Recent Developments in the Cutting of Ultra Hard Materials Using Water Jet-Guided Laser Technology

*Alexandre Pauchard, Marie Di Marco, Benjamen Carron, Grigore Suruceanu, Bernold Richerzhagen, Arnaud Brulé, Notker Kling**

Synova SA, Ch. de la Dent-d'Oche 1, CH-1024 Ecublens, Switzerland
Phone +41 21 694 35 00; fax +41 21 694 35 01; www.synova.ch
E-mail: brule@synova.ch
**Synova USA Inc., 48521 Warm Springs Blvd, suite 314, Fremont CA 94359, USA*
Phone +1 510 438 8900; fax +1 510 438 8805

Abstract

Ultra hard materials, such as polycrystalline diamond (PCD), cubic boron nitride (CBN) and tungsten carbide (WC), are widely used in the tooling industry, e.g. for the fabrication of inserts. Processing these ever-harder materials is an increasing challenge, in particular when thick samples have to be cut following complex shapes.

The water jet-guided laser technology (also known as Laser MicroJet® or LMJ) has proven to be an efficient technique in cutting ultra hard materials. One remaining issue however was the water nozzle lifetime, which was negatively affected by the high power levels required in these demanding cutting applications.

Recent LMJ technology improvements have enabled a significant increase in the reliability of hard material cutting processes, in particular that of the nozzle lifetime. This paper will present the latest results of ultra hard material cutting with the improved LMJ technique. No post-processing steps are required to clean the inserts after cutting, as the level of contamination is very low and heat influence is negligible.

Keywords: water jet-guided laser, micro-machining, cutting, drilling, hard materials

Introduction

The water jet-guided laser technology - also known as Laser MicroJet® or LMJ - was developed in 1993 as a solution to avoid cracks, chipping and deposits of silicon slag in wafer dicing. It is now used in a variety of applications like solar cells, integrated circuits, stencils, OLED masks, etc. More recently, research was carried out to develop this technology for the machining of hard materials, and as a result, very competitive cutting speed and unequalled quality were achieved.

In this article, a brief introduction to the Laser MicroJet® technology is given, then the hard material application problematic is exposed, an overview of other common techniques is discussed, and finally examples of applications are presented.

1. The water jet-guided laser principle

The Laser MicroJet® is a unique process based on the combination of a laser beam and a water jet. The concept is to focus a laser beam into a nozzle while passing through a pressurized water chamber; a schematic of the principle is shown in Figure 1. The low-pressure water jet emitted from the diamond nozzle guides the laser beam by means of total internal reflection at the water/air interface, in a manner similar to conventional glass fibers.

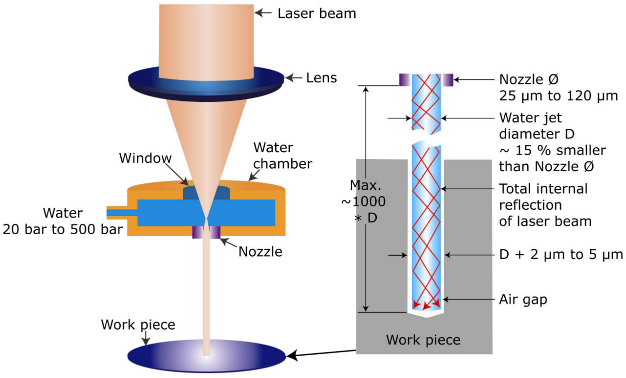


Fig. 1: *Schematic principle of the LMJ coupling unit*

The water jet acts thus as a fluid optical wave-guide of variable length that remains stable while penetrating into the material, which means that the beam size impacting the material is always constant. Only the laser is used for ablation; the main function of the water jet is to guide the laser beam onto the work piece. It ensures the consistency of the spot diameter and consequently enables a single, centimeters-long focus. The water jet has other beneficial effects that prove extremely interesting for precision cutting: maintaining kerfs absolutely clean, simultaneously cooling the edges between the laser pulses and thus preventing heat damage within the material. Hence the water jet-guided laser can be called a "cold laser".

