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Cutting diamond tools using the Laser MicroJet® technology on a 5-axis machine

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Abstract

The Laser MicroJet® technology uses a water coupled ns-laser to cut various materials e.g. diamond, semiconductors, ceramics and metals. The laser light is guided to the workpiece by the water jet and the material is cut by the laser radiation. This technology can thus cut the same materials as a dry laser. However, the Laser MicroJet® technology exhibits several advantages over dry laser cutting such as a parallel sided kerf, less heat damage due to the additional cooling of the water, no adjustment of the laser focus and higher kerf depth to kerf width aspect ratios. The cutting of ultra-hard diamond tool materials with this technology is now showing very promising results in terms of low surface roughness and high cutting speed. PCD, PcBN, and single crystal diamond tool materials, including those backed with cemented tungsten carbide, can all be cut and shaped with the Laser MicroJet®. Latest results show a surface roughness Ra for the PCD/PcBN region of the cut surfaces of < 0.3 µm and < 0.5 µm on the cemented carbide. The effective cutting speed on 2 mm thick, carbide backed PCD/PcBN is 5 mm/min. The cutting edge radius (i.e. sharpness) achieved is r < 10 µm for PcBN samples and r < 5 µm for PCD or CVD samples. For some applications, this level of edge sharpness will be more than adequate and finish grinding will not be necessary. This paper presents the first results cutting ultra-hard tooling materials on the 5-axis platform using the already well established Laser MicroJet® technology.

diamond tool cutting, Laser MicroJet, precision cutting, PCD, PCBN

1. Introduction

The Laser MicroJet® technology is already widely used in precision cutting of various materials. The markets addressed are the watch industry, gem and industrial diamond for diamond tools and the semiconductor industry. A rather new application is drilling of cooling holes into turbine blades.

The Laser MicroJet® technology uses a water coupled laser to cut the material. Lasers with a wavelength of 532 nm are usually employed since the absorption in the water is minimized to < 0.1 % per cm. To couple the laser into a water jet, the laser beam is focused on the entry aperture of the nozzle which is generating the water jet. The nozzle size can range from 30-125 µm. For diamond tool cutting such as PCD or PcBN a

40 µm or 50 µm diameter nozzle is usually used. The so-called break-up length, which is the length over which the water jet is stable, is usually approximately 1000 times the size of the nozzle diameter and therefore the maximum theoretically achievable aspect ratio is 1000. However, the achievable aspect ratio is also limited by the cutting process so that for very small cutting kerfs of 30 µm the aspect ratio is usually limited to < 100 depending on the material being cut. This is due to the absorption of the laser radiation in the material and also due to the ejection process of the water and debris from the kerf. Although the water helps significantly to remove the ablated debris compared to conventional dry laser cutting this process is restricted with very small kerf widths and the cutting process is perturbed so that cutting with small nozzle sizes becomes less efficient. However, small nozzle diameters are still used for applications such as watch parts cutting which need high precision and low roughness on the kerf.

The drilling of cooling holes into turbine blades and the cutting of diamond tools are examples where the workpiece must be orientated and manipulated in complex ways and this requires machines with 5 simultaneous axes. Results achieved on a 3-axis machine and the first results achieved on a 5-axis machine when cutting of ultra-hard, PCD tools are presented below.

2. Experimental setup

The machines used for cutting with the Laser MicroJet® technology consists of several components specially developed for this technology. A machine consists of following key parts:

1. Optical head
2. Water treatment and water pump
3. Laser source
4. Axes system

The components are described in more detail in the following:

1. Optical head:

A special optical setup couples the laser into the water jet. A photo of this setup is shown in Figure 1.

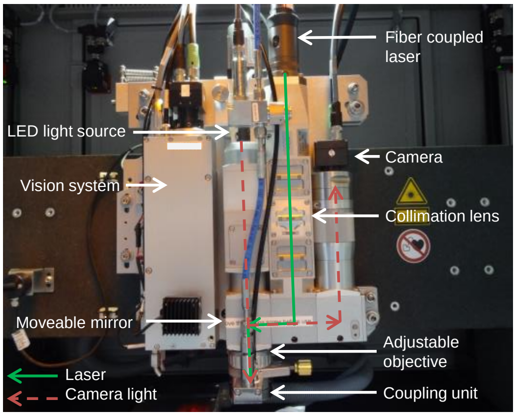


Figure 1: Setup of the optical head which couples the laser into the water jet.

