ENHANCED CUTTING OF POLYCRYSTALLINE DIAMOND WITH A Q-SWITCHED DIODE PUMPED SOLID STATE LASER

Paper #202

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Abstract

In this paper a progressive empirical study is conducted refining the laser cutting of Polycrystalline Diamond (PCD) as ongoing work.

PCD is one of the hardest substances known and is used extensively in cutting tools for non-ferrous materials. It is extremely difficult to cut by conventional means and the current incumbent technology, Electro-Discharge Machining (EDM), is relatively slow and has some serious drawbacks in terms of tool wear, unidirectional cutting and post processing. The PCD is extremely hard but brittle and so is typically mounted on Tungsten Carbide (WC) in the form of a laminar disk. Cutting this laminar structure creates additional challenges because the materials have dissimilar properties.

In previous work the authors have successfully demonstrated and modelled rapid laser cutting and drilling of PCD using high average power Q-switched diode pumped solid-state lasers. In this paper the cutting process is refined empirically to improve cut edge quality, reduce surface dross and create complex shapes whilst still achieving a comparatively high cutting velocity.

Introduction

Recent advances in industrial diode pumped solid state lasers (DPSSLs) have resulted in new possibilities for materials processing applications involving super hard materials such as polycrystalline diamond (PCD) and tungsten carbide (WC). This new class of DPSSL combines high average power, nanosecond pulse widths and superior beam quality to achieve new operating conditions and processing results. DPSSLs offer a combination of high efficiency, rugged construction and long lifetime. This makes them a very attractive option to industries seeking an advantage in cutting edge manufacturing on both the macro and micro scale [1].

PCD is a synthetic, extremely tough, mass of randomly orientated diamond particles in a metal matrix. It is produced by sintering together selected diamond particles at high pressure and temperature. The sintering process is rigidly controlled within the diamond stable region and an extremely hard and abrasion resistant structure is produced.

Polycrystalline diamond cutting tool blanks can be regarded as a composite material that combines the hardness abrasion resistance and thermal conductivity of diamond with the toughness of WC [2]. These properties are best utilised in cutting tools for machining a wide variety of materials as well as in wear part applications, where they contribute to improved tool lifetime and offer additional technological advantages such as process reliability and more accurate machining tolerances.

PCD cutting tools are typically used to process non-ferrous metals, wood and rubber [3]. The PCD blanks are cut to shape and brazed into individual holders which are assembled into a cutting tool, often with multiple PCD cutting teeth per tool. As shown in Table 1, PCD has good compressive strength and heat conductivity. The hardness of PCD is inferior only to that of single crystal diamond [3]. The wear resistance of PCD cutting tools has been shown to be superior to both cemented carbide and high speed steel (HSS), making it an outstanding choice for cutting tools.

Previous work developed a model of the milling process for the constituent materials of the PCD cutting tool blank [4]. The model produced good results for WC but not for diamond. This paper considers why this is the case and modifies the model to incorporate the changing material properties of diamond during the material removal process. The paper continues with an assessment of the laser cutting described in previous work and identifies several undesirable features and describes developments in the laser cutting process that can remove these unwanted effects.

Table 1: Comparison of material properties of polycrystalline diamond, tungsten carbide and stainless steel [2] [3] [5].

	Polycrystalline Diamond	Tungsten Carbide	Stainless Steel Grade 316
Density [g cm^{-3}]	3 to 4 †	16	8
Thermal Conductivity [Wm^{-1}K^{-1}]	540	100	16
Modulus of Elasticity [GPa]	749 to 953 †	680	193
Compressive Yield Stress [MPa]	1900 to 6900 †	2683	205
Vickers Hardness [kg mm^{-2}]	5098	1730	228
Melting Point [K]	1530††	2850	1400

† These values depend on the grade of PCD
†† This is complex since PCD is a composite material

Milling Trials

Laser milling characteristics using this type of laser for the constituent materials of PCD has been previously analysed [4]. A model of the laser milling process was developed and the experimental and modelled results were compared.

