APPLICATION OF DPSS Nd: YAG (532nm) LASER FOR PRECISE MACHINING OF DIAMOND

Dominik WYSZYŃSKI, Józef GAWLIK, Marta JANUSZ

Abstract: Laser machining has become more and more cost and time effective method of diamond machining. Application of high pulse energy laser sources, as solid state diode pumped Nd:YAG KTP (λ=532nm), results in a high productivity and a very good cutting edge and surface quality in relation to a level of the capital investment and the cost of maintenance. The paper presents results of approach to diamond micromachining, related to application of DPSS Nd: YAG KTP (λ=532nm) laser. The role of the focused laser beam waist area in diamond machining is described. The Rayleigh effective length was roughly assumed as a distance-determining Tool Affected Zone.

Key words: laser precise machining, diamond.

1. Introduction

Diamond machining has been the onerous and time-consuming work demanding a lot of experience in a field of many aspects. Diamond is the most precious and the hardest of available materials and the abrasive machining is costly and limited. Recent progress in synthetic diamond manufacturing made diamonds more available and affordable. The gem-diamond industry still demands natural diamonds, the cutting of which is an art in itself. Laser technology gives a big advantage in the gem-diamond machining, improving time effectiveness and cutting possibilities, thus being strongly ahead of traditional abrasive diamond machining.

Diamond excellent optical properties as the high refractive index, reflectivity and the wide spectrum of transparency, make it very attractive for jewelers. The other physical properties as thermal conductivity, hardness, stiffness, density and widely interpreted resistance make it extremely attractive to industrial and medical applications. With help of modern material science technologies, synthetic diamond is a perfect and relatively cheap material for many applications. Starting from optical elements, through eye surgery tools, diamond anvil cells for material research, LCD scribers, cutting tools and finishing with heat spreaders. Synthetic diamond appears in mono crystalline, polycrystalline as well as metal compacted matrix forms. Each type of synthetic diamond has to some extent different physical properties, but still remains the most untoward of materials.

2. Laser ablation

Ablation, in general, is a removal of the material by means of the laser light. In most cases, like metals and glasses or crystals, the removal is realized by vaporization of the material due to heat. Once the removal appears by vaporization, special attention must be given to the plume. The plume is a plasma-like substance that consists of molecular fragments, neutral particles, free electrons and ions, and products of chemical reactions. The plume strongly determines optical absorption and scattering of the incident laser beam

and can be condensed on the surrounding work material and/or the beam delivery optics. The ablation products can be easily removed by jet of a pressurized inert gas, such as nitrogen or argon.

If the machined material has a poor light absorption coefficient, like diamond, but a thermally converted form of the material has relatively good absorption, such as graphite, then it is reasonable to cover the diamond surface with a thin coating of carbon consisting material or graphite. The laser beam will softly burn the material and ablate the graphite layer on the surface. This will protect diamond against thermal shock that can occur when high energetic laser beam hits the unprotected surface. Doing so the surface of the underlying diamond, will be converted to graphite allowing efficient absorption. Sequentially, the graphite is ablated and a new layer of diamond is converted Fig. 2. The ability of the material to absorb laser energy limits the depth where the energy can perform useful ablation. Ablation depth is determined by the absorption depth of the material and the heat of vaporization of the work material. This depth is also related to beam energy density, the laser pulse duration, and the laser wavelength. Laser energy per unit area on the work material is measured in terms of the energy fluence.
The peak intensity and fluence of the laser is given by:

$$\text{Intensity (Watts/cm}^2) = \text{peak power (W) / focal spot area (cm}^2)$$
$$\text{Fluence (Joules/cm}^2) = \text{laser pulse energy (J) / focal spot area (cm}^2)$$

while the peak power is

$$\text{Peak power (W) = pulse energy (J) / pulse duration (sec)}$$

Micromachining generally requires high energy pulse excimer lasers which have a relatively low duty cycle. It means that the pulse width (time) is very short compared to the time between pulses. Therefore, even though excimer lasers have a low average power compared to other larger power lasers, the peak power of the excimers can be quite large. That make them ideal for micro hole drilling and machining of small volumes. Serious disadvantage of use of excimer laser is the cost of the investment and maintenance. The other one is low productivity and poor surface quality (even if UV light beam of the excimer laser can be focused to the very small spot areas) caused by low mean power and pulse repetition rates (ca. 100Hz).