The laser which diverges from the fiber is collimated by a collimation lens and then focused on the nozzle aperture which is generating the water jet. The laser is thus coupled into the water jet. To align the laser onto the nozzle orifice, two half transmittance mirrors and an LED allow observation of the nozzle aperture with a camera during a set-up procedure.

Figure 2 is a sketch illustrating how the laser couples into the water jet by focussing the laser on the nozzle aperture.

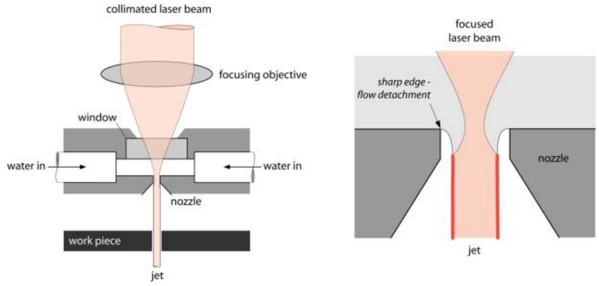


Figure 2: Sketch of the coupling of the laser into the water jet.

An important component of the optical head is the nozzle which creates the water jet. Nozzle diameters between 25 and 150 µm are used depending on the application. Because the water jet contracts, the jet diameter produced is about 80% of the nozzle diameter. On the material a stagnation point of the water jet leads to widening of the water jet. Therefore the kerf which can be achieved is slightly larger than the water jet itself. As a result the kerf width is about the size of the nozzle orifice.

2. Water treatment and water pump:

The requirements on the water quality are relatively high because any dust particle in the water jet can lead to scattering of the laser light. In addition, the water jet perfection may be disturbed if there are too many particles in the water jet. The water treatment consists of several particle filters, a degassing system and reverse osmosis purification. The water treatment and the water pump are very important components for the Laser MicroJet® technology and have been specially developed for this application as the process is very sensitive to the water quality. The water quality can be controlled by monitoring its resistivity and particle content.

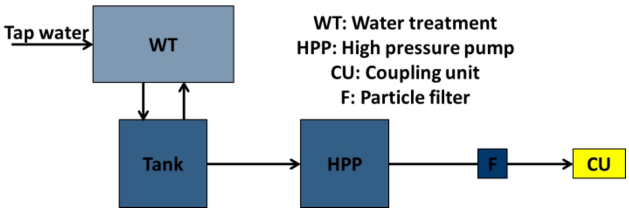


Figure 3: Sketch of water pump and water treatment.

3. Laser source:

The laser source is always chosen carefully for the application and the cutting requirements. Usually ns-pulsed lasers are used in the range of 1-500 ns. For applications that require high precision and high kerf quality shorter pulse length lasers are used. For industrial applications that require high production rates such as turbine blade drilling and diamond cutting, longer pulse widths and higher energy pulses are used. The laser light is delivered by an optical fiber to the optical head.

4. Axes system:

Usually, the optical head/water jet assembly is fixed and the part to be cut is moved with a suitable multi-axis system. The precision achieved is therefore a function of the precision of the axis system, the diameter of the nozzle orifice and the process parameters used. The axis system must be chosen carefully since most of the dimensional precision stems from this component. Several different machines with 2-axis X and Y tables, suitably adapted to the needs of different markets are available. A 2-axis system combined with a rotary axis for gem diamond cutting is also available. The precision of this type of axis system is ±

3 µm. The two most common machines are shown in Figure 4 left. Due to the demand from the industrial diamond tool market a 5-axis machine has now been developed at Synova for cutting the complex geometries required for diamond tools. A photo of the LCS50 machine with its associated water treatment unit is shown in Figure 4 right.