Laser Milling of Tungsten Carbide

A laser milling model was developed that used the simplified assumption that each laser pulse acts in two stages : a melting stage where the surface of the work-piece is raised to the vaporisation temperature, followed by a material removal stage where vaporisation occurs in a constant controlled manner [6]. This is illustrated in Figure 1. Using initial conditions of the material characteristics shown in Table 2 and laser pulse characteristics taken from experimental trials, the model initially calculates the duration of the melting stage and then determines the material removed by the remainder of the pulse, leading to a predicted removal rate.

In the case of tungsten carbide the modelled and experimental results showed a good correlation and the model was used to explain and predict how variations in laser settings (pulse repetition frequency, pulse width and pulse irradiance) could affect the volume of removed material.

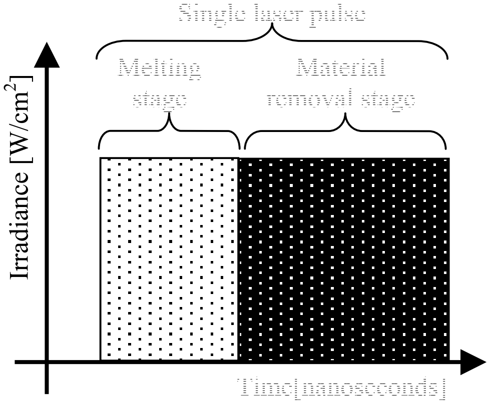

Figure 1 : The representation of a laser pulse for the milling model.

Table 2: Material characteristics required for modelling of laser milling process.

Characteristic	**Units**
Thermal Conductivity	W m^{-1} K^{-1}
Density	g cm^{-3}
Heat Capacity	J kg^{-1} K^{-1}
Vaporisation temperature	K
Specific heat of vaporization	kJ kg^{-1}
Reflectivity of target surface	%

Laser Milling of Polycrystalline Diamond

In the case of polycrystalline diamond, the above model showed a poor correlation between modelled and experimental results, so it could not be used for further analysis of the milling process for diamond. It was clear that the present model would need further development. This configuration of the model has been applied to many metallic and non-metallic materials with good results so the basic function of the model appeared to be sound [6]. It was suspected that the material properties of the diamond during the ablation process were not being properly represented within the present model, and so further analysis of the material characteristics of polycrystalline diamond was needed.

PCD is composed of many diamond particles bonded together with a cobalt binding agent. In order to apply the laser-milling model to this material, a set of material properties have to be determined, but in the case of PCD this becomes difficult because it is a composite material. For the purposes of simplifying the model an assumption was used that PCD comprises only of diamond. This is not such a gross assumption given that the cobalt binder is a small percentage of the overall PCD weight [2].

At relatively low pressure, diamond is metastable - kinetically stable but not thermodynamically stable [7][8]. Since both diamond and graphite are different lattice arrangements of carbon, the thermodynamic and kinetic relationship between them is shown in the phase diagram for carbon, which is shown in Figure 2. Graphite is the thermodynamically preferred (minimum energy) state rather than diamond, but the activation energy needed for the conversion from diamond to graphite is very high (728 kJ/mol) so at ambient temperature and pressure this conversion is extremely slow. This conversion process starts to be noticeable at around 1000°C [9]. Note that in Figure 2 the diamond used in PCD cutting tool blanks was manufactured synthetically using the Catalytic HPHT (High Pressure High Temperature) synthesis method.

