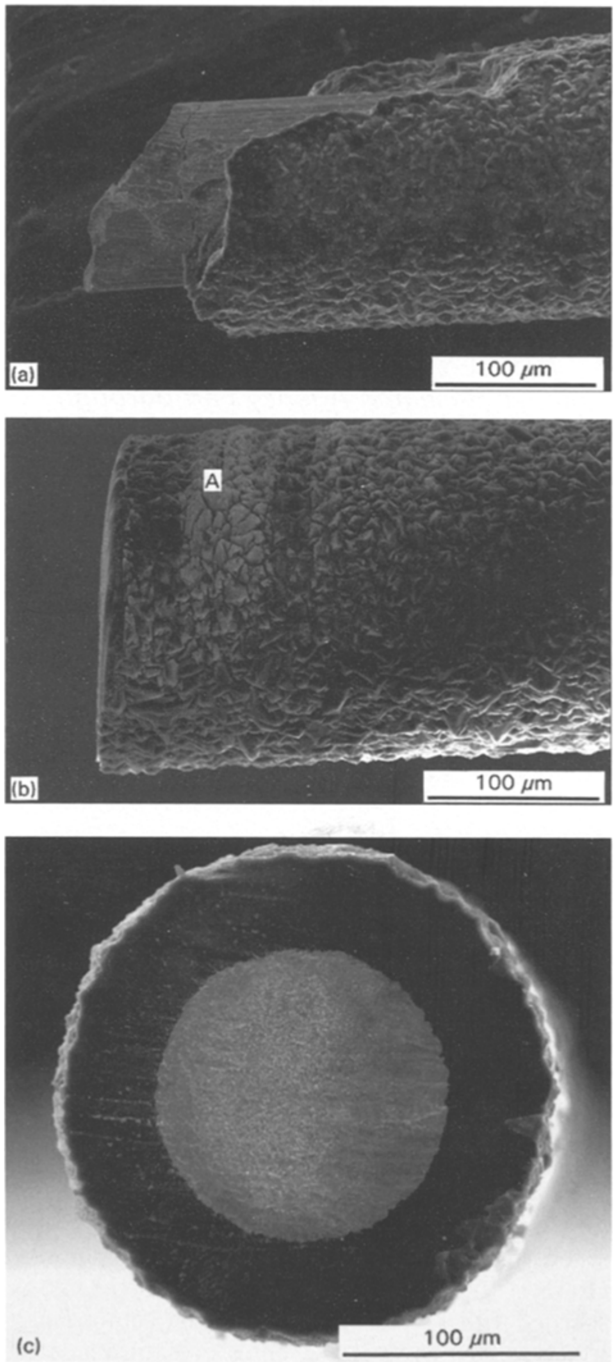

Figure 3 Scanning electron micrograph of cut diamond fibres (a) mechanically cut (b) laser cut (c) plane of laser cut normal to fibre axis.

Fibres cut mechanically showed cracks in the tungsten core and cracking and spalling of the diamond coating (Fig. 3a). This damage was absent in a fibre cut with a Nd–YAG laser operating at a wavelength of 355 nm (Fig. 3b). The cut surface was planar and very smooth across both the diamond and the core (Fig. 3c). A back-scattered electron image in the SEM showed that a film of condensed tungsten was deposited around the ablated tungsten-core and on to the fibre surface, e.g. at A in Fig. 3b.

Short-term low-power ablation of fibres produced various laser-cut profiles depending on the laser optics and processing conditions. Smooth-sided “slots” (short-term doughnut-shape beam), wider V-notches (gaussian beam) or a series of narrow sharp peaks (long-term doughnut-shaped beam) were obtained (Fig. 4a–c). The relative ablation rates were revealed in partially cut sections. In Fig. 5 the ablation front ABCD shows the greater depth of cut at the SiC core, BC, indicating a greater ablation rate for SiC compared with CVD diamond. The tungsten core ablated at a slower rate than the diamond (Fig. 4c). The measured depth of cut in the CVD diamond versus total exposure time is plotted in Fig. 6. The rate of ablation was 0.45 μm s^{-1}, at an estimated fluence of 10 J cm^{-2}. The laser ablation appeared progressively to smooth the individual diamond façets until very smooth areas were produced across many grain boundaries in the diamond (Fig. 7a, b). Smoothing of CVD diamond deposits has been reported by many workers [7, 10, 11]. The extent of smoothing depended on the laser angle of incidence as described elsewhere [12].