Figure 4: Photos of the laser cutting systems available of Synova.
Left: Laser cutting system (LCS) 300 with a X-Y capacity of 300 x 300 mm^2 suitable for most cutting applications.
Middle: Diamond cutting system (DCS) 150 for diamond cutting with a capacity of 150 x 150 mm and a rotary axis.
Right: Laser cutting system (LCS) 50 with a 50 x 50 x 50 mm^3 working zone and the laser and water pump cabinet next to it.

The design specification for the precision of the axis system on the LCS50 is ± 1 µm which is higher than the previous ± 3 µm found on 2 and 3 axis machines and is still under development. The Laser MicroJet© technology is not only used for industrial quality diamond cutting but also for cutting and shaping gem quality diamond which has also gained significant interest recently.

3. Procedure and analysis

This paper will show current cutting results which have been achieved with a standard 2-axis and the newly (May 2015) developed 5-axis machine. Results when cutting PCD tools with a tungsten carbide substrate are given. A picture of the brazed tools is shown in Figure 5.

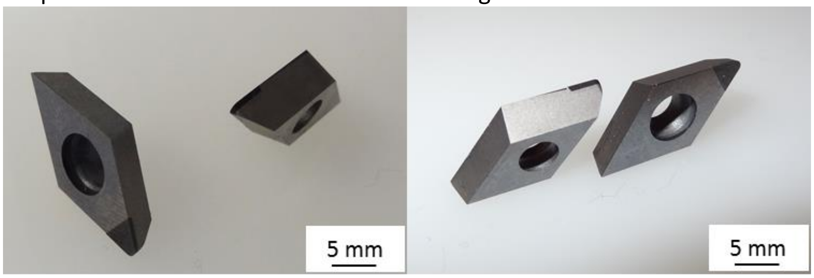


Figure 5: Picture of PCD tipped indexable inserts

The PCD layer is typically 500µm and the thickness of the tungsten carbide layer is therefore 1.1 mm since the overall thickness is 1.6 mm. The process parameters for the different machines and number of axes tested are listed in

Table 1.

Table 1: Processing parameters for the different cutting experiments

Characteristic/Name	LCS150, 2 axes	LCS150, 2 axes, angle	LCS50, 2 axes	LCS50, 5 axes
Machine	LCS150	LCS150	LCS50	LCS50
# of axes used for cutting	2	2	2	5
# of geometry cut	1	2	1	3
Scanning speed [mm/s]	20 mm/s	15 mm/s	15 mm/s	10 mm/s
# of passes	200	150	150	200
Overall cutting speed [mm/s]	0.1 mm/s	0.1 mm/s	0.1 mm/s	0.05 mm/s

The cutting quality was evaluated in terms of the surface roughness of the kerf surface and radius of the cutting edge formed between the cut flank and the top surface of the PCD. The roughness for: the polycrystalline diamond layer and the tungsten carbide substrate were measured although the roughness of the tungsten carbide substrate has no impact on the application of the tools. The roughness analysis procedure is explained in more detail in the section 3.2 and the analysis for the radius measurement is explained in section 3.3. The cutting speed was slightly lower for the 5 axis system but we expect to reach the same values with the 5 axis system after some further development.

3.1. Cut geometry

Three different cutting designs to evaluate the process for 5-axis cutting were tested:

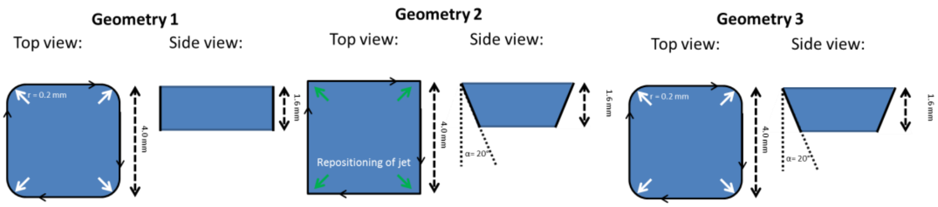


Figure 6: Geometry 1: Cutting geometry used for 2-axis cutting. Geometry 2: Cutting geometry used for cutting with a 2-axis system with clearance angle. Geometry 3: Cutting with 5 axes.