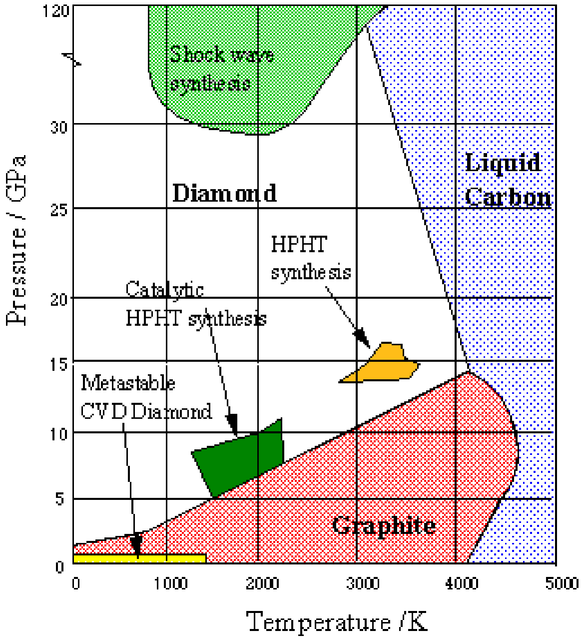

Figure 2 : Phase diagram for carbon [7]

The material properties for diamond and graphite are shown in Table 3. Note that there are significant differences between the two materials, particularly thermal conductivity and density.

Table 3: PCD modelling parameters [9] [10]

Characteristic	Units	Diamond	Graphite
Thermal Conductivity	$Wm^{-1} K^{-1}$	540	24 to 85[a]
Density	$g\ cm^{-3}$	4.13	2.25
Heat Capacity	$J\ kg^{-1} K^{-1}$	0.512	0.7
Vaporisation temperature	K	n/a	5100
Specific heat of vaporization	$kJ\ kg^{-1}$	n/a	59600

[a] Note that this depends on the crystal lattice orientation and has a range of typical values.

The conversion of diamond into graphite has been incorporated into the milling model, so what was previously the melting stage is divided into two subsections as shown in Figure 3, so that overall each laser pulse is considered to have three distinct stages, as described below.

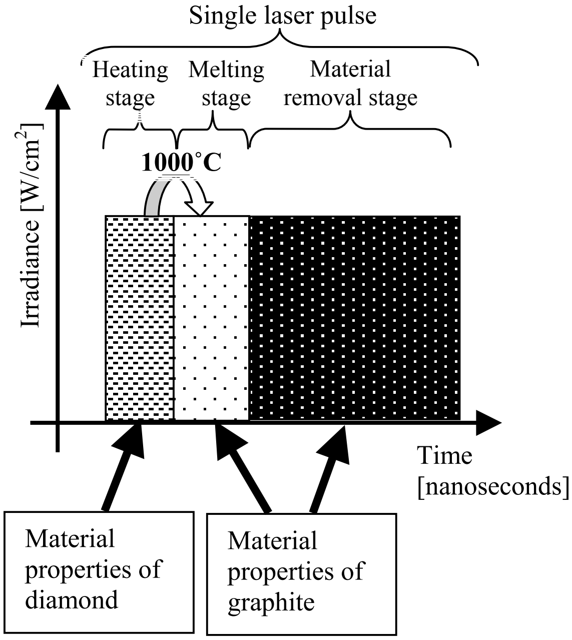

Figure 3: The representation of a laser pulse for the revised diamond milling model.

Diamond Heating Stage: The target material is initially diamond at ambient temperature. The incident laser beam is absorbed and the surface temperature starts to rise at a rate defined by the material characteristics of diamond. When the temperature reaches 1000°C conversion of diamond into graphite commences, which, for the sake of this simplified model was considered to be instantaneous.

Graphite Melting Stage: The target has now converted to graphite and takes on the material characteristics as shown in Table 3. The temperature continues to rise and the graphite firstly melts and then reaches it's vaporisation point.

Material Removal Stage: For the remainder of the laser pulse, material is vaporised from the target at a constant rate as governed by the material characteristics of graphite.

This "diamond milling model" is implemented in a similar way to the original model. The duration of both the Diamond Heating Stage and the Graphite Melting Stage can be calculated, given the initial conditions of the material characteristics and the laser pulse characteristics [11]. The Material Removal Stage takes the remainder of the pulse duration. The velocity of material removal is calculated, which leads to the calculation of a volume removed per pulse given the laser beam focal diameter. Finally, multiplying the volume removed per pulse by the laser pulse repetition rate gives an overall material removal rate.

