High Speed Processing Applications of High Average Power Diode Pumped Solid State Lasers

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Abstract

Investigations are reported in a number of applications areas for high average power, nanosecond pulsed Diode-Pumped Solid-State Lasers operating at the fundamental wavelength of 1064nm. This includes cutting and polishing polycrystalline diamond and high-speed milling of industrial materials such as aluminium and steels. The results are investigated with regard to processing these materials at superior rates by comparison with conventional technologies. The effects of varying laser parameters are reported with respect to the inter-related phenomena of plasma formation, dimensional accuracy, material removal, dross formation and processed material properties.

Keywords: diode-pumped, pulsed, nanosecond, aluminium, stainless steel, polycrystalline diamond, high speed, laser milling

1 Introduction

Recent advances in industrial diode pumped solid state lasers (DPSSLs) have resulted in new possibilities for materials processing applications. This new class of pulsed DPSSL combines high average powers, nanosecond pulse widths and superior beam quality to achieve new operating conditions and processing results. In addition, DPSSLs also offer rugged construction and long diode lifetime, making them a very attractive option to industries seeking an advantage in cutting edge manufacturing on both the macro and micro scale [1] [2].

Two applications that have been significantly improved by the use of this type of laser are considered – high speed laser milling of metals and laser processing of polycrystalline diamond. Both applications are considered separately in the next sections.

2 High Speed Milling

2.1 Laser ablation

Q-switched DPSS lasers are particularly suited to laser milling since each nanosecond laser pulse can easily achieve the power density required to cause ablation of the target material [3][4]. The high repetition rate of this type of laser allows accurate, controlled material removal at rates which are industrially attractive. The ablation process forms the basis of many industrial applications and a subset of these are high speed milling applications. High speed laser milling has been developed from in-house laser milling trials and certain parameters have been identified for optimisation.

2.2 Milling trials

Laser milling trials were performed on samples of aluminium grade NS4 and stainless steel grade 316. The results of these trials are presented in the following section.

The laser milling tests used a Starlase AO2 Nd:YAG Q-switched DPSSL at the fundamental wavelength of 1064 nm. This pulsed laser offers average powers up to 220 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 is varied using a proprietary attenuator unit and then collimated with a Galilean telescope and directed into a galvanometric scanner (ScanLab HurryScan25). During the course of the tests the scanner was fitted with an 80 mm focal length f-theta telecentric objective lens with a working target area of 25x25 mm which produced at best focus a Ø160µm focal spot. All of the processing work was performed in air at standard atmospheric conditions and no gas assist was used.

Samples were analysed using a Nikon LM1500 optical microscope with a PC interface via a 12 megapixel camera into Lucia G software. This software allowed microscopic measurements to be made against a Nikon standard. Depth measurements were made using a Mitutoyo dial gauge.

The ablation characteristics of both materials were investigated by a matrix of tests which varied specific laser parameters and measured material removal rates in a 2 mm by 2 mm area. Different pulse repetition rates were selected and the output power was adjusted using the variable optical attenuator to produce a range of operating intensities. The maximum laser pulse characteristics for varying laser repetition rates for both sets of milling trials is shown in Table 1. For each test in the matrix the laser pulse width, irradiance, and ablation time were recorded. Ablation depth measurements were used to calculate the volume of material removed and removal rate.

***Table 1** : Laser pulse characteristics for milling trials*

Laser Rep. Rate [kHz]	Pulse Irradiance [W/cm^2]	Output Power [W]	Pulse Energy [mJ]	Pulse Width [nsecs]
10	1.5 x 10^9	179	18	59
20	5.1 x 10^8	192	9.6	94
30	2.4 x 10^8	201	6.7	137
40	1.5 x 10^8	214	5.4	172
50	1.1 x 10^8	222	4.4	204