The laser beam is coupled to the water jet in the nozzle, which shape contracts the water jet. The diameter of the water jet is about 83% of the nozzle diameter. A 300-500 µm water chamber is formed between a quartz window and the nozzle, with up to 500 bars of water pressure.

2. Hard Materials

The tooling industry relies on hard materials such as cubic boron nitride (CBN), polycrystalline diamond (PCD), polycrystalline cubic boron nitride (PCBN) and tungsten-carbide (WC) for the manufacturing of inserts as replaceable attachments for tools.

The usual requirements for the cutting quality of materials in the industry are: smooth and parallel edges, narrow kerfs (minimal material loss), no burrs, and no changes in the properties of the material (low heating). The Laser MicroJet® fulfills these requirements thanks to the presence of the water jet, which cools down and evacuates the debris during the machining. Industrial applications also require a high processing speed, which is a feature of machines equipped with Laser MicroJet®.

The additional requirements of tool manufacturing, like the machining of hard materials, machining of inserts cutting edges in a variety of geometries, such as diamond-shape (lozenge) and triangle, make it even a greater challenge.

2.1 Technical challenge

When machining hard materials, a very high peak power laser beam is required, which heats and wears out the different components of the cutting head. For those applications, it became necessary to further develop the design of the cutting head to handle the secondary products of the cutting such as heat and debris, and to stabilize the water jet. The numerous design improvements, in particular the optimization of the thermal dissipation, greatly improved the overall process reliability, in particular the nozzle lifetime.

3. Application examples

Thanks to those improvements, several applications were further developed in the laboratories of Synova SA. A few examples are given below, with the aim of combining high quality results with competitive cutting speed for industrial applications.

3.1 Experimental conditions

The cutting experiments described hereafter were done using a LCS 300 machine from Synova. The Nd:YAG laser used operated at a wavelength of 532nm, a repetition rate of 12 to 18 kHz, and an average power of 125 to 140W.

The following parameters were varied for optimizing the cutting quality and cutting speed: nozzle / micro-jet diameter, water pressure, cutting speed and number of passes. Table 1 shows a selection of the sample series used for the present analysis.

Sample ID	Material	Thickness (mm)	Cutting angle	Type
S-01	WC	3		insert
S-02	PCD/WC	1.6		wafer
S-03	PCD/WC	1.6	7 °	insert
S-04	PCD/WC	1.6	16 ° long. 6 ° latit.	insert
S-05	PCD/WC	1.6		insert + spirals
S-06	PCD/WC	1.6		wafer, pattern 1
S-07	CBN/WC	1.6		wafer, pattern 2
S-08	PCD/WC	3	11°	insert
S-09	WC	5		insert
S-10	WC	3	15 °	insert
S-11	WC	5	15 °	insert
S-12	WC	1.42		rod
S-13	pure CBN	4.8		wafer

Table 1

A wide variety of shapes were successfully cut, showing the great versatility of the Laser MicroJet® technology: inserts with rounded and sharp angles, or lozenge shape, spiral-shape grooves, wafers with linear and triangle patterns, bars and rods.

3.2 Cutting speed results

Table 2 summarizes the parameters for each sample optimized to obtain the best cutting quality. The nozzle diameter is 80 µm for all applications, yielding a micro-jet of about 72 µm and a cut width of about 120 µm. The water pressure is set between 250 and 350 bars.