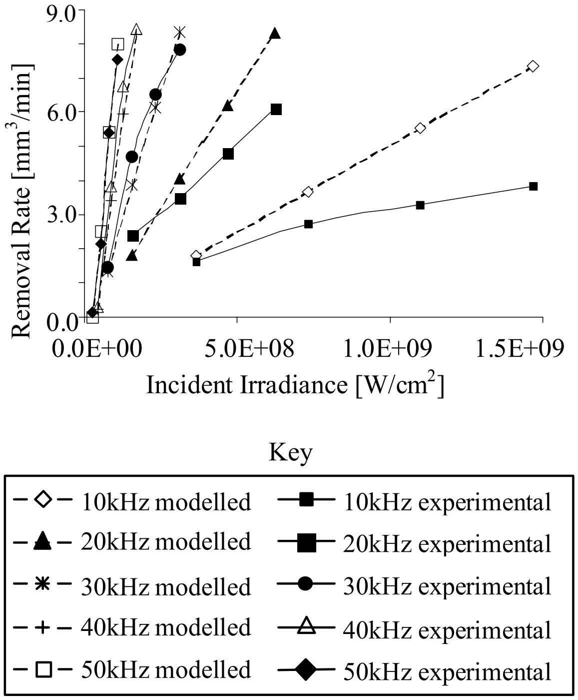

Figure 4 : Experimental and modelled laser milling results for polycrystalline diamond.

The results of the modelling work for PCD are reproduced in Figure 4 alongside the experimental results. For higher repetition rates there is a good correlation between modelled and experimental results, However, at lower repetition rates there is a difference. This could be due to over simplification of the model, since it doesn't take into account any effects of the laser pulse shock wave (and the consequent change in pressure) or any other laser pulse effect, particularly laser-induced absorption waves which can block the delivery of the laser beam to the target, particularly at high pulse irradiances which could occur at lower repetition rates [11][12].

Laser Cutting PCD

Laser cutting of PCD cutting tool blanks has been previously investigated [5]. However, the work reported to date has described only basic laser cutting that had several undesirable features. This section of the paper investigates the chemical reaction that takes place during the cutting process and then looks at ways to improve the cut quality.

The Reactive Fusion Laser Cutting Mechanism for PCD

The laser cutting process uses a co-axial laser beam and oxygen gas jet to cut through the PCD composite material. Both diamond and tungsten carbide will combust in oxygen, and both reactions are exothermic [8] [13]. For the case of diamond, the chemical equation of the reaction is shown in Equation 1, and an energy diagram for the reaction is shown in Figure 5 [8].

$$C_{\text{diamond}} + O_2 \rightarrow CO_2 + \text{heat}$$

$$\Delta H = -2.9\text{kJ/mol} \qquad (1)$$

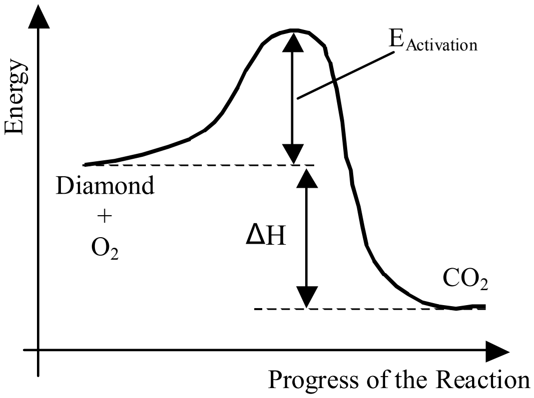

Figure 5 : Energy Diagram for diamond combustion.

Note that although the overall reaction is exothermic, there is a transition stage within the reaction that requires an input of energy, which is known as the Activation Energy. In the case of diamond this is very high (~728 kJ/mol), however the enthalpy of the reaction released by the reaction, ΔH, is quite small.