There are some important aspects to be considered for laser ablation. The first is correlation between a laser beam wavelength λ with absorption coefficient of the material (that is dependent on λ), because it will determine the absorption depth and the volume of the removed material. Knowing this relation one can ensure a high energy deposition in a small volume for rapid and complete ablation. The other aspect is a pulse duration time to maximize peak power and to minimize thermal effect on the surrounding material. It can be described by analogy to a vibrating system where the mass is large and the forcing function is of high frequency. This combination reduces the amplitude of the response. The third aspect is the pulse repetition rate. If the rate is too low, all of the energy which was not used for ablation will leave the ablation zone allowing cooling. If the residual heat can be retained, thus limiting the time for conduction, by a rapid pulse repetition rate, the ablation will be more efficient. More of the laser energy will be used for ablation and less will spread in the surrounding material and the environment. The last of the most important parameters is the beam quality. Beam quality is measured by the brightness (energy), the

focusability, and the homogeneity. The laser beam energy is worthless if cannot be properly and efficiently delivered to the ablation region. Further, if the beam is not of a controlled size and shape, the ablation region may be larger than desired with excessive slope in the sidewalls [1].

That is why, the authors of the present paper focused on research aiming to reveal possibility of application maybe not as high peak power and less ablation prone laser source like Nd:YAG, which is more suitable for precision treatment of diamond for industrial application, not only by means of lower investment and maintenance cost but also by high material removal rate and satisfactory surface quality after machining.

3. Laser machining

3.1. Laser Micromachining

Conventional laser precise machining system has many similarities to a traditional CNC machine tool. The system consists of central programmable computer which controls the movements in x, y axis of the stages for translating the work piece under the focused laser spot and for maintaining the proper vertical location in z axis to maintain the focus.
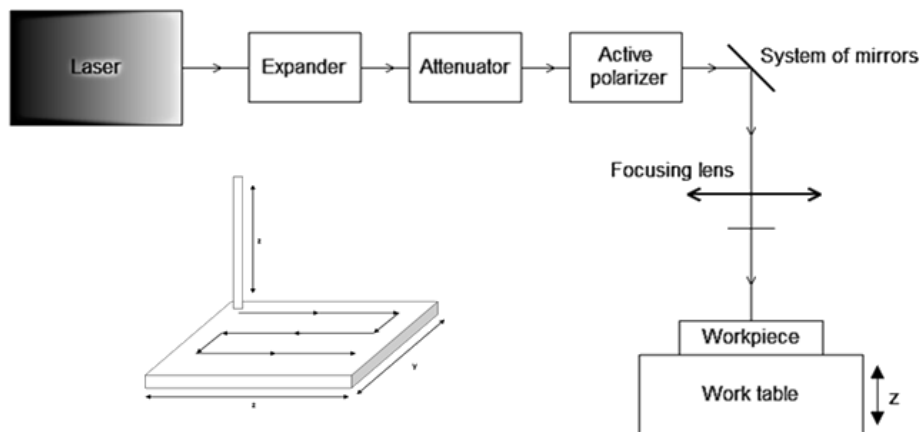

Fig. 1. Scheme of research test stand and the scheme of laser beam machining [2]

The controller also commands the laser pulse control system to adjust the pulse rate and to halt laser pulsing at dwells and for general work movements. The controller can also change the laser pulse repetition rate to maintain a constant pulse spacing as the speed of the work movements change. The microscope camera system is necessary for proper part location and to monitor the operation. The power monitor is used to adjust optical attenuation to reduce or increase the power in the conditioned optical beam. The parameters which control laser machining are mainly material dependent. Another aspect to this is the distance the laser energy will diffuse into the surrounding material. This is a more complex characteristic to predict because the material thermal properties, as well as its optical properties, come into play. Because thermal diffusion is a time-dependent factor, the shorter the laser pulse duration the shorter the diffusion distance. However the diffusion distance also depends on the thermal conductivity of the material. To better estimate the results of

laser machining, it is necessary to have some knowledge of the interaction of the light with the work material. This is not unlike conventional machining where a knowledge of the machinability of the material will aid in estimating the results. Machining with a laser beam is quite different than other machining techniques in that the effectiveness of the process depends on many material properties, some of which the user has no control over. The basic concept of laser machining is shown below. The work piece surface and subsurface characteristics are how well the incident light is absorbed and what type of thermal effect there may be. When light interacts with metals the light will "couple" with free electrons.