2.3 Laser Milling Results for Aluminium

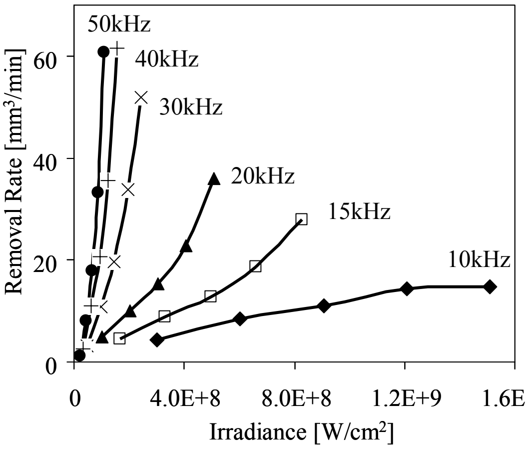

***Figure 1** : Removal rate of aluminium alloy as a function of pulse irradiance and laser pulse repetition rate.*

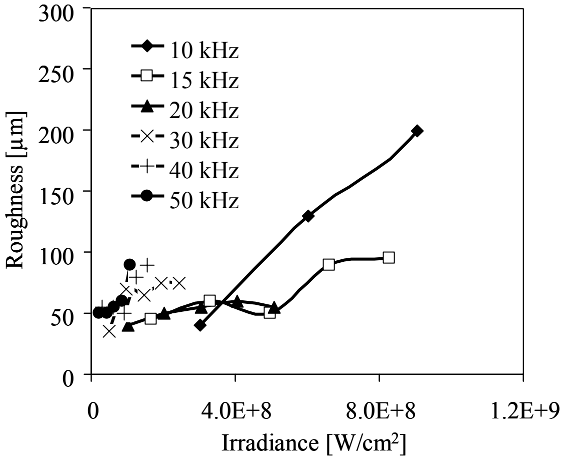

***Figure 2** : Roughness measurements for aluminium*

Figure 1 shows the results of the aluminium laser milling trials. It can be seen that as the repetition rate increases, the removal significantly increases. One of the measures of the quality of the laser milling is the variation in base depth, which will be referred to in this paper as roughness and this is shown in Figure 2. It can be seen from this figure that for low repetition rates the roughness is much larger, indicating low quality milling.

2.4 Laser Milling Results for Stainless Steel

Figure 3 shows the results of the stainless steel laser milling trials. It shows that as the laser repetition rate increases the removal rate also increases. Figure 4 shows the roughness measurements for these tests, and it can be seen that although the roughness levels are higher, the general trends are the same as for aluminium, i.e. high levels of roughness at lower repetition rates, minimising in the mid-range and rising slightly at higher repetition rates.

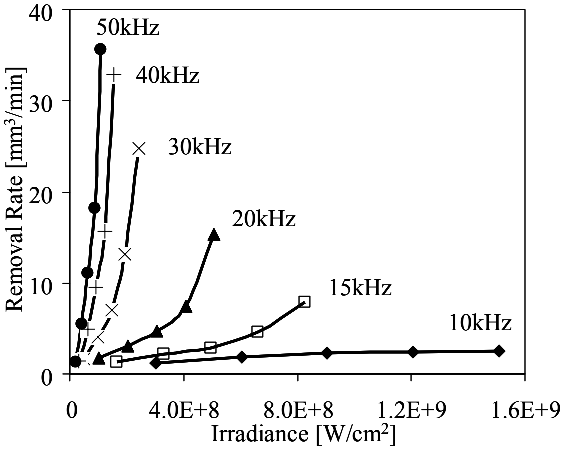

***Figure 3** : Removal rate of stainless steel as a function of pulse irradiance and laser pulse repetition rate.*

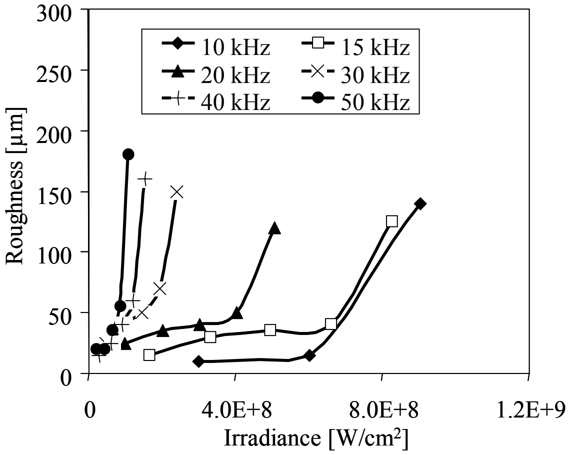

***Figure 4** : Roughness measurements for stainless steel*

2.5 High Speed Laser Milling

The laser milling process has been optimised, maximising the removal speed whilst maintaining a quality level that is sufficient for the applications in hand. This has been achieved by identifying and optimising the following parameters :

Process Efficiency : The ablation process is much more effective at higher repetition rates, and this is shown in Table 2. This is valid for both aluminium and stainless steel.