The geometries 1 were cut with the LCS150 2-axis system and using two of the available 5 axes of the 5-axis system of the LCS50. Geometry 2 was cut with a clearance angle of 20° by tilting the PCD sample using the LCS150 2-axis system. Geometry 3 was cut with the 5-axis system. Examples of the geometry 3 shapes are shown in Figure 7.

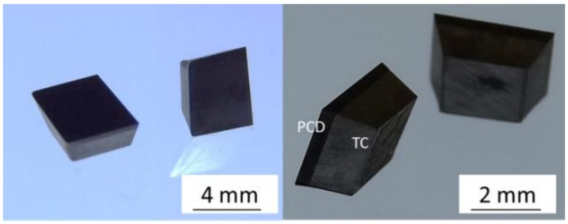


Figure 7: Examples for PCD samples of geometry 3 cut with the Laser MicroJet©.

3.2. Roughness measurements

The roughness measurements were carried out using an Alicona Infinite Focus digital microscope. A profile roughness Ra and a surface roughness Sa were measured. The parameters for the measurement are listed in Table 2.

Table 2: Measurement parameters to measure the roughness on the kerf

Magnitude	**Ra measurement**	**Sa measurement**
Vertical resolution	50 nm	50 nm
Lateral resolution	2 µm	2 µm
Measuring length/field	4 mm	1.00 x 0.35 mm^2
Cut off wavelength Λ_{cut}	800 µm	200 µm
# fields/ # profiles for average per measurement	10	1
# fields /# profiles for average per piece	3	1

An example of a roughness measurement image is shown in Figure 8.

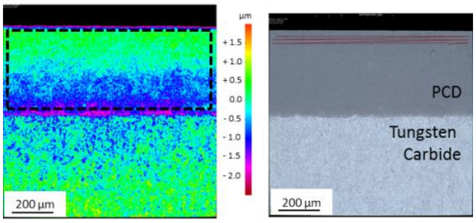


Figure 8: Example for a roughness measurement: Left: Image of measurement, Middle: Surface height of measurement with marked region for the measurement of the roughness on the PCD part.

Figure 9 shows an example for a surface roughness measurement with the parameters of Table 2.

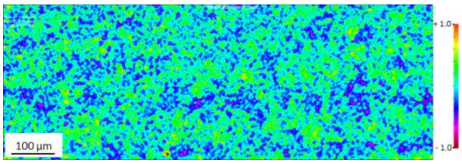


Figure 9: Example for surface roughness measurement Sa

The profile roughness was measured on 3 different lines, 4 mm long on the top, middle and bottom part of the sample. In Figure 10 the profile roughness measurement on the top part from the measurement shown in Figure 8 is shown.

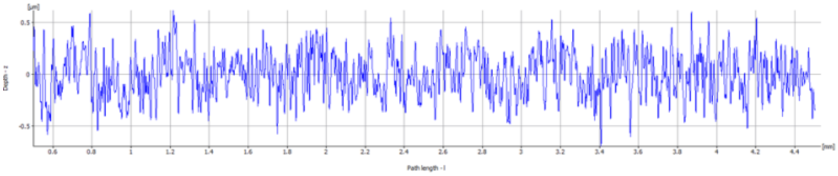


Figure 10: Example of roughness profile for measurement of the roughness on the top with Ra = 168 nm

3.3. Radius measurements

For the cutting edge radius r, a measurement was taken at right angles to the edge. An example for this measurement is shown in Figure 11.