The efficiency of how well the photonic energy can be transferred to electron vibrational energy is a measure of this coupling. As the electrons are excited they will collide with the metal crystal lattice thus raising the temperature. If the temperature is high enough, melting or vaporization will occur. If the coupling is very low, the metal is said to be reflective and the temperature will not be raised enough for material removal to take place. Sometimes a poor absorption can be overcame by covering the material with a good absorber to increase the temperature and change the absorption properties of the underlying substrate [1].

Laser machining of diamond in visible (λ = 532nm) and infrared (λ = 1064nm) range is, despite of his optical transparency, possible thanks to multi photon absorption activated by use of Q - switching technique. The transparency of diamond at above-mentioned wavelengths translates to a less efficient energy absorption process requiring more energetic photons to affect the material removal process [3]. Diamond machining with use of visible and IR wavelengths, due to poor diamond light absorption rate, is pyrolitic process and divides in three stages. Incident light, due to high pulse energy and repetition rate, interacts with diamond valence electrons. When the light interacts with material photons will "couple" with free electrons. The efficiency of how well the photonic energy can be transferred to electron vibration energy is a measure of this coupling. As the electrons are excited they will collide with the material crystal lattice thus raising the temperature. Thermal decomposition mechanism is dominant. The diamond surface temperature is rapidly elevated enabling sublimation effect and graphitisation of structure. Carbon diamond crystalline lattice transforms to graphite. Graphite has a good absorption rate for this range of electromagnetic wavelengths, thus melts and evaporates, creates plasma and carbon dioxide. In the ablation process a part of the previously graphitised layer is removed, but simultaneously a deeper layer of diamond is converted to graphite, so the laser etching occurs as a pulse by pulse penetration of graphitic "piston" into diamond [4]. The scheme of laser removal process is presented below, Fig. 1.

As it was shown on the picture above, the material is removed not only at the laser focused beam spot area, but also at some space surrounding. The space where the material is removed is limited by:

$$\begin{cases} d_{TAZ} \geq d \geq d_f \\ z_0 - C \leq z \leq z_0 + h_{TAZ} \end{cases} \qquad (1)$$

where: h_{TAZ} – tool affected zone depth,
z_0 – the crater bottom level,
h – diamond plate height,
v – machining speed vector,
d_{TAZ} = $2r_{TAZ}$ (Fig. 2); d_f = $2r_f$,
C – the crater depth.

Such a phenomena results from energy density distribution in focused laser beam as well as from spatial beam character. This active space can be assumed as a tool shape, Tool Affected Zone (TAZ).
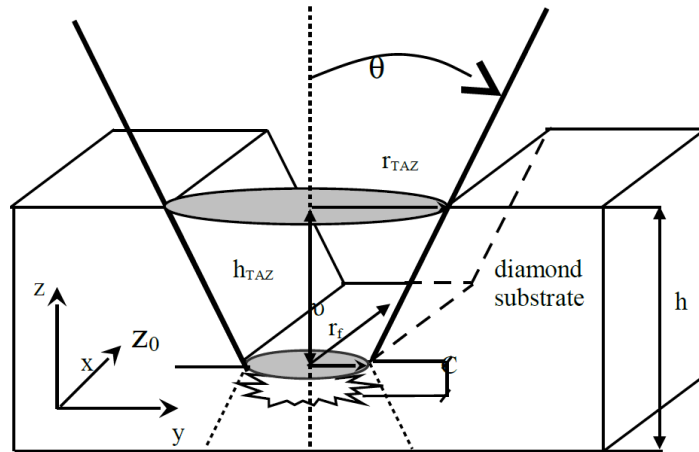

Fig. 2. Scheme of laser diamond machining [2], r_f – focused beam radius, r_{TAZ} – tool affected zone radius, Θ – focused beam divergence

The h_{TAZ} distance can be roughly approximated by a half of the depth of the focus distance, called Rayleigh length z_r:

$$h_{TAZ} \approx \frac{1}{2}z_r = \frac{\pi r_f^2}{2M^2\lambda} \tag{2}$$

where: M^2 is beam propagation factor and λ is laser wavelength.
As the energy density in a laser beam has the Gaussian distribution in xy plane, some advantages and drawbacks can be noticed.