Likewise if the diamond has converted into graphite before combustion occurs there will be a similar reaction but the enthalpy of combustion of graphite is much bigger (394 kJ/mol)[13].

For the case of tungsten carbide the chemical equation of the reaction is shown in Equation 2 [13]. Note that this equation shows the reaction of multiple moles so the enthalpy of reaction is large. The combustion of WC also has a transition stage requiring an energy input prior to energy release.

$$2WC + 5O_2 \rightarrow 2WO_3 + 2CO_2$$

$$\Delta H = -2391.6 \text{ kJ} \qquad (2)$$

The laser cutting process is enabled when the high irradiance, high repetition rate laser pulses provide the Activation Energy to initiate the combustion of both materials within the region of the oxygen assist gas. These exothermic reactions become another heat source, further adding to the cutting speed. Furthermore, laser milling trials have shown that the laser pulses alone are capable of vaporising both materials, so the combustion reaction could be occurring within the gaseous form of these materials rather than being a surface based reaction. This would have large implications on the rate of reaction, and the overall cutting speed.

Laser Cutting Improvements

Laser cutting of PCD cutting tool blanks has been previously investigated and published [5]. However, the work reported to date has described only basic laser cutting, and further improvements were necessary to produce a part ready for use as a cutting tool. Figure 6 shows the laser cut face of work previously reported. This figure shows a laser cut edge cut through 1.6mm thick PCD at a cutting speed of 24mm/min. The darker material on the left is the diamond, whilst the lighter material on the right is WC. Note that the edge of the diamond on the left (i.e. furthest from the tungsten carbide) is the cutting edge and must be cut as straight and sharp as possible. The figure shows a generally good cut, however for the part to be used as a cutting tool a very high quality cut is required, therefore the following effects, as described below, must be eliminated :

Striations. These are caused by the reactive fusion laser cutting process [14]. They are a serious problem because they degrade the straightness of the PCD cutting edge.

Dross formation. The PCD cutting tools are brazed into a holder prior to use. Dross can interfere with the brazing process, resulting in a weaker joint.

Step at the diamond-WC interface. This introduces a weakness at the interface between the two materials and could be a source of premature failure of the cutting tool.

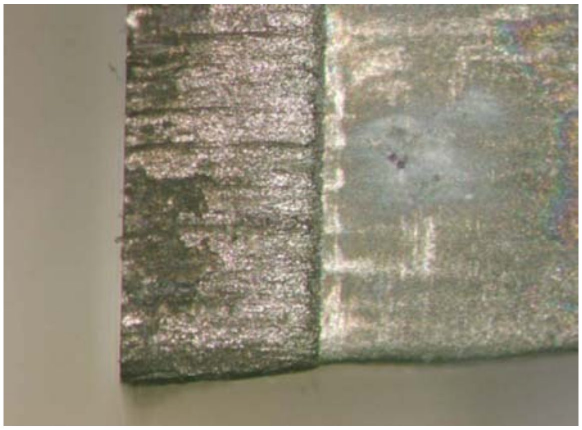

Figure 6 : Laser cut edge quality from earlier work

Laser cutting Trials

A set of trials were performed to investigate ways of improving the laser edge of the PCD, and in particular methods of obtaining a sharp, straight cutting edge.

The PCD processing trials used a high power Starlase AO4 Nd:YAG Q-switched DPSSL at the fundamental wavelength 1064 nm. This pulsed laser offers average powers up to 420 W at a range of repetition rates and pulse durations between 3 to 50 kHz and 20 to 200 ns respectively. The output beam power was varied using a proprietary attenuator unit, collimated with a Galilean telescope and then directed into an Anorad XYZ motion stage. This stage moved the target in the XY directions and the focussing head in the Z direction. The Anorad system is granite mounted and has linear drives capable of a top speed of 2 m/s with an accuracy of +/-1 µm over an XY travel of 450 x 450 mm. The laser beam was focussed with a lens of focal length 149 mm which produced at best focus a Ø200 µm spot. The cutting head allowed a co-axial gas jet to be used to assist the cutting process which could be either compressed air, oxygen or nitrogen and could be supplied to the work-piece at pressures up to 10 Bar.