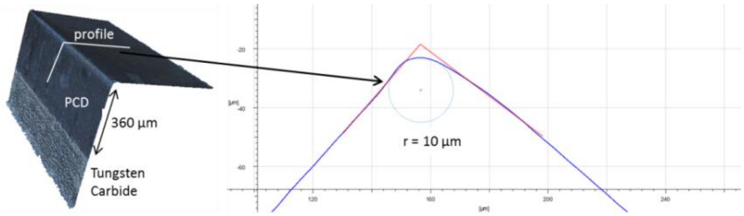


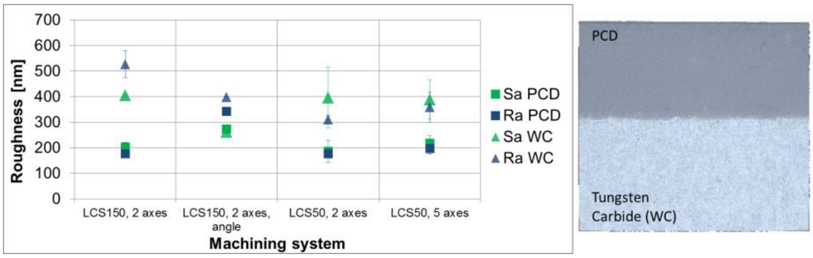
Figure 11: Right: Example for measurement to determine the radius of the tool cutting edge between the top surface of the PCD and the flank Left: Example for the measurement for the radius along a profile

The radius was measured at 5 different positions for each sample and the average was taken as a value for the sample.

4. Laser cutting results

In the first section below, the cutting results achieved by the Laser Mircojet© technology are summarized. In the second section, the results are compared to conventional processing techniques used for making PCD sharp edged tools.

4.1. Cutting of PCD with the Laser MicroJet© technology



In Figure 12 the roughness results for cutting with the different setups listed in

Table 1 are shown.

Figure 12: Roughness Sa and Ra for the PCD and the Tungsten Carbide (WC) cut surfaces with the Laser MicroJet© technology depending on the cutting system and the number of axes used.

The roughness of the kerf on the 2 different machining systems achieved with different number of axes was similar and ranges from Sa = 0.19-0.22 µm (Ra = 0.18-0.30 µm) for the PCD layer and from Sa = 0.26-0.40 µm (Ra = 0.30-0.52 µm) for the tungsten carbide (WC) substrate. The parameters for the 2 axis results seem not be optimal since with the LCS50 system with 5 axis the roughness is lower. So this is not a limitation of the process. Additional the surface roughness of the carbide substrate has up to now not a known influence on the application in which it is used. Nevertheless the roughness of the substrate is included in the comparison here. An example of the characteristic of the surface is shown in Figure 9.

In Figure 13 the results for radius measurement for cutting with the different setups listed in

Table 1 are shown.

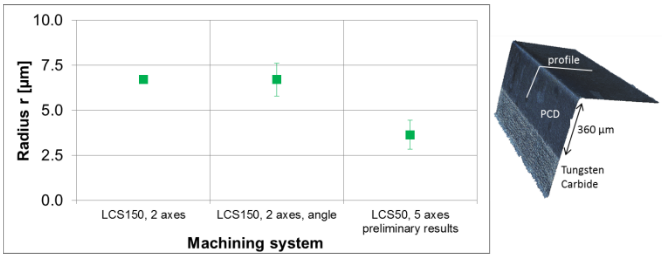


Figure 13: Cutting edge radius measurements PCD tools cut with the Laser MicroJet© technology depending on the cutting system and the number of axes employed

Figure 13 shows that an edge radius (sharpness) in the range of 6-7 µm can be achieved with the standard two axis machining systems. For the LCS50 the development so far was focused on the roughness on the kerf surface. Nevertheless preliminary results show a radius which is similar or even lower to the radius achieved on the standard 2 axis system. The radius is influenced by the cutting strategy used and the laser parameters.

The PCD thickness and the processing parameters were kept constant for this study. However, previous work has shown that different cutting regimes can achieve higher cutting speeds but at the cost of lower cut quality i.e., a greater roughness on the kerf and a less sharp edge radius. Additionally the effective cutting speed depends on the workpiece thickness and the speed reduces as workpiece thickness increases. For a 10 mm thick sample e.g. the effective cutting speed is reduced by the factor of six compared to a 1.6 mm thick PCD sample [1].