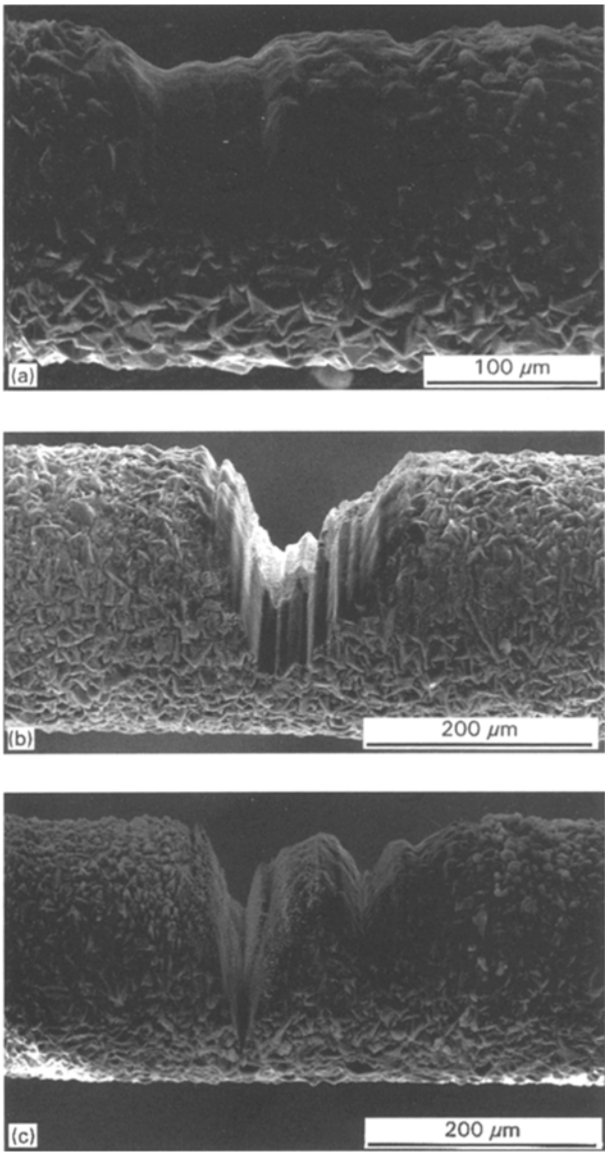

Figure 4 Partially laser-cut diamond fibres: (a) short-term cut demonstrating the polishing effect, (b) longer term with "filled-in" beam optics, (c) longer term cut with unstable resonator (doughnut) type beam.

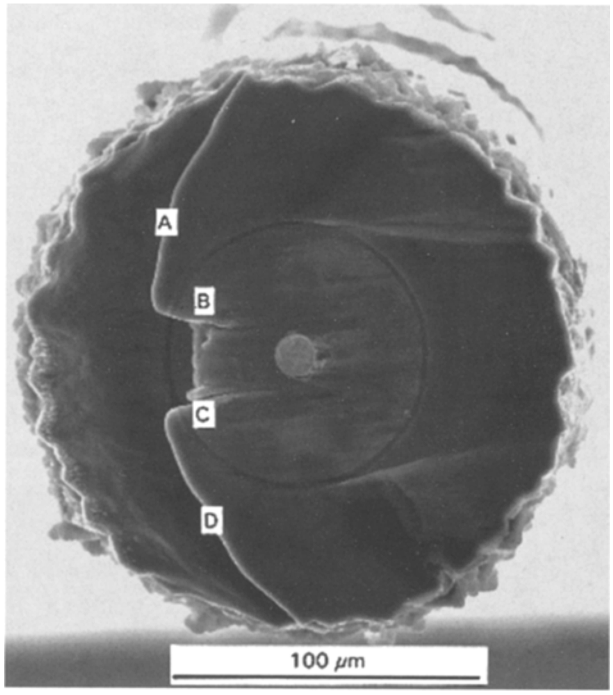

Figure 5 Plane normal to diamond-coated SiC fibre axis showing partial cut. Area BC shows where the cut has penetrated the SiC core and the cutting rate has increased relative to diamond.

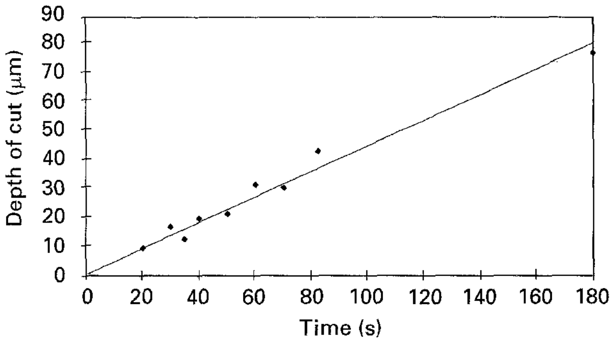

Figure 6 Plot of depth of laser cuts against time for an estimated laser fluence of $10 \mathrm{~J\,cm^{-2}}$.