Sample ID	Material	Thickness [mm]	Cutting angle (^{o})	Water pressure [bar]	Cutting speed [mm/s]	Nb of passes	Overall speed [mm/min]
S-01	WC	3		300	15	80	12
S-02	PCD/WC	1.6		250	25	46	28
S-03	PCD/WC	1.6	7	300	25	70	14
S-06	PCD/WC	1.6		300	25	120	11.5
S-07	CBN/WC	1.6		300	25	120	11.5
S-08	PCD/WC	3	11	300	20	180	6
S-09	WC	5		300	20	200	5.5
S-10	WC	3	15	300	20	130	11.3
S-11	WC	5	15	300	25	300	5

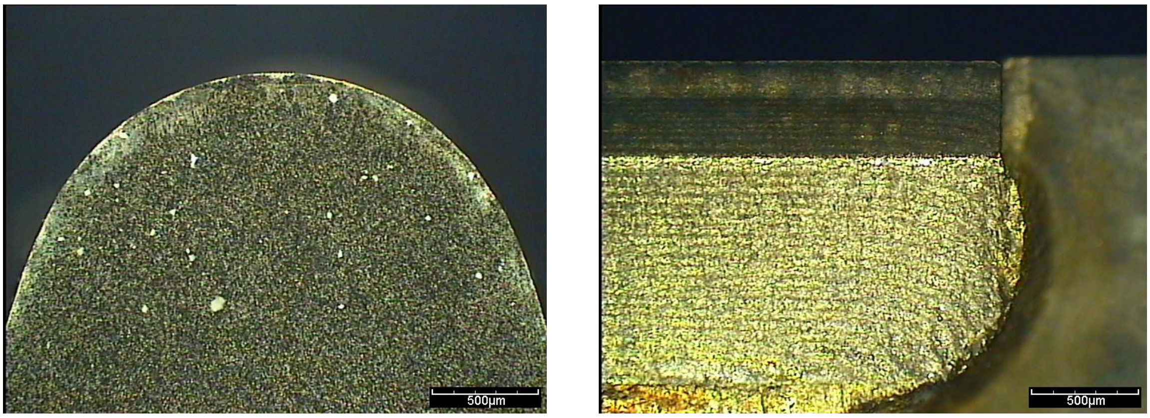
Table 2

The overall speed takes into account the cutting speed and the number of passes necessary to achieve the desired cut. As expected, the overall speed is inversely proportional to the sample's thickness and number of passes. The cutting angle also decreases the overall speed, as the incident angle makes the laser less efficient. Because of its hardness, the machining of WC takes longer; the presence of PCD does not have an impact on the overall speed. The Laser MicroJet® technology is especially unrivaled with pure CBN cutting, as discussed hereafter.

3.3 Cutting quality results

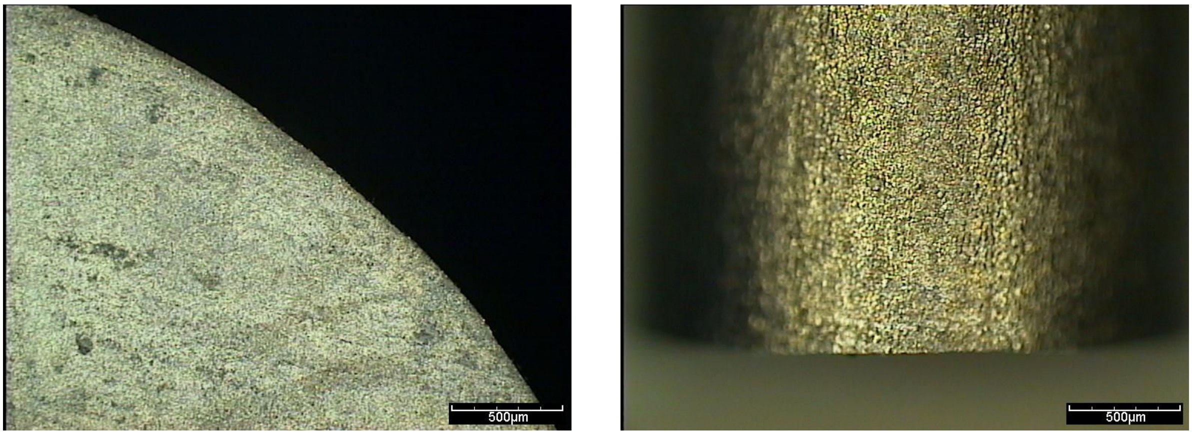
After the cutting, the quality of the samples is evaluated by observing the cutting edges with a microscope with three points of view: front side, where the LMJ is incident; back side, where the LMJ comes out after the cut; and cross-section.