4.2. Cutting of PCD with the Laser MicroJet© technology compared to conventional techniques

One of the main advantages of the Laser MircoJet© technology is that the walls of the kerf are always parallel sided as clearly shown in the SEM image of such a cut in 1.6 mm thick PCD on a tungsten carbide backed PCD (Figure 14, left). In contrast, dry lasers lead to a V-shaped cut.

On the right of Figure 14 the problem of undercut caused by preferential erosion during wire EDM cutting is apparent. This is due to a higher concentration of cobalt at the interface between the PCD layer and the carbide substrate. No such problem results when cutting with the Laser MircoJet© technology as the process is independent of the workpiece's electrical conductivity.

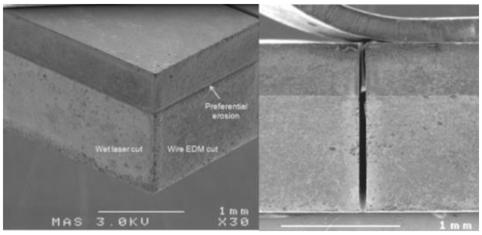


Figure 14: Left: SEM picture of a wire cut and wet laser cut (Laser MircoJet© cutting) PCD showing excessive EDM erosion at the PCD/HM interface. Right: An SEM picture of a cross-section through a parallel sided 50 µm wide kerf in 1.6mm PCD cut with the Laser MicroJet

The current wet laser results shown in section 4.1 have been compared to the conventional PCD processing technologies of wire cutting and grinding. Wire cutting can be used for a direct comparison of the achieved results with the Laser MicroJet©. Afterwards the wire cut samples might be grinded/polished to further smoothen the surface. For this, 5 tools for both techniques were measured with the same standard measurement technique. In Figure 15 the roughness on the kerf for wire cutting and mechanical grinding is compared with the results achieved on the LMJ machine. Unfortunately the dry laser cutting is missing in this comparison which is a very important competitor in this application. We will include the results of dry laser cutting in the presentation of the conference.

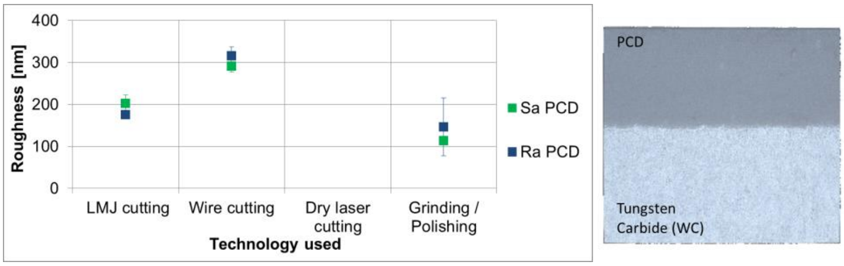


Figure 15: Comparison of the roughness on the kerf for PCD cutting tools processed using the conventional techniques of wire EDM cutting and mechanical grinding and with the Laser MicroJet© technology.

The smoothness on the PCD part of the kerf produced by the Laser MicroJet© technology is lower than that produced by the wire cutting. Compared to grinding, the LMJ roughness is higher by a factor of about 1.5-2.0. But since grinding does not include cutting of the pieces it cannot be directly compared to the other cutting technologies. It might also be applied after the PCD was cut by wire cutting and therefore is an additional processing step. Processing times are compared in Table 3. Further development of the LMJ process to improve the surface roughness is still taking place at Synova.

In Figure 16 the radius on the kerf edge for the different technologies is summarized.

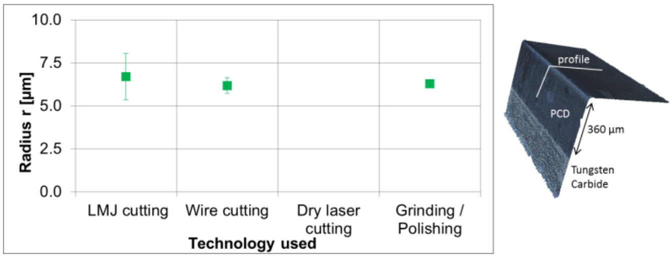


Figure 16: Comparison of the edge radius (sharpness) for PCD cutting tools processed with the conventional techniques wire cutting and grinding with the Laser MicroJet©.