Table 2 *: Comparison of Removal Efficiency*

Laser Rep Rate [kHz]	Laser Output Power [%]	Removal Rate, Aluminium [%]	Removal Rate, Stainless Steel [%]
10	100	100	100
20	107	244	615
30	112	352	991
40	120	417	1313
50	124	412	1425

Focal Spot Size : Within limits, smaller focal spot sizes produce a higher removal rate. A comparison was made between two scanner objective lenses, an 80mm and a 163mm focal length. The rest of the system was kept the same, and the same pulse overlap was used for both lenses. It was found that that the 80mm FL lens produced a removal rate up to 250 % higher than for the 163mm lens. This is with the condition that the irradiance was kept below the plasma blocking threshold, where laser-induced absorption waves block the delivery of the beam [3][5]. This improvement is probably caused by the reduction of thermal losses into the workpiece due to the reduction in focal spot diameter.

Pulse Overlap : Pulse overlap can be considered in 2 dimensions : pulse to pulse overlap, where each pulse overlays the previous pulse by a certain amount, and scan-line overlap, where lines of pulses (each pulse having a fixed pulse to pulse overlap) overlays adjacent lines of pulses by a certain amount. Note that the pulse to pulse overlap governs the amount of residual heat left in the material between pulses, thus the optimum pulse to pulse overlap tends to be material specific. Experimental milling trials have shown that the optimal pulse to pulse overlap is usually in the region 60 to 90 %, whereas the optimal scan-line overlap is much lower, usually in the region 20 to 50 %.

Scan Path : Optimising the scan path creates the least number of mirror movements which means that there are more laser pulses in a given scan time, which results in a higher material removal rate.

2.6 Comparison to Other Milling Methods

High speed laser milling has many advantages over other milling methods in terms of the combination of speed, resolution and flexibility and the ability to process hard materials. There are many other milling methods, and the main ones are summarised below. Note that the milling methods listed here are based around some sort of mechanical contact with the workpiece, which causes tool wear resulting in dimensional instability and increased operating costs as the tools are replaced.

Mechanical milling : This method can achieve very high milling rates, but only with a large milling tool where the resolution is limited. Small milling tools are available but they are expensive, have a low milling rate and are prone to breakage, especially when milling hard materials such as stainless steel [6].

EDM milling : EDM Milling is the process in which complex shapes are machined using a simple shaped electrode. This method produces very high quality parts but is very slow, making it unsuitable for high speed work.

Stamping : This method involves the use of a die which is pressed into the workpiece to create an impression. There is no material removed from the substrate and therefore damage due to the large forces applied can be considerable. This method has a limited flexibility due to the requirement of a die for every pressed shape, but it can be very fast.

Ultrasonic Machining : This method uses a tool which is oscillated at a frequency of about 20 kHz. The milling process uses an abrasive grit in the gap between the tool and the workpiece to impact on the work surface, thereby machining the workpiece. This method produces good quality work but has a very low machining rate.

2.7 Applications of Laser Milling

A set of applications have been identified that can be achieved with high speed laser milling. These are applications that have the characteristics described in Table 4.

Table 3 *: Characteristics of High Speed Milling Applications*

Parameter	Comment
Removal Rate	As high as possible whilst maintaining a reasonable base roughness
Depth	Typically up to 1mm deep. Deeper work possible with active focus control
Quality	Some surface dross allowed. Base variation 50 to 100µm (or 10% of overall depth). Generally quality level sufficient for application in order to maximise removal rate.
Resolution	Comparable with focal spot size, typically Ø 200 µm

High speed laser milling has many industrial applications in a wide range of areas. There are many reasons for using this technology, including increased speed, increased security, reduced damage to substrate material and improvement to production processes. Possible applications include not only milling 3D shapes but also barcodes and serial numbers. A typical application is shown in Figure 5, which is a sample identification plate. This plate has approximately 90mm^3 of material removed during the milling process, which took 2 minutes to engrave. A variety of depths are achieved between 200 and 800 µm, which can be seen in the figure as a variation in the shade of the milled areas.