Using the best settings found from previous work, (laser repetition rate 45 kHz, output power 300 W, pulse energy 6.7 mJ, irradiance 120 MW/cm^2 and assist gas 8 Bar oxygen), a set of trials were performed but nothing could be done to completely remove the striations. Up to this point all of the cutting trials had been performed with the WC side uppermost (i.e. closest to the nozzle) with best focus positioned halfway through the WC.

A new approach was tried by turning over the cutting tool blank so that the PCD side was closest to the cutting nozzle. This meant that the assist gas would pass through the PCD layer in order to reach the WC, preventing any WC dross being deposited on the PCD. The best focus position was maintained in the same position in the material (i.e. halfway through the WC). This method produced a good result, eliminating the striations on the PCD and removing the step at the interface between the PCD and WC. However there was still a large amount of dross on the cut-face.

A polishing phase was introduced in the form of a second cutting pass. It used the same cut path as the first pass and trials showed that the best results were obtained with different laser settings and gas pressure for the polishing phase using the following procedure:

<u>Basic Cutting Pass</u>: Three sides (out of four) of the component are cut out using the previously developed settings (laser pulse repetition frequency 45 kHz, output power 300 W, pulse energy 6.7 mJ, irradiance 120 MW/cm^2 and assist gas 8 Bar oxygen) at a speed of up to 20 mm/min.

<u>Polishing Pass</u>: The same cutting path is repeated using the polishing settings (laser pulse repetition frequency 10 kHz, output power 300 W, pulse energy 30 mJ, irradiance 2 GW/cm^2 and assist gas 2 Bar oxygen) with a speed of up to 20 mm/min.

<u>Final Cutting Pass</u>: The last side of the component is cut out using the settings of the Basic Cutting Pass. Note that the last side of the component cannot be cut out earlier (i.e. during the Basic Cutting Phase) because the part would drop out of the cutting tool blank before being polished.

This method gives a large improvement to the quality of the cutting edge, significantly reducing the PCD striations and giving a straight, sharp edge. The PCD layer was seen to be dross free, and there was no discontinuity between the PCD and WC layers. The average speed using this cutting method is around 10mm/min, however the process could be speeded up by only polishing the cutting edge and not the other sides.

Figures 7, 8 and 9 show three views of a laser cut sample, which can be compared to the EDM cutting edge that is shown in Figure 10. Note that striations are still present on the WC layer, but since the layer is dross free the striations may actually be useful as they represent a larger surface area for the brazing process which is used to attach the PCD to the cutting tool.

Figure 10 shows a cutting edge produced by EDM. Note that there is little difference between this edge and the laser-cut edge, however the laser-cut edge was produced at around twice the speed.

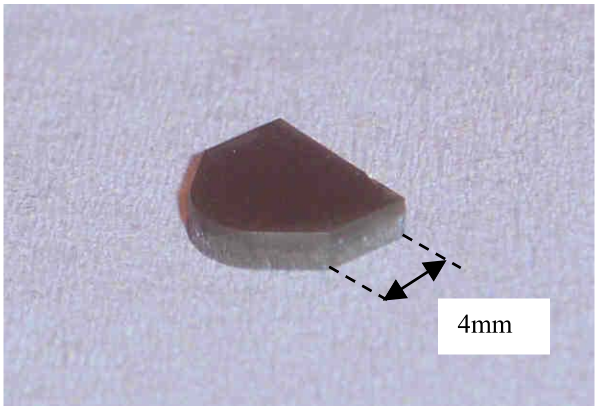

Figure 7: Laser cut sample.