Ultraviolet (355 nm) radiation was one or more orders of magnitude more efficient than the infrared fundamental wavelength at ablating both the CVD diamond and the SiC (or tungsten) core. At this ultraviolet wavelength there is a threshold laser intensity (estimated at ca. $2 \times 10^8 \mathrm{~W\,cm^{-2}}$ at 355 nm) below which no material ablation occurred. This effect and the ablation rate observed with excimer lasers has been shown to depend upon the absorption coefficient [9]. At any constant energy (intensity) above this threshold, the cut depth increased linearly with exposure time (Fig. 6).

3.2. Laser cutting of diamond fibre-reinforced titanium-alloy composite

A polished section normal to the fibre axis in a Ti–6Al-4V/tungsten cored diamond fibre composite is shown in Fig. 8a. The rough diamond surface caused by mechanical abrasive damage is shown in Fig. 8b. The corresponding surface of a laser-cut section through the same composite is shown in Fig. 9a. Although the laser-cut surface was not planar on a macroscopic scale, locally the surface was smooth, for example in the titanium alloy matrix at X and across the titanium diamond–tungsten phases (AB in Fig. 9b). The smooth surface and lack of surface damage is revealed by the sharp edges around the residual pore present in the titanium-alloy matrix at C. The cut areas away from the ablation front became coated with a titanium deposit as shown at D in Fig. 8a, b.

4. Discussion

Compared with alternative methods, laser processing is particularly attractive for cutting and polishing and profiling diamond fibres. With the wavelengths used to date, CVD diamond ablates significantly faster than the tungsten cores, but slower than the SiC cores. Neither of the lasers available had the ideal spatial homogeneity required for optimum fibre processing.

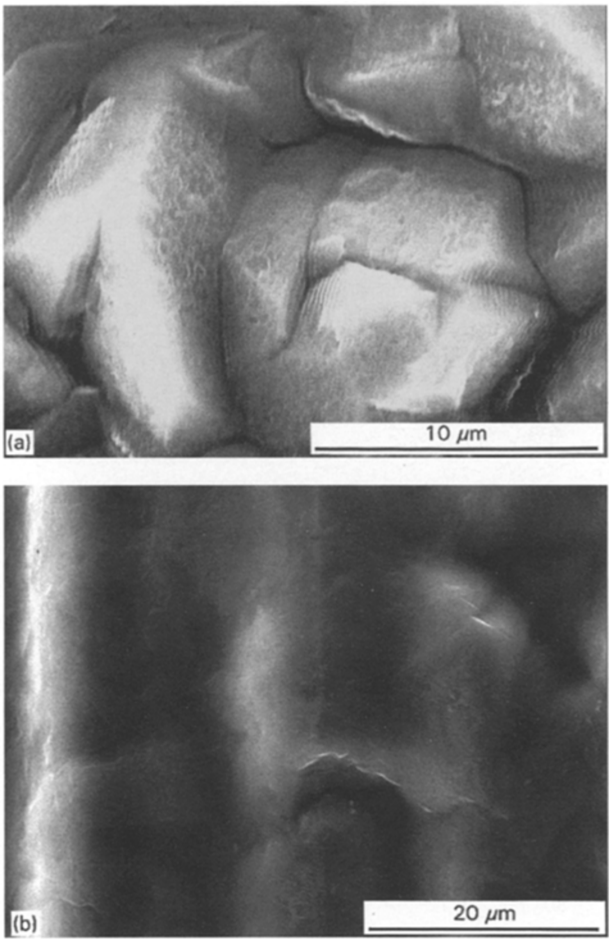

Figure 7 The smoothing effect of laser irradiation on surface diamond facets: (a) initial smoothing, and (b) almost complete smoothing.