Precise laser shaping of diamond strongly decreases manufacturing time and costs of production in various industrial and medical applications. The presented below photographs relate to variety of applications of diamond tools.
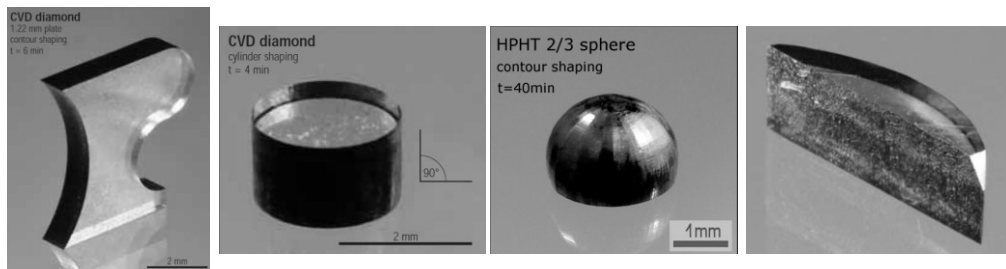
Fig. 3. Examples of precise cutting of mono crystalline and rough diamond

The high-pressure research require opposed anvil device with small flat areas that are pressed one against the other with a lever-arm. The anvils previously were made of

a tungsten-carbon alloy (WC). This device could achieve pressure of a few GPa, and was used in electrical resistance and compressibility measurements. The invention of the diamond anvil cell in the late 1950s at the National Bureau of Standards (NBS) by Weir, Lippincott, Van Valkenburg, and Bunting further refined the process. The principles of the DAC are similar to the Bridgman anvils (pioneer) but in order to achieve the highest possible pressures without breaking the anvils, they were made of a single crystal diamond.
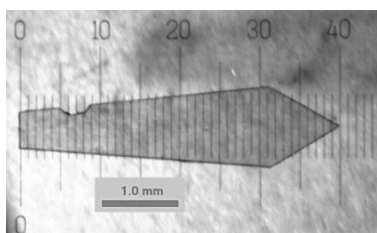
Fig.4. Eye surgery diamond knife blank (before polishing). Shaping time <5min
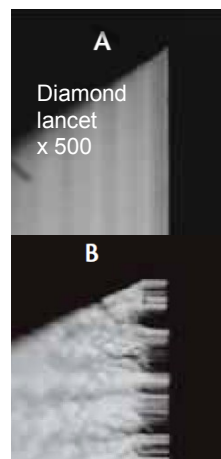
Fig. 5. Comparison of polished diamond and steel edge of the eye surgery knife [5]

The first prototypes were limited in their pressure range and there was not a reliable way to calibrate the pressure. During the following decades DACs have been successively refined, the most important innovations being the use of gaskets and the ruby pressure calibration. The DAC evolved to be the most powerful lab device for generating static high pressure. The range of static pressure attainable today extends to the estimated pressures at the Earth's center (~360 GPa).
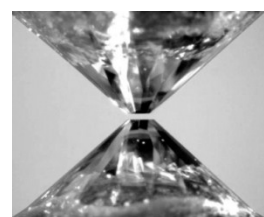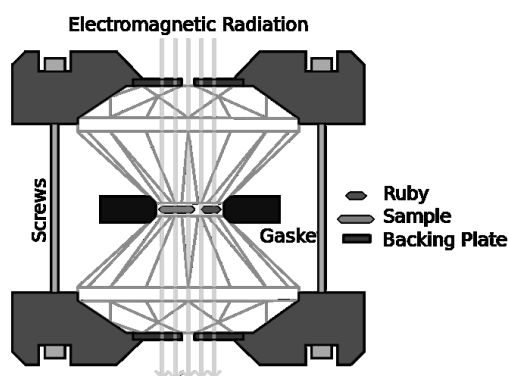

Fig. 6. Scheme of laser-heated diamond-anvil cell. A photography of the diamond anvil cell for high-pressure squeezing. Credit Vitali Prakapenka