Pictures, as shown in Fig. 2 to 5, show in most cases edges linearity down to 10 µm (less than 1% of the thinnest sample). The edges are sharp and perfectly clean, and there is no recast nor thermal effect. This demonstrates the potential of the Laser MicroJet® technology for achieving very high cutting quality of hard materials.



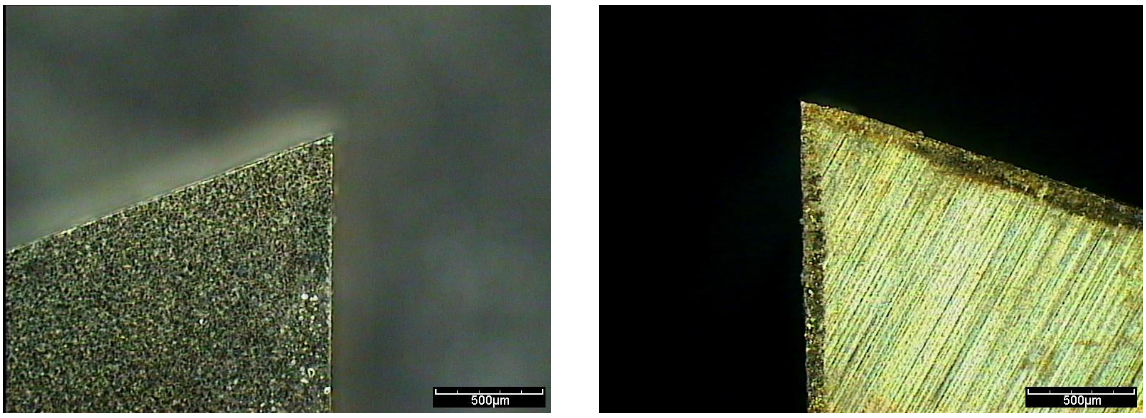
2.1 2.2

Fig. 2: *Microscopic image of PCD/WC (sample S-03); 2.1: front side, round edge; 2.2: cross-section*



3.1 3.2

Fig. 3: *Microscopic image of WC (sample S-09); 3.1: back side, round cut; 3.2: cross-section of cylinder shape*



4.1 4.2

Fig. 4: *Microscopic image of PCD/WC (sample S-06); 4.1: front side; 4.2: back side*

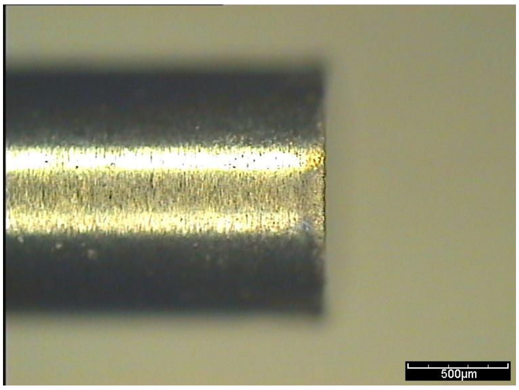


Fig. 5: *Microscopic image WC (sample S-12), cross-section*

3.4 Insert grooving results

Table 3 shows the results for the machining of the central and 5 external grooves of sample S-05. The 5 external grooves overlap on the previous by 40 µm, and each of the grooves (including the central groove) requires 20 spirals overlapping by 20 µm. The machining of the central and external groove uses the same parameters, except for the laser power, which was slightly less for the external groove (12W instead of 16 W for the central groove, all other parameters as specified in Section 3.1).

Sample ID	Xaterial	Thickness [mm]	Nozzle diameter [mum]	Micro-jet diameter [mum]	Water pressure [bar]	Cutting speed [mm/s]	Cutting time [s]
S-05	PCD/WC	1.6	120	~100	120	10	160

Table 3

The total time for machining the central groove and 5 external grooves was of 16 minutes. The technique was further improved and a much smoother surface was obtained (image not available at this time).