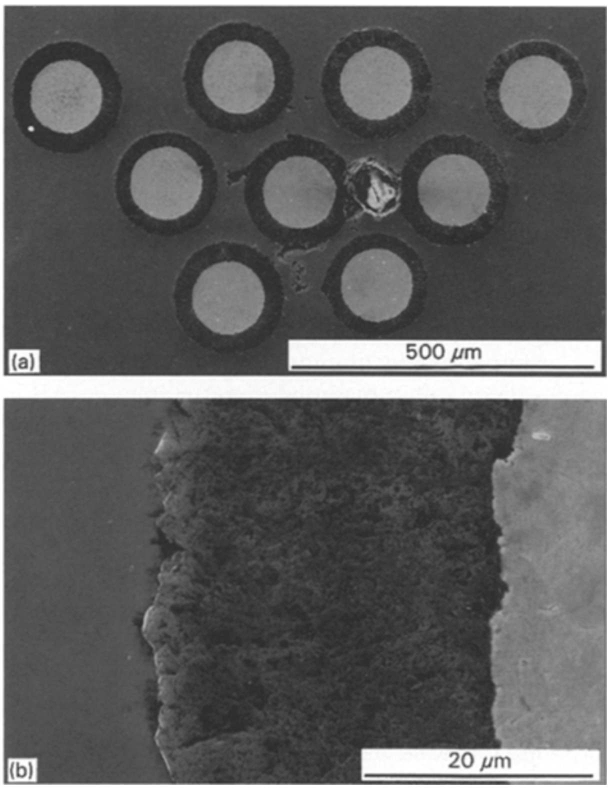

Figure 8 Scanning electron micrograph of Ti–6Al–4V/tungsten cored diamond fibre composite: (a) polished section normal to fibre axis, (b) rough abraded diamond surface in the polished section.

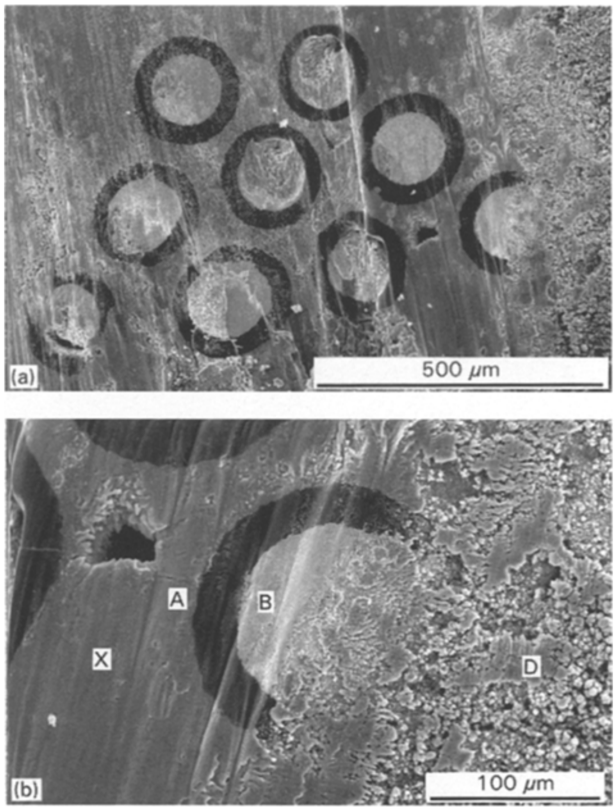

Figure 9 (a) Laser-cut section of composite shown in Fig. 8a, titanium deposited at D from the ablation front, (b) smooth areas extending across titanium–diamond–tungsten phases. Titanium deposited at D from the ablation front.

Studies of cut depth as a function of laser fluence, were also complicated by the fact that the spatial distribution of the beam profile is dependent on the laser output energy. Faster cutting rates are expected using the fourth harmonic (266 nm) further into the ultraviolet of a Nd–YAG laser equipped with gaussian optics or with an excimer laser operating at a photon energy above the band gap of diamond.

There are a number of other factors that can affect the ablation rate of fibres. As the grain size of CVD diamond increases with thickness, this will decrease the absorption coefficient [7] and increase thermal conductivity [13]. With fibres, the angle of incidence, a, of the laser beam changes across the fibre and this can significantly affect the ablation rate [12] and surface roughness [14]. For example, using an excimer laser on a flat deposit the surface roughness decreased from $R_a = 0.65$–0.8 μm for the as-deposited diamond to 0.38 μm ($a = 0°$) and to 0.15 μm ($a = 75°$–$80°$), with a corresponding decrease in the etching depth [14]. A chemical factor may also arise with low-power continuous lasers, when etching and polishing of the diamond occurs in oxygen but not in argon or vacuum [7].

The results show that diamond fibres embedded in a reactive metal such as titanium alloy may also be cut with a smoother cut surface than is obtained with a mechanical method. However, as with mechanical cuts, the greater thermal conduction of the diamond may lead to a greater heat-affected zone for these types of composite.

5. Conclusion

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. This could allow greater flexibility in the design of both solid and hollow diamond fibres and composites based on the fibres.

Acknowledgements

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