Diamond thanks to his relevant physical and chemical properties is also very attractive material for cutting tools. In example hardness at 600° C is 10000 Vickers. Figure below presents possibility of preparation of the cutting toll insert by means of precise diode pumped solid state laser machining in very fast and reliable way.
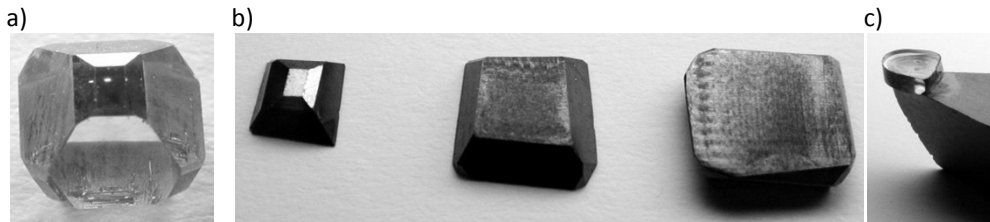

Fig. 7. Stages of preparation of the cutting tool insert: a) Synthetic HPHT diamond, b) laser slicing, work time 5min., c) pre-shaped soldered cutting tool insert (shaping time 1m,45s)

Tool inserts can be prepared of mono crystalline HPHT (High Pressure High Temperature) diamond as well as of CVD (Chemical Vapor Deposition) polycrystalline blanks, Fig. 8.
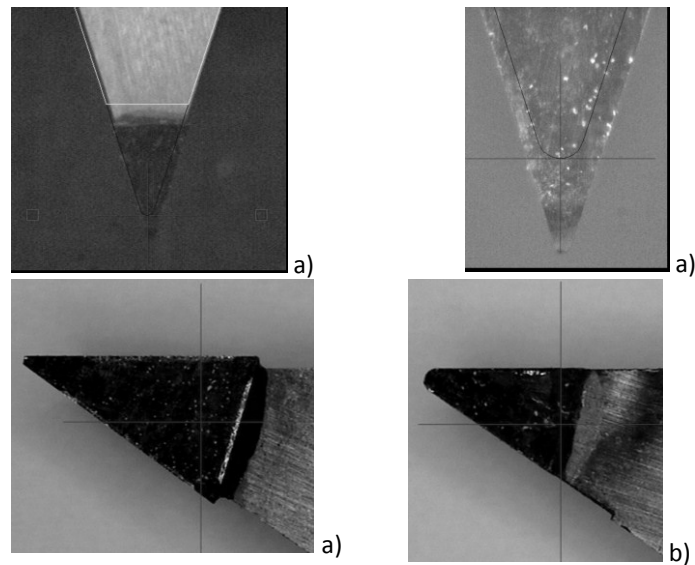

Fig. 8. CVD cutting tool insert before (a) and after (b) shaping. Blue line defines laser shaping geometry. Color changes are not from laser machining, originate from soldering process
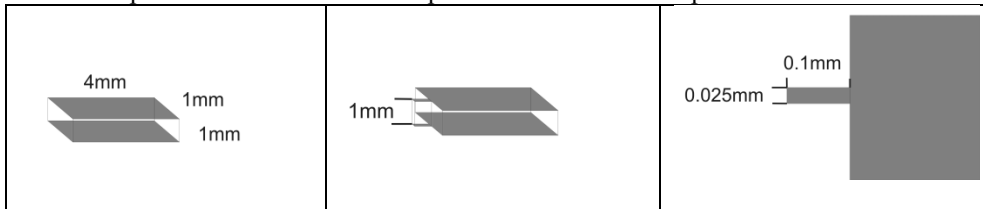
3. Experimental data

The experiment was carried to check feasibility of shaping v –grooves, spring and holes in the CVD diamond plate according to the manner presented below, Table 1, 2 and Table 3.