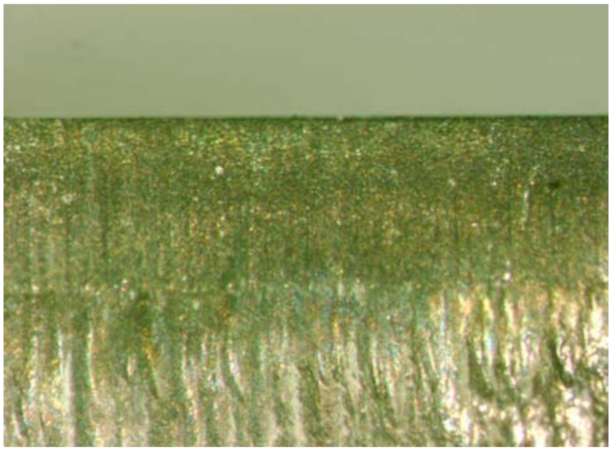

Figure 8 : Laser polished cutting edge
(side view, mag x5)

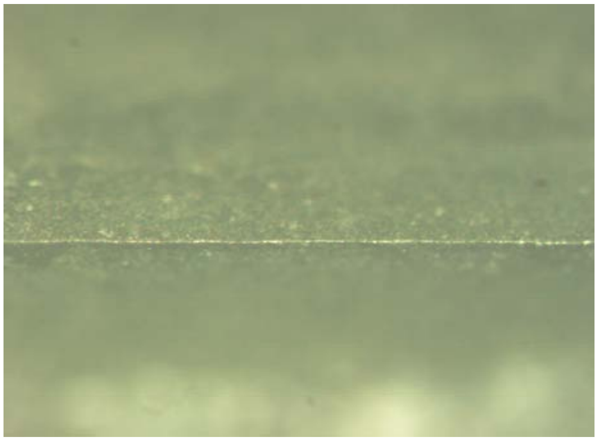

Figure 9 : Laser polished cutting edge
(cutting edge viewed at 45°, mag x5)

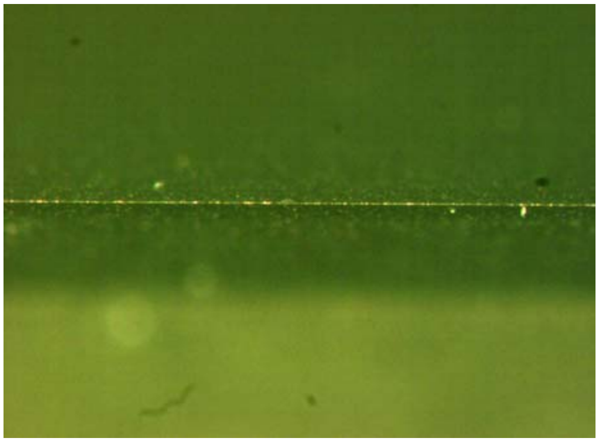

Figure 10 : Cutting edge made by EDM
(viewed at 45°, mag x5)

Conclusions

The polycrystalline milling model has been improved through a better understanding of the material properties of diamond at elevated temperatures. Diamond is metastable and upon heating above 1000°C undergoes a conversion to graphite. The modelled and experimental results show a much closer fit for higher laser pulse repetition rates.

Laser cutting of polycrystalline diamond cutting tool blanks has been developed and improved to the point where good quality cuts can be made with a sharp and straight cutting edge. This has been achieved through the introduction of a laser polishing phase and by processing the material from the opposite side to earlier trials.

Laser cutting has the potential to be much more versatile in the manufacture of cutting tools as it has many advantages, including reduced access requirements, no lubrication required, no tool wear and omnidirectional cutting capability. These advantages will allow the development of new PCD cutting tool designs.

Acknowledgement

The authors would like to thank the Powerlase Applications Team for their assistance with this paper. The experimental work of this paper was performed using the Starlase range of lasers, which is manufactured exclusively by Powerlase Ltd, UK.

Note

A Patent has been applied for the techniques described in this paper.

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