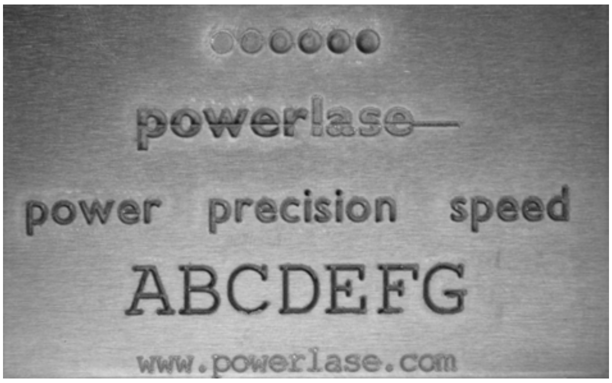

Figure 5 *: Example of High Speed Laser Engraving*

3 Polycrystalline Diamond

3.1 Laser Cutting

Polycrystalline diamond (PCD) 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 tungsten carbide (WC) [7]. 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 [8]. 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. During the life of the tool the cutting edges wear down (although at a slower rate than traditional cutting tools), which necessitates sharpening of the cutting edges of the PCD teeth. If this is not done then dimensional tolerances are increased and cutting quality is lowered. Therefore, laser processing of PCD cutting tool blanks has two applications: cutting the initial tool shape and maintaining the tool sharpness [9].

Laser cutting of PCD cutting tool blanks has been previously investigated and published by Powerlase [9]. However, the work reported to date has described only basic laser cutting and not parts that have sharp edges. Figure 6 shows the edge quality of work previously reported.

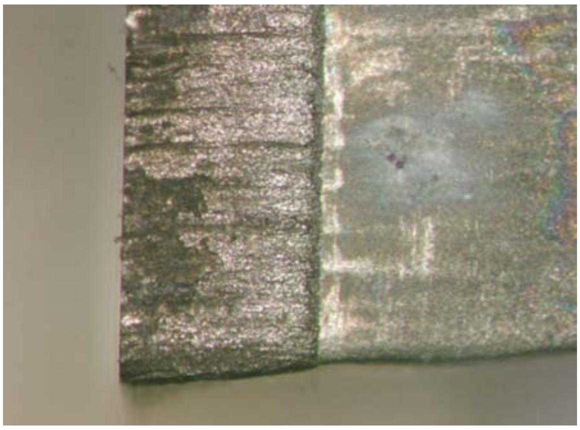

Figure 6 *: Edge quality from earlier work*

Figure 6 shows part of a laser cut edge cut through 1.6mm thick PCD at 24mm/min. The central darker material is the PCD, whilst the whiter material on the right is WC. Note that the edge of the PCD 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 but has some unwanted effects, as described below :

- **Striations.** These are caused by the reactive fusion laser cutting process [4]. They are a serious problem because they degrade the straightness of the 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 PCD-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.

3.2 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 of 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 Ø200µm 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 45kHz, output power 300W, pulse energy 6.7mJ, 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. The best focus position was maintained in the same position in the material (i.e. halfway through the WC). This meant that the assist gas would go through the PCD layer in order to reach the WC, so there is much less deposited on the PCD, leaving it mostly clean and dross free. This method gave a large improvement, significantly reducing the PCD striations and a straight, sharp edge is seen on the cutting edge. The PCD layer was seen to be dross free, and there was no discontinuity between the PCD and WC layers.

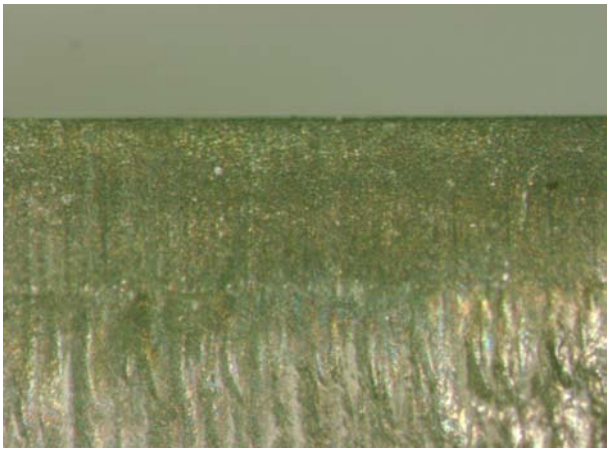

***Figure** 7 : Laser polished cutting edge (side view)*

***Figure 8 :** Laser polished cutting edge (cutting edge viewed at 45°)*

Figures 7 and 8 shows two views of a sample cut using this method. 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 to adhere to.

4 Conclusions

Q-switched DPSS lasers can be used to enhance many different applications, and this paper reports on two such applications.

High Speed Laser Milling has been developed through the identification and optimisation of particular laser parameters that enable the process to operate at high removal rates. A set of applicable areas for industrial use have been indicated, and one application of this milling method has been shown.

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.

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.

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