Tab. 1. Shape and dimensions of the experimental diamond sample 1
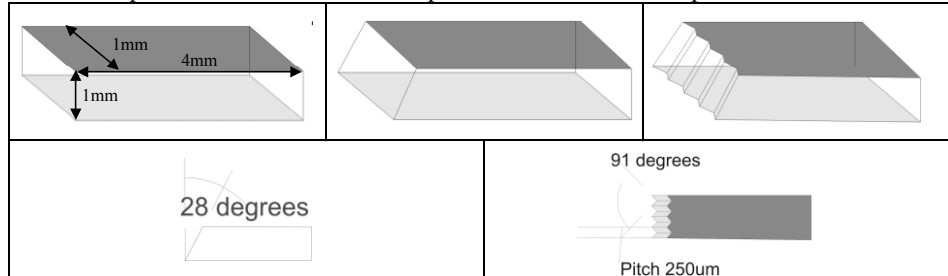
Tab. 2. Shape and dimensions of the experimental diamond sample 2

Tab. 3. Processing parameters

laser type	DPSS KTP Nd:YAG
wavelength λ	532 nm
focused beam radius r_f	8 µm
focal length	77 mm
M^2	1,2
average power	9,3 W
pulse repetition rate	10 kHz
pulse duration (width)	115 ns
speed	0,5 mm/s
h_{TAZ}	150 µm

4. Results

Scanning microscope photography below depicts the first attempt to prepare required geometries basing upon typical approach for diamond machining.

After the inspection these samples were disqualified because of poor quality of obtained diamond edge. The topside edge quality and underlying surface were acceptable, whereas going deeper the surface was damaged and bottom side edge quality and geometry were of a very poor quality. The reason why the cutting results differ with depth of cutting, was defined by the influence of the previously mentioned Tool Affected Zone. It means, that even if the vertical step was determined to cut the material on time, the out of focus part of the beam (h_{TAZ}), was destructive.
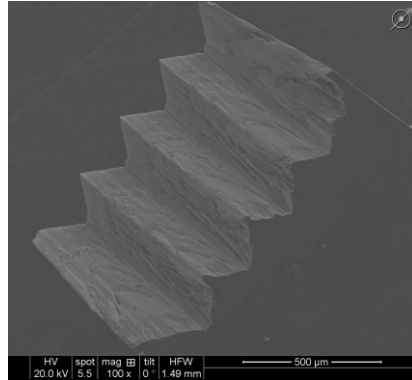
Fig. 9. The edge and surface quality. Bottom edge - foreground, top edge – background [7]

The new approach was assumed. The idea was to set the vertical step value too small, so in the beginning the material was removed in focus and going deeper the beam was focused beneath the machined surface. In consequence, the material was cut before all vertical steps were done, but the process was carried until the end. This regime, using both in focus and smart TAZ machining brought a very good effect. Precise micro -products were produced by 30% - 50% overlap. Out of this range the roughness increases steeply [6]. The results are presented below, Fig. 10 and Fig. 11.
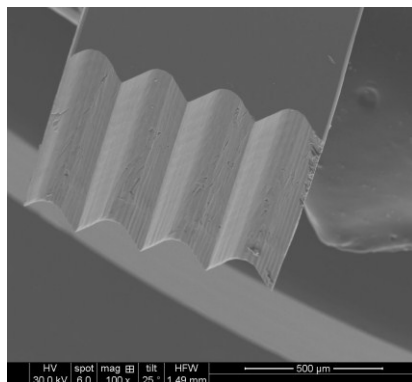

Fig. 10. The edge and surface quality. Bottom edge – bottom, top edge – top [7].

The quality of the top and bottom edge, as well as of the surface was satisfying. The geometry of top and bottom edge was comparable; the edge was sharp without chip outs. The surface area was smooth and scorch - free. Noticeable fragments are fixing glue leftovers.
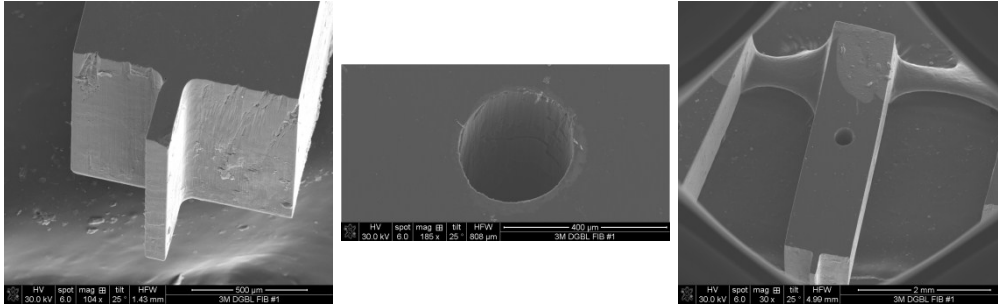
Fig. 11. Top view for the springboard and hole