The radius of the edge produced by the Laser MicroJet© technology is similar to that achieved with the conventional processing technologies of wire cutting and grinding. For the application of diamond tools also the edge chipping plays a big role. There is not a magnitude that represents directly the edge quality but it is well known that chipping for EDM cut edges is a problem. In Figure 17 the edge cut by the different cutting technologies are shown.

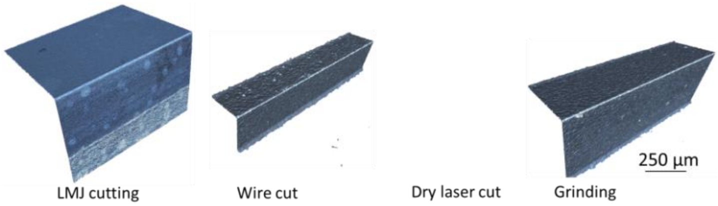


Figure 17: Comparison of the edge quality (sharpness) for PCD cutting tools processed with the conventional techniques wire cutting and grinding in comparison with the Laser MicroJet©.

For LMJ cutting no chips are visible. For wire cutting and grinding the surface the edge looks slightly less homogeneously but also no chips are visible. In Table 3 the characteristics of the different cutting technologies in terms of roughness, radius of the edge and cutting speed are summarized. Unfortunately the dry laser cutting results are missing in this comparison but will be included in the presentation for the conference

Table 3: Roughness on the kerf, radius of the edge and cutting speed for a 1.6 mm thick PCD sample for different cutting technologies.

Technology	LMJ cutting	Wire cutting	Laser cutting	Grinding/Polishing
Sa/Ra PCD	0.20±0.02 µm /0.18±0.00 µm	0.29±0.02 µm /0.32±0.02 µm		0.11±0.00 µm /0.15±0.07 µm
Sa/Ra WC	0.40±0.00 µm /0.53±0.05 µm	0.31±0.01 µm /0.28±0.01 µm		0.12±0.01 µm /0.12±0.01 µm
Radius on the edge r [µm]	6.7±1.4 µm	6.2±0.5 µm		6.3±0.2 µm
Cutting speed [mm/min]	6 mm/min	1 mm/min		1 mm/min (without cutting)

5. Summary

This paper has shown that the results achieved with the Laser MicroJet© technology on a two axis machine can be repeated on a 5 axis machine. On 1.6 mm total thickness PCD on a carbon tungsten substrate (WC), a surface area roughness of Sa = 0.19±0.02 µm can be achieved on the PCD layer and Sa = 0.42±0.08 µm can be achieved on the carbide substrate at an overall cutting speed of 6 mm/min for 2 axes and 3 mm/min for 5 axes. The cutting speed was slightly lower for the 5 axis system but we expect to reach the same values with the 5 axis system after some additional development. At the parameters selected, the radius of the edge (the tool sharpness) was 6.7±1.4 µm for the 2 axis machining regime and preliminary results showed similar values for the 5 axis regime.

Compared to conventional PCD processing techniques, the roughness on the PCD for the LMJ cutting was lower than for wire EDM cutting (Sa =0.29±0.02 µm) but higher than for grinding (Sa = 0.11±0.00 µm). The processing time is about 5 times faster for LMJ cutting than for wire cutting. The processing time for grinding is about the same as for LMJ cutting but does not involve a cutting process so it needs to be added e.g. to the wire cutting processing time. Most importantly, the sharpness of the cutting edge radius was very similar to the radius achieved with conventional tool processing techniques which were 6.2±0.5 µm for wire cutting and 6.3±0.2 µm for grinding – but, it must be emphasized, the LMJ was able to produce a very satisfactory edge at a production rate significantly higher than by wire EDM.

Acknowledgements

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References

[1] P. J. Heath, "Wetter is better," in *Intertech*, Indianapolis, 2015.