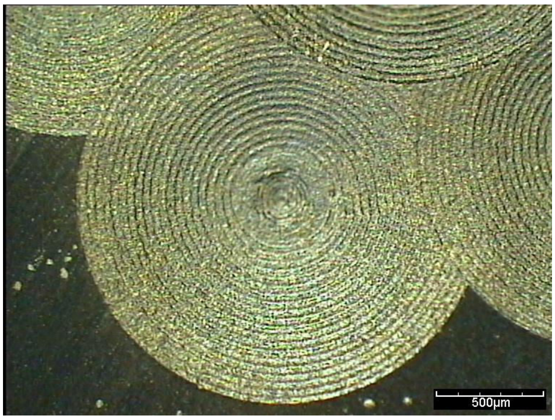


Fig. 6: *Microscopic image of PCD/WC (sample S-05); front side, external groove*

Different shapes, slopes, flatness and depth of grooves were tested on a PCD/WC sample, using additional parameters such as cutting pattern, laser power, line and layer overlap. A few examples shown in figure 7 demonstrate a good cutting quality.

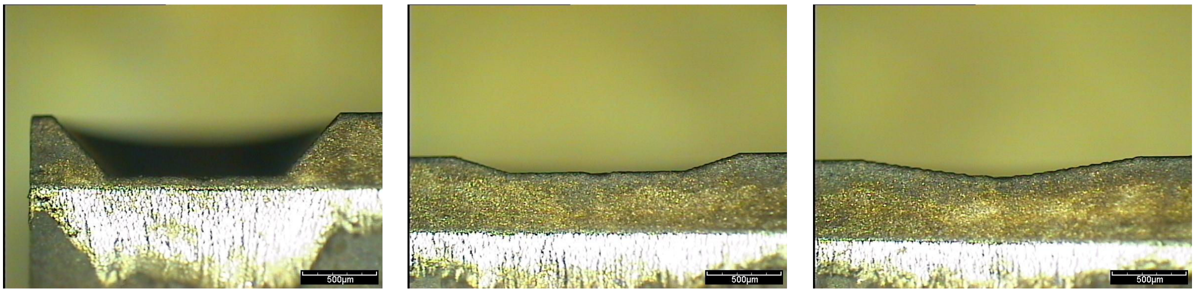


Fig. 7: *Microscopic images of PCD/WC (sample* S-05*); cross section views*

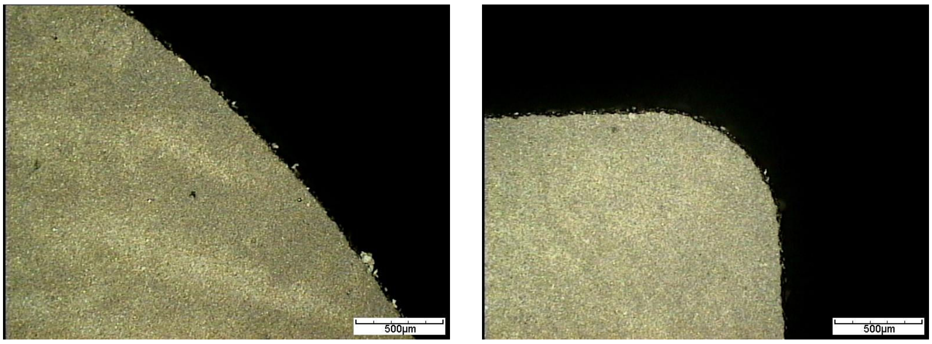
3.5 Pure CBN cutting results

Table 4 shows the parameters used for the machining of three pure CBN samples in custom shapes (disc insert, square insert and triangular insert).

Sample ID	Material	Thickness [mm]	Nozzle diameter [mum]	Micro-jet diameter [mum]	Water pressure [bar]	Cutting speed [mm/s]	Nb of passes	Overall speed [mm/min]
S-13	pure CBN	4.8	80	~66	300	8-9	70-90	6-6.85

Table 4

Figure 8 shows the excellent cutting quality obtained: the front side is clean, and the backside is sharp and regular. The cross-section is smooth and parallel. The LMJ obtained unprecedented results, which are particularly interesting for the tooling industry. Indeed, this material cannot be machined by EDM, as it is not conductive, and the required thickness makes the conventional laser inappropriate.



8.1 *8.2*

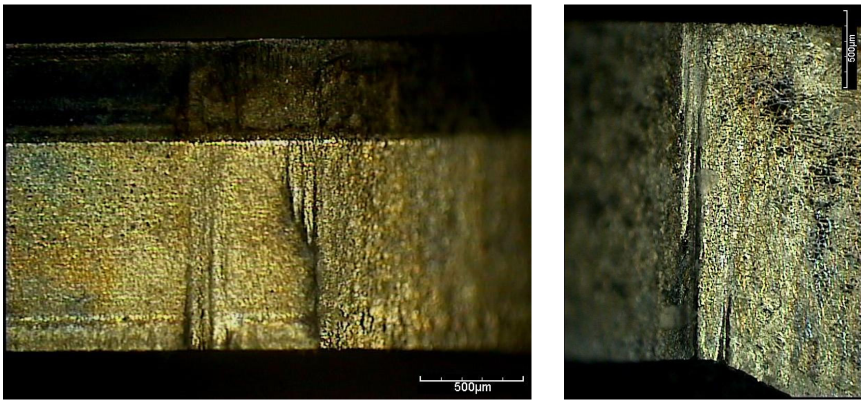
Fig. 8: *Microscopic images of CBN (sample S-13); 8.1: front side; 8.2: backside illumination*

4. Caveats

The Laser MicroJet® technology allows to machine on a much larger depth than conventional laser. Nevertheless, the cutting quality can be compromised if the water jet is perturbed. This was observed for cutting path tangential to the material, and to some extent for sharp angles.

In the first case, the cut is not smooth at the point where the tangential cut starts, like shown in figure 9.1. The issue was solved by simply starting the tangential cut at some distance from the kerf, resulting in a minimal waste of material.

Figure 9.2 shows a small defect appearing in the case of a sharp angle cut. This issue was solved by forcing a round cut with a diameter of >250 µm for the parameters listed above. It is worth noting that this issue is common to all techniques used for machining hard materials; it is presently being addressed within the company's Research Department.



9.1 *9.2*

Fig. 9*: Microscopic images of WC (sample S-01), cross-section*
9.1: tangential cut; 9.2: a small lip is present on the lower half of the sample

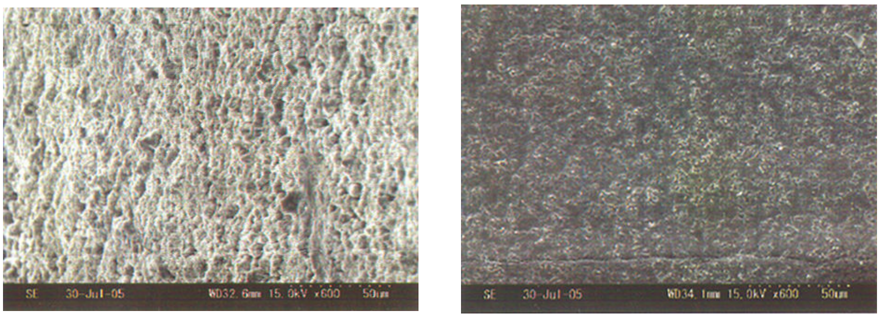
The only limitation of the LMJ to be known so far involves work piece containing copper. Copper has a low absorption coefficient at 532 nm, therefore the technique described in this article is less efficient on work pieces which contain copper layers (note that the same issue arises for conventional lasers). In the case of sample S-08, the cut through was difficult to achieve because of this reason. In the present case the issue was bypassed by removing the copper layer below the cut trajectory.

5. Comparison with other techniques

In this section, the Laser MicroJet® performance with hard material is compared to the most common techniques of diamond saw, EDM (electro-discharge machining) and conventional laser.

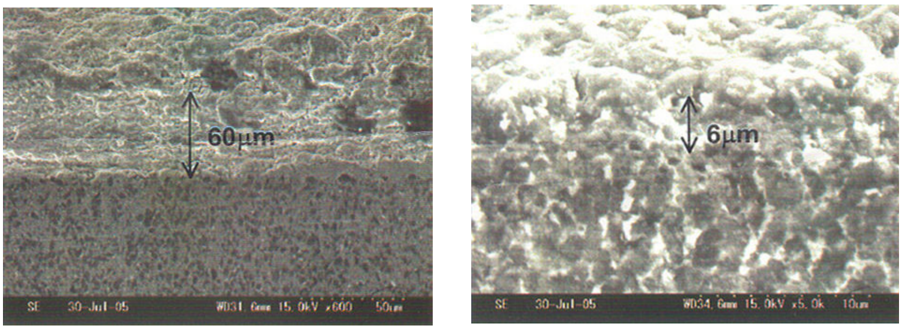
EDM requires electrically-conductive materials and is a very slow process. Conventional laser suffers from depositions, thermal damage, conical kerfs. Often it requires post-processing treatments. The Laser MicroJet® on the other hand achieves good cutting speed, similar to conventional laser (2 to 4 times faster than EDM). It offers edge quality even higher than EDM, 10 times higher than conventional laser. The samples to cut do not need to be electrically conductive. Omni-directional cutting is achievable. No polishing or brazing is required.

Figure 10 and 11 show a CBN sample cut by conventional laser and Laser MicroJet®. The general aspect is very smooth in the case of the LMJ and there is no need for polishing or brazing after the machining; in the case of the conventional laser, some locally deep defects can be seen, which might lead to the breaking of the sample. The heat affected zone (HAZ) in the case of the conventional laser spans over 60 μm, and less than 6 μm in the case of the LMJ.



10.1 *10.2*

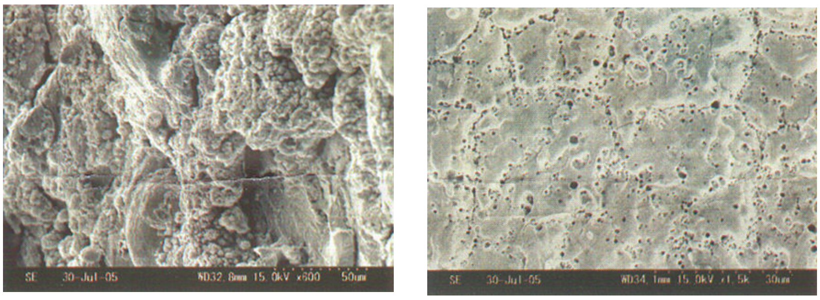
Fig. 10: *SEM photo with x600 magnification. CBN sample cut with conventional laser (10.1) and cut with Laser MicroJet® (10.2)*



11.1 *11.2*

***Fig. 11**: CBN sample cut*
11.1: with conventional laser laser with x600 magnification; 11.2: with Laser MicroJet® with x5000 magnification

The results were conclusive with WC, for which the Laser MicroJet® HAZ pore depth is of 3 μm, and very deep for a conventional laser (not measurable). The cut obtained with the EDM technique achieved a pore depth of 5 μm (not shown).



12.1 *12.2*

Fig. 12: *WC sample cut*
12.1: with conventional laser laser with x600 magnification; 12.2: with Laser MicroJet® with x1500 magnification

6. Conclusion

The results presented in this article demonstrate the potential of the Laser MicroJet® technology for the machining of hard material. An increasing number of tool manufacturers are adopting the process, as it presents major advantages over other techniques:

- Higher throughput than standard diamond blades or EDM.
- Superior quality to standard lasers, no burring, eliminating the need for post-processing
- Vastly greater tool flexibility, as the LMJ is able to cut any pattern, which greatly increases the range of inserts to be easily programmed and fabricated.
- Low operating costs, as there are no blades or cooling liquid to constantly replenish.
- Faster prototyping: the overall speed ranges from 5 to 50 mm/minute, depending on the shape and depth of the cut, which makes the LMJ appropriate for industrial applications.

The Laser MicroJet® allows the machining of a wide range of materials with a good cutting speed and high reproducible quality (smooth edges, small kerf width), without burrs and HAZ, and therefore there is no need for post-treatment.

Biographies

Dr. Alexandre Pauchard

Dr. Alexandre Pauchard is R&D Manager at Synova SA. He has over 12 years of R&D experience in optical systems, working as Director of Engineering at Nova Crystals (San Jose, California) and VP of Engineering at id Quantique (Geneva, Switzerland). He holds a M.S. in Physics from the Swiss Federal Institute of Technology Zurich (ETH) and a Ph.D. in Microengineering from the Swiss Federal Institute of Technology Lausanne (EPFL). He has published over 60 journal and conference papers and has been awarded 6 international patents.

Dr. Marie Di Marco

Dr. Marie Di Marco obtained a PhD in particle physics at the Universite de Montreal (Canada), and worked as a research associate at the Queen's University (Canada), CERN (Switzerland) and Universite de Geneve (Switzerland). Author of several articles in nuclear experiment, instrumentation and detectors in reviewed journals such as NIM A (Nuclear Instruments and Methods in Physics Research Section A) and PRL (Physics Review Letters), she is now working at Synova as a technical writer.

Dr. Benjamin Carron

Dr. Benjamin Carron graduated in Physics at the EPFL. Then in 2005 he obtained a Ph.D in High Energy Physics at CERN (Geneva). His thesis focused on the realization of a micro-strip silicon detector and on a simulation tool to study the early universe matter-anti-matter asymmetry. In 2006 he started to work as an Application Engineer for Synova. He developed there, with Dr Suruceanu, the Laser Microjet® cutting process of hard materials (PCD, CBN, CVD, WC).

Dr. Grigore Suruceanu

Dr. Grigore Suruceanu received a degree in physics from the Chisinau State University, Republic of Moldova in 1983. From 1983 -1989 he worked as product design engineer in the company "Schetmas", Republic of Moldova. In 1989 he joined the Optoelectronics Laboratory of Technical University of Moldova. From 2000-2006 he was with the Laboratory of Nanostructures, EPFL, Switzerland and afterwards with BeamExpress SA. He worked as R&D engineer in the field of semiconductor lasers – long wavelength VCSELs. He is now senior R&D engineer at Synova.

Dr. Bernold Richerzhagen

Dr. Bernold Richerzhagen received his M.Sc in mechanical engineering from Aachen Polytechnic in Germany. During his PhD in microtechnology at the EPFL in Lausanne, he proved the feasibility of guiding laser light in water. Starting with an engineering office in 1996, which enabled him to realize the first industrial prototype, he successfully achieved the commercialization of the Laser Microjet® with the foundation of Synova SA in 1997, to which he is today the CEO & President.

Notker U. Kling

Notker Kling is the General Manager for Synova's North America activities. He has extensive international experience in leading high-technology companies, where he has held numerous management and executive positions at companies such as Leybold, BPS, Unaxis and Singulus in Europe, Asia and North America. He holds a diploma in Electrical Engineering and Information Technology from the University Giessen-Friedberg.

Arnaud Brulé

Arnaud Brulé is Marketing Manager at Synova SA. He has over 12 years of business experience in companies of various industries and services, including Swatch Group and Orange Communications. He holds a B.A. in Economics from the University of Paris X (France), an M.A. in Business Administration from the University of Reading (UK) and a M.Sc. in International Management from the HEC Lausanne Business School (Switzerland).