5. Summary

The experiment revealed a new regime for diamond laser machining. The standard manner of vertical step optimisation proved to be correct only for sawing (cutting in line). The sawing line was straight, long and the surface quality in such a case was smooth and scorches free. Standard laser sawing speeds are relatively high (more than 5mm/s). Machining of complicated shapes and drilling of small holes requires significantly smaller speeds, which is related to inertia of the x-y table. The relation between laser power, sawing speed, pulse repetition rate (and a resulting pulse overlapping) must be preserved. Decreasing the speed results in a higher pulse overlapping. Pulse energy can be certainly decreased by increasing the pulse repetition rate, but it is limited by the pulse width, which is fixed. Low speed machining results in a remarkable energy density growth in the machined area. Even a very good diamond heat conductivity does not protect a sample against undesirable warming, which can result in a surface mating. Ablated material (graphite and CO_2) has to be blown away from the machining gap, because the created hot plasma [6] may undesirably contribute to TAZ (uncontrolled laser beam reflections and heat impact). The airflow removes the plasma, graphite debris and excessive heat from the gap.

Although the changing of the pumping diode current enables changes of the laser power, the quality of the beam is badly affected. Therefore, to control the laser power without influencing the beam quality, a system consisting of polarizer, retardation plate and dumping element should be applied (Fig. 9). More over the additional system for active polarisation control (Fig. 1.) has to be applied in order to meet quality requirements.

Fig. 12. Motorized variable attenuator for linearly polarized laser beam [8]

The Rayleigh length has a relevant impact on a laser machining of small, complex shaped parts. Especially, as such a transparent material as diamond is strongly exposed to the undesirable phenomena. Machining in a range of the Rayleigh length may bring benefits, as it was described in the present paper, by taking the advantage of the surface smoothing by boundary areas of TAZ, where the energy density is lower. However, it may also become damaging to the material, if the machining occurs in TAZ, but laser beam focus is situated under the machined surface. Such a case usually results in an internal explosion, which creates uncontrolled cracks, chip outs and an inevitable waste of such a precious material as diamond.

Further research will be focused on precise treatment of diamond and diamond based composites (PCD) as well as sapphire, titanium and other biocompatible materials used for hip implant manufacturing.

Literature

1. Friedrich C. R., http://www.me.mtu.edu/~microweb/.
2. Wyszynski D., Skoczypiec S., Furyk K..: Mathematical modeling of the precise laser cutting process of Al2O3 (sapphire) crystal. Journal of Machine Enginering, Vol 12, No. 2, 2012, Page 20-28, ISSN 1895-7595X.
3. Rothschild M., Arnone C., Ehrlich D.J.: Excimer - laser etching of diamond and hard carbon - films by direct writing and optical projection. Journal of Vacuum Science & Technology B.; 4 (1), Jan - Feb 1986,p. 310-314.
4. Hellrung D., Gillner A., Poprawe R.: Laser beam removal of microstructures with Nd:YAG lasers. Proceedings of Lasers in Material Processing Laser'97, SPIE 3097, 1997, p. 267-273
5. http://www.meyco.ch
6. Park J.K.., Ayres V.M., Asmusen J., Mukherjee K..: Precision micromachining of CVD diamonds. Diamond and Related Materials 9, 2000, p. 1154-1158
7. Wyszynski D.: Uwzględnienie strefy oddziaływania wiązki laserowej w obróbce diamentu. Inżynieria Maszyn, R. 12, z. 4, 2009, p. 94-102, ISSN 1426-708X
8. http://www.eksmaoptics.com/

Dr inż. Dominik Wyszyński
Prof. dr hab. inż. Józef Gawlik
Mgr inż. Marta Janusz
Instytut Technologii Maszyn i Automatyzacji Produkcji
Politechnika Krakowska im. Tadeusza Kościuszki
31-155 Kraków, ul. Warszawska 24
tel.: 12 374 3749; 12 3743246
e-mail: wyszynski@m6.mech.pk.edu.pl
        jgawlik.pk@gmail.com
        majowa88@